WIRELESS TECHNOLOGY EVOLUTION

Transition from 4G to 5G

3GPP Releases 14 to 16

5G Americas Whitepaper

OCTOBER 2018

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1 INTRODUCTION

5G is said to be disruptive…. change is evident and it is unknown what the future may hold. And yet, analysts are projecting the expected results from 5G technology while the early stages of trials and pre-standardized deployments are just beginning and commercial 5G deployment is clearly on the horizon.

- *5 Billion people forecast to be accessing the internet via mobile by 2025*
- *5G coverage will roll out rapidly to cover 440 percent of the global population by 2025*
- *5G will account for almost 1 in 7 connections (14 percent) by 2025*
- *Global penetration rate for all mobile connections will reach 110 percent worldwide by 2025*
- *9 Billion mobile connections by 2025*
- *5.9 Billion unique subscribers in 2025*
- *25 Billion Internet of Things devices globally in 2025*
  (11.4 Billion Consumer IoT; 13.7 Billion Industrial IoT in 2025)
- *Global Mobile Annual Revenue of $1.1 Trillion in 2025*[1]

All of this may be enabled through the LTE-Advanced and 5G specifications created by hundreds of contributing scientists and engineers at the Third Generation Partnership Project (3GPP). The transformation to 5G will also transform our lives, our economy, our jobs, our industries. The early signs are beginning to show. Wearables are developing in such a way that they may become self-contained mobile computing devices, for example the cellular Apple Watch or connected glasses. The big expectation is the connected car; autonomous vehicles will give us back commute time for new activities in our lives. The healthcare system is changing as remote monitoring and robotic surgery provides a different level of care. Drones will be used for transportation, surveillance and rescue operations. Robots and Artificial Intelligence (AI) will result in a new relationship for both humans and machines. The wireless industry is virtualizing; Multi-Access Edge Computing (MEC) is going to redefine computing itself and certainly impact the mega-networks of things in the future… billions of connected things… billions of connected people… and a major shift in network operations and management.

Since the wireless industry coalesced around Long-Term Evolution (LTE) in recent years, it has brought together the entire mobile industry, evolving deployments to a single technology, enabling an ecosystem larger than ever before. Already more than a quarter of all global mobile subscribers are using (LTE) and it's expected that by 2021 this will increase to more than half. While LTE deployments continue to expand, and grow across the world, certain regions such as Korea, Japan, China and the U.S. have nearly reached or exceeded 90 percent penetration of LTE. This pushed up the focus in the mobile industry towards 5th Generation (5G) mobile technology, standards development, demos and trials. There continues to be growing demands for higher throughputs and more data capacity, particularly for video, to provide better broadband services. But data demand is just one of the drivers for 5G. In addition, 5G is targeted to address new vertical markets including massive Machine-Type Communications (mMTC), Ultra-Reliable Low Latency Communication (URLLC) and a broad range of Internet of Things (IoT) applications in general.

The evolution of LTE (LTE-Advanced Pro) continued its standardization in 3GPP Rel-14, which was frozen by mid-2017 and potentially ended specifications on LTE -- a decade since its initial specification in Rel-8 -- included features such as further Multiple-Input Multiple-Output (MIMO) antenna enhancements, Carrier Aggregation (CA) enhancements, enhanced Licensed Assisted Access (eLAA), enhanced LTE Wireless Local Area Network Aggregation LWA (eLWA), Voice-over-LTE (VoLTE) enhancements and

[1] *Mobile World Congress Daily*, GSMA Intelligence. 1 March 2018.

enhancements to Proximity Services/Device-to-Device (ProSe/D2D). Rel-14 also focused on the study items towards the 5th Generation (5G) mobile wireless technology and architecture, therefore the initial work on the 5G standards.

As in the past, the International Telecommunication Union (ITU) is providing guidance, requirements and recommendations that are setting the stage for this next generation of mobile wireless technologies. Just as the ITU defined International Mobile Telecommunications-2000 (IMT-2000) to drive towards Third Generation (3G), and IMT-Advanced to drive towards Fourth Generation (4G), the ITU now is defining IMT-2020 to drive towards 5G specification. As the name implies the IMT-2020 process is targeted to define requirements, accept technology proposals, evaluate the proposals and certify those that meet the IMT-2020 requirements, all by the 2020 timeframe.

3GPP defined a two-phased 5G work program starting with study items in Rel-14 followed by two releases of normative specs spanning Rel-15 and Rel-16 with the goal being that Rel-16 includes everything needed to meet IMT-2020 requirements and that it will be completed in time for submission to the IMT-2020 process for certification.

The 5G work in 3GPP on Rel-14 study items focused on both new Radio Access Network (RAN) technologies and new System Architecture (SA) aspects. The studies on new RAN technologies for 5G are called New Radio (NR) and are focused on defining a new radio access flexible enough to support a much wider range of frequency bands from <6 GHz to millimeter wave (mmWave) bands as high as 100 Gigahertz (GHz). Given this wide range of carrier frequencies that must be supported, Orthogonal Frequency Division Multiplexing (OFDM) will be the basis for the 5G NR air interface. All new, state-of-the-art frame structures, coding, modulation, MIMO, beamforming, etc. technologies were investigated as part of the 5G NR study item. Given this was the first 3GPP technology targeted at providing optimized performance in the mmWave bands, much of the focus in 3GPP 5G NR is on channel modeling and radio access features designed to address the quasi-optic nature of mmWave communications. In parallel, the System Architecture (SA) groups in 3GPP studied the Services and Markets Technology Enablers (the SMARTER study) that will drive the next generation system architecture, which has led to design principles, requirements and target deployment scenarios for the 5G network architecture. This has led to the identification of many key issues that need to be addressed as part of defining the 5G network architecture such as the support for Network Slicing, Quality of Service (QoS), Mobility and Session Management, Policy, Security and more.

Rel-15 began work on the first phase of normative specifications for 5G. Following numerous requests from leading companies, 3GPP escalated their timeline for Rel-15 Non-Standalone 5G New Radio (NSA 5G NR) specifications which were completed December 2017. The 5G NSA specifications have an LTE anchor for the control plane communications with a 5G NR cell to boost user data. The Rel-15 Standalone 5G NR specification will offer a full suite with a Standalone NR system with no reliance on LTE. The new core for Rel-15 will provide interaction with the Evolved Packet Core (EPC) 4G system with orchestration, virtualization, a clearly separate control and user plane, and signaling architecture. Network slicing and Service Level Agreement (SLA) for groups of devices of new vertical industries and services will be provided for by the 5G core specifications. Rel-15 SA NR specifications were completed in June 2018.

To meet the timeline and full compliance with ITU IMT-2020 requirements, the standardization in Rel-16 continues to progress. Definition of the study items and work items was completed in July 2018, on schedule, with the option of adding additional Study Items/ Work Items (SIs/WIs) in the future, as needed. Rel-16, or phase 2 of 5G, will primarily address any outstanding issues in Rel-15, expansion of 5G technology features and increased 5G efficiency. Expansion of 5G will include New Radio (NR) based

Cellular-Vehicle to Everything (C-V2X) capabilities, Industrial IoT, enhancements to Ultra-Reliable Low Latency Communications (URLLC), and 5G in operation in unlicensed spectrum and above 52.6 GHz. 5G efficiency improvements will include enhancements to 5G Self-Organizing Networks (SON) and Big Data capabilities, MIMO enhancements, improved power consumption, support for device capabilities exchange, and a study of support for non-orthogonal multiple access (MOMA).

This paper provides a detailed status of key areas of work in 3GPP on Release 14 LTE enhancements and studies towards definition of the radio access and system architecture for 5G in Releases 15 and 16 and beyond. The 3GPP timeline is shown in Figure 1.1.

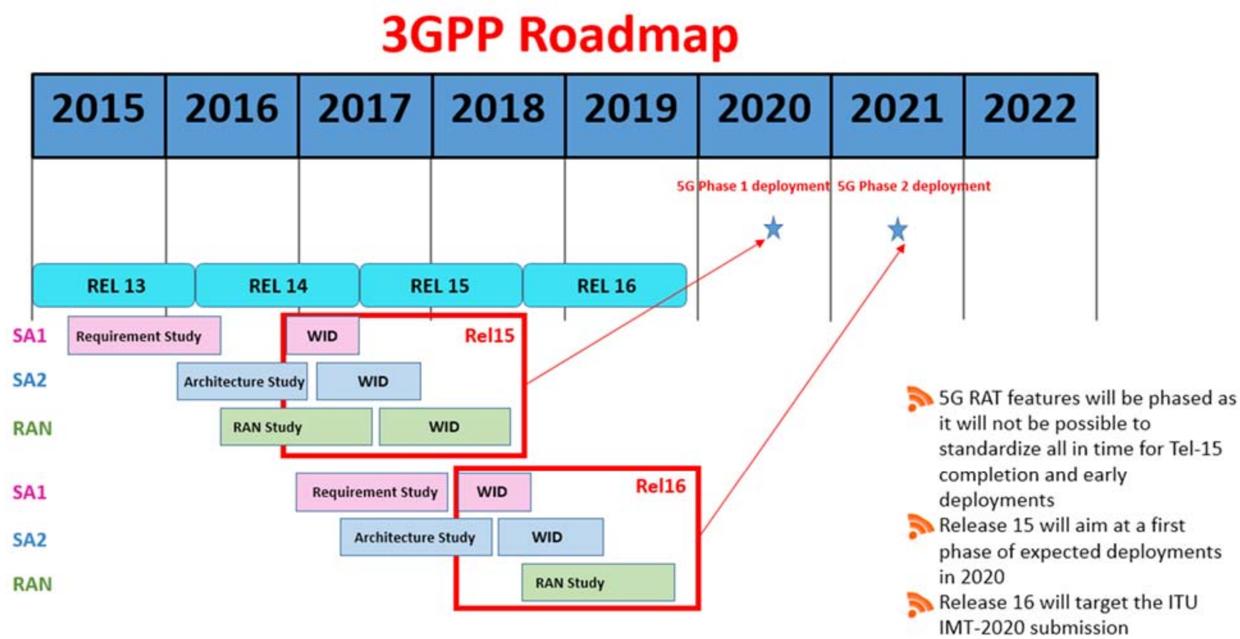

Figure 1.1. 3GPP Timeline Releases 13 to 16.

2. GLOBAL MARKET TRENDS, MILESTONES AND STANDARDIZATION

By the end of March 2018, nearly 40 percent[2] of the 7.5 billion people worldwide had access to a Fourth-Generation Long Term Evolution (4G LTE) network, providing them with high-speed services and applications including mobile internet. Global LTE coverage stood closer to 44 percent by the end of the 1Q 2018.

[2] *WCIS*, Ovum. March 2018.

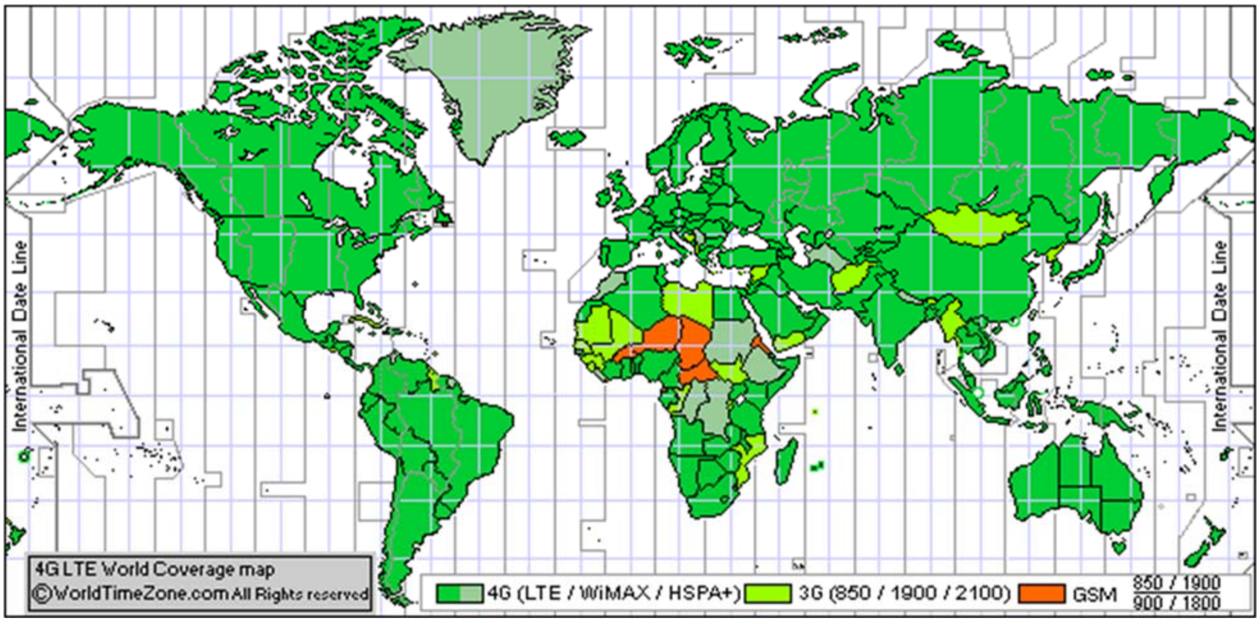

Figure 2.1. 4G LTE Global Deployment - 2Q 2018.[3]

By 2021, LTE is expected to account for 58 percent of global connections.[4] However, by 2022, LTE forecasts indicate a market share peak at 60 percent of all connections after which time 5G subscriptions begin to grow and LTE growth declines.[5]

While GSM represented 49 percent of the global market in 2015, this declined to 41 percent in 2016, and will decline to 13 percent worldwide by 2021.[6] The shift from 2G is evident; some service providers (e.g., AT&T) have sunset their 2G networks (2017) to properly plan in areas such as Machine-to-Machine (M2M) communications and other connected devices. The need for service providers to sunset their networks weighs heavily on their available spectrum assets, reframing their spectrum and getting the best efficiencies by using more advanced 4G technology in those limited spectral resources.

[3] Worldtimezone.com, August 2018.
[4] *WCIS,* December 2017.
[5] *Ibid.*
[6] *Ibid.*

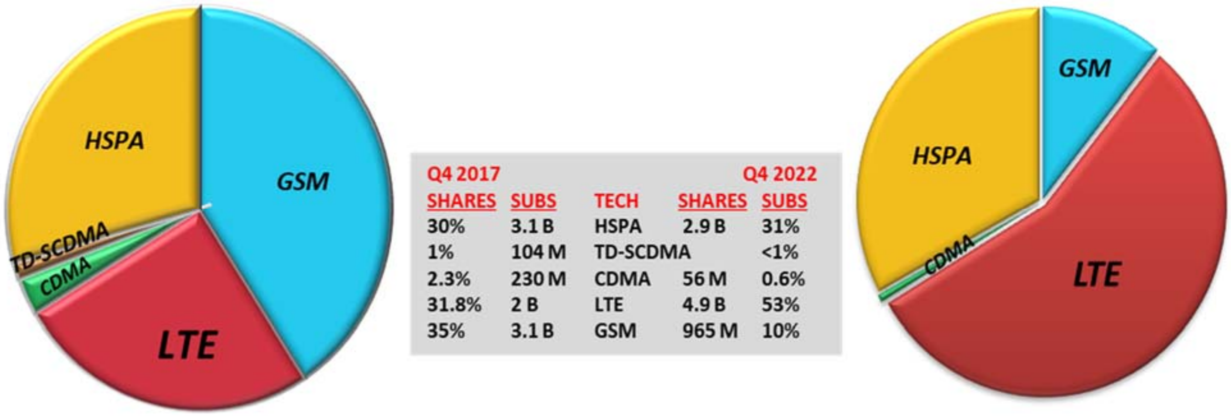

Figure 2.2. Global Mobile Technology Shares and Subscribers 4Q 2017 – Forecast 4Q 2022.[7]

More than half of the global population, 4.2 billion of the world's 7.5 billion people, had internet connections by end of 2017, as shown in Table 2.1.[8] At 95 percent, North America is the world leader in Internet penetration compared to all other world regions. The majority of growth is from the emerging or developing world regions in terms of increasing number of connections to the internet due largely to mobile technology.

Table 2.1. World Internet Usage and Population Penetration.[9]

WORLD INTERNET USAGE AND POPULATION STATISTICS DECEMBER 30, 2017 - Update						
World Regions	**Population (2017 Est.)**	**Population % of World**	**Internet Users 30 December 2017**	**Penetration Rate (% Pop.)**	**Growth 2000-2018**	**Internet Users %**
Africa	1,287,914,329	16.9 %	453,329,534	35.2 %	9,941%	10.9 %
Asia	4,207,588,157	55.1 %	2,023,630,194	48.1 %	1670%	48.7 %
Europe	827,650,849	10. 8 %	704,833,752	85.2 %	570%	17.0 %
Latin America / Caribbean	652,047,996	8.5 %	437,001,277	67.0 %	2318%	10.5 %

[7] *WCIS*, Ovum. December 2017.
[8] *InternetWorldStats.com*. December 2017.
[9] *InternetWorldStats.com*. December 2017.

Middle East	254,438,981	3.3 %	164,037,259	64.5 %	4893%	3.9 %
North America	363,844,662	4.8 %	345,660,847	**95 %**	219%	8.3 %
Oceania / Australia	41,273,454	0.6 %	28,439,277	68.9 %	273%	0.7 %
WORLD TOTAL	**7,634,758,428**	**100.0 %**	**4,156,932,140**	**54.4 %**	**1052%**	**100.0 %**
NOTES: (1) Internet Usage and World Population Statistics updated as of December 30, 2017. (2) Demographic (Population) numbers are based on data from the United Nations Population Division. (3) Internet usage information comes from data published by Nielsen Online, by ITU, the International Telecommunications Union, by GfK, by local ICT Regulators and other reliable sources.						

Data traffic from wireless and mobile devices, including both WiFi and cellular connections, will account for more than 63 percent of total IP traffic by 2021.[10] In 2016, wired devices accounted for the majority of IP traffic at 51 percent, however that is changing. In 2016, Personal Computers (PCs) accounted for 46 percent of total IP traffic and smartphones 13 percent, but by 2021 PCs will account for only 25 percent of traffic while smartphones will account for 33 percent of total IP traffic.[11] PC-originated traffic will grow at a CAGR of 10 percent, while TVs, tablets, smartphones, and Machine-to- Machine (M2M) modules will have traffic growth rates of 21 percent, 29 percent, 49 percent, and 49 percent, respectively. Global Internet Protocol (IP) traffic will increase nearly sevenfold over the next 5 years,[12] and will have increased 127-fold from 2005 to 2021.[13]

The number of mobile data subscriptions is increasing rapidly along with a continuous increase in the average data volume per subscription, driving growth in data traffic. Global mobile data traffic grew 55 percent in 12 months ending at Q4 2017.[14]

Mobile broadband continues to grow strongly as demonstrated in the *Ericsson Mobility Report February 2018 and the June 2017 report:*[15]

- On average, more than 1 million new mobile broadband subscribers will be added every day up to the end of 2022[16]
- 103 percent global subscription penetration in Q 2017
- LTE becomes the dominant mobile access technology in 2017
- In 2023, there will be 9.1 billion mobile subscriptions, 8.5 billion mobile broadband subscriptions and 6.2 billion unique mobile subscribers
- 1 billion 5G subscriptions for enhanced mobile broadband are expected in 2023

[10] *Cisco Visual Networking Index: Forecast and Methodology, 2016–2021.* September 2017.
[11] *Cisco Visual Networking Index: Forecast and Methodology, 2016–2021.* 2018.
[12] *Cisco Visual Networking Index: Forecast and Methodology, 2016–2021.* September 2017.
[13] *Ibid.*
[14] *Ericsson Mobility Report*. Interim, February 2018
[15] *Ibid.*
[16] *Ericsson Mobility Report.* June 2017.

New LTE network deployments continue, as well as many network upgrades from LTE to LTE-Advanced. As of end of July 2018, there were more than 600 commercial LTE deployments worldwide, while 261 of those operators already evolved to LTE-Advanced.[17]

North America's rapid migration to LTE and its leadership role for several years has led to the highest LTE share of subscriptions for this technology in the world—365 million subscriptions and a market share at 1Q 2018 that reached 76 percent compared to the global market share of 37 percent and compared to the next two highest regions, Oceania, Eastern and Southeastern Asia, at 57 percent and Western Europe at 46 percent penetration.[18] Market share represents the percentage of mobile wireless connections that are LTE technology versus all other mobile technologies. In North America, LTE penetration passed 100 percent in March 2018. Growth in Latin America and the Caribbean was also impressive; the region added 77 million new LTE connections year-over-year in 1Q 2018 achieving a 31 percent share of market. By the end of 2022, LTE is forecast to reach 504 million connections in Latin America and the Caribbean (forecast includes M2M) and a 64 percent share of market.[19]

In another outstanding milestone for North America, the penetration rate of LTE connections reached 100 percent in the first quarter 2018, with 365 million LTE connections compared to the population of 363.8 million. This penetration rate compares to the next two highest world regions, Oceania, Eastern and Southeastern Asia, at 57 percent and Western Europe at 46 percent penetration.[20] Interestingly, it corresponds with the highest penetration rate for Internet worldwide with mobile increasingly the access of preference to IP connectivity (see Table 2.1).

The strong growth in mobile broadband subscriptions in the Latin America region will be driven by economic development and consumer demand. With heavy investment in LTE, Latin America has seen a substantial increase in LTE deployments which numbered 111 commercial networks in 42 countries by July 2018,[21] and subscribers which totaled 217 million at 1Q 2018.[22] This may be largely attributed to the spectrum auctions that have occurred throughout the region allowing service providers the ability to offer LTE services to their customers beginning primarily in the densely populated urban cities. LTE passed 200 million connections at the end of 2017 (including M2M) and achieved a 31 percent share of market. By 2019, LTE will be the dominant technology in the Latin America region with about 45 percent market share and HSPA/WCDMA is expected to have a higher percentage of the market at 42 percent than GSM/EDGE-only subscriptions at 14 percent.[23]

As previously noted, global uptake of LTE continues aggressively and reached the milestone of 3 billion out of the total of 8 billion total cellular connections worldwide at the end of the first quarter of 2018 with an increase of 809 million new LTE subscriptions in one year.[24] LTE connections are forecast to reach close to four billion by the end of 2019, when the market share worldwide for LTE will reach 47 percent.[25]

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[17] *GlobalComm*, TeleGeography. July 2018.
[18] *WCIS*, Ovum. March 2018.
[19] *Ibid.*
[20] *Ibid.*
[21] *GlobalComm,* TeleGeography. December 2017.
[22] *WCIS*, Ovum. March 2018.
[23] *Ibid.*.
[24] *Ibid.*
[25] *Ibid.*

LTE innovations with LTE-Advanced and LTE-Advanced Pro are ongoing. It is significant to note that by July 2018, there were 261 LTE-Advanced commercial deployments worldwide.[26] By 2020, over 53 percent of all LTE subscribers will be supported by LTE-Advanced networks.[27]

In this section [2], the global market trends of wireless data are demonstrated as well as the 3GPP technology commercial milestones achieved by numerous leading operators and manufacturers worldwide on the new standards through Release 15.

2.1 MOBILE DATA GROWTH FORECASTS AND TRENDS

Mobile data traffic continues its rapid growth, driven largely by video. According to Ericsson, overall worldwide data traffic grew 55 percent between 4Q 2016 and 4Q 2017.[28] Data traffic is forecast to grow at a CAGR of 42 percent from 2016 to 2022, from 8.8 exabytes to 71 exabytes in 2022.[29] Mobile video traffic accounted for 60 percent of total mobile data traffic in 2016.[30] Three-fourths (75 percent) of the world's mobile data traffic will be video by 2020.[31]

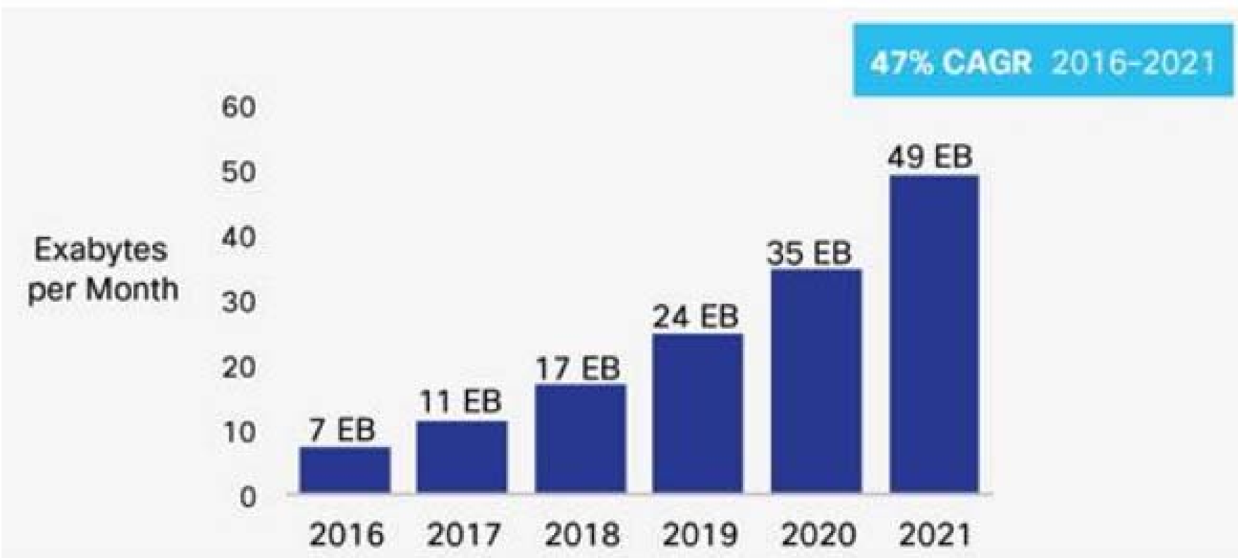

Figure 2.3. Global Mobile Data Traffic 2016 to 2021.[32]

U.S. mobile trends are shown in Table 2.2 between 2015 and 2016. Clearly, data and MMS traffic are rising, while SMS is declining.

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[26] TeleGeograpy.GlobalComm. July 2018.
[27] *Ibid.*
[28] *Ericsson Mobility Report – Interim*, February 2018
[29] *Ericsson Mobility Report,* June 2017.
[30] *Cisco VNI: Global Mobile Data Traffic Forecast Update 2016-2021.* February 2017.
[31] *Cisco VNI: Global Mobile Data Traffic Forecast Update 2015-2020.* February 2016.
[32] *Cisco VNI: Global Mobile Data Traffic Forecast Update 2016-2021.* February 2017.

Table 2.2. Key Mobile Trends in the U.S.[33]

	2015	2016	
Subscriber Connections	377.9M	395.9M	Up 4.8%
Smartphones	228.3M	261.9M	Up 14.7%
Tablets	41.0M	47.9M	Up 16.7%
Data Traffic	965T	13.72T	Up 42.2%
SMS Traffic	1.89T	1.66T	Down 12.1%
MMS Traffic	218.5B	277.9B	Up 27.2%
Wireless Penetration	115.7%	120.6%	Up 4.2%

2.2 WIRELESS DATA REVENUE

In 2017, mobile technologies and services generated 4.5 percent of GDP globally, a contribution that amounted to $3.6 trillion. By 2022, this contribution will reach $4.6 trillion or 5 percent of GDP.[34]

Analyst firm Sharma Consulting noted that in 2Q 2017, U.S. mobile data revenues eclipsed 80 percent of total wireless revenues for the first time, becoming the second nation in the world after Japan to do so.[35] However, much of that growth was related to the rush toward unlimited-data plans in the U.S. “The average data consumption in the U.S. is likely to cross 6 GB/month by the end of 2017,” Chetan Sharma Consulting firm said. “The first 1 GB took roughly 210 months. The last one just four months. Overall, the U.S. is No. 1 in total Zettabytes consumed on mobile networks ahead of second-place China by a distance.”[36]

But while consumption increased, U.S. operators are increasingly struggling to monetize that trend in an intensely competitive market. Quarter-over-quarter revenue from mobile data services shrank among American operators during the first quarter [2017] for the first time in 17 years, Sharma’s firm said, and Verizon—the nation’s largest mobile network operator—saw its first-ever decline in services revenue year over year. Meanwhile, postpaid net additions were negative in the United States for the first time, and net

[33] *Annual Wireless Industry Survey,* CTIA. 9 May 2017.
[34] *The Global Economy 2018*, GSMA.
[35] *U.S. Mobile Market Q2 2017*, Chetan Sharma Consulting. July 2017.
[36] Mobile revenues flatten even as data consumption ramps up in U.S., analyst says, Colin Gibbs, Fierce Wireless. 16 May 2017.

subscriptions for cellular-connected tablets also shrank.[37] In the U.S. wireless market, 2018 started similarly to the last three years – with a service revenue decline. Even mobile data service revenues dipped below the 0 percent growth market for only the second time in history.[38]

Other ominous signs emerged in early 2017 according to Sharma Consulting: Handset upgrade cycles averaged more than 2.7 years; SMS traffic declined to levels not seen since a decade before; and the smartphone market declined in terms of both revenues and profits.[39]

A growing number of operators are focusing on convergence of multiple products and services into a variety of bundled services packages and by partnering with value-added IP-based communications and content providers to achieve improved revenues.[40] Other growth opportunities include the shift to the Internet of Things and connected cars for new additions into the ecosystem.

2.3 MOBILE BROADBAND DEVICES AND M2M

In 2014, the number of mobile connected devices exceeded the world's population. Device growth continues; each year several new devices in different form factors and increased capabilities and intelligence are introduced into the market.

As some countries approach or exceed 100 percent penetration (the U.S. adoption was 120.6 percent or 1.2 wireless devices per American as of 1Q 2017[41]) the opportunity for growth of mobile connections coupled with the competitive nature of the mobile market constrain the revenue potential for mobile operators. But the emerging Internet of Things (IoT) segment is the proverbial light at the end of the tunnel. Net additions from the IoT and connected cars led new additions to the ecosystem, according to Sharma Consulting, and the two segments accounted for 71 percent of all new net connections for the 2Q 2017 leading all new additions to the ecosystem.[42]

The U.S. became the second country to cross the 100 million milestones for the connected devices (non-phone) segment in 2017 according to Chetan Sharma Consulting.[43] Connected cars and IoT continue to dominate the net-adds as shown in Figure 2.4. Their share of the net-adds reached historic highs in Q1 2018. In fact, the combined category commanded well over 90 percent share for the first time. The non-phone category went from 39 percent in 2014 to 71 percent in 2016. In 2017, the non-phone category again dominated with connected vehicles leading the field for the first time in history.

Connected devices (non-phones) accounted for over 90 percent of the net-adds in 1Q 2018 indicating that while there is a healthy smartphone sales pipeline, it is for the existing subscriptions and as such net-adds for the phone business are tapering off and it is expected that new net-adds will continue to be dominated by the connected devices segment.

[37] Mobile revenues flatten even as data consumption ramps up in U.S., analyst says, Colin Gibbs, Fierce Wireless. 16 May 2017.
[38] *U.S. Mobile Market Update Q1 2018*, Chetan Sharma Consulting. May 2018.
[39] Mobile revenues flatten even as data consumption ramps up in U.S., analyst says, Colin Gibbs, Fierce Wireless. 16 May 2017.
40 *Report: Mobile Data Revenue Nearly Half of Total Mobile Revenue and Growing,* Telecompetitor. Andrew Burger. 31 August 2016.
[41] *Annual Wireless Survey*, CTIA. May 2017.
[42] *U.S. Mobile Market Q2 2017*, Chetan Sharma Consulting. July 2017.
[43] *US Mobile Market Update Q1 2018*, Chetan Sharma Consulting. May 2018.

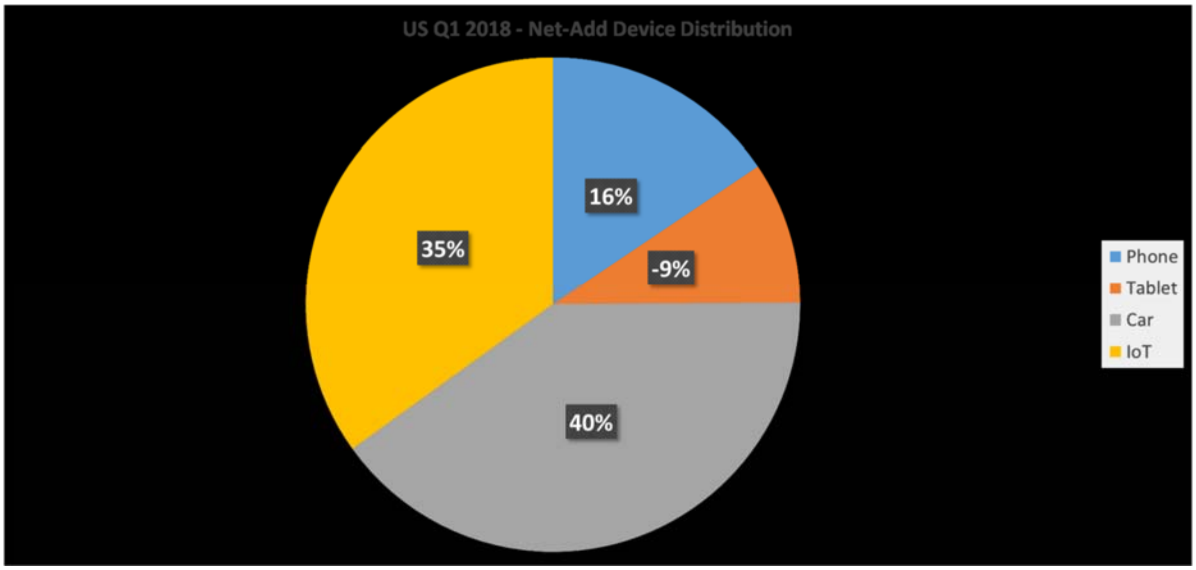

Figure 2.4. Net-Add Device Distribution – U.S. 1Q 2018.[44]

Commenting on the U.S. trends, Sharma Consulting wrote: "In the first quarter of the year [2017], there was a first-ever decline in tablet net-adds. This made [the] cars category reach 50 percent of the overall net-adds—a big milestone. While the ARPUs from such net-adds is quite low compared to postpaid net-adds, it does reflect the changing dynamics in the industry. AT&T dominates the car net-adds by a mile. Overall net-adds have stayed flat and [are] just going through the normal gyrations. Overall, phones still dominate and that's what generates the bulk of the industry revenue, but IoT is starting to inch up in material impact."[45]

The phenomenal growth in smarter end-user devices and M2M connections is a clear indicator of the growth of IoT, which is bringing together people, processes, data, and things to make networked connections more relevant and valuable. M2M connections—such as home and office security and automation, smart metering and utilities, maintenance, building automation, automotive, healthcare and consumer electronics, and more—are being used across a broad spectrum of industries, as well as in the consumer segment. As real-time information monitoring helps companies deploy new video-based security systems, while also helping hospitals and healthcare professionals remotely monitor the progress of their patients, bandwidth-intensive M2M connections are becoming more prevalent. Globally, M2M connections will grow from 780 million in 2016 to 3.3 billion by 2021, a 34-percent CAGR—a fourfold growth.[46] M2M capabilities, similar to end-user mobile devices, are experiencing an evolution from 2G to 3G and 4G and higher technologies.

An important factor contributing to the growing adoption of IoT is the emergence of wearable devices, a category with high growth potential. Wearable devices, as the name suggests, are devices that can be worn on a person and have the capability to connect and communicate to the network either directly through embedded cellular connectivity or through another device (primarily a smartphone) using WiFi, Bluetooth, or another technology.

These devices come in various shapes and forms, ranging from smart watches, smart glasses, heads-up displays (HUDs), health and fitness trackers, health monitors, wearable scanners and navigation devices, smart clothing, etc. These advances are being combined with fashion to match personal styles, especially

[44] *US Mobile Market Update Q1 2018,* Chetan Sharma Consulting. May 2018.
[45] *Mobile revenues flatten even as data consumption ramps up in U.S., analyst says,* Colin Gibbs, Fierce Wireless. 16 May 2017.
[46] *Cisco VNI: Global Mobile Data Traffic Forecast Update 2016-2021.* February 2017.

in the consumer electronics segment, along with network improvements and the growth of applications, such as location-based services, virtual reality (VR) and augmented reality (AR).

Figure 2.5. Global Machine-to-Machine Growth and Migration from 2G to 3G and 4G+.[47]

By 2021, there will be an estimated 929 million wearable devices globally, growing nearly threefold from 325 million in 2016 at a CAGR of 23 percent. Only 7 percent will have embedded cellular connectivity by 2021, up from 3 percent in 2016.[48] Currently, wearables are included within the M2M forecast. Global shipments of wearables are due to increase at a 24.8 percent compound annual growth rate over the next five years, reaching 162.9 million units in 2020.[49]

Applications such as virtual reality are also adding to the adoption of wearables such as headsets. VR headsets are going to grow from 18 million in 2016 to nearly 100 million by 2021, a fivefold growth. More than half of these will be connected to smartphones by 2021.[50] The remaining VR headsets will be connected to PCs, consoles and a few will be standalone. The wearables category will have a tangible impact on mobile traffic, because even without embedded cellular connectivity wearables can connect to mobile networks through smartphones. With high bandwidth applications such as virtual reality taking off the traffic impact might become even greater.

A great deal of information and research has been dedicated to the IoT and M2M as the approaching Massive IoT (MIoT) provides tremendous opportunities for growth. 3GPP standards in Releases 13 and beyond address these opportunities with Narrowband IoT (NB-IoT) and LTE-M. The 5G Americas white paper, *LTE Progress Leading to the 5G Massive Internet of Things* is an excellent resource for IoT market information and an exploration of the categories and devices.[51]

There were about 400 million IoT devices with cellular connections at the end of 2016 and that number is projected to reach 1.5 billion in 2022.[52] It is expected that 70 percent of the wide-area IoT devices will use

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[47] *Cisco VNI: Global Mobile Data Traffic Forecast Update 2016-2021.* February 2017.
[48] Statista.com
[49] Wearable Technology is more than just a fashion statement, Cisco. May 2017.
[50] Berg Insight. May 2018.
[51] *LTE Progress Leading to the Massive Internet of Things*, 5G Americas. November 2017.
[52] *Ericsson Mobility Report,* June 2017.

cellular technology in 2022.[53] This growth is due to increased industry focus and 3GPP standardization of cellular IoT technologies which is further explained in this whitepaper and the previously mentioned broader IoT report.

Mobile phones continue to be the largest category of connected devices, but by 2018 they are expected to be surpassed by IoT, which includes connected cars, machines, utility meters, wearables and other consumer electronics.

2.4 MOBILE DATA SPEEDS

As of November 2017, according to Open Signal research, the average global speed for an LTE connection was 16.6 Mbps compared to the average mobile data connection in the top two fastest countries, Singapore and South Korea at 46.6 and 45.9 Mbps respectively.[54] There are many factors that weigh in on the average global data speeds in a country, such as: how much spectrum is devoted to LTE; whether it has adopted 4G technologies like LTE-Advanced; how densely networks are built; and how much congestion is on those networks. In general, though, the countries with the fastest speeds tend to be the ones that have built LTE-Advanced networks and have a large proportion of LTE-Advanced capable devices.

Figure 2.6 compares the average global download connection speed of the major wireless network technologies. 2G includes GSM and CDMA 1X connections; while 3G includes UMTS, HSPA and CDMA EV-DO connections; 4G is LTE technologies only.

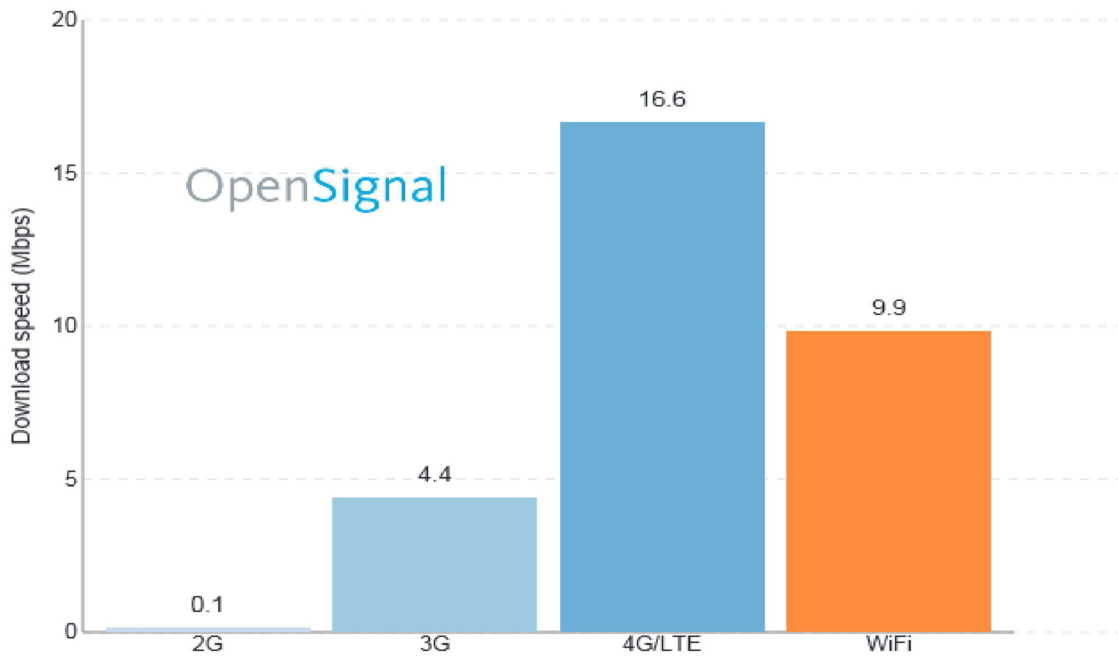

Figure 2.6. Average Global Download Connection Speed by Technology.[55]

[53] Ibid.
[54] *The State of LTE*, Open Signal research. November 2017.
[55] *The State of LTE*, Open Signal research. November 2017.

A trend revealed by Open Signal was that as mobile data speeds increase, users are spending large amounts of time with mobile devices connected to WiFi networks. For instance, in South Korea mobile users spend 50 percent of their time connected to WiFi and in Norway (another country with very fast LTE speeds) it's 55 percent while in LTE-high-speed country Hungary it's 53 percent. This suggests that mobile access is being used to supplement WiFi networks rather than to replace them.[56]

Gigabit LTE has the three key enabling technologies of 4x4 MIMO, 256 QAM and three-carrier aggregation. If there was any doubt about operator commitment to Gigabit LTE, this was dismissed in 2017 due to remarkable momentum. Analyst firm, CCS Insight, noted that in November 2017, 43 operators either had deployed or were trialing Gigabit LTE in more than 25 countries with 16 compatible devices.[57]

Telstra in Australia reports 100-300 Mbps with Gigabit LTE, which is 18 times faster than typical LTE speeds. One example is that a 2-hour movie could be downloaded in 15 seconds with these super-high speeds. The benefits are not simply quicker download speeds; this would free up more data capacity for all users on the network.

In the U.S., the leading operators have firmly committed to Gigabit LTE. For example, in the case of T-Mobile, the carrier said that it had expanded LTE-Advanced to more than 920 markets, and that the principal technologies of 4x4 MIMO, 256 QAM and three-carrier aggregation are enabled in 430 markets.[58] AT&T has branded their Gigabit LTE network as '5G Evolution' due to its important step into the future network. Sprint was the first U.S. operator to trial Gigabit LTE and in 2017 increased its average network speed by 65 percent year-over-year (December 2017) with a commitment to deploy 256 Quadrature Amplitude Modulation (QAM) and 4X4 MIMO in 2018 for Gigabit LTE with their 3-channel Carrier Aggregation (CA) already available in more than 100 top markets.

Furthermore, as licensed spectrum is no longer a limitation, Gigabit LTE deployments and coverage are set to grow substantially. With the introduction of LTE for Unlicensed Spectrum (LTE-U) and Licensed-Assisted Access (LAA), more than 90 percent of operators can roll out Gigabit LTE using just one band of 10 MHz licensed spectrum.[59] This is a powerful option for operators with limited spectrum assets, particularly in markets where the combination of small cells and fibre means unlicensed spectrum needn't have a compromise on throughput.

T-Mobile plans to keenly roll out LAA in combination with small cells. It has contracted deployment of 31,000 small cells and is currently deploying those. This will play a big part in spreading the availability of Gigabit LTE. Both operators and consumers stand to benefit; as the number of supporting devices increases, network capacity and efficiency are boosted for all users.

According to Geoff Blaber, analyst at CCS Insight, "Despite the name, Gigabit LTE really isn't about gigabit speeds. It's about improving average throughput, increasing network efficiency, reducing congestion and enhancing the experience for all network's users. With the rise of LTE in Unlicensed (LTE-U) and LAA, we predict that momentum for Gigabit LTE will continue globally over the coming two years, as the industry paves the way for 5G. Furthermore, the LTE road map has at least two more generations before we get to 5G."[60]

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[56] Joon Ian Wong, Quartz.com. Based on research from Open Signal. 22 February 2017.
[57] *Gigabit LTE: Delivering Breadth and Depth,* blog by Geoff Blaber. 29 November 2017.
[58] *Fastest Mobile Broadband Networks 2017*, by Sascha Segan, PC Mag.com. 19 June 2017.
[59] *Gigabit LTE: Delivering Breadth and Depth,* blog by Geoff Blaber. 29 November 2017.
[60] *Ibid.*

Gigabit LTE is crucial as an underlying technology that will offer the coverage layer for 5G (and the control and signalling for the first launches of non-standalone 5G), and a reminder of why operators are committed to network investment and development.

2.5 MOBILE BROADBAND SERVICES AND APPLICATIONS

Mobile video traffic is forecast to grow by around 50 percent annually through 2023, when it should account for nearly three-quarters of all mobile data traffic.[61] While social networking is forecast to grow by 34 percent annually over the coming six years, its relative share of traffic will decline from 12 percent in 2017 to around 8 percent in 2023, as a result of the stronger growth in the video category. The rest of the application categories have annual growth rates ranging from 20 to 32 percent, so they are shrinking in proportion to the overall traffic. The trend is accentuated by the growing use of embedded video in social media and web pages, which is considered video traffic in this context, fueled by larger device screens, higher resolution and new platforms supporting live streaming.[62]

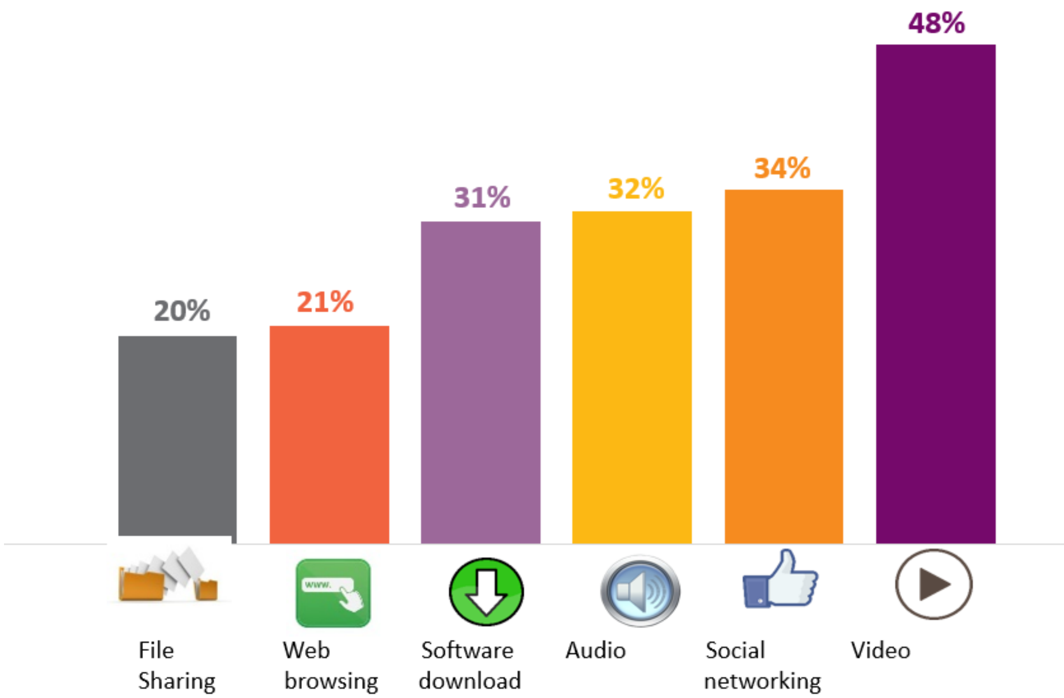

Figure 2.7. Mobile Traffic by Application Category- CAGR 2017-2023.[63]

By 2023, more than 30 billion connected devices are forecast; 20 billion will be related to the IoT. Connected devices include connected cars, machines, meters, sensors, point-of-sale terminals, consumer electronics and wearables. Between 2017 and 2023, connected IoT devices are expected to increase at a CAGR of 19 percent, driven by new use cases and affordability.[64]

[61] *Ericsson Mobility Report*, November 2017.
[62] *Ibid.*
[63] *Ericsson Mobility Report*, November 2017.
[64] *Ibid.*

As previously covered in this section, data traffic is expected to continue growing significantly. The introduction of laptops, tablets and high-end mobile handsets onto mobile networks are key drivers of traffic, since they offer content and applications not supported by the previous generations of mobile devices.

2.6 MOBILE BROADBAND DEPLOYMENTS AND SPECTRUM

LTE has seen the most aggressive deployment of any mobile technology in history. It took just five years for LTE to cover 2.5 billion people, compared to eight years for WCDMA/HSPA. From the first launch of LTE by TeliaSonera in Sweden and Norway in 2009, the technology deployments have grown consistently to 595 LTE networks of which 244 are LTE-Advanced technology (June 2018).[65] LTE's global population coverage is currently around 55 percent and is forecast to grow to more than 85 percent by 2023.[66]

LTE is driven by demand for improved user experience and faster networks. The reasons for LTE's success include the careful development of the 3GPP standards. There were 14 Gigabit LTE networks commercially launched by November 2017, and the deployment rate is expected to increase in 2018. In order to provide faster data speeds and increased capacity, one of the limiting factors is the availability of a sufficient amount of licensed spectrum. The challenge has been the allocation by governments of premium internationally harmonized licensed spectrum. In fact, the ITU studied the spectral requirements for the growing demand of wireless data and confirmed that there is a gross deficit in current allocations in many countries.

In its *Report ITU-R M. 2290*, the International Telecommunication Union (ITU) outlines the need for a minimum amount of spectrum for the year 2020 depending on the market development status (referring to two Radio Access Techniques Groups, RATG1 and RATG2 in Table 2.3). For the sake of simplicity, the markets are categorized as either lower user density setting or higher user density setting.

Table 2.3. Predicted Spectrum Requirements for RATG 1 and RATG 2 in 2020.[67]

Market Setting	***Spectrum Requirement for RATG 1***	***Spectrum Requirement for RATG 2***	***Total Spectrum Requirement***
Higher user density setting	540 (MHz)	1420 (MHz)	1960 (MHz)
Lower user density setting	440 (MHz)	900 (MHz)	1340 (MHz)

The target spectrum requirements represent the total amount of spectrum in a given country market. An example of a country that would fall into the category of a higher market setting would be the U.S., and its need for additional spectrum is evident. New services, applications, devices and continued increases in the usage of smartphones, tablets and connected machines are only amplifying the need for additional spectrum.

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[65] *GlobalComm,* Telegeography. June 2018.
[66] *Ericsson Mobility Report*. November 2017.
[67] *Report ITU-R M. 2290.* International Telecommunications Union, December 2013.

4G adoption is closely correlated to coverage, which in turn is dependent on the timing, type and amount of spectrum assigned to operators for 4G services. 5G Americas advocates for internationally harmonized licensed spectrum to achieve the required spectrum allocations needed across the Americas and numerous other members of the ecosystem worldwide likewise are working toward that goal. However, in the future, licensed, shared and unlicensed spectrum will be essential to the mobile broadband industry in low, mid and high bands for the deployment of 5G or IMT-2020 technology.

Although today licensed-spectrum networks operate most efficiently, and are deployed most efficiently, that will change in the future as technology improves by using a combination of low-band, mid-band and high band spectrum to supplement capacity with bands in 3 GHz to 100 GHz and eventually higher.

Although 5G research and standards development is in underway, to achieve the throughput rates of 20 Gbps or higher envisioned for 5G, radio carriers of at least 1 GHz will be required; these bandwidths are typically only available at frequencies above 5 GHz. High frequency spectrum options will be important to 5G, including both centimeter wave (cmWave) frequencies of 3 GHz to 30 GHz and millimeter wave (mmWave) frequencies of 30 GHz to 300 GHz; these bands will be a key element of 5G technology deployments. Ten times as much spectrum, or more, could be available in these higher frequencies than in all current cellular spectrum.

World Radio Conference 2015 (WRC-15) approved the study of 11 high band spectrum allocations for WRC-19, however many governments around the world will not wait for the WRC-19 process to finish before they allocate high band 5G spectrum. For example, the 2016 allocation by the FCC in the U.S. of 28 GHz, 37 GHz and 39 GHz licensed spectrum for 5G is the first important high band licensed spectrum for 5G in the Americas region and the first such allocation in the world.

Spectrum planning and policies that are in consideration around the world today should allocate enough licensed high band spectrum to allow for a complete 5G environment. 5G Americas recommended high band licensed spectrum allocations of 200 MHz or more at the 2016 FCC Notice of Proposed Rule Making (on the 28GHz, 37GHz and 39 GHZ bands). More internationally harmonized licensed spectrum is critical to support the explosive growth in mobile wireless services, applications and the move to 5G.

In addition, 5G Americas advocates for new licensing terms for the proposed 3.5 GHz Citizens Broadband Radio Service Spectrum in the U.S. with longer licensing terms and larger geographic areas, similar to past FCC auctions, for mobile wireless licensed spectrum.

Licensed Assisted Access (LAA) is a new technology that allows operators to use unlicensed spectrum in combination with their licensed spectrum to improve network capacity and speed. Commercial deployments are expected in 2018.

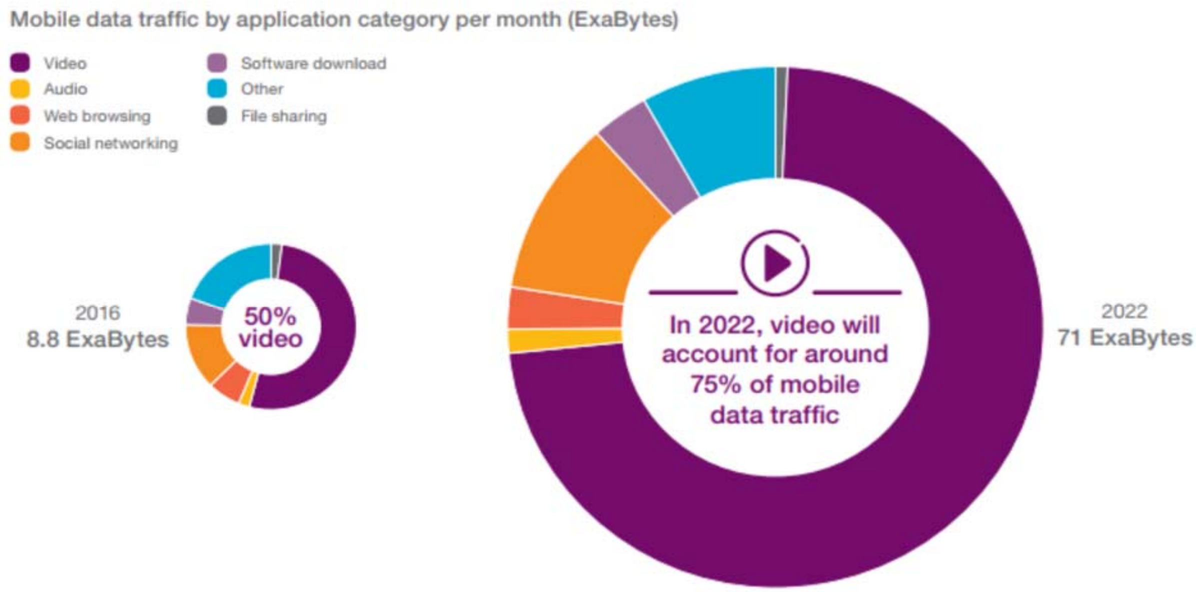

Figure 2.8. Ericsson's Mobile Data Traffic Demand Forecast.[68]

Figure 2.8 effectively shows that the traffic in 2021-2022 will be about 7-8 times more than 2016. Additional spectrum is the only way to accommodate that demand. The amount of spectrum required depends upon multiple factors, including application types, deployment configuration, radio access technology, spectrum efficiency, geographic location and quality of service requirements. As noted previously, some of the additional spectrum needs to be at very high frequencies, which can support higher data rates, and some of it needs to be at lower frequencies, such as to ensure reliable indoor service.

ITU-R WP5D in preparation for IMT-2020 (5G) considered two approaches in estimating the spectrum needs of terrestrial components of IMT in the 24.5 GHz to 86 GHz frequency range: an application-based approach, and a technical performance-based approach.

The application-based approach focuses on the advanced applications for IMT-2020, using a frequency range between 24.25 GHz and 86 GHz, which are mainly expected to require higher data rates than IMT-Advanced. Table 2.4 summarizes some example use cases.

Table 2.4. IMT-2020 Estimated Spectrum Needs Based on Application-based Approach for the Frequency Ranges above 24 GHz.[69]

Example	Tele-densities	24.25-33.4 GHz	37-52.6 GHz	66-86 GHz	Total

[68] *Ericsson Mobility Report.* November 2017.
[69] *Spectrum Landscapes for Mobile Services*, 5G Americas white paper. November 2017.

Example 1	Overcrowded, Dense urban and Urban areas	3.3 GHz	6.1 GHz	9.3 GHz	18.7 GHz
	Dense urban and Urban areas	2.0 GHz	3.7 GHz	5.7 GHz	11.4 GHz
Example 2	Highly crowded area	666 MHz	1.2 GHz	1.9 GHz	3.7 GHz
	Crowded area	333 MHz	608 MHz	933 MHz	1.8 GHz

METIS-II has expanded the frequency range of the IMT-2020 estimates in Table 2.5 and included frequency ranges both below and above 6 GHz. The bandwidth demand of extreme mobile broadband (eMBB or xMBB) has been estimated for three use cases (UCs) described in Table 2.5. Note that the estimated bandwidth demand is dependent upon many factors, such as the assumed deployment scenario, user density and Spectral Efficiency (SE).

Table 2.5. Deployment Assumptions and Performance Requirements Use Cases in METIS-II xMBB Bandwidth Estimation.[70]

	UC1 Dense urban information society	UC2 Virtual reality office	UC3 Broadband access everywhere
BS deployment	HetNet (macro layer with ISD of 200m and micro layer with multiple small cells per macro sector)	12 sites per floor with ISD of 20m	Macro layer with ISD of 1732m
Carrier frequency	Below 6 GHz for macro layer and above 6 GHz for micro layer	Both below and above 6 GHz	Below 6 GHz
Experienced user throughput (requirement)	DL: 300Mbps, UL: 50Mbps	DL: 1Gbps, UL: 1Gbps	DL: 50Mbps, UL: 20Mbps

[70] Spectrum Landscapes for Mobile Services, 5G Americas white paper. November 2017.

Other use cases, such as massive Machine-Type Communications (mMTC) and Ultra Reliable Low Latency Critical Communications (URLCC), are not considered in the demand estimation shown in Figure 2.9.

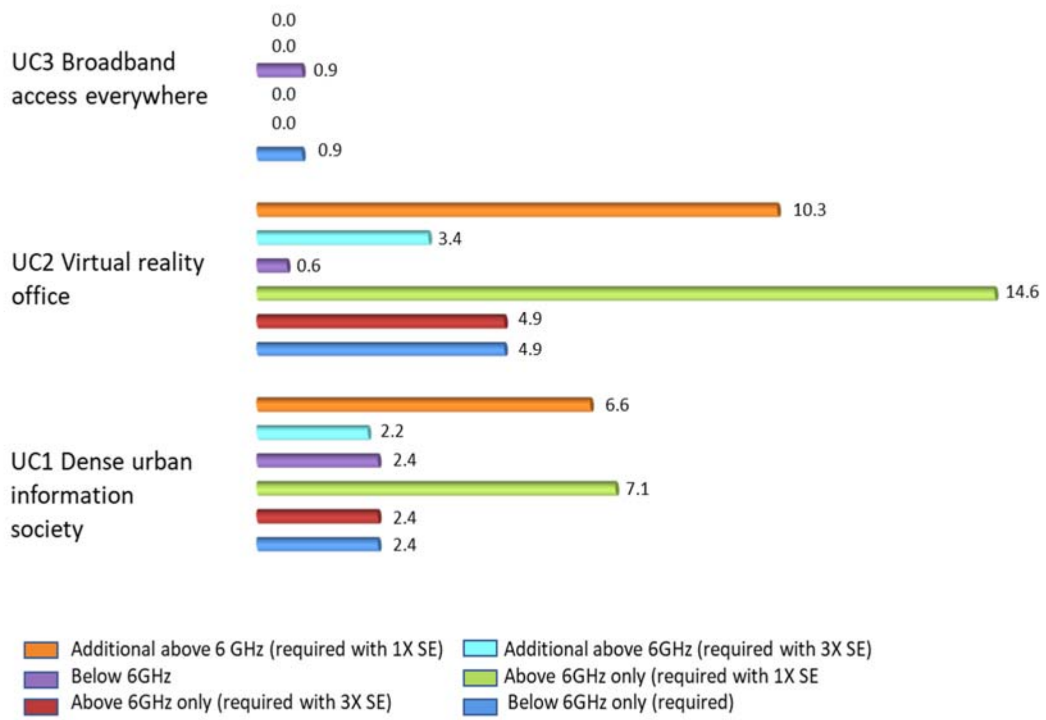

Figure 2.9. Spectrum Bandwidth Demand of METIS-II xMBB Use Cases.[71]

The technical performance-based approach uses factors such as peak data rate, spectral efficiency, user experienced data rate and expected device density. In addition, usage scenarios—including their associated expected coverage area, deployment environments and target applications—introduce technical requirements and conditions on a radio system that directly or indirectly impact spectrum needs.

Using the technical performance-based approach, IMT-2020 has provided a spectrum needs estimate for frequency ranges below 6 GHz and above 24 GHz. Although the 6-24 GHz spectrum range hasn't explicitly been considered in this estimation, that swath is very much needed to supplement the spectrum below 6 GHz and provide further resource for the spectrum below 30 GHz.

IMT-2020 has estimated the spectrum needs for the frequency ranges below 6 GHz and above 24 GHz for all the IMT-2020 deployment scenarios including into indoor hotspot, micro and macro layers in dense urban and urban macro. Table 2.6 shows these deployment scenarios and their associated frequency ranges. Table 2.7 provides the spectrum needs estimates, which are based on IMT-2020 requirements for user experienced data rate, peak data rate and area traffic capacity.

[71] Ibid.

Table 2.6. Deployment Scenarios and Frequency Ranges.[72]

Deployment scenarios	Indoor hotspot	Dense urban		Urban macro
		Micro	Macro	
Frequency range	24.25-86 GHz	24.25-43.5 GHz	<6 GHz	<6 GHz

Table 2.7. Spectrum Needs Estimate Result of IMT-2020 for Below 6 GHz and Above 24 GHz.[73]

<table>
<tr><th>Deployment scenario</th><th>Macro</th><th colspan="2">Micro</th><th>Indoor hotspot</th></tr>
<tr><td>Total spectrum needs for below 6 GHz</td><td>808-1078 MHz*</td><td>–</td><td colspan="2">–</td></tr>
<tr><td>Total spectrum needs for 24.25-86 GHz</td><td>–</td><td colspan="3">14.8-19.7 GHz*</td></tr>
<tr><td>Spectrum needs for 24.25-43.5 GHz</td><td>–</td><td colspan="2">5.8-7.7 GHz</td><td rowspan="2">9-12 GHz</td></tr>
<tr><td>Spectrum needs for 45.5-86 GHz</td><td>–</td><td colspan="2">–**</td></tr>
</table>

** Considering the coexistence between multiple network operators (e.g. the guard band(s) may be required in the case of multiple network operator scenarios), the total spectrum needs are expected to be increased. ** The division in this table regarding frequency ranges and deployment scenarios is just an indicative example how spectrum needs could be distributed for different spectrum sub-ranges within 24.25-86 GHz and different deployment scenarios. This table should not be understood nor used to exclude any possible IMT-2020 deployment options in these sub-ranges.*

Clearly, a variety of spectrum bands will be necessary for future 5G networks. For more information on spectrum for 5G, review the *Spectrum Landscape for Mobile Services* white paper by 5G Americas published in November 2017.

[72] METIS II
[73] METIS II

2.7 MILESTONES FROM RELEASE 13 TO RELEASE 14: LTE/EPC/LTE-ADVANCED

This section summarizes the commercial progress of the 3GPP standards beginning with Rel-13 through Rel-16 and includes several important milestones in the industry. Leading manufacturers and service providers worldwide support the 3GPP evolution. To illustrate the rapid progress and growth of LTE and beyond, participating 5G Americas member companies have each provided detailed descriptions of recent accomplishments through Rel-16 in the Member Progress section in Appendix A.

2.7.1 LTE AND LTE-ADVANCED PROGRESS TIMELINE

LTE has become a phenomenal success. More than 2.8 billion LTE connections were counted by the end of 2017, and it is expected that almost 700 operators will deploy LTE technology in almost 200 countries worldwide in the future. The LTE ecosystem is thriving due to the historical development of the standards, explained below, with highlights of some key commercial milestones.

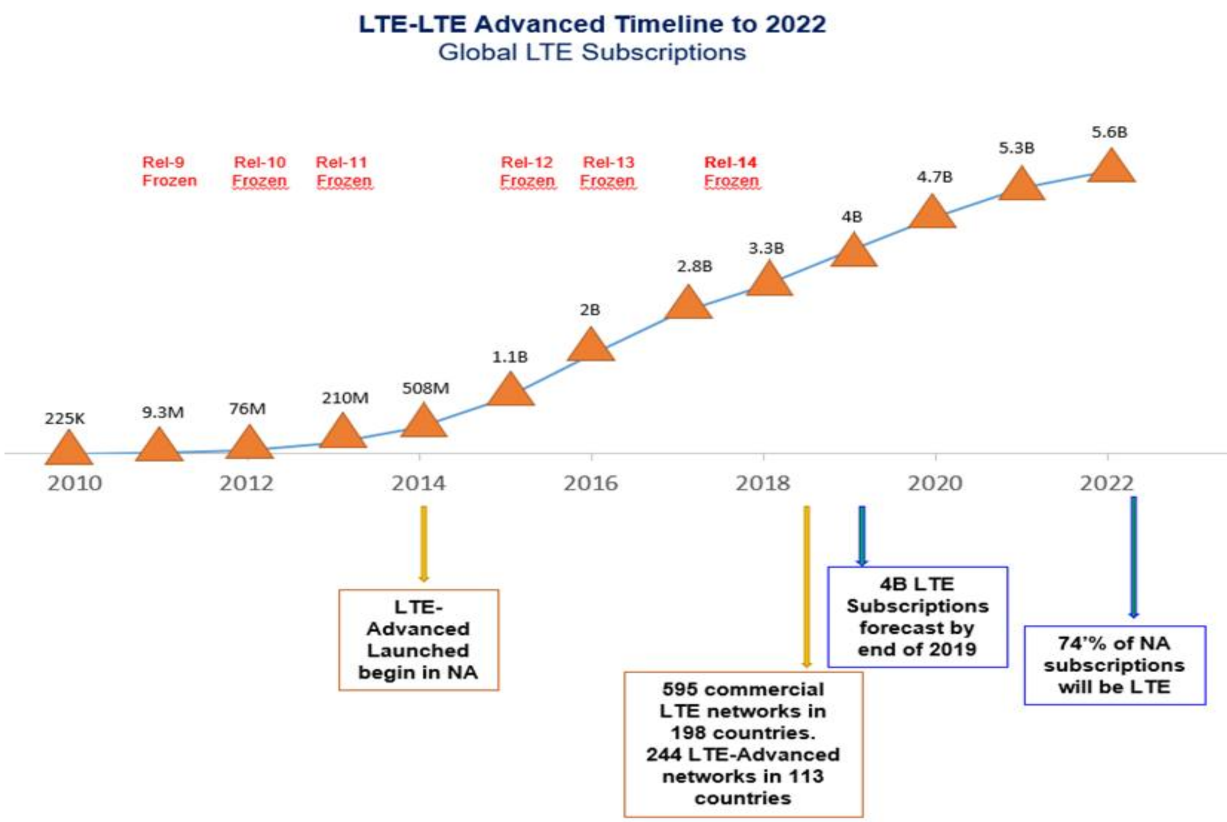

Figure 2.10. LTE and LTE-Advanced Timeline 2010-2021.[74]

Spectrum is increasingly important. New spectrum developments are in consideration for the low, mid and high bands for 5G. There exists up to 500 MHz of unlicensed spectrum around the world in the 5 GHz band used for various applications and services, primarily WiFi. By leveraging the performance characteristics of

[74] 5G Americas and Ovum, March 2018. TeleGeography, May 2018.

LTE, the industry plans to take advantage of this spectrum to address the data challenge. In some world regions, LTE for Unlicensed Spectrum (LTE-U) could be deployed as a pre-standard solution and offer meaningful coverage and capacity gains (2x to 4x, depending on the assumptions) over what is possible with WiFi.[75] In other regions of the world, certain regulatory requirements exist which necessitate some important changes to the LTE standard in order to leverage the unlicensed spectrum. These changes, referred to as LAA (Licensed Assisted Access) were incorporated into Rel-13 of the LTE standard, completed in March 2016. T-Mobile committed to bringing LAA trials to life in 2015 and is currently deploying the technology. LTE-U will apply technology features that are comparable to what WiFi uses today to ensure how multiple WiFi Access Points, WiFi devices, and other wireless applications, like radar, can use the unlicensed spectrum in a harmonious manner and without interference. LTE-U will be used primarily, if not entirely, in conjunction with small cells. Leading vendors are developing LTE-U.

AT&T is implementing a variety of LTE-Advanced features within its network and will continue to add more to take full advantage of LTE's rich functionality. These features include carrier aggregation, higher-order MIMO and self-optimizing networks, to name a few. AT&T continues to build a foundation for 5G; they launched their '5G Evolution' technology' in parts of 141 markets by April 2018 with plans to broadly make 5G Evolution technology available in over 500 markets by the end of 2018. Capable devices on these '5G Evolution' networks can deliver theoretical peak speeds of up to 400 megabits per second. In November 2017, AT&T launched the first commercial deployment of LTE-LAA technology in Indianapolis. By April 2018, AT&T was offering LTE-LAA in parts of seven markets, delivering theoretical peak speeds for capable devices of up to 1 gigabit per second;[3] AT&T plans to launch LTE-LAA in at least 24 markets in 2018. In early 2018, AT&T announced that they will be the first U.S. carrier to deploy mobile 5G to customers in a dozen cities, learning from what they learned in 5G fixed wireless field trials where speeds nearing 1 Gbps over millimeter wave (mmWave) spectrum bands were experienced.

Sprint CTO John Saw commented on plans in 2018, "you'll see us roll out 256 QAM and 4X4 MIMO nationwide for greater spectral efficiency and faster data speeds. These critical ingredients will join three-channel carrier aggregation (using 60 MHz of 2.5 GHz) already available [in 2017] in more than 100 top markets, to form the Sprint recipe for Gigabit Class LTE service," Sprint plans to begin to deploy commercial 5G services by late 2019. Sprint debuted the first U.S. deployment of Gigabit LTE live on a commercial network with a premium tier smartphone at Smoothie King Center in New Orleans with leading vendors. The service utilized three-channel carrier aggregation and 60 MHz of Sprint's 2.5 GHz spectrum in combination with 44X4 MIMO and 256-QAM higher order modulation to achieve Category 16 LTE download data speeds on a TDD network.

Gigabit LTE will provide high-speed coverage in areas where 5G signals aren't available and a consistency of experience for users of 5G devices that have Gigabit multimode capability. Additionally, Gigabit LTE improves network capacity and provides an enhanced mobile experience. Gigabit LTE continues to gain momentum as more operators and mobile device Original Equipment Manufacturers (OEMs) jump on board. As of February 2018, 45 operators in 26 countries embraced the technology and 17 commercially available devices are powered by a single vendor's Gigabit LTE modems.[76]

There has been continued progress since the first Gigabit LTE modem announcement in 2016; in February 2018, a leading vendor announced its third generation Gigabit LTE modem, representing several significant mobile industry firsts:

- announced modem to support Category 20 LTE download speeds of up to 2 Gbps

[75] *The Prospect of LTE and WiFi Sharing Unlicensed Spectrum*, Signals Research Group, February 2015.
[76] Qualcomm.

- announced 7nm chip, the most advanced commercially available silicon manufacturing process
- announced LTE modem to support downloads on up to 20 independent spatial streams, including 4x4 MIMO on up to 5 aggregated carriers
- announced LTE modem to support up to 7x carrier aggregation

With partners, this leading chipset manufacturer delivered the first commercial Gigabit LTE network with Telstra in Australia in January 2017 – an essential anchor to the 5G mobile experience.

Small cells play a pivotal role in bringing a huge amount of data capacity, where it is needed the most, by bringing the network closer to the users—indoors outdoors, homes, offices, enterprises, shopping malls and lamp posts. Small cells are available in 3G, 4G, and WiFi and in all the different forms such as user-installed small cells and operator-installed picos and metros. For such dense small cell networks, the key is to make sure interference is managed, mobility is robust and a reliable and consistent user experience is delivered. Though small cells have been commercially available for many years, they are seeing momentum in the development of the hyperdense network. Operators worldwide are now using small cells. The deployment of small cells – fueled by 5G — will reach 2.838 million units in 2018 and 4.329 million units in 2019, an annual growth of 52.5 percent.[77] Techniques developed by a leading vendor allow multiple users to share the same frequencies, effectively multiplying system capacity through a Cloud-RAN small cell system that delivers superior LTE performance for enterprise and public areas at lower deployment costs. Equipment consists of a baseband controller and multiple radio points that form a single 'super cell' – eliminating handovers and interference across large areas. Another vendor's design also optimizes performance while accelerating deployments. Encompassing RF delivery, equipment housing and concealment, the small cell antennas improve performance of the RF air link, expedite construction and enable faster zoning approvals, thereby decreasing OPEX and CAPEX and improving time to revenue.

As part of next-generation networks, facilitating small cell deployments will support delivery of increased speeds through the so-called millimeter wave spectrum bands, such as 28, 24, and 39 GHz, and provide more access to new spectrum types such as unlicensed and shared spectrum. These bands are all uniquely well-suited to small cells, as they can be placed strategically, in very close proximity to where additional coverage/performance is needed. Small cells can carry large sum of data transmission brought by Internet of Things (IoT) and integrated wireless backhaul, reducing investment costs significantly.

Currently, mobile operators in China, the United States and South Korea are the most active with small cell deployments, including China Mobile, Verizon, AT&T, and SK Telecom.

Sprint unveiled the Sprint Magic Box, the *world's first all–wireless small cell* in May 2017.[78] Sprint Magic Box is a revolutionary new plug–and–play LTE small cell for businesses and consumers that dramatically improves data coverage and increases download and upload speeds on average by 200 percent.[1] The breakthrough new technology allows Sprint to very quickly and cost–effectively densify its nationwide LTE Plus network, and provide an improved experience for its millions of customers today and in the future, while building a strong foundation for 5G. Sprint Magic Box greatly accelerates Sprint's strategy to densify its network as it improves performance. It uses Sprint's ample, dedicated 2.5 GHz spectrum with backhaul provided by Sprint's outdoor macro cell sites. This removes the cost of backhaul, along with many of the challenges typically associated with small cell deployments, providing a low-cost, effective way to make the Sprint network – already performing at its best–ever–levels – even better for customers.

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[77] *Trendforce: Small Cell deployment to reach 2.835 M units in 2018; 4.329 M units in 2019 on CAG of 52.5*%, IEEEComSoc technology blog, Alan Weissburger. March 14, 2018.
[78] Sprint press release. May 3, 2017.

Machine Type Communications (MTC) was standardized in Rel-12 and Rel-13. With forecasts for the IoT at some 50 billion connected devices, many of which will be cellular connections, the work in standards development and by leading manufacturers is increasingly significant. In 3GPP Release 13 standards, the development of Cellular-Internet of Things (C-IoT) features was studied, along with other features for LTE-Advanced Pro. In Release 13, the developing C-IoT is addressed with LTE Category M1 (LTE Cat-M1) architecture, also called LTE-M, that further reduces cost, improves range, and extends battery life of IoT devices. Release 13 also adds Narrowband-IoT capability with Category NB-1 and an IoT solution for GSM, called "EC-GSM-IoT," that extends coverage by 20 dB. Category M-1 and NB-IoT devices could achieve battery life as high as 10 years.

Rel-13 enhanced Machine-Type Communications (eMTC) introduces LTE Category M1 User Equipment supporting the broadest range of IoT capabilities, with complexity reduction and coverage enhancements to at least 155.7 dB Maximum Coupling Loss (MCL); data rates up to 1 Mbps utilizing only 1.08 MHz bandwidth; supporting full-duplex Frequency Divisio Duplex (FDD), half-duplex FDD and Time Division Duplex (TDD) modes, and ability for deployment in any LTE spectrum. Cat-M1 can also support voice through Voice over LTE (VoLTE) and full-to-limited mobility and is designed to fully coexist with regular LTE traffic (Cat-0 and above). LTE-M, as this category is commonly called, was commercially deployed by 13 global operators as of July 2018 primarily in Asia-Pacific and Western Europe.[79]

LTE Cat-NB1 (NB-IoT) scales down further in cost and power for low-end IoT user cases. NB-IoT User Equipment further reduces complexity and extends coverage to 164 dB MCL. NB-IoT is ideal for low-throughput, delay-tolerant use cases with low mobility support, such as smart meters, remote sensors and smart buildings. Cat-NB1 uses 180 kHz bandwidth and supports stand-alone, guard-band and in-band operation. NB-IoT is currently specified for LTE FDD, although some 3GPP member companies have expressed interest in specifying TDD operation in future releases. NB-IoT supports in-band deployment by utilizing a single RB within a normal LTE carrier. It can be deployed in a LTE carrier's guard-band utilizing unused resource blocks while still minimizing interference with neighboring carriers. In standalone mode, NB-IoT can be deployed in re-farmed spectrum from GERAN systems utilizing standalone 200 kHz carriers. Thus, NB-IoT provides flexible deployment options to operators. NB-IoT was commercially deployed by 31 operators as of June 2018 primarily in Asia-Pacific and Western Europe.[80]

Having launched LTE-M nationwide in U.S. in 2017, AT&T finished their network in Mexico in January 2018. AT&T's LTE-M network brings with it carrier-grade security, as well as extended battery life, lower cost modules and improved coverage both underground and deep inside buildings. T-Mobile launched NB-IoT in October 2017 and reached nationwide coverage in mid-2018. The T-Mobile strategy is to also build LTE-M where the use cases make sense in 2018. One of the main differences between the two technologies is that LTE M supports voice and NB-IoT does not. Both technologies can be rolled out through software upgrades, so they are much easier to roll out than standard LTE technology, for example, which requires completely new antennas and other hardware. AT&T continues to evaluate whether they want to invest in NB-IoT.

Verizon also launched nationwide LTE-M in 2017 and plans to test NB-IoT as well and potentially add NB-IoT capabilities to its existing Cat M1 network.

Sprint will complete LTE Cat 1 technology across its nationwide network at the end of July 2018 and begin deploying LTE M in mid-2018 followed by NB-IoT.

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[79] *GlobalComms* database, TeleGeograhy. June 1, 2018. http://www.5gamericas.org/files/3215/2693/6198/LTE_Advanced_Pro.pdf
[80] *Ibid.*

In September 2017, the *first Cellular Vehicle-to-Everything (C-V2X) chipset and Reference Design* to support automotive road safety and help pave a path for the future of autonomous driving was announced. The C-V2X commercial solution, based on 3GPP Release 14 specifications for PC5-based direct communications met automaker production demands for road safety, and was expected to be available in the second half of 2018. To help accelerate the automotive ecosystem for commercial readiness, the C-V2X Reference Design featured integrated Global Navigation Satellite System (GNSS) capability and an application processor running the Intelligent Transportation Systems (ITS) V2X stack and a Hardware Security Module (HSM). Global Certification Forum (GCF) announced in June 2018 that they are including LTE-based vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) communication technologies in their certification program, specifically LTE sidelink, which is an adaptation of core LTE standards as defined in Rel-14.

C-V2X's overarching technologies encompass two transmission modes of direct communications and network-based communications, which are designed to serve as key features for safety conscious and autonomous driving solutions, while complementing other Advanced Driver Assistance Systems (ADAS) sensors, such as cameras, radar and LIDAR (Light Detection and Ranging), to provide information about the vehicle's surroundings, including non-line-of-sight (NLOS) scenarios. C-V2X direct communications is designed to support active safety and helps enhance situational awareness by detecting and exchanging information using low latency transmission in the globally harmonized 5.9 GHz ITS band for Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) and Vehicle-to-Pedestrian (V2P) scenarios without the need for a Subscriber Identity Module (SIM), cellular subscription or network assistance. Complementing direct communication transmissions, the network-based communications is designed to utilize the wireless operator's 4G and emerging 5G wireless networks for Vehicle-to-Network (V2N) and operates over licensed operator spectrum to support telematics, connected infotainment and a growing variety of advanced informational safety use cases. The C-V2X standards include both the global 3GPP specifications at the radio layers and reuse the established service, and application layers, defined by the automotive industry.

Leading in the IT strategy space, another vendor long recognized the IoT as a critical enabler of the idea economy and the data-driven enterprise. As such, they launched a *Universal IoT Platform for licensed and unlicensed spectrum*, 3G-4G-WiFi-LPWAN (Low-Power Wide-Area Network), including the emerging cellular standards such as LTE-M and NB-IoT. The platform dramatically simplifies integrating diverse devices with different communications protocols. It provides Subscriber Identity Module (SIM) and Device Lifecycle Management and Data Analytics. The company also introduced the industry's first converged system for IoT bringing a robust analytics platform to deliver IoT insights and machine learning at the edge, enhanced IoT security and new IoT services and ecosystem capabilities. Real time analysis is enabled at the edge, rather than forcing companies to transfer vast amounts of sensor data to a central location for processing.

LTE-R (LTE-Rail) is a next generation communications technology for smart train and metro services, enabling high-speed wireless voice and data communications inside trains, from train-to-ground and from train-to-train. LTE-R was deployed on the new Wonju-Gangneung line, Korea Rail Network Authority in partnership with KT and a leading vendor *to enable mission-critical communications – including mission critical push-to-talk (MCPTT), group calls and VoLTE between train personnel and control centers*. Another leading vendor announced *successful completion of LTE networks for similar railway solutions* at simulated speeds close to 125 mph with Canadian transportation company Bombardier in 2016.

Multi-access Edge Computing or MEC is essentially a cloud-based IT service environment at the edge of the network. MEC is a network architecture that brings real-time, high-bandwidth, low-latency access to radio network information, allowing operators to open their networks to a new ecosystem and value chain.

MEC permits multiple types of access at the edge, including wireline. The benefits of edge computing technology reach beyond mobile and into WiFi and fixed access technologies.

The primary goal of multi-access edge computing is to reduce network congestion and improve application performance by achieving related task processing closer to the user. Further, it aims to improve the delivery of content and applications to those users. Use cases already being realized include Augmented Reality (AR) and Virtual Reality (VR), which benefit from lightning-fast response times and low latency communications; connected cars, which also thrive in high-bandwidth, low-latency, highly available settings; and other Internet of Things (IoT) applications that rely on high performance hand smart utilization of network resources.

Leading vendors' Multi-access Edge Computing (MEC) platforms can rapidly process content at the very edge of the mobile network, delivering an experience that is ultra-responsive as latency is significantly reduced. Multi-access Edge Computing takes full advantage of the telco cloud, enabling new possibilities to serve the operator's radio network and to co-exist with our other Virtualized Network Functions. As a software function, it delivers flexibility, scalability and efficiency to multiple base station sites using existing interfaces and innovative Ethernet-based fronthaul. MEC processes data close to where it is generated and consumed. This enables the network to deliver the ultra-low latency required by business-critical applications and to support interactive user experiences in busy venues. By processing data locally, MEC applications can also significantly reduce data transfer costs.

The Multi-access Edge Computing ETSI Industry Specification Group has over thirty participating members driving standardization and fostering an open environment around IT and cloud-computing capabilities within the radio access network.

Virtualized Multi-access Edge Computing (vMEC) is a software-only solution that can be deployed on commercial off-the-shelf (COTS) servers, making it easy to integrate with existing Information Technololgy (IT) infrastructure.

A leading vendor and its partners demonstrated for the *first time in the world in an operator's live LTE network how Multi-access Edge Computing can be used for V2V and V2-Infrastructure communications*. Vehicles connected via the distributed cloudlets based on the vendor's MEC platform receive information such as warnings from other vehicles almost in real time, which is particularly important for traffic safety applications. MEC is an enabler for optimized infrastructure investments and the first step towards 5G and autonomous driving. Large public venues and enterprise organizations are also excellent beneficiaries of MEC. In large-scale situations where localized venue services are important, content is delivered to onsite consumers from a MEC server located at the venue. The content is locally stored, processed, and delivered—not requiring a backhaul or centralized core network. Large enterprises are also increasingly motivated to process users locally rather than backhaul traffic to a central network, using small cell networks instead.

Another industry development is Network Function Virtualization (NFV). Industry leaders have been instrumental in the evolution of network architecture and the management plane to virtualize current and next generation networks to create enhanced communication services. One leading vendor has been actively enabling the industry to virtualize the cellular network and transition to general purpose hardware based on x86. The vendor has invested in R&D to make x86 processors more efficient for high-speed packet processing while contributing its own set of libraries, such as DPDK (Data Plane Development Kit).

In early 2015, AT&T stated a plan to virtualize and software-control 75 percent of their core network functions by 2020. In 2017, AT&T achieved a goal of 55 percent; 2018 will raise that to 65 percent. As a frontrunner in the goal of virtualizing and controlling over 75 percent of its network using Software-Defined Networking (SDN) and NFV by 2020, they will help pave the way for the industry. The launch of virtualized core network platforms and NFV/SDN has enabled AT&T to rapidly deploy additional mobile core sites and expand its mobile core network within the U.S. as well as build out mobile cores in Mexico and Europe. AT&T's Integrated Cloud (IC) enables gathering and analyzing extremely large volumes of network data which enhances its Big Data based intelligence capabilities. The ability to grow the mobile core in an agile manner using NFV/SDN is a key enabler for new services, IoT growth and 5G.

Telefonica has also progressed their NFV/SDN solution, being awarded best in the LTE and 5G World Awards 2016. During Mobile World Congress 2018, Telefónica presented the development of its Telco Cloud-UNICA platform, by integrating a virtualized network function (virtual Evolved Packet Core (vEPC)) and loading it on 4 network slices. This demonstrated, on the one hand, the concept of 5G Network Slicing with end-to-end vision and, on the other, the advantages of the UNICA network transformation program. Fundamentally, it showed the interrelation between the two, that is to say, the importance of network virtualization for the optimal deployment of 5G technology and functionalities. Telefónica keeps evolving towards the virtualization of its network, with the aim of increasing agility, flexibility, and scalability. Through UNICA, the company continues defining a general-purpose network and services architecture in a multi-vendor cloud environment, key to its versatility to incorporate new functionalities, including 5G.

As note previously, a leading chipset manufacturer led the industry with the *first commercially announced Gigabit Class LTE chipset* designed to deliver fiber-like LTE Category 16 download speeds of up to 1 Gbps, and was the mobile industry's *first announced LTE Advanced Pro modem with support for LAA* (Rel-13). In addition, new modem solutions were designed and introduced to support reliable, global connectivity to the IoT such as scalable, power-efficient and cost-optimized Cat 1 LTE connectivity and to provide a path to LTE eMTC and NB-IoT standards in Rel-13.

In Suwon, South Korea, Sprint and a leading vendor tested *Massive MIMO (multiple input, multiple output) in 2.5 GHz spectrum* in June 2017. The Massive MIMO test represented a real-world application of the new technology, slated to help Sprint dramatically boost LTE Plus wireless capacity and coverage, and offer Gigabit LTE service to its customers.

Günther Ottendorfer, Chief Operating Officer – Technology, Sprint commented that, "Massive MIMO is a tremendous differentiator for Sprint because it is easily deployed on 2.5 GHz spectrum due to the small form factor of the radios needed for a high frequency band. In lower frequency bands, wavelengths are much longer and therefore the radios require much larger, impractical form factors. This makes Massive MIMO an important tool for unleashing our deep 2.5 GHz spectrum holdings." During field testing in Suwon, Massive MIMO Samsung radios, equipped with vertical and horizontal beam-forming technology, reached peak speeds of 330 Mbps per channel using a 20 MHz channel of 2.5 GHz spectrum. Capacity per channel increased about four times, cell edge performance increased three times, and overall coverage area improved as compared to current radios.

In September 2017, Sprint and its vendor partner unveiled results of the *first U.S. 2.5 GHz Massive MIMO field tests* conducted in Seattle, Washington and Plano, Texas using Sprint's spectrum and the vendor's 64T64R (64 transmit, 64 receive) radios. The two companies were preparing for commercial deployment in 2018 with Massive MIMO radios capable of increasing Sprint's network capacity up to ten times.

As 3GPP continues to develop standards for LTE-Advanced, the world's leading mobile broadband technology, 5G technology is on the horizon. Many global organizations joined with private and public partnerships including ventures with universities and leading associations such as 5G Americas, NGMN

Alliance, 5G-IA, 5G Forum, 5GMF, IMT-2020, 5G Brazil and others, along with top industry manufacturers and service providers – all of which are developing the framework for 5G. Some world regions such as the European Union, Korea and Japan are investing billions of dollars in research for taking on leadership in 5G technology. Publications such as the white papers, *5G Americas Spectrum Recommendations for the U.S*., published in April 2018[81] and *5G Network Transformation* published in December 2017[82] and others on the 5G Americas website provide additional information.

2.8 ROAD TO 5G – 3GPP RELEASE 15 STANDARDIZATION

The big news for the industry was the accelerated completion of the first 5G New Radio (NR) specifications with the ratification of the 3GPP Release 15 Non-Standalone (NSA) 5G NR specification in December 2017 for what will form the basis of commercial 5G products. Specifications covered support for low-, mid- and high-band spectrum, from below 1 GHz (600 or 700 MHz), up to 50 GHz and include the 3.5 GHz band. The Standalone (SA) version is due for completion in June 2018, defining the full user and control plane capability for 5G NR using the new 5G core network architecture also being defined by 3GPP. However, both the NSA and SA versions share physical radio interface aspects.

Section 5 of this paper explains in detail the current work in Releases 15 and 16 in the progress towards 5G. However, a lot of innovative developmental work is currently underway with numerous commercial announcements. For example, a leading infrastructure company announced shortly after the December specifications for NSA 5G NR were finalized that they were raising $370 million for 5G development and other investments; the previous month they filed a patent application that 'contained everything needed to build a 5G network', from devices to overall network architecture, and would enable use cases involving connected factories and self-driving cars. The landmark filing, a culmination of years of research, includes 400 pages and combines the work of 130 inventors at their company.

3GPP remains vigilant in progressing specifications for 5G and has set forth their timeline for completion of 5G standards through 2019 as shown in Figure 2.11.

[81] *5G Americas Spectrum Recommendations for the U.S.* 5G Americas. April 2018.
[82] 5G Network Transformation. 5G Americas. December 2017.

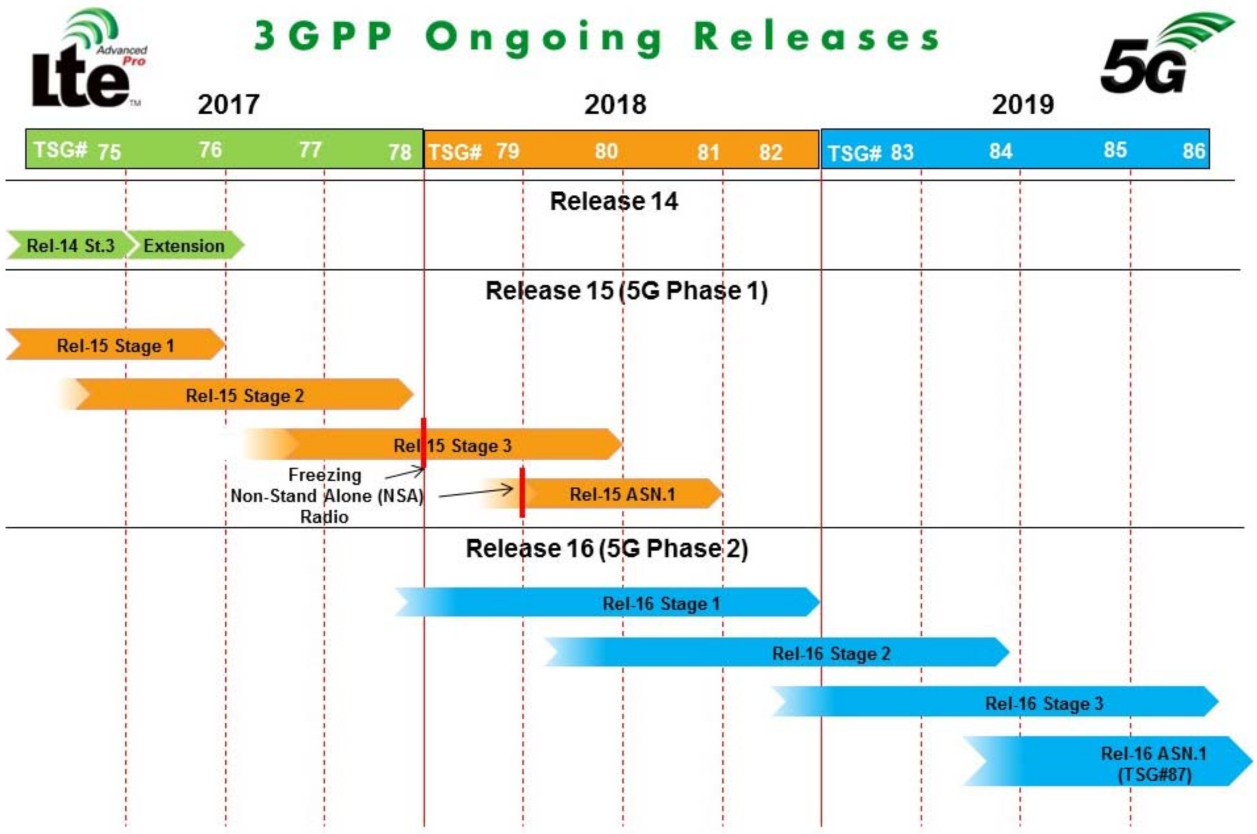

Figure 2.11. 3GPP Release 15 and Release 16 Timeline.[83]

However, it is the vast number of demonstrations, trials, and new product announcements that are monopolizing the industry news in the recent years. Many of these trials formed the basis for 3GPP's standardization and the accelerated delivery of the NSA NR specifications in December 2017. There are far too many to enumerate, so a sampling of examples of these milestones is provided in this section.

In early 2016, AT&T began 5G trials in Austin, Texas, having secured special licensing to do so from the U.S. government. Outdoor testing began in the summer and field trials to provide wireless connectivity to fixed locations in Austin were planned prior to the end of the year. AT&T is structuring its trials in such a way that it is able to contribute to the international 5G standards development and pivot to compliant commercial deployments once standards are set by 3GPP. AT&T's fundamental technology approach to 5G is unique. Built on its industry leading positions in Software-Defined Networking (SDN), data analytics, security and open source software, the approach will help deliver a cost-effective wireless experience that can quickly adapt to new consumer and business demands. AT&T has said it expects to launch a standards-based mobile 5G service by the end of 2018.

In June 2016, Sprint was the first U.S. carrier to demonstrate elements of 5G at a large scale public event (Copa America Centario). The Sprint demonstration with a leading infrastructure vendor utilized 73 GHz

[83] http://www.3gpp.org/specifications/67-releases

millimeter wavelength spectrum to deliver peak download speeds of more than 3 Gbps. With another leading vendor, Sprint demonstrated utilizing 15 GHz centimeter wavelength spectrum to deliver download speeds up to 4 Gbps (Rel-15). Sprint plans to provide commercial 5G services and devices in late 2019.

A leading chipset manufacturer showcased a live over-the-air demonstration of 5G NR spectrum sharing technologies. The use of 5G spectrum sharing technologies is expected to bring higher levels of mobile broadband performance to unlicensed and shared spectrum, as well as play an important role in extending 5G into new types of deployments such as private networks for industrial IoT. The demonstration showcased advanced spatial domain spectrum sharing technology that relies on Spatial Domain Multiplexing (SDM) and Coordinated Multi-Point (CoMP) concepts. This is designed to deliver higher network capacity and user throughput, through tighter coordination among users of unlicensed and shared spectrum bands. The demonstration utilized the previously announced 5G NR spectrum sharing prototype system, which is also designed to support testing of 5G NR operation in unlicensed spectrum, both licensed-assisted access (LAA) and standalone operation without a licensed anchor, also known as 5G MulteFire™.

Leading vendors are also driving the 5G standards work from research and pre-standard field trials. Through advances such as 5G Radio Prototypes and cloud-based network slicing, a leading vendor and its operator customers will be key players in defining this next generation of network technology all the way through to commercialization. The 5G Radio Prototypes that operators can deploy in live field trial environments are showing exceptional performance under real-world conditions, achieving a peak throughput of 27.5 Gbps and latency as low as 2ms in a live demonstration in August 2016. The 5G Ready Core is about flexibility and efficient management of that new flexibility; it is based on five key technologies – Virtualization (VNF), Software-Defined Networking (SDN), Distributed Cloud, Network Slicing and Orchestration and Management. By managing resources dynamically, service providers can add value to their offerings by creating “network slices” on-demand, software-defined, and amenable to ecosystems involving third party service providers, at industrial scale. This successful Proof-of-Concept (PoC) for dynamic network slicing technology for 5G core networks was demonstrated in June 2016.

At Mobile World Congress in February 2016, three leading vendors announced collaboration to develop and trial what is expected to be the industry’s first 5G router for enterprises. Other announcements at the World Congress focused on a multi-country, multi-services Ultra Services Platform to simplify, automate and accelerate the Mobile Cloud. The Platform makes 5G capabilities like Control and User Plane Separation (CUPS) and network slicing available today. Operators can take advantage of these features without having to wait for end-to-end 5G.

In February 2016, it was announced that Deutsche Telekom was creating a multi-country mobile cloud and SK Telecom of South Korea was automating new service creation in minutes versus days and bringing network control to one place—all through a vendor’s “Ultra Service Platform.” This complete, virtualized, feature-rich, mobile services platform helps mobile operators launch and deploy new services faster and more efficiently. Benefits include:

- A software-defined networking (SDN) distributed network: It applies SDN to separate control and user plane functionality. User plane functionality can be distributed close to the radio access network, allowing data to shortcut to the Internet. This can help save up to 35 percent of backhaul costs
- Service creation and control can be centralized, allowing operators to be more agile
- Massive scale: In its first release, the system is tested to over two terabytes per second of traffic handling capacity, and over 20 million connections

- It simplifies and speeds the introduction of new services, from Connected Car to enterprise private mobile networks reducing time to revenue
- It automates the deployment of services through an easy to use user interface. Deployment intervals can be reduced from months to minutes, and deployment costs can be reduced by 30 percent or more
- It helps reduces total cost of ownership up to 30 to 35 percent
- It is open and extensible: it easily integrates with third-party components
- Deployable over public, private, or hybrid clouds, and may be combined with the vendor's other Software-as-a-Solution (SaaS)
- Makes 5G capabilities like CUPS and network slicing available. Operators can take advantage of these features without having to wait for end-to-end 5G

Similar platforms from other manufacturers, such as Mobile Trial Platform 2016, had continued advancements including the 5G Mobile Trial Platform which provides a high level of flexibility and processing power for the early development and testing of 5G technologies. By developing a virtualized, flexible Radio Access Network (RAN) mobile operators could realize 49 percent savings in CAPEX and 31 percent annual savings in OPEX [Senza Fili Consulting].

There have been numerous iterations of successful 5G New Radio (NR) demonstrations and trials including:

- *5G Non-Standalone NR multivendor over-the-air interoperability* for lower layer data connections at both 3.5 and 28 GHz bands with nine operators around the world (December 2017) using existing LTE radio and evolved packet core as an anchor for mobility management and coverage while adding a new 5G NR radio access carrier to enable certain 5G use cases starting in 2019 (Rel-15)

- *Deployment of fixed wireless access 5G systems* by Verizon and partners in five U.S. cities in preparation to begin customer trials of 5G technology (February 2017). The customer trials, planned to begin in April 2017, will gauge user experiences, evaluate the performance of 5G technologies, and help streamline the delivery of mmWave 5G in 28 GHz with advanced beam-forming antenna technology across various environments. 5G Access Units, installed throughout a city's business and residential neighborhoods, link radio signals to a virtualized core network set up in Verizon's data centers. The 5G system was designed to be upgradable to support 3GPP standards for NR and Next-Gen Core. Pre-commercial testing demonstrated multi-gigabit throughputs at radio distances of up to 1,500 feet across different environments

- *World's first 4G LTE and 5G end-to-end network interworking trial* in a real outdoor environment was demonstrated by SK Telecom in Seoul in September 2017. The 4G LTE commercial network in the 2.6 GHz band and newly built 5G networks using frequencies of 3.5 GHz and 28 GHz, as well as virtualized core and a test device that supported both 4G and 5G technologies, were utilized. 360-degree virtual reality video was streamed live between a user in a traveling car and another in their headquarters' building. The significant radio frequency (RF) challenge that the two companies faced for this trial was with the dense urban outdoor environment consisting of closely situated office buildings and busy traffic. The successful trial showed that users can experience seamless uninterrupted streaming service when transitioning from 4G to 5G networks and vice versa. Furthermore, this test also implied a potential 5G deployment scenario, where end users still will be able to enjoy seamless mobile service going to and from 4G and 5G service areas during the initial phases of 5G network deployment where full coverage areas have not been fully built out

- *5G New Radio (NR) sub-6 GHz prototype system* and trial platform to test, demonstrate and trial 5G design (Rel-15) was announced by a leading semiconductor company. In addition, that vendor demonstrated robust 5G millimeter (mmWave) design (Rel-15)

- *3GPP-compliant 5G New Radio-based hardware* was provided to Japan's largest mobile operator, NTT DOCOMO by a leading manufacturer to integrate into their network (January 2018), enabling a smooth evolution from LTE to 5G to launch its 5G mobile service by 2020

- *5G NR field trials with operators in 2018* will focus on the commercialization of 5G technology with New Radio as its foundation— more than 35 operators on every continent in the world are in various stages of testing and trials with vendors

Critical for the success of 5G is research with many industries to gain knowledge and experience in leveraging 5G technology. Projects to spearhead development of innovative use cases for 5G with industries ranging from mining to agriculture to intelligent transportation are ongoing. The understanding of how 5G and IoT capabilities will be used in the real world is working hand-in-hand while building innovative solutions for enterprise customers.

The connected car has shown popularity and growth for many use cases. An Automotive Trial Platform was demonstrated by a leading vendor, in partnership with NTT DoCoMo and Toyota, for the world's *first interoperable 5G trial mobile network* - testing at 28GHz frequency and realizing data transfer rates of *over 1Gbps in a moving car*.

Verizon announced plans for customer trials of 5G technology for home broadband service (Fixed Wireless Access) in five U.S. cities to begin in the second quarter of 2017, with pilot trials in a total of 11 markets expected by the middle of the year. Each location offered a unique set of test parameters, including vendors, geographies, population densities and demographics, and Ann Arbor, Michigan was announced as the site for the *first multi-vendor end-to-end 5G trial network*. The solution included a 5G virtualized packet core as part of the Ultra Services Platform and virtual RAN solutions (vRAN), paired with 5G Radio base stations and 5G home routers that will deliver broadband services to Verizon's trial customers. The comprehensive Network Vendor Interoperability Tests (NVIOT) demonstrated seamless interworking between core network, radio edge and user devices that showcased a core principle of next-generation network virtualization via multi-vendor support. The trial highlights the readiness of key 5G technologies, paving the way for deployment of commercial 5G networks. It also demonstrated that service providers can deploy 5G networks specialized to their unique market needs by selecting individual network infrastructure components from a selection of multiple vendors.

5G Plug-Ins can introduce software-driven innovations that bring essential 5G technology concepts to today's cellular networks. The Plug-Ins include modules for Massive MIMO, Multi-User MIMO, RAN Virtualization, Intelligent Connectivity and Latency Reduction to facilitate a rapid evolution of 5G access networks and the successful adoption of 5G services.

A top chipset manufacturer announced the *first 5G NR multi-mode chipset solution* in February 2017 with the first commercial products expected to be available in 1H-2019. In February 2018, 18 global operators selected the 5G modem for mobile 5G NR standard-compliant (3GPP Rel.15+) trials in 2018, and 19 global device OEMs also selected the 5G NR modem family for device launches in 2019. The 5G modems will be for use in live, over-the-air mobile 5G NR trials with multiple global wireless network operators in both the sub-6 GHz and millimeter wave (mmWave) spectrum bands. AT&T, British Telecom, China Telecom, China Mobile, China Unicom, Deutsche Telekom, KDDI, KT Corporation, LG Uplus, NTT DOCOMO, Orange, Singtel, SK Telecom, Sprint, Telstra, TIM, Verizon and Vodafone Group will conduct the trials, which will be based on the 3GPP Release 15 5G NR standard. The mobile 5G NR trials will utilize the chipset vendor's 5G mobile test platform and smartphone reference design and optimize 5G technology within the power and form factor constraints of a smartphone, while maintaining interoperability and coexistence with 4G LTE. The planned trials underscore the readiness of this mobile 5G NR solution in a smartphone form factor and aim to commercialize standard-compliant 5G NR products and services over 2018.

The world's *first global 5G modem supporting both sub-6GHz and mmWave bands* was introduced in 2016; in 2017, a portfolio of commercial 5G ready modems was introduced to enable a range of devices to connect to 5G networks – from PCs and phones to fixed wireless consumer premise equipment (CPE) and even vehicles. Complementing the 5G modem, a *5G Radio Frequency Integrated Circuit* (RFIC) was announced, working in the 3.3 to 4.2 GHz and 20 GHz bands and supporting 50 MHz to 800 MHz transmission with 2x2 and 4x4 MIMO.

The role of 5G NR-based Cellular Vehicle-to-Everything (C-V2X) technology in autonomous driving showcased how the technology is designed to help the vehicle communicate its intentions, thus supporting the level of predictability needed for advanced path planning. 5G NR-based C-V2X is engineered to augment existing C-V2X technology with complementary capabilities, bringing in high throughput and URLLC capabilities, while maintaining backwards compatibility, which are needed to support advanced use cases for autonomous vehicles, including high throughput sensor and intent sharing, and 3D HD map updates.

The excitement continues to build as we approach the launch of mobile 5G networks. Consumers will have 5G smartphones in their hands by the first half of 2019. In anticipation, operators are strengthening the Gigabit LTE foundation on which their future 5G networks will be built and taking their nets steps in 5G development and deployment.

Mobile carriers are now making their 5G deployment plans widely known:

- AT&T plans to offer standards-based mobile 5G to customers in a dozen cities by the end of 2018. (February 2018) "After significantly contributing to the first phase of 5G standards, conducting multi-city trials, and literally transforming our network for the future, we're planning to be the first carrier to deliver standards-based mobile 5G – and do it much sooner than most people thought possible," said Igal Elbaz, senior vice president, Wireless Network Architecture and Design. "Our mobile 5G firsts will put our customers in the middle of it all."

  AT&T sees 5G and SDN hand in hand; A virtualized and software-defined network allows development, deployment, and protection of new network applications faster than with a hardware-based model. Ultimately, AT&T expects to reach theoretical peak speeds of multiple gigabits per second on devices through mobile 5G. Learnings from extensive 5G real-world trials will drive our commercial deployments in 2018; 5G field trials with mmWave started in mid-2016 and 5G service was tested with residential customers, small and large businesses, and high-traffic retail locations. AT&T's lab in Austin, Texas has mobile 5G network equipment and devices from multiple vendors; the lab is also equipped with an outdoor 5G testbed to trial a variety of 5G applications and real-world use cases. One of the first in-house projects built at the lab was the Advanced 5G NR Testbed System (ANTS). ANTS is a first-of-its kind 5G testbed system and is proprietary to AT&T. ANTS allows testing unique and forward-looking features on a simulated 5G network for eventual standardization and use on our commercial network.

  In September 2018, in Waco, Texas, working with key technology collaborators, AT&T made the *world's first wireless 5G data transfer over millimeter wave* using standards-based, production equipment with a mobile form factor device.

AT&T's 5G deployment strategy will include using millimeter wave spectrum to deploy 5G in pockets of dense areas – where demand on our network is high and extra capacity and coverage is needed most. AT&T has been encouraged by the performance of mmWave in their 5G trials and found that it performs better than expected and is successful in delivering ultra-high wireless speeds under a variety of conditions. In other parts of urban areas and in suburban and rural areas, AT&T plans to deploy 5G on mid and low-band spectrum. AT&T plans to introduce mobile 5G in parts of twelve cities in 2018 - Houston, Jacksonville, Louisville, New Orleans, San Antonio, Atlanta, Charlotte, Dallas, Indianapolis, Oklahoma City, Raleigh, and Waco. In early 2019, AT&T will ntroduce mobile 5G in parts of Las Vegas, Los Angeles, Nashville, Orlando, San Diego, San Francisco, and San Jose. From these 19 cities, AT&T will continue to expand.

- Canadian carrier, Shaw Communications announced in May 2018 results of their first 5G technical trials using 28 GHz millimeter wave spectrum and 3.5 GHz spectrum in Calgary with leading vendors to better understand interoperability between the bands.

- T-Mobile USA plans to build out 5G in 30 cities in 2018, with customers in New York, Los Angeles, Dallas and Las Vegas first to experience 5G when the first 5G smartphones launch in early 2019. In addition to deploying 5G-ready equipment currently and lighting up 5G in low-band spectrum (600 MHz), T-Mobile also plans to begin building out 5G on millimeter wave spectrum in 2018. They will additionally deploy 25,000 small cells to light up LAA technology to add extra capacity and speed, while paving the way for 5G.

- Sprint promised in February 2018, that it will launch mobile 5G services on its 2.5 GHz spectrum holdings on a nationwide basis in the first half of 2019. Sprint will achieve this by deploying antennas on its cell towers that support massive MIMO transmissions; the carrier can upgrade hardware to the 5G NR standard via a software update. Sprint offers 2.5 GHz capabilities on roughly half of its towers [February 2018], and will expand those capabilities to almost all of the carrier's towers in 2019. It also plans to increase the number of its macro tower sites by around 20 percent. Sprint's 5G buildout will be bolstered by the deployment of roughly 40,000 outdoor small cell solutions, 15,000 strand mounted small cells through the company's partnerships with cable companies, along with the deployment of up to 1 million Sprint Magic Boxes.

Use cases are beginning to develop for 5G services and are driving innovations in the networks. A leading vendor worked with Japan's KDDI on 5G trials involving service on moving trains with a 5G pre-commercial end-to-end solution to demonstrate 5G on a moving train traveling over 60 mph; they were able to achieve a successful downlink and uplink handover as well as a peak speed of 1.7 Gbps. Use cases as a result of the technology could pave the way for vastly improved backhaul for onboard WiFi, superior passenger infotainment and increased security and analytics.

Driving 5G NR evolution into the next phase of 3GPP Release 16+, the *first demonstration of wireless Industrial Ethernet over 5G NR URLLC for Industrial IoT* cases was announced in February 2018. Following the December 2017 completion of the first 5G NR standard to accelerate enhanced mobile broadband deployments starting 2019, 3GPP has approved various technology studies that are expected to define the next phase of 5G NR in Rel-16 and beyond.

The industry is quickly coalescing a strong 5G ecosystem, a closely interlinked series of symbiotic relationships that includes operators, large infrastructure vendors (e.g., Ericsson, Nokia and Samsung), semiconductor vendors (e.g., Intel and Qualcomm), IT-infrastructure providers (e.g., Cisco and Mavenir), device manufacturers (e.g. Samsung), antenna system providers (e.g., Commscope and Kathrein), standards bodies (e.g., 3GPP and ITU), associations (5G Americas, 5GPPP, 5MF, 5G Forum, IMT-2020, Next Generation Mobile Networks Alliance (NGMN), Small Cell Forum), academia, governments and more. The result will be a path that is well-paved and researched for a connected future.

3 STATUS OF 3GPP RELEASE 14: HSPA+ AND LTE-ADVANCED PRO

3GPP Release 14, which was frozen by mid-2017 and potentially ended specification on LTE, produced additional LTE-Advanced Pro features, such as eLAA (adding uplink to LAA), Multiple-Input Multiple-Output (MIMO) antenna enhancements, Carrier Aggregation (CA) enhancements, enhanced LTE Wireless Local Area Network Aggregation LWA (eLWA), Voice-over-LTE (VoLTE) enhancements and enhancements to Proximity Services/Device-to-Device (ProSe/D2D). Rel-14 also focused on the study items towards the 5th Generation (5G) mobile wireless technology and architecture, therefore the initial work on the 5G standards and cellular V2X communications. Details on the specifications in Release 14 are explained in section 3.

3.1 E-UTRAN/LTE-ADVANCED PRO ENHANCEMENTS

A decade after LTE specifications began in Release 8, it appears that the evolution may be nearing its full maturity in terms of specifications. However, there will be another decade of leadership for this rapidly growing mobile broadband technology. Many of the 5G envisioned technology features will be built upon the 4G LTE networks. Key features are explained in detail.

3.1.1 ENHANCEMENTS ON FULL-DIMENSION (FD) MIMO FOR LTE

With the recent advances in active antenna technology, it is possible to deploy base stations with a large number of antenna elements to enhance cell capacity and coverage. Antenna elements can be deployed in 2D arrays, providing horizontal (azimuth) as well as vertical beamforming. In urban environments, with high rise buildings, this can improve indoor coverage and increase capacity. Wireless networks with base stations having a large number of antenna elements, are known as massive MIMO, or EB/FD-MIMO (Elevation Beamforming/Full Dimension MIMO) systems. Realizing the benefit and feasibility of such systems, 3GPP initiated a study on EB/FD-MIMO in the Release-13 time frame. The enabling technologies and results of this study item are described in technical report TR-36.897.

The Rel-13 FD-MIMO work item only addressed a part of the proposals from the study item. The Rel-13 FD-MIMO work item specified the following:

- Channel Information State Reference Signal (CSI-RS) enhancements. For non-precoded CSI-RS, the number of antenna ports was increased to 16 ports.
- CSI reporting mechanism enhancements to support non-precoded CSI-RS and beamformed CSI-RS.
- Downlink (DL) Demodulation Reference Signals (DMRS) enhancements to support higher order Multi-User-MIMO (MU-MIMO).

There are some aspects of the EB/FD-MIMO study item not addressed in the Rel-13 FD-MIMO work item:

- First, only up to 16 antenna ports are supported in Rel-13, thus the benefit from Active Antenna Arrays (AAA) with more than 16 Transceiver Units (TXRUs) is limited

- Second, CSI reporting to enable efficient Multi-User (MU) spatial multiplexing was not completed in Rel-13 and needed to be enhanced
- Lastly, there is no support, in Rel-13 for providing higher robustness against CSI impairments, such as inter-cell interference or for higher-speed User Equipment (UEs)

The Rel-14 eFD-MIMO WI addresses these limitations. It provides support for systems with a larger number of AAA (Active Antenna Array) in addition to supporting a variety of deployment scenarios, including both high speed UEs and higher-order MU spatial multiplexing, by enhancing the reference signal design, CSI reporting mechanisms and introducing new transmission schemes.

3.1.1.1 ENHANCEMENT ON REFERENCE SIGNAL DESIGN

DL CSI-RS is enhanced for both non-precoded CSI-RS and beamformed CSI-RS. First, the number of antenna ports is increased to up to 32 antenna ports. In addition, aperiodic and multi-shot CSI-RS transmission is introduced to facilitate the flexibility of CSI measurement and reporting. Uplink (UL) Demodulation Reference Signal (DMRS) is also enhanced and interleaved with frequency domain multiplexing (IFDM), a new comb pattern-based transmission in frequency domain. This is adopted to transmit DMRS, thus a higher number of MU layers are supported and higher UL capacity can be achieved. More specifically, the following enhancements on the reference signal design have been introduced:

- Enhanced non-precoded CSI-RS:
    - Increased number of CSI-RS ports from 16 to 32. New non-precoded CSI-RS patterns for 20, 24, 28, and 32 ports have been introduced. This enables CSI measurement and reporting for base stations equipped with large AAA
- The frequency density of these new patterns can be configured between normal and at reduced density value {1/2, 1/3}. This allows the network to limit the CSI-RS overhead

- Enhanced beamformed CSI-RS:
    - The following mechanisms have been introduced to enable more efficient usage of UE-specific beamformed CSI-RS resources (e.g. to allow more UEs to share a pool of CSI-RS resources)
        - Aperiodic CSI-RS, where a UE is configured to measure CSI-RS in a given subframe for reporting aperiodic CSI
        - Multi-shot CSI-RS, where a UE is configured to measure periodic CSI-RS and report periodic CSI during a fixed time period
    - Configurable frequency density is designed to boost the efficiency of reference signal usage
    - Two step resource configurations by combining usage of Radio Resource Control (RRC) and Medium Access Control (MAC) Control Element (CE) parameters is introduced to facilitate flexible resource selection while keeping the signaling overhead under control

- Enhanced UL DMRS:
    - The number of orthogonal Uplink (UL) DMRS ports is increased, leading to an increase in multiplexing capacity. To achieve this, UL DMRS patterns with lower IFDM/comb density are designed
    - Legacy DCI formats (format 0 and format 4) are extended to indicate Cyclic Shift Field (CSF), the new UE search space CSF index mapping is shown in Table 3.1. As indicated in the table, up to 8 layers can be supported with the new design

Table 3.1. Cyclic Shift Index Mapping.

CSF in Uplink related DCI	Cyclic Shift				OCC				IFDMA configuration
000	0	6	3	9	[1 1]	[1 1]	[1 -1]	[1 -1]	odd subcarrier
001	6	0	9	3	[1 -1]	[1 -1]	[1 1]	[1 1]	odd subcarrier
010	3	9	6	0	[1 -1]	[1 -1]	[1 1]	[1 1]	odd subcarrier
011	4	10	7	1	[1 -1]	[1 -1]	[1 1]	[1 1]	even subcarrier
100	2	8	5	11	[1 -1]	[1 -1]	[1 1]	[1 1]	even subcarrier
101	8	2	11	5	[1 1]	[1 1]	[1 -1]	[1 -1]	even subcarrier
110	10	4	1	7	[1 1]	[1 1]	[1 -1]	[1 -1]	even subcarrier
111	9	3	0	6	[1 1]	[1 1]	[1 -1]	[1 -1]	odd subcarrier

3.1.1.2 ENHANCEMENT ON CSI REPORTING

Release 14 introduces two mechanisms to facilitate efficient joint utilization of two distinct types of CSI-RS: non-precoded CSI-RS (Class A); and beamformed CSI-RS (Class B). Both are referred to as Hybrid CSI reporting. The relevant enhancements include CSI reporting optimization and the associated DL signaling support.

- Mechanism 1: Hybrid CSI is realized with one CSI process, supports at least CLASS A for the 1st step and CLASS B with K=1 CSI-RS resource for the 2nd step
- Mechanism 2: Hybrid CSI reporting is realized with one CSI process, support Class B with K>1 CSI-RS resources for the 1st step and Class B with K=1 CSI-RS resources for the 2nd step

Mechanism 1 is targeted at a better quality of CSI feedback by adopting a two-step CSI report, where in the second step, the CSI report is measured based on the beamformed CSI-RS, and the beamer applied on what is acquired from the first step. Mechanism 2 is targeted at providing high flexibility of CSI-RS resource usage with a limited number of CSI processes supported by the UE. Since CSI report from the first step will be used in the second step, it is encoded together with CRI (CRS-RS Resource Indicator)/RI (Rank Indicator) and assigned a higher priority when collision happens, and parts of the CSI report need to be dropped to fit within the allocate resources. Both aperiodic and periodic CSI reports are supported for hybrid CSI reporting.

3.1.1.3 A NEW TRANSMISSION SCHEME: SEMI-OPEN-LOOP TRANSMISSION

Release 14 introduces a new diversity-based transmission scheme aided by partial reporting of Precoding Matrix Indication (PMI) for 1- and 2-layer transmission. The partial PMI reporting enables the base station to perform diversity operation combined with wideband/long-term beamforming. Compared to a typical DMRS-based precoding, this transmission scheme tends to be more robust for high-speed UEs and more robust against inter-cell interference.

For 1-layer transmission, Space Frequency Block Code (SFBC) on top of wideband beamforming using the long-term PMI feedback is used. The orphan Radio Exchange (RE) problem for SFBC in legacy LTE releases is solved by allowing REs to be paired across one rate matched RE within a symbol time. For 2-layer transmission, RE level co-phasing cycling is adopted and combined with long term PMI based beamforming, thus diversity gain can be attained at both the RB and the RE levels. Note that the RB level precoder cycling can be applied based on the implementation at base station. Simulation results are shown in Table 3.2 and Table 3.3 for 1-layer and 2-layer semi-open-loop transmission solutions selection. In the 120kmph scenario, 1-layer semi-open-loop transmission compared to CDD SFBC solution can bring ~27% mean throughput gain, and compared to fixed sector beamforming Parallel Receive Beamforming (PRB) level beam cycling can bring ~35% gain for 2-layer transmission.

Table 3.2. System Performance for Rank-1 Semi-Open-Loop Transmission.

Mean/cell edge throughput Mbps/Kbps	**UE speed**		
	3 kmph	30 kmph	120 kmph
2TX SFBC+ GoB	24.7,740	24.2, 600	23.0, 470
2TX CDD + GoB (rank-1 only)	20.0, 640	19.4, 500	18.2, 400

Table 3.3. System Performance for Rank-2 Semi-Open-Loop Transmission, 120km/h.

UE speed	Partial PMI based Precoder Group And its Cycling Pattern	Co-phasing for two virtualized Xpol ports And its Cycling pattern	Sector capacity (Mbps) Cell Edge (Kbps)
120km/h	Option 0: sector beamforming	RE level Xpol port co-phasing Co-phasing vectors or Rank-2 ONLY	24.7 (100%) 330(100%)
	Option 1: fixed beam selection		32.7 (132%) 420 (127%)
	Option 2: per PRB beam cycling		33.3 (135%) 440 (133%)

3.1.1.4 ENHANCEMENT ON CODEBOOK DESIGN

Precoding codebook extension for non-precoded CSI-RS: Since the design of the non-precoded CSI-RS is extended to support additional number of ports (20, 24, 28, and 32), the precoding codebook designed in Rel-13 for 8, 12, and 16-port CSI-RS is extended to support these four additional number of ports. All four legacy beam grid mapping configurations for Class A codebook column selection from Rel-13 are extended. Note that, in Rel-13, the codebook for Rank 5-8 transmission adopts a different codebook design principle for 8/12 ports and for 16 ports settings. In Rel-14, the 16-port codebook design is extended for rank 5-8 transmission for the four additional number of ports. With higher number of ports and codebook extension, system performance is improved. Simulation results are shown in Figure 3.1 for low traffic load scenario and Figure 3.2 for medium traffic load.

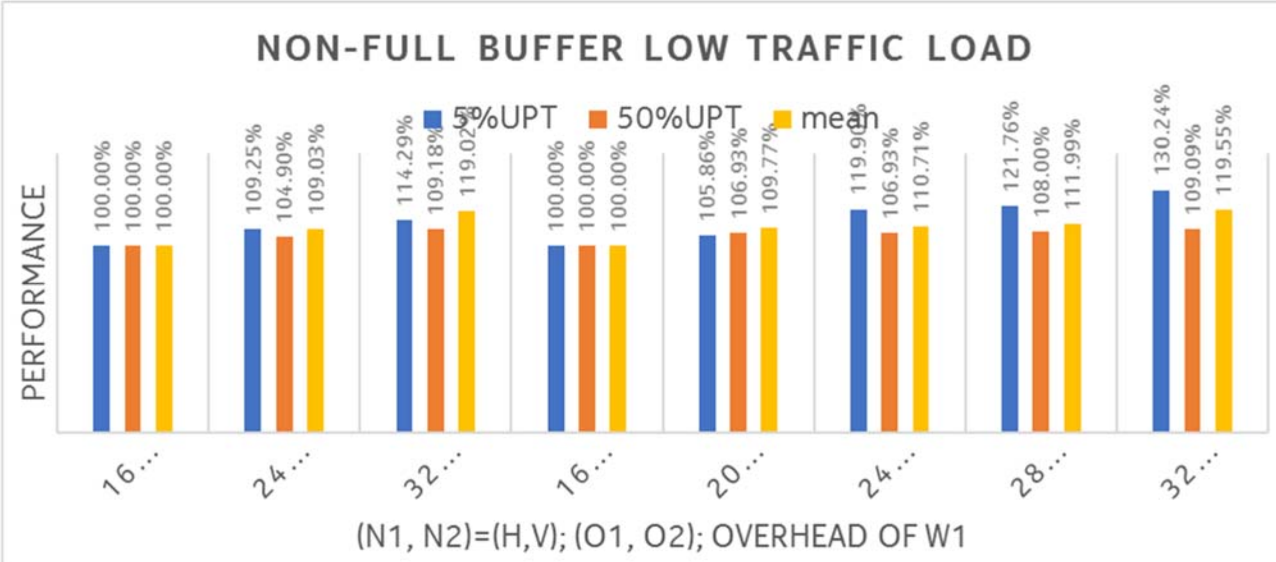

Figure 3.1. Performance with Codebook Extended to Support up to 32 Ports, Low Traffic Load.

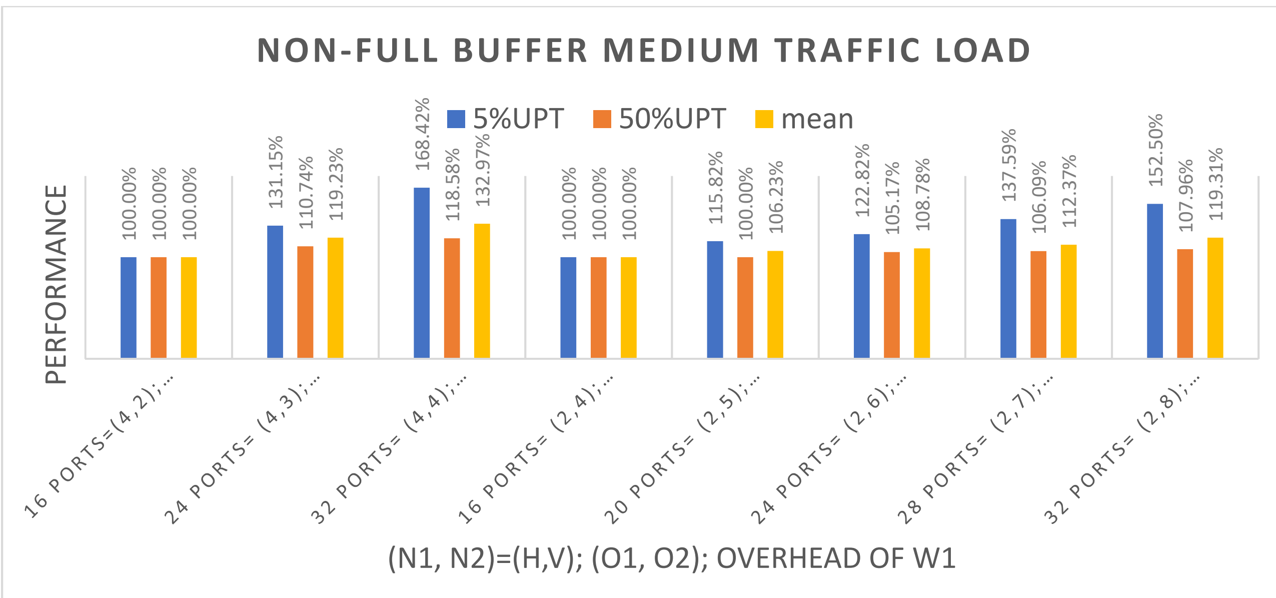

Figure 3.2. Performance with Codebook Extended to Support up to 32 Ports, Medium Traffic Load.

Advanced CSI for MU spatial multiplexing: a new high-resolution dual-stage codebook for facilitating 1- and 2-layer DL transmission per UE and improving MU precoding at the base station is introduced. The codebook is designed based on the concept of linear combination of orthogonal beams. Instead of reporting codebook indexes, beam index and its combing coefficients, both amplitudes and phases, are reported. Such scheme allows finer quantization of channel eigenvectors at the UE. Simulation results in Figure 3.3 and Figure 3.4 show that with this new advanced CSI codebook ("Rel-14, WB scaling" represents the Rel-14 advanced CSI codebook) the spectrum efficiency can be improved by 20 percent for certain scenario. To save CSI report payload, wideband (WB) scaling of the combing coefficients amplitude is selected instead of sub-band (SB) scaling, which can boost the SE by up to 60 percent.

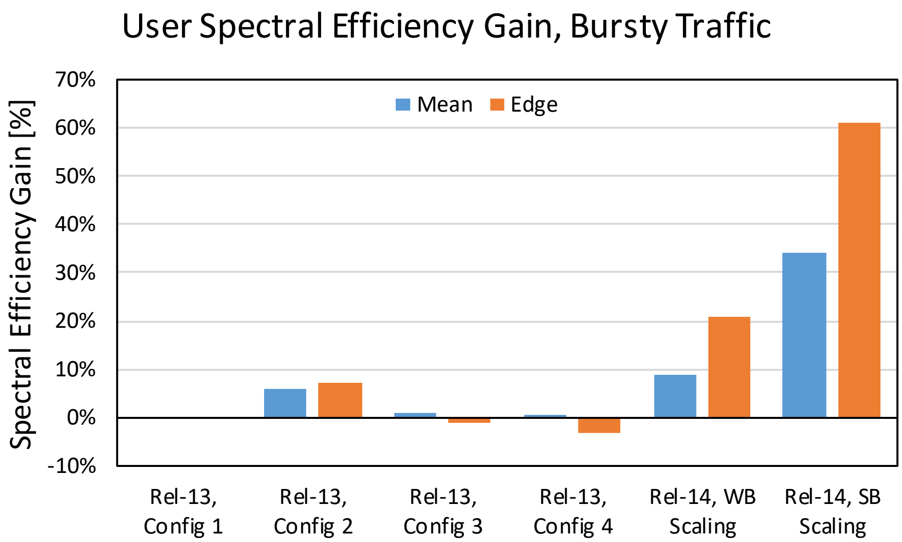

Figure 3.3. Performance of Advanced CSI Codebook (Rel-14, WB Scaling), 32 Antenna Ports (2,8,2) (25Mbps offered load).

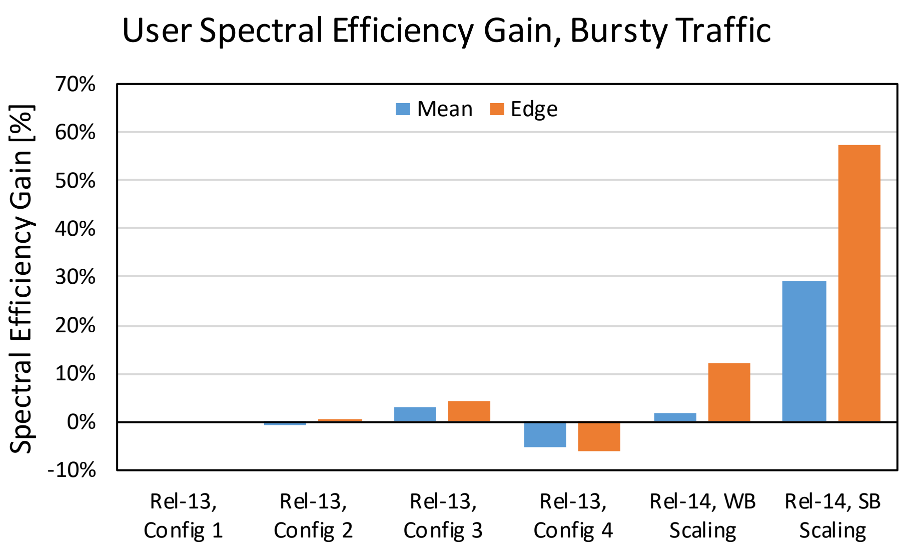

Figure 3.4. Performance of Advanced CSI Codebook (Rel-14, WB Scaling), 32 Antenna Ports (4,4,2) (22Mbps offered load).

3.1.2 ENHANCED LAA FOR LTE (UL LAA)

The fast uptake of LTE throughout the world shows both that demand for wireless broadband data is increasing, and that LTE is an extremely successful platform to meet that demand. The main drivers of this growth are the increase in the number of broadband users, average traffic consumption per user and adoption of richer content of which a large proportion is video traffic. To meet the expected traffic growth, additional spectrum will be needed. Given the large amount of spectrum available in the unlicensed bands around the globe, unlicensed spectrum is increasingly being considered by mobile operators as a complementary tool to augment their service offering.

Introducing LTE in unlicensed spectrum is an attractive solution to increase the capacity of a network and boost user performance by offering higher data rates, particularly in concentrated high traffic areas or hot spots. While unlicensed spectrum can never match the qualities of licensed spectrum, solutions that allow its efficient use as a complement to licensed deployments have the potential to bring great value to the 3GPP mobile operators, and, ultimately, to the 3GPP industry as a whole.

Licensed-Assisted Access (LAA), which is an initiative for LTE to operate on the 5GHz unlicensed spectrum, was first introduced in LTE Rel-13[84]. As illustrated in Figure 3.5, LAA utilizes LTE Rel-10 Carrier Aggregation (CA) technology to aggregate carriers across both licensed and 5 GHz unlicensed bands. The primary cell (P-Cell) on a licensed carrier will retain the exchange of essential control messages and guarantee good Quality of Service (QoS), reliability and mobility. On top of that, faster data speeds will be provided by utilizing additional carriers, when available, in the unlicensed spectrum bands. Rel-13 includes the specification of DL-only LAA operation, while UL LAA specification is part of enhanced LAA (eLAA) specified Rel-14.

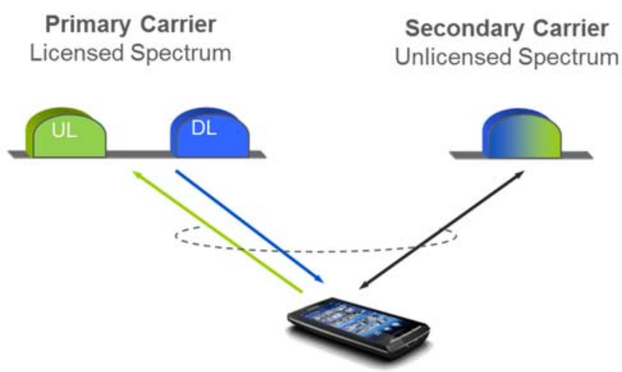

Figure 3.5. Overview of Licensed Assisted Access.

Unlicensed spectrum refers to the frequency bands for which no exclusive rights are granted. Any technology can use it as long as it fulfils the regional spectrum regulations. Some of the key regulatory requirements in certain regions of the world include:

- Listen Before Talk (LBT) mechanism where transmissions in the unlicensed spectrum is not permitted without prior channel sensing
- Limits on the maximum channel occupancy time (MCOT)
- Maximum transmit power

Rel-13 LAA targeted a single global framework for LAA, with configurable functionality to fulfil the regulatory requirements of different regions and (sub) bands. In addition, it is essential to ensure fair coexistence between the different technologies operating in the unlicensed spectrum. Today, the unlicensed 5 GHz spectrum is widely used by equipment implementing the IEEE 802.11 Wireless Local Area Network (WLAN)

[84] TR 36.889: *Feasibility Study on Licensed-Assisted Access to Unlicensed Spectrum* V13.0.0.

standard, also known as WiFi. When designing LAA in LTE Rel-13, guaranteeing fair and friendly coexistence with WiFi was one of the key targets.

The design of UL LAA access in Rel-14 respects the regional spectrum regulations as specified in Rel-13. Rel-14 also targets guaranteeing fair and friendly coexistence with WiFi just as in Rel-13 LAA. In principle, UL LAA follows the same concept as in scheduled UL LTE. However, the channel access mechanism for UL LTE has primarily been designed for licensed spectrum where the enhanced Node B (eNB) has full control of managing channel access and time-frequency resources. Thus, using the traditional UL LTE mechanisms in combination with Listen-Before-Talk (LBT) on unlicensed bands slows UL LAA channel access down thereby making it more challenging to maintain consistently good performance. The main reason lies in the fundamental difference between LAA and WiFi channel access mechanisms. While WiFi users can asynchronously send data without waiting for permission from the WiFi Access Point (AP), LAA users require multiple steps before the user equipment (UE) gets permission from the eNB to start the UL transmission.

3.1.2.1 HIGH LEVEL PRINCIPLE

The Rel-14 LAA Work Item focused on LAA uplink in unlicensed spectrum. Key areas included channel access mechanisms, core and RF requirements for base stations and UEs, and Radio Resource Management (RRM) requirements. The LAA study and work items in Rel-13 provided the many of the concepts from which to develop the Enhanced LAA functionality.

The key functionalities of the eLAA work item include the following:

- UL carrier aggregation for LAA Secondary-Cell(s) (S-Cell) (with one or more UL carriers in unlicensed band) using Frame Structure type 3:
    - Channel access mechanism for uplink transmission on an LAA S-Cell in unlicensed spectrum
    - Support for Physical Uplink Shared Channel (PUSCH) and Sound Reference Signal (SRS) transmissions on the LAA S-Cell
    - Support for both self-scheduling and cross-carrier scheduling from licensed spectrum on the LAA S-Cell
- Support for 10 MHz system bandwidth for an LAA S-Cell when the absence of IEEE 802.11 technologies using the carrier can be guaranteed

3.1.2.2 SCHEDULED UL ON UNLICENSED BANDS

LAA uplink follows the same principles as standard LTE to grant access for UL transmission.

In LTE, the UL access is eNB controlled (scheduled). The UE is not allowed to transmit data unless it is granted resources by the eNB. In this case, the UE notifies the eNB when data is available for transmission by sending a Scheduling Request (SR) using the Physical UL Control Channel (PUCCH) and indicating that it needs UL access. The UE has periodic timeslots for SR transmissions (typically on a 5, 10, or 20 ms interval). Once the eNB receives the SR request, it responds with a UL grant using the Physical DL control channel (PDCCH). The grant contains the information needed by the UE to perform the Physical UL Shared Channel (PUSCH) transmission (assigned resource blocks, modulation, coding schemes, reference signal parameters, etc.).

The UE expects to receive the grant on the PDCCH on just one carrier – either the same carrier, or a different carrier-- via cross-carrier scheduling. After the UE receives and processes its UL grant, it can transmit the UL data on the specific time-frequency resources granted by the eNB.

There is a fixed time relation between UL grant and UL transmission which is 4 ms. In addition, the UE is required to perform Clear Channel Assessment (CCA) checks using energy detection (ED) before transmitting on the channel. This procedure is illustrated in Figure 3.6.

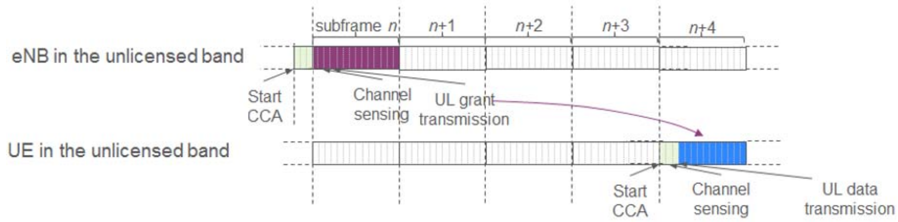

Figure 3.6. One DL LBT and one UL LBT for Self-scheduled UL Transmissions.

The scheduled UL transmission in LTE is constrained and fundamentally different from an autonomous UL used by other technologies such as WiFi. With autonomous UL, a node is allowed to asynchronously transmit at any time, not restricted by grants for transmissions and not required to have explicit permission to transmit in any way from another node. This allows a WiFi node more flexibility to contend for the channel and acquire access for transmission. The scheduled UL concept inherent in LTE imposes certain challenges when used on unlicensed channels. Many of these challenges were solved in Rel-14 eLAA, and others are left open for future enhancements.

Scheduled mode UL transmission on the unlicensed band leads to several potential problems:

- The UE suffers incremental delays before it can access the channel
- Two LBTs must succeed before the UE can transmit:
  - LBT performed by the eNB to access the channel for transmission of the UL grant
  - LBT performed by the UE to send the actual UL data
- High signaling overhead since 4 consecutive subframes with a UL grant are needed to indicate a single 4 ms UL burst

3.1.2.2.1 SELF AND CROSS CARRIER SCHEDULING

In Rel-14 eLAA, UL grant(s) for a UE in a subframe can enable PUSCH transmission in LAA Secondary Cell (S-Cell) for both cross-carrier scheduling case and self-scheduling case which are shown in Figure 3.7.

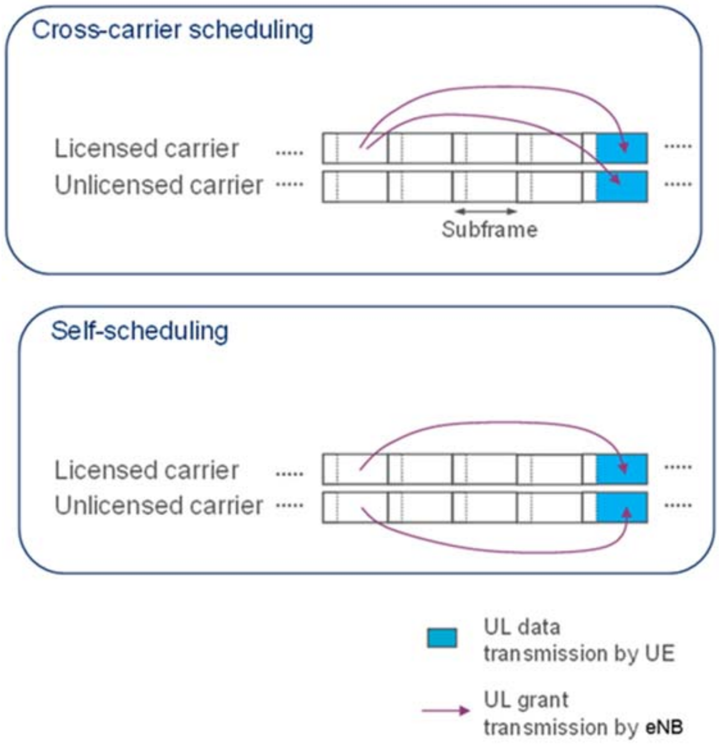

Figure 3.7. Different Scheduling Options for UL LAA.

3.1.2.2.2 MULTI-SUBFRAME SCHEDULING

In legacy LTE, a UE can receive multiple single subframe UL grants for PUSCH transmissions in different subframes where the granted UL subframes can be non-consecutive. In Rel-14 eLAA a new concept was agreed. The concept is referred to as multi-subframe scheduling, where a single UL grant in a DL subframe can be used to schedule a single or multiple consecutive UL transmission. Multiple multi-subframe grants can be scheduled in one DL subframe.

3.1.2.2.3 DCI FORMAT

New DCI formats (0B/4B) are specified to support multi-subframe scheduling. Single subframe scheduling (0A/4A) is also supported.

The UE may be configured to detect multiple uplink grants which may be chosen without restriction from DCI 0A/4A/0B/4B. The maximum number of uplink grants to be transmitted for a single UE in a subframe is four.

3.1.2.2.4 CHANNEL ACCESS FRAMEWORK

Primarily, all uplink transmissions (PUSCH, PRACH, and SRS) are conditional on successful LBT operation. The eNB indicates to the UE the LBT type in the UL grant for the transmission of the PUSCH. In Rel-14 eLAA, there are two LBT types as follow:

- UL LBT Type 1 which means that the UE is assumed to perform CAT 4 LBT for accessing the channel for UL transmission
- UL LBT Type 2 which means that the UE is assumed to perform a 25us CCA for accessing the channel for UL transmission

The UE will follow the LBT type that is signaled for accessing the channel unless otherwise stated.

3.1.2.2.5 LBT PRIORITY CLASSES

If the eNB instructs the UE to perform Cat. 4 LBT, the UE uses the priority class that is signaled by the eNB. The signaled LBT priority class is defined in Table 3.4. In addition, there is no restriction on when the UE starts Cat. 4 LBT. Nevertheless, the PUSCH transmission start point is restricted and signaled. Besides, if the UE fails to complete Cat. 4 LBT for the first subframe in a multi-subframe UL grant, it can continue the Cat. 4 LBT procedure and attempt transmission for subsequent subframes.

Table 3.4. Rel-14 eLAA UL LBT Priority Classes.

LBT priority class	n	CWmin	CWmax	MCOT	Set of CW sizes
1	2	3	7	2 ms	**{3,7}**
2	2	7	15	4 ms	**{7,15}**
3	3	15	1023	6ms (see note 1) or 10 ms (see note 2)	**{15,31,63,127,255,511,1023}**
4	7	15	1023	6ms (see note 1) or 10 ms (see note 2)	**{15,31,63,127,255,511,1023}**
NOTE 1: The MCOT of 6 ms may be increased to 8 ms by inserting one or more gaps. The minimum duration of a pause shall be 100 µs. The maximum duration (Channel Occupancy) before including any such gap shall be 6 ms. The gap duration is not included in the channel occupancy time. NOTE 2: If the absence of any other technology sharing the carrier can be guaranteed on a long term basis (e.g. by level of regulation), the maximum channel occupancy time (MCOT) for LBT priority classes 3 and 4 is for 10 ms, otherwise, the MCOT for LBT priority classes 3 and 4 is 6ms as in note 1.					

3.1.2.3 UL PHYSICAL CHANNEL OPERATIONS

The use of a carrier in an unlicensed spectrum should be done in a fair and equal manner for different devices. One component when securing this fair sharing is to have requirements on how to distribute transmissions over the system bandwidth. Two requirements related to fair sharing are commonly found in regulations:

- Occupied Channel Bandwidth
- Maximum Power Spectral Density

For example, both these requirements are enforced for 5 GHz carriers according to ETSI 301 893 while only the maximum Power Spectral Density (PSD) requirements are enforced in the US regulation for 5 GHz and 3.5 GHz.

The Occupied bandwidth requirement is expressed as “the bandwidth containing 99 percent of the power of the signal, shall be between 80 percent and 100 percent of the declared Nominal Channel Bandwidth. The frequency allocations for one UE must thus vary between sub-frames in such a way that the requirement is fulfilled.

Maximum PSD requirements exist in many different regions. For most cases the requirement is stated with a resolution bandwidth of 1 MHz. For example, the ETSI 301 893 specs require 10 dBm/MHz for 5150-5350 MHz. The implication of the PSD requirement on the physical layer design is that, without proper designs, a signal with small transmission bandwidth will be limited in transmission power. This can negatively affect coverage of the operation. The maximum PSD requirement is a binding condition that requires changes to LAA UL transmission PHY formats.

Interlacing transmissions was agreed in Rel-14 eLAA to give LAA UL signals with small bandwidth (BW) higher transmission power when needed (and, to a lesser extent, to satisfy the transmission BW requirement). The interlacing transmissions can be done on a Physical Resource Block (PRB) basis. Block-Interleaved FDMA (B-IFDMA) is the baseline uplink transmission scheme used for any uplink transmission in unlicensed spectrum. With B-IFDMA, one carrier is divided into N interlaces (N = 10 for 20 MHz carrier, and N = 5 for 10 MHz carrier), each interlace consisting of M equally spaced resource blocks in frequency domain. (M = 10 for both 10 MHz and 20 MHz carrier). For example, for 20 MHz eLAA S-Cell: interlace 0 is composed of resource blocks 0,10, 20, ...,90. This design offers a good tradeoff between satisfying regulatory requirements on occupied bandwidth and transmit power spectral density, overhead required for resource allocation signaling, and the degradation in single-carrier properties of the UL signal.

Legacy resource allocation is not suited for unlicensed operation due to the spectral power density requirements and hence not used in Rel-14 S-Cells. All uplink transmissions in eLAA are based on B-IFDMA. This applies to Physical Uplink Shared Channel (PUSCH). PUSCH symbols are Single Carrier Frequency Division Multiple Access (SC-FDMA) symbols (or DFT-S-OFDM symbols). The principle of Block-IFDMA for UL transmissions is schematically illustrated in Figure 3.8.

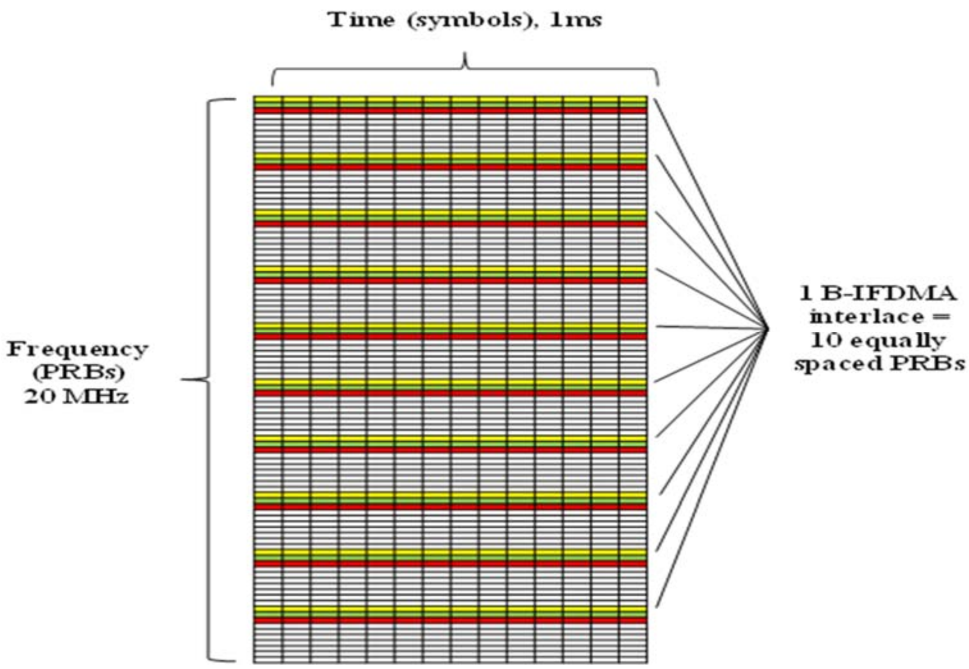

Figure 3.8. UL B-IFDMA structure with Equi-spaced RB Interlaces.

Unlike the 20MHz operation, 3GPP agreed that LAA with a 10 MHz bandwidth shall not be used on a carrier where the absence of IEEE 802.11 technologies cannot be guaranteed on a long-term basis.

For the UL Demodulation Reference Symbols (DMRS) for eLAA, the legacy UL DMRS generation sequence is reused. That is, the sequence is generated based on the transmitted bandwidth and mapped in a way similar to that of the legacy resource allocation type 1. The symbol position of the UL DMRS of eLAA is the same as the UL DMRS position in LTE PUSCH subframe. The frequency position of the UL DMRS is the same as the PUSCH Resource.

In addition, only aperiodic CSI transmissions are supported on unlicensed carrier due to the irregular availability of both DL and UL channel access. CSI reference subframe is defined according to the existing rules in TS 36.213 s.7.2.3.

For Rel-14 eLAA, 3GPP did not agree on new formats for SRS, PUCCH and PRACH. SRS follows the same format as legacy LTE while PUCCH and PRACH are not supported at all on the unlicensed carrier.

3.1.2.3.1 HARQ DESIGN

eLAA uses asynchronous UL HARQ operation. That means UL retransmissions may not only occur one RTT (e.g. n+8) after the initial transmission but rather at any point in time. This is considered beneficial, especially when retransmissions are blocked and postponed due to LBT.

There is no support for non-adaptive HARQ operation, and the UE shall ignore any information content on the Physical Hybrid-ARQ Indicator Channel (PHICH) resources with respect to HARQ operation. Any uplink transmission (new transmission or retransmission) is scheduled through UL grant through PDCCH / EPDCCH.

For LAA uplink with single codeword, maximum number of HARQ processes = 16 is supported. For LAA uplink with two codewords, supportable number of HARQ processes is doubled without introducing explicit HARQ process IDs. The same principles of handling two codewords in DL scheduling are applied for UL scheduling.

As for the HARQ-ACK transmission for a DL HARQ processes, eLAA can operate without the introduction of HARQ-ACK transmission on an LAA S-Cell. A UE can be configured to simultaneously transmit feedback on Licensed cell PUCCH and LAA S-Cell PUSCH transmission.

3.1.2.4 FUTURE LAA DEVELOPMENT

Future LAA enhancements for later 3GPP releases may include:

- Adding PUCCH for LAA S-Cell to reduce control channel overhead on the P-Cell
- Enabling standalone and/or dual connectivity operation - adding PSS / SSS / PBCH / PRACH in addition to PUCCH
- LAA Unscheduled UL Access
- LAA Coverage Enhancements
- Latency Reduction
- HARQ-ACK Transmission On The LAA S-Cell
- NB-IoT In Unlicensed Spectrum

LAA using the wider sub-carrier spacing, shorter Transmission Time Interval (TTI) and new channel coding designs from NR is also being investigated as part of NR in Unlicensed Bands.[85]

3.1.2.5 SUMMARY

Existing and new spectrum licensed for exclusive use by IMT technologies will remain fundamental for providing seamless coverage, achieving the highest spectral efficiency, and ensuring the highest reliability of cellular networks through careful planning and deployment of high-quality network equipment and devices. To meet the ever increasing data traffic demand from users, especially in concentrated high traffic buildings or hot spots, radio access in the unlicensed spectrum is increasingly being considered by cellular operators as a complementary tool to augment their mobile broadband service offering.

Licensed Assisted Access (LAA) is a solution based on carrier aggregation of a licensed band Primary-Cell (P-Cell) with unlicensed band S-Cells to enable an efficient use of the large amount of available spectrum in the unlicensed bands around the globe. The P-Cell on a licensed carrier will guarantee good Quality-of-Service (QoS), reliability and mobility. On top of that, faster data speeds will be provided by utilizing additional carriers in the unlicensed spectrum. Given the limited maximum transmit powers allowed by the unlicensed band regulation, the LAA S-Cells will generally be more suited for small cell deployments.

Rel-13 includes the specification of DL-only LAA operation, while UL LAA specification is a part of enhanced LAA (eLAA) Rel-14. A single global solution framework for LAA has been defined to ensure that LAA can be operated according to any regional regulatory requirements. Furthermore, LAA design provides

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[85] RP-162235: *Work Item on enhanced LAA for LTE* and RP-170269: *Summary for WI Enhanced LAA for LTE*.

sufficient configurability to enable efficient operation in different geographical regions. The LAA must target fair coexistence with existing WiFi networks to not impact WiFi services more than an additional WiFi network on the same carrier, with respect to throughput and latency. The LAA design further targets fair coexistence among LAA networks deployed by different operators so that the LAA networks can achieve comparable performance, with respect to throughput and latency.

3.1.3 L2 LATENCY REDUCTION TECHNIQUES FOR LTE

Packet data latency is a key performance metric that is regularly measured by vendors and operators but also end-users (via speed test applications, see example in Figure 3.9). Latency measurements are performed in all phases of a radio access network system lifetime; starting when verifying a new software release or system component and continuing when deploying a system and after the system is put in commercial operation.

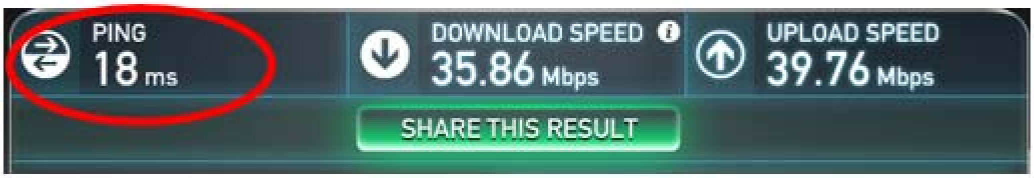

Figure 3.9. Speed Test Application Results.

LTE was designed with low latency in mind and as a result LTE does have better packet data latency than previous generations of the 3GPP Radio Access Technologies (RATs). Since the introduction of LTE, several improvements have been introduced to increase the system and user data rates (for example, Carrier Aggregation, 8x8 MIMO, etcetera). To obtain the full benefit of these data rate enhancements, continuous enhancements of the latency of LTE are needed in the future evolution track of LTE towards 5G.

Packet data latency is a parameter that indirectly influences the perceived packet data rates of the system. Hypertext Transfer Protocol (HTTP) and Transmission Control Protocol (TCP) are the dominating application and transport layer protocol suite used on the internet today. According to HTTP Archive (http://httparchive.org/trends.php), the typical size of HTTP-based transactions over the internet are in the range of a few 10’s of Kbytes up to 1 Mbyte. In this size range, the TCP slow start period is a significant part of the total transport period of the packet stream. And as it turns out, during TCP slow start the perceived packet data rate is latency limited in current LTE.

Latency reduction may not only be good for improving TCP performance and give better speed test ping times. Radio resource efficiency could also be positively impacted by latency reduction. Lower packet data latency could increase the number of transmission attempts possible within a certain delay bound; hence higher Block Error Rate (BLER) targets could be used for the data transmissions, freeing up radio resources but still keeping the same level of robustness for users in poor radio conditions.

There are a number of existing applications that would be positively impacted by reduced latency in terms of increased perceived quality of experience: examples are gaming, real-time applications like Voice over LTE (VoLTE), Over-the-Top (OTT), Voice-Over-IP (VoIP) and video telephony/conferencing.

For eMBB, there is a 5G requirement set in 3GPP and ITU on one-way UL/DL average latency below 4ms. As of Rel-13, the one-way RAN latencies are estimated to 11.5ms for UL and 4.5ms for DL.

Today, various pre-scheduling strategies are in use to lower the latency in LTE, but typically these solutions are limited by the current LTE standard and cannot address all efficiency aspects.

3.1.3.1 HIGH LEVEL PRINCIPLE

In an LTE system there are multiple components contributing to the total end-to-end delay for connected UEs. Little has been done in 3GPP since the introduction of LTE in Rel-8 when it comes to latency improvements.

In general, a UE with data to send must send a Scheduling Request (SR) to receive a UL scheduling grant before transmitting the data packet. In order to send a SR, a UE must wait for a SR-valid PUCCH resource and a corresponding scheduling grant transmitted on PDCCH to the UE in response. When the grant on PDCCH is decoded, the data transmission can start over the PUSCH.

To reduce the grant request delay in the procedure above, the eNB may choose to pre-schedule a UE by either issuing a dynamic grant via PDCCH without a-priori buffer status information, or alternatively, use a Semi Persistent Grant (SPS). By doing so, the network may avoid additional delay in the grant request procedure given that the time to the next grant opportunity is short.

In the Work Item (WI) for Latency reduction, enhancements to pre-scheduling and SPS have been defined and specified, in order to increase the latency reduction gains, reduce UL interference and increase the effectiveness of available scheduling tools.[86]

In the WI, the following enhancements to SPS in FDD and TDD are introduced:

- Introduction of short periodic UL SPS grant intervals in order to reduce the latency of the first UL transmission compared to legacy intervals using Radio Resource Control (RRC) configured UL SPS grants
- Introduction of the UE to skip padding transmissions in SPS UL grant if there is no UL data in the UE buffer in order to decrease UL interference and improve UE battery efficiency
- Introduction of the transmission of a SPS activation and de-activation confirmation from UE, triggered as new MAC Control Element (MAC CE) to increase robustness in SPS when UL grants are skipped by UE
- Introduction of non-adaptive retransmission on SPS resource (prioritized over new data transmission) to allow configured SPS UL grant resources in subsequent TTIs

In the WI, the following enhancement to dynamic scheduling (PDCCH) in FDD and TDD is introduced:

- Introduction of an RRC configurable option to mandate UE to skip padding transmissions on a dynamic grant received on PDCCH if there is no UL data in the UE buffer in order to decrease UL interference and improve UE battery efficiency

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[86] RP-160667, New WI proposal: *L2 latency reduction techniques for LTE* , source Ericsson, RAN#71 and RP-161514*, Status report of WI L2 latency reduction techniques for LTE; rapporteur, Ericsson, RAN#73 and* RP-172559, *Summary for WI Latency reduction techniques for LTE.*

3.1.3.2 INSTANT UPLINK ACCESS (“FAST UL”)

With Instant Uplink Access (IUA), or also known as “Fast Up Link”, the signaling delay-overhead associated with dynamic scheduling in LTE is eliminated. With dynamic scheduling in LTE, the UE should be granted UL radio resources, which it must request as part of the scheduling request (SR) procedure. In IUA, a long-lasting grant for uplink resources is provided by the eNB even before UL data becomes available in the UE. The grant indicates recurring resources that the UE may use, if data becomes available, but does not mandate the UE to do a padding transmission, in case no UL data is available. This way the UL access latency is reduced, while UE power consumption and uplink interference are not increased.

The basic concept of instant uplink access is illustrated in Figure 3.10. To speed up small data transmissions in UL (for example, TCP ACKs), UEs are configured with an IUA grant, therefore, a small reoccurring UL resource. While no data is available, the UE is in an inactive phase, therefore does not use the granted resources. Once data becomes available, it can instantly (therefore, on the next available IUA resource) transmit the data, ensuring lower latency. If the eNB realizes, (for example, based on a received Buffer Status Report - BSR) that larger amounts of UL data are available, the eNB would provide the UE with dynamic grants of a larger resource allocation. This would be considered the active phase.

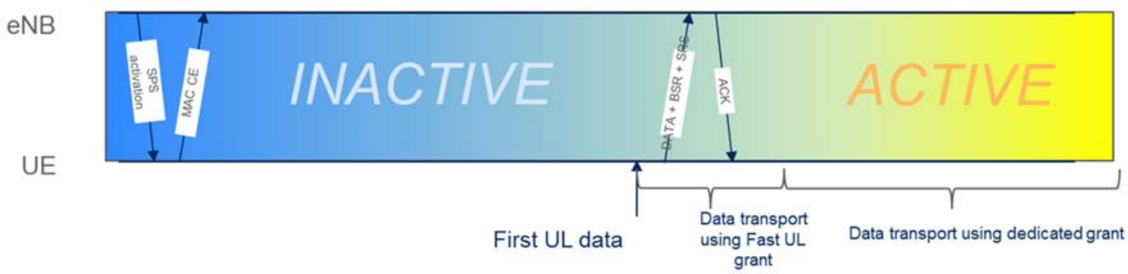

Figure 3.10. Instant Uplink Access.

Within the 3GPP Rel-14 work item, IUA had been standardized as part of the Semi-Persistent-Scheduling (SPS) framework. Thereby, more frequent occurrences of SPS subframes have been introduced, i.e. shorter periods of down to 1ms are configurable, and the mandate to send padding if no data is available has been removed. It had been further specified that reception of the provided IUA grant (or release) is to be confirmed by the UE with a MAC control element. This way the eNB is sure that the UE is configured with IUA (or released of IUA). Further, non-adaptive retransmissions in IUA are enabled on SPS-resources. In fact, non-adaptive retransmissions are prioritized over sending newly available data. (Note that previously on SPS resources only new transmissions were done).

For the eNB, IUA comes with the following complexities: when an uplink transmission is skipped by the UE, the eNB does not necessarily know or is able to identify if the UE skipped the transmission or if the transmission had failed. It is proposed to solve this dilemma by eNB always sending a NACK on PHICH in these cases. The UE would, if it had sent data previously, attempt a retransmission; otherwise ignore the NACK. This way, UE data cannot be mistakenly considered as ACKed, in which case the HARQ buffer for the retransmission may be overridden by a new data transmission. Furthermore, HARQ retransmissions can be configured with a fixed redundancy version, which is helpful for the eNB, since it might have missed the first transmission and thus might not be able to decode a subsequent retransmission with an unexpected redundancy version.

3.1.3.3 SKIPPED PADDING ON DYNAMICALLY GRANTED UL RESOURCES

Besides IUA, as discussed in the previous section, a further enhancement has been standardized in 3GPP Rel-14 work item: The UE can be configured to skip UL padding transmissions if no UL data is available also when scheduling based on dynamic grant; this feature is *not* limited to SPS. This rather simple enhancement comes with some further complexities for the eNB. When UL transmission is skipped after a grant had been provided, the eNB needs to differentiate between the error cases including grant lost, UL skipped or UL transmission lost. This would require a reliable Discontinuous Transmission (DTX) detection mechanism to determine whether to react with a NACK or a new grant transmission to the user.

The feature is useful in combination with pre-scheduling or overscheduling, since it reduces the cost of scheduling the UE redundantly. If the UE has been unnecessarily scheduled, i.e. no UL data available, the UE would skip the padding transmission, saving battery consumption, and also reducing UL interference. Therefore, the feature could be seen as allowing more aggressive pre-scheduling algorithms (at the same cost of UE power consumption and UL interference).

3.1.3.4 CONTENTION-BASED ACCESS

Contention-based access had not been standardized for LTE as part of the Rel-14 work on low latency communication. However, it has been proposed as a part of the IUA concept, in which long-lasting resource allocations are required, and where it would be beneficial for UL efficiency reasons to allocate the same UL resources to multiple UEs. The eNB could determine the transmitting UE’s by their respective DMRS-cyclic shift. In current 3GPP specs, this DMRS-cyclic shift is hardcoded for SPS/IUA, but it was proposed to make it configurable in Rel-14, however this was not successful. It is being proposed again as part of a new WI on Critical Machine-Type Communication (C-MTC).

Successful decoding of the colliding UL transmissions would depend on the eNB receiver complexity. If the eNB is able to identify at least the collisions (by energy detection), the eNB would further be able to spread out further retransmissions of the colliding UEs in the frequency domain, by scheduling adaptive retransmission.

3.1.3.5 SHORT TTI

The Short TTI concept and LTE feature consists of three main components:

- introduction of transmissions shorter than one subframe in the PDSCH and PUSCH
- introduction of new short in-band DL control and new short UL control
- reduction of processing time and related procedures

The main idea is to scale the entire LTE subframe exchange in time to achieve scaled latency. For this to be possible, the time needs to be reduced for waiting for a transmit opportunity and DL control, also reducing the transmission length itself, and reducing the processing time in the UE and eNB. The HARQ loop should also be shortened as much as possible in order to keep the average latency low. Many other aspects of the PHY and MAC layers are affected by this fundamental change in the transmission design.

Short TTI should be supported together with:

- Carrier Aggregation in DL
- SU-MIMO in DL and UL
- DMRS and CRS based transmission

- Legacy PDSCH and PUSCH transmissions

For FDD the shortest TTI should be 2 symbols, while for TDD the shortest TTI should be 7 symbols, since the frame alignment time places a minimum delay on a transmission.

3.1.3.6 REDUCED PROCESSING FOR 1MS TTI

With reduced processing the UE can be configured with n+3 timing, meaning that the DL data to DL HARQ timing and the UL grant to UL data is set to 3 subframes instead of 4. This reduces the maximum processing time in the UE from 3ms to 2ms, which partly is achieved by reducing the maximum Timing Advance (TA) from the current value of 0.67ms to a significantly lower value, 0.33ms or less.

The n+3 timing is introduced together with asynchronous UL HARQ, meaning that PHICH is not used for feedback.

By reducing the timing, the HARQ RTT and the TCP RTT are reduced, which improves the throughput.

3.1.3.7 SUMMARY

LTE is being equipped with new modes of operations targeting low latency and high reliability, which will make it possible to address the emerging URLLC use cases, and thereby firmly establish LTE in a 5G context. The new operation modes are backwards compatible and can be co-scheduled with legacy LTE UEs. It is expected to see enhancements to these items in future 3GPP releases.

3.1.4 ENHANCEMENT OF NB-IOT

Narrowband IoT (NB-IoT) was introduced in 3GPP Rel-13 to provide low-power, wide-area cellular connectivity for IoT devices. It offers ultra-low complexity devices, coverage improvement of 20 dB compared to legacy GPRS, improved power efficiency with battery life of 10 years, massive cell capacity, and exception report latency of less than 10 seconds. In 3GPP Rel-14, further enhancements were introduced for NB-IoT as follows:

- Location services based on Enhanced Cell-ID (E-CID) and Observed Time Difference of Arrival (OTDOA).
- Multicast downlink transmission based on using Single-Cell Point-to-Multipoint (SC-PTM).
- Higher peak data rates to reduce power consumption and latency.
- Support of paging and random access on non-anchor carriers to improve capacity and provide load balancing.
- Mobility enhancements, release assistance indication, and coverage authorization.
- New user equipment (UE) power class with a maximum output power of 14 dBm suitable for small form-factor batteries.

In this section 3.1.5, a brief description of the Rel-14 enhancements is provided.

3.1.4.1 POSITIONING

In Rel-13, only a simple positioning technique based on Cell-ID is supported. In Rel-14, advanced positioning techniques using Enhanced Cell -ID (E-CID) and Observed Time Difference of Arrival (OTDOA) were introduced.

E-CID positioning utilizes the geographical coordinates of the serving cell for UE positioning. In E-CID positioning, UE reports the following measurements to the network – Narrowband Reference Signal Received Power (NRSRP) and Narrowband Reference Signal Received Quality (NRSRQ). In Rel-14, performance requirements were defined for E-CID.

OTDOA positioning requires the UE to measure the time of arrival (ToA) of reference signals received from multiple transmission points and report the Reference Signal Time Difference (RSTD) to the location server for positioning purposes. In Rel-14, Narrowband Positioning Reference Signal (NPRS) was introduced. NPRS occurs periodically in the time domain and can be indicated using:

- Part A - a bitmap (10 bits or 40 bits)
- Part B - start subframe, number of repetitions, and periodicity

The network can indicate subframes containing NPRS using either “Part A”, “Part B”, or “Part A + Part B” configuration. The NPRS itself is based on LTE PRS and transmitted on antenna port 2006. Figure 3.11 illustrates an example of NPRS mapping for different operation modes.

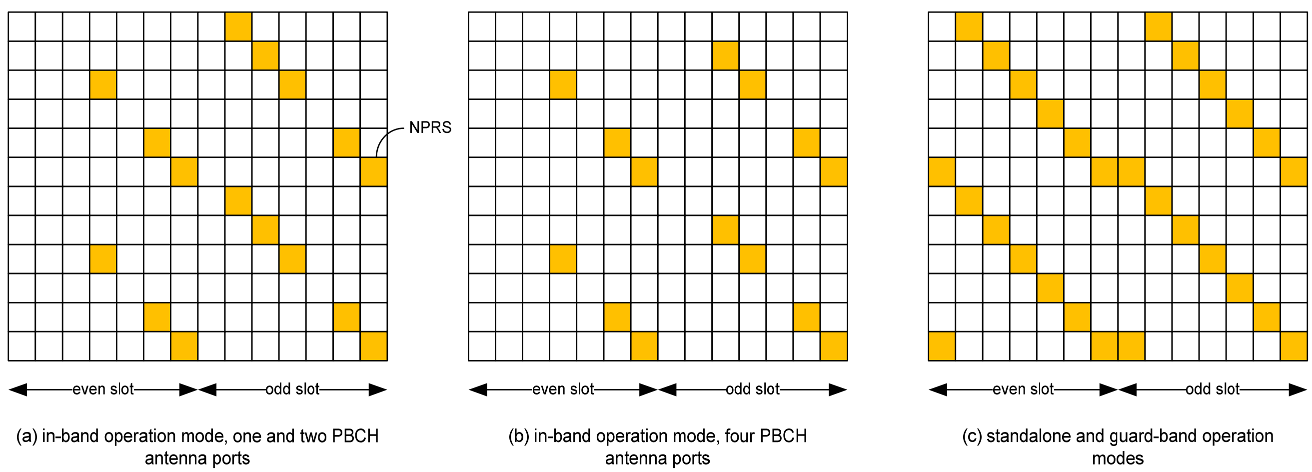

Figure 3.11. NPRS Mapping for Different Operation Modes.

In OTDOA positioning, when the UE uses a narrow bandwidth for Positioning Reference Signal (PRS) measurement, the ToA estimation of accuracy of the first path will be impacted due to the lower sampling rate and uncoupled multiple paths of the signal at the UE side. This limits OTDOA positioning accuracy for NB-IoT. To mitigate this issue, NB-IoT Rel-14 enables both wideband-based and narrowband-based RSTD measurements. The UE could select narrowband-based RSTD measurement based on the newly defined NPRS, which is transmitted over one or more NB-IoT carriers, or wideband-based RSTD measurement based on the existing PRS with the PRS transmission bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz. Each transmission point can be configured with up to 3 different PRS time-frequency configurations. An example of PRS time-frequency configurations is shown in Figure 3.12, where three different PRS bandwidths are configured.

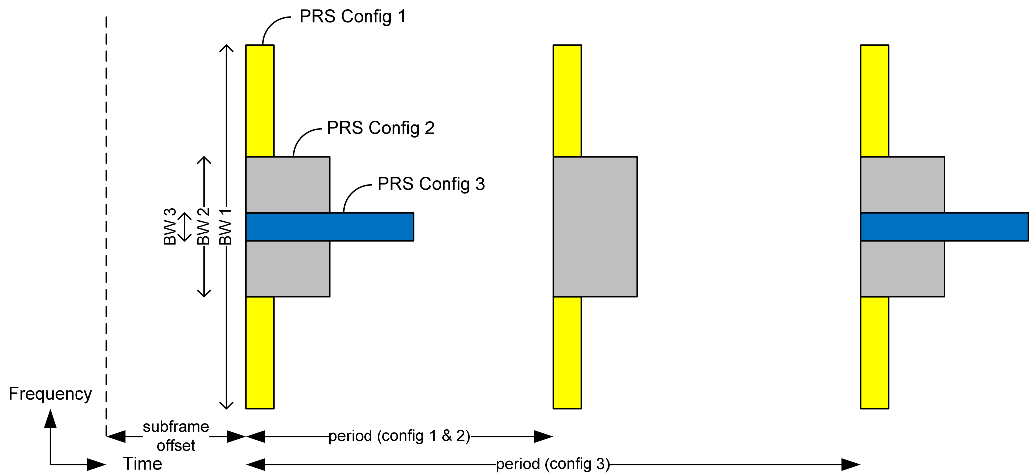

Figure 3.12. Example of PRS Configurations per Transmission Point.

In NB-IoT, positioning measurement is only performed in RRC_IDLE mode. In this case, the Evolved Serving Mobile Location Center (E-SMLC) sends the location request message to the UE. The UE may finish any other activities in process and wait until the network releases or suspend the connection before entering RRC_IDLE mode and performing positioning measurement.

3.1.4.2 MULTICAST

Multicast support for IoT devices is beneficial for use cases such as firmware or software updates. For NB-IoT, multicast is supported via Single-Cell Point-to-Multipoint (SC-PTM) feature that was standardized in Rel-13. SC-PTM uses two logical channels, the control channel (SC-Multicast Control CHannel (MCCH)) and the transport channel (SC-MTCH). The SC-MCCH contains SC-PTM configuration with the following information: carrier information (both anchor and non-anchor NB-IoT carriers can be used); list of Multimedia Broadcast Multicast Services (MBMS) sessions; and related scheduling information. Information about when the SC-MCCH may be scheduled is broadcast by the cell in SIB20-NB. The SC-MTCH is used to carry MBMS sessions, up to 64 MBMS sessions can be supported. Note that SC-MCCH and SC-MTCH may be scheduled on different carriers to support load balancing. At the physical layer, these logical channels are transmitted on NPDSCH, which is scheduled on NPDCCH. These channels can be repeated to reach UEs that are in poor coverage. In addition, to support large number of repetitions, the modification period of the SC-MCCH has been extended.

To maintain low UE complexity, SC-PTM applies only to NB-IoT UEs in RRC_IDLE mode. In addition, the UE is not required to monitor both SC-MCCH and SC-MTCH at the same time. DCI format N1 is reused for scheduling with some minor differences in how scheduling delay is done. New NPDCCH search space definitions have also been introduced. The largest transport block size (TBS) that can be supported for SC-PTM on SC-MTCH is 2536 bits.

3.1.4.3 HIGHER DATA RATES

In Rel-14, a new UE category (Cat. NB2) with higher peak data rates was introduced. Higher data rates can reduce latency and power consumption for UE in good radio conditions. This new UE category can support a maximum TBS of 2536 bits for both uplink and downlink (compared to 1000 bits in the uplink and 680 bits in the downlink for a Cat. NB1 UE). It can also optionally support two Hybrid Automatic Repeat reQuest (HARQ) processes instead of one. Rel-13 scheduling delay values and timing relationships are reused for each HARQ process while allowing a gap of at least 1 ms for the UE to switch from transmission of NPUSCH to reception of NPDCCH. Figure 3.13 illustrates the timing diagrams when two HARQ processes are used. This allows the Cat. NB2 UE to achieve peak data rates of ~127 kbps in the downlink and ~159 kbps in the uplink.

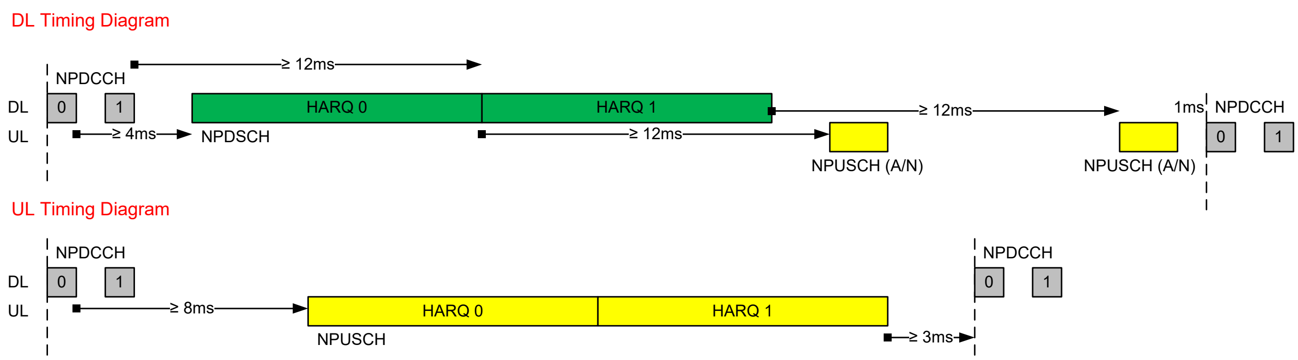

Figure 3.13. Timing Diagrams with two HARQ Processes.

3.1.4.4 NON-ANCHOR CARRIER ENHANCEMENTS

For NB-IoT, downlink anchor carrier refers to the carrier with NPSS/NSSS/NPBCH and SIBs transmitted, while uplink anchor carrier refers to the carrier with NPRACH. Additional NB-IoT non-anchor carriers can be configured to provide additional capacity. In Rel-13, paging and random access can only be performed on an anchor carrier. In Rel-14, paging and random access can also be supported in non-anchor carriers. This increases paging and random-access capacity and allows the network to perform load balancing of paging and random access among carriers.

For both paging and random access, it is necessary to support uneven load balancing among different carriers as Rel-13 NB-IoT UEs always use an anchor carrier. For paging, up to 16 downlink carriers can be configured to support this procedure. This configuration is provided in the SIB and UE selects the carrier based on its UE ID. In addition, the network supports uneven paging load distribution between anchor and non-anchor carriers using weighted distribution between all carriers. Similarly, up to 16 carriers can be configured to support random access. UE selects NPRACH resource (including carrier) based on a random draw by using different carrier selection probabilities for anchor and non-anchor carriers.

3.1.4.5 SERVICE CONTINUITY, RELEASE ASSISTANCE AND COVERAGE AUTHORIZATION

Since measurement reporting and handover is not supported in NB-IoT, the UE will declare a radio link failure and select a new cell when a UE in Connected mode moves out of the coverage area of the serving cell. To maintain service continuity, RRC connection re-establishment and S1 eNB CP relocation indication procedures were introduced for UE that only support data transfer via control plane. RRC Connection Re-establishment in Rel-13 is supported only for C-IoT User Plane optimization. This allows the UE to maintain S1 connectivity in case of radio link failure.

In addition, release assistance indication was also introduced in Rel-14. The UE may be configured to send assistance information to the eNB to assist the eNB in connection release handling. The indication is defined in Medium Access Controller (MAC) signaling using the Buffer Status Report. The Buffer Status Report with no data indicates that the UE expects no transmissions and receptions in the near future. This allows the network to quickly move the UE to RRC_IDLE mode.

Finally, Rel-14 also supports coverage authorization feature. This feature can restrict a UE from using coverage enhancements which can consume a lot of network resources. In this case, a UE that is not authorized to use coverage enhancements will have to find another cell when the signal strength of its serving cell drops below a threshold.

3.1.4.6 UE POWER CLASS

In Rel-13, two UE power classes have been defined for NB-IoT: 20 dBm and 23 dBm. In Rel-14, a new UE power class with a maximum output power of 14 dBm has been introduced with relevant RF requirements defined. This new power class is suitable for small form-factor batteries supporting use cases such as wearables. It can also reduce power consumption and enable chip design with integrated power amplifier. However, due to the significantly lower maximum output power, coverage of these devices is reduced as a larger number of repetitions was not defined to compensate for this reduction in power. During random access, the UE will modify its selection of the NPRACH coverage level by adjusting the NPRACH RSRP threshold by the amount corresponding to the reduction in maximum output power. In addition, the UE capability needs to be available in the eNB before sending Msg4.

3.1.5 FURTHER ENHANCED MTC FOR LTE

In 3GPP Rel-12 a new lower complexity UE (lower cost), Cat-0, was introduced for the Machine-Type Communication (MTC) market. Complexity reductions were achieved by means of a smaller supported maximum TBS of 1000 bits, reduction to 1 receiving antenna, and (optional) half-duplex FDD operation. The Power-Saving Mode (PSM) was also introduced in Rel-12 as a means to provide long battery life for MTC UEs.

In Rel-13, significant enhancements to MTC were introduced and it is, in practice, a new radio access technology for MTC, called eMTC. The Cat-M1 UE category was introduced which decreased complexity (cost) even further by operating narrowband within 1.4 MHz (i.e., on top of the reductions made for Cat-0). Furthermore, the Cat-M1 UEs can optionally be a lower UE power class of 20 dBm. Another large change was the introduction of Coverage Enhancements by up to 15 dB. The coverage enhancement and the reduced device bandwidth in combination with the enhanced Discontinuous Reception (eDRX) operation also introduced in Rel-13, enabled eMTC to address the KPIs for massive-MTC:

- Low device complexity (cost)
- High capacity for large numbers of devices
- Enhanced coverage
- Low device power consumption to be able to provide long battery life of up to 10 years

In Rel-14, further enhancements are introduced:

- More accurate positioning of UEs
- Multicast of the same content to several UEs
- Higher data rates in order to serve a wider range of applications and also reduce latency and extend battery life,
- Improvements to VoLTE speech at enhanced coverage[87]

3.1.5.1 POSITIONING

UE positioning and tracking are important in many IoT applications, such as asset tracking. Global Navigation Satellite System (GNSS) -based positioning methods are not appropriate for many IoT applications, as they require a separate GPS chip, which would increase the total price of the UE. Additionally, the narrow UE bandwidth poses challenges for the positioning accuracy when using the 3GPP positioning functionalities defined for normal UEs. In Rel-13, only limited positioning functionality is provided for these UEs. Hence, completing the core requirements from Rel-13 and considering improvements of the 3GPP positioning methods are necessary to improve the 3GPP-based IoT eco-system.

To further increase the market impact of eMTC, improving support for positioning has been incorporated into Further Enhanced MTC in Rel-14. The following positioning methods are considered in LTE (3GPP 36.305):

- **Cell ID**: Cell identity information to associate the UE to the serving area of a serving cell
- **Enhanced Cell ID**: Essentially Cell ID with additional radio measurements such as Reference Symbol Received Power (RSRP), Reference Signal Received Quality (RSRQ), UE Rx-Tx time difference, eNodeB Rx-Tx time difference, and eNB angle of arrival (AoA)
- **Assisted GNSS**: Global Navigation Satellite System information retrieved by the UE based on the assistance information received from the network
- **OTDOA (Observed Time Difference of Arrival)**: The UE estimates the time difference of reference signals from different base stations, then a multi-lateration technique is used either in the UE or by the positioning node to derive the position of the UE
- **UTDOA (Uplink TDOA):** The UE is requested to transmit a specific waveform that is detected by multiple location measurement units, which may be integrated in different eNBs at known positions. These measurements are forwarded to the positioning node for multi-lateration

MTC UEs had the Enhanced Cell ID (E-CID) and OTDOA support in Rel-13, however, the RAN4 requirements on the UE measurements were needed to be revisited to enable better positioning capability for these UEs. The objective of positioning in 3GPP Rel-14 for FeMTC are as follows:

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[87] RP-170532, *Revised WID for Further Enhanced MTC for LTE* and RP-171175, *Status Report for Further Enhanced MTC for LTE*

- E-CID: RSRP/RSRQ measurement
- E-CID: UE Rx-Tx time difference measurement
- OTDOA: core requirements
- OTDOA: consider improvements of accuracy, UE complexity and power consumption for OTDOA

The objective was to aim for any potential enhancement in terms of positioning of FeMTC UEs, in order to have positioning as one of the key features differentiating the use cases for these devices compared to solutions.[88]

3.1.5.2 SINGLE CELL-PTM MULTICAST FOR EMTC

The objectives for Further Enhanced MTC for LTE regarding multicast are the following:

- Extend Rel-13 SC-PTM to support multicast downlink transmission (e.g., firmware or software updates and group message delivery)
- Introduction of necessary enhancements to support narrowband operation (e.g., support of MPDCCH) and coverage enhancement (e.g., repetitions)

The Rel-14 multicast for eMTC is based on Single Cell Point-To-Multipoint (SC-PTM) operation mode of Rel-13 Multimedia Broadcast Multicast Service (MBMS). In Rel-13, SC-PTM supports broadcast/multicast services over a single cell. There are similar objectives for work item Enhancements of NB-IoT.

The motivation for introducing multicast operation can be seen in situations where the same message needs to be transmitted in downlink to multiple UEs. As mentioned in the objectives of the work item, use cases of such situations include firmware or software updates and group message delivery. Introducing multicast for such use cases improves the spectral efficiency of the transmission essentially by a multiplier relative to the number of receiving UEs; instead of transmitting the same data separately to a number of UEs, it can be transmitted just once for all UEs. This reduces the time and resources used for the transmission.

3.1.5.3 HIGHER DATA RATES

The Rel-13 MTC work items achieved complexity reduction, extended battery life, and coverage enhancements for the target use cases of sensors, meters, smart readers, etcetera. There are some other use-cases like voice capable wearable and health monitoring devices which share some of these requirements. However, they require higher data rates above 1 Mbps, mobility and are also more delay sensitive compared to Rel-13 requirements. Therefore, it is important to introduce new functionalities in Rel-14 that fulfil higher data rates and mobility requirements alongside the existing Rel-13 solution. These functionalities are:

- Specify DL HARQ-ACK bundling in Coverage Extension (CE) mode A in HD-FDD
- Larger maximum Transport Block Size (TBS); both CAT-M1 enhancements and CAT-M2 device introduction

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[88] RP-170623 & RP-171204, RAN1 CR packs for Further Enhanced MTC for LTE; RP-170636 & RP-171223, RAN2 CR pack for Further Enhanced MTC for LTE; RP-170691, RAN3 CR pack for Further Enhanced MTC for LTE; RP-170560 & RP-171266, RAN4 CR pack for Further Enhanced MTC for LTE; and RP-171441, Summary for WI Further enhanced MTC for LTE

- Larger maximum. PDSCH/PUSCH channel bandwidth in connected mode at least in CE mode A in order to enhance support, e.g., voice and audio streaming or other applications and scenarios
- Up to 10 DL HARQ processes in CE mode A in FD-FDD

3.1.5.4 HD VOLTE COVERAGE EXTENSION

Within the Rel-14 work item on “Further Enhanced MTC for LTE”, one objective was to achieve VoLTE enhancements with the objective to increase VoLTE coverage for half-duplex FDD/TDD through techniques to reduce DL repetitions, new repetition factors, and adjusted scheduling delays.

Support for VoLTE requires that a discrete flow of small data packets produced at regular time intervals may be scheduled with a short packet delay. The maximum packet delay budget for RAN is 80 ms. It is considered that, in a coverage situation where RAN has either of the two options: keeping the packet loss at a low level and extending the packet delay; or keeping the delay and delay variations within pre-defined level and introducing extra packet loss; it is preferred to keep the loss rate low and allow for an increased delay, up to at least 150 ms.

VoLTE supports a range of voice codecs producing a speech packet bit rate between ranging from 7.2 kbps to 24.4 kbps. The speech codec produces packets every 20 ms; hence, this translates to speech packet sizes of 18 to 61 bytes.

The speech packet may be bundled at the MAC layer to reduce the number of transmissions of RTP packets and possibly also on the application layer to encapsulate several speech packets into one single RTP packet. The resulting UL TBS for using EVS 7.2 kbps is displayed in Table 3.5 assuming different packet inter-transmission times. The TBS may be slightly reduced by assuming no Power Head Room (PHR) reporting and possibly also short BSR (2 bytes). For the DL the TBS is reduced by 48 bits (6 bytes) due to no Buffer Status Report (BSR) and PHR being needed.

Table 3.5. UL TBS for EVS 7.2kbps and Different MAC Scheduling and Application Layer Configurations.

RAN aggregation (Note 1)	Application encapsulation (Note 2)	Payload (Note 3)	RTP header (ROHC)	PDCP	RLC	MAC	BSR	PHR	Inter tx time (ms)	Total (bytes)	Min UL TBS (bits)
1	1	18	3	2	2	1	4	2	20	32	256
2	1	18*2	3*2	2*2	4	1	4	2	40	57	456
3	1	18*3	3*3	2*3	5	1	4	2	60	81	648
4	1	18*4	3*4	2*4	7	1	4	2	80	106	848
1	2	19*2	3	2	2	1	4	2	40	52	416
1	3	19*3	3	2	2	1	4	2	60	71	568
1	4	19*4	3	2	2	1	4	2	80	90	720

Note 1: **RAN aggregation of RTP packets each composed of one speech frame**

Note 2: **Application encapsulation of speech frames in one RTP packet requires updates to the VoLTE service description GSMA PRD IR.92** Error! Reference source not found.

Note 3: **For Payload, Compact Format is used for RAN aggregation and Header-Full Format is used for Application encapsulation as described in Annex A of TS 26.445**

The speech codecs used in VoLTE include source rate control that reduces the speech packet size and production rate in situations with no active speech. In this situation, packets of size 48 bits are produced every 160 ms. This may be taken into consideration for the impact on the capacity of the system but a key feature of a voice service is the interactivity of the communication. In addition to the delay, the ability to simultaneously transmit speech from both ends of the communication. Thus, for evaluating the coverage of the service the situation with simultaneous speech transmission on both the UL and DL should be considered. This is particularly challenging for a half-duplex UE.

For a full-duplex higher category UE a 100 percent duty cycle on the PUSCH transmission may be efficiently achieved via Rel-10 TTI bundling. Thus, the maximum PUSCH coverage is obtained for a continuous transmission on the UL. For a half-duplex CE Mode, a subframe needs to be allocated for the DL transmission and also for the DL DCI on MPDCCH and the L1 scheduling constraints, and a 100 percent duty cycle may not be achieved on the UL.

An example of the timing relationship for a half-duplex UE for the scheduling of one UL and one DL transmission within a speech frame period of 40 ms (assuming either MAC bundling of two RTP speech packets or application encapsulation) is depicted in Figure 3.14.

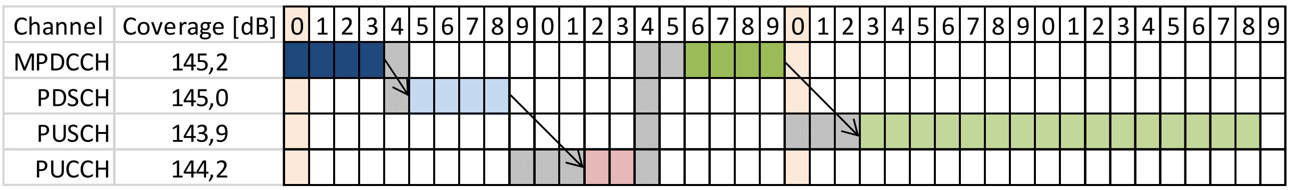

Figure 3.14. Timing Relationship for Scheduling of one DL and one UL Transmission within RTP Frame Bundling Time of 40ms with four (4) Repetitions of MPDCCH.

In this scenario, only 16 of the 40 subframes may be used for the PUSCH transmission, resulting in a maximum of 40 percent UL transmission duty cycle.

Since the number of subframes that are available within one speech frame period is limited, and restricted by the timing relationships between the physical channels, it is of importance to utilize the available subframes efficiently for the channels to maximize the coverage. The PUSCH uses the most subframes and by providing a finer granularity of the number of repetitions, a better optimization of the coverage may be performed.

For Rel-14, enhancements for improved handling of a continuous flow of packets from delay sensitive traffic with simultaneous UL and DL transmissions are introduced. The enhancements are adjustments of the scheduling relationships between the physical channels and the available set of repetitions for PUSCH. Enhancements are also included for the Service Request Signal (SRS) coverage.

3.1.5.5 MOBILITY ENHANCEMENTS

Rel-13 has full standard support for intra-frequency measurements for Cat-M1 and other UEs in CE mode including signaling and measurement performance requirements and has signaling support for inter-frequency measurements. Rel-14 introduces full standard support for inter-frequency measurements by also including measurement performance requirements.

3.1.5.6 SUMMARY

In Rel-14, LTE MTC is further enhanced in the following areas:

- **Positioning**
  - Denser PRS configurations, more frequent PRS transmissions and muting are some of the ways to support FeMTC with more accurate positioning estimations
  - Frequency hopping and the support for multiple PRS configurations aligned with legacy LTE are supported for FeMTC
  - UE measurement requirements introduced for E-CID; RSRP/RSRQ measurement and UE Rx-Tx time difference measurement

- The horizontal positioning accuracies are very dependent on the assumed channel condition, but based on a 3D MIMO channel a positioning accuracy of ~40 m and ~30 m can be expected for 67% of 6PRB and 24PRB UEs, respectively

- **Multicast**
  - Multicast of the same content to several UEs based on legacy SC-PtM in RRC Idle Mode
    - 1 SC-MCCH per cell which is scheduled dynamically and new SIB20 introduced to carry the scheduling information
    - RLC UM segmentation for SC-MCCH enables up to 128 simultaneous Multicast services (SC-MTCHs) in spite of the 1000 bit DL TBS limitation
  - No ACK is introduced in Rel-14 (sufficient reliability can instead be achieved by higher layer redundancy coding, Forward Error Correction (FEC), etcetera)
  - Large commonality between eMTC and NB-IoT solutions

- **Higher Data Rates**
  - Support for higher data rates for FeMTC UEs are introduced by HARQ-ACK Bundling, increased PDSCH/PUSCH channel bandwidth, and 10 HARQ processes
    - HARQ-ACK bundling can increase the data rate from 300 kbps to 580 kbps for half-duplex FDD UEs in CE mode A
    - 10 HARQ processes increases the peak throughput from 800 kbps to 1 Mbps for full-duplex FDD UEs in CE mode A
    - A new UE category "Cat-M2" introduces a higher device bandwidth of 5 MHz or 24 PRBs and increases instantaneous throughput from 1 Mbps to 4 Mbps
      - Unlike the previous features this is not only beneficial in good coverage
    - These features are configured via dedicated RRC signaling and can be applied to PUSCH/PDSCH transmissions in RRC Connected Mode

- **Half-duplex VoLTE Coverage Enhancements**
  - In order to provide better VoLTE Coverage Enhancements to half-duplex UEs, scheduling delays are adjusted and finer (1-1.5 dB) granularity is introduced for the repetition levels for PUSCH and PDSCH
    - A new optional RRC configuration bit introduced to override the PUSCH repetition range with a new set of {1, 2, 4, 8, 12, 16, 24, 32}
    - A new optional RRC configuration bit introduced to enable a dynamic timing relationship between PDSCH and HARQ-ACK controlled by the DCI

3.1.6 ENHANCEMENTS OF DEDICATED CORE NETWORKS FOR UMTS AND LTE

Mobile networks are evolving to provide different types of use cases which impacts how the network is used and what types of services run on the network. New use cases typically bring new types of devices optimized for the particular service. Likewise, new types of customers with different usage characteristics are also brought to the network. Examples include machine-type applications / devices, best effort packet applications, smartphones, Mobile Virtual Network Operator (MVNO), etcetera. These new groups of customers and devices often have different requirements towards the operator's network. This may mean different features, traffic characteristics, availability requirements, congestion management capabilities, signaling and user plane data usage, etcetera. It is expected the variety of device and customer type combinations will continue to grow.

A cost-effective mechanism for mobile operators is to create separate dedicated core networks consisting of specialized core network elements / resources that are designed and deployed to meet the requirements of a certain group of devices and customers. This allows for the various network requirements to be achieved in a cost and performance optimized manner. Separate core networks can enable capabilities such as independent scaling or specific feature provisioning for specific users or traffic types and isolating specific users and traffic from each other.

These dedicated core networks need to support both future and previous device releases. Although the existing specification allows for a UE to provide a notification so the network understands the type of device / application, it is assumed that not all devices support such a capability and hence the network cannot always rely upon it.

3.1.6.1 FEATURE DESCRIPTION

Enhancements to Release 13's DECOR (Dedicated Core Networks selection mechanism) feature were made in Release 14. Two new functionalities were introduced:

- UE-Assisted DCN Selection" - reduces DECOR re-routing
- E-UTRAN mechanism to improve the load balancing between Mobility Management Entities (MMEs) when DCN is used

This work item specifies the use of DCN-ID (Dedicated Core Network – Identity) in the range of 0.65535. The DCN-ID assists the RAN in selecting the correct DCN and hence reduce the use of DECOR re-routing.

- The DCN-ID is allocated by the core network and sent to the UE in the Non-Access Stratum (NAS) "accept" messages
- The DCN-ID is stored in the UE per PLMN
- The UE provides the DCN-ID in the RRC message in Attach Request, Tracking Area Update Request (TAU) or Routing Area Update Request (RAU) messages
- If the RAN cannot find a serving MME/SGSN related to GUTI, NRI, etc. provided by the UE, the RAN uses the DCN-ID to select correct MME/SGSN serving the requested DCN
- The DCN-ID is also sent to the selected MME/SGSN over S1AP

In E-UTRAN, the MME sends for each DCN-ID (that it supports) a weight factor in the S1 Setup and MME Configuration update procedure. The weight factor per DCN represents the relative processing capacity of an MME node for a specific DCN relative to other MME nodes' capacity for that DCN within the same MME pool area. The eNB can use this information to perform load balancing.[89]

3.1.7 REQUIREMENTS FOR CATEGORY 1 UES WITH SINGLE RECEIVER FOR LTE

Rel-14 defines the requirements and signaling support for a new UE category called “1bis”, which has the same data rate capabilities as LTE category 1 but with only a single receiver chain. This new category is

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[89] RP-170547: Summary for WI Enhancements of Dedicated Core Networks for UMTS and LTE and RP-151048: New Work Item on Dedicated Core Networks, NTT DOCOMO, INC., Ericsson.

targeting devices that have a very small form factor (e.g., wearables) and reduced number of components, while requiring higher data rates than other “machine type” categories (M1/N1).

The following new features/requirements were introduced:

- A new UE category 1bis was defined (to differentiate these devices from UE category 1)
- Support for the following bands: 1, 2, 3, 4, 5, 7, 8, 12, 13, 18, 20, 26, 28, 39, 41, and 66
- Radio Resource Management (RRM) core and performance requirements for intra-frequency and inter-frequency mobility
- RRM core and performance requirements for OTDOA positioning
- Demodulation and Continuous Quality Improvement (CQI) tests

3.1.8 SRS SWITCHING BETWEEN LTE COMPONENT CARRIERS

Carrier Aggregation (CA) has been part of the LTE standard since Rel-10. A typical CA scheme has more downlink (DL) than uplink (UL) carriers set up for transmission, reflecting the asymmetrical nature of the user need for data throughput. Moreover, for the existing UE categories, the typical CA capable UEs only support one or two uplink CCs. Because of this lack of UL carriers, it is difficult to fully exploit channel reciprocity in CA.

For the carrier supporting both uplink and downlink, transmit diversity-based CSI feedback with SRS (without PMI) is beneficial as channel reciprocity can be used. However, since UEs generally have the capability of aggregating a greater number of DL carriers than UL carriers (as shown in Figure 3.15), some of TDD carriers with DL transmission for the UE will have no UL transmission (including SRS) and channel reciprocity cannot be utilized for these carriers.

Such situations will become more common with the CA enhancement of up to 32 Component Carriers (CCs) where a large portion of CCs are TDD. Allowing fast carrier switching to and between TDD UL carriers can be a solution to allow SRS transmission on these TDD carriers.

The aim of the 3GPP work item “SRS Carrier Based Switching” is to specify enhancements for networks operating with CA. Specifically, to Support SRS switching to and between TDD CC(s), where the CCs available for SRS transmission correspond to the CCs available for carrier aggregation of PDSCH, while the UE has fewer CCs available for carrier aggregation of PUSCH.

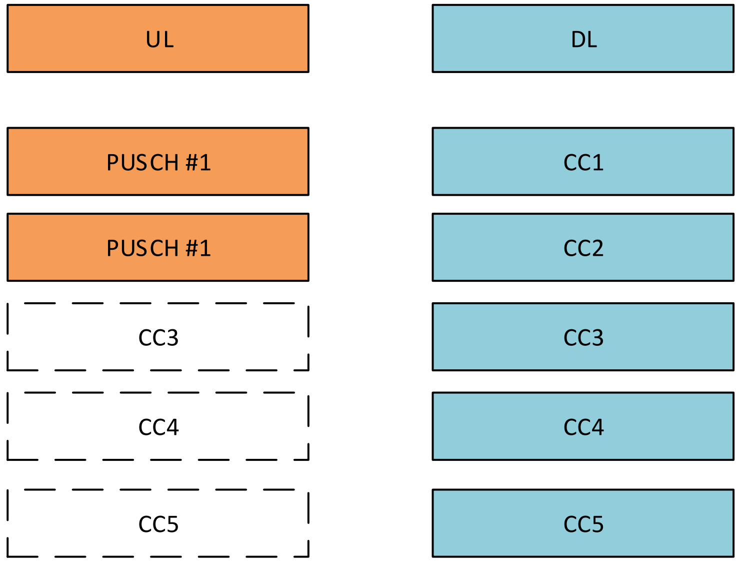

Figure 3.15. CA Scenario which will Benefit from SRS Carrier-based Switching; DL has more CCs than UL.

3.1.8.1 HIGH LEVEL PRINCIPLE

Figure 3.16 shows the basic principle of SRS carrier-based switching. A UE with more DL than UL carriers turns off one of the UL carriers to allow transmission of SRS on one of the non PUSCH carriers. The transmission involves interruptions to tune to the SRS carrier as well as its return.

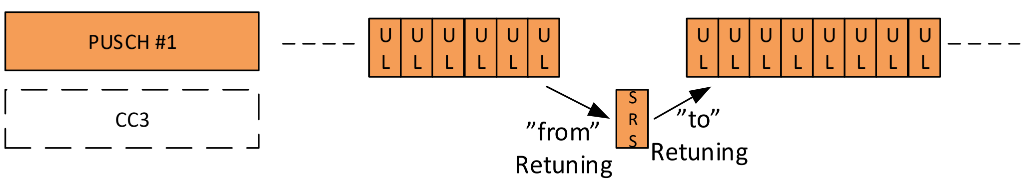

Figure 3.16. SRS Switching Principle.

The following items were defined while specifying SRS switching:

- SRS Subframe and Symbol Position: to minimize interruption time, different positions can be used
- Interruption Time: define the range of tolerable interruption
- Power Control: Since the SRS is now sent on its own, without PUSCH present for reference
- Timing Advance Initialization: Needed when the switching to carrier is not a TAG member
- Periodic / Aperiodic Sounding: depending on the needs versus cost for sounding with SRS switching; to define the type of sounding preferred

3.1.8.2 SRS CONFIGURATION

Periodic and aperiodic SRS switching are supported on a CC without PUSCH. RRC configuration is used for identifying the "to" and "from" carrier for switching, while the aperiodic transmission is signaled via DCI. The "from" carrier suspends its UL transmission while the "to" CC is transmitting.

Group Triggering is supported via DCI. For the triggering of multiple CCs from a common DCI, the ordering of SRS transmission is as follows:

- For Type A DCI, it follows the order in the RRC configuration
- For Type B DCI, it follows the order in the DCI

The resources used for SRS transmissions when multiple SRSs are triggered by the same DCI are obtained as follows:

- First the timing of the first SRS transmission (n=1) follows legacy timing
- Then, for the n-th SRS transmissions, the first SRS resource is determined after, or at the same time as, the (n-1)-th that does not collide with the 1, …, n-1 SRS transmissions (including retuning times). Note that the SRS resources are obtained as in legacy LTE (i.e., based on A-SRS configuration)

For SRS request, the UE does not expect to receive multiple triggers in the same subframe that result in uplink transmission beyond its UL CA capability including switching time after applying priority rules.

3.1.8.3 INTERRUPTION TIME

The UE signals its capability indicating the one-way switching time to or from a carrier of {0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 5.5, 6, 6.5, 7} OFDM symbol(s).

When the SRS collides with other signals, the following is defined:

- Priority list:
  - A/N, SR, RI/PTI/CRI, PRACH > Rel-14 A-SRS > other A-periodic CSI > Rel-14 P-SRS > other CSI > Legacy SRS
  - A UE is not expected to monitor PDCCH or to receive PDSCH when it collides with SRS switching and transmission time according to the UE's capability
  - For a UE that SRS switching interrupts downlink reception, the UE is not expected to be configured with SRS resource(s) such that SRS switching and transmission time may collide with its PDCCH monitoring in subframe 0 or 5
- Puncturing: Support puncturing the first or last symbol of PUSCH when it collides with SRS switching and transmission time according to the UE's capability

3.1.8.4 POWER CONTROL (TPC)

SRS is normally power controlled following the PUSCH. In SRS switching, there is no PUSCH on at least one TDD CC; therefore, a new power control loop is designed so the UE can set SRS power without referring to the PUSCH. The higher layers configure open-loop power control parameters for SRS transmission, and the physical layer signals transmit power control (TPC) command for closed-loop SRS power control. The TPC command is sent in a new group downlink control information (DCI) called format 3B.

Transmit Power Control (TPC) for SRS switching to CC supports both accumulative and absolute mode configured by the RRC. The TPC command bit interpretation is the same as for PUSCH. In the case that multiple TPC is applied in the same subframe for the same CC, the UE expects the values of TPCs are the same.

The TPC signaling in DCI is divided between Type A TPC-only group DCI with or without an SRS request field. A CC group is configured via RRC signaling for Type A TPC-only group DCI (maximum number of CCs of a group: 8). When SRS request is present, 2-bit SRS request can trigger 1 out 3 CC groups, and the TPC commands are applied to the triggered CC group. If no CC group is triggered, the TPC commands are applied to a CC group configured via RRC signaling.

3.1.8.5 TIMING ADVANCE (TA)

SRS TA needs to be determined for each "switching-to" CC. This CC first shall be configured with a TA group (TAG). If TA is not available for a TAG with all PUSCH-less TDD CCs, then a non-contention based random access procedure needs to be performed, which also requires the UE to switch from a CC with PUSCH to a PUSCH-less CC for transmitting random access preamble. After the TA is acquired, TA command can provide finer adjustment of the SRS TA.

3.1.8.6 TDD-FDD SUPPORT

SRS carrier-based switching is compatible with a TDD-FDD system. That is to say, the TDD carrier in a TDD-FDD system is allowed to be re-tuned to another CC to transmit the SRS symbol. Regarding switching time, RAN1 has been agnostic to inter or intra band time (same support for both) and support up to 7 OFDM symbol switching time with a reporting granularity of half a symbol (14 possible values).

3.1.8.7 SUMMARY

SRS Carrier Switching is aimed at enabling reciprocity-based channel state information acquisition when the UL and DL are asymmetrical, i.e., when the number of DL carriers exceeds the UL in carrier aggregation. The switching between carriers implies a switching interruption time that must be considered for potential collision between the SRS transmission and other channels.

Within the work item, 3GPP working groups designed DCI and RRC signaling to enable triggering and power control of the SRS signals on the non PUSCH CC. A set of dropping rules to handle collision was also designed.[90]

3.1.9 LTE BASED V2X SERVICES INCLUDING NETWORK & SIDELINK BASED

The work in 3GPP RAN working groups on V2X (vehicle-to-everything) features based on LTE technology started during the second half of 2015 with a Release 13 study item: "Feasibility Study on LTE-based V2X Services". The justification for such a study was that it was realized that LTE-based networks provide opportunity for the vehicle industry to realize the concept of 'connected cars. Various research projects and field tests of connected vehicles were initiated in many countries and regions in US/Europe/Japan/Korea/China at that time. In order to respond to the market requirements, a study item was agreed. The objective of the study was to evaluate new functionalities needed to operate LTE-based V2X. 3GPP had already specified direct device-to-device (D2D) sidelink communication based on the PC5 interface in Release 12 and 13, and that could be used as a starting point when specifying V2V

[90] RP-160935, *WID for SRS (sounding reference signal) switching between LTE component carriers* and RP-162137, *Summary for WI: SRS (sounding reference signal) switching between LTE component carriers.*

communications. Compared to the existing 802.11p/DSRC (Dedicated Short-Range Communications) technology, it was recognized that performance of an LTE-based system could be much better. The use cases or communications modes of V2X included in the study were:

- V2V (vehicle-to-vehicle): covering LTE-based communication between vehicles
- V2P (vehicle-to-pedestrian): covering LTE-based communication between a vehicle and a device carried by an individual (e.g., handheld terminal carried by a pedestrian, cyclist, driver or passenger)
- V2I/N (vehicle-to-infrastructure/network): covering LTE-based communication between a vehicle and a roadside unit/network. A roadside unit (RSU) is a transportation infrastructure entity (e.g., an entity transmitting speed notifications) implemented in an eNodeB or a stationary UE

The outcome of the study was the technical report TR 36.885.[91] The TR defines three V2X operation scenarios:

3.1.9.1 SCENARIO 1

Scenario 1 supports V2X operation only based on PC5 i.e., a UE transmits a V2X message to multiple UEs at a local area using sidelink communications. In this scenario V2V and V2P communication are possible. Also, V2I communications is possible if the infrastructure unit is UE-type RSU.

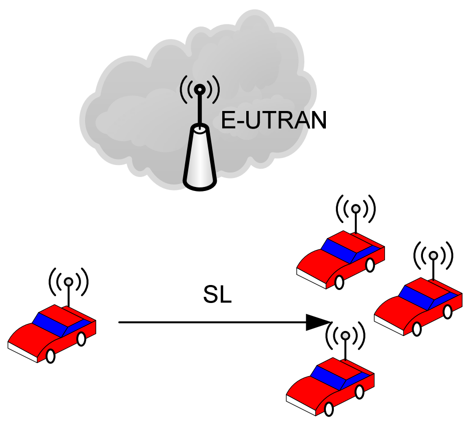

Figure 3.17. V2V Operation Using Sidelink Communications Based on the PC5 Interface.

3.1.9.2 SCENARIO 2

In scenario 2, communications between devices takes place only via Uu. The Uu interface is the air interface between the UE and E-UTRAN, which includes downlink (DL) signals and channels from the E-UTRAN to the UE and uplink (UL) signals and channels from the UE to the E-UTRAN. This means that for V2V and V2P, a UE transmits a V2X message to E-UTRAN in uplink and E-UTRAN transmits it to multiple UEs at a local area in downlink. Downlink transmission may be realized using broadcast mechanism.

[91] TR 36.885 V14.0.0 (2016-06), *Study on LTE-based V2X Services*, 3GPP

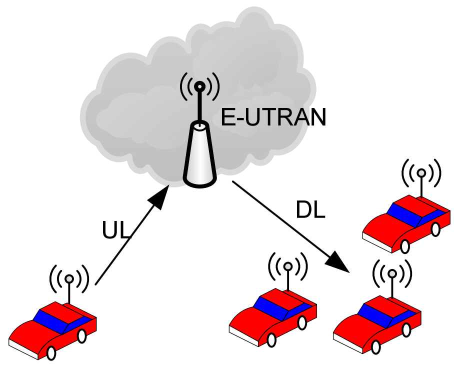

Figure 3.18. V2V Operation Based on Uu Interface.

3.1.9.3 SCENARIO 3

Scenario 3 is a mixed scenario where both PC5 and Uu interfaces are used. An example of such an operation is depicted in Figure 3.19. This scenario was deprioritized in the study item.

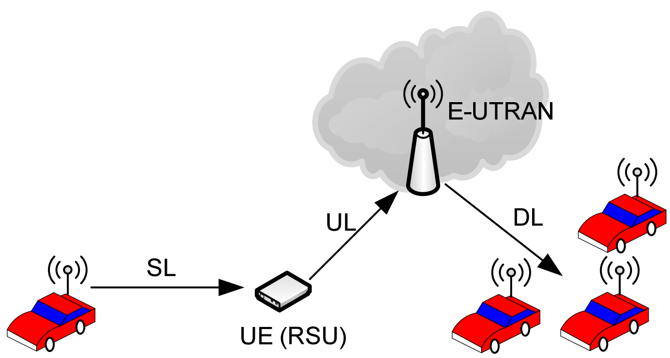

Figure 3.19. Uu/PC5 based V2V Operation.

TR 36.885 covers aspects related to technical support for V2V using the PC5 and Uu interfaces, technical support for V2I/N and support of V2P. More detailed study/specification work related to these issues took place in the V2V and V2X work item phases. Furthermore, some architecture and high-level aspects are discussed in the TR including MBMS for V2X and multiple operator support. Performance results covering capacity analysis in PC5 and Uu based operation and latency analysis is also included in the TR.

3.1.9.4 WORK ITEM ON SUPPORT FOR V2V SERVICES BASED ON LTE SIDELINK

The study item was followed by a work item. As mentioned above, D2D communications specified in earlier releases was the starting point for specification of V2V. Some of the aspects of D2D can be directly reused but there are issues where modifications and further development are needed. These issues include:

- Packet size: D2D was designed for voice communication and size of the VoIP packet is rather small. In V2V packets are larger

- Latency: Latency is important in V2V; safety related message transmission delay is especially important and should be minimized. The latency requirements in V2V are between 20 and 100ms which is more challenging than in D2D

- UE density: D2D was designed for public safety, the number of UEs in that scenario is relatively low while in V2V, for example, in traffic jams, the number of UEs can be high

- Dynamic environment: D2D was designed with pedestrian speeds in mind. V2V UEs can move at much higher speed and in some cases, speeds up to 250km/h should be supported

The key enhancements to D2D introduced in Rel-14 V2V work item were:

- Handling of high Doppler: The 5.9 GHz Intelligent Transportation Systems (ITS) band is the main target for V2V communications and relative UE speeds up to 500km/h should be supported. This means that the Doppler frequency offset can be much higher than in D2D communications or in Uu uplink. Additional DMRS symbols were added to handle the higher Doppler frequency offsets. As illustrated in Figure 3.20, the V2V subframe has 4 DMRS symbols (#2, #5, #8, #11) in addition to the Tx-RX turnaround symbol at the end of the subframe. Compared to D2D subframe, the number of DMRS symbols is doubled to allow for better tracking of the channel at high speed.[92]

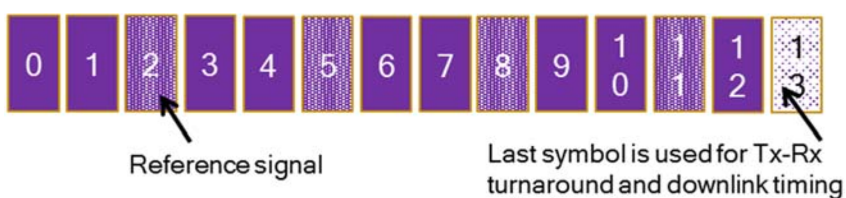

Figure 3.20. Subframe Structure of the PC5 Interface for V2V.

- Support of lower latency under high UE density: In legacy D2D, the scheduling assignment (SA) is sent first; then, in a later subframe, the corresponding data is sent. In V2V, the arrangement of scheduling assignment and data resources is such that the SA and associated data transmission

[92] RP-161272, Revision of WI: *Support for V2V services based on LTE sidelink*, LG Electronics, Huawei, HiSilicon, CATT, CATR and RP-161788, *V2V Work Item Completion*, Qualcomm Incorporated, LGE, CATT, III, Panasonic, Huawei, HiSilicon, Kyocera, Ericsson, Vodafone, Sony.

are in the same subframe i.e., there is no delay between SA and data. This is illustrated in Figure 3.21.

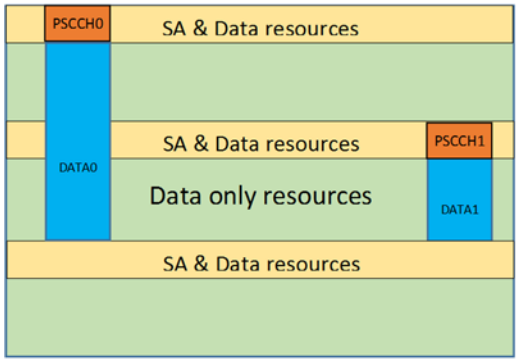

Figure 3.21. Arrangement for SA and the Corresponding Data Transmission in PC5.

- Reduction of collisions in high UE density scenario: V2V traffic from the device side is mostly periodic in nature. When UEs autonomously select resources for transmission this can be utilized by sensing the channel to get information about the congestion on a resource and to estimate future congestion on that resource. Based on this estimation, the UE can try to book the resource for transmission so that collisions can be avoided

- GNSS based synchronization: Many of the V2V messages are based on information derived from GNSS signal (location, speed, and etcetera). Because V2V UEs are almost always able to receive GNSS signal, it is used to provide an accurate synchronization reference and it can be used also outside of network coverage; thus, it is a natural choice for synchronization reference for V2V transmissions. In addition, synchronization based on eNB timing continues to be supported as it can be useful in the carriers where both PC5 and Uu transmissions are possible

- To support V2V, sidelink related configuration RRC broadcast (SIB21) and dedicated signaling needed to be enhanced

Based on features introduced in this work item, two high level deployment configurations are supported as shown in Figure 3.22. Both configurations use a dedicated carrier for V2V transmission. Band 47, in the 5.9 GHz frequency range, has been specified as a dedicated carrier for V2V communication. Both configurations use GNSS as a synchronization reference. In Configuration 1, scheduling and interference management of V2V traffic is supported based on distributed algorithms (a.k.a. Mode 4) implemented between the vehicles. In Configuration 2, scheduling and interference management of V2V traffic is assisted by eNBs (a.k.a. Mode 3) via control signaling over the Uu interface. The eNodeB will assign the resources being used for V2V signaling in a dynamic manner.

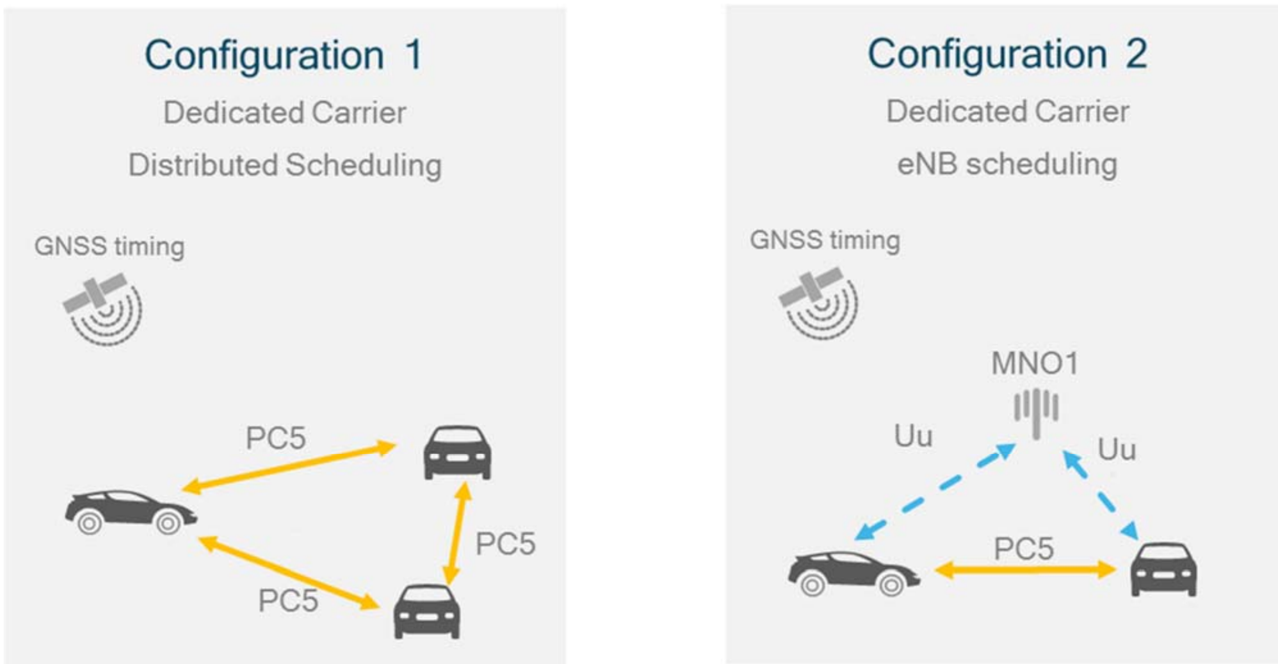

Figure 3.22. Autonomous and eNB-based Scheduling of V2V Transmissions.

3.1.9.5 WORK ITEM ON V2X LTE-BASED V2X SERVICES

This WI extends and builds on the earlier Rel-14 WI, "Support for V2V services based on LTE sidelink",[93] the main enhancements are:

- Uplink and sidelink Semi-Persistent Scheduling (SPS) enhancements: An eNB configures multiple SPS configurations each of which may have different parameters such as the resource period. The UE reports assistance information to the eNB to indicate the expected message generation period, time offset, maximum message size, etcetera. Based on the reported information, the eNB activates/releases each SPS configuration

- Shorter message transmission periods in downlink and sidelink: In order to provide sufficiently low latency for V2X services, shorter control and data periods are introduced for network-based SC-PTM (Single Cell Point-To-Multi-point – in case of multicast/broadcast transmissions within a cell) and MBSFN (Multicast/Broadcast Single Frequency Network – in case of multicast/broadcast transmissions across cells) transmissions. Shorter message transmission periods are also introduced for sidelink and the minimum period of 20 ms can be supported

- Additional transmission procedure for pedestrian UEs to allow for power saving: Random resource selection is supported such that a pedestrian UE not having the sidelink reception capability can transmit its own V2X messages. Partial sensing is also supported, where the pedestrian UE can

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[93] RP-162519, Revised WI proposal: *LTE-based V2X Services*, LG Electronics and RP-170237, Summary for WI *LTE-based V2X Services*, LG Electronics.

monitor the channel only in a subset of subframes. Partial sensing reduces collision probability with the power consumption of the UE being kept at a relatively low level

- Sidelink congestion control: The UE measures the channel busy ratio (CBR) which denotes the portion of time/frequency resources in which strong signal is observed. Higher CBR will be typically measured when more UEs transmit more V2X messages in a given channel. Congestion control can adjust each UE's transmission parameters such as transmit power and resource size based on the CBR measurement either in the centralized manner or distributed manner. In centralized congestion control, CBR measured at the UE is reported to the eNB, and the eNB can adjust the resource configuration appropriately, for example, by commanding each UE to lower the transmit power and resource size. In distributed congestion control, the UE adjusts its own transmission parameters within the allowed range which is a function of CBR measurement

- Enhancement to sidelink synchronization using sidelink signals/channels: SLSS-based (sidelink synchronization signal) operation was introduced so that V2V transmission can be supported in the case that the preferred synchronization source of the carrier (GNSS or eNB) cannot be received. Also, priority rules for synchronization sources were defined for the case when the UE receives multiple different synchronization signals

- Support of simultaneous V2X operations over multiple carriers: In one scenario, a UE can operate Uu-based V2X in one carrier while operating PC5-based V2X in another carrier. In another scenario, a UE can operate PC5-based V2X simultaneously over two carriers. Tables 3.6 and 3.7 list the combinations of V2X carriers supported

Table 3.6. V2X Inter-band Multi-carrier Configurations.									
V2X multi-carrier Configuration	**E-UTRA Bands**	**Interface**	**1.4 MHz**	**3 MHz**	**5 MHz**	**10 MHz**	**15 MHz**	**20 MHz**	**Maximum bandwidth [MHz]**
V2X_3A-47A	B3 (@1.8 GHz)	Uu	Yes	Yes	Yes	Yes	Yes	Yes	**40**
	B47 (@5.9 GHz)	PC5				Yes		Yes	
V2X_7A_47A	B7 (@2.6 GHz)	Uu			Yes	Yes	Yes	Yes	**40**
	B47 (@5.9 GHz)	PC5				Yes		Yes	
V2X_8A-47A	B8 (@900 MHz)	Uu	Yes	Yes	Yes	Yes			**30**
	B47 (@5.9 GHz)	PC5				Yes		Yes	
V2X_39A-47A	B39 (@1.9 GHz)	Uu			Yes	Yes	Yes	Yes	**40**
	47 (@5.9 GHz)	PC5				Yes		Yes	
V2X_41A-47A	B41 (@2.5 GHz)	Uu			Yes	Yes	Yes	Yes	**40**

	47 **(@5.9 GHz)**	**PC5**				**Yes**		**Yes**		

Table 3.7. V2X Intra-band Multi-carrier Configurations.

V2X multi-carrier Configuration	Channel BW of carrier 1	Channel BW of carrier 2	Maximum aggregated BW [MHz]
V2X_47A_47A (@5.9 GHz)	10	10	20

In conclusion, the V2V work item introduced support for vehicle-to-vehicle communication using the sidelink channels on the PC5 interface (this is scenario 1 in TR 36.885). The V2X work item expanded this support to vehicle-to-everything communication using the downlink/uplink channels on the Uu interface (this is scenario 2 in TR 36.885) and using both the PC5 and Uu interfaces (this is scenario 3 in TR 36.885).

3.1.10 EMBMS ENHANCEMENTS FOR LTE

Rel-14 has introduced some (RAN) eMBMS enhancements for LTE, for example:

- New numerologies: with cyclic prefix of 200 μs and subcarrier spacing of 1.25 kHz, designed to cover 15km Inter-Site-Distance (ISD) at a spectral efficiency of 2 bps/Hz (with rooftop antennas); signalling for the numerology with 33 μs CP and 7.5 kHz subcarrier spacing
- MBMS-dedicated cell supporting 100 percent MBSFN subframe allocation
- A new type of MBSFN subframe, without unicast control region and cell-specific reference signals, to reduce overhead in MBMS transmissions
- Corresponding UE/BS RF requirements and RRM/ Demodulation requirements

3.1.11 FURTHER INDOOR POSITIONING ENHANCEMENTS

The Work Item for further indoor positioning enhancements in LTE Rel-14 started in March 2016 and completed in December 2016. LTE Rel-14 indoor positioning enhancements introduced UE-based mode for barometric pressure positioning, TBS positioning and WLAN positioning, as well as the support of network assistance data from the location server to the target UE for both UE-assisted mode and UE-based mode of these positioning solutions. Several OTDOA enhancements to improve the Reference Signal Time Difference (RSTD measurement accuracy were also introduced. In addition, information exchange from eNB to location server was also enhanced to provide available WLAN measurements at the eNB for use with E-CID positioning.

3.1.11.1 BAROMETRIC PRESSURE POSITIONING

The barometric pressure method, which was introduced in LTE Rel-13, utilizes barometric pressure sensors for height information identification and vertical information determination, and should be combined with other positioning methods for 3D positioning together [TS 36.305]. This barometric pressure method in LTE Rel-13 includes UE-assisted mode and standalone mode. In the UE-assisted mode, the UE performs the barometric pressure sensor measurements without network assistance and then sends the measurement results to the E-SMLC for vertical information derivation. While in the standalone mode, the UE performs the barometric pressure sensor measurements and calculates its own vertical information without network assistance. LTE Rel-14 further introduces new UE-based mode, where the UE calculates its own vertical information with network assistance information from E-SMLC. The barometric sensor assistance data includes reference pressure and reference temperature along with a reference point where this reference pressure and temperature are valid.

3.1.11.2 TBS POSITIONING

The TBS in LTE network includes Metropolitan Beacon System (MBS) introduced in LTE Rel-13 and PRS-Based Beacon System introduced in LTE Rel-14. Similar to the barometric pressure method previously described, MBS positioning supports UE-assisted mode and standalone mode without network assistance in LTE Rel-13, and UE-assisted mode and UE-based mode with optional network assistance in LTE Rel-14. In the UE-assisted mode, the E-SMLC calculates the UE position based on at least the TBS measurement results from the UE. While in the UE-based mode and the standalone mode, the UE performs TBS measurements and calculates its own location. The assistance data for both UE-assisted and UE-based modes from the E-SMLC to the UE include acquisition assistance information and almanac information. The acquisition assistance information is about visible beacons, PN Codes, and other information of the MBS signals to enable a fast acquisition of the MBS signals. The almanac information is about the MBS beacon position. PRS-Based Beacon is a new network node for PRS transmission and can work with conventional LTE network together for OTDOA positioning purpose. Compared to the eNB in LTE Rel-13, PRS-Based Beacon can transmit PRS signal more densely, for example, more PRS subframes in one PRS occasion and/or shorter PRS periodicity.

3.1.11.3 WLAN POSITIONING

The WLAN positioning method was introduced in LTE Rel-13 and uses the WLAN measurements (AP identifiers and optionally other measurements) and databases for UE positioning [TS 36.305]. WLAN positioning in LTE Rel-13 supports UE-assisted mode and standalone mode. In the standalone mode, the UE performs WLAN position measurements and location computation without network assistance. While in the UE-assisted mode, the UE provides WLAN position measurements with or without assistance from the network to the E-SMLC for location calculation. LTE Rel-14 introduces the UE-based mode, in which the UE performs WLAN position measurements and location derivation with network assistance. The assistance data for both UE-assisted and UE-based modes that may be sent from the E-SMLC to the UE include Basic Service Set IDentifier (BSSID) of WLAN access point, Service Set Identifier (SSID), Access Point (AP) Type Data and AP location.

3.1.11.4 OTDOA POSITIONING

In some network deployments, the transmission points (for example RRH) may have identical Physical Cell Identifier (PCI) with their associated network nodes (for example macro cell). In this case, these transmission points would not be used for PRS transmission and consequently the number of possible RSTD measurements for OTDOA positioning is reduced due to unexploited transmission points. Additionally, if multiple network nodes with same PCI transmit PRS, then they will transmit PRS over same time and frequency resources and meanwhile use same PRS sequence due to same PCI. In this case, the UE is unable to derive the ToA corresponding to one specific network node. In order to solve these problems, the transmission-point-specific PRS sequence generation using a Transmission Point specific Identifier (TP ID) is supported in LTE Rel-14 for OTDOA positioning.

LTE Rel-14 also introduces other OTDOA enhancements to improve the accuracy of reported RSTD measurements. These include improved granularity of reporting of RSTD measurement, reporting of multipath Time of Arrival information of PRS signal and use of combined PRS and CRS signals for RSTD measurement. Additionally, due to possible different CP lengths used by same TP for PRS transmission in different subframes, the MBSFN subframe configuration information could be sent from eNB to the location server and then from the location server to the UE.

3.1.11.5 E-CID POSITIONING

To improve the UE location estimates in E-CID positioning, LTE Rel-14 enables the eNB to report information to the location server such as WLAN Received Signal Strength Indicator (RSSI), BSSID, SSID, Homogeneous Extended Service Set IDentifier (HESSID), channel(s), operating class, country code and band, if corresponding WLAN measurement information is already available in the eNB.

3.1.12 OTHER REL-14 LTE WORK ITEMS NOT INCLUDED IN THIS SECTION

- RP-160680, Downlink Multiuser Superposition Transmission for LTE
- RP-160664, Uplink Capacity Enhancements for LTE
- RP-160540, Signaling reduction to enable light connection for LTE
- RP-160636, Mobility enhancement in LTE
- RP-160600, Enhanced LTE-WLAN Aggregation
- RP-152263, Performance enhancements for high speed scenario
- RP-152205, Multi-Band BS testing with three or more bands
- RP-160548, Further Enhancement of BS RF and EMC requirements for AAS
- RP-160678, Measurement Gap Enhancement for LTE
- RP-160603, Radiated performance requirements for the verification of multi-antenna reception of UEs

3.2 UTRAN/HSPA+ ENHANCEMENTS

3.2.1 MULTI-CARRIER ENHANCEMENTS FOR UMTS

In Rel-9, the UMTS standard introduced “Dual Carrier HSUPA (DC-HSUPA)” aiming at increasing the uplink data throughput by means of allowing the UE to transmit on two uplink carriers at the same time. Later in Rel-13, Dual-Band Dual-Carrier HSUPA (DB-DC HSUPA) was added to the standard aiming at configuring two uplink carriers on different frequency bands. One aspect to be considered when DB-DC HSUPA is configured relies on the fact that high-frequency carriers have relatively smaller coverage than the low-frequency carriers. For example, there is a coverage difference of around 7.3 dB between a carrier operating at 900 MHz and a carrier operating at 2.1GHz.

The UMTS standard allows to configure a Transmission Time Interval (TTI) equal to 2 ms or 10 ms in the case of single carrier HSUPA. However, it only allows (i.e., before Rel-14) to configure a TTI equal to 2 ms on both carriers for (DB-DC)/DC-HSUPA. Nonetheless, and continuing with the evolution of the UMTS standard, the Rel-14 WI on “Multi carrier enhancements for UMTS” opens the possibility of configuring a 10 ms TTI length on one or both uplink carrier frequencies in (DB-DC)/DC-HSUPA scenarios. In other words, “Multi carrier enhancements for UMTS” allows keeping 2 ms TTI configured on both carriers, or having 10 ms TTI configured on both carriers, or enabling a mixed TTI configuration (i.e., 2ms TTI in one carrier, and 10 ms TTI on the other carrier). Figure 3.23 shows the region where the Rel-14 “Multicarrier Enhancements for UMTS” may be usable.

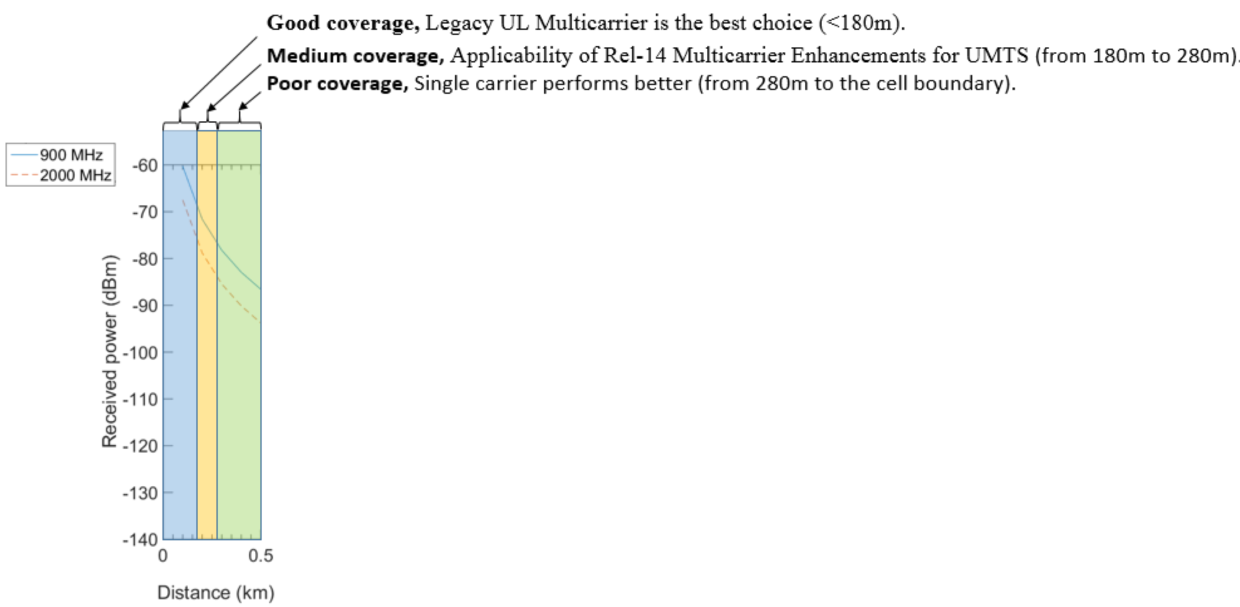


Figure 3.23. Applicability of Legacy UL Multicarrier, Rel-14 Multicarrier Enhancements, and Single Carrier as a function of the Path-loss.

As can be seen from Figure 3.23, the main applicability region of the Rel-14 “Multicarrier Enhancements for UMTS” is medium coverage (around 100 meters). Enabling a different TTI configuration per carrier in (DB-DC)/DC-HSUPA opens the possibility of having a variety of scenarios. For example, a 10 ms TTI may be configured on a high frequency band, while a 2 ms TTI may be configured on the low frequency band aiming at trying to compensate (slightly by 1 dB or 2 dB) for the different propagation properties associated to each of the bands. Moreover, in (DB-DC)/DC-HSUPA a mixed TTI configuration can also be used to find/achieve different coverage/throughput trade-offs mainly for intermediate path loss ratios as compared to the legacy performance.

3.2.2 DTX / DRX ENHANCEMENTS IN CELL_FACH

HS-DSCH/E-DCH transmission in CELL_FACH was introduced in Release 7/8 and is currently deployed in 3G networks. This feature is useful for smart phone services to improve resource utilization and latency of state transition between CELL_FACH and CELL_DCH. In Release 11, other enhancements for CELL_FACH were introduced, e.g., stand-alone HS-DPCCH without E-DCH transmission, concurrent support for 2 ms and 10 ms TTI in a cell, fallback to R99 PRACH, second UE DRX in CELL_FACH, and etcetera.

3GPP Rel-14 has introduced mechanisms to reduce UE power consumption in CELL_FACH, i.e., shorter wake-up time during DRX operation.

With this feature, called *HS-SCCH DRX in CELL_FACH,* a UE in CELL_FACH is allowed to periodically monitor the HS-SCCH channel only, without having to decode HS-DSCH, unless a specific HS-SCCH order is received.

Going into some further operation details, the UTRAN indicates to the UEs an inactivity time, a HS-SCCH DRX cycle length and a HS-SCCH RX burst length by dedicated signaling, in addition to the legacy parameters broadcasting in SIBs for HS-DSCH DRX operation in CELL_FACH state. The HS-SCCH DRX operation is initialized when, during a period of no data transmission, the inactivity timer expires. At this point, the UE is required to monitor HS-SCCH order continuously for the length for the Rx burst length of the DRX Cycle configured, and it does not have to decode HS-DSCH. If the UE receives a HS-SCCH order, it starts receiving HS-DSCH continuously a certain time (8 ms) after the HS-SCCH order.

This operation is illustrated in Figure 3.24.

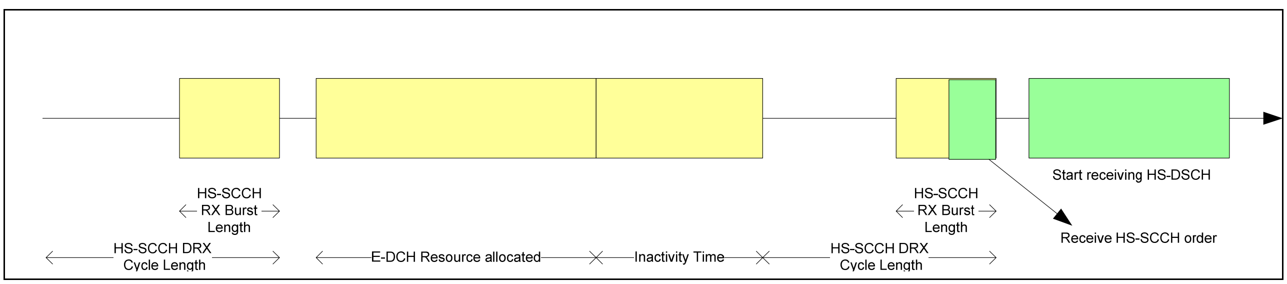


Figure 3.24. Discontinuous HS-SCCH Reception in CELL_FACH State.

3.2.3 RRC OPTIMIZATION

RRC optimization consists of two enhancements: Simultaneous RAB/RB Setup and Release and Generic UPH Reporting.

In earlier releases of UMTS the setup, release and reconfiguration of radio bearers has been done using different RRC messages, namely the messages Radio Bearer Setup, Radio Bearer Release and Radio Bearer Reconfiguration. In cases where, for example, one radio bearer has been setup at the same time as another radio bearer has been modified, it has been necessary to send two different RRC messages. The simultaneous RAB/RB setup and release enhancement allows setup, release and reconfiguration of radio access bearers and radio bearers in the same RRC message. The RRC message is the Radio Bearer Reconfiguration message.

In MAC layer, the UE may report the Uplink Power Headroom (UPH). The UPH of a frequency indicates the ratio of the maximum UE transmission power and the corresponding DPCCH code power of that frequency. In the enhancement for Generic UPH Reporting, the option to configure RRC events for UPH reporting is introduced. The RRC events allow the UE to perform measurements on UE Power Headroom (UPH) and signal the RRC events 6h and 6i when the UPH becomes larger or less than an absolute threshold respectively. The thresholds are configurable, as well as hysteresis, time-to-trigger, filter coefficient and pending time after trigger for each of the events.

3.2.4 QOE MEASUREMENT COLLECTION FOR STREAMING

The QoE Measurement Collection feature aims at providing means to better estimate the user (streaming) Quality of Experience.

With this feature, the network can configure collection of measurements from the UE using the Mobile Data Terminal (MDT) framework. QoE measurement configuration received, by UTRAN, from OAM or CN is encapsulated in a container, which is inserted in a RRC Measurement Control message and forwarded to the UE transparently. QoE measurements received from UE higher layer are inserted in a container in a Measurement Report message and sent to UTRAN.

The QoE measurement configuration is supported in CELL_DCH and CELL_FACH states, whereas the QoE measurement reporting is supported in CELL_DCH state only.

Both signaling-based and OAM-based initiation are allowed. For the signaling-based case, the QoE Measurement Collection is initiated (from CN) towards a specific UE; in the other case, the QoE Measurement Collection is initiated from OAM targeting a UTRAN area (not UE specific).

3.2.5 HSPA & LTE JOINT OPERATION

A Rel-14 study was done on optimized Inter-Radio Access Technology (RAT) Circuit Switched (CS) and Packet Switched (PS) operation, particularly to investigate some possible solutions to support CS in UMTS and PS in LTE.

This Study was completed in December 2016 (see outcomes in Technical Report 37.805), without further normative work.

3.2.6 DL INTERFERENCE MITIGATION

This feature introduces new signaling for indicating presence of interference (e.g., GSM). The indication, from the network to the UE, is about DL adjacent channel interference, and can be beneficial for optimizing DL performance, e.g., UE could try to filter out the interference signal(s).

The feature is applicable to FDD only and has been standardized starting from Rel-14.

More specifically, the new signaling (optional) is conveyed in existing RRC broadcast messages (SIB 5/6), indicating a certain “Adjacent channel interference level” (MODERATE, HIGH). UEs could use such indication to mitigate the DL interference, for example, using optimized Rx filtering.

3.3 NETWORK SERVICES RELATED ENHANCEMENTS

3.3.1 CONTROL AND USER PLANE SEPARATION (CUPS)

The goal of the Control and User Plane Separation (CUPS) architecture enhancements is to define a more flexible, distributed architecture that can provide greater function utilization efficiencies, leveraging the evolution to NFV and SDN implementations as well as the introduction of capabilities such as network slicing and mobile edge compute and storage (e.g., MEC), by placing exact services and functions where needed and optimal for the QoE of the applications. Specifically, CUPS separates the user plane functionality from control plane functionality in the Serving Gateway (S-GW), Public Data Network Gateway (P-GW) and Traffic Detection Function (TDF) functions to further enable flexible (i.e., distributed or centralized) network deployment and operation. This separation must be done while not affecting the overall functionality provided by these nodes. This feature defines the reference points, interfaces and procedures between these nodes and identifies any impacts to other EPC entities and interfaces required to enable a wide range of deployment scenarios that can take advantage of flexible, independent placement of control and user plane functions.

One of the key advantages to a CUPS architecture is that it will be a primary enabler for realizing Mobile Edge Compute (MEC) deployments that can benefit from a distributed user plane with centralized control plane as shown in figure 3.25. As shown in this figure, there are various deployment scenarios and use cases from enterprise, to connected commerce to providing optimized video delivery through MEC that will benefit from a CUPS architecture that allows the distribution of user plane and SDN forwarding functions out to the edge of the network, while still maintaining centralized control plane to support functions such as mobility, charging, policy, Authentication, security and Legal Intercept. And using NFV/SDN implementations with network slicing, each of the applications shown in Figure 3.25 can be configured and orchestrated to support only the needed set of user plane and control plane functions at the optimized locations to improve utilization efficiency and enhance QoE for the specific application.

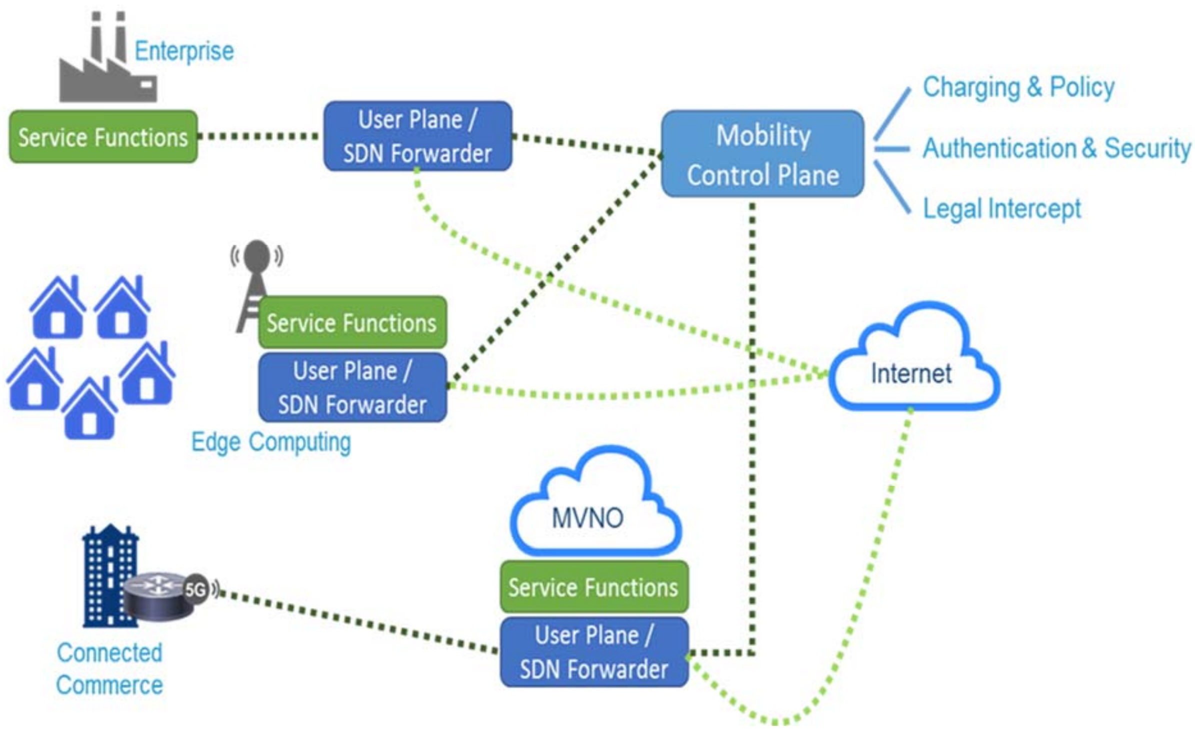


Figure 3.25. Example of Distributed UP with Centralized CP Using CUPS.

The initial studies in 3GPP on CUPS are starting from the existing EPC architecture, with Figure 3.26 showing the baseline EPC architecture, interfaces and reference points from 3GPP TR 23.714. These interfaces and reference points are explained and remain consistent with the existing EPC architecture, with explicit identification of user plane (solid lines) and control plane (dotted lines).

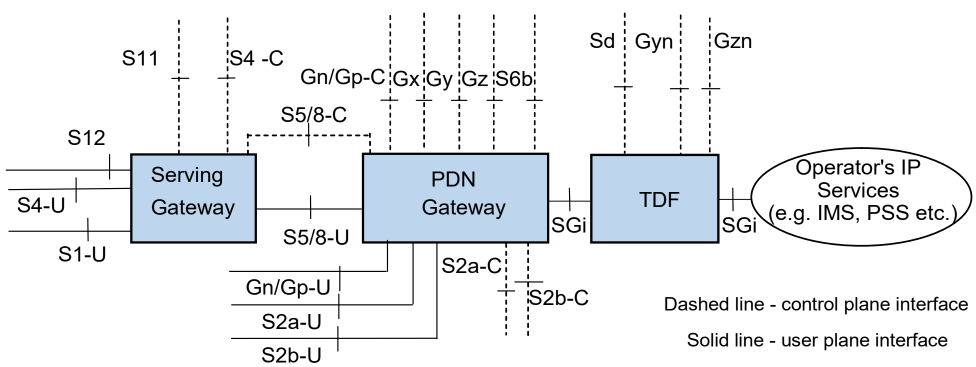


Figure 3.26. Baseline S-GW, P-GW, TDF and their Reference Points from 3GPP TS 23.401.

S1-U Reference point between E-UTRAN and Serving GW for the per bearer user plane tunneling and inter eNodeB path switching during handover. S1-U does not apply to the Control Plane CIoT EPS optimization

S2a-U User Plane Reference point between P-GW and Trusted Non-3GPP IP Access

S2a-C Control Plane Reference point between P-GW and Trusted Non-3GPP IP Access

S2b-U User Plane Reference point between P-GW and ePDG for Untrusted Non-3GPP IP Access

S2b-C Control Plane Reference point between P-GW and ePDG for Untrusted Non-3GPP IP Access

S4-U User Plane Reference point between S-GW and SGSN (from 2G/3G packet core)

S4-C Control Plane Reference point between S-GW and SGSN (from 2G/3G packet core)

S5/8-U User Plane Reference point between P-GW and S-GW (S8 for inter-PLMN scenario)

S5/8-C Control Plane Reference point between P-GW and S-GW (S8 for inter-PLMN scenario)

S6b Reference point between P-GW and AAA

S11 Reference point between MME and Serving GW

S12 Reference point between UTRAN and Serving GW for user plane tunneling when Direct Tunnel is established. It is based on the Iu-u/Gn-u reference point using the GTP-U protocol as defined between SGSN and UTRAN or respectively between SGSN and GGSN. Usage of S12 is an operator configuration option

Gn/Gp Control Plane Reference point based on GGSN to SGSN interface

Gx, Gy, Gz Reference points between EPC Policy, Charging & Rules functions

SGi It is the reference point between the PDN GW and the packet data network. Packet data network may be an operator external public or private packet data network or an intra operator packet data network, e.g., for provision of IMS services. This reference point corresponds to Gi for 3GPP accesses.

Sd Reference point between Traffic Detection Function (TDF) and Policy Control and charging Rules Function (PCRF)

Gyn, Gzn Reference point between TDF and Online Charging System (OCS) and Offline Charging System (OFCS)

The CUPS architecture model in Rel-14 builds off the EPS architecture shown in Figure 3.26 and is based on the following general concepts:

- Interworking with networks not applying control and user plane separation is possible (i.e., in case of roaming scenarios)
- Split network entities can interwork with network entities that are not split within the same network
- Split network entities have no requirement to update UE, and Radio Access Network
- The SGW/PGW selection function of the MME/ePDG/TWAN described in 3GPP TS 23.401 and TS 23.402 [yy] is used for the selection of the respective CP function
- The configuration-based mechanism (in PGW or PCRF) described in 3GPP TS 23.203 is used for the selection of the CP function of the TDF

- A CP function can interface with one or more UP functions (e.g., to enable independent scalability of CP functions and UP functions)

Based on these concepts, 3GPP TS 23.214 has defined the architecture reference model for CUPS shown in Figure 3.27. Note that for S2a, S2b, S5 and S8 reference points, this architecture reference model is only supported with General Packet Radio Service Tunneling Protocol (GTP)-based interface (PMIP-based interfaces and S2c interface are not supported).

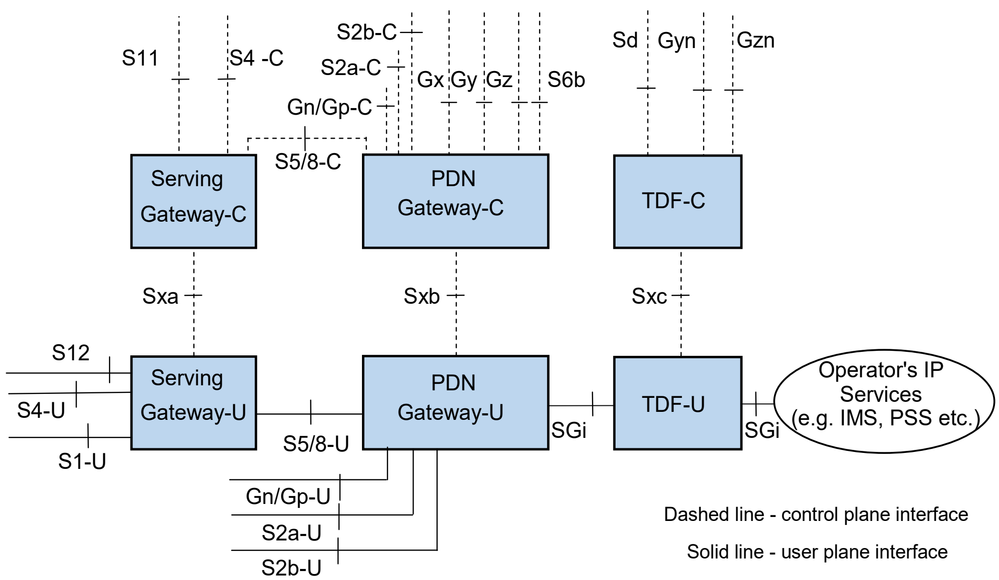


Figure 3.27. Architecture Reference Model with Separation of User Plane and Control Plane.

Compared to the baseline architecture in Figure 5.30, three new interfaces are introduced in Figure 3.27:

Sxa – Interface between the S-GW CP and UP functions

Sxb – Interface between the P-GW CP and UP functions

Sxc – Interface between the TDF CP and UP functions

These are generically defined interfaces that will carry signaling traffic between the defined functions/nodes as needed based on the high-level functions and the functional splits between UP and CP as defined in 3GPP TS 23.214.

3.3.2 MISSION CRITICAL IMPROVEMENTS INCLUDING PUBLIC SAFETY

After the Mission Critical Push-to-Talk over LTE service specified in Release 13, two new Mission Critical services were specified in Release 14: Mission Critical Video over LTE and Mission Critical Data over LTE. These services are intended to be used in conjunction with the Mission Critical PTT service in order to provide more data for use by first responders.

The Mission Critical Video service will provide useful video functionality for first responders. When a first responder's UE is equipped with a camera, display or both, this will allow functions such as video group calls, video private calls, video pull, video push, capability information sharing and transmission control and reception control for both on-network and off-network operation. Additional functions allow emergency and imminent peril group calls, remotely initiated procedures for video push and support for local and remotely initiated ambient viewing.

The Mission Critical Data service will provide additional data functionality such as short data service (SDS) for on and off network, file distribution (on network), data streaming (on network), conversation management (on network), transmission and reception control (on network), communication termination (on network), secure internet browsing and secure database enquiries (on network) and enhanced status reports (on and off network).

The set of MCPTT services (talk, video, data) are collectively referred to as MCX services, and all three are subject to a set of common requirements. Although these Mission Critical services were defined with Public Safety in mind, they can also be used for general commercial applications, such as utility companies.

MCX Services fall into three accessibility categories: “on-network”, “off-network”, and “common”. On-network services are available only when the UE is attached to the PLMN. Off-network services are available only when the UE is not attached to the PLMN. Common services are available both on and off-network.

The full set of MCX services, descriptions and requirements for Release 14 are described in the following 3GPP documents:

- TS 22.179 for MCPTT
- 22.281 for MCVideo
- 22.282 for PTT Data, and
- 22.280 for requirements common to all MCX services

Although these Mission Critical services were defined with Public Safety in mind, they can also be used for general commercial applications, such as utility companies.

3.3.3 PAGING IMPROVEMENTS

In Release 14, 3GPP continued the efforts to provide more efficient and accurate paging policies, with the intent of reducing the paging signaling both by M@M devices and by smart phones’ OTT (Over the Top) applications. The work item, *Paging Policy Enhancements and Procedure Optimizations in LTE* provided requirements to further optimize paging policies in LTE based on application characteristics known and trusted at the serving network. This work included optimizing signaling load and radio resource usage by selecting an appropriate paging policy based on:

- mobility of the UE (e.g., stationary, restricted mobility)
- application characteristics that are known and trusted at the serving network (e.g., expected QoS, priority)
- likely location of the UE within the paging area

There is no stage 2/3 work related to this requirement. It is expected that the internal policy of the MME can be enhanced to take these additional criteria into account for paging policy selection. Stage 1 of this item is described in CRs to 3GPP 22.101.

3.3.4 OAM&P

Operations, Administration, Maintenance, and Provisioning (OAM&P)) has been an important part of all 2G, 3G and 4G systems over the years. The introduction of NFV-based networks creates a whole new set of challenges for management of virtualized networks.

3.3.4.1 OAM&P FOR NETWORKS THAT INCLUDE VIRTUALIZED NETWORK FUNCTIONS

Five work items related to network management were completed in Release 14 (including management of networks that contain NFV technology). They are:

- Management concept, architecture and requirements for mobile networks that include virtualized network functions, Ref TS 28.500, TS 32.101
- Configuration Management for mobile networks that contain virtualized network functions, Ref TS 28.513, TS 28.512, TS 28.511, TS 28.510, TS 28.621, TS 28.622
- Fault Management for mobile networks that include the virtualized network functions, Ref TS 28.515, TS 28.516, TS 28.517, TS 28.518, TS 32.111-1, TS 32.111-2
- Performance Management for mobile networks that include virtualized network functions, Ref TS 28.523, TS 28.522, TS 28.521, TS 28.520, TS 32.426, TS 32.409, and
- Lifecycle Management for mobile networks that include virtualized network functions, Ref TS 28.525, TS 28.526, TS 28.527, TS 28.528, TS 28.704, TS 28.705

3.3.4.1.1 MANAGEMENT CONCEPT, ARCHITECTURE AND REGULATIONS FOR MOBILE NETWORKS THAT INCLUDE VIRTUALIZED FUNCTIONS

NFV Management architecture developed by 3GPP SA5 clarifies the relationship between 3GPP management architecture and ETSI ISG NFV Management and Orchestration architecture (see Figure 3.28.)

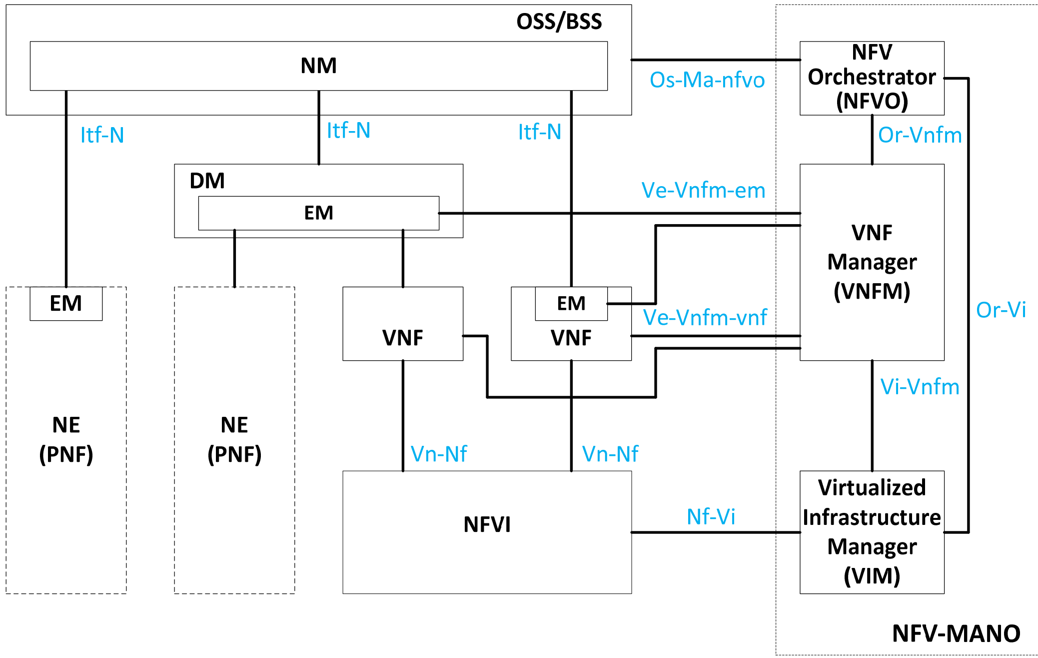


Figure 3.28. NFV Management Architecture.

The legacy 3GPP management system is composed of Network Management (NM) and Domain Manager/ Element Manager (DM/EM) which provide for classic Fault, Configuration, Accounting, Performance, Security (FCAPS) management functionalities. For the networks where some Network Elements (NEs) are virtualized, system the combined architecture in addition provides for connection with NFV Management Nodes (MANO) via the reference points Os-Ma-nfvo, Ve-Vnfm-em, Ve-Vnfm-vnf. Details can be found in the 3GPP TS 28.500.

For the virtualized part of the network, the concept of Network Element (NE) in this new architecture has been transformed into VNF. Relation between these two concepts is outlined by Figure 3.29.

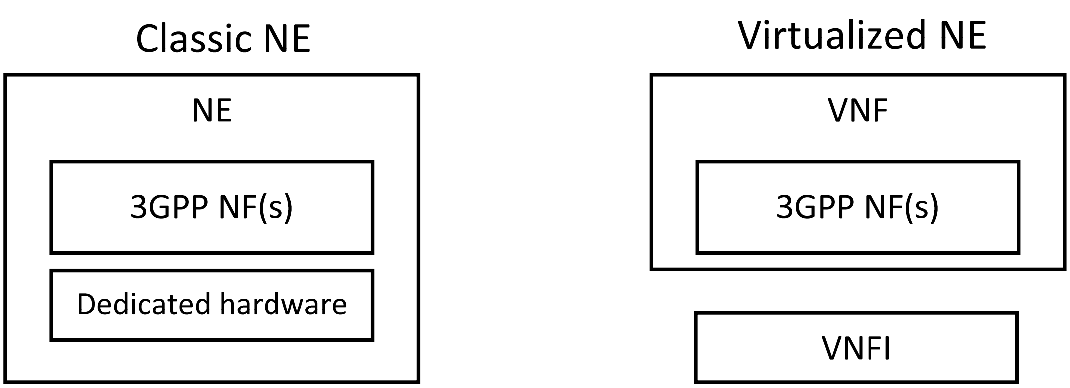


Figure 3.29. Relation between NE and VNF.

3.3.4.1.2 CONFIGURATION MANAGEMENT FOR MOBILE NETWORKS THAT INCLUDE VIRTUALIZED NETWORK FUNCTIONS

The Configuration Management (CM) specifications are provided in 3GPP TS 28.510/1/2/3. CM of virtualized networks includes the following aspects:

- Legacy Configuration Management (often called "application level" management) of the network functions; this part is basically the same as non-virtualized network functions. The CM is performed from the NM layer to the EM via Itf-N interface and further to the Network Elements (NEs) such as MME or PGW

- Configuration Management of the virtualization part is a new aspect that includes communication between the NM and EM (the left side of the Figure 5.34 diagram) and the MANO block (the right-hand side of the Figure 5.34 diagram)

Example of Use Cases for this aspect are:

- VNF instance information retrieving and modification

- Creation, deletion and update of the Management Object Instance (MOI) associated with the VNF with connection to the VNF Life Cycle Management (LCM) operations such as VNF instantiation and termination

3.3.4.1.3 FAULT MANAGEMENT FOR MOBILE NETWORKS THAT INCLUDE VIRTUALIZED NETWORK FUNCTIONS

The Fault Management specifications are provided in 3GPP TSs 28.515/6/7/8. Fault Management (FM) functionality traditionally includes fault detection, generation of alarms, clearing of alarms, alarm forwarding and filtering, storage and retrieval of alarms, correlation of alarms and events, alarm root cause analysis and fault recovery. With the introduction of virtualized network functions (VNFs) into mobile networks, Fault Management functionality is distributed over different functional blocks located at different levels such as NFV Infrastructure (NFVI) level, NE level, NFV Management and Orchestration level and 3GPP network management levels NM and EM.

Network virtualization adds new category of faults: physical hardware faults of NFVI are detected by NFVI and corrected jointly with the support from NFV-MANO. Only information about those faults that affect the proper functioning of VNF needs to be provided to 3GPP management system. Virtualization-specific fault information, sometimes called Virtual Resources FM information or VR FM, is detected by the NFVI. The collection of FM data is performed by the Virtual Infrastructure Manager (VIM) and VNF Manager (VNFM) from which the FM notifications are transferred to the EM where they can be correlated with application level FM information. From the EM, correlated or uncorrelated VR FM information is delivered to the NM, through the Itf-N interface.

3.3.4.1.4 PERFORMANCE MANAGEMENT FOR MOBILE NETWORKS THAT INCLUDE VIRTUALIZED FUNCTIONS

The Performance Management (PM) specifications are provided in 3GPP TSs 28.520/1/2/3. Figure 3.30 outlines PM data collection methods for virtualized networks. The performance data provides information on “application level” performance (legacy PM data related to 3GPP Network Function) and the PM data related to Virtual Resources (VR), sometimes called Virtual Resources PM information or VR PM, for example, utilization of Compute, Storage or Networking resources.

For PM data related to 3GPP Network Function, EM requests VNF(s) to collect the PM data, typically by request of the NM. For VR PM collection, NM creates a PM collection task at the EM and specifies the measurement types, the measured resources, the recording periods, and etcetera. Then the EM creates a PM collection task at the VNFM, and the VNFM in turn creates a PM collection task at VIM. The VIM requests NFVI to collect the VR PM data as specified by VNFM. The collected information is transferred through the chain of PM collection tasks to the NM. As usual, various PM data is stored in data repositories from which it may be fetched by NM (or any authorized user).

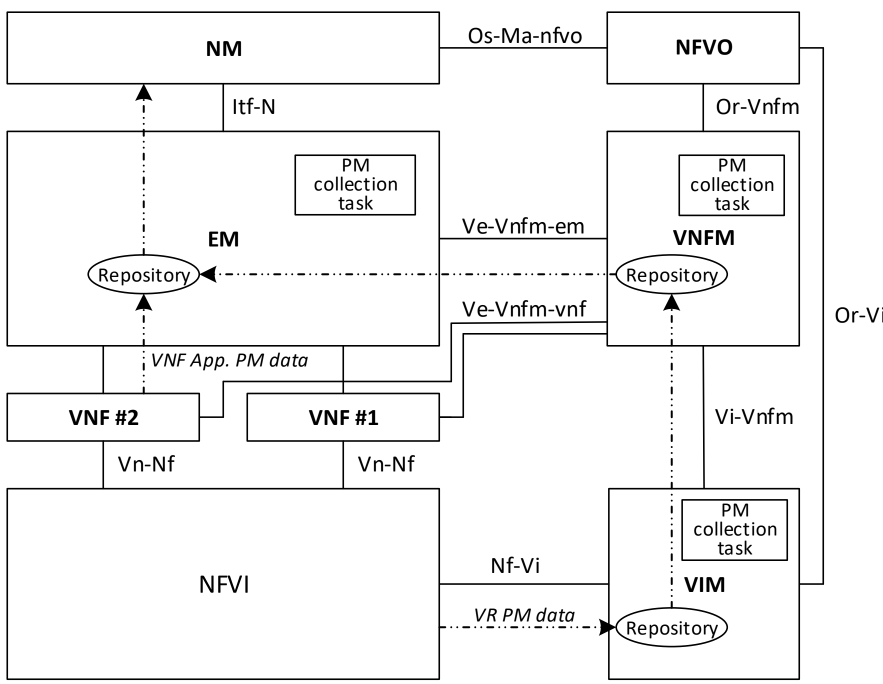


Figure 3.30. PM Data Collection Methods for Virtualized Networks.

3.3.4.1.3 LIFECYCLE MANAGEMENT FOR MOBILE NETWORKS THAT INCLUDE VIRTUALIZED NETWORK FUNCTIONS

The Lifecycle Management (LCM) specifications are provided in 3GPP TSs 28.525/6/7/8. This includes the lifecycle management of:

- Virtual Network Functions (VNFs) including such operations as VNF instantiation, scaling and termination

- Network Services (NSs), which are essentially collections of VNFs and PNFs interconnected with virtual links. The LCM operations for the NSs include instantiation, scaling, querying, termination
- VNF Packages that are used for VNF instantiation and specify properties of the VNF; The LCM operations for the VNF Package include VNF package on-boarding, enabling, disabling, deletion
- Network Service Descriptors (NSDs) that are used in LCM operations with the NS have a set of LCM operations of their own, such as on-boarding, enabling, disabling, update, etc.

3.3.4.2 FILTERING OF PM MEASUREMENTS AND DATA VOLUME MEASUREMENTS FOR SHARED NETWORKS

3GPP RAN has defined in TS 36.314 data volume measurements for RAN Sharing, such as Data Volume for Shared Networks. For the latter, the measured quantity is the data volume transmitted or received by the eNB in a configured measurement period, for one of multiple PLMNs in a shared RAN. The measurement is performed per configured QoS profile criteria, such as QoS Class Identifier (QCI), Guaranteed Bit Rate (GBR) range, Allocation Retention & Priority (ARP), and etcetera.

In this work item, 3GPP addresses cross-operator accounting between a Master Operator (MOP), i.e., the operator who owns the RAN and a Participating Operator (POP) in a RAN sharing arrangement. It addresses three areas:

- Use cases and requirements for management of measurements for cross-operator accounting
- Subscription of data volume measurement that can be filtered on uplink and downlink QoS profiles (QCI, ARP and GBR)
- Statistical Measurements for data volume for cross-operator accounting

To follow up, 3GPP SA5 started the Study on management of measurement collection in the context of RAN sharing, the outcome of which was summarized in 3GPP TR 32.817. One example of requirements defined by SA5 is that the management system should enable the Master Operator (or MOP; the one that controls / owns the shared RAN), to charge the Participating Operators (POPs) for the data volume used by POP's users per selected QCI criteria via statistical measurements defined for shared networks.

The findings of the Study were implemented in 3GPP TS 32.130, 3GPP TS 32.412 and 3GPP TS 32.416.

3.3.4.3 OAM SUPPORT FOR LICENSED SHARED ACCESS (LSA)

A new concept for sharing of spectrum has resulted in ECC Report 205 on Licensed Shared Access and ETSI RRS-defined system requirements for operation of mobile broadband services in 2300 – 2400 MHz band under Licensed Shared Access (LSA), ETSI TS 103 154. LSA is a new licensing method that allows current spectrum owners (incumbents) to share their spectrum with Mobile Network Operators (Licensees) according to this regulatory framework (sharing framework) issued by a National Regulatory Authority (NRA). The advantage of LSA is that QoS is supported even with that shared spectrum.

The LSA Architecture Reference Model is based on a LSA Repository (LR) and LSA Controller (LC) with the LSA1 reference point between them The WI OAM support for Licensed Shared Access (LSA) provides functionality for connecting the LC to the 3GPP Management System. Two deployment scenarios are considered:

- Deployment scenario 1: The LSA controller (LC) communicates LSA Spectrum Resource Availability Information (LSRAI) received from the LR to the NM.
- Deployment scenario 2: The LSA controller performs planning decisions (some or all) based on the LSRAI received from the LR internally and communicates the calculated constraints on configuration attributes (max TX power, allowed down tilt range, allowed azimuth range, maximum antenna height, and etcetera) to the NM

Implementation of these solutions is described in 3GPP TS 28.301/2/3.

3.3.5 ENHANCEMENT FOR TV SERVICE

To cope with the expected growth of HD TV content accessed over cellular networks, 3GPP Rel-14 has introduced important MBMS-based enhancements to enable efficient and dynamic/flexible TV service over EPS (including linear TV, Live, Video on Demand, smart TV, managed and OTT content).

As a general service definition, the Rel-14 *enhancement for TV service* is a feature whereby 3GPP networks can provide unicast and broadcast transport, referred to as "TV transport services", to support distribution of TV programs. TV transport services can support the three types of TV services: Free-to-Air (FTA), Free-to-View (FTV) and Subscribed services.

From a technology and architecture point view, enhanced TV service over EPS/E-UTRAN enables operators and service providers to deliver TV services from broadcasters as well as third party service providers, allowing separate content delivery and transport services. At high level, the following key architectural enhancements and functionalities have been standardized:

- A broadcast component, with mechanisms to enable decoupling of content, MBMS service and MBMS transport; this allows the system to offer MBMS transport only, a shared MBMS network, and/or a broadcast only TV service (including devices with no PLMN-MBMS subscription, therefore, operating in receive only mode)
- A unicast component, via PDN connectivity through operator's EPC network, in which operator subscription for TV service may be achieved via dedicated APN
- Mechanisms for broadcast/unicast fallback support, and switching between unicast/broadcast (e.g., consumption-based)
- A standardized interface between BM-SC and the content provider in order to facilitate both transport and user services delivery for TV services via MBMS (for broadcast) and EPC (for unicast)

System-wise, two main MBMS Service Types can be eventually identified for TV service:

- MBMS transport only mode
  - The 3GPP network provides only transport of data/TV content in a transparent manner
  - The 3rd party content provider's signaling and data transferred via MBMS bearer(s) are transparent to BM-SC and the MBMS bearer service

    - All other service aspects, e.g., decision of whether to send data over broadcast or unicast, is not within 3GPP network, and assumed to be performed by application server

- MBMS full service mode

  - 3GPP MBMS system provides full service layer capability
  - BM-SC is aware of the content stream and is capable of transforming the content stream into 3GPP compliant stream

  - BM-SC can perform the decision on whether to switch an MBMS user service between broadcast or unicast service

3.3.6 S8 HOME ROUTING FOR VOLTE

With more operators starting to deploy VoLTE on their LTE networks, VOLTE roaming has become an urgent topic on many operators' agendas.

In general, there are two VoLTE roaming models that can be implemented by a mobile operator: Local Breakout (LBO) and S8-Home Routed (S8HR). LBO was initially proposed as the preferred roaming architecture by some operators, however, due to the fact that the pace in VoLTE development varies among carriers and VoLTE inter-carrier operability is still an outstanding issue even among carriers in the same region, the challenges for partner operators to use LBO architecture for VOLTE roaming is substantial considering the amount of tight integration and customization work that have to be done for an operator to be able to achieve commercial grade VOLTE performance on their own network. It will require tremendous efforts and collaboration among carriers to make VOLTE work seamlessly across multiple operators' IP Multimedia Subsystem (IMS) platforms if LBO is adopted. In the meantime, the need to make VOLTE roaming work is becoming increasingly prominent. As a result, S8HR based architecture has gained a lot momentum recently.

GSMA has been actively engaging major operators, vendors and 3GPP to address the issues related to VOLTE roaming. Although LBO is still be discussed as an option, the main focus has been shifted to S8HR due to the fact that many operators, especially the regional carriers, are eager to make VOLTE roaming work quickly. With S8HR architecture, IMS support is not required on the visited network. Since the IMS traffic is routed home, interoperability tests between carriers are not necessary. It greatly simplifies the VOLTE roaming implementation and reduces the amount of testing needed for inter-carrier interoperability.

For comparison purpose, the general VoLTE roaming architecture with LBO is shown in Figure 3.31 (from 3GPP TS. 23.228).

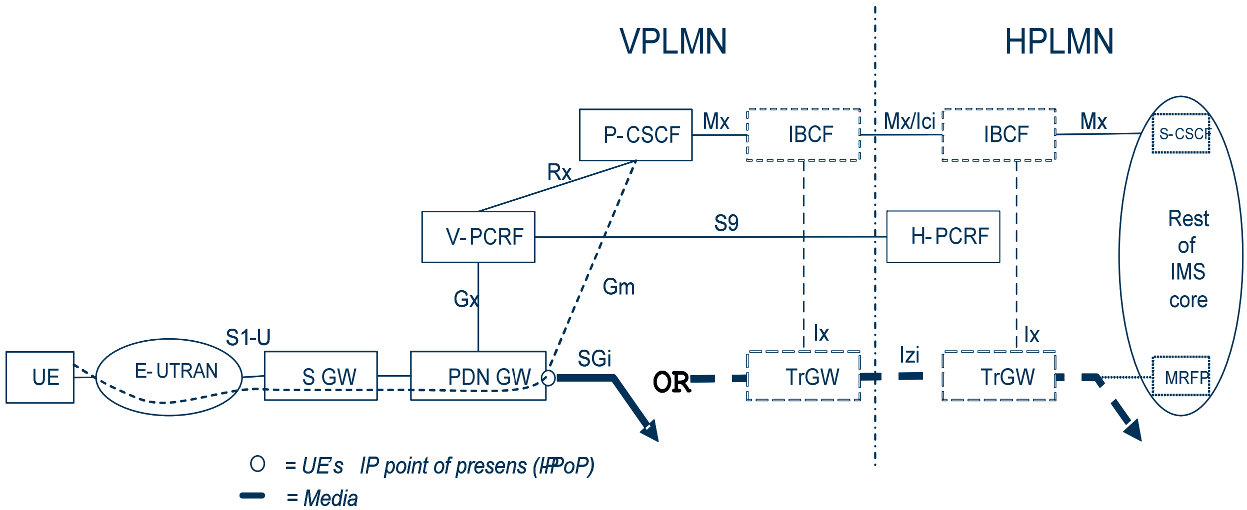


Figure 3.31. VoLTE Roaming Architecture with LBO.

In the LBO model, the enhanced packet core network (EPC) and P-CSCF are located in the visited network for a VoLTE roaming user. The roaming user attaches in a visited network, with the IMS Public Data Network (PDN) anchored on a P-GW in the visited network and registers for IMS services in its home IMS network. The Proxy Call Session Control Function (P-CSCF) then interacts with the S-CSCF and Telephony Application Server (TAS) in the home network for SIP signaling and setting up a VoLTE session.

In the S8HR, VoLTE roaming architecture as shown in Figure 3.32, the P-GW, PCRF and the IMS core network are located in the home network. IMS services are home routed via the S8 interface. The well-known IMS Access Point Name (APN) is used for the home routing, SIP signaling and RTP media transferring with the HPLMN. The HPLMN has full control of call routing and VoLTE service logic for its users in the VPLMN. The VPLMN supports the required capabilities for inbound roamers, such as the 'IMS Voice over PS' (IMSVoPS) supported indication and specific QCIs required for SIP signaling (QCI=5) and voice media (QCI=1). The IMS APN configuration in the user's profile in the HSS must be set to 'VPLMN address not allowed'.

The S8HR roaming architecture is shown in Figure 3.32.

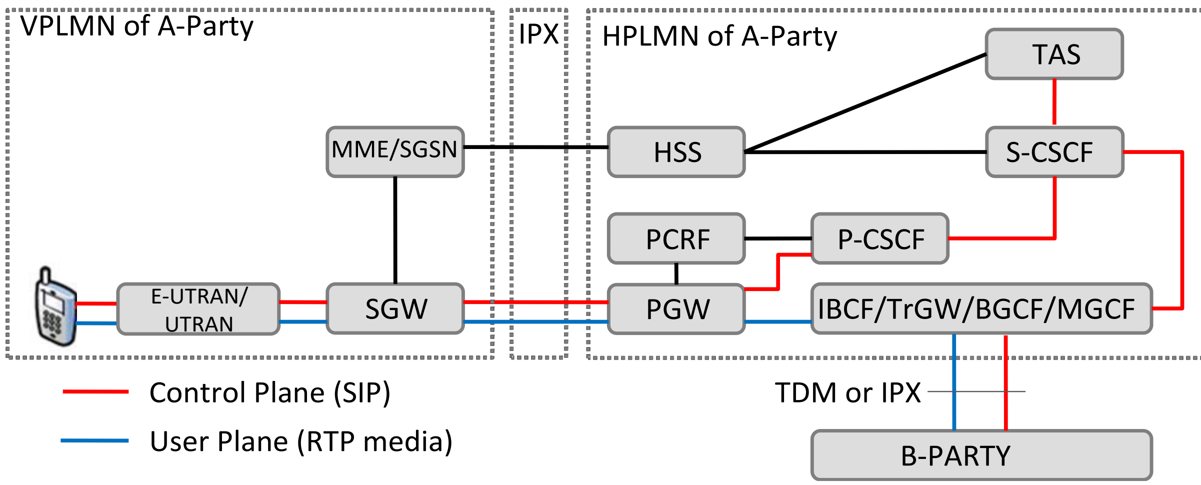


Figure 3.32. S8HR Roaming Architecture.

4. STATUS OF IMT 2020 IN ITU AND 3GPP

ITU's existing family of standards for International Mobile Telecommunication systems (IMT-2000 and IMT-Advanced), serve as a global framework and reference for today's 3G and 4G mobile systems. As an extension/evolution of that, ITU is now setting the IMT stage for the 5th Generation of mobile wireless broadband technologies, known as "IMT-2020".

4.1 SPECIFYING IMT-2020 – THE ITU-R (WP5D) ROLE

Figure 4.1 illustrates the overall ITU-R IMT-2020 roadmap/process.[94]

[94] For additional info/details, see www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx.

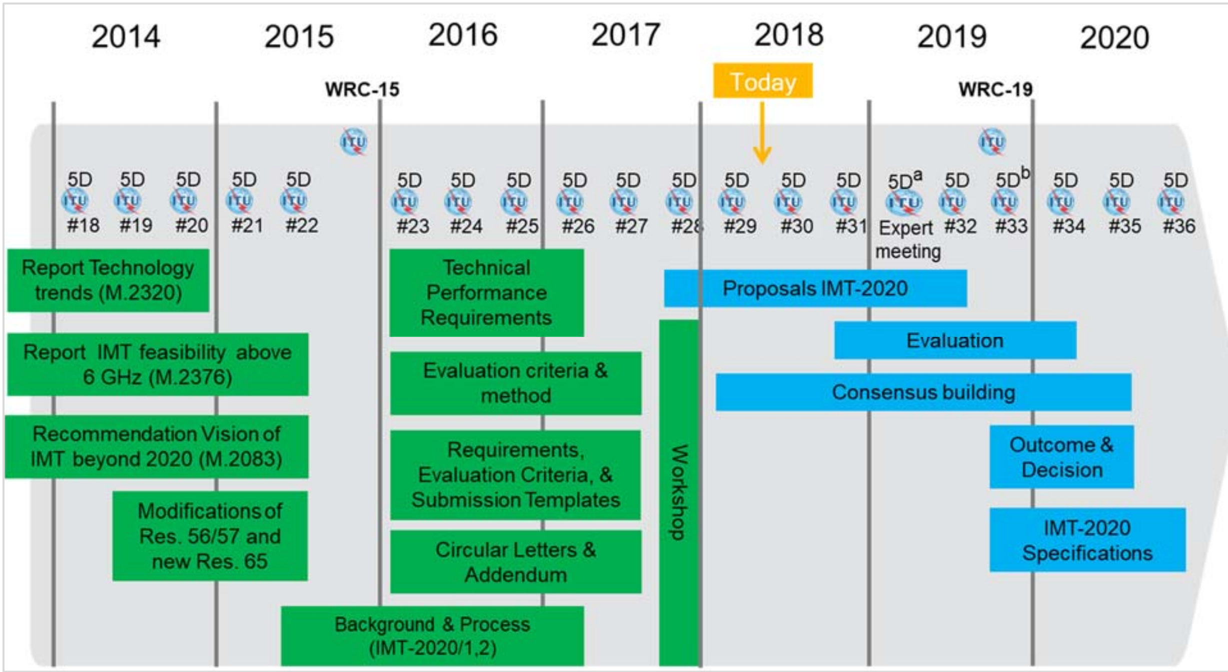


Figure 4.1. The ITU-R IMT-2020 Process/Timeline.

Within ITU-R, Working Party 5D (WP5D) has been working on the finalization of IMT-2020 process, submission criteria, technical performance requirements and evaluation methods for IMT-2020.

As of today, ITU-R WP5D has completed the IMT-2020 Reports on Requirements, Evaluation and Submission[95] and has already received some preliminary proposals for candidate IMT-2020 technologies. Initial submission inputs were provided by 3GPP (see sec. 4.2), and some national administrations (e.g., from Korea and China, based mostly on 3GPP).

Going forward, WP5D will be responsible for the final evaluation, selection/decision and standardization of suitable technologies as part of the IMT-2020 specifications.

For the evaluation phase, aiming at verifying fulfillment of the submission/acceptance criteria by the proposed technology, WP5D will rely on:

- Self-evaluation reports from the proponents
- Evaluation reports from several registered Independent Evaluation Groups (IEGs), for example, expert groups from ATIS, Canada and several others[96]

The following paragraphs provide an overview of the work done/occurring in ITU-R WP5D, including the IMT-2020 targets identified in the ITU-R "5G Vision", and the final recommendations on IMT-2020 requirements and evaluation.

[95] https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/submission-eval.aspx
[96] Ibid.

4.1.1 THE ITU-R “VISION” TOWARD 5G

In 2015, ITU published Recommendation ITU-R M.2083: “IMT Vision – Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond”[97] on the vision of the 5G mobile broadband connected society and future IMT. This Recommendation defines the framework and overall objectives of the future development of International Mobile Telecommunications (IMT) for 2020 and beyond. It includes a broad variety of capabilities associated with envisaged usage scenarios.

The usage scenarios for IMT 2020 and beyond include:

- **Enhanced Mobile Broadband:** The enhanced mobile broadband usage scenario will come with new application areas and requirements, in addition to existing mobile broadband applications, for improved performance and an increasingly seamless user experience

- **Ultra-reliable and low latency communications:** This use case has stringent requirements for capabilities such as throughput, latency and availability. Some examples include wireless control of industrial manufacturing or production processes, remote medical surgery, distribution automation in a smart grid and transportation safety

- **Massive machine-type communications:** This use case is characterized by a very large number of connected devices typically transmitting a relatively low volume of non-delay-sensitive data. Devices are required to be low cost and have a very long battery life, such as five years or longer

Figure 4.2 illustrates some examples of envisioned usage scenarios for IMT for 2020 and beyond.

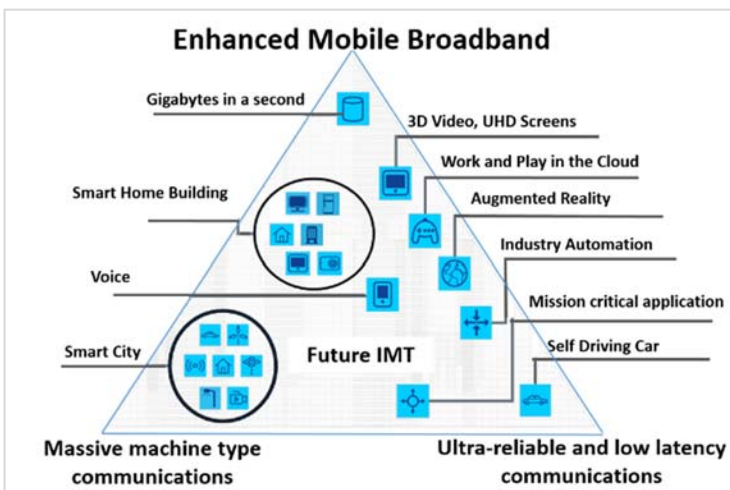


Figure 4.2. IMT-2020 Usage Scenarios.

The main perspectives on IMT-2020 capabilities with a focus on the RAN, are captured in Figure 4.3.

[97] http://www.itu.int/rec/R-REC-M.2083-0-2 01509-I/en

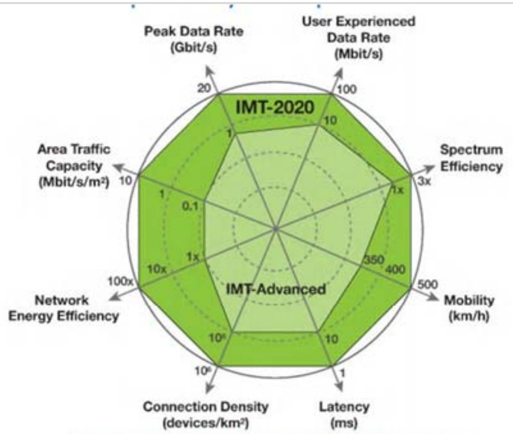


Fig 3. Enhancement of key capabilities from IMT-Advanced to IMT-2020

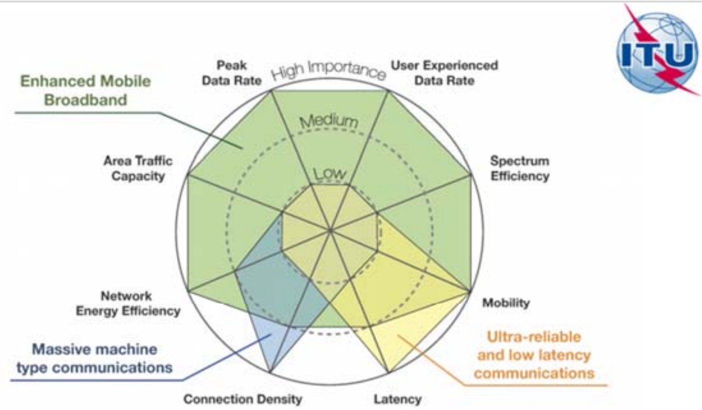


Fig 4. The importance of key capabilities in different usage scenarios

The values in the Figure 3 above are targets for research and investigation for IMT-2020 and may be further developed in other ITU-R Recommendations, and may be revised in the light of future studies. Additional descriptions and further details for both Figures are in the IMT-2020 Vision Recommendation - Recommendation ITU-R M.2083

Figure 4.3. 5G Capability Perspectives from the ITU-R IMT-2020 Vision Recommendation.

4.1.2 IMT-2020 COMPLIANCE, REQUIREMENTS AND EVALUATION

This section includes a summary of IMT-2020 compliance criteria, performance requirements and evaluation framework.

In general, a technology submission to IMT-2020 can consist of an individual Radio Interface Technology (RIT), or a set of RITs (SRIT) - made of multiple “component” RITs. Certain compliance requirements can be less stringent for a component RIT (compared to an individual RIT).

4.1.3 RIT/SRIT COMPLIANCE CRITERIA

Two main compliance criteria can be identified for IMT-2020, related to Spectrum, and Service & Technical performance requirements.

The main spectrum requirements are:

- **Frequency bands identified for IMT**: The proposal should be able to utilize at least one frequency band identified for IMT in the ITU Radio Regulations
- **Higher Frequency range/band(s)**: The proposal should be able to utilize the higher frequency range/band(s) above 24.25 GHz.
    - NOTE: In the case of a SRIT, at least one of the component RITs need to fulfil this requirement.

Regarding compliance to Services and Technical performance, the proposal needs to satisfy the minimum performance requirements defined for the three IMT-2020 Usage Scenarios (eMBB, URLLC, mMTC).

More specifically, the final acceptance criteria can be summarized as: a RIT/SRIT shall fulfill the required Technical Performance Requirements (TPR) targets, across a certain number of Test Environments (5 TEs for a RIT or SRIT, at least 2 TEs for a component RIT).

An overview of the IMT-2020 (TPR) and targets, and TEs / evaluation configurations, is provided in the next two paragraphs.

4.1.4 IMT-2020 TECHNICAL PERFORMANCE REQUIREMENTS AND TARGETS

Starting from the IMT-2020 capabilities identified in the IMT-2020 Vision recommendation, WP5D has defined a set of TPRs (14) and targets, as summarized in the Table 4.1, together with the applicable Usage scenarios / Test Environments, and the recommended evaluation method (inspection, analytical or simulation based).

Table 4.1. IMT-2020 Technical Performance Requirements.

TPR	Target	Usage scenario/TE	Evaluation
Peak spectral efficiency	DL: 30 bps/Hz; UL: 15 bps/Hz	eMBB	Analytical
Peak data rate	DL: 20 Gbps; UL: 10 Gbps	eMBB	Analytical
Cell spectral efficiency (Average)	3x IMT-A	eMBB – TE dependent	Simulation
Cell-edge User spectral efficiency (5%-ile)	3x IMT-A	eMBB – TE dependent	Simulation
Cell-edge User data rate (5%-ile)	DL/ UL: 100 / 50 Mbit/s	eMBB - Dense Urban	Analytical/ Simulation
Area traffic capacity	10 Mbit/s/sqm	eMBB - Indoor-Hotspot	Analytical
Mobility (UE speed)	4 mobility classes, up to 500km/h	eMBB – TE dependent	Simulation
Mobility interruption time	0 ms	eMBB & URLLC	Analytical
Control Plane Latency	20 ms	eMBB & URLLC	Analytical
User Plane Latency	4 ms for eMBB 1 ms for URLLC	eMBB & URLLC	Analytical
Reliability	$(1\text{-}10^{-5})$ / 1 ms	URLLC	Simulation

Connection density	1 Million devices/sqkm	mMTC	Simulation
Bandwidth	At least 100 MHz, up to 1 GHz (above 6 GHz).	Generic	Inspection
NW/UE energy efficiency	Qualitative target	eMBB	Inspection

Details on the TPR definitions and targets can be found in the IMT-2020 TPR report.[98]

4.1.5 TEST ENVIRONMENTS AND EVALUATION CONFIGURATIONS

A Test Environment is a combination of a Usage Scenario and a "geographic environment". There are 5 TEs defined for IMT-2020 evaluation, as illustrated in the following table, and described further below.

Table 4.2. IMT-2020 Test Environments.

Usage Scenario	Geographic environment			
	Indoor Hotspot (InH)	Dense Urban (DU)	Rural (RU)	Urban Macro (UM)
eMBB	**InH-eMBB**	**DU-eMBB**	**Ru-eMBB**	
mMTC				**UM-mMTC**
URLLC				**UM-URLLC**

- Indoor Hotspot-eMBB: An indoor isolated environment at offices and/or in shopping malls based on stationary and pedestrian users with very high user density
- Dense Urban-eMBB: An urban environment with high user density and traffic loads focusing on pedestrian and vehicular users
- Rural-eMBB: A rural environment with larger continuous coverage, supporting pedestrian, vehicular and high-speed vehicular users
- Urban Macro–mMTC: An urban environment with continuous coverage focusing on high number of connected machine type devices
- Urban Macro–URLLC: An urban macro environment targeting ultra-reliable low latency communications

Those TEs are to be used for verifying the TPR targets using system/link level simulations.

For each Test environment, multiple evaluation/simulation configurations are defined (A, B, …). The main differentiating characteristic/option is the carrier frequency; in few cases (e.g. for eMBB-Ru and mMTC) it can be multiple inter-site distance (ISD). Table 4.3 lists the identified TE configurations (highlighting only the carrier freq/ISD options).

[98] Report ITU-R M.2410.

Table 4.3. IMT-2020 Test Environments - Evaluation Configurations.

TE	InH-eMBB			DU-eMBB		Ru-eMBB			UM-URLLC		UM-mMTC	
Config.	A	B	C	A	B	A	B	C	A	B	A	B
Carrier Freq.(*) (ISD)	4GHz	30GHz	70GHz	4GHz	30GHz	700MHz (ISD 1732m)	700MHz (ISD 6km)	4GHz	700MHz	4GHz	700MHz (ISD 500m)	700MHz (ISD 1732m)

(*) Note: Values represent a range, i.e., 700MHz = 450-960 MHz; 4GHz = 3-6 GHz; 30GHz= 24.25-52.6 GHz; 70GHz = 66-86 GHz

General evaluation principle is: either configuration can be used to evaluate/fulfil a certain TE.

Details on the whole set of parameters/assumptions (including channel model options) can be found in the IMT-2020 Evaluation report.[99]

4.1.6 ADDITIONAL INFORMATION ON IMT-2020 AND ITU-R PUBLICATIONS

For further and updated information on the ITU-R's IMT-2020 work program and reports/deliverables, please consult the official ITU-R web pages.[100]

4.2 3GPP PLANS TOWARD IMT-2020

This section provides a short status update of 3GPP plans and activities toward IMT-2020 submission.[101] At the ITU IMT-2020 Workshop held in October 2017, 3GPP has presented the plan for a Rel-15 onward submission. Main characteristics/content are illustrated in Figure 4.4.

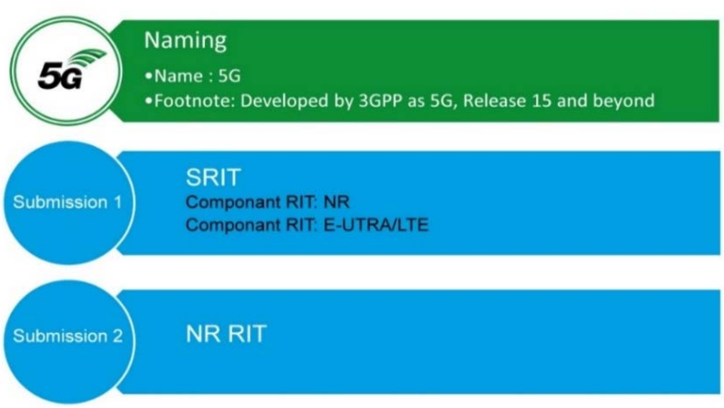


Figure 4.4. Planned 3GPP IMT-2020 submission – Overview.

[99] Report ITU-R M.2412.
[100] Working Party 5D home page at www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/Pages/default.aspx, which has a dedicated section (IMT-2020) providing relevant information on the background and development of IMT-2020 and ITU-R published documents on IMT-2020 at http://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/submission-eval.aspx.
[101] See recent 3GPP news at *http://www.3gpp.org/news-events/3gpp-news/1937-5g_description.*

3GPP is currently working on the initial description of the 3GPP 5G solution - based on the first Rel-15 5G NR (and LTE evolution) specifications approved in December.

A preliminary description template[102] has been sent over to the ITU (at WP5D#29, Feb '18) in accordance with the IMT-2020 submission and evaluation process. This summary is not complete and final but provides a good overview of the contents of 3GPP Rel-15, December version, mainly to allow ITU-R and Independent Evaluation Groups to identifying the key technology components, and to start their ITU-R evaluation process.

This document is the first of three planned submission steps, as depicted in the figure below (agreed 3GPP time plan).

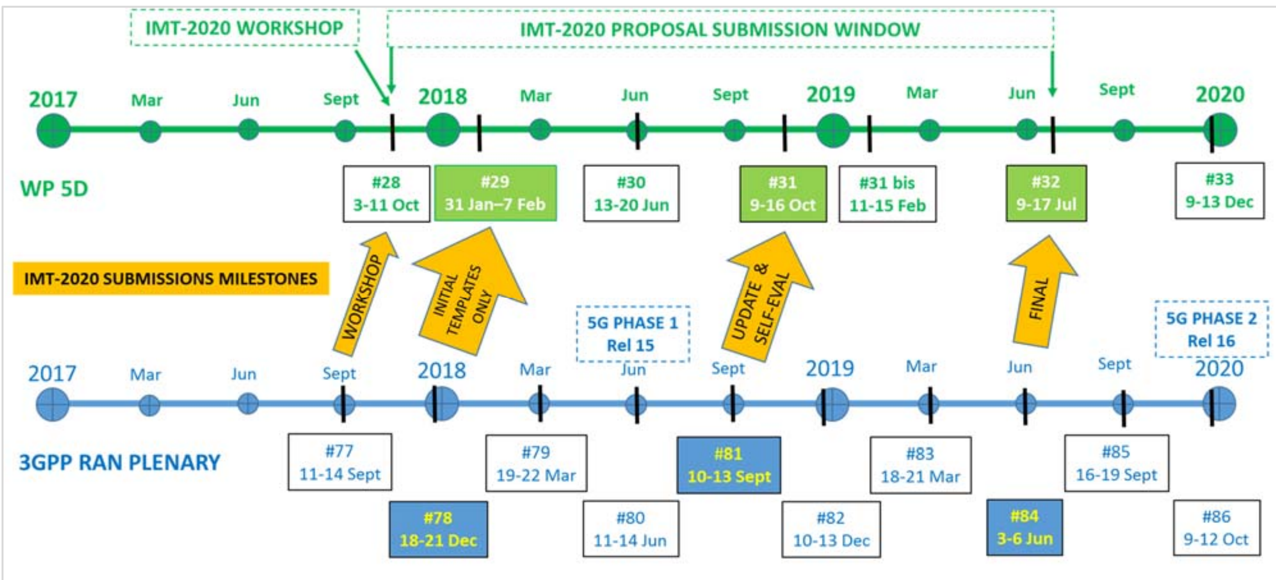


Figure 4.5. Planned 3GPP IMT-2020 submission – Overview.

The final and fully comprehensive 3GPP IMT-2020 submission (encompassing both Rel-15 and 16) is planned for July 2019.

[102] http://www.3gpp.org/ftp/Information/presentations/PCG40_11.zip.

5 PROGRESS OF 3GPP RELEASE 15 AND RELEASE 16

The following sections describe a summary of 3GPP Rel-15 content, together with a snapshot of new Rel-16 studies/work.

Sections 5.1 to 5.3 cover Rel-15 RAN (5G New Radio/RAN and evolved LTE/E-UTRAN) and service/core-network aspects. The Rel-15 summary is based on 3GPP specifications work completed through June 2018. A final section 5.4 provides a list of ongoing/new Rel-16 5G studies and enhancements, as approved by 3GPP through June 2018.

5.1 5G RAN

The radio access network (RAN) has been in use since the beginning of cellular technology and has evolved through the generations of mobile communications (1G, 2G, 3G, 4G, and in anticipation of the forthcoming 5G). Components of the RAN include a base station and antennas that cover a given region depending on their capacity. The Evolved Universal Terrestrial Radio Access Network (E-UTRAN) focuses only on packet-switched services, provides high data rates and low latency and is the basis for LTE networks today. 5G will see the introduction of the appropriately named "new radio" or NR as a key component of the 5G RAN.

5.1.1 OVERVIEW

This section provides an overview of the 5G Radio Access Network and New Radio (NR) interface, studied and standardized by 3GPP. Several aspects are covered in the next paragraphs, starting with the 3GPP RAN roadmap leading to 5G (and its evolution), and the initial 5G RAN studies and requirements; afterwards, an extensive summary is given of the first Rel-15 5G RAN standards (architecture, protocols and main features/procedures), followed by a heads-up on the first 5G RAN evolution studies toward Rel-16.

5.1.1.1 3GPP RAN STANDARDIZATION ROADMAP TOWARD 5G

The main 5G RAN technology/design study started in Rel-14 (from March 2016), after identifying proper requirements and channel model aspects, and lasted around one year (see Table 5.1).

Table 5.1. RAN initial 5G Studies.

RAN Study Item	Start	End	3GPP Release
Study on Channel Model for Frequency Spectrum above 6 GHz	Sep-15	Jun-16	End of Rel-13
Study on Scenarios and Requirements for Next Generation Access Technologies	Dec-15	Dec-16	End of Rel-13

Study on New Radio (NR) Access Technology	Mar-16	Mar-17	Rel-14

Note: further information on the above RAN 5G studies is provided in a later section of this paper.

Following the design study, 3GPP RAN started the “normative” phase of 5G standardization in Rel-15 (from March 2017), planning to complete the first 5G Release (Phase1) in June 2018.

As mentioned earlier, in December 2017, 3GPP completed (“froze”) the first version of Rel-15 5G RAN specifications, defining the so-called NR Non-Standalone (“Option 3”) architecture, using EPC/LTE as anchor.[103]

June 2018 marks the completion of NR Standalone (SA) specifications (NR connected to the new 5G Core). Figure 5.1 shows the overall RAN Rel-15 timeline, and the two initial milestones for 5G.

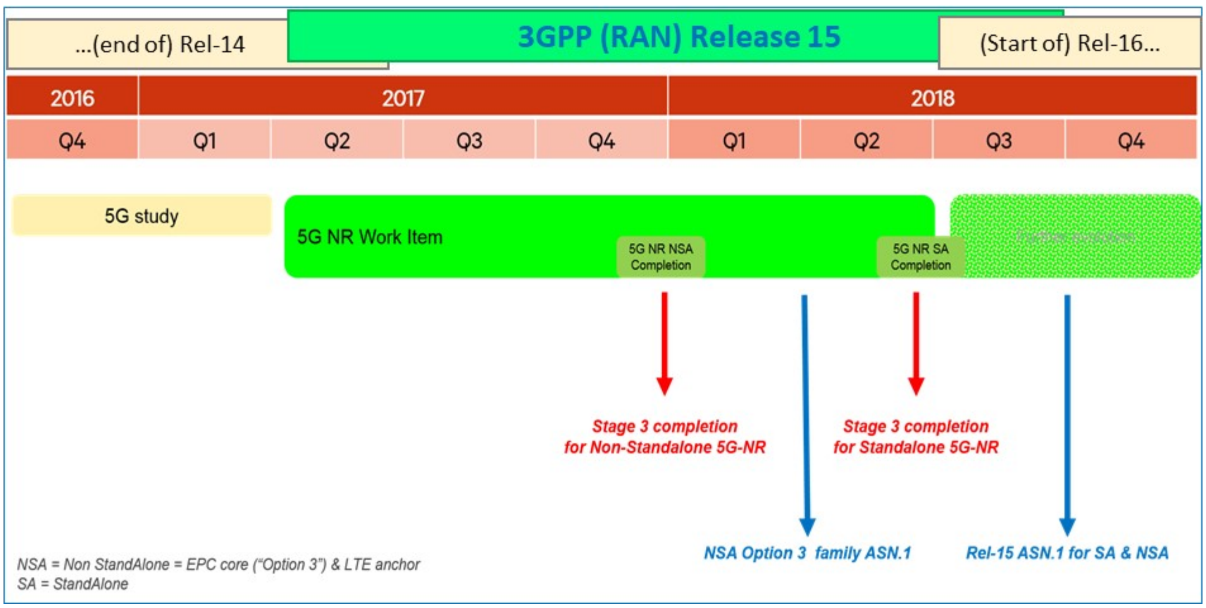


Figure 5.1. The First 5G Release: Rel-15 (2017-2018).

By June 2018, it was agreed to have an additional Rel-15 late “drop” in December 2018, including other 5G-RAN architecture/connectivity options, for example:

- NR connected to the 5G Core network, with Non-standalone LTE (“option 4”)
- eLTE connected to the 5G Core network, with Non-standalone NR (“option 7”)
- NR-NR Dual Connectivity (synchronous operation)

More details on 5G architecture options are provided in following sections.

At that time, 3GPP also defined their initial Rel-16 plans for next 5G evolution phase with a set of studies and normative work laid out till end of 2019.

[103] See also 3GPP news at http://www.3gpp.org/news-events/3gpp-news/1931-industry_pr_5g.

The latest 3GPP RAN timeline/roadmap, for Rel-15 and Rel-16, is illustrated in the Figure 5.2.

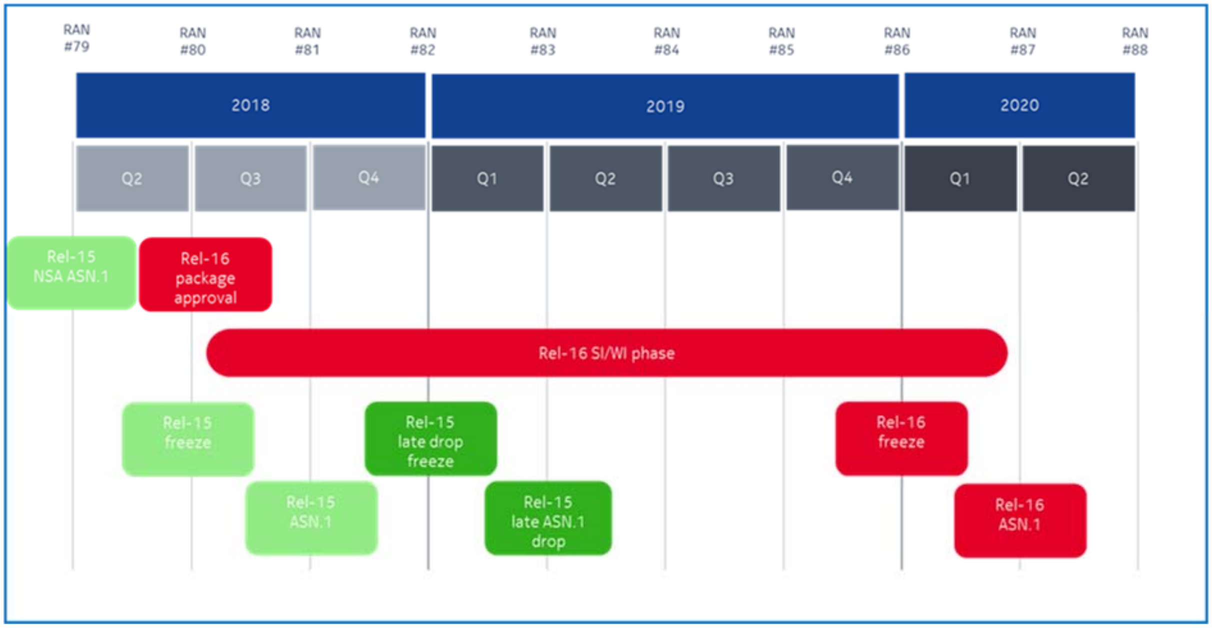


Figure 5.2. The Latest 5G RAN Roadmap for Rel-15-16 (2018-2020).

5.1.1.2 RAN 5G INITIAL STUDIES AND REQUIREMENTS

3GPP RAN completed a few studies on the New Radio (NR) Access Technology in Rel-15, including a study on Channel Modeling, a study on overall RAN Requirements and a study on Radio/RAN technologies and solutions.

The studies aimed at developing an NR access technology and network to meet a broad range of use cases and the identified requirements and targets. The main use cases are those envisioned by IMT-2020, such as enhanced mobile broadband (eMBB), massive MTC (mMTC), and ultra-reliable low latency communications (URLLC).

The following paragraphs list the outcomes and references of the RAN studies on Requirements, Technologies, and 5G channel model.

5.1.1.3 NEW RADIO/RAN REQUIREMENTS

The RAN study item on requirements identified typical deployment scenarios for next generation access technologies and the required performance and main functional capabilities.

The RAN requirements, as captured in TR 38.913, have been defined in terms of:

- A range of Key Performance Indicators (KPIs), and their target requirements
- Several target deployment scenarios, covering eMBB, URLLC, mMTC, and also eV2X
- Other requirements, for example, covering architecture, services and operation

A summary of KPIs, performance targets, and applicable usage scenarios, is provided in Table 5.2.

Table 5.2. NR Radio Requirements – KPIs and Targets.

KPI	Target	Applicability
Bandwidth	No target KPI (defined by ITU)	Generic
Peak data rate	DL: 20 Gbps; UL: 10 Gbps	Mainly for eMBB
Peak spectral efficiency	DL: 30 bps/Hz; UL: 15 bps/Hz	Mainly for eMBB
Cell spectral efficiency	3x IMT-A	Mainly for eMBB- Indoor Hotspot, Dense Urban, Rural, Urban Macro
User spectral efficiency	3x IMT-A	
User experienced data rate	No target KPI	
Area traffic capacity	No target KPI	
Latency (Control Plane)	10ms	Mainly for eMBB and URLLC
Latency (User Plane)	eMBB: 4ms for UL, and 4ms for DL URLLC: 0.5ms for UL, and 0.5ms for DL	Mainly for eMBB and URLLC
	For infrequent small packets: < 10 sec in UL, at MCL = 164dB	Mainly for mMTC
Mobility interruption time	0ms	Mainly for eMBB and URLLC
Reliability	General URRLC: $(1-10^{-5})$/1ms eV2X : $(1-10^{-5})$ /[2-10] ms	For URLLC, and also eV2X
Connection density	1 Million devices/km^2	For mMTC Urban environment
UE battery life	Beyond 10 years, 15 years desirable	For mMTC

Coverage	MCL = 164dB, for a data rate of 160bps	Mainly for mMTC
Extreme Coverage	MCL = 140dB @2Mbps/60kbps DL/UL; 143dB @ 1M/30k	For "basic" MBB service
Mobility (UE Speed)	Up to 500 km/h	For eMBB High speed train
UE/NW energy efficiency	Efficient data delivery and granular DTX/DRX	Mainly for eMBB

The deployment scenarios identified during the study are:

- (eMBB) Indoor Hotspot, Dense urban, Urban Macro, Rural, High speed, Extreme long distance
- (URLLC) Indoor Hotspot, Urban Macro
- (mMTC) Urban coverage for massive connections
- (V2X) Urban Grid for connected car, and Highway
- Others: for example, Air-to-Ground and Satellite

Other Radio/RAN qualitative or functional requirements identified during the study include the following:

- Spectrum related requirements, for example,
    - Spectrum range, for example, support potential use of frequency range up to 100 GHz
    - Channel bandwidth scalability, for example, the ability to operate with different bandwidth allocations (with max aggregated BW up to e.g., 1GHz, at least for evaluation purpose)
    - Duplexing flexibility, for example, the ability to adapt allocation of resources flexibly for uplink and downlink for both paired and unpaired spectrum
    - Support of shared spectrum, therefore, efficient mechanisms to share either licensed or unlicensed spectrum with other IMT/Non-IMT systems
- Requirements for architecture and migration
- Service related requirements, for example, MBMS, Location/Positioning Service, Critical Communications services (Public safety/Emergency, Public warning, V2X)
- Operational requirements, for example, on UL Link Budget, Interworking with legacy RATs, Interworking with non-3GPP systems, Lawful Interception, Backhaul/Relay, and a few others

5.1.1.4 STUDY OF NR TECHONOLOGIES AND SOLUTIONS

Following the outcome of the RAN requirements study, the technology study was started in March 2016 for the Identification and evaluation of technical solutions.

The study has been split into multiple studies (handled by different Working Groups), to cover and focus on the four main RAN specification areas: Physical layer aspects, Radio interface protocols and procedures, Radio Network architecture, interfaces and protocols/procedures, RF and performance requirements. The study outcomes are captured in the following Technical Reports (with the last one being a merge/summary from the other 4 TRs).

Table 5.3. RAN Technology Study - Technical Reports.

Spec No.	Title	Lead WG
TR 38.802	Study on New Radio Access Technology: Physical Layer Aspects	RAN1
TR 38.804	Study on New Radio Access Technology: Radio Interface Protocol Aspects	RAN2
TR 38.801	Study on New Radio Access Technology: Radio Access Architecture and Interface	RAN3
TR 38.803	Study on New Radio Access Technology: RF and co-existence aspects	RAN4
TR 38.912	Study on New Radio Access Technology	RAN

5.1.1.5 CHANNEL MODELING FOR NR

3GPP RAN has performed a study on 5G CM, whose outcome is captured in TR 38.901.

5.1.2 RELEASE-15 5G RAN: ARCHITECTURE, PROTOCOLS AND FEATURES

This section covers RAN architecture options, protocols, main physical layer aspects and radio procedures in Release 15 which specifies NR functionality for enhanced mobile broadband (eMBB) and ultra-reliable low latency communications (URLLC) for frequency bands up 52.6 GHz.

5.1.2.1 5G RAN ARCHITECTURE

Due to the diverse and extreme requirements of the previously mentioned main 5G service types, it is clear that the 5G RAN must be designed to operate in a wide range of spectrum bands with diverse characteristics, such as channel bandwidths and propagation conditions. It must further be able to scale to extremes in terms of throughput, number of devices, connections, and etcetera, which is likely only possible if it can handle the so-called user plane (UP), related to the transmission of actual application payload, and control plane (CP), related to control functionality and signaling, individually. To provide scalability also in the context of various possible deployments and an evolving application landscape, it is essential that the overall 5G network (both RAN and CN) is software-configurable, meaning that, e.g., the logical and physical entities to be traversed by CP and UP packets are configurable. In addition, as often explained, a key aspect is that the 5G RAN should offer the option to integrate Long-Term Evolution Advanced (LTE-A) evolution and novel 5G radio technology on RAN level.

5.1.2.1.2 5G RAN DEPLOYMENT/ARCHITECTURE OPTIONS AND LTE INTERWORKING

5G RAN is designed from the start to interwork fully with existing 4G LTE networks. 3GPP Rel-15 standards allow multiple NR deployment options, with varying RAN-CN interconnection, and NR-LTE interworking architectures (standalone, non-standalone, NR/LTE anchoring):

- 5G RAN connected to LTE Core Network (EPC)
    - Non-Standalone (NSA) – LTE anchor, with non-standalone NR; also referred to as “option 3” (NOTE), or EN-DC (E-UTRA-NR Dual Connectivity)
- 5G RAN connected to 5G Core Network (5GC)
    - Standalone (SA) NR; also referred to as “option 2”
    - Non-Standalone - NR anchor, with non-standalone LTE; also referred to as “option 4”, or NE-DC (NR-E-UTRA Dual Connectivity)
    - Non-Standalone - LTE anchor, with non-standalone NR; also referred to as “option 7”, or NGEN-DC (NG-RAN E-UTRA-NR Dual Connectivity).
    - Standalone LTE, also referred to as “option 5”, or NG-RAN E-UTRA.

NOTE: the “option x” terminology comes from the initial 5G architecture study; other options were studied, but eventually not standardized.

The Rel-15 5G RAN architecture options are briefly described in the following writing. With regard to their completion timelines (core functionality “frozen”) and corresponding Rel-15 specification versions, “option 3” was completed in December 2017; at 3GPP TSG #80 Plenary Meeting in June 2018, the completion of the standalone (SA) Release 15, 5G specifications was approved. Other options are planned to be finalized later (December 2018).

Deployment architecture “Option 3”:

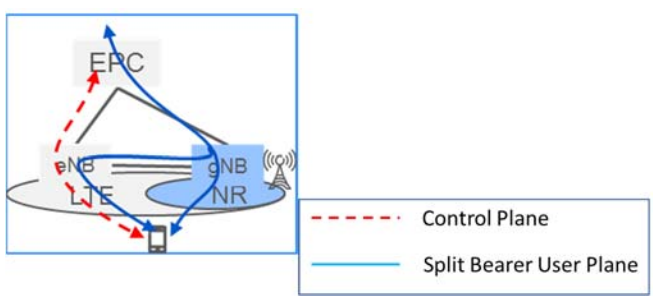


Figure 5.3. Control Plane and User Plane Connectivity for Option 3.

As mentioned previously, the first 5G standard Release 15, finalized at the end of 2017 includes non-standalone Option 3 architecture. This allows 5G being deployed initially in Non-Standalone (NSA) configuration, as an extension of LTE, supported by dual connectivity between LTE and NR. LTE access is used for the Control Plane.

There are three flavors of Option 3 (3/3A/3X): LTE eNB or NR gNB decides if User Plane traffic is routed to EPC via NR gNB (Option 3A) and/ or LTE eNB (Option 3). In Option 3x, the U-plane is split in the gNB.

In Option 3/3a/3x, Dual Connectivity (DC) between LTE and NR is reused as baseline, therefore, for the X2/Xn interface between LTE eNB and gNB, the procedures and protocols would remain similar to those of LTE-based Dual Connectivity (DC) with some enhancements on top.

Deployment architecture "Option 2":

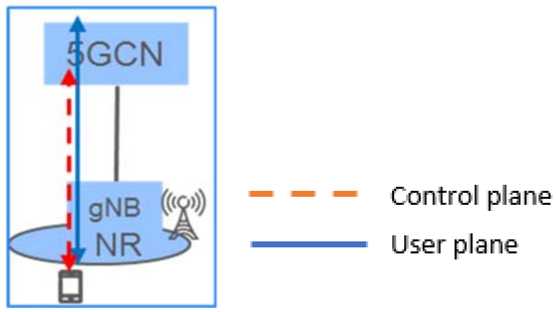


Figure 5.4. Control Plane and User Plane Connectivity for Option 2.

3GPP RAN specifications for NR Standalone (SA) architecture and operation was approved in 3GPP TSG #80 Plenary Meeting in June 2018. This creates an 'independent' 5G network, with gNB directly connected to 5GC for user plane and control plane.

This architecture offers the greatest potential for future evolution, with full 5GC and 5G RAN/NR functionalities and capabilities.

Deployment architecture "Option 7":

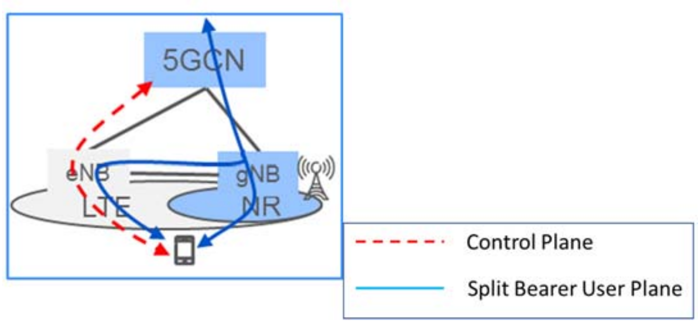


Figure 5.5. Control Plane and User Plane Connectivity for Option 7.

In Option 7, the eLTE eNB as well as gNB is connected to the 5GC using Dual Connectivity and LTE access is used for Control Plane. There are two flavors of Option 7 (7/7a): the NR user plane connection to the 5GC goes via the eLTE eNB (Option 7) or directly (Option 7a).

Deployment architecture “Option 4”:

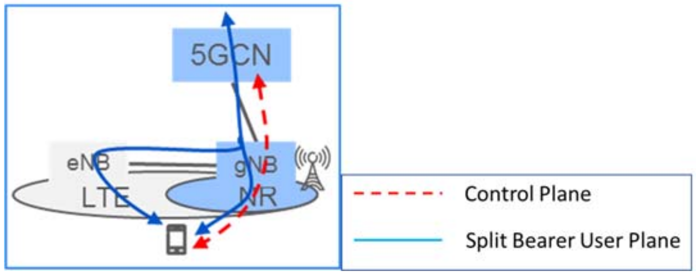


Figure 5.6. Control plane and User Plane Connectivity for Option 4.

In Option 4, the eLTE eNB as well as gNB is connected to the 5GC, using Dual Connectivity, and NR access is used for Control Plane. The LTE user plane connection to the 5GC goes via the gNB (Option 4) or directly (Option 4a).

Deployment architecture “Option 5”:

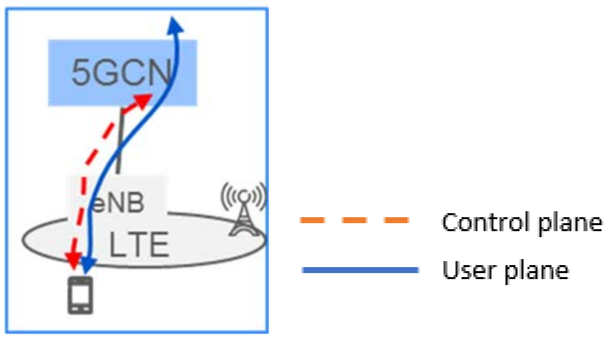


Figure 5.7. Control Plane and User Plane Connectivity for Option 5.

This option pertains to LTE deployment with 5GC. As shown in **Error! Reference source not found.**7, LTE user plane and control plane are both integrated with 5GC.

Summary of deployment/architecture options

A summary of deployment/architecture options is provided in Table 5.4.

Table 5.4. Summary of Deployment/Architecture Options.

5G EPC			5G Next Gen Core			
"LTE Assisted" NR with EPC Core			Stand-alone NR with 5G Core	"NR Assisted" LTE with 5G Core	Stand-alone LTE with 5G Core	"LTE Assisted" NR with 5G Core
Option 3	Option 3a	Option 3x	Option 2	Option 4	Option 5	Option 7
NR User Plane (UP) via LTE eNB, to EPC	NR UP directly to EPC	LTE UP via NR gNb, to EPC	User & Control Plane via NR only	CP anchored in NR gNB; LTE UP via gNB or directly (4/4a), to 5GC	User & Control Plane via LTE only	CP anchored in LTE eNB, NR UP via LTE eNB or directly (7/7a), to 5GC
NAS Control Plane: EPC-NAS via LTE			NAS Control Plane: 5G-NAS			

5.1.2.1.3 5G RAN SPLIT ARCHITECTURE

The flexibility of 5G from various use case perspectives makes it important to consider change in the RAN architecture compared to today's deployment, for example, the capability to place selected functions closer to the network edge, or the ability to increase RAN resilience for ultra-reliable use cases. Cost is naturally a key factor, as spectrum availability and site infrastructure continue to dominate expenditure for wide-area systems.

The evolution of RAN architecture includes measures and capabilities for flexible RAN deployment (centralized/distributed), enhanced spectrum efficiency and other improvements in the areas of optimized hardware performance and energy efficiency. Some examples are:

- Functional split: Separation of User Plane and Control Plane in RAN would optimize handling of 5G services, like ultra-low latency and ultra-high bandwidth
- Deployment flexibility: Allow Service Provider to deploy and configure the RAN (e.g. centralized/distributed units) maximizing spectrum efficiency and service performance, with large flexibility versus site topology, transport network characteristics, and spectrum scenario
- Seamless Radio Resource Management: Best combination of any radio beam/s should be used for connectivity across all network technologies, access points and sites

As per 38.801, following functional splits between central and distributed unit are possible as depicted in Figure 5.8.

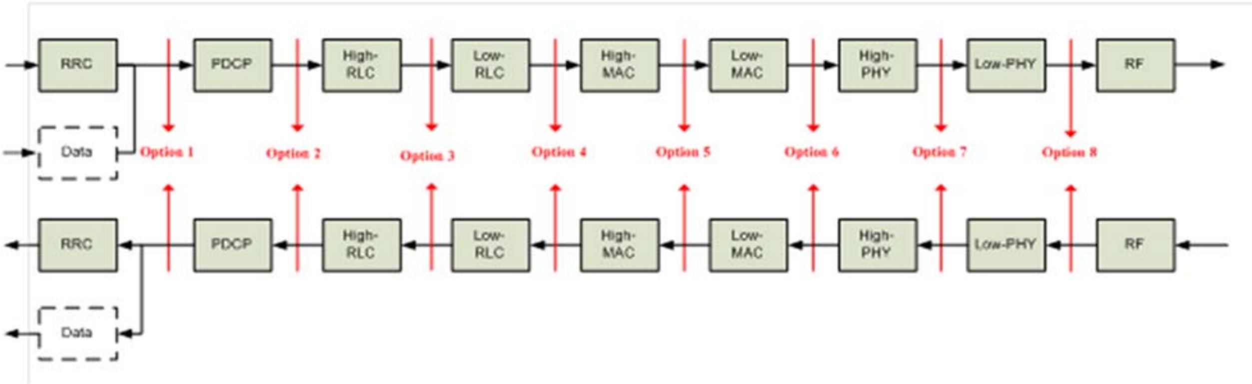


Figure 5.8. Function Split Options between Central and Distributed Unit.

An illustration of the 5G-RAN architecture and interfaces is shown in Figure 5.9, including UP/CP and centralized/distributed split.

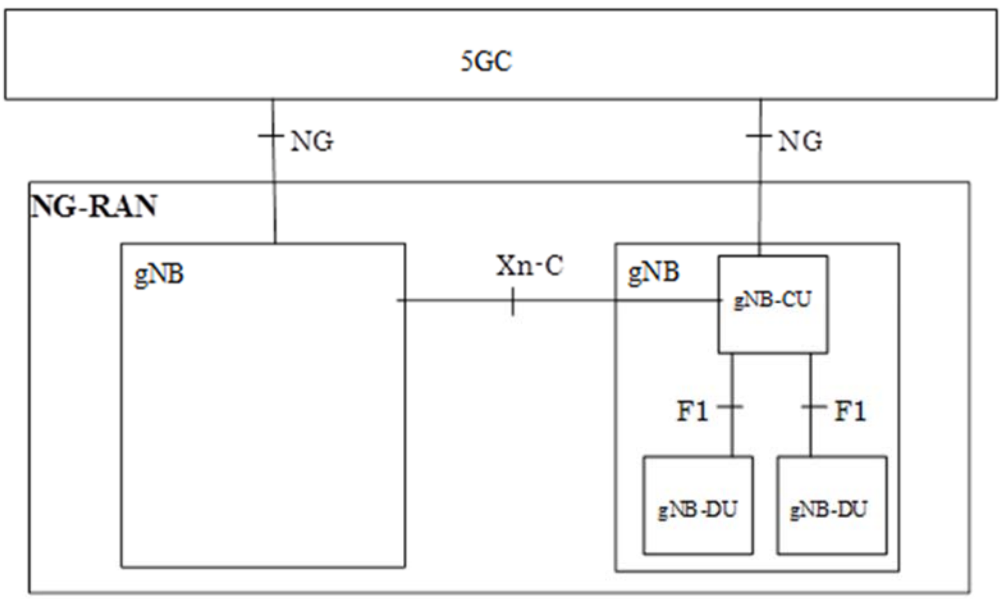


Figure 5.9. NG-RAN Architecture Overview.

It includes the following logical RAN nodes and functions:

Central Unit – User Plane (CU-U)

This is the Packet Processing Function (PPF) which contains user-plane functions that are asynchronous to the Hybrid Automatic Repeat Request (HARQ) loop and includes the Packet Data Convergence Protocol (PDCP) layer such as encryption and the multipath handling function for the dual connectivity anchor point and data scheduling.

CU-U interfaces towards the core network via NG3 interface with the User Plane Function (UPF) of NextGen Core.

Central Unit – Control Plane (CU-C)

This is the Radio Control Function (RCF) which handles load sharing among system areas and different radio technologies, as well as the use of policies to control the schedulers in the BPFs and PPFs. At the user and bearer level, the CU-C negotiates QoS and other policies with other domains and is responsible for the associated SLA enforcement in the RAN. The CU-C controls the overall RAN performance relative to the service requirement, creates and manages analytics data, and is responsible for the RAN SON functions.

CU-C interfaces towards the core network via NG2 interface with the Access and Mobility Management Function (AMF) of NextGen Core.

Distributed Unit (DU)

This logical node includes a subset of the gNB functions, depending on the functional split option. Its operation is controlled by the CU. Distributed Unit (DU) is also known by other names like Base Band Unit/Remote Radio Head/Remote Radio Unit/ Radio Unit (BBU/ RRH/ RRU/RE/RU).

Interfaces in evolved RAN architecture:

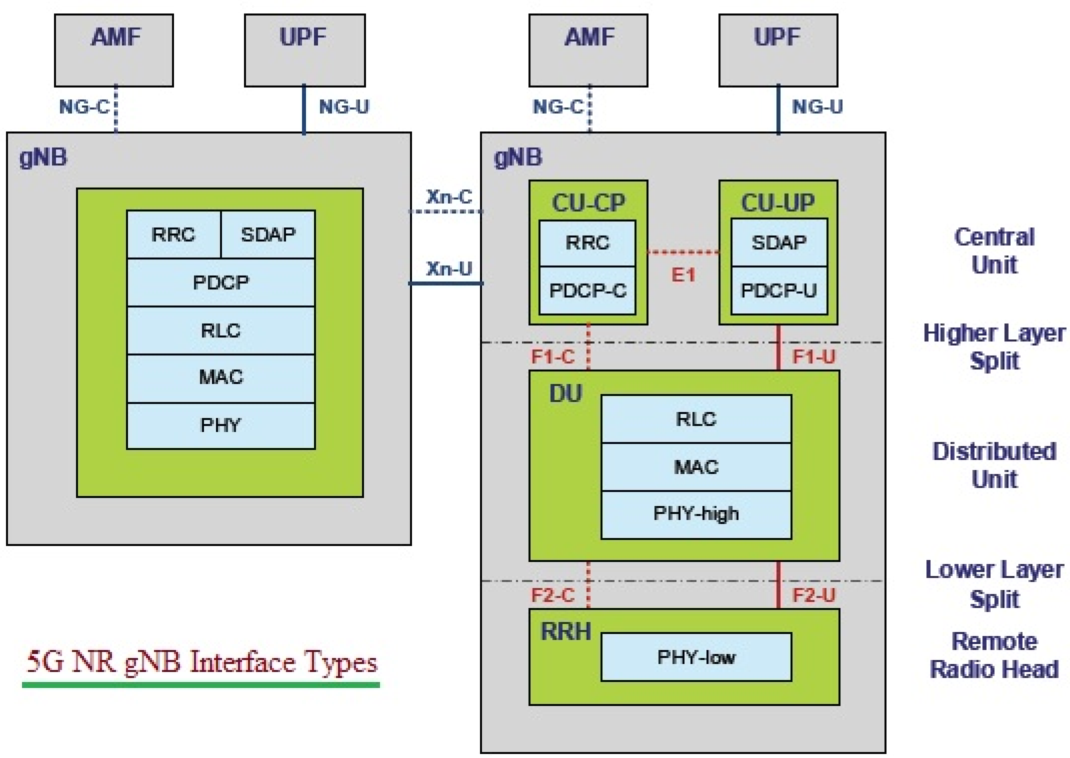


Figure 5.10. 5G NR gNB Interface Types.

F1 Interface: A gNB may consist of a gNB-CU and one or more gNB-DU(s). A gNB-CU and a gNB-DU is connected via F1 interface. One gNB-DU is connected to only one gNB-CU. A general principle of the F1 interface is as follows: it is an open interface that supports the exchange of signaling information between the endpoints, in addition the interface supports data transmission to the respective endpoints. The interface supports Control Plane (F1-C) and User Plane (F1-U) separation. The interface also enables exchange of UE associated information and non-UE associated information.

E1 Interface: E1 is a point-to-point interface between a gNB-CU-CP and a gNB-CU-UP. This is an open interface that supports exchange of signaling information between the end points. It is a control interface and is not used for user data forwarding.

Xn interface: It supports the exchange of signaling information between two NG-RAN nodes and the forwarding of PDUs to the respective tunnel endpoints. From a logical standpoint, the Xn is a point-to-point interface between two NG-RAN nodes. The Xn interface supports procedures over the control plane (Xn-C) and user plane (Xn-U). The Xn interface enables procedures for intra-NG-RAN mobility and dual connectivity between NG-RAN nodes.

Virtualization of RAN functions

Control functions that are asynchronous to the radio interface tend to be suitable for virtualization and NFV deployments, as they are transaction-based and do not involve heavy packet processing. Functions such as multipath handling, PDCP and S1-U termination involve packet processing which can be challenging to virtualize. However, if the underlying hardware contains ciphering offload and packet processing accelerators, virtualization is possible without performance degradation. The PPF and RCF functions are therefore suitable for virtualization.

Most RAN processing cycles occur in the HARQ synchronous functions. Tasks like uplink radio decoding and scheduling are, for example, highly processing intense. And so, the more processing that can be carried out in the uplink decoding, the better the uplink sensitivity, and the more processing that can be allocated to the scheduler, the better the spectral efficiency. Special-purpose multi-core hardware is best suited to this type of processing, as its price-performance ratio is presently multiple times that of single-core hardware. And so, HARQ synchronous functions are likely to continue to run on Special Purpose Processor (SPP) hardware for a long time. To avoid flow control issues between the MAC and the RLC and given the level of interaction between the scheduler and RLC, the MAC, RLC, and the fast RRM should run on the same hardware instance. Due to such stringent requirements on Beamforming Processing Function (BPF), it benefits from being placed on an SPP.

5.1.2.1.4 5G QOS

In-order to support a multitude of services with different QoS requirement, it is important that the RAN has mechanisms to handle relevant QoS attributes.

In 5G, the QoS framework differs from the current EPS bearer-based framework in that a flow can be assigned a QoS profile, rather than a whole bearer as in EPC. The “flow marking” is carried in the encapsulation header down to the RAN. Multiple QoS flows may belong to a PDU session, and the whole PDU session is carried in one GTP-U tunnel between the core network and the RAN. The RAN is responsible for mapping the QoS flows to DRBs. QoS flows from the same PDU session may be multiplexed onto the same DRB.

The main attribute in NR will be the 5QI (corresponding to QCI in LTE), using operator configured 5QIs or standard defined 5QIs. There is also the option to send the QoS profile including all QoS characteristics dynamically set from the Core Network to the RAN, therefore, without a 5QI, or modifying some QoS characteristics of a 5QI for the specific flow.

The scheduler needs to support co-scheduling of multiple users with different TTI length and different numerology. The users from different services and potentially in different scenarios might have different QoS focus, characteristics and delay requirements which are boiled down to different TTI length, scheduling schemes and numerologies. Such services, for example cMTC, typically has tight delay requirements, and high reliability and robustness requirements; mMTC typically has longer Transmission Time Interval even with multiple subframe repetitions transmissions to enhance coverage, varied packet size and insensitivity to delay.

The 5G QoS profile will be used to control QoS forwarding treatment for the QoS flows which will provide possibilities to configure, for example, scheduling weights, admission thresholds, mobility thresholds, queue management thresholds, link layer protocol configuration, and etcetera. The RAN-based QoS is controlled by the CU-C, which receives the QoS class and attributes from the CN and signals relevant attributes to selected functions; the CU-U for higher level scheduling, for example, between DUs, and the DU for air interface scheduler impacts. QoS attributes as UE Aggregated MBR also require additional coordination between multiple nodes (when UE bearers are spread over multiple PPFs). Both QoS specification requirements as well as the RAN QoS realization in NR are re-designed on 5G framework.

The gNB may support both 5G QoS as well as 4G QoS. Which QoS identifier will be used, clearly depends on the 5G deployment mode (NSA or SA) and to which type of Core (5G capable EPC or 5G Core) the master node (eNB or gNB) will be connected. For UE's connected using NR NSA mode with a master eNB connected to EPC, the 4G QoS with QCIs will be used in the gNB for those UEs.

Some of the key components in the new QoS framework are:

- Network controlled QoS
- Per flow UP marking for QoS differentiation, one tunnel per PDU session
- Separation of concern between CN and AN
- No 1:1 relation between QoS flow and DRB
- RAN decides mapping of QoS flows to DRBs
- Per flow U-plane marking in NG3 tunnel encapsulation header
- Marking done in CN and UE
- Per flow authorized QoS distributed to RAN and optionally UE
- Minimized signaling
- Reflective QoS for UL traffic
- Standardized (in addition for dynamic) values for QoS flow marking

The 5G QoS parameters that are part of the QoS profile are:

- 5G QoS Identifier (5QI)
- Allocation and Retention Priority (ARP)
- Reflective QoS Attribute (only for non-GBR QoS flows)
- Maximum flow bitrate (MFBR) for GBR QoS flows
- Guaranteed flow bitrate (GFBR) for GBR QoS flows
- Notification control (only for GBR QoS flows)
- Maximum Packet Loss Rate (only for GBR QoS flows)

The 5G QoS characteristics are

- Resource Type

- Priority Level
- Packet Delay Budget
- Packet Error Rate
- Averaging window
- Maximum Data Burst Volume (for 5QIs with 5G Access Network PDB <=20ms)

Table 5.5 shows the mapping of 5QI attribute to specific priority level, delay budget and example of service.

Table 5.5. Standardized 5QI to QoS Characteristics Mapping.[104]

5QI Value	Resource Type	Default Priority Level	Packet Delay Budget	Packet Error Rate	Default Maximum Data Burst Volume (NOTE 2)	Default Averaging Window	Example Services
10	Delay Critical GBR	11	5 ms	10^{-5}	160 B	TBD	Remote control (see TS 22.261 [2])
11 **NOTE 4**		12	10 ms NOTE 5	10^{-5}	320 B	TBD	Intelligent transport systems
12		13	20 ms	10^{-5}	640 B	TBD	
16 **NOTE 4**		18	10 ms	10^{-4}	255 B	TBD	Discrete Automation
17 **NOTE 4**		19	10 ms	10^{-4}	1358 B NOTE 3	TBD	Discrete Automation
1	GBR	20	100 ms	10^{-2}	N/A	TBD	Conversational Voice

[104] 3GPP TS 23.501 v15.1.0.

2	NOTE 1	40	150 ms	10^{-3}	N/A	TBD	Conversational Video (Live Streaming)
3		30	50 ms	10^{-3}	N/A	TBD	Real Time Gaming, V2X messages Electricity distribution – medium voltage, Process automation - monitoring
4		50	300 ms	10^{-6}	N/A	TBD	Non-Conversational Video (Buffered Streaming)
65		7	75 ms	10^{-2}	N/A	TBD	Mission Critical user plane Push To Talk voice (e.g., MCPTT)
66		20	100 ms	10^{-2}	N/A	TBD	Non-Mission-Critical user plane Push To Talk voice
75		25	50 ms	10^{-2}	N/A	TBD	V2X messages
E **NOTE 4**		18	10 ms	10^{-4}	255 B	TBD	Discrete Automation
F **NOTE 4**		**19**	**10 ms**	$\mathbf{10^{-4}}$	**1358 B** **NOTE 3**	**TBD**	Discrete Automation

5	Non-GBR NOTE 1	10	100 ms	10^{-6}	N/A	N/A	**IMS Signaling**
6		60	300 ms	10^{-6}	N/A	N/A	Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		70	100 ms	10^{-3}	N/A	N/A	Voice, Video (Live Streaming) Interactive Gaming
8		80	300 ms	10^{-6}	N/A	N/A	Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file
9		90			N/A	N/A	sharing, progressive video, etc.)
69		5	60 ms	10^{-6}	N/A	N/A	Mission Critical delay sensitive signalling (e.g., MC-PTT signalling)
70		55	200 ms	10^{-6}	N/A	N/A	Mission Critical Data (e.g. example services are the same as QCI 6/8/9)
79		65	50 ms	10^{-2}	N/A	N/A	V2X messages
80		66	10 ms	10^{-6}	N/A	N/A	Low Latency eMBB applications Augmented Reality

NOTE 1: a packet which is delayed more than PDB is not counted as lost, thus not included in the PER.

NOTE 2: it is required that default Maximum Data Burst Volume is supported by a PLMN supporting the related 5QIs.

NOTE 3: This Maximum Burst Size value is intended to avoid IP fragmentation on an IPv6 based, IPSec protected, GTP tunnel to the 5G-AN node.

NOTE 4: A delay of 1 ms for the delay between a UPF terminating N6 and a 5G-AN should be subtracted from a given PDB to derive the packet delay budget that applies to the radio interface.

NOTE 5: The jitter for this service is assumed to be 20 msec as per TS 22.261.

5.1.2.1.5 SECURITY

The 5G RAN provides secure communication between the UEs and the RAN and for the network domain between the RAN entities. The security design of 5G RAN follows similar principles as those used in the LTE RAN but has been enhanced to meet the requirements imposed by the 5G system.

Signaling traffic between the UE and RAN is ciphered and integrity protected. In addition, user plane traffic is ciphered and can optionally be integrity protected. Integrity protection of the user plane is a new functionality which can be useful for IoT use cases. The strong security algorithms as in LTE are reused. The ciphering and integrity algorithms are based on SNOW 3G, a stream cipher for UMTS confidentiality, Advanced Encryption Standard AES) and ZUC, a stream cipher for LTE.

To protect subscribers' privacy a new mechanism has been defined in 5G where the subscriber's long-term identifier (typically International Mobile Subscriber Identity) can be concealed (i.e., ciphered) also in roaming cases. The mechanism is based on home operator's public key. This feature, when enabled, is a strong mitigation against active attacks, especially against International Mobile Subscriber Identity (IMSI) catchers. Using the measurement reports from the UEs, the 5G RAN also has a mechanism to detect false base stations which are typically used as IMSI catchers.

The new RRC Inactive state allows UEs to save energy but still quickly resume connectivity with the base station without needing to start the connection from idle state. This is enabled by storing the UE's context, including security context, in the base station.

RAN infrastructure includes Xn interfaces between base stations, the backhaul interfaces N2 and N3 between RAN and core network, and, due to the split of the base station, also the new interface F1 between the Central Unit (CU) and Distributed Units (DU). It is important to secure all the RAN interfaces in untrusted domains in distributed, centralized, and virtualized RAN architectures for both macro and small cells in NSA or SA deployments. All the RAN interfaces will have ciphering, integrity protection and replay protection for user plane and control plane traffic.

The split of the base station to CU and DUs enables flexible deployment of security functions of the 5G RAN, such as user plane ciphering, in a secure central location while keeping non-security sensitive functions in less secure distributed locations.

Because the security functions are placed in the CU, the split also enables that the 5G RAN can reuse the same security configuration and keys during handovers.

5.1.2.2 5G RAN PROTOCOLS

This section describes the main protocols stacks and functionalities, over the radio and across the RAN network interfaces.

5.1.2.2.1 RADIO PROTOCOLS

Radio Interface Protocol stack

The "over-the-air" NR protocol stack is shown in Figure 5.11 and Figure 5.12.

For the User plane, it includes the following protocols (terminated in UE and gNB): Service Data Application Protocol (SDAP), Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC), Media Access Control (MAC), and PHYsical layer (PHY).

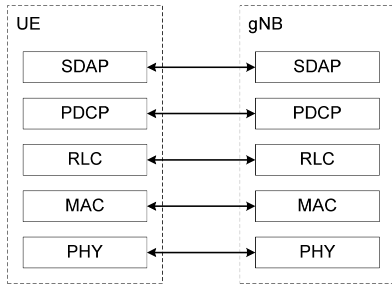


Figure 5.11. Radio Interface - User Plane Protocol Stack.

On the Control plane, the following protocols are defined:

- RRC, PDCP, RLC, MAC and PHY sublayers (terminated in UE and gNB)
- Network Access Server (NAS) protocol (terminated in UE and AMF)

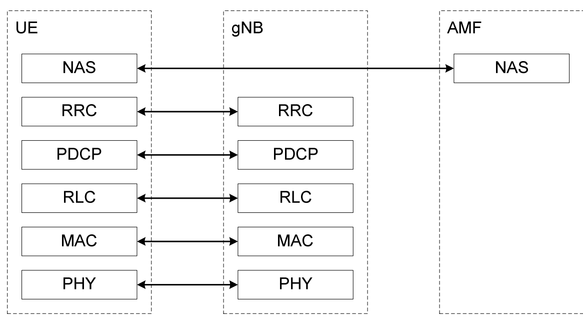


Figure 5.12. Radio Interface - Control Plane Protocol Stack.

Radio Interface Protocols Functions

The physical layer performs several functions, for example:

- Error detection/indication
- FEC encoding/decoding
- Hybrid ARQ soft-combining
- Rate matching
- Modulation and demodulation of physical channels
- Frequency and time synchronization
- Radio measurements
- RF processing

The main services and functions of the MAC sublayer include:

- Multiplexing/demultiplexing of MAC Service Data Units (SDUs) into/from Transport Blocks (TB)
- Scheduling information reporting

- Error correction through HARQ (one HARQ entity per carrier in case of CA)
- Priority handling between UEs (dynamic scheduling), or logical channels (of one UE)
- Padding

The main services and functions of the RLC sublayer depend on the transmission mode, either Transparent Mode (TM), Unacknowledged Mode (UM), or Acknowledged Mode (AM) and include:

- Sequence numbering (UM and AM)
- Segmentation (AM and UM) of RLC SDUs
- Reassembly of SDU (AM and UM)
- RLC SDU discard (AM and UM)
- Duplicate Detection (AM only)
- Error Correction through ARQ (AM only)

The main services and functions of the PDCP sublayer include, for the user plane:

- Sequence Numbering
- Header compression and decompression Robust Header Compression (ROHC)
- Reordering, duplication, retransmission
- PDCP PDU routing (in case of split bearers)
- Ciphering, deciphering and integrity protection
- PDCP SDU discard
- PDCP re-establishment and data recovery for RLC AM
- Duplication of PDCP PDUs

Some apply to the control plane as well, for example, Sequence Numbering; Ciphering, deciphering and integrity protection; Duplication handling.

The main services and functions of SDAP (new L2 sublayer in NR) include:

- Mapping between a QoS flow and a data radio bearer
- Marking QoS flow ID (QFI) in both DL and UL packet

The main services and functions of the RRC sublayer include:

- Broadcast of System Information
- Paging
- RRC connection handling
- Security functions (including key management)
- Management of Signaling Radio Bearers (SRBs) and Data Radio Bearers (DRBs)
- Mobility functions
- QoS management functions
- UE measurement config/reporting
- Detection of and recovery from radio link failure
- NAS message transfer to/from NAS from/to UE

Radio Connection Modes/States

RRC supports three main radio connection modes/states: IDLE, INACTIVE (new state introduced in NR), and CONNECTED. Main characteristics and differences are listed in Table 5.6.

Table 5.6. Three main RRC Radio Connection Modes/States.

RRC_IDLE	RRC_INACTIVE	RRC_CONNECTED
• PLMN selection; • Broadcast of system information; • Cell re-selection mobility; • Paging is initiated by 5GC; • DRX for CN paging configured by NAS.	• Broadcast of system information; • Cell re-selection mobility; • RAN based Paging (RAN notification area - RNA); • 5GC - NG-RAN connection (both C/U-planes) is established for UE; • UE AS context is stored in NG-RAN and the UE.	• Transfer of unicast data to/from the UE; • Network controlled mobility; • 5GC - NG-RAN connection (both C/U-planes) is established for UE; • UE AS context is stored in NG-RAN and the UE; • NG-RAN knows the UE at cell level.

A UE is either in RRC_CONNECTED state or in RRC_INACTIVE state when an RRC connection has been established. Otherwise (no RRC connection is established) the UE is in RRC_IDLE state.

Figure 5.13 illustrates an overview of UE RRC state machine and state transitions in NR. Some aspects, therefore, transition from Inactive, are still FFS (for further study).

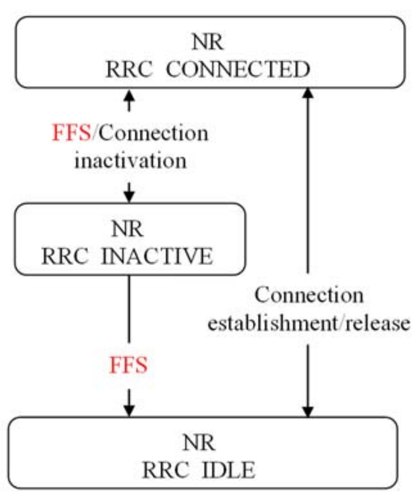


Figure 5.13. UE State Machine and State Transitions in NR.

Other Radio Protocols aspects - Dual Connectivity (DC)

NR supports Dual Connectivity (DC) operation, whereby a UE in RRC_CONNECTED is configured to utilize radio resources provided by two distinct schedulers, located in two gNBs connected via a non-ideal backhaul.

gNBs involved in DC for a certain UE may assume two different roles: a gNB may either act as an MgNB or as an SgNB. In DC, a UE is connected to one MgNB and one SgNB.

In DC, the radio protocol architecture depends on how the radio bearer is setup. Four bearer types exist: Master Cell Group (MCG) bearer, MCG split bearer, Secondary Cell Group (SCG) bearer and SCG split bearer. Those four bearer types are depicted in the Fig 5.14 (showing user plane protocols).

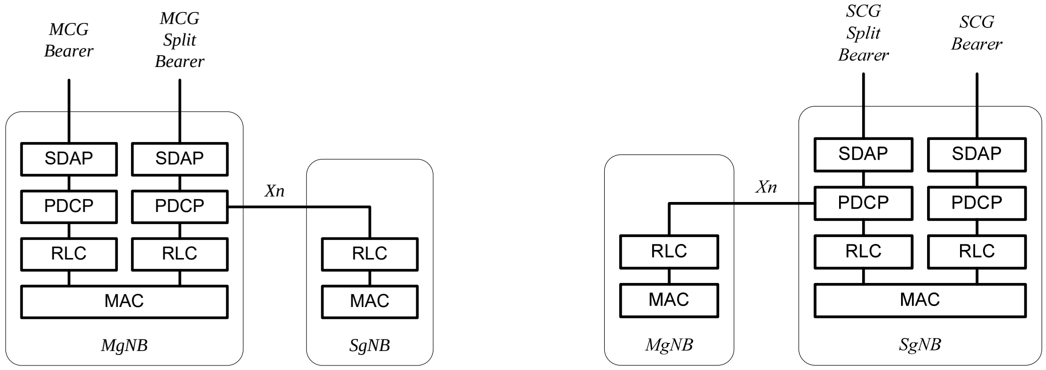


Figure 5.14. MgNB (left) and SgNB (right) Bearers for Dual Connectivity.

The above protocol stacks also apply to Multi-RAT Dual Connectivity (MR-DC), therefore, DC between NR and E-UTRAN (EN-DC, NE-DC, or NGEN-DC).

5.1.2.2.2 RAN NETWORK PROTOCOLS

This section provides a short overview of the protocols, and functions, defined over the RAN network interfaces, therefore NG (between gNB and Access Management Function (AMF) / User Plan Function (UPF), and Xn (between gNBs).

NG Interface

Protocol stack is shown in Figure 5.15 for both the user and control plane.

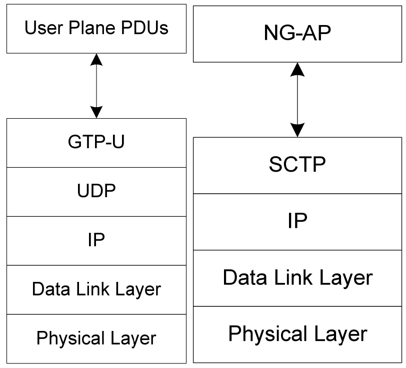


Figure 5.15. NG-U (left) and NG-C (right) Protocol Stacks.

Next Generation – Unit (NG-U) provides non-guaranteed delivery of user plane PDUs between the NG-RAN node and the UPF.

NG-Core (NG-C) between NG-RAN and AMF provides the following main functions:

- NG interface management
- UE context management
- UE mobility management
- Transport of NAS messages
- Paging
- PDU Session Management

Xn Interface

Protocol stack is shown in Figure 5.16.

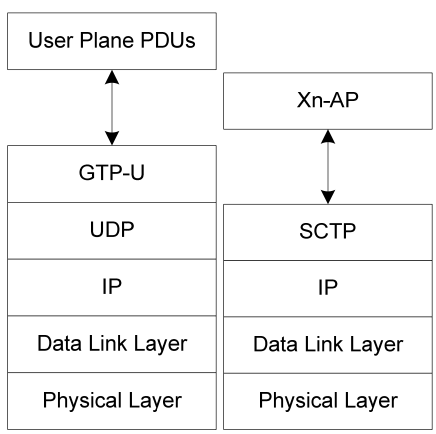


Figure 5.16. Xn-U (left) and Xn-C (right) Protocol Stacks.

Xn-U provides non-guaranteed delivery of user plane PDUs and supports the following functions:

- Data forwarding
- Flow control

Xn-C supports the following functions:

- Xn interface management
- UE mobility management, including context transfer and RAN paging
- Dual connectivity

5.1.2.2.3 RADIO CHANNELS AND BEARERS

Figure 5.17 shows the different channels/bearers defined across the NR radio interface (access stratum) layers:

- The physical layer provides to the MAC sublayer transport channels
- The MAC sublayer provides to the RLC sublayer logical channels
- The RLC sublayer provides to the PDCP sublayer RLC channels
- The PDCP sublayer provides to the SDAP (and RRC) sublayer radio bearers
- The SDAP sublayer provides to 5GC QoS flows

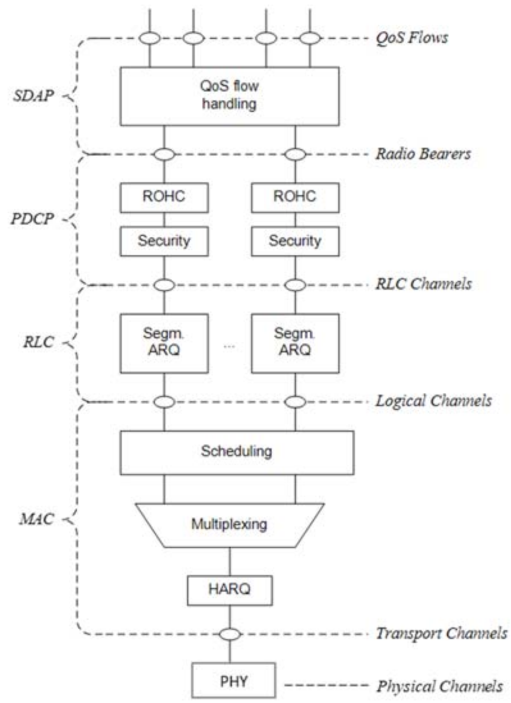


Figure 5.17. Channels/Bearers Architecture.

The **physical channels** defined in the downlink are:

- Physical Downlink Shared Channel (PDSCH)
- Physical Downlink Control Channel (PDCCH)
- Physical Broadcast Channel (PBCH)

The physical channels defined in the uplink are:

- Physical Random-Access Channel (PRACH)
- Physical Uplink Shared Channel (PUSCH)
- Physical Uplink Control Channel (PUCCH).

In addition to the physical channels above, three types of PHY layer “signals” are defined, which can be reference signals, primary and secondary synchronization signals.

The following **transport channels**, and their mapping to PHY channels, are defined:

Uplink:

- Uplink Shared Channel (UL-SCH), mapped to PUSCH
- Random Access Channel (RACH), mapped to PRACH

Downlink:

- Downlink Shared Channel (DL-SCH), mapped to PDSCH
- Broadcast channel (BCH), mapped to PBCH
- Paging channel (PCH), mapped to PDSCH

More details on PHY and transport channels are described in section 5.1.2.3.4

Logical channels are classified into two groups: Control Channels and Traffic Channels.

Control channels are:

- Broadcast Control Channel (BCCH), a downlink channel for broadcasting system control information
- Paging Control Channel (PCCH), a downlink channel that transfers paging information and system information change notifications
- Common Control Channel (CCCH), channel for transmitting control information between UEs and network
- Dedicated Control Channel (DCCH), a point-to-point bi-directional channel that transmits dedicated control information between a UE and the network

Traffic channels are: Dedicated Traffic Channel (DTCH), which can exist in both UL and DL.

The following connections between logical and transport channels are defined:

In Downlink:

- BCCH can be mapped to BCH, or DL-SCH
- PCCH can be mapped to PCH
- CCCH, DCCH, DTCH can be mapped to DL-SCH

In Uplink, CCCH, DCCH, DTCH can be mapped to UL-SCH.

Two main types of **Radio bearers** are defined:

- Data radio bearers (DRB) for user plane data, mapped to traffic channels

- Signaling radio bearers (SRB) for control plane data, mapped to control channels

5.1.2.2.4 MOBILITY AND OTHER RRM ASPECTS

This section provides a high-level overview of some Mobility and RRM functions and procedures, therefore, cell (re)selection, Handover, and Paging and Measurements, focusing mainly on intra-NR aspects (based on what is specified as of June 2018).

Cell selection/reselection

Cell selection is based on the following principles:

- The UE NAS layer identifies a selected PLMN and equivalent PLMNs
- The UE searches the NR frequency bands and for each carrier frequency identifies the strongest cell. It reads cell system information broadcast to identify its PLMN(s)
- The UE may search each carrier in turn ("initial cell selection") or make use of stored information to shorten the search ("stored information cell selection")
- The UE seeks to identify a suitable cell (or an acceptable cell), then it “camps” on that cell and commences the cell reselection procedure

A UE in RRC IDLE or INACTIVE state, performs cell reselection. The main principles of the procedure are the following:

- Cell reselection identifies the cell that the UE should camp on. It is based on cell reselection criteria which involves measurements of the serving and neighbor cells
- Intra-frequency reselection is based on ranking of cells
- Inter-frequency reselection is based on absolute priorities where a UE tries to camp on the highest priority frequency available
- An Neighbor Cells List (NCL) can be provided by the serving cell to handle specific cases for intra- and inter-frequency neighboring cells
- Black lists can be provided to prevent the UE from reselecting to specific intra- and inter-frequency neighboring cells
- Cell reselection can be speed dependent

Handover

Network controlled mobility, or handover, applies to UEs in RRC_CONNECTED and is categorized into two types of mobility: cell level mobility and beam level mobility.

Cell Level Mobility requires explicit RRC signaling to be triggered, therefore, handover. For inter-gNB handover, the signaling procedures at high level are illustrated in Figure 5.18.

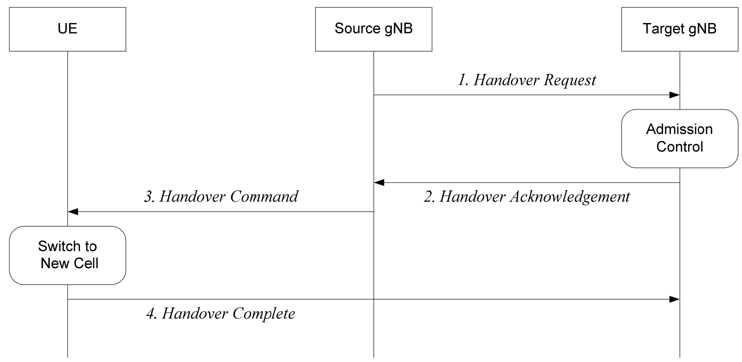


Figure 5.18. Inter-gNB Handover Procedure.

1. The source gNB initiates handover and issues a Handover Request over the Xn interface.
2. The target gNB performs admission control and provides the RRC configuration as part of the Handover Acknowledgement.
3. The source gNB provides the RRC configuration to the UE in the Handover Command.
4. The UE moves the RRC connection to the target gNB and replies the Handover Complete.
5. Beam Level Mobility does not require explicit RRC signaling to be triggered - it is managed by lower layers.

Paging

While in RRC_IDLE the UE monitors 5GC-initiated paging. In RRC_INACTIVE and Connected states, the UE is reachable via RAN-initiated paging and 5GC-initiated paging.

The UE in RRC_IDLE and RRC_INACTIVE states may use DRX in order to save battery. During DRX operation, the UE is required to monitor one paging occasion per DRX cycle for the reception of paging as follows:

- Paging DRX cycle length is configurable
    - A default DRX cycle for CN paging is configurable via system information;
      a UE specific DRX cycle for CN paging is configurable via UE dedicated signaling
    - NG-RAN can configure a UE with a DRX cycle for RAN paging (can be UE specific)
- The number of paging occasions in a DRX cycle is configurable via system information
    - A network may distribute UEs to the paging occasions based on UE id when multiple paging occasions are configured in the DRX cycle
- Paging occasion can consist of multiple time slots (e.g. subframe or OFDM symbol). The number of time slots in a paging occasion is configurable via system information
- A network may transmit a paging using a different set of DL Tx beam(s) or repetitions in each time slot

If the UE is in RRC_CONNECTED state, it will receive paging messages over dedicated channels (details are TBD).

Measurements

Measurements to be performed by a UE are classified in at least three measurement types:

- Intra-frequency measurements
- Inter-frequency measurements
- Inter-RAT measurements

The network may configure an RRC_CONNECTED UE to perform measurements and report them in accordance with the measurement configuration. Several Measurement reporting configurations can be defined (based on reporting criteria).

Three reporting criteria are used: event triggered reporting, periodic reporting and event triggered periodic reporting. Examples of triggering “events” are:

- Event A1: Serving becomes better than absolute threshold
- Event A2: Serving becomes worse than absolute threshold
- Event A3: Neighbor becomes amount of offset better than PCell/PSCell
- Event A4: Neighbor becomes better than absolute threshold
- Event A5: PCell/PSCell becomes worse than absolute threshold1, and neighbor becomes better than another absolute threshold2
- Event A6: Neighbor becomes amount of offset better than SCell

The measurement procedures distinguish the following types of cells:

- The NR serving cell(s) - these are the SpCell and one or more SCells
- Listed cells - these are cells listed within the measurement object(s)
- Detected cells - these are cells that are not listed within the measurement object(s) but are detected by the UE on the carrier frequency(ies) indicated by the measurement object(s)

For NR, beam measurements are also defined. In RRC_CONNECTED, the UE can measure multiple beams (at least one) of a cell and the measurements results (power values) are averaged to derive the cell quality. In doing so, the UE is configured to consider a subset of the detected beams: The *N* best beams above an absolute threshold.

Measurement reports are characterized by the following:

- Measurement reports include the measurement identity of the associated measurement configuration that triggered the reporting

- Cell and beam measurement quantities to be included in measurement reports are configured by the network; examples of measurement quantity are: Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ) and Signal-to-Interference Ration (SINR)

- Beam measurements to be included in measurement reports are configured by the network (beam identifier only, measurement result and beam identifier, or no beam reporting)

5.1.2.2.5 RADIO SECURITY ASPECTS

The following principles apply to NR connected to 5GC security:[105]

- For user data (Data Radio Bearers or DRBs), ciphering and integrity protection
- For RRC signaling (SRBs), ciphering and integrity protection

Ciphering and integrity protections are optionally configured except for RRC signaling for which integrity protection is always configured.

Integrity protection can be configured per DRB.

- For key management and data handling, any entity processing clear text shall be protected from physical attacks and located in a secure environment
- After connection establishment, enabling or disabling integrity protection on a DRB requires a handover

Table 5.7 describes the radio security termination points.

Table 5.7. Radio Security Termination Points.

	Ciphering	Integrity Protection
NAS Signaling	AMF	AMF
RRC Signaling	gNB	gNB
User Plane Data	gNB	gNB

5.1.2.3 RAN PHYSICAL LAYER

The 5G physical layer aspects and procedures described in this section apply to Release 15. 3GPP undertook a study of the enabling technologies for the next generation radio access networks to meet the ITU vision of IMT-2020. At the physical layer, several enabling technologies have been introduced, such as scalable numerology, dynamic frame structure, support of mmW and larger BWs, enhanced MIMO and beam management schemes, improved channel coding algorithms, and many more. In this section, we look at these technologies in more detail.

[105] 3GPP TS 33.501.

5.1.2.3.1 WAVEFORMS, MULTIPLEX ACCESS AND MODULATION

The waveform used by the NR physical layer is based on orthogonal frequency division multiplexing (OFDM) with a cyclic prefix (CP). Channels and signals transmitted are allocated orthogonal subcarriers, a cyclic prefix is added to each symbol to simplify the receive processing and reduce inter-symbol interference. Figure 5.19, shows an example of a CP-OFDM waveform.

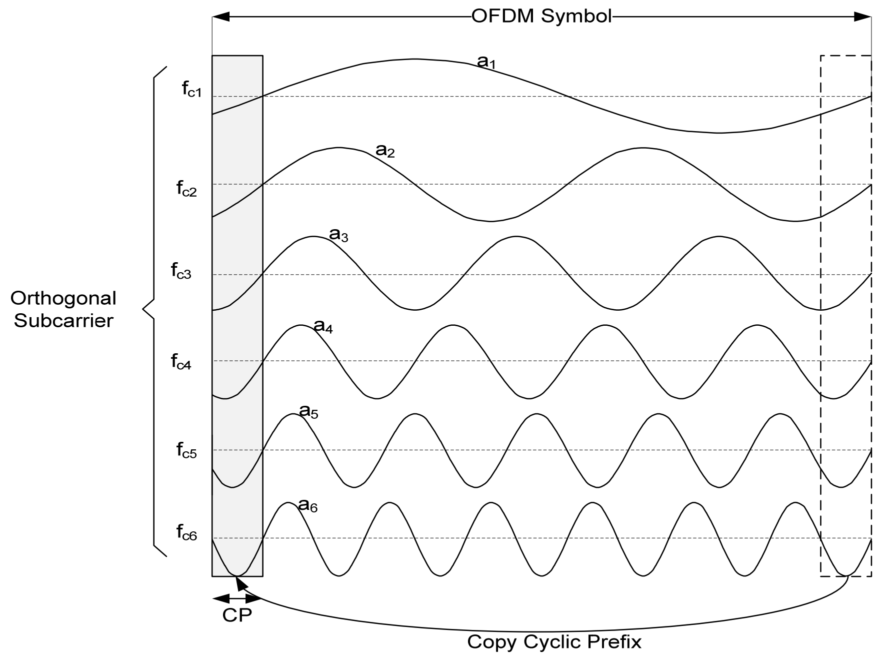


Figure 5.19. CP-OFDM Waveform.

In addition to CP-OFDM, DFT-S-OFDM (Discrete Fourier Transform Spread Orthogonal Frequency Division Multiplexing) based waveform is supported in the uplink for single layer (stream) transmission. DFT-S-OFDM has a single carrier property which is characterized by its lower peak-to-average power ratio (PAPR) when compared to CP-OFDM. **Error! Reference source not found.** shows the DFT transform precoding within the baseband transmit processing chain. DFT-S-OFDM is only supported for single layer transmission in the uplink, while CP OFDM is supported for single layer and multi-layer transmission.

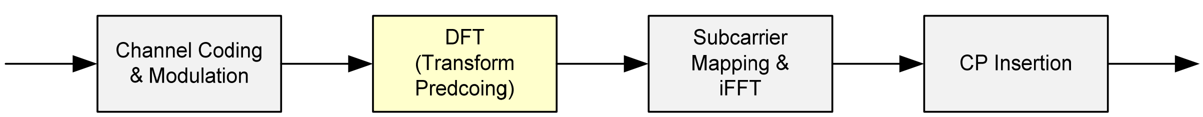


Figure 5.20. Block diagram showing DFT Transform Precoding.

Dynamically scheduled or semi-statically configured, synchronous orthogonal multiple access is supported for downlink and uplink transmissions.

The numerology of a carrier refers to the subcarrier spacing configuration and cyclic prefix length. In NR, multiple subcarrier spacing configurations, in powers of 2 relative to 15 KHz, therefore $2^{\mu} \times 15\text{KHz}$ are supported. The supported subcarrier spacing configurations are {15, 30, 60, 120, 240} KHz. 240 KHz is only used for the Synchronization Signals and the Broadcast channel as described in section 5.1.2.3.5.

By having different subcarrier spacings, NR can support a wider range of carrier frequencies, with lower subcarrier spacings, therefore 15 KHz used for low carrier frequencies (e.g., sub 2 GHz), and higher subcarrier spacings for example, 60 or 120 KHz used for mmWaves (e.g., 28 GHz or 37 GHz).

The maximum FFT size in NR is 4096, compared to a maximum FFT size of 2048 in LTE. Furthermore, NR has a higher spectral utilization than LTE (increased from 90 percent to above 95 percent), and a higher relative subcarrier occupancy for the same FFT size. For example, in LTE for an FFT size of 2048, the maximum subcarrier occupancy is 1200 (i.e., 58.6 percent). In NR, for an FFT size of 4096, the maximum number of subcarriers is 3300 (275 RBs x 12 subcarriers per RB) (i.e., 80.6 percent). As a result, for a subcarrier spacing of 15 KHz, NR supports a larger transmission bandwidth and channel bandwidth. A comparison between LTE and NR at 15 KHz subcarrier spacing is shown in Table 5.8.

Table 5.8. Comparison between LTE and NR at 15 KHz Subcarrier Spacing.

	LTE (20 MHz BW)	NR (20 MHz BW)	NR (50 MHz BW)
Channel BW	20 MHz	20 MHz	50 MHz
FFT Size	2048	2048	4096
Occupied PRBs	100	106	270
Spectrum Utilization	90%	95.4%	97.2%

In Release 15 NR, the operating bands are divided in two frequency ranges; Frequency Range 1 (FR1) and Frequency Range 2 (FR2). The definition of the frequency ranges is shown in Table 5.9.[106]The physical layer and higher layers designs are frequency agnostic, but separate radio performance requirements are specified for each frequency range. Furthermore, different testing methodologies are used in FR1 and FR2. In FR1, both conducted and over-the-air (OTA) testing methodologies are utilized, while in FR2 only OTA methodology is utilized.

Table 5.9. Definition of Frequency Ranges in release 15 NR.

Frequency Range Designation	Corresponding Frequency Range
FR1	450 MHz – 6000 MHz
FR2	24.25 GHz – 52.6 GHz

[106] TS 38.101-1.

In FR1, the supported subcarrier spacings are {15, 30, 60} KHz. The supported transmission bandwidths and maximum transmission bandwidth configuration N_{RB} for each bandwidth and subcarrier spacing is as shown in Table 5.10.[107]

Table 5.10. Maximum Transmission Bandwidth Configuration NRB in FR1.

SCS (KHz)	5 MHz (N_{RB})	10 MHz (N_{RB})	15 MHz (N_{RB})	20 MHz (N_{RB})	25 MHz (N_{RB})	40 MHz (N_{RB})	50 MHz (N_{RB})	60 MHz (N_{RB})	80 MHz (N_{RB})	100 MHz (N_{RB})
15	25	52	79	106	133	216	270	N/A	N/A	N/A
30	11	24	38	51	65	106	133	162	217	273
60	N/A	11	18	24	31	51	65	79	107	135

In FR2, the supported subcarrier spacings are {60, 120} KHz. The supported transmission bandwidths and maximum transmission bandwidth configuration N_{RB} for each bandwidth and subcarrier spacing is as shown in Table 5.11.[108]

Table 5.11. Maximum Transmission Bandwidth Configuration NRB in FR2.

SCS (KHz)	50 MHz (N_{RB})	100 MHz (N_{RB})	200 MHz (N_{RB})	400 MHz (N_{RB})
60	66	132	264	N/A
120	32	66	132	264

NR supports the following modulation schemes for downlink and uplink transmissions: QPSK, 16QAM, 64QAM and 256QAM; with the same constellation mapping as in LTE. Furthermore, π/2-BPSK is supported in the uplink with DFT-S-OFDM. π/2-BPSK is characterized by its lower PAPR when compared to other modulation schemes.

5.1.2.3.2 CARRIER AGGREGATION

To achieve wider bandwidth, beyond the bandwidth values of a single carrier given in Table 5.10 and Table 5.11, NR supports carrier aggregation (CA) with up to 16 NR carriers. NR supports intra-band CA and inter-band CA, with self-carrier scheduling and cross-carrier scheduling.

[107] TS 38.101-1.
[108] TS 38.101-2.

5.1.2.3.3 BANDWIDTH PARTS (BWP)

Bandwidth Part (BWP) is a new concept introduced in NR. A BWP is a set of contiguous PRBs with a given numerology and a given cyclic prefix. The UE can be configured with up to four BWPs per NR carrier, but only one BWP part can be active at a time. The motivation for introducing the BWP concept is:

- Support of UEs with bandwidth capabilities smaller than that of a wideband NR carrier
- Bandwidth adaptation for UE power saving. For example, a BWP with a smaller bandwidth is active if there is no data and is dynamically switched to a BWP with a wider bandwidth when data transmission occurs
- RRC parameter configuration change. For example, different BWPs can be configured with different numerologies/configurations, the network activates a BWP for a UE depending on the desired numerology/configuration

During initial access, the initial DL BWP and initial UL BWP are used. The location and size of the initial DL and UL BWPs is given by parameters in the MIB (sent in the broadcast channel) and SIB1.

5.1.2.3.4 DUPLEXING AND FORWARD COMPATIBILITY

NR supports paired and unpaired spectrum and strives to maximize commonality between the technical solutions of both. Frequency Division Duplex (FDD) is supported on paired spectrum. In FDD, downlink transmissions and uplink transmissions occupy different parts of the spectrum. Time Division Duplex (TDD) is supported. In TDD, downlink and uplink transmissions occupy the same spectrum, but are transmitted at different times. NR supports two flavors of TDD, TDD operation where the transmission direction of time resources is not dynamically changed, and TDD operation where the transmission direction of most time resources can be dynamically changing.

To ensure forward compatibility of future services and features, NR supports the explicit signaling to UEs of reserved resources in the downlink and uplink directions.

5.1.2.3.5 TIME DOMAIN AND FREQUENCY DOMAIN STRUCTURE

In electronics, control systems engineering, and statistics, the frequency domain refers to the analysis of mathematical functions or signals with respect to frequency, rather than time. Put simply, a time-domain graph shows how a signal changes over time, whereas a frequency-domain graph shows how much of the signal lies within each given frequency band over a range of frequencies. A frequency-domain representation can also include information on the phase shift that must be applied to each sinusoid in order to be able to recombine the frequency components to recover the original time signal.

A given function or signal can be converted between the time and frequency domains with a pair of mathematical operators called transforms. An example is the Fourier transform, which converts a time function into a sum or integral of sine waves of different frequencies, each of which represents a frequency component. The 'spectrum' of frequency components is the frequency-domain representation of the signal. The inverse Fourier transform converts the frequency-domain function back to the time function. A spectrum analyzer is a tool commonly used to visualize electronic signals in the frequency domain.

Some specialized signal processing techniques use transforms that result in a joint time–frequency domain, with the instantaneous frequency being a key link between the time domain and the frequency domain.

5.1.2.3.6 FRAME STRUCTURE

In the time domain, the physical layer transmissions are organized in radio frames. A radio frame has a duration of 10 ms. Each radio frame is divided into 10 subframes, each with a duration of 1 ms. Each subframe is further divided into slots. The number of slots in a subframe depends on the subcarrier spacing as shown in Table 5.12. The number of OFDM symbols per slot depends on the duration of the cyclic prefix and is independent of the subcarrier spacing. Subframe boundaries are aligned to frame boundaries, slot boundaries are aligned to subframe boundaries, and OFDM symbol boundaries are aligned to slot boundaries. Figure 5.21 shows the frame structure for a subcarrier spacing of 120 KHz with Normal CP.

Table 5.12. Slot Duration in NR.

Subcarrier Spacing	Slot duration	Slots per subframe
15 KHz	1 ms	1
30 KHz	500 μs	2
60 KHz	250 μs	4
120 KHz	125 μs	8
240 KHz	62.5 μs	16

In NR, there are two durations of cyclic prefix:

- Normal CP (NCP). This has a duration of 144 T_a or 144 T_a + 16 T_s. The symbols at the start of the subframe and right after the half subframe boundary have a duration of 144 T_a + 16 T_s. All other symbols have a duration of 144 T_a. In case of NCP, there are 14 OFDM symbols per slot. NCP is supported for all subcarrier spacings.

- Extended CP (ECP). This has a duration of 512 T_a. In case of ECP, there are 12 OFDM symbols per slot. ECP is only supported for 60 KHz subcarrier spacing.

Where, $T_a = \frac{1}{2048.(\text{Subcarrier Spacing})}$, and $T_s = \frac{1}{2048.(15\text{ KHz})}$.

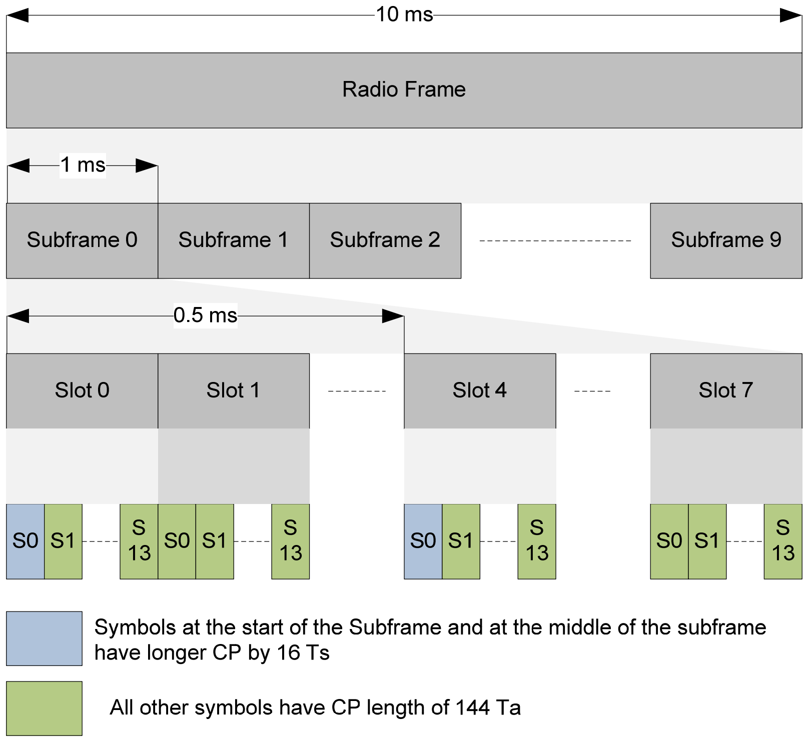


Figure 5.21. Frame Structure in for Subcarrier Spacing of 120 Khz with Normal CP.

5.1.2.3.7 FREQUENCY DOMAIN SRUCTURE

In the frequency domain, transmissions are organized in resource blocks, a resource block occupies 12 subcarriers.

$$N_{sc}^{RB} = 12$$

In the frequency domain, the location of a carrier or a Bandwidth Part (BWP) is given relative to point A. Point A is a common reference point, identifying the center frequency of subcarrier 0 of common resource block (CRB) 0 for subcarrier configuration μ. Point A is common for all subcarrier configurations. Common resource blocks are number in ascending order starting from point A. Point A is determined as follows:

- In case the cell is determined by SS/PBCH Block during initial access (e.g., downlink PCell), point A is determined relative to the SS/PBCH block by parameters provided in the MIB and SIB1
- For all other cases, point A is determined by absolute FrequencyPointA, which represents the absolute frequency of point A

5.1.2.3.8 NESTED STRUCTURE

By having the subcarrier spacing configurations as multiples of a power of two it is possible to have a nested structure as shown in Figure 5.22.

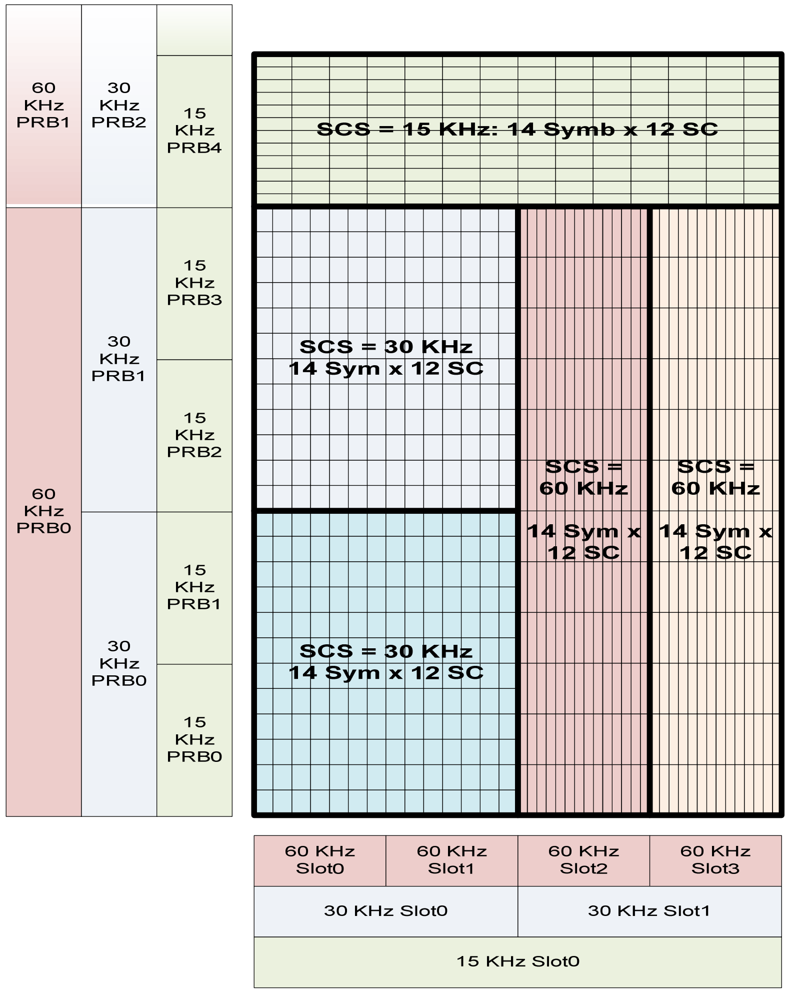


Figure 5.22. Nested Structure with Different Subcarrier Spacing.

5.1.2.3.9 PHYSICAL LAYER CHANNELS AND SIGNALS

The physical layer provides data transport services to the higher layers. As introduced previously [section 5.1.2.2.3], these services are accessed through the transport channels. Transport channels describe how and with what characteristics the data is transferred over the air interface. In the physical layer, the transport channels are mapped to the physicals as shown in Table 5.13.

Table 5.13. Mapping of Transport Channels to Physical Channels in NR.

Direction	Transport Channel	Physical Channel
DL	DL-SCH	PDSCH
	BCH	PBCH
	PCH	PDSCH
UL	UL-SCH	PUSCH
	RACH	PRACH

The physical layer-generated control information in downlink and uplink is mapped to physical channels as shown in Table 5.14.

Table 5.14. Mapping of Physical Layer Control Information to Physical Channels.

Direction	Physical Layer Control Information	Physical Channel
DL	DCI	PDCCH
UL	UCI	PUCCH

In addition, physical layer signals are defined to assist in the physical layer reception, channel sounding and physical layer measurements as shown in Table 5.15.

Table 5.15. Mapping of Physical Layer Signal to Physical Procedure.

Direction	Physical Layer Signal	Physical Procedure
DL	PSS	Cell Search
	SSS	Cell Search
	DM-RS	Receiver processing
	PT-RS	Receiver phase tracking
	CSI-RS	Downlink channel state estimation, fine time/frequency tracking, mobility measurements, and beam management measurements.
UL	DM-RS	Receiver processing
	PT-RS	Receiver phase tracking
	SRS	Uplink channel sounding

Downlink Shared Channel

Figure 5.22 shows a high-level block diagram of the physical layer processing of the downlink transport channel:

- A codeword of the downlink shared channel (DL-SCH) delivered from higher layers to the physical layer goes through channel encoding, as previously described. This includes, CRC attachment, code block segmentation, LDPC encoding, code block concatenation and rate matching. Up to two codewords can be transmitted on PDSCH
- The coded bits are scrambled by a pseudorandom sequence that depends on the codeword ID and a data scrambling identity
- The scrambled bit sequence is modulated, the allowed modulation schemes for PDSCH are QPSK, 16QAM, 64QAM and 256QAM
- The complexed valued modulation symbols are mapped to one or several layers. In case of one codeword, the number of layers is between 1 and 4. In case of two codewords, the number of layers is between 5 and 8
- Precoding maps the layers to antenna ports

- Finally, the complexed valued modulation symbols of each antenna port are mapped to resource elements (REs) in the resource blocks assigned to PDSCH, avoiding REs used for DMRS, PTRS, CSI-RS and reserved REs

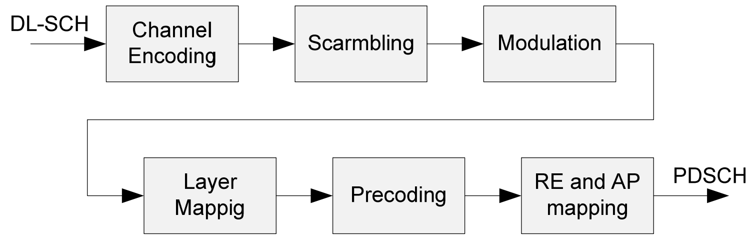


Figure 5.23. Physical Layer Processing of the DL Transport Channel.

There are two PDSCH mapping types:

- PDSCH mapping type A. This is used for slot based scheduling, there is one PDSCH scheduled per slot. The PDSCH start symbol is 0 to 3, and PDSCH duration is 3 to 14 symbols, with the restriction that the PDSCH doesn't extend beyond the slot boundary

- PDSCH mapping type B. This is used for mini-slot based scheduling. The PDSCH duration is 2, 4 or 7 (6 in case of extended CP) symbols. The PDSCH can start at any symbol within the slot with the restriction that the PDSCH doesn't extend beyond the slot boundary

The demodulation reference signal (DMRS) for PDSCH is generated using a pseudorandom sequence that is initialized by the slot number within a radio frame and the DL-DMRS scrambling ID or the cell ID. The DMRS and the PDSCH are transmitted using a precoder. The same precoder is used across a set of Physical Resource Blocks known as a Physical Resource Group (PRG).

Front-loaded DMRS is supported to improve pipelining at the UE's receiver and reduce latency. Additional DMRS symbols can be inserted to enhance performance in fast fading channels.

There are two configuration types for PDSCH DMRS:

- Configuration type 1: This supports 8 DMRS ports in case of double-symbol DMRS, and 4 DMRS ports in case of single-symbol DMRS

- Configuration type 2: This supports 12 DMRS ports in case of double-symbol DMRS, and 6 DMRS ports in case of single-symbol DMRS

Configuration type 1 has 8 antenna ports, as shown in Figure 5.23, with 2 frequency-domain OCC x 2 combs x 2 time-domain OCC. Configuration type 2 has 12 antenna ports, as shown in 5.24, with 2 frequency-domain OCC x 3 frequency offsets x 2 time-domain OCC

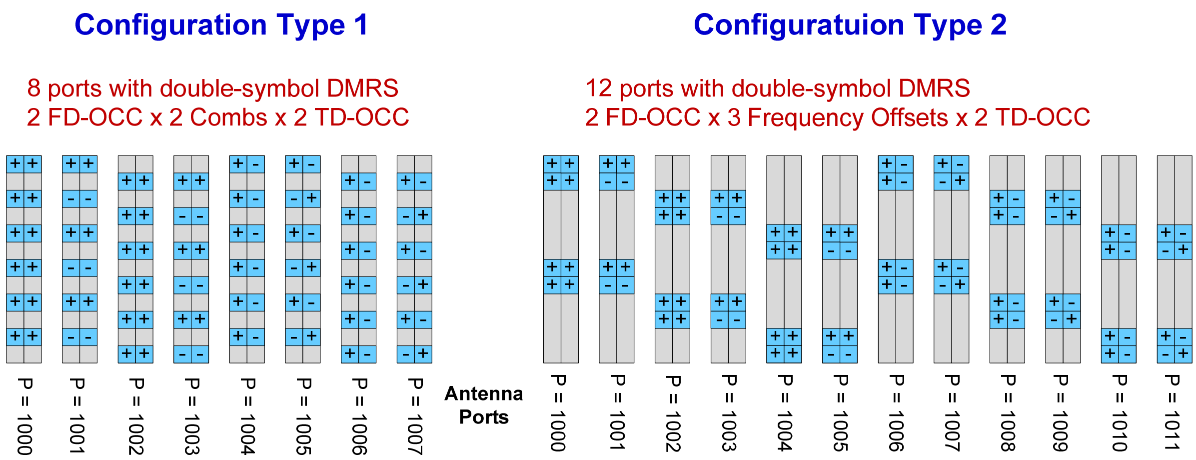


Figure 5.24. DMRS Configuration Type 1 and Configuration Type 2.

There can be up to 4 single-symbol DMRS, or 2 double-symbol DMRS within one PDSCH transmission. The maximum number of DMRS symbols that can be configured for PDSCH is determined based on the duration of PDSCH.

The phase tracking reference signal (PT-RS) for PDSCH is transmitted on addition REs to track phase errors at the receiver. The PTRS can be enabled or disabled. The density of the PT-RS in time domain (L_{PT-RS}) depends on the MCS, and configured MCS thresholds. $L_{PT-RS} \in \{1,2,4\}$ symbols. The density of the PT-RS in the frequency domain (K_{PT-RS}) depends on the PRB allocation size of PDSCH. $K_{PT-RS} \in \{2,4\}$ PRBs.

Downlink Control Channel

Downlink control information is transmitted on the Physical Downlink Control Channel (PDCCH). Downlink control information includes:

- Uplink grants to schedule PUSCH (DCI format 0-0 and DCI format 0-1)
- Downlink assignments to schedule PDSCH (DCI format 1-0 and DCI format 1-1)
- Slot Format Indicator (DCI format 2-0)
- Preemption Indicator (DCI format 2-1)
- Group TPC commands (DCI format 2-2)
- SRS switching (DCI format 2-3)
- Triggering PRACH preamble transmission (DCI format 1-0)

PDCCH is transmitted in a control resource set (CORESET), which spans $N_{RB}^{CORESET}$ PRBs in the frequency domain and $N_{symb}^{CORESET}$ symbols in the time domain, where $N_{symb}^{CORESET} \in \{1,2,3\}$. Unlike LTE, the frequency domain span of a CORESET can be less than the carrier bandwidth, this is:

- For supporting UEs with different bandwidth capabilities
- For forward compatibility

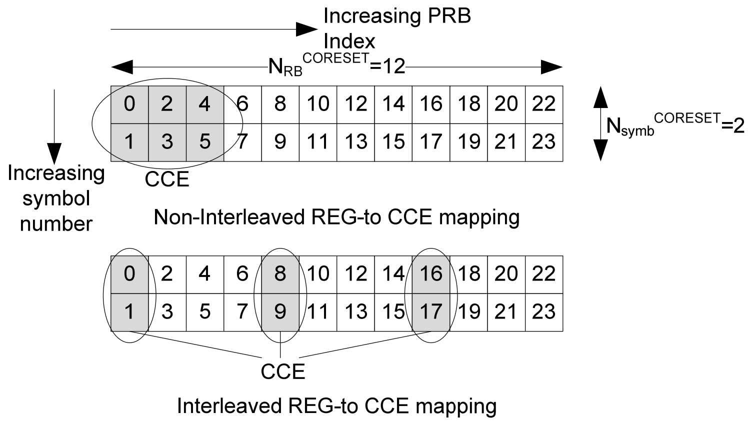


Figure 5.25. PDCCH CORESET with Non-interleaved and Interleaved REG-to-CCE Mapping.

PDCCH consists of one or more control-channel elements (CCE). The number of CCEs in a PDCCH channel is determined by the aggregation level. The aggregation level can be {1, 2, 4, 8, 16}. Each CCE consists of 6 resource element groups (REG). A resource element group consists of one resource block spanning 1 symbol. REGs within a CORESET are number in increasing order of time (symbol number) followed by increasing order of frequency (resource block index), starting with the first OFDM symbol and lowest-numbered resource block, as shown in Figure 5.25. The resource element group consists of 12 REs, there are 3 REs assigned to the PDCCH DMRS the remaining 9 REs can be allocated to the downlink control information (DCI) as shown in Figure 5.26. The DMRS can be configured to occupy the same REGs as the DCI, which is known as narrowband DMRS. Alternative, the DMRS can be configured to occupy all the REGs of the CORESET, which is known as wideband DMRS.

0	1	2	3	4	5	6	7	8	9	10	11
DCI	DMRS	DCI	DCI	DCI	DMRS	DCI	DCI	DCI	DMRS	DCI	DCI

Figure 5.26. Resource Element Group Structure.

REGs are arranged in REG bundles that span L consecutive REGs. Within a REG bundle the same Tx precoder is used. There are 6/L REG bundles in a CCE. The mapping type determines how CCEs bundles are mapped to REGs, there are two mapping types:

- Non-interleaved CCE-to-REG mapping: consecutive REG bundles are mapped to one CCE
- Interleaved CCE-to-REG mapping: interleaved REG bundles are mapped to one CCE

Error! Reference source not found. shows an example of non-interleaved and interleaved CCE-to-REG mapping, with a bundle size, L, of 2, and a CORESET spanning 12 resource blocks and 2 symbols.

Downlink control information (DCI) is transmitted on PDCCH. The DCI payload is encoded as previously described using Polar code. The encoded bit stream is scrambled, modulated using QPSK modulation and then mapped to physical resources assigned to the PDCCH channel. Table 5.16 shows the DCI formats supported in NR Release 15.

Table 5.16. DCI Formats.[109]

DCI Format	Usage	RNTI used to scramble CRC
DCI 0_0	Scheduling of PUSCH in one cell	C-RNTI or new-RNTI or CS-RNTI or TC-RNTI
DCI 0_1	Scheduling of PUSCH in one cell	C-RNTI or new-RNTI CS-RNTI or SP-CSI-RNTI
DCI 1_0	Scheduling of PDSCH in one cell Random access procedure initiated by a PDCCH order	C-RNTI or new-RNTI or CS-RNTI or P-RNTI or SI-RNTI or RA-RNTI or TC-RNTI
DCI 1_1	Scheduling of PDSCH in one cell	C-RNTI or new-RNTI or CS-RNTI
DCI 2_0	Notifying a group of UEs the slot format	SFI-RNTI
DCI 2_1	Notifying a group of UEs the PRB(s) and OFDM symbol(s) where UE may assume no transmission is intended for the UE	INT-RNTI
DCI 2_2	Transmission of TPC commands for PUCCH and PUSCH	TPC-PUSCH-RNTI or TPC-PUCCH-RNTI
DCI 2_3	Transmission of a group of TPC commands for SRS transmissions by one or more UEs	TPC-SRS-RNTI

Uplink Shared Channel

Figure 5.27 shows a high-level block diagram of the physical layer processing of the uplink transport channel:

- A transport block of the uplink shared channel (UL-SCH) delivered from higher layers to the physical layer goes through channel encoding, as previously described. This includes, CRC attachment, code block segmentation, LDPC encoding, code block concatenation and rate

[109] TS 38.212.

matching. There is only one UL-SCH codeword transmitted on PUSCH. Uplink control information (UCI) can be multiplexed with the UL-SCH on PUSCH

- The coded bits are scrambled by a pseudorandom sequence that depends on a data scrambling identity
- The scrambled bit sequence is modulated, the allowed modulation schemes are QPSK, 16QAM, 64QAM and 256QAM. In addition, Pi/2-BPSK is supported in case transform precoding is enabled
- The complexed valued modulation symbols are mapped to one or several layers. The number of layers in the uplink is between 1 and 4
- If the number of layers is 1, transform precoding can be enabled. When transform precoding is enabled, the modulation symbols of layer 0, are divided into sets. Each set corresponds to one OFDM symbol. DFT transform is applied to each set
- Precoding maps the layers to antenna ports
- Finally, the complexed valued modulation symbols of each antenna port are mapped to resource elements (REs) in the resource blocks assigned to PUSCH, avoiding REs used for DMRS, PTRS and DMRS for co-scheduled users

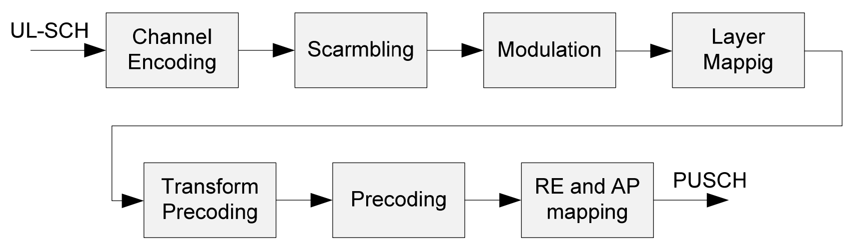


Figure 5.27. Physical Layer Processing of the UL Transport Channel.

Uplink Control Channel

Uplink control information (UCI) is transmitted on the Uplink Physical Control Channel (PUCCH), or Uplink Physical Shared Channel (PUSCH). If UCI is sent by the UE at the same time as UL-SCH, the UCI and UL-SCH are multiplexed and sent on the PUSCH channel. Otherwise, UCI is sent on the PUCCH channel.

Uplink control information includes:

- HARQ-ACK feedback, therefore, positive or negative acknowledgements corresponding to the reception of a PDSCH transport block
- Scheduling request (SR), for the UE to request an uplink grant
- Channel state information

The PUCCH channel formats supported in NR release 15 are shown in Table 5.17. PUCCH formats can be classified based on the length of the PUCCH transmission as short PUCCH, with 1 or 2 OFDM symbols these are Formats 0 and 2; or long PUCCH with 4 to 14 PUCCH symbols these are Formats 1, 3 and 4. PUCCH formats can be classified based on the payload size. There are PUCCH formats that support small payload up to 2 bits, these are formats 0 and 1. There are PUCCH formats that support large payloads more than 2 bits, these are Formats 2, 3 and 4.

Table 5.17. PUCCH Formats.

PUCCH Format	Length in OFDM Symbols	Payload Size	Multiplexing Capacity	Number of PRBs
Format 0	1 or 2	≤ 2	Up to 6	1
Format 1	4 – 14	≤ 2	Up to 84	1
Format 2	1 or 2	> 2	1	1 – 16
Format 3	4 – 14	> 2	1	1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 15, 16
Format 4	4 – 14	> 2	2 or 4	1

PUCCH format 0 uses sequence selection. In case of 1-bit HARQ-ACK, 2 sequences are used, one for ACK, and the other for NACK separated by 6 cyclic shifts. Hence, 1 PRB with 12 cyclic shifts can multiplex 6 one-bit HARQ-ACK users. In case of 2-bit HARQ-ACK, 4 sequences are used separated by 3 cyclic shifts. Hence, 1 PRB with 12 cyclic shifts can multiplex 3 two-bit HARQ-ACK users.

PUCCH format 1 has UCI OFDM symbols time division multiplexed with DMRS OFDM symbols as shown in Figure 5.28. DMRS is transmitted on even symbols, while UCI is transmitted on odd symbols. If frequency hopping is enabled, the frequency hopping boundary is close to the middle of the PUCCH transmission. HARQ-ACK data is modulated using BPSK (1-bit HARQ-ACK) or QPSK (2-bit HARQ). The modulated symbol multiples a sequence that is transmitted in the UCI symbol. The maximum multiplexing capacity is determined by the number cyclic shifts in one symbol (12) multiplied by maximum length of the orthogonal cover code (OCC). The OCC length is largest when there are 14 symbols with no frequency hopping. In this case, the OCC length is 7 and the maximum multiplexing capacity is 84.

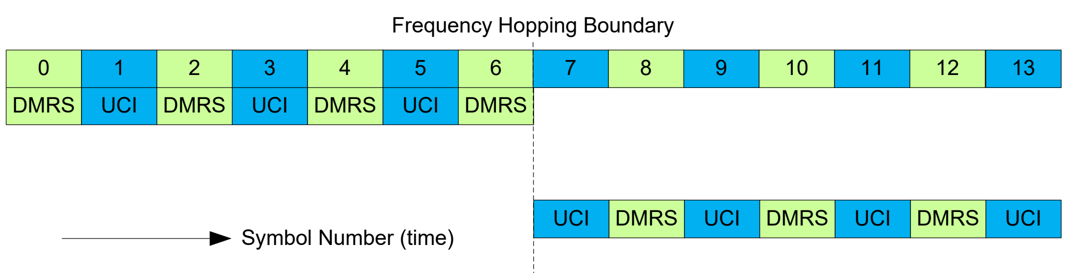


Figure 5.28. PUCCH Format 1 with Duration 14 Symbols and Frequency Hopping Enabled.

PUCCH format 2 has DMRS REs frequency division multiplexed with UCI REs. Within each PRB allocated to PUCCH format 2, the DMRS overhead is 1/3, i.e. 4 REs are assigned to DMRS, and 8 REs are assigned to UCI as shown in Figure 5.29. As previously described, the UCI data is encoded using Reed-Muller code, if the UCI payload size is 11 or less bits, or using Polar code, if the UCI payload size is more than 11 bits. The encoded bits are scrambled, modulated and mapped to the resources assigned to UCI transmissions.

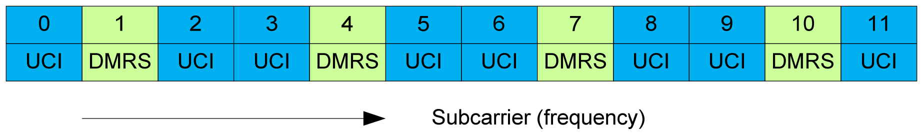


Figure 5.29. PUCCH Format 2: RE Allocation within one PRB.

PUCCH formats 3 and 4 have UCI OFDM symbols time division multiplexed with DMRS OFDM symbols as shown in Figure 5.30. There can be 1, 2 or 4 DMRS symbols in a PUCCH transmission. Figure 5.31 shows a high-level block diagram of the physical layer processing of the uplink control information for PUCCH format 3 or format 4. As previously described, the UCI data is encoded using Reed-Muller code, if the UCI payload size is 11 or less bits, or using Polar code, if the UCI payload size is more than 11 bits. The encoded bits are scrambled, modulated, passed through transform precoding (DFT transform) and mapped to the resources assigned to UCI transmissions. An additional step is performed for PUCCH format 4 between modulation and transform precoding, this is block-wise spreading. Block-wise spreading is done within each OFDM symbol, this allows 2 or 4 users to be multiplexed within the same time frequency resource.

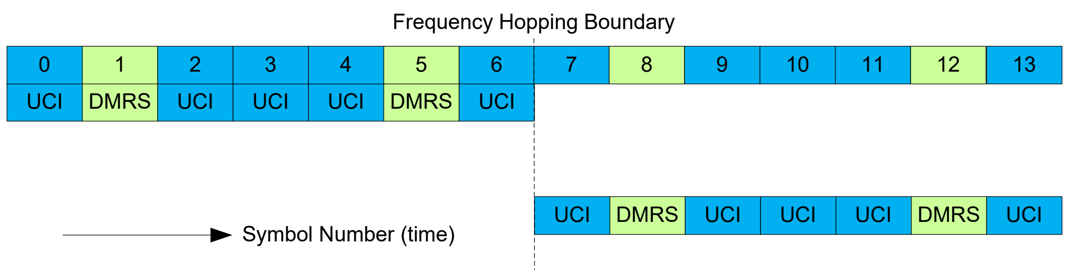


Figure 5.30. PUCCH Format 3 or Format 4 with Duration 14 Symbols and Frequency Hopping Enabled.

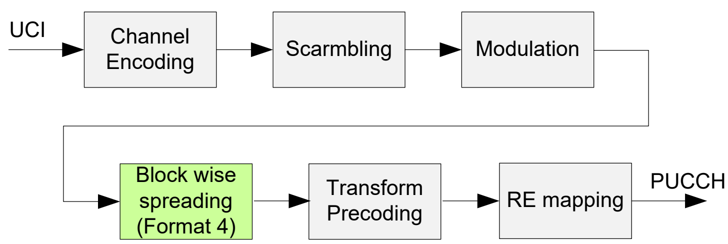


Figure 5.31. Physical Layer Processing of the UL Control Information for PUCCH Format 3 or Format 4.

5.1.2.3.10 INITIAL ACCESS

Cell Search

Cell search is the procedure by which a UE acquires time and frequency synchronization with the network and determines the physical layer cell ID. The UE uses the SS/PBCH block to perform cell search. The SS/PBCH block consists of the Primary Synchronization Signal (PSS), the Secondary Synchronization Signal (SSS) and Physical Broadcast Channel spanning 4 symbols and 240 subcarriers as shown in 5.32. PSS occupies the first symbol of the SS/PBCH block and spans 127 subcarriers. SSS occupies part of the third symbol of the SS/PBCH block and spans 127 subcarriers. The PBCH channel occupies the second and forth symbols and part of the third symbol of the SS/PBCH block. In the second and fourth symbols, the PBCH channel occupies 240 sub-carriers. In the third symbol, the PBCH channel occupies 48 subcarriers on either side of SSS.

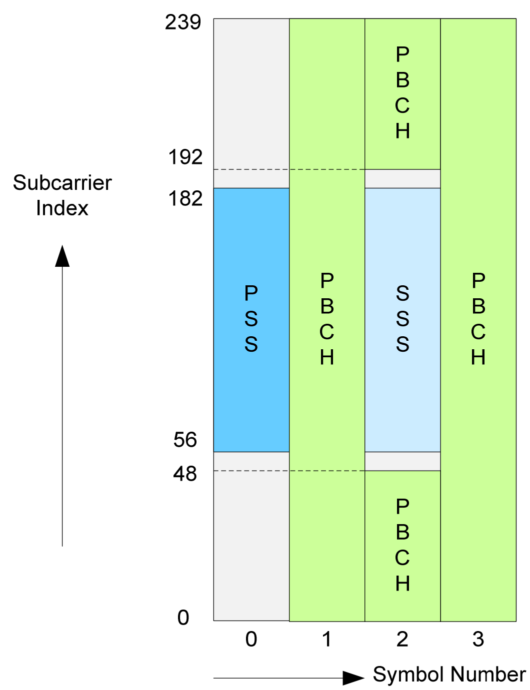


Figure 5.32. Time and Frequency Structure of SS/PBCH Block.

SS/PBCH blocks are organized in bursts, known as SS bursts. SS burst span less than half a frame, and are then repeated periodically. The SS burst period can be {5, 10, 20, 40, 80, 160} ms. The number of SS/PBCH blocks in a SS burst depends on the carrier frequency.

In FR1, therefore, carrier frequencies below 6 GHz, the subcarrier spacing of the SS/PBCH block is either 15 KHz or 30 KHz. If the carrier frequency is less than 3 GHz, there is up to 4 SS/PBCH blocks in an SS burst if the carrier frequency is between 3 and 6 GHz, there is up to 8 SS/PBCH blocks in an SS burst. There is one SS/PBCH block pattern for subcarrier spacing 15 KHz, and two SS/PBCH block patterns for subcarrier spacing 30 KHz, as shown in Figure 5.33. The applicable pattern for the cell depends on the frequency band.

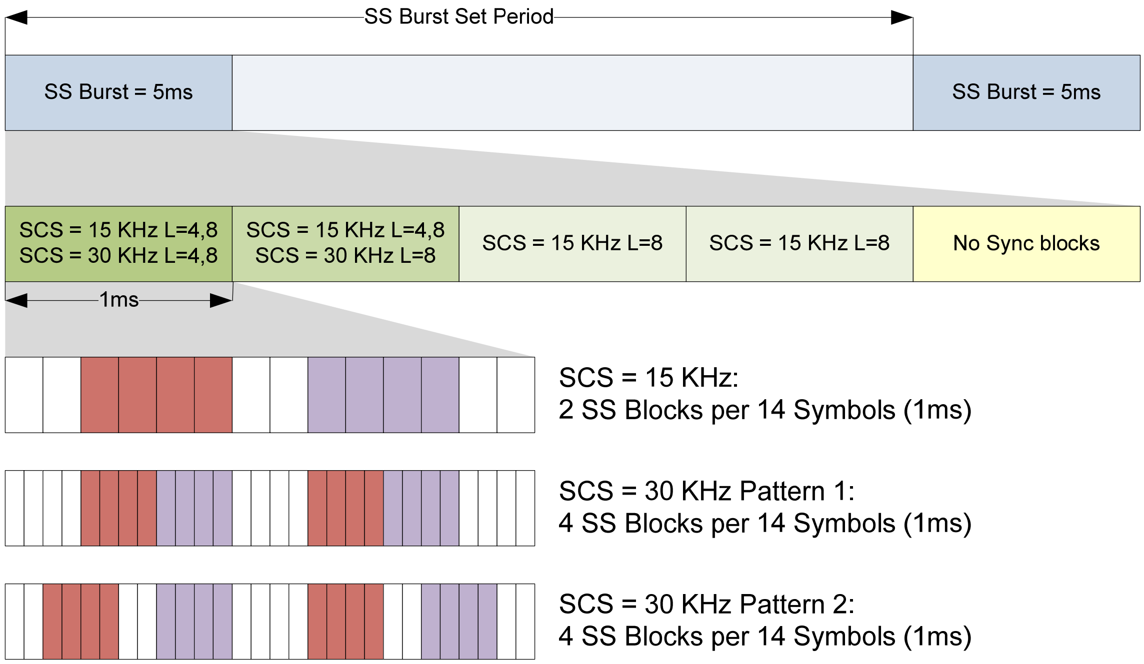


Figure 5.33. SS/PBCH Block Pattern in FR1.

In FR2, therefore, mmWave, the subcarrier spacing of the SS/PBCH block is either 120 KHz or 240 KHz. In this frequency range, there are up to 64 SS/PBCH blocks in an SS burst. There is one SS/PBCH block pattern for each subcarrier spacing in this frequency range.

The channels and signals of one SS/PBCH block transmitted with the same block index on the same center frequency location are quasi co-located with respect to Doppler spread, Doppler shift, average gain, average delay, delay spread, and spatial Rx parameters.

The UE determines the physical cell ID after receiving PSS and SSS. There are 1008 unique physical cell identities given by:

$$N_{ID}^{cell} = 3N_{ID}^{(1)} + N_{ID}^{(2)}$$

Where,

$N_{ID}^{(1)} \in \{0, 1, \ldots, 335\}$ and is given by SSS.

$N_{ID}^{(2)} \in \{0, 1, 2\}$ and is given by PSS.

The Physical Broadcast CHannel (PBCH) occupies 48 PRBs across 3 symbols as shown in 5.31. Within each PRB, there are 3 PBCH-DMRS resource elements, the remaining 9 resource elements are allocated to the PBCH payload, as shown in Figure 5.34.

0	1	2	3	4	5	6	7	8	9	10	11
PBCH DMRS	PBCH	PBCH	PBCH	PBCH DMRS	PBCH	PBCH	PBCH	PBCH DMRS	PBCH	PBCH	PBCH

Figure 5.34. PBCH PRB Structure.

Physical Broadcast CHannel (PBCH) payload carriers the Master Information Block (MIB). The MIB is transmitted every 80 ms. The MIB contains information needed for time and frequency synchronization (e.g. the System Frame Number (SFN), and the SSB subcarrier offset), PDCCH configuration information for receiving the DCI of SIB1, as well as other relevant information for initial access. The PBCH is encoded as previously described [section 5.1.2.3.9] using polar code, and modulated using QPSK.

SIB1

After the UE receives the MIB, it receives the remaining minimum information in System Information Block 1 (SIB1). The MIB provides the UE with a Common Control Resource Set (CORESET) and a common search space configuration for monitoring the PDCCH used to schedule the PDSCH carrying SIB1. SIB1 contains system information that allows the UE to continue with accessing the network. For example, SIB1 contains the Random Access CHannel (RACH) configuration which allows the UE to start the random access procedure.

Random Access

From the physical later perspective, the contention based random access procedure is a four-step procedure, which encompasses:

- Transmission of the random access preamble, also known as message 1. The preamble is transmitted in the uplink by the UE
- Transmission of random access response (RAR) also known as message 2, on PDSCH. The RAR is sent by the base station upon detecting a preamble
- Transmission of message 3 on PUSCH. Message 3 is transmitted by the UE when it receives a RAR with the preamble ID the UE sent. Message 3 is scheduled in the RAR. If the base station doesn't receive message 3, it can send a DCI to the UE to retransmit message 3
- Transmission of message 4 on PDSCH. Message 4, for contention resolution, is transmitted by the base station. The UE acknowledges message 4 with a HARQ-ACK

In NR, the preamble is based on Zadoff-Chu sequences. There are two preamble sequence length:

- Long sequence preamble. This has a sequence length of 839. There are 4 long sequence preamble formats as defined in Table 5.18.
- Short sequence preamble. This has a sequence length of 139. There are 9 short sequence preamble formats as defined in Table 5.19

Table 5.18. Long Sequence Preamble Formats.

Format	SCS	Sequence Duration	CP Duration
0	1.25 KHz	1 * 24576 T_s	3168 T_s
1	1.25 KHz	2 * 24576 T_s	21024 T_s
2	1.25 KHz	4 * 24576 T_s	4688 T_s
3	1.25 KHz	4 * 6144 T_s	3168 T_s

Table 5.19. Short Sequence Preamble Formats.

Format	SCS	Sequence Duration	CP Duration	Total Duration
A1	{15, 30, 60, 120} KHz	2 * 2048 T_a	288 T_a	2 Symbols
A2	{15, 30, 60, 120} KHz	4 * 2048 T_a	576 T_a	4 Symbols
A3	{15, 30, 60, 120} KHz	6 * 2048 T_a	864 T_a	6 Symbols
B1	{15, 30, 60, 120} KHz	2 * 2048 T_a	216 T_a	2 Symbols
B2	{15, 30, 60, 120} KHz	4 * 2048 T_a	360T_a	4 Symbols
B3	{15, 30, 60, 120} KHz	6 * 2048 T_a	504 T_a	6 Symbols
B4	{15, 30, 60, 120} KHz	12 * 2048 T_a	936 T_a	12 Symbols
C0	{15, 30, 60, 120} KHz	1 * 2048 T_a	1240 T_a	2 Symbols
C2	{15, 30, 60, 120} KHz	4 * 2048 T_a	2048 T_a	6 Symbols

A PRACH occasion is a time-frequency resource during which a PRACH preamble can be transmitted by the UE. The PRACH occasions are organized in PRACH configuration periods and are repeated periodically. The PRACH occasions are configured in SIB1. Furthermore, there is an association between PRACH occasions and the actually transmitted SS/PBCH block. After the UE detects an SS/PBCH block that exceeds a threshold, it transmits the preamble in the PRACH occasions associated with this SS/PBCH block. This allows the network to determine which beam to use when transmitting channels or signals to that UE (for example., when transmitting the RAR). Figure 5.35 shows an example of such association.

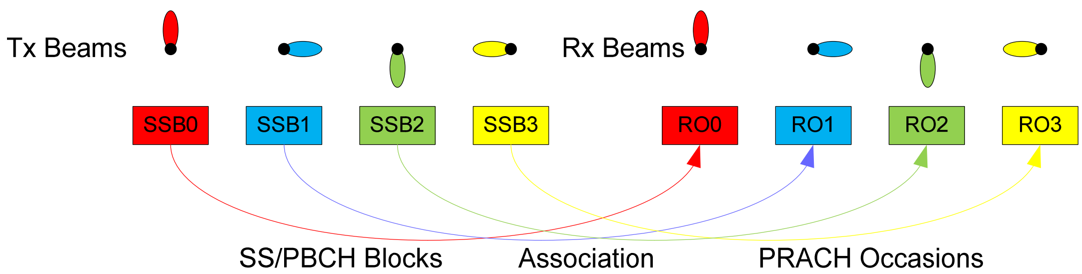


Figure 5.35. Association between SS/PBCH Blocks and PRACH Occasions.

5.1.2.3.11 MIMO

One of the major enabling technologies of NR, is the support of advanced antenna systems, with a large number of antenna elements, also known as Massive MIMO. This allows support of:

- Beamforming, for coverage enhancement, which is an essential technology to support mmWaves
- Massive MIMO with higher order spatial multiplexing, for capacity enhancement and higher spectral efficiency

Definitions

Antenna Ports: An antenna port is defined[110] such that the channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed.

Quasi co-located antenna ports: Two antenna ports are said to be quasi co-located if the large-scale properties of the channel over which a symbol on one antenna port is conveyed can be inferred from the channel over which a symbol on the other antenna port is conveyed.[111] The large-scale properties include one or more of delay spread, Doppler spread, Doppler shift, average gain, average delay, and spatial Rx parameters. There are four types of QCL:[112]

- QCL Type-A: Doppler shift, Doppler spread, average delay, delay spread
- QCL Type-B: Doppler shift, Doppler spread
- QCL Type-C: Doppler shift, average delay
- QCL Type-D: Spatial Rx parameter

Transmission Configuration Index (TCI) States: This provides QCL association, in the downlink, between one or two source reference signals (e.g. SS/BPCH block or CSI-RS for beam management) and a target downlink reference signal along with the QCI type for this association.

[110] TS 38.211
[111] TS 38.211.
[112] TS 38.214.

Spatial Ratio Information: This provides spatial domain UL transmission filter (UL Tx beam) association between the Reference Signal (RS) of an uplink channel and another reference signal that can be:

- SS/PBCH Block index: UE transmits UL channel using the same spatial domain filter as that used to receive the indicated SS/PBCH block
- CSI-RS index: UE transmits UL channel using the same spatial domain filter as that used to receive the indicated CSI-RS
- SRS index: UE transmits UL channel using the same spatial domain filter as that used to transmit the indicated SRS

5.1.2.3.12 BEAM MANAGEMENT

As mentioned previously, NR is designed to support a wide range of frequency bands including support of mmWave frequency bands. Radio propagation in mmWaves is characterized by higher attenuation and is impacted more by blockage due to obstacles and foliage. To counteract these effects, NR uses beamforming to concentrate the RF energy in the direction of the UE. With beamforming, the user's mobility and time varying environment require the UE to constantly look for new beams and dynamically change beams. NR defined procedures for beam management and beam recovery. The beam management procedure includes: beam determination, beam measurement, beam reporting and beam sweeping. The beam recovery procedure includes: beam failure detection, new beam identification and beam recovery request.

Downlink beam management framework is a three-step procedure:

1. P1: Initial coarse-beam acquisition based on SS/BPCH blocks or CSI-RS

2. P2: Downlink Tx beam-referment using narrower CSI-RS beams

3. P3: Downlink Rx beam-refinement (at UE). gNB transmits the same CSI-RS beam over multiple transmission occasions to allow the UE to refine its Rx beam

When the UE is receiving a downlink control channel (PDCCH), it uses the TCI state configured and activated by the network to determine the DL Tx beam used by the gNB. When the UE is receiving a downlink data channel (PDSCH), it can either use the TCI state index (a 3-bit field) in the corresponding DCI to determine the DL Tx beam from a set of configured and activated TCI states, or it can assume the same Tx beam for PDSCH as that used for PDCCH.

When the UE is transmitting an uplink control channel (PUCCH), it uses the spatial relation information configured and activated by the network to determine the UL Tx beam. When the UE is transmitting an uplink data channel (PUSCH) and for codebook-based transmission, the SRS resource indicator and the precoding information given by DCI format 0_1 determine the PUSCH transmission precoder. When the UE is transmitting an uplink data channel (PUSCH) and for non-codebook-based transmission, the SRS resource indicator given by DCI format 0_1 determines the PUSCH transmission precoder. When the UE is transmitting an uplink data channel (PUSCH) scheduled by DCI format 0_0, it uses the same spatial relation as that of the PUCCH resource, with the lowest ID within the active UL BWP of the cell.

Channel State Information Acquisition Framework

To support Massive MIMO in the downlink, the UE is required to measure the channel on different antenna ports and report the channel state measurements to the network. The network configures resources for the

UE to report the Channel State Information (CSI) and it configures reference signals for the UE to measure the CSI. The CSI information reported by the UE consists of:

- Layer Indicator (LI)
- Channel Quality Indicator (CQI)
- Precoding Matrix Indicator (PMI)
- Rank Indicator (RI)
- CSI-RS Resource Indicator (CRI)
- L1-RSRP

From a time-domain perspective, the CSI report can be configured to be periodic, semi-persistent on PUCCH, semi-persistent on PUSCH or aperiodic. Periodic reporting requires no activation or triggering. Semi-persistent reporting on PUCCH is activated by higher layers. Semi-persistent reporting on PUSCH is triggered by a DCI. Aperiodic reporting on PUSCH is triggered by a DCI or higher layer activation.

The reference signals for measuring CSI can be:

- CSI-RS resources (NZP CSI-RS or CSI-IM). NZP CSI-RS resources are used for channel measurement, while NZP CSI-RS/ CSI-IM resources are used for interference measurement
- SS/PBCH Block resources for L1 RSRP

From a time-domain perspective, the CSI resource can be periodic, semi-persistent or aperiodic.

There are two types of CSI feedback reports based on the level of PMI granularity:

1. Type 1 CSI: Normal spatial resolution Feedback

   This is based on two stage precoding: $W = W_1 W_2$ where, W_1 compromises of wideband beam groups/vectors. In case of 3D MIMO (2D antenna panels), W_1 is the Kronecker product of vertical and horizontal oversampled DFT beams. W_2 is for sub-band beam selection and beam co-phasing across polarizations.

   Type 1 feedback is specified for single panel and multi-panel codebooks.

   a. Single panel codebook supports rank 1 to 8, with up to 32 CSI-RS ports

      - For ranks 1 and 2, there are two configurations; with 1 beam (L=1), or 4 beams (L=4). A wideband beam (L=1), or a cluster of 4 beams (L=4), is selected for each layer with sub-band co-phasing across polarizations, and sub-band beam selection (in case of L=4)

      - For ranks 3 and 4 with less than 16 ports, a wideband beam is selected for layers 1 and 3, and another wideband beam is selected for layers 2 and 4, with subband co-phasing across polarizations

      - For ranks 3 and 4 with 16 or more ports, a wideband beam is selected for one half of the antenna array, and is wideband co-phased for the other half of the antenna array to generate two orthogonal beams across the array. The resultant beams are subband co-phased across polarizations

- For ranks 5 and 6, a wideband beam is selected, and two other beams with fixed offset relative to the selected wideband beam are generated. The resultant beams are co-phased across polarizations, subband co-phasing across polarizations is for a subset of layers

- For ranks 7 and 8, a wideband beam is selected, and three other beams with fixed offset relative to the selected wideband beam are generated. The resultant beams are co-phased across polarizations, subband co-phasing across polarizations is for a subset of layers

- Multi-panel codebook supports 2 and 4 panels, with up to 32 CSI-RS ports across all panels, with identical wideband beams selected for each polarization/panel, and with subband co-phasing across polarizations and wideband co-phasing across panels. Supports 1 to 4 MIMO layers

2. Type 2 CSI: Enhanced spatial resolution feedback. Supports 1 or 2 MIMO layers. There are two codebook designs for the type 2 codebook:

   a. Eigenvector approximation: Eigenvectors are approximated by linear combination of L $\boldsymbol{b}_{k_1,k_2}$ oversampled 2D DFT beams, $L \in \{2,3,4\}$:[113]

   $$\widetilde{\boldsymbol{w}}_{r,l} = \sum_{i=0}^{L-1} \boldsymbol{b}_{k_1^{(i)} k_2^{(i)}} \cdot p_{r,l,i}^{(WB)} \cdot p_{r,l,i}^{(SB)} \cdot c_{r,l,i}$$

   Where, r=0,1 (polarization), l=0,1 (layer),

   $p_{r,l,i}^{(WB)}$ wideband (WB) beam amplitude scaling factor for beam i and on polarization r and layer l,

   $p_{r,l,i}^{(SB)}$ sub-band (SB) beam amplitude scaling factor for beam i and on polarization r and layer l,

   $c_{r,l,i}$ sub-band (SB) beam combining phase coefficient for beam i and on polarization *r* and layer l,

   b. Port selection codebook, based on linear combination of beams

Uplink MIMO Framework

NR supports codebook and non-codebook based transmissions schemes.

- Codebook-based uplink transmission supports 2 and 4 antenna ports for CP-OFDM and DFT-s-OFDM. For DFT-s-OFDM, rank 1 codebook is supported. For CP-OFDM, rank 1 to 4 codebook is supported

- Non-codebook based uplink transmission, where the UE transmits multiple precoded SRS resources. The gNB detects the SRS and signals to the UE, via the DCI, the desired transmission layers for PUSCH transmission

[113] R1-1709232.

5.1.2.3.13 HARQ AND SCHEDULING

Several new technologies were introduced for HARQ and scheduling in NR.

Code Block Group (CBG) Retransmission

As previously described [section 5.1.2.3.9], for large transport blocks, the transport block is segmented into multiple code blocks, with each code block having its own Cyclic Redundancy Check (CRC). In addition, there is a CRC for the entire transport block. At the receiver, each code block is decoded and its CRC is checked. NR supports code block group (CBG) based retransmission, where the code blocks are organized into groups. If one or more code blocks fail CRC in a CBG, that CBG is retransmitted. If all code blocks of a CBG pass CRC, that CBG is not retransmitted. The HARQ-ACK feedback has one bit for each CBG to indicate whether to retransmit that CBG or not.

NR also supports transport block-based retransmission, where the entire transport block is retransmitted if any code block fails CRC, or if the transport block CRC fails. With transport-block based retransmission, there is only one HARQ-ACK bit per transport block. While CBG-based retransmission increases the overhead of the HARQ-ACK feedback, it optimizes the data transmission, as it is only the CBGs that fail CRC that get retransmitted.

HARQ-ACK Codebook

This is for the HARQ-ACK feedback of downlink transmissions on PDSCH or SPS PDSCH release. There are two types of HARQ-ACK codebooks:

1. Type 1 HARQ-ACK codebook, also known as semi-static codebook. The codebook is constructed based on semi-static information

2. Type 2 HARQ-ACK codebook, also known as dynamic codebook. The codebook is constructed dynamically as DCIs for PDSCH/SPS release are received. To guard against missed DCIs at the UE, and potential misalignment between the HARQ-ACK codebook at the UE and at the gNB, downlink assignment index fields (DAI) are included in the DCI. There are two DAI fields:

    a. Counter DAI which indicates the accumulative number of (serving cells, PDCCH monitoring occasion) pairs up to the current serving cell and PDCCH monitoring occasion, indicating PDSCH reception or SPS PDSCH release acknowledged in the same HARQ-ACK occasion
    b. Total DAI which indicates the total number of (serving cells, PDCCH monitoring occasion) pairs up to the current PDCCH monitoring occasion (including all serving cells in the current PDCCH monitoring occasion), indicating PDSCH reception or SPS PDSCH release acknowledged in the same HARQ-ACK occasion

Flexible TDD

In NR, the direction of transmission in each symbol can be flexibly configured. There several ways to configure the direction of transmission of a symbol:

1. Common TDD UL-DL configuration in SIB1, where symbols can be semi-statically configured as DL symbols, UL symbols, or flexible symbols that can be later used as UL or DL symbols or left unused to create a gap between DL and UL transmissions. There can be one or two common TDD

UL-DL configurations in SIB1. Each common TDD UL-DL configuration has a period, the slots and symbols at the start of the period are downlink. The slots and symbols at the end of the period are uplink. The remaining slots and symbols in the middle are flexible. The SIB1 common TDD UL-DL configuration applies to all users in a cell

2. UE TDD UL-DL dedicated configuration. This overrides the flexible symbols configured in SIB1. The TDD UL-DL dedicated configuration configures slots as DL slot, UL slots, or a mixed slot with some DL symbols at the start of the slots and some UL symbols at the end of the slot

3. Using group-common slot format indicator (SFI). This is a DCI sent to a group of UEs indicating a slot format that overrides flexible symbols configured in SIB1 or configured by a UE dedicated TDD UL-DL configuration

4. Using a DCI that schedules DL or UL data. Data scheduled for transmission in flexible symbols (from 1, 2 and 3 above), changes the direction of these symbols to DL or UL symbols as scheduled

Scheduling

NR supports asynchronous and adaptive HARQ for dynamically scheduled DL and UL transmissions.

For time domain resource allocation, NR supports same slot scheduling and cross scheduling for DL and UL transmissions. A field in the DL assignment DCI, or UL grant DCI indicates the slot, starting symbol and duration (number of consecutive symbols) in which the DL or UL transmissions takes place.

For frequency domain resource allocation, NR supports contiguous (resource allocation type 1) and non-contiguous (resource allocation type 0 – based on a bit map of the resource block groups (RBG)) resource block allocation for data transmission with CP-OFDM. Contiguous resource block allocation for data transmission is supported for Discreet Fourier Transform Spread Orthogonal Frequency Division (DFT-S-OFDM).

NR supports dynamically scheduled transmissions that are triggered based on a DCI uplink grant. NR also supports configured grant (semi-static) uplink transmissions on preconfigured time and frequency resources and using a preconfigured Modulation and Coding Scheme (MCS). There are two types of configured UL grants; configured grant type 1, where the UE can transmit PUSCH on the configured resource once configured by RRC. Configured grant type 2, where the UE can transmit on the configured resource after it has been activated by a DCI with a CRC scrambled by CS-CRNTI.

Interrupted Transmissions

NR supports the co-existence of different types of traffic ranging from eMBB, which could have high throughput and large transport blocks to URLLC with tight latency requirements. If a latency-critical URLLC packet arrives during the transmission a large eMBB packet, the URLLC packet could experience a large delay. To handle this situation, NR allows the preemption of ongoing eMBB transmissions, when a low latency URLLC packet is transmitted. When preemption occurs, the network sends a DCI signaling the preempted resources, to facilitate demodulation and decoding at the eMBB UEs.

Multiple CQI tables

To support URLLC with ultra-reliable traffic, NR supports two CQI tables for CSI feedback. One table with a Block Error Rate (BLER) target of 10^{-1} and the other table with a BLER target of 10^{-5}.

MCS tables

There are three MCS tables defined in NR[114] for PDSCH, PUSCH with CP-OFDM, and PUSCH with 256QAM:

- 64QAM MCS table
- 256 QAM MSC table
- 64 QAM MCS table with low spectral efficiency for URLLC-based applications

The low spectral-efficiency table can be configured semi-static by higher layer signaling or can be indicated dynamically if “new-RNTI” is configured and PDSCH or PUSCH is scheduled with “new-RNTI”.

There are two MCS tables defined in NR[115] for PUSCH with DFT-S-OFDM and up to 64QAM:

- 64QAM MCS table
- 64 QAM MCS table with low spectral efficiency for URLLC-based applications

The low spectral-efficiency table can be configured semi-static by higher layer signaling or can be indicated dynamically if “new-RNTI” is configured and PUSCH is scheduled with “new-RNTI”.

5.1.2.3.14 CHANNEL CODING AND MULTIPLEXING

In NR channel coding involves the following:

- Error detection coding. This is done by calculating and appending CRC to the payload and/or code blocks
- Error correction coding (a.k.a. channel coding). NR supports different error correction coding schemes such as LDPC, and Polar codes as explained later in this section (Included in the error correction coding is code block segmentation/concatenation and interleaving based on the coding scheme and the payload size)
- Rate matching, this adapts the output bits from channel coding to the resources allocated for transmission
- Channel multiplexing of the data and control channels

Error correction coding (a.k.a. channel coding) plays a central role in determining the performance and implementation complexity of the physical layer. As a result, 3GPP undertook an extensive study to evaluate different channel coding schemes in terms of:

- Performance (BLock Error Rate versus Signal to Noise Ratio)
- Implementation complexity including energy efficiency (J/bit) and area efficiency (Gbps/mm^2)
- Encoding and decoding latency
- Flexibility, in terms of being able to support variable code length, variable code rate, as well HARQ combining

Because of this study, NR supports the channel coding schemes shown in Table 5.20.

[114] TS 38.214.
[115] TS 38.214.

Table 5.20. Channel Coding Schemes in NR.

Transport Channel/Control Information	Channel Coding Scheme
DL-SCH, PCH, UL-SCH	LDPC
DCI, UCI with 12 or more bits	Polar Code
UCI with 1 bit	Repetition Code
UCI with 2 bits	Simplex Code
UCI with 3 to 11 bits	Reed-Muller Code

In NR, Quasi Cyclic-Low Density Parity Check (QC-LDPC) is used for data channels, it provides latency and implementation advantages over other channel coding schemes at the same performance. The parity check matrix is defined by base graph and shift values. There are two base graphs defined depending on the code block size and code rate to optimize for performance and throughput. Fig 5.35 shows the base graph matrix used to construct the parity check matrix. The base graph matrix is of size mb x mn. To get the H matrix replace each element in the base graph matrix by a ZxZ matrix. Zero elements are replaced by a zero matrix, non-zero elements are replaced by a weight circulant permutation matrix, which is a circularly shifted identity matrix. The resulting H matrix has a size (mb x Z) x (nb x Z). Z is determined by the code block size, and the base graph used. Z ranges from 2 to 384. The maximum code block size for base graph 1 is 8448 bits, and the maximum code block size for base graph 2 is 3840.

LDPC in NR supports HARQ combining with Increment Redundancy and Chase Combining.

LDPC base graph 2 is selected if any if the following conditions is satisfied:

- Payload size is less than or equal to 292 bits
- Payload size is less than or equal to 3824 bits, and code rate is less than or equal to 0.67
- Code rate is less than or equal to 0.25

Else, base graph 1 is selected.

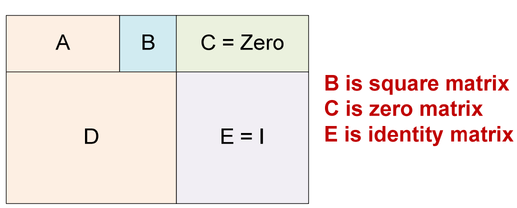


Figure 5.36. Base Graph Matrix Used to Construct the Parity Check Matrix.

Polar codes are used for encoding control information (L1 control information and the broadcast channel) with a payload size of 12 or more bits. The basic principle of Polar coding is that successive combining of binary channels, as shown in Figure 5.37, channels are polarized; some channels' capacity approaches 1, these are the channels used for data transmissions, others approach zero, these are frozen bits.

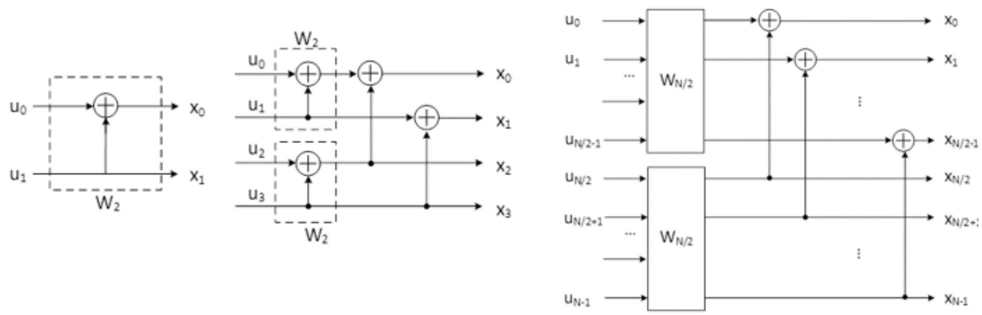


Figure 5.37. Polarization in Polar Codes.

The encoding matrix of polar codes, G_N is given by the nth Kronecker power of matrix G_2, over GF (2);

$$G_N = (G_2)^{\otimes n}$$

Where,

$$G_2 = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$$

$$N = 2^n$$

Assuming that there are K information bits, including CRC, and n_{PC} parity bits (when it is applicable in uplink channel information), a vector u of size N is generated such that $K + n_{PC}$ entries of u have the information and parity bits. The location of these bits is selected to correspond to the channels with the highest information, the remaining entries of u are set to 0. The output of the polar encoder is given by (over GF (2)):

$$\boldsymbol{d} = \boldsymbol{u}G_N$$

The output the encoders is rate matched to fit in the resources allocated to the transmission the data and control channels. The full details of the NR channel encoding algorithm are found in TS 38.212.

5.1.3 RELEASE 15 5G RAN STUDY ITEMS

In this section, we present the NR study items started in 2018 towards standardization in Release 16. These study items were approved in RAN plenary meeting #75 (March 2017). The RAN plenary decided at that time and in subsequent meetings to defer the start of these study items until 2018 for WG#1 and WG#2 to focus on the completion of NR Release 15. In RAN plenary meeting #80 (June 2018) additional NR study items were approved.

5.1.3.1 NON-TERRESTRIAL NETWORKS

The Non-Terrestrial Network study item considers extending NR to support non-terrestrial networks using space-borne vehicles or airborne vehicles as access points:

- Spaceborne vehicles, which include: Satellites such as Low Earth Orbiting (LEO) satellites, Medium Earth Orbiting (MEO) satellites, Geostationary Earth Orbiting (GEO) satellites as well as Highly Elliptical Orbiting (HEO) satellites
- Airborne vehicles, which include: High Altitude UAS Platforms (HAPs) encompassing Unmanned Aircraft Systems (UAS) including tethered UAS and Lighter than Air UAS (LTA), Heavier than Air UAS (HTA), and all operating in altitudes typically between 8 and 50 km

Non-terrestrial networks provide complimentary coverage to terrestrial networks, with the following benefits:

- Providing ubiquitous coverage by extending coverage to remote locations
- Providing reliable and resilient coverage especially for public safety in case the terrestrial networks are impacted by physical attacks or natural disasters
- Providing coverage to terminals in airborne and moving platforms such as drones, plans, trains and vessels, that traverse areas outside the coverage of terrestrial networks
- Providing efficient delivery of multicast/broadcast services

Figure 5.38 shows the architecture of National Telecommunications Network (NTN). The NTN terminal can be a very small aperture terminal mounted on a moving platform providing broadband access, or a terminal with omni or semi-directional antennas providing narrowband access, such as handheld terminals. A handheld terminal can also access the terrestrial RAN network. The space or airborne platform can be a bent pipe, which does frequency filtering, frequency conversion and amplification. It can also be regenerative platform, which additional does demodulation/decoding, switching/routing and modulation/coding. Finally, the gateway connects the non-terrestrial network to the core network.

The "service link" is the link between the NTN terminal and the space/airborne platform. In addition, the NTN terminal may also be connected to the terrestrial RAN. The "feeder link" is the link between the space/airborne platform and the gateway. Additionally, "inter satellite/aerial links" are used to connect a constellation of satellites.

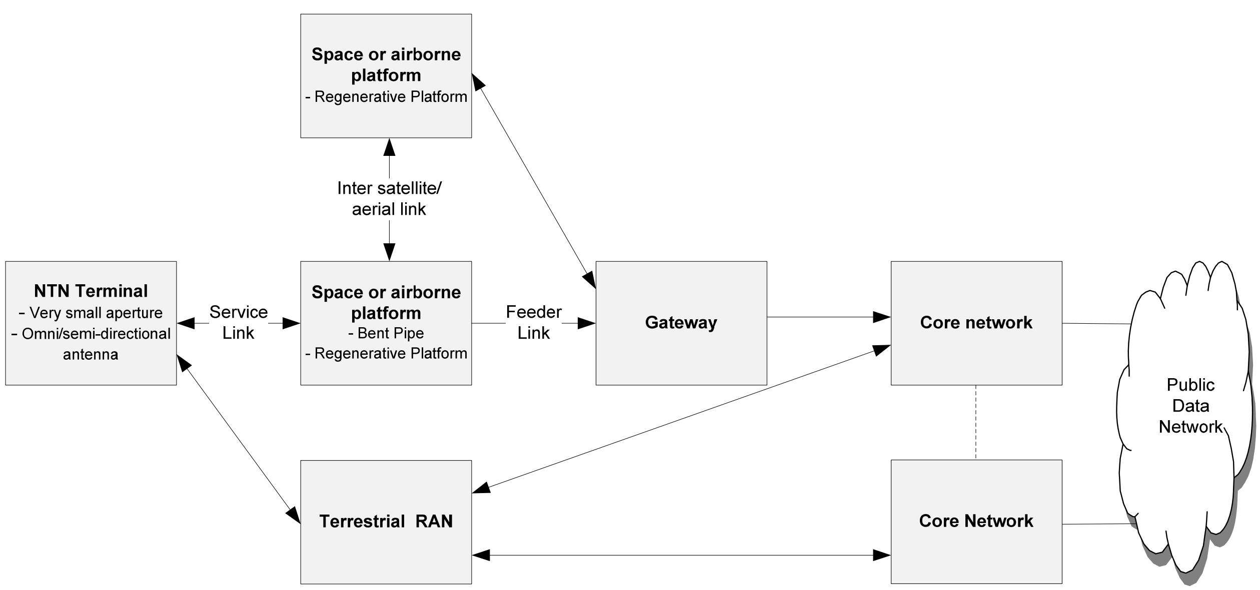


Figure 5.38. Architecture of Non-Terrestrial Network.

The first phase of the NTN study item, which is within the Rel- 15 study item, focuses on identifying the deployment scenarios and related parameters, the channel model for NTN in the frequency range 0.5 to 100 GHz, and identifying the parts of the NR radio access networks that are impacted by non-terrestrial wireless communications, with emphasis on the S and Ka bands. A second phase of the study item, will evaluate solutions for the identified impacts.

The channel model study complements the non-terrestrial channel model defined in TR 38.901. Figure 5.39 shows how the terrestrial model from TR 38.901, is reused for non-terrestrial networks for path loss and shadowing at the terminal. On top of the terrestrial model, the NTN model is augmented to include additional dynamic delay and Doppler shift to account for the satellite orbit and motion, as well as dynamic attenuation due to atmospheric conditions such as scintillation, rain and cloud.

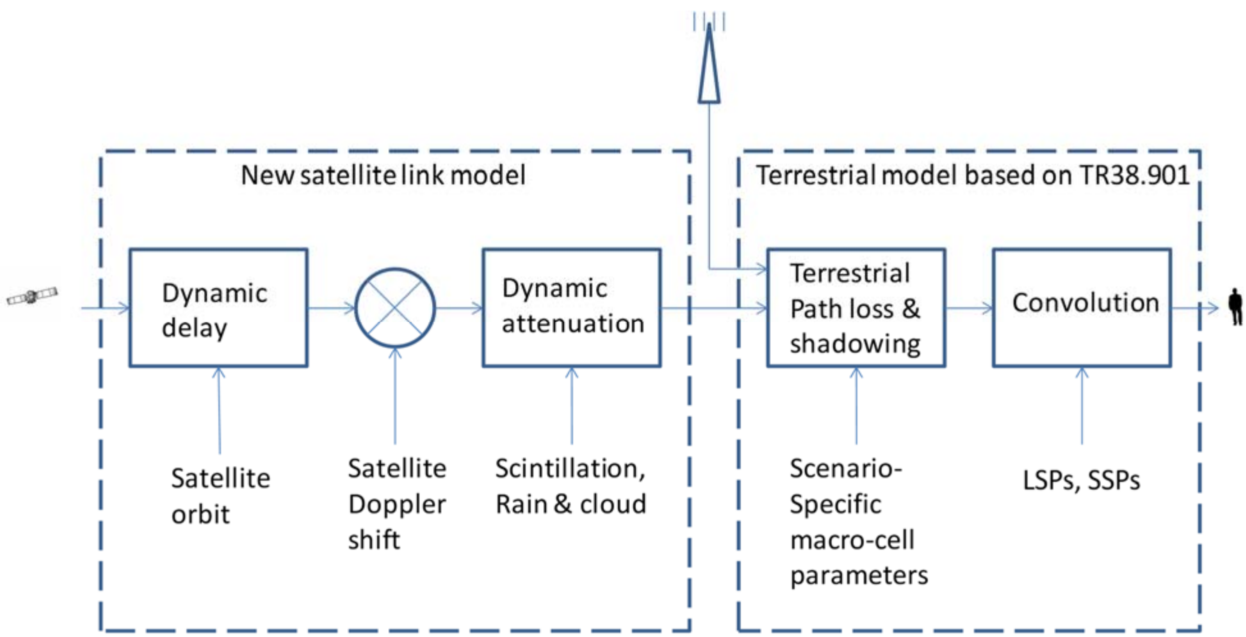


Figure 5.39. Combined Non-terrestrial and Terrestrial Channel Model for NTN.[116]

The antenna pattern at the satellite is defined[117] by the Bessel function of the first kind and first order, while the antenna pattern of HAPs can be defined by the Bessel function first kind and first order or can be defined as the base station pattern in TR 38.901.

The reference UE antenna pattern for fast fading can be quasi Isotropic with linear polarization, or co-phased array with dual linear polarization (one for below 6 GHz, and the other for above 6 GHz). In case of flat fading, Very-Small Aperture Terminal (VSAT) type antenna pattern can be used with circular polarization.

Table 5.21 shows the deployment scenarios for non-terrestrial networks.

[116] TR 38.811.
[117] TR 38.811.

Table 5.21. Non-Terrestrial Network Deployment Scenarios.[118]

	Deployment-D1	Deployment-D2	Deployment-D3	Deployment-D4	Deployment-D5
Platform orbit and altitude	GEO at 35 786 km	GEO at 35 786 km	Non-GEO down to 600 km	Non-GEO down to 600 km	HAPS between 8 km and 50 km
Carrier Frequency on the link between Air / space-borne platform and UE	Around 20 GHz for DL Around 30 GHz for UL (Ka band)	Around 2 GHz for both DL and UL (S band)	Around 2 GHz for both DL and UL (S band)	Around 20 GHz for DL Around 30 GHz for UL (Ka band)	Below 6 GHz
Maximum Channel Bandwidth (DL + UL)	Up to 2 * 800 MHz	Up to 2 * 20 MHz	Up to 2 * 20MHz	Up to 2 * 800 MHz	Up to 2 * 80 MHz
UE antenna pattern + polarization	VSAT type - circular polarization Co-phased array - Dual Linear polarization (Note 1)	Quasi Isotropic - Linear polarization (Note 4) Co-phased array - Dual Linear polarization (Note 2)	Quasi Isotropic - Linear polarization (Note 4) Co-phased array - Dual Linear polarization (Note 2)	VSAT type - circular polarization Co-phased array - Dual Linear polarization (Note 1)	Quasi Isotropic - Linear polarization (Note 4) Co-phased array - Dual Linear polarization (Note 2)
UE type	Handheld, nomadic, fixed, moving platform mounted	Handheld, moving platform mounted	Handheld, moving platform mounted	Handheld, nomadic, fixed, moving platform mounted	Handheld, moving platform mounted

[118] TR 38.811.

Airborne & space borne antenna pattern modelling + polarization	Bessel function and circular polarization	Bessel function and circular polarization	Bessel function and circular polarization	Bessel function and circular polarization	Bessel function and circular polarization 3GPP antenna pattern of Base Station (Dual Linear polarization)

The studied areas about potential key NR impacts for NR supporting NTN in this SI include initial downlink synchronization, DMRS, CP, random access, timing advance (TA), HARQ, PTRS, PAPR, adaptive coding/modulation (ACM) and power control, handover/paging, MAC/RLC procedures, and duplexing mode (FDD/TDD), with the conclusion below:

- Initial downlink synchronization, DMRS and CP: No NR impact
- Random access: Enhancements on PRACH waveform/format may be needed if accurate geolocation and time information is unavailable at the UE side. While the enhancements on random access procedure can be considered regardless of whether or not the accurate geolocation and time information is available at the UE side
- TA: Possible NR impact to support the extension of maximum allowed cell size and the concept of common propagation delay for TA in random access response message. The solutions of uplink signal alignment for TA adjustment may need to be investigated to overcome the predictable delay of NTN
- HARQ: NR impact for deactivation and/or enhancements of NR HARQ can be considered
- PTRS: Further investigation for NR impact is needed in the case of important Doppler shifts and/or residual CFO, or in the presence of phase noise masks significantly different from the phase noise masks considered in existing NR, or with very large channel bandwidths
- PAPR: PAPR reduction techniques of CP-OFDM signal on the downlink would be beneficial to optimize the capacity of non-terrestrial networks but is not mandatory to support non-terrestrial networks
- ACM and power control: Further study is needed to define the required margin for power and ACM control loops to accommodate to the long RTT
- Handover/paging: No NR impact for HAPS or GEO satellite-based NTN. Adaptation of the NR handover and paging protocols needs further study possibly taking advantages of the knowledge of the UE location and satellite ephemeris information for Non-GEO satellite-based NTN
- MAC/RLC procedures: Potential NR impact to support the extension of timer limitation of MAC/RLC and higher layers loop protocols
- Duplexing mode: FDD is preferred especially for most NR-based NTN access networks and may require possible adaptations of the frequency band definition, channel numbering and spacing aspects depending on the regulatory regime applying to the targeted frequency bands. If allowed by the regulations, TDD mode can be considered for both HAPS and LEO satellite-based access networks with potential NR impacts, if required

5.3.1.2 NON-ORTHOGONAL MULTIPLE ACCESS (NOMA)

In NR, the basic multiple access scheme is Orthogonal Multiple Access (OMA). Users are assigned non-overlapping time and frequency resources or are assigned orthogonal codes within the same time frequency resource, for example, in the case of uplink control channels. It is also possible to use the spatial domain and assign spatially orthogonal users to the same time-frequency resource, this is known as Multi-User MIMO (MU-MIMO). On the other hand, non-orthogonal multiple access has been gaining popularity in the last few years. In LTE, non-orthogonal multiple access was considered in a Rel-13 study item on downlink Multi-User Superposition Transmission (MUST) and showed promising results leading to the Rel-14 work item on MUST. Furthermore, it has been shown that non-orthogonal multiple access can improve the UL system capacity.

The focus of the NR NOMA study item in Rel-15 is on the evaluation of uplink non-orthogonal multiple access (NOMA) schemes and providing recommendation on the scheme(s) to be specified. The study item focuses on 4 aspects of NOMA:

- Transmitter side signal processing schemes for NOMA
- Receivers for NOMA
- Procedures related to NOMA
- Link and system level performance evaluation or analysis for NOMA

There are two design considerations of NOMA transmitter schemes. The first design consideration is to distinguish between users sharing the same time-frequency resource by assigning a unique MA (Multiple Access) signature to each user. The second design consideration is to reduce the multi-user interference between the transmitted users; this can be achieved, for example, by using low correlation spreading or low code rate.

Many schemes have been proposed for NOMA, Figure 5.40 shows a block diagram of a generic NOMA transmitter. The blocks highlighted in blue provide NOMA specific functionality. Not all of these blocks are needed for each NOMA scheme. A bit-level scrambler or interleaver that is user-specific, or a symbol-level scrambler or interleaver that is user-specific, provide a unique MA signature for each user. Low correlation spreading and/or low code reduces multi-user interference.

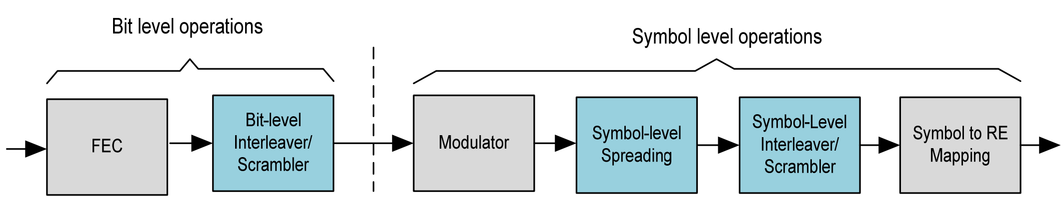


Figure 5.40. High-level Block Diagram of NOMA Transmitter.

NOMA schemes have more than one user sharing the same time frequency resource. Hence, as the system overload increases, inter-user interference becomes more dominate in a non-orthogonal multi-access system. The receiver plays a major role in mitigating and cancelling inter-user interference. A generic block diagram of such a receiver is shown in Figure 5.41. The detector can be an equalizer (e.g., MMSE equalizer), or a matched filter or any other signal processing function that mitigates the channel between the transmitter and receiver. The detector can also provide multi-user separation, for example an IRC receiver utilizes the spatial properties of each user's channel in a multi-antenna system to separate users. The output of the detector then goes to the decoder, for example an LPDC decoder in the case of the NR data channel to decode the data of each user. The output of the decoder is fed back to the detector, giving a more reliable estimate of that user's signal that can be cancelled, for the benefit of the other users. This type of scheme is known as an interference cancellation receiver architecture.

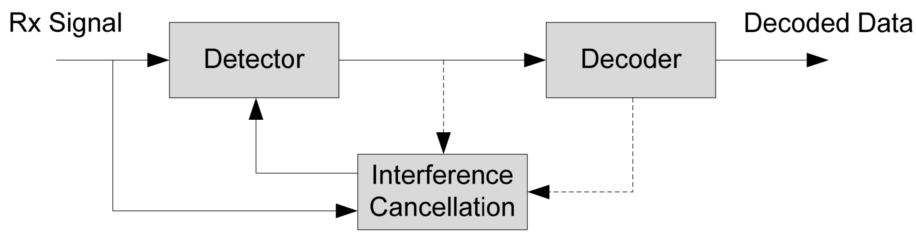


Figure 5.41. Receiver Architecture for NOMA.

Interference cancellation receiver architectures can be classified in different ways:

- *Hard versus soft interference cancellation.* In a hard interference cancellation scheme, if the output of the decoder has a passing CRC, the data is re-encoded and that user's channel is applied to the re-encoded data to get an estimate of the user's signal at the receiver's input that can then be cancelled for the benefit of the other users. In a soft interference cancellation scheme, soft LLRs are fed back from the decoder to the detector
- *Parallel versus serial interference cancellation (PIC / SIC).* In PIC schemes data of all users is decoded and the decoder's output is fed back to the detector. In SIC schemes, users are decoded successively; for example, users are arranged in order of most likely to decode correctly. PIC receivers have lower latency at the expense of more hardware complexity
- *Feedback point for interference cancellation*. The feedback point can be at the output of the decoder after a codeword has been decoded. This is known as codeword level IC. Alternatively, the feedback point can be at the output of the detector, i.e., after the data has been demodulated. This is known as symbol level IC. Symbol level IC has less latency at the expense of error propagation as it doesn't benefit from the coding gain

NOMA receivers require the use of more advanced receivers as described previously; there are tradeoffs between performance, implementation complexity and latency that need to be considered when comparing different NOMA schemes. This is part of the NOMA Rel-15 study item.

Several NOMA procedures are being considered in the study item:

- Detection of UL transmission at the receiver
- HARQ schemes including feedback and combining schemes
- Multiple-Access (MA) signature allocation and selection
- Synchronous and asynchronous schemes
- Adaptation between orthogonal and non-orthogonal multiple access

NOMA is being evaluated for different deployment scenarios including eMBB, URLLC and mMTC with grant-based and grant-free transmissions.

For link level performance evaluation, two sets of metrics are considered:

- Performance related metrics. These include:
    - o BLER versus SINR at a given spectral efficiency and a given number of UEs
    - o Sum throughput versus SNR at a given BLER, and for a given spectral efficiency and a given number of UEs
    - o Maximum Coupling Loss (MCL)
- Implementation related metrics. These include:
    - o Peak-to-Average-Power-Ratio (PAPR) and Cubic Metric (CM)
    - o Receiver complexity
    - o Processing latency

For system level performance evaluation, the following metrics are considered:

- For mMTC scenarios: Higher layer Packet Drop Rate (PDR) vs. offered load
- For URLLC scenarios: Percentage of users satisfying reliability and latency requirements versus Packet Arrival Rate (PAR)
- For eMBB scenarios: Higher layer Packet Drop Rate (PDR) versus offered load, and User Perceived Throughput (UPT) versus offered load
- Other metrics can also be considered for each of these scenarios

5.3.1.3 NR-BASED ACCESS TO UNLICENSED SPECTRUM (NR-U)

As known, 3GPP has standardized LTE unlicensed access (licensed assisted, i.e., LAA and eLAA features) since Rel-12, which is now deployed or being rolled-put in several markets. In Rel-15, as part of 5G/NR evolution, 3GPP is studying how to introduce/support operation in unlicensed spectrum for NR. This work is currently ongoing, and planned to be completed in December 2018.

The study considers solutions applicable to sub-6GHz and mmW unlicensed bands, and multiple scenarios, for example, where NR-LAA is anchored to a legacy LTE carrier by dual-connectivity (DC), or Carrier Aggregation (CA) with a 5G NR anchor, as wells as standalone NR operation in unlicensed spectrum.

Fair coexistence with other technologies (WiFi or cellular) is a key part of the investigation, to ensure that a NR-based unlicensed access wideband system operates as a “good neighbor” towards all forms of legacy systems.

A sample of technical objectives of the Rel-15 study items[119] are listed below:

- Physical channels inheriting the choices of duplex mode, waveform, carrier bandwidth, subcarrier spacing, frame structure, and physical layer design of NR
- Considering unlicensed bands both below and above 6GHz, up to 52.6GHz
- Considering unlicensed bands above 52.6GHz to the extent that waveform design principles remain unchanged with respect to below 52.6GHz bands
- Considering NR forward compatibility principles
    - Initial access, channel access. Scheduling/HARQ, and mobility including connected/inactive/idle mode operation and radio-link monitoring/failure
    - Coexistence methods within NR-based and between NR-based operation in unlicensed and LTE-based LAA, and with other incumbent RATs in accordance with regulatory requirements (e.g. in 5GHz, 37GHz, 60GHz bands)

[119] TR 38.811.

- LAA and standalone architectural scenarios:
  - A NR-based LAA cell(s) connects with an LTE or NR anchor cell operating in licensed spectrum
  - A NR-based cell operating standalone in unlicensed spectrum, connected to a 5G-CN network with priority on frequency bands above 6GHz, e.g., for private network deployments

In the initial study phase, some agreements were made regarding scenarios, topologies, and assumptions to evaluate/simulate. A few of those are summarized in Table 5.22 (from RAN1#92, March 2018).

Table 5.22. A Sample of Scenarios and Topologies to Simulate in Initial Study Phase.

Connectivity Scenarios	Network Topologies
CA between licensed NR (PCell) and NR-U (SCell) NR-U SCell may have both DL and UL, or DL-only	Indoor (Hotspot, Enterprise), sub7GHz or mmW
DC between licensed band LTE (PCell) and NR-U (PSCell) Stand-alone NR-Unlicensed An NR cell with DL in unlicensed band and UL in licensed band DC between licensed band NR (PCell) and NR-U (PSCell)	Outdoor (Dense Urban/ Micro), sub7GHz or mmW

5.3.1.4 EVALUATION METHODOLOGY OF NEW V2X USE CASES

Technical solutions for vehicle-to-anything (V2X) communications were first developed by 3GPP in Rel-14, mainly targeting safety use cases. As the next step in the evolution of V2X, SA WG1 has identified several advanced V2X use cases[120] to be targeted by 5G technology. Based on the requirements, the different use cases have been classified into four groups: platooning, advanced driving, extended sensor sharing and remote driving. Although part of the use cases and requirements will be covered by the LTE V2X enhancements being introduced in Rel-15, full support will only be delivered by 5G NR.

For this purpose, RAN WG1 is discussing the evaluation methodology to be used for developing technical solutions supporting the 5G V2X use cases.[121] This methodology encompasses simulation models as well as performance metrics.

The simulation models include:

- Channel models covering a larger range of frequencies that are both below and above 6 GHz. The new sidelink channel models (used for vehicle-to-vehicle or V2V, vehicle-to-pedestrian or V2P, etc.) extend those in LTE with additional modelling components such as blocking and moving

[120] TR 22.886.
[121] RP-171093.

scatterers. For uplink and downlink evaluations in vehicle-to-network (V2N), the channel models in TR 38.901 are reused

- Deployment models including urban and highway scenarios with new vehicle dropping models (compare to Rel-14), including a clustered UE dropping model for platooning
- Traffic models with a large degree of variation in terms of packet arrivals (including periodic and aperiodic), data rates, and packet sizes. In addition, MBB traffic is also considered

The performance metric for reliability and latency used since Rel-14, Packet Reception Ratio (PRR) has been redefined to cover broadcast, multicast and unicast transmissions. Additional performance metrics such as Packet Inter-Reception (PIR) and absolute/relative positioning error have been introduced to evaluate persistent collisions as well as the accuracy of positioning-related features.

It is to be noted that the study item, RP-171093, to develop the evaluation methodology for 5G V2X ended in June 2018. Furthermore, it is important that the 5G V2X system not only addresses individual uses cases but also allows the coexistence of multiple use cases having different traffic types and communication requirements. Therefore, the evaluation methodology covers the coexistence of multiple use cases.

5.3.1.5 INTEGRATED ACCESS AND BACKHAUL (IAB)

Another important target of 5G NR evolution is the support for wireless backhaul and relay links, enabling flexible and very dense deployment of NR cells at an effective cost (e.g., minimizing transport network scaling).

From a technical point of view, the NR larger bandwidths (e.g., in mmWave spectrum), as well as the native support of massive MIMO and multi-beams are expected to facilitate/optimize design and performance of integrated access and backhaul.

An example of a network with integrated access and backhaul links is shown in Figure 5.42, where relay nodes (rTRPs) can multiplex access and backhaul links in time, frequency, or space (e.g., beam-based operation).

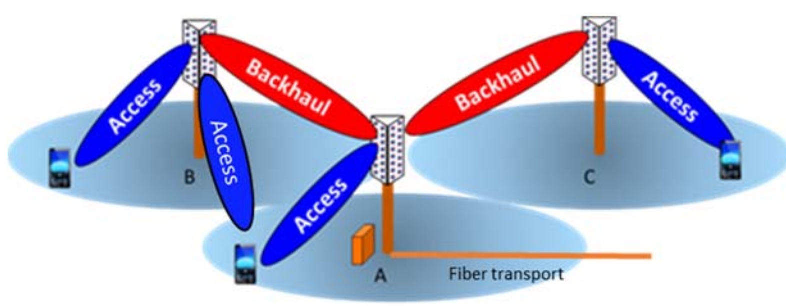


Figure 5.42. Examples of Integrated Access and Backhaul Links.

The operation of the different links may be on the same or different frequencies, also called ‘in-band’ and ‘out-band’ relays, respectively. As expected, in-band operation implies tighter interworking to account for duplex constraints and avoid/mitigate interference.

The RAN study started in Rel-15, and is currently ongoing and planned to be completed in December 2018. Some specific requirements and technical objectives are listed below:[122]

- Efficient and flexible operation for both inband and outband relaying, in indoor and outdoor scenarios
- Multi-hop and redundant connectivity
- End-to-end route selection and optimization
- Support of backhaul links with high spectral efficiency
- Support of legacy NR UEs
- Frequency ranges up to 100 GHz will be considered

Detailed study objectives are:

- Topology management for single-hop/multi-hop and redundant connectivity, for example-
    - Protocol stack and network architecture design (including interfaces between rTRPs), considering operation of multiple relay hops between the anchor node (e.g. connection to core) and UE
    - Control and User plane procedures, including handling of QoS, for supporting forwarding of traffic across one or multiple wireless backhaul links
- Route selection and optimization, for example –
    - Mechanisms for discovery and management of backhaul links for TRPs with integrated backhaul and access functionalities
    - RAN-based mechanisms to support dynamic route selection (potentially without core network involvement) to accommodate short-term blocking and transmission of latency-sensitive traffic across backhaul links
    - Evaluation of the benefit of resource allocation/route management coordination across multiple nodes, for end-to-end route selection and optimization
- Dynamic resource allocation between the backhaul and access links, for example-
    - Mechanisms to efficiently multiplex access and backhaul links (for both DL and UL directions) in time, frequency, or space under a per-link half-duplex constraint across one or multiple backhaul link hops for both TDD and FDD operation
    - Cross-link interference (CLI) measurement, coordination and mitigation between rTRPs and UEs
- High spectral efficiency while also supporting reliable transmission, for example-
    - Identification of physical layer solutions or enhancements to support wireless backhaul links with high spectral efficiency

While the work is still ongoing, various agreed proposals/aspects have been captured in the study report[123] for example, regarding general requirements, access/backhaul/RAT options, and NSA/SA scenarios. Some of those requirements/aspects are summarized here after.

General requirements include:

- Support for out-of-band and in-band (subject to half-duplexing constraints)
- Focus on fixed relays
- Focus on NR access and NR backhaul with highest priority
- Connectivity of Rel-15 NR UEs and legacy LTE UEs to IAB is supported

[122] RP-172290.
[123] TR 38.874.

- Support for SA and NSA mode for access link and backhaul link (backhauling over LTE is excluded)
- Support for multi-hop backhauling
- Support for topology adaptation
- L2- and L3-relaying architectures are included in the study
- Minimization of impact on core network
- Reuse of Rel-15 NR specifications

Regarding Access/Backhaul/RAT options:

- IAB can support access and backhaul in above-6GHz- and sub-6GHz spectrum
- The focus of the study is on backhauling of NR-access traffic over NR backhaul links. Solutions for NR-backhauling of LTE-access may be included
- The IAB design shall at least support the following UEs to connect (transparently) to an IAB-node:
    - Rel-15 NR UE
    - Legacy LTE UE, if IAB supports backhauling of LTE access

Specific agreements/requirements on Standalone/non-standalone deployments are:

- IAB can support stand-alone (SA) and non-stand-alone (NSA) deployments-
    - For NSA, relaying of the UE's SCG path (NR) is included in the study. Relaying of the UE's MCG path (LTE) is contingent on the support for IAB-based relaying of LTE-access
    - The IAB node itself can operate in SA or NSA mode

- Since EN-DC and SA (option 2) represent relevant deployment options for early rollout of NR, EN-DC and SA for UEs and IAB-nodes have high priority in this study. Other NSA deployment options or combinations of SA and NSA may also be explored

- For IAB nodes, the following options are studied:
    - Case 1 - Connection in Networks without 5GC: The IAB nodes connects as a UE to EPC using EN-DC
    - Case 2 – Connection in Networks with 5GC: The IAB node connects as a UE to 5GC using NR
        - This can also be used when access UEs support option 3/3X

5.3.1.6 SEPARATION OF CONTROL AND USER PLANE IN 5G

In E-UTRAN or the evolved UMTS RAN, the eNB is the logical node that hosts all the E-UTRA radio interface protocols and functions. In NG-RAN, the next generation RAN, the equivalent of the eNB, therefore, the NG-RAN node hosting the new 5G NR access technology, is referred to as gNB. The NG-RAN architecture supports deployments where the gNB is internally split into separate functional components hosting different parts of the NR radio interface protocols and functions. These functional components of the gNB are interconnected by means of open, standardized network interfaces.

The gNB can be split into a Central Unit (gNB-CU) and a Distributed Unit (gNB-DU). The gNB-CU hosts the RRC, SDAP and PDCP radio protocols, while the gNB-DU hosts the PHY, MAC and RLC radio protocols. The gNB-CU and the gNB-DU are connected via the F1 interface. Furthermore, the gNB-CU can be split into a Control Plane entity and a User Plane entity, which are referred to as gNB-CU-CP and gNB-CU-UP respectively. The gNB-CU-CP hosts the RRC and the instance of the PDCP protocol serving the control plane, while the gNB-CU-UP hosts the SDAP and the instance of the PDCP protocol serving the user plane. The gNB-CU-CP and the gNB-CU-UP are connected via the E1 interface. The gNB-CU-CP is connected to the gNB-DU via the control plane part of the F1 interface (F1-C), while the gNB-CU-UP is connected to the gNB-DU via the user plane part of the F1 interface (F1-U). The resulting gNB architecture inclusive of both the CU-DU split and the CP-UP split, is illustrated in Figure 5.43.

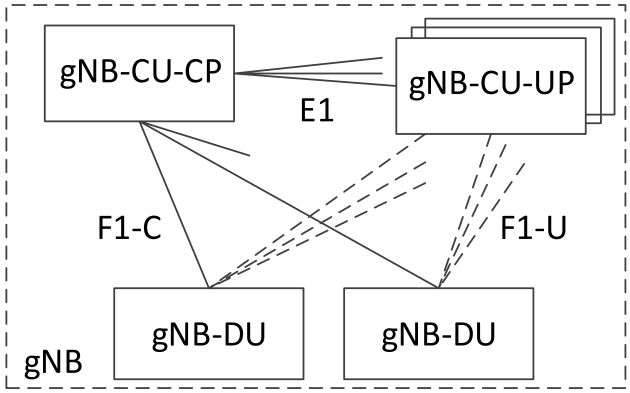


Figure 5.43. Architecture with gNB-CU-CP and gNB-CU-UP Split.

The main advantages of splitting the gNB-CU into gNB-CU-CP and gNB-CU-UP are the following:

- Possibility of optimizing the location of different RAN functions based on the scenario and the performance requirements
- Alignment with SDN concept and support for radio resource isolation for network slicing
- Independent scaling of CP and UP capacity for efficient resource utilization

Three network deployment scenarios are possible:

- *Centralized gNB-CU-CP and gNB-CU-UP:* The gNB-CU-CP and gNB-CU-UP are deployed in a centralized location, either as one or separate entities. The gNB-CU-CP coordinates the operation of several gNB-DUs. The gNB-CU-UP provides a central termination point for UP traffic in dual-connectivity (DC) configurations

- *Distributed gNB-CU-CP and centralized gNB-CU-UP:* The gNB-CU-CP is deployed in a distributed manner and co-located with the gNB-DU. The gNB-CU-CP supervises the operation of a single gNB-DU or of a local cluster of gNB-DUs. The gNB-CU-UP is centralized to provide a central termination point for UP traffic in DC configurations. In this scenario, the latency of the control signaling toward the UE is reduced as the gNB-CU-CP is co-located with the gNB-DU

- *Centralized gNB-CU-CP and distributed gNB-CU-UP:* The gNB-CU-CP is centralized to coordinate the operation of several gNB-DUs. The gNB-CU-UP is distributed and co-located with a single gNB-DU or with a local cluster of gNB-DUs and provides low UP latency to support latency-critical services

5.1.4 RELEASE 15 5G RAN SPECIFICATIONS

The Rel-15 5G RAN specifications are handled by the different RAN working groups. A new series of specifications covers 5G as shown in Figure 5.44. Working Group 1 (WG1) is responsible for the physical layer aspects of 5G, which is covered by the 38.2xx series of documents as shown in Figure 5.23.[124]

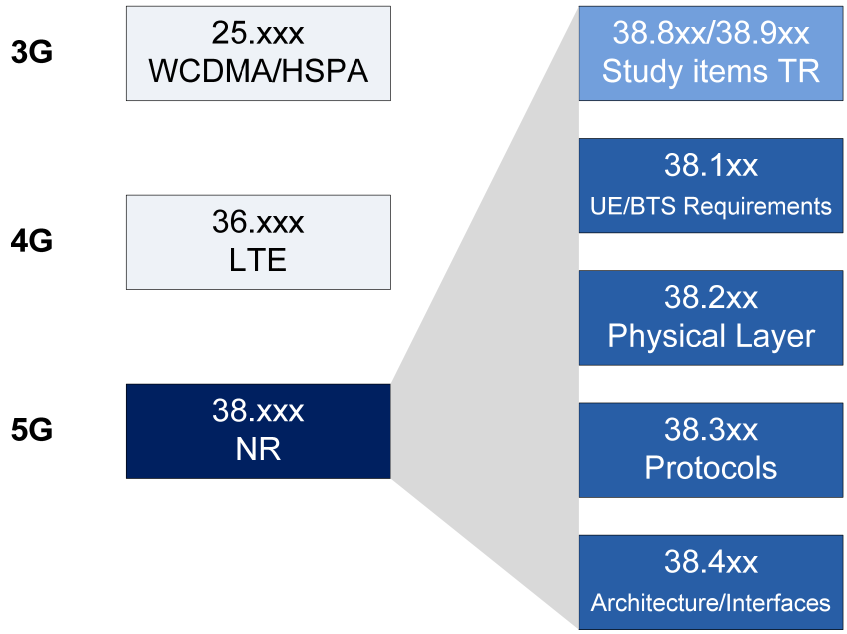


Figure 5.44. New Series of Specifications for 5G.

Table 5.23. 5G Physical Layer Specifications.

Specification	Title
38.201	NR; Physical layer; General description
38.202	NR; Services provided by the physical layer
38.211	NR; Physical channels and modulation
38.212	NR; Multiplexing and channel coding

[124] For information on the physical layer specification: http://www.3gpp.org/DynaReport/TSG-WG--r1.htm.

38.213	NR; Physical layer procedures for control
38.214	NR; Physical layer procedures for data
38.215	NR; Physical layer measurements

Working Group 2 (WG2) is responsible for the radio interface protocols and procedures of 5G, which is covered by the 38.3xx series of documents as shown in Table 5.24.[125]

Table 5.24. Interface Protocols and Procedures Specifications.

Specification	Title
37.324	Evolved Universal Terrestrial Radio Access (E-UTRA) and NR; Service Data Adaptation Protocol (SDAP) specification
37.340	NR; Multi-connectivity; Overall description; Stage-2
38.300	NR; Overall description; Stage-2
38.304	NR; User Equipment (UE) procedures in idle mode and in RRC Inactive state
38.305	NG Radio Access Network (NG-RAN); Stage 2 functional specification of User Equipment (UE) positioning in NG-RAN
38.306	NR; User Equipment (UE) radio access capabilities
38.321	NR; Medium Access Control (MAC) protocol specification
38.322	NR; Radio Link Control (RLC) protocol specification
38.323	NR; Packet Data Convergence Protocol (PDCP) specification
38.331	NR; Radio Resource Control (RRC); Protocol specification

[125] Interface protocols and procedures specification can be found at: http://www.3gpp.org/DynaReport/TSG-WG--r2.htm.

Working Group 3 (WG3) is responsible for the radio network architecture and interfaces of 5G, which is covered by the 38.4xx series of documents as shown in Table 5.25.

Table 5.25. 5G Radio Network Architecture and Interfaces Specifications.

Specification	Title
38.401	NG-RAN; Architecture description
38.410	NG-RAN; NG general aspects and principles
38.411	NG-RAN; NG layer 1
38.412	NG-RAN; NG signaling transport
38.413	NG-RAN; NG Application Protocol (NGAP)
38.414	NG-RAN; NG data transport
38.415	PDU Session User Plane protocol
38.420	NG-RAN; Xn general aspects and principles
38.421	NG-RAN; Xn layer 1
38.422	NG-RAN; Xn signaling transport
38.423	NG-RAN; Xn Application Protocol (XnAP)
38.424	NG-RAN; Xn data transport
38.425	NG-RAN; NR user plane protocol
38.455	NG-RAN; NR Positioning Protocol A
38.460	NG-RAN; E1 general aspects and principles

38.461	NG-RAN; E1 layer 1
38.462	NG-RAN; E1 signaling transport
38.463	NG-RAN; E1 Application Protocol (E1AP)
38.470	NG-RAN; F1 general aspects and principles
38.471	NG-RAN; F1 layer 1
38.472	NG-RAN; F1 signaling transport
38.473	NG-RAN; F1 Application Protocol (F1AP)
38.474	NG-RAN; F1 data transport

Working Group 4 (WG4) is responsible for the RF and performance aspects of 5G, which is covered by the 38.1xx series of documents and TS 38.307 as shown in Table 5.26.[126]

Table 5.26. 5G RF and Performance Specifications.

Specification	Title
38.101-1	NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone
38.101-2	NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone
38.101-3	NR; User Equipment (UE) radio transmission and reception; Part 3: Range 1 and Range 2 Interworking operation with other radios
38.101-4	NR; User Equipment (UE) radio transmission and reception; Part 4: Performance requirements

[126] RF and performance specification can be found at: http://www.3gpp.org/DynaReport/TSG-WG--r4.htm.

38.104	NR; Base Station (BS) radio transmission and reception
38.113	NR; Base Station (BS) and repeater Electro-Magnetic Compatibility (EMC)
38.124	NR; Electromagnetic compatibility (EMC) requirements for mobile terminals and ancillary equipment
38.133	NR; Requirements for support of radio resource management
38.141-1	NR; Base Station (BS) conformance testing Part 1: Conducted conformance testing
38.141-2	NR; Base Station (BS) conformance testing Part 2: Radiated conformance testing
38.307	NR; Requirements on User Equipment (UEs) supporting a release-independent frequency band

5.2 LTE/E-UTRAN ENHANCEMENTS

This section provides an overview of some of the main LTE/E-UTRAN features and enhancements being introduced or studied in Release-15 and related to the radio interface and RAN. Given the ongoing status of Rel-15, many features are yet to be finalized, thus descriptions may be partial.

The final section captures a list of other Rel-15 LTE features not previously described.

5.2.1 ENHANCEMENTS ON LTE-BASED V2X SERVICES

The work in RAN working groups on V2X features based on LTE technology continued in 2017 – 2018 with the phase 2 work item after Rel-14 was completed in March 2017. The motivation of this work item was to specify 3GPP V2X Phase 2 to support advanced V2X services as identified in SA1 TR 22.886. The specified technologies should be backward compatible with Rel-14 V2X for the delivery of safety messages, therefore, Cooperative Awareness Message / Decentralized Environmental Notification Message (CAM/DENM) messages.

SA1 working group has identified 25 different use cases in the TR 22.866 for advanced V2X services and they are categorized into four use case groups: vehicles platooning, extended sensors, advanced driving and remote driving. The description of each use case group is provided:

Vehicles Platooning enables the vehicles to dynamically form a platoon travelling together. All the vehicles in the platoon obtain information from the lead vehicle to manage this platoon. This information allows the vehicles to drive closer than normal in a coordinated manner, going in the same direction and travelling together.

Extended Sensors enables the exchange of raw or processed data gathered through local sensors or live video images among vehicles, road site units, devices of pedestrian and V2X application servers. The vehicles can increase the perception of their environment beyond of what their own sensors can detect and have a more broad and holistic view of the local situation. High data rate is one of the key characteristics.

Advanced Driving enables semi-automated or full-automated driving. Each vehicle and/or RSU shares its own perception data obtained from its local sensors with vehicles in proximity and that allows vehicles to synchronize and coordinate their trajectories or maneuvers. Each vehicle also shares its driving intention with vehicles in proximity.

Remote Driving enables a remote driver or a V2X application to operate a remote vehicle for those passengers who cannot drive by themselves or remote vehicles located in dangerous environments. For a case where variation is limited and routes are predictable, such as public transportation, driving based on cloud computing can be used. High reliability and low latency are the main requirements.

The requirements for each use case group are presented in the Table 5.27:

Table 5.27. Use Cases and Requirements.

Use case	Description	Payloads (Bytes)	Latency (ms)	Data rate (Mbps)	Range (meters)	Reliability (%)
Vehicles platooning	Vehicles dynamically form a platoon travelling together. Vehicles in the platoon obtain information from the leading vehicle to manage this platoon.	50 - [6500]	10 – 25	[50-65]	80 - 350	90 - 99.99
Advanced driving	Vehicle/RSU shares its own perception data obtained from its local sensors with vehicles in proximity and that allows vehicles to coordinate their trajectories.	[300 – 12000]	[3 – 100]	[10 – 53} (including UL: [50] DL: [0.5])	[360] - [700]	[90 - 99.999]

Extended sensors	Exchange of data gathered through local sensors or live video images among vehicles, RSUs, Pedestrian and V2X server.	[1600]	3 – 100	[10] - 1000	50 - 1000	90 – 99.999
Remote driving	Enables a remote driver or a V2X application to operate a remote vehicle.	-	[20]	UL: 25 DL: 1	-	[99.999]

To support the advanced V2X services as identified in TR 22.866, it was agreed to specify the following functionalities in RAN working groups:

- Carrier aggregation (up to 8 PC5 carriers)
- 64QAM
- Reduction of the maximum time between packet arrival at Layer 1 and resource selected for transmission
- Radio resource pool sharing between UEs using mode 3 and UEs using mode 4
- In addition, it was agreed to study feasibility and gain of Transmit diversity and Short TTI, assuming that they would co-exist in the same resource pools as Rel-14 functionality and potentially use the same scheduling assignment format
- Also, it was agreed to specify necessary RF requirements for the specified PC5 functionalities in Band 47 that were not covered by the Rel-15 work item “V2X new band combinations for LTE”

5.2.1.1 CARRIER AGGREGATION

Three use cases are considered for carrier aggregation:

- Parallel transmission of MAC PDUs (‘parallel’ means at the same or different transmission time, but on different carriers). The MAC PDU payloads are different
- Parallel transmission of replicated copies of the same packet (‘parallel’ means at the same or different transmission time, but on different carriers)
- Capacity improvements from the receiver perspective. It can be assumed that CA capable UE can receive simultaneously on multiple carriers. Simultaneous transmission on multiple carriers requires that UE transmit power needs to be divided to many carriers. Likely PC5 CA capable UEs support multiple RX chains but not necessarily many TX chains

In PC5 CA, operation in different component carriers is rather independent. For example, PSCCH and its associated PSSCH are transmitted in the same carrier, therefore, cross-carrier scheduling is not supported. Also per-carrier independent sensing procedure and resource (re)selection is supported and for transmission of a given MAC PDU, single carrier is provided by higher layer for its transmission. But, from synchronization point of view all the aggregated carriers use the same synchronization source both in TX and RX side.

5.2.1.2 64QAM

For PC5 transmissions, the MCS table for LTE PUSCH is reused, therefore, it already includes entries for 64QAM. However, some modifications are needed. In PC5 V2V transmissions the number of DMRS symbols is four and the last symbol is reserved as guard time and the first symbol is potentially punctured for AGC settling. Because of higher overhead than in PUSCH, coding rates can be high. To handle this issue, it is agreed that TBS scaling is used and the scaling factor value of 0.8 is used.

Rel-15 UEs will have the choice to use either Rel-14 MCS table or Rel-15 MCS table. It is agreed to use reserved bit(s) in Sidelink Control Information (SCI) to indicate Rl-15 PSSCH transmission format/features.

5.2.1.3 LATENCY REDUCTION

One way of reducing latency and also alleviating the half duplex problem is to introduce sTTI for PC5 transmissions. RAN1 has made studies on this feature and the current conclusion is that decisions having standardization impact are not made for this feature.

Regarding the reduction of latency between packet arrival and resource selection in Rel-14 LTE-V2X, latency of 100 ms is assumed for the baseline resource selection solutions but also 20 ms and 50 ms are introduced. When shorter delays are used for resource selection collision probability increases. Rel-15 V2V will likely support smaller latency and it will be (pre)configurable for each Prose Per Packet Priority (PPPP) by RRC.

5.2.1.4 TRANSMIT DIVERSITY

Extensive study on different transmit diversity schemes for V2V transmissions including Small-Delay Cyclic-Delay Diversity (SD-CDD), Space Time Block Code (STBC), Space Frequency Block Code (SFBC) and Precoding Vector Switching (PVS) in time domain was carried out in RAN1. It was shown that these schemes can provide gain for V2V transmissions. However, due to concerns on the impact on Rel-14 UEs with IRC receivers, there was no consensus to adopt a non-transparent tx diversity scheme for Rel-15 V2V. The agreement for Rel-15 was that transmit diversity is not specified in RAN1 specifications. The use of SD-CDD is assumed when the number of antennas is larger than one. Bounds for the delay will still be discussed. It is assumed that there is a UE capability to indicate the support of SD-CDD.

5.2.1.5 RESOURCE POOL SHARING

It has been agreed to:

- Support resource pool sharing between Rel-15 mode-3 (eNB scheduled) and Rel-15 mode-4 (distributed or autonomously scheduled) UE
- Support resource pool sharing between Rel-15 mode-3 and Rel-14 mode-4 UE
- Not support resource pool sharing between Rel-14 mode-3 and Rel-15 mode-4 UE

Also, to improve sensing operation of mode 4 UEs, it has been agreed that Rel-15 Mode 3 UEs shall set the resource reservation field in SCI to the SPS period.[127]

5.2.2 FURTHER NB-IOT ENHANCEMENTS

Narrowband IoT (NB-IoT) was introduced in 3GPP Rel-13 to provide low-power, wide-area cellular connectivity for IoT devices. It offers ultra-low complexity devices, coverage improvement of 20 dB compared to legacy GPRS, improved power efficiency with battery life of 10 years, massive cell capacity, and exception report latency of less than 10 seconds. In 3GPP Rel-14, enhancements were introduced including location services, multicast, higher peak data rates, support of paging and random access on non-anchor carriers, new user equipment (UE) power class with a maximum output power of 14 dBm suitable for small form-factor batteries, mobility enhancements, release assistance indication, and coverage authorization. In 3GPP Rel-15, further enhancements are being standardized for NB-IoT, including:

- Support for TDD
- Wake up signals for power consumption reduction
- Early data transmission during random access procedure for power consumption and overhead reduction
- Reduced system acquisition time through additional repetitions for SIB1-NB
- Support for physical layer scheduling request
- Relaxed monitoring for cell reselection
- Narrowband measurement accuracy improvement
- NPRACH range and reliability improvement
- Small cell support
- Support extended power headroom report range
- UE differentiation
- Support for RLC UM
- RRC connection release enhancement

Rel-15 enhancements were finalized in June 2018. This section provides a brief description of key Rel-15 enhancements.

5.2.2.1 DD SUPPORT

In Rel-15, support for TDD will be introduced. With respect to the requirements for TDD compared to FDD, latency and capacity targets may be relaxed. However, coverage target of 164 dB maximum coupling loss should be satisfied for at least one TDD configuration. In addition, NB-IoT will support LTE TDD UL/DL configurations 1, 2, 3, 4, and 5. Configurations 0 and 6 are not supported since they have too few downlink subframes. However, support for UL/DL configuration 6 can be revisited once the TDD design is near completion. All special subframe formats are supported.

[127] TR 22.886 V15.1.0 (2017-03), *Study on enhancement of 3GPP Support for 5G V2X Services*, 3GPP and RP-171740, Revision of WID: *V2X phase 2 based on LTE,* Huawei, CATT, LG Electronics, HiSilicon, China Unicom.

The design goal is to keep TDD design the same as FDD as much as possible to minimize changes. The following key points summarize design agreements that are unique to TDD:

- Downlink
    - TDD and FDD NB-IoT deployment are distinguished by the relative location of NPSS and NSSS
    - SIB1-NB may be transmitted on either anchor or non-anchor carrier as indicated by MIB-NB
    - For in-band operation mode, NPDSCH and NPDCCH can be transmitted on DwPTS when the number of OFDM symbols in DwPTS is greater than 3
    - For standalone and guard-band operation modes, NPDSCH and NPDCCH can be transmitted on DwPTS for all configurations
    - NRS mapping is the same as FDD for normal subframe. For special subframe, NRS mapping depends on the special subframe configuration
- Uplink
    - NPUSCH transmissions with 15 kHz subcarrier spacing are supported in all supported UL:DL configurations with the same definition of slot and resource unit as FDD
    - NPUSCH transmissions with 3.75 kHz are supported in UL:DL configurations #1 and #4 with the same definition of slot and resource unit as FDD
    - NPRACH uses only 3.75 kHz subcarrier spacing. Five NPRACH formats are defined and the supported formats depend on the UL:DL configuration
    - UpPTS is not used for NPUSCH and NPRACH

5.2.2.2 WAKE UP SIGNAL

A major enhancement in Rel-15 is the specification of a power-saving signal for improving the efficiency of receiver operation. In the use cases for which NB-IoT is targeted, the UE is likely to be scheduled to receive data infrequently by the eNB, but it may still be expected to be reachable by the network within a reasonable period. Therefore, the UE must continuously monitor the Paging Occasion (PO) for NPDCCH (scheduling a paging message) which consumes a lot of power. To mitigate this problem, a Wake-Up Signal (WUS) is being defined. Operation with the WUS is illustrated in Figure 5.45.

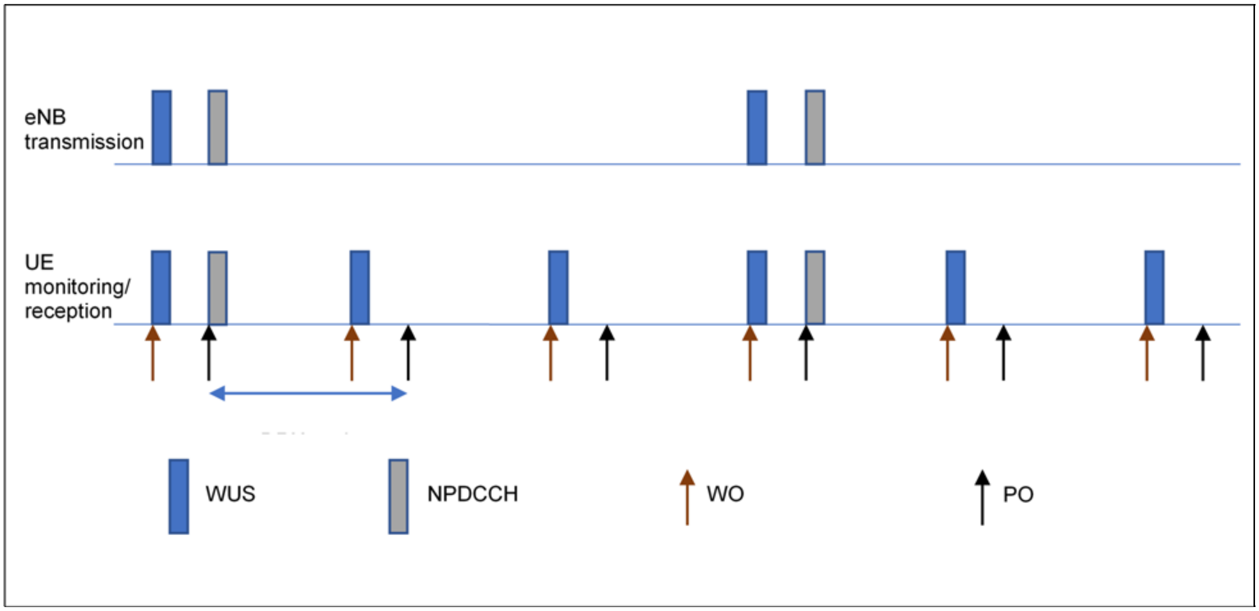


Figure 5.45. WUS Operation.

When the eNB needs to page the UE, it first transmits the WUS at a predefined time before the PO, referred to in the figure as the Wake-up Occasion (WO), to 'wake up' the receiver for normal operation. A UE configured with Discontinuous Reception (DRX) wakes up periodically from sleep to monitor the PO for NPDCCH. When the UE is also configured with WUS operation, a UE in DRX wakes up from sleep and monitors the WUS at the WO. Depending on the receiver architecture, a separate receiver may be used for WUS detection. If the UE detects the WUS, normal receiver operation is resumed and the UE monitors the PO for NPDCCH.

If the WUS is not detected, the UE does not monitor the PO and may go back to sleep. Since multiple UEs may share a PO, the WUS may be common to all those UEs. Therefore, since the WUS is transmitted if any UE within the PO is being paged, other UEs monitoring the WO would also detect the WUS and would monitor the PO even though they are not being paged. To prevent this wasteful operation, 3GPP is considering the usefulness of dividing UEs into sub-groups and associating a separate WUS for each sub-group of UEs. Although a maximum duration is defined for the WUS to allow a transmission to cover the entire cell, the actual duration of the transmitted WUS may be shorter (e.g., consisting of fewer repetitions of a base sequence) since the targeted UE may be in better coverage conditions such that the WUS need not be of maximum duration. A gap is provided between the end of the maximum duration allocated for the WUS and the PO to allow the UE to process the WUS and warm up if necessary before monitoring the PO.

5.2.2.3 EARLY DATA TRANSMISSION

In Rel-15, Early Data Transmission (EDT) during random access procedure will be introduced. EDT can reduce UE power consumption as well as messaging overhead. In the downlink, data can already be transmitted in Msg4 and there is no change for EDT. In the uplink, however, uplink data can be transmitted in Msg3. In this case, the eNB can broadcast the maximum transport block size (TBS) per coverage level to be used for EDT. The possible maximum transport block size values are {1000, 936, 808, 680, 584, 504, 408, 328} bits. UE can initiate EDT if the size of its data packet is smaller than the maximum indicated by the eNB. A dedicated set of preamble resources is reserved for exclusive use by UE performing EDT.

However, while UE can indicate its interest in EDT, it cannot indicate the amount of data in the buffer. To reduce padding by the UE, it has been agreed to let UE autonomously select a transport block size that is smaller than the broadcast maximum transport block size as shown in table 5.28. For instance, if the eNB broadcasts 936 bits as the maximum TBS, the UE can choose from {328, 504, 712, 936} bits for its actual transmission. The eNB will then perform blind decoding to detect the actual TBS used by the UE.

Table 5.28. Allowed Transport Block Sizes Based on Broadcast Maximum Transport Block Size.

Allowed TBS	Broadcast Maximum TBS							
	328	**408**	**504**	**584**	**680**	**808**	**936**	**1000**
TBS_1	328	328	328	328	328	328	328	328
TBS_2		408	408	408	456	504	504	536
TBS_3			504	504	584	680	712	776
TBS_4				584	680	808	936	1000

Note that blind decoding can be disabled or limited by the eNB to reduce its receiver complexity. In particular, the eNB can disable blind decoding (i.e., UE always has to transmit using the maximum configured TBS), limit it to two values (i.e., UE can choose from up to two values), or support up to four values (i.e., UE can choose from up to four values).

Furthermore, in the random-access response, the eNB can allocate legacy or EDT grant. For scheduling of EDT, the eNB will use the 5 spare values in the MCS/TBS/RU allocation field in the random-access response grant to indicate the resource unit. The TBS will be chosen by the UE. In this case, the number of repetitions changes depending on the actual TBS selected by the UE. The 3 legacy MCS/TBS/RU indices are used for fallback to non-EDT transmission.

5.2.2.3.1 REDUCED SYSTEM ACQUISITION TIME

To reduce system acquisition time, it has been agreed to transmit additional copies of SIB1-NB on an anchor carrier. This can be enabled only when the legacy SIB1-NB is already repeated 16 times. In this case, 16 additional copies are transmitted on subframe #3 with periodicity of 20ms. The additional transmissions are indicated by one of unused bits in MIB-NB. The subframes carrying additional SIB1-NB transmissions are marked as invalid downlink subframe. However, Rel-15 UEs still use those subframes marked as invalid for NPDCCH monitoring if those subframes don't carry additional SIB1-NB transmissions.

5.2.2.3.2 PHYSICAL LAYER SCHEDULING REQUEST

Currently, UE in RRC connected mode with pending uplink data will use random access procedure to inform the eNB of its buffer status. In Rel-15, physical layer Scheduling Request (SR) will be supported. This can reduce latency as well as overhead. Two types of SR transmission are considered – SR multiplexed with HARQ-ACK and dedicated SR. For SR multiplexed with HARQ-ACK, the scheduling request is indicated via orthogonal cover codes on ACK/NACK data symbols. It is currently a working assumption that dedicated SR will also be supported. If this working assumption is confirmed, the dedicated SR will be transmitted in NPRACH resource using NPRACH based signal.

5.2.2.3.3 RELAXED MONITORING

In Rel-15, relaxed monitoring will be introduced to reduce UE power consumption. When enabled, the UE can relax neighbor cell detection and measurements when its measured cell selection value does not deviate from the reference value by more than a delta (i.e., measure values are relatively stable). This is intended for stationary UE to reduce cell reselection monitoring instances. In this case, the UE may choose to perform intra-frequency or inter-frequency measurement only once every 24 hours. Otherwise the UE perform neighbor cell detection and measurements according to current requirements.

5.2.2.3.4 NARROWBAND MEASUREMENT ACCURACY IMPROVEMENT

In Rel-15, Narrowband Secondary Synchronization Signal (NSSS) maybe used in addition to the Narrowband Reference Signal (NRS) for improving measurement accuracy. To aid the UE, the eNB may signal the power difference between the NSSS and NRS, and the number of consecutive NSSS occasions that use different precoders for NSSS transmission.

5.2.2.3.5 NPRACH RANGE AND RELIABILITY IMPROVEMENT

In Rel-15, two enhancements are being standardized for the NPRACH: range enhancement to support 100 km cell size; and reliability improvement to reduce impact from inter-cell interference. For range enhancement, it has been agreed to introduce a new NPRACH format with 1.25 kHz subcarrier spacing with minimum hop distance of 1.25 kHz and cyclic prefix length of 800 μs. The NPRACH bandwidth is an integer multiple of 45 kHz and may be configured to overlap with legacy NPRACH regions. For reliability enhancement, scrambling will be used to randomize inter-cell interference.

5.2.2.3.6 SMALL CELL SUPPORT

Rel-15 will introduce small cell support for NB-IoT. For this enhancement, the work is mostly confined to defining eNB RF transmitter and receiver requirements. It is expected that the physical layer will not require any change to support small cell.

5.2.2.3.7 EXTENDED POWER HEADROOM REPORT RANGE

In NB-IoT, the Data Volume and Power Headroom Report (DPR) is used to inform the eNB about the amount of data available in the uplink buffer and the difference between maximum and estimated power for NPUSCH transmission. Only 4 power headroom levels are defined for NB-IoT in Rel-13/Rel-14. In Rel-15, two reserve bits in the DPR will be used to increase the number of reporting levels to 16. This will provide better range and granularity for the power headroom report.

5.2.2.3.8 UE DIFFERENTIATION

It has been agreed to introduce vendor specific UE differentiation information IE on S1-AP/X2-AP interface for NB-IoT. This is intended to exchange UE differentiation information that has been monitored in the eNB. Differentiation information may include information regarding communication pattern (for example, whether communication is periodic, whether UE is stationary, and etcetera), traffic profile (for example, single packet transmission, typical packet size, and etcetera), and battery indication (for example, non-replaceable, non-rechargeable battery, and etcetera).

5.2.2.3.9 SUPPORT FOR RLM UM

Radio link control (RLC) unacknowledged mode (UM) will be supported for the Dedicated Radio Bearer (DRB) in Rel-15. This mode was already supported for single-cell point-to-multipoint transmission in Rel-14 and is now extended to the DRB as well. RLC UM has lower overhead due to the absence of status messages required in acknowledged mode. This may result in lower UE power consumption.

5.2.2.3.10 RRC CONNECTION RELEASE ENHANCEMENT

In Rel-15, upon reception of RRC Connection Release Message, UE can go to Idle mode immediately after sending HARQ-ACK without any waiting time. This eliminates the waiting time which may be as long as 10 seconds for Rel-13 UEs and therefore reduces UE power consumption.

5.2.3 UE POSITIONING ACCURACY ENHANCEMENTS FOR LTE

In March 2017, 3GPP approved a new Rel-15 work item on UE Positioning Accuracy Enhancements for LTE with a planned completion of June 2018. One of the main objectives of the work item is enhancements to GNSS positioning and support for broadcast of positioning assistance data. These enhancements involve introduction of Real Time Kinematic (RTK) GNSS, which is a differential GNSS positioning technology which enables positioning accuracy improvement from meter level to decimeter or even centimeter level in the right conditions in real-time by exploiting the carrier phase of the GNSS signal rather than only the code phase. Naturally, Rel-15 adds support for a new UE GNSS carrier phase measurement [TS 36.214]. RTK GNSS technology is nothing new and had already been standardized in different regional GNSS standards with RTCM being one. The basic concept of RTK GNSS is explained in the next paragraph.

Centimeter-accurate positioning using RTK GNSS can be achieved outdoors by detecting signals transmitted from conventional GNSS satellites. In conventional A-GNSS positioning, the UE measures the code phase of signals transmitted from multiple visible satellites, enabling accuracy on the order of a couple of meters. To achieve significantly improved accuracy, RTK GNSS requires three additional technical enhancements: 1) the UE measures the carrier phase (in addition to the code phase) of each satellite signal, 2) one or more reference receivers (also called reference stations) in the vicinity of the UE, each with precisely known position, measures the code and carrier phase measurements of the same GNSS signals observed by the UE and 3) raw measurements from these reference receivers (also called corrections data) need to be communicated to the UE. Because the location of the reference receiver(s) is known, the raw observable measurements can be used to compute corrections which characterize GNSS error sources due to atmospheric effects, satellite orbits and signals. Using these corrections in conjunction with the code and carrier phase measurements at the UE, an RTK GNSS algorithm can achieve centimeter-level accuracy in positioning.

The RTCM Special Committee No. 104 published standard RTCM 10403.3 Differential GNSS Services – Version 3 is used as the basis for the Release 15 3GPP work item on UE Positioning Accuracy Enhancements for LTE. The use of cellular network to broadcast corrections data is where 3GPP adds value as it can be done over a wide geographic area. Broadcast of corrections data (which is considered as positioning assistance data) can be encrypted and provided as a subscription-based service. In Release 15 the system information broadcast function of the RRC protocol [TS 36.331] is used for broadcast of corrections/positioning assistance data. 3GPP may add additional enhancements to broadcast service or add new assistance data to enable new high precision positioning services.

There are several RTK GNSS techniques or service levels like basic single reference stations RTK GNSS service, network-RTK GNSS service which involves a network of continuously operating reference stations, precise point positioning (PPP), and etcetera. In Rel-15 3GPP supports several network-RTK methods [TS 36.305] through Master Auxiliary Concept (MAC) method, Non-physical Reference Station method and FKP method. Also, the SSR/PPP method is supported in Rel-15. The different network-RTK methods and SSR/PPP method results in the broadcast [TS 36.331] or dedicated [TS 36.355] signaling of different types of corrections assistance data. Within the 3GPP reference architecture for location services the positioning server (E-SMLC) obtains the corrections data and provides it to the UE but how it obtains the corrections data is not standardized in 3GPP and thereby allowing the possibility of use of third party correction services providers. The E-SMLC supports transport of corrections/positioning assistance data from E-SMLC to the eNB using the LPPa protocol [TS 36.455].

5.2.4 1024QAM FOR LTE DL

3GPP Rel-15 has extended LTE DL modulation order to 1024QAM (from 256QAM, which was introduced in Rel-12), allowing to achieve higher peak data rates and spectral efficiency (in favorable scenarios).

Among the main motivations and target use cases, the focus was on:

- devices with high capacity connection and data rate requirements (e.g. a laptop or smartphone in a small cell, supporting video streaming, gaming, tethering, and etcetera), or
- stationary/nomadic intermediate devices (e.g., CPEs, IOT aggregation points, wireless backhaul gateways), further communicating with end users via other links

Such high capacity (stationary/low-mobility) wireless links are known to have distinctive RF characteristics, for example, better LoS and/or higher SNR, which enable to exploit higher order modulation gains.

Work started [WID RP-171738] with a study phase on the feasibility and performance benefits of DL 1024QAM, whose outcome is captured in a technical report [TR 36.783].

The final specification work consisted in introducing DL 1024QAM, together with other enhancements targeting high capacity stationary wireless links, therefore, DM-RS overhead reduction.

With focus on DL1024QAM, main standard changes include:

- Updating L1 CQI/MCS/TBS tables, and other aspects, to support 1024QAM for PDSCH. For example, a larger max TBS size (125808 bits, for a single layer) allows to achieve a peak L1 data rate of ~125Mbps per layer (with 20MHz bandwidth)
- Defining higher-layer procedures and signaling, including UE capability / categories (yet to be finalized)
- Defining RRM/RF aspects (e.g., EVM and BS power range) and performance requirements (e.g,. on demodulation and CSI reporting)

5.2.5 ENHANCING LTE CARRIER AGGREGATION (CA) UTILIZATION

LTE Carrier Aggregation (CA), a widely used feature nowadays, continues to be enhanced in standards. In Rel-13 CA was extended to cover up to 32 aggregated carriers (from the earlier maximum of 5). Rel-15 adds some latency and signaling overhead improvements, compared to the legacy CA framework (based on Rel-10), such as secondary cell (SCell) quick configuration, SCell configuration signaling optimization, SCell new Dormant State to enable low SCell activation delay.

The main motivations come from the fact that those delays are known to reduce the efficiency of radio resource and CA usage, especially in small cell multi-carrier deployments with large number of carriers. In dense small cell deployments, there is also substantial signaling overhead for each Scell to be (separately) configured. Optimized and efficient CA latency is also important for LAA scenarios, for example, to increase traffic offloading gains as data is moved froma licensed (Pcell) to unlicensed (Scell) carrier.

When the number of aggregated carriers is extended beyond 5 carriers, the delays and signaling overhead are expected to increase even further. Dual Connectivity (DC) framework has similar constraints as CA framework, thus also benefiting from similar latency reduction techniques.

The enhancements targeted by the normative work focused on macro and small cell deployment scenarios with (CA) support beyond 5 carriers (up to 32). Such enhancements aim to be applicable for traditional CA deployments, as well as LAA and DC scenarios.

More specific standard changes are summarized as:[128]

- Reduced delays in Scell set-up, including transition from idle to connected, by optimizing the following:
    - UE Measurements on Scell candidates (e.g. network assistance in identifying Scell candidate carriers, and best effort UE measurements for Scell candidates)
    - UE Measurement reporting (e.g. utilize UE's earlier idle mode measurements for configuring Scell)
    - Scell configuration and fast SCell activations (e.g. the network could immediately configure Scell for CA without additional measurements when UE's earlier idle mode measurements are available for setting up Scell)
    - Reduced Scell configuration siganling and activation signaling overhead
- Consider optimizations related to UE mobility and carrier switching in licensed and unlicensed deployment using LAA and configurations of multiple Scells
- Specify necessary UE/BS performance requirements, for example, demod and RRM related

5.2.6 LAA FOR THE CBRS 3.5GHZ BAND IN US

This Rel-15 feature was completed in December 2017. The motivation comes mostly from new spectrum allocation and requirements for commercial use of the 3550-3700 MHz band (US/FCC, from 2015) to support the mobile broadband service called "Citizens Broadband Radio Service (CBRS)".

The standard work aimed at defining usage of LAA/eLAA (i.e., LTE Frame Structure 3) in the 3550-3700 MHz CBRS band. Requirements have been defined for LAA as well as eLAA operation in that band. Detailed objectives and normative Rel-15 outcomes are:[129]

- Specified new band characteristics/arrangements, therefore, introduced Band 49, and related channel roster
- Specified LTE access with Frame Structure 3 for the 3550-3700 MHz band (to operate in USA), therefore aggregating with a licensed anchor carrier
    - downlink (LAA) access in the band, or

[128] WID RP-180561.
[129] WID 3GPP RP-172626.

- uplink and downlink (eLAA) access in the band

- Defined Core and Performance requirements for the band
  - Applicability is limited to CBSD's with a maximum conducted transmit power of 24 dBm and a maximum EIRP of 30 dBm in 10 MHz
  - Channel bandwidths to be supported are: 10MHz and 20MHz

- Specified core requirements for the support of E-UTRA Carrier Aggregation (2DL/2UL) between Band 2 and the 3550-3700MHz band supporting Frame Structure 3

Some examples of the new band/channel arrangements are captured in the following tables:[130]

Table 5.29. E-UTRA Operating Bands – Band 49.

E-UTRA Operating Band	Uplink (UL) operating band F_{UL_low} – F_{UL_high}	Downlink (DL) operating band F_{DL_low} – F_{DL_high}	Duplex Mode
49	3550 MHz – 3700 MHz	3550 MHz – 3700 MHz	TDD[1,2]
NOTE 1: This band is restricted to licensed-assisted operation using Frame Structure Type 3 NOTE 2: In this version of the specification, restricted to E-UTRA DL operation when carrier aggregation is configured.			

Table 5.30. E-UTRA Channel Numbers – Band 49.

E-UTRA Band	Downlink			Uplink		
	F_{DL_low} MHz]	$N_{Offs\text{-}DL}$	Range of N_{DL}	F_{UL_low} [MHz]	$N_{Offs\text{-}UL}$	Range of N_{UL}
49	3550	56740	56740 – 58239	3550	56740	56740 – 58239

Table 5.31. Inter-band CA Operating Band Definitions in Band 2 and Band 49.

E-UTRA CA Band	E-UTRA Band	Uplink (UL) operating band F_{UL_low} – F_{UL_high}			Downlink (DL) operating band F_{DL_low} – F_{DL_high}			Duplex Mode
CA_2-49	2	1850 MHz	–	1910 MHz	1930 MHz	–	1990 MHz	FDD
	49	3550 MHz	--	3700 MHz	3550 MHz	--	3700 MHz	TDD

Table 5.32. E-UTRA CA Configurations and Bandwidth Combos for Inter-band CA (Bands 2 and 49).

E-UTRA CA configuration / Bandwidth combination set										
E-UTRA CA Configuration	Uplink CA config.	# Bands	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz	Max aggr. BW [MHz]	Bandwidth combo set
CA_2A-49A	-	2			Yes	Yes	Yes	Yes	40	0

5.2.7 ENHANCED LTE SUPPORT FOR AERIAL VEHICLES

This section captures a summary of both study and normative work conducted in Rel-15 for LTE Support of Aerial Vehicles.

[130] 3GPP TR 36.790.

5.2.7.1 STUDY ON ENHANCED LTE SUPPORT FOR AERIAL VEHICLES

The main goal of Rel-15 study item on enhanced LTE support for aerial vehicles was to investigate the capability of LTE to provide connectivity services to low altitude unmanned aerial vehicles. Performance of LTE networks with up to LTE Rel-14 functionality to support aerial vehicles was assessed and the outcomes of the study were documented in 3GPP TR 36.777. An overview of the key activities and outcomes is provided.

5.2.7.1.1 PERFORMANCE REQUIREMENTS

Performance requirements for two types of data traffic were defined in the study. For command and control type of traffic, a one-way latency requirement of 50 ms from eNodeB to an aerial vehicle, with data rate requirement of 60-100 kbps for both uplink and downlink, and a reliability requirement of 10^{-3} packet error loss rate were identified. For application data type of traffic, the latency requirement was identified to be similar to LTE terrestrial users and the uplink data rate requirement was identified to be up to 50 Mbps.

5.2.7.1.2 SCENARIOS AND CHANNEL MODELS

During the study, three scenarios were considered, namely urban-micro with aerial vehicles, urban-macro with aerial vehicles, and rural-macro with aerial vehicles. In each of these scenarios, the ratio of aerial vehicles in the cell were varied to study the impact of supporting aerial vehicles with different densities in the cell. For the three scenarios, the channel models of 3GPP TR 38.901 were adopted for users on the ground. New models for LOS probability, pathloss, shadow-fading, and fast-fading were defined to characterize the channels between aerial vehicles and eNodeBs.

5.2.7.1.3 UPLINK AND DOWNLINK INTERFERENCE ISSUES

Evaluations were performed during the Rel-15 study, and interference issues were identified in both uplink and downlink for scenarios involving aerial vehicles. Since aerial vehicles experience more line-of-sight (LOS) propagation conditions compared to typical terrestrial users, if not properly managed they were found to cause interference to more cells in the uplink than a typical terrestrial user equipment could. In the downlink, the aerial vehicles were found to observe downlink interference from more cells compared to a typical terrestrial user equipment.

5.2.7.1.4 POTENTIAL SOLUTIONS FOR INTERFERENCE DETECTION AND FLYING MODE DETECTION

Since interference detection is generally required prior to applying interference mitigation techniques, various solutions were studied during Rel-15. One identified solution is to use existing measurement framework for RSRP, RSRQ, and RS-SINR reporting for interference detection. As an improvement, enhancements to measurement reporting mechanisms such as the definition of new measurement events, enhancements to measurement triggering conditions were identified. Additionally, UE based information such as mobility history report, speed estimation, timing advance adjustment values, and location information can be used by the network as a possible solution for interference detection.

Exchanging of information between eNodeBs was also discussed as a potential solution for detection of an aerial vehicle causing interference in uplink. Some examples of information exchanged between the eNodeBs include uplink reference signal confirmation of aerial vehicles and measurement quantities (therefore, RSRP, RSRQ, RS-SINR, CSI) reported by the aerial vehicle. However, the feasibility of this solution depends on the type of backhaul and the feasibility of exchanging such information over a large number of eNodeBs.

An aspect related to interference detection is flying mode detection as interference from/to an aerial vehicle is usually more prominent when the aerial vehicle is flying well above the ground. Various solutions were identified for flying mode detection. Some examples of identified solutions for flying mode detection are:

- Using altitude or location information from the aerial vehicle, using the flight mode indication from the aerial vehicle, or using enhanced measurement reporting from the aerial vehicle are one set of solutions identified which require specification enhancements
- Using mobility history reports/patterns is another identified solution which does not require specification enhancements

5.2.7.1.5 POTENTIAL SOLUTIONS FOR UPLINK INTERFERENCE MITIGATION

The following uplink mitigation techniques were evaluated and found to be beneficial for LTE networks serving aerial vehicles:

- *Uplink Power Control:* techniques such as applying UE specific fractional pathloss compensation factor, the application of UE specific P_0 parameter, and the use of closed loop power control with increased step size of the transmit power control command were identified. These techniques require small specification enhancements on top of what is already supported in LTE up to Release-14
- *FD-MIMO:* the use of full-dimensional MIMO (FD-MIMO) was identified as another solution. Since FD-MIMO is already supported in LTE up to Rel-14, no further specification enhancements are needed for this technique
- *Directional Antennas at Aerial Vehicles:* this technique is yet another identified solution which is implementation-based. Hence, no specification enhancements are needed on top of what is already supported in LTE up to Rel-14.

5.2.7.1.6 POTENTIAL SOLUTIONS FOR DOWNLINK INTERFERENCE MITIGATION

The following downlink mitigation techniques were evaluated and found to be beneficial for LTE networks serving aerial vehicles:

- *FD-MIMO:* the use of FD-MIMO was identified as a solution. Since FD-MIMO is already supported in LTE up to Release-14, no further specification enhancements are needed for this technique
- *Directional Antennas at Aerial Vehicles:* this technique is yet another identified solution which is implementation-based. Hence, no specification enhancements are needed on top of what is already supported in LTE up to Rel-14
- *Receive Beamforming at Aerial Vehicles:* this solution is implementation-based and does not require specification enhancements
- *Intra-site Joint Transmission COordinated Multi-Point (CoMP):* in this solution, data is transmitted jointly from multiple cells belonging to the same site to the user equipments. Since this is already possible in LTE up to Rel-14, no further specification enhancements are needed for this solution
- Coverage Extension: coverage extension techniques were studied to enhance synchronization and initial access performance of aerial vehicles. Since coverage extension is already supported in LTE up to Rel-14, no specification enhancements are needed

It should be noted that other solutions such as transmitting data and control channels in a coordinated fashion over multiple sites were also discussed in the Rel-15 study. However, the specification impact for these techniques and the benefit these techniques bring over others with no specification impact (listed above) needs further study.

5.2.7.1.7 MOBILITY PERFORMANCE AND POTENTIAL ENHANCEMENTS

During the Rel-15 study, mobility simulations and field trial results showed that the mobility performance of an aerial vehicle is worse than terrestrial user equipment. The underlying reason for this is that due to downlink interference and down-titled eNodeB antennas, the aerial vehicles may experience more handover failures, more radio link failures, longer handover interruption time, and etcetera. However, simulations performed during the Rel-15 study also showed that the mobility performance was better in the rural macro scenario when compared to the urban macro scenario.

The following techniques were identified to improve the mobility performance of aerial vehicles:

- Handover procedure enhancements such as conditional handover, introduction of information such as location information, airborne status of aerial vehicle, and flight path plans

The techniques above require specification enhancements beyond what is supported in LTE up to Rel-14.

5.2.7.1.8 IDENTIFICATION OF AERIAL VEHICLES

Identification of aerial vehicles is of paramount importance as regulations in different regions may require certain conditions to be met before the LTE network can be used for aerial vehicle connectivity. During the Rel-15 study, a solution was identified where subscription information in combination with radio capability indication is used for aerial vehicle identification. This solution requires specification enhancements.

5.2.7.1.9 CONCLUSIONS

The study item concluded with the following findings:

- LTE networks are capable of serving aerial vehicles
- There may exist some challenges related to uplink/downlink interference and mobility performance
- These challenges are more visible when the density of the aerial vehicles in a cell is high
- Implementation-based solutions and solutions requiring specification enhancements are identified to address the interference and mobility related issues identified during the study
- Specification enhancements are beneficial to more efficiently serve aerial vehicles in LTE networks while limiting the impact to existing LTE users

5.2.7.2 STANDARD SUPPORT FOR LTE AERIAL VEHICLES

The Rel-15 work item on enhanced LTE support for aerial vehicles is based on the preceding study item. The work item aims to specify features that can improve the efficiency and robustness of terrestrial LTE networks for providing aerial connectivity services, particularly for low altitude unmanned aerial vehicles (a.k.a., drones). The key features are:

- Subscription-based Aerial UE identification and authorization

- Height and location reporting based on the event that the UE's altitude has crossed a network-configured threshold altitude
- Interference detection based on a measurement reporting that is triggered when a configured number of cells fulfils the triggering criteria
- Introduction of UE specific fractional pathloss compensation factor for UL power control
- Signaling of flight path information from UE to E-UTRAN

Support of Aerial UE function is stored in the user's subscription information in HSS. HSS transfers this information to the MME from where it can be provided to the eNB via the S1 AP. In addition, for X2-based handover, the source eNB can include the subscription information in the X2-AP Handover Request message to the target eNB. For the intra and inter MME S1 based handover, the MME provides the subscription information to the target eNB after the handover procedure. The eNB may then combine this information with radio capability indication from the aerial UE in order to identify whether the aerial UE has been authorized to be connected to E-UTRAN network while flying.

The flying mode detection is a separate issue. The flying mode detection is also related to interference detection as the interference conditions for flying aerial UE are different from aerial UE in terrestrial mode. For interference detection, which may also serve as input to flying mode detection, an enhancement to existing events triggering RSRP/RSRQ/RS-SINR reports was introduced. The UE may be configured to trigger an event such as A3, A4, A5, which all consider neighbor cell measurements, such that measurement report is triggered when multiple cell measured RSRPs (RSRQs/RS-SINRs) are above a threshold. For example, event A3 triggers when neighbor cell measured RSRP becomes better than the measured RSRP of PCell/PSCell by a certain amount. The enhanced triggering would require, for example, three neighbor cell RSRP values to become higher than the PCell/PSCell RSRP value by a certain amount.

Another input to flying mode detection is event triggered height and location reporting. A new configurable event within RRM with height threshold is introduced for Rel-15 Aerial UEs. When UE is configured with this event, a report is triggered when UE's altitude crosses the threshold altitude. In addition to flying mode detection, the exact height information is considered useful as E-UTRAN may choose to reconfigure for example measurements for the UE when it crosses a height threshold. Figure 5.46 depicts this situation.

For UL interference mitigation, UE specific fractional pathloss compensation factor has been introduced. In addition, the range of the UE specific P_0 parameter (which is an open loop power control parameter) is extended to further help mitigate the UL interference for aerial UEs to multiple cells. The introduction of UE specific power control parameter enables E-UTRAN to reconfigure the parameter per UE, for example, based on RSRP reports or based on height reports.

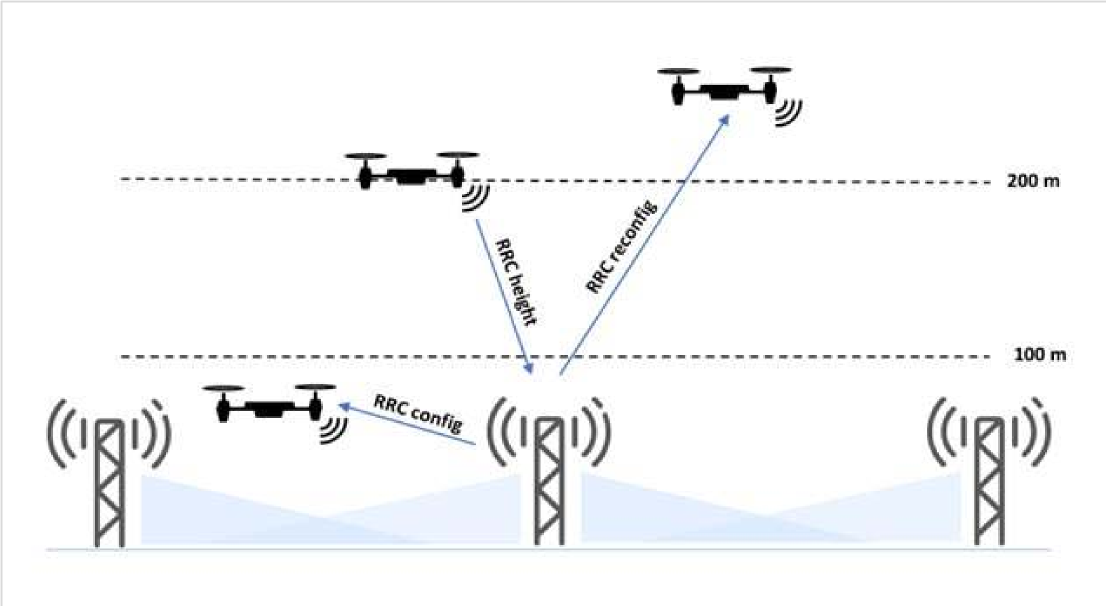


Figure 5.46. E-UTRAN Reconfigures Aerial UE Based on Flying Altitude.

Finally, Rel-15 introduces support for E-UTRAN to request flight path/direction information from UE using RRC signaling.

5.2.8 UL DATA COMPRESSION IN LTE

The Uplink Data Compression (UDC) Study Item (SI) was initiated in February 2017. The motivation for this study is that the air interface may get congested in uplink, for example with DL-heavy TDD configurations and hence it may, in some scenarios, be beneficial to compress the uplink data before it is sent over the air interface.

The scope of SI was primarily to identify potential compression/decompression algorithms and to evaluate these algorithms using different UL oriented traffic PCAP files such as FTP UL data, long video UL data, SIP Signaling, Web-Surfing (UL), and etcetera.

Two compression algorithms were proposed:

- Adaptive Packet Data Compression (APDC) [TR 36.754]
- Deflate RFC 1951

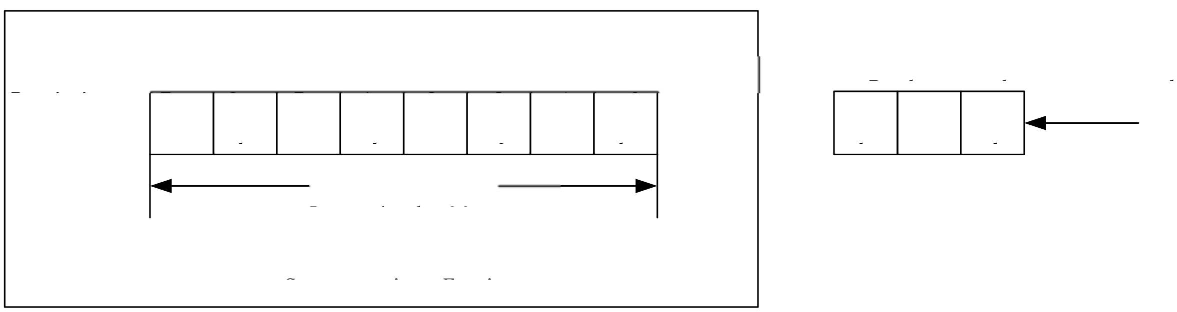
Both Deflate and APDC uses LZ77 compression algorithm. Deflate further uses Huffman coding (Variable length encoding) to further compress some of the parameters and output of LZ77.

APDC on the other hand optimizes LZ77 compression algorithm. It adds some intelligence as which packet should be inserted into buffer to get maximum gain. It employs two compression formats and depending upon the possible gain achieved the algorithm can select one of them or both of them.

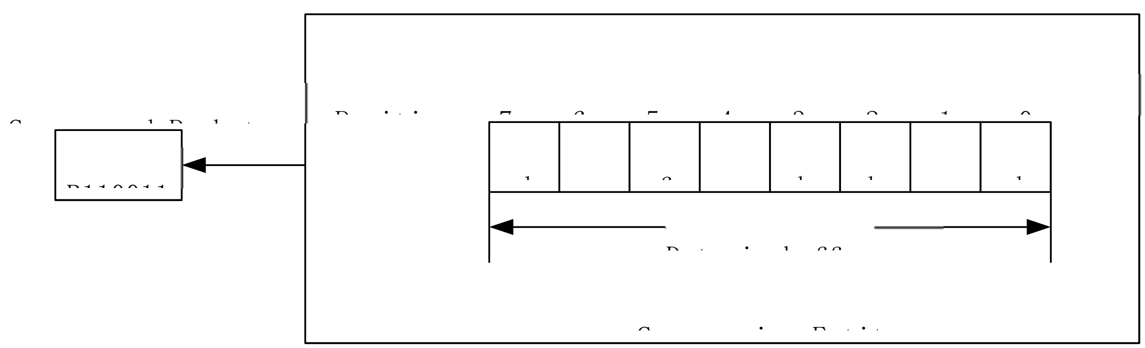
The LZ77 algorithm achieves compression by replacing repeated occurrences of data with a 8 + 15 bit <*length, distance*>-pair that specifies an earlier copy of the data in the previous uncompressed data stream. The *length* parameter indicates the length of the matching copy of data, and the *distance* parameter indicates how far back in the previous uncompressed data stream the duplicate occurred. To find matches, the compressor must keep a certain amount of the most recent data in a sliding window buffer. In the same way, the decompressor must have access to the same data to be able to interpret the matches referred to in the compressed packet. For compression/de-compression to work it is crucial that the buffered data on the compressor and the decompression side is synchronized; any loss of data would force the algorithm out-of-synch.

In the DEFLATE algorithm, the *length* of the matching pattern is restricted to 3-258 bytes, with a lookback length (*distance*) of maximum 32 KB where as APDC supports up to 16 KB.

UDC algorithm based upon DEFLATE and APDC needs to have a buffer memory context on the compressor and decompressor side. For example, to perform cross-packet compression, in DEFLATE a FIFO buffer is used to buffer original packets which have been compressed. Within the packets which have not been compressed, if a repeated string in buffer is identified, a backreference is inserted linking to the previous location and the length of that identified string, as shown in Figure 5.47.



(a) Before compression



(b) after compression

Figure 5.47. Illustration of Packet Compression.

In Figure 5.47, the buffer size is 8 bytes. When a new packet which has content of “bcd” coming, a cross-packet match can be identify in the buffer, with the previous position 6, length 3. The new packet which original length is 3 byte can be compressed to 6 bits (therefore, 3 bits to identify 8 positions in the buffer, and 3 bits for length). After compression, the new packet is inserted in the buffer. The decompressor similarly has a decompression entity with same buffer content so that it can decompress the compressed packet.

Both the algorithms had similar performance, however there was eventually a preference to standardize only the Deflate algorithm.

One advantage that UDC can have over ROHC is that UDC can target both header and payload. However, if the payload is encrypted, the payload cannot be compressed. With the increasing trend of encrypted traffic, the compression gains achieved by UDC may shrink over years, whereas from ROHC stable compression gain is expected as shown in Figure 5.48.

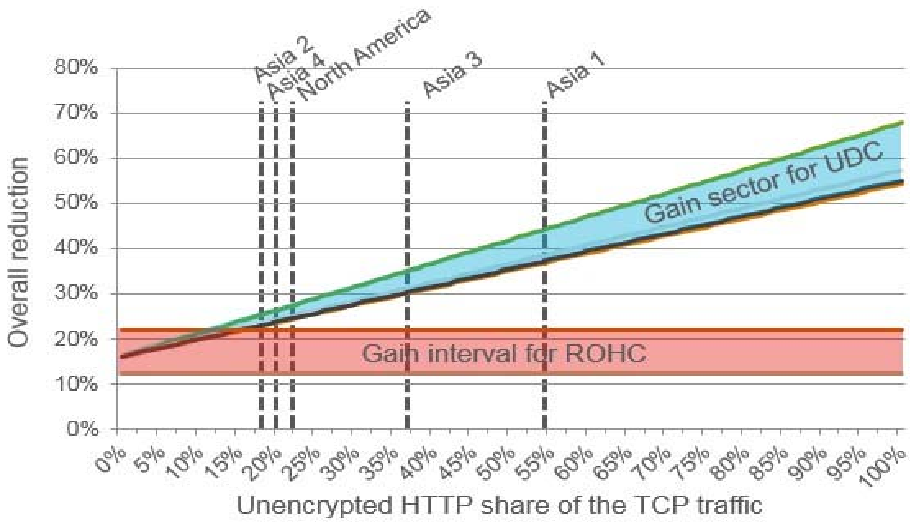


Figure 5.48. Unencrypted HTTP Share of the TCP Traffic.

The general trend in many areas of the world is that encryption is growing and therefore the benefit of UDC is not expected to be very significant in these areas, but, there may be other areas of the world where the ratio of encryption is less and, in those areas, UDC can result in a considerable compression of the UL traffic.

5.2.9 OTHER LTE REL-15 FEATURES/ENHANCEMENTS

A list of other LTE Rel-15 features/enhancements is provided below, for information:[131]

- Highly Reliable Low Latency Communication for LTE
- Even Further Enhanced MTC for LTE
- Enhancements to LTE operation in Unlicensed Spectrum
- Study on Enhancements to D2d, and UE-to-NW Relay for IOT and Wearables

[131] More details and references can be found in the 3GPP Work Plan.

- Increased number of E-UTRAN data bearers
- Further video enhancements for LTE
- Quality of Experience (QoE) Measurement Collection for streaming services in E-UTRAN
- Bluetooth/WLAN measurement collection in LTE Minimization of Drive Tests (MDT)
- Further enhancements to Coordinated Multi-Point (CoMP) Operation for LTE
- LTE Advanced intra/inter-band Carrier Aggregation enhancements, including
  - LTE Advanced intra-band CA Rel-15 for xDL/yUL (contiguous / non-contiguous spectrum
  - LTE Advanced inter-band CA Rel-15 for xDL/1UL with x=2, 3,4,5
  - LTE Advanced inter-band CA Rel-15 for xDL/1UL with x>5
  - LTE Advanced inter-band CA Rel-15 for xDL/2UL with x=3,4,5
  - LTE Advanced inter-band CA Rel-15 for xDL/3UL with x=3,4,5
  - LTE Advanced inter-band CA (4DL/4UL) of Band 41C & 42C
- Other enhancements related to new bands/RF/UE requirements, e.g.
  - V2X new band combinations for LTE
  - Additional LTE bands for UE category M0/M1/M2 and/or NB1/2 in Rel-15
  - Extended-Band12 new E-UTRA Band
  - ProSe Support for Band 72 in LTE
  - 450 MHz Band for LTE in Region 3
  - US 600 MHz Band for LTE
  - New LTE band for 3.3-3.4 GHz for Africa
  - Introduction new band support for 4Rx antenna ports for LTE for REL-15
  - LTE Advanced high power TDD UE (power class 2) for Rel-15
  - UE requirements for network-based CRS interference mitigation for LTE
  - UE requirements for LTE DL 8Rx antenna ports
  - Performance requirements of interference cancellation receiver for LTE BS

5.3 5G SYSTEM ARCHITECTURE AND NETWORK RELATED FEATURES

The 5G system architecture, introduced in 3GPP Releases 15 and 16, represents a philosophical shift relative to previous 3GPP architectures, and has been designed to support a number of key objectives. Broadly stated, the basic architectural principles include:

- Further separation of UP and CP functions, allowing independent scalability and evolution, relative to CUPS defined in Release 14
- Allowing for a flexible deployment of UP separate from CP functions, i.e., central or distributed (remote) location
  - Modularizing the function design, e.g., to enable flexible and efficient network slicing
  - Support unified authentication framework for UEs which may support only subset of NGS functionality (e.g., not supporting mobility)

- Separated access and mobility management (AMF) as well as session management (SMF) which enables independent evolution and scaling; supports UE simultaneously connected to multiple network slices
- Supporting a flexible information model with subscription and policy separated from network functions and nodes
- Minimizing access and core network dependencies by specifying a converged access-agnostic core with a common AN - CN interface which integrates different 3GPP and non-3GPP access types
- Supporting "stateless" NFs (where the "compute" resource is decoupled from the "storage" resource that stores state as opaque data), 3GPP will specify (possibly by referencing) interfaces from NFs to a data storage function. NFs may use data storage function to store opaque data

5.3.1 KEY ARCHITECTURE REQUIREMENTS:

- The architecture shall support capability exposure
- Each Network function can interact with the other NFs directly. The architecture shall not preclude the use of an intermediate function to help route control plane messages (e.g., like a DRA)
- Support transmission of different PDU types, e.g., IP, Ethernet
- Support separate Policy function to govern the network behavior and end user experience
- Allow for different network configurations in different network slices
- The architecture supports roaming with both Home routed traffic as well as Local breakout traffic in the visited PLMN in an efficient way

5.3.2 CONTROL PLANE REQUIREMENTS

- Enable multi-vendor interworking between access network, and network functions within the core network, and between the network functions within the core network. At the same time, it is sufficient that a single interface is exposed towards the radio while abstracting the modular (elementary) functions supported in the core network
- Procedures (i.e., set of interactions between two NFs) are defined as a service, wherever applicable, so that their re-use is possible and enables support for modularity.

5.3.3 USER PLANE REQUIREMENTS

- A generic user-plane function (UPF) is defined, which supports various user-plane operations (including forwarding operations to other UP functions/data networks/the control-plane, bitrate enforcement operations, service detection operations, and etcetera)
- The control plane configures the UP functions to provide the traffic handling functionality needed for a session. One or multiple UP functions per session can be activated and configured by the control-plane as needed for a given user-plane scenario.
- To support low latency services and access to local data networks, user plane functions can be deployed close to the radio. For central data networks, UPFs can be deployed centrally
- To support home routed roaming at least a UP function is located in the HPLMN, and there also needs to be at least another UP function located in the VPLMN which includes roaming functionality such as Charging, LI, and etcetera

5.3.4 SUPPORT OF CONCURRENT ACCESS TO LOCAL AND CENTRALIZED SERVICES

- Multiple PDU sessions including a PDU session providing access to a local UP function (providing access to local data networks) and a PDU session providing access to central data networks (central UP function)
- A single PDU session, for which the control plane may configure multiple UP functions

The following sections will talk about the new 5G Next Generation Core architecture that has been specified to support these objectives and requirements, and also about some of the capabilities it will enable.

5.3.5 5G NEXT GENERATION SYSTEM ARCHITECTURE

3GPP TS 23.501 describes the System Architecture for the 5G Network. The most recent version of this document as of this writing is version f10, published in March 2018.

While revolutionary in most respects, in other respects the 5G architecture is evolutionary, building on trends already in flight, for example, CUPS, network function virtualization, and etcetera. Rel-14 enabled new capabilities in a system built largely on the network architecture and elements defined in prior releases. The 5G Next Generation Core (NGC), beginning with Rel-15, takes a more “clean slate” approach, designing in the concepts of CUPS, Network Slicing, Edge Computing and virtualization from the start, and also defines an elegant and flexible methodology for incorporating non-3GPP access mechanisms.

5.3.5.1 SERVICE BASED ARCHITECTURE

The 5G system architecture defined in 3GPP Releases 15 and 16 is Service Based. The architectural elements that make up the control plane of the network are network functions (NFs) that offer their services to any other applicable network functions, via a common framework of interfaces accessible to all network functions. Network Repository Functions (NRF) allow every network function to discover the services offered by other network functions present in the network; Network Exposure Functions (NEFs) permit NF discovery within the network, and also securely to external networks. This model aims at maximizing the modularity, reusability, and self-containment of network functions, and at fostering the ability to grow flexibly while taking advantage of the latest virtualization technology.

The system architecture is defined in TS 23.501 in two ways: a service-based view and a reference point view. The following section describes both views of the basic reference architecture and describes each of the network functions from which the network is built.

5.3.5.2 NEXT GENERATION NETWORK REFERENCE ARCHITECTURE

Figure 5.49 depicts the service-based view of the 5G Next Generation Network. Control plane elements expose their services to all other control plane elements via a set of common interfaces, all available to every control plane element, supporting a common service discovery mechanism.

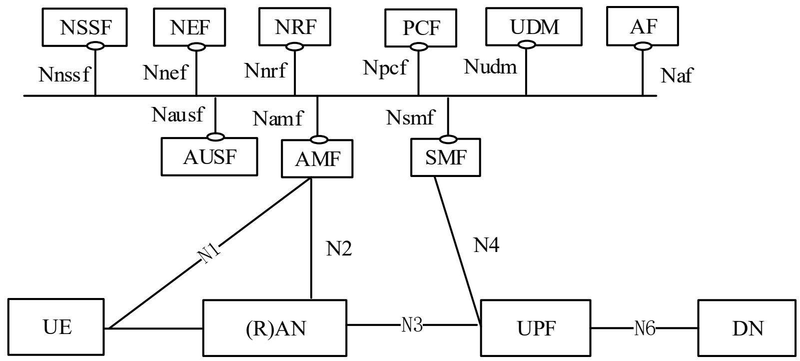


Figure 5.49. Service Based View of the 5G Next Generation Network System Architecture.[132]

Figure 5.50 depicts the reference point view of the 5G Next Generation Network. This view shows the functional interfaces (or reference points) between network functions. To illustrate the difference between these views, consider an example: in the service-based view, the Session Management Function (SMF) exposes the services it offers and other information (e.g., capacity) via the Namf interface, making that information (as well as other information, including its capacity) discoverable by all other control plane network functions via the NRF. The SMF has access to the service descriptions for all other present control plane functions, also via the NRF. In the operating network, the SMF interacts directly with the User Data Module (UDM) via the N10 interface, the Policy Control Function (PCF) via the N7 interface, the Access and Mobility Management Function (AMF) via the N11 interface, and the User Plane Function (UPF) via the N4 interface.

[132] 3GPP TS 23.501.

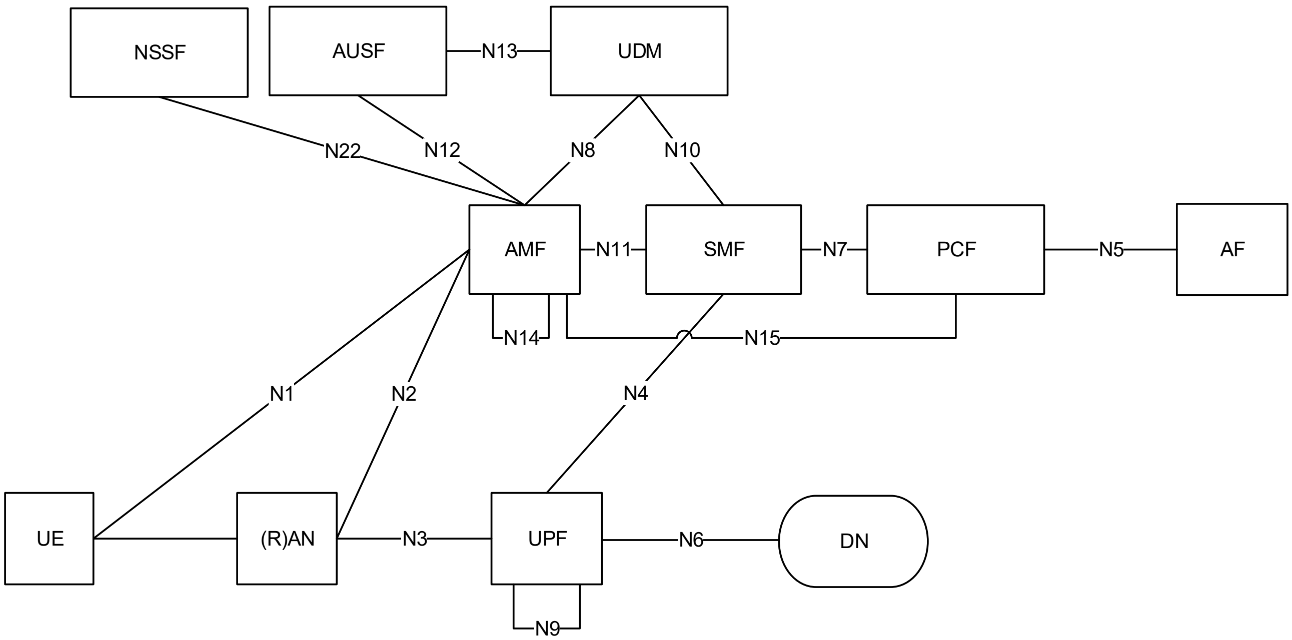


Figure 5.50. 5G Next Generation Reference Architecture – Reference Point View.[133]

5.3.5.3 5G NETWORK FUNCTION DESCRIPTIONS

This section describes the NFs that make up the 5G Next Generation Network. The encompassing reference for all of these definitions is 3GPP TS 23.501. Other references will be listed for specific NFs as applicable. In describing the NFs below, the most important functionalities provided are described at a high level. A more comprehensive treatment appears in the references.

- *Authentication Server Function (AUSF):* 3GPP TS 23.502. The AUSF provides UE authentication service to requester NFs
- *Access and Mobility Management Function (AMF):* The AMF definition includes the following functionalities, all of which may or may not be present in a single AMF instance
    - Termination of RAN CP interface (N2)
    - Termination of NAS (N1), NAS ciphering and integrity protection
    - Management of registration, connection, reachability and mobility
    - Lawful intercept (for AMF events and interface to LI System)
    - Provide transport for SM messages between UE and SMF
    - Transparent proxy for routing SM messages
    - Access authentication and authorization
    - Transport for SMS messages between UE and SMSF
    - SEcurity Anchor Functionality (SEAF)
    - Security Context Management (SCM). The SCM receives a key from the SEAF that it uses to derive access-network specific keys
    - Location Services management for regulatory services

[133] 3GPP TS 23.501.

- Transport for Location Services messages between UE and LMF as well as between RAN and LMF
- EPS Bearer ID allocation for interworking with EPS
- UE mobility event notification

In addition to the functionalities described above, the AMF may also include functionalities to interwork with non-3GPP networks as described in 3GPP TS 23.501 and may include policy related functionalities as described in 3GPP TS 23.503.

- *Unstructured Data Storage Function (UDSF***):** The USDF is an optional NF that can be used to provide storage and retrieval of unstructured data for any other NF. The USDF functions can be subsumed by the UDR in a network deployment, making it unnecessary to have a separate UDSF

- *Network Exposure Function (NEF):* The NEF performs the following functions:
  - Exposure of capabilities and events using a standard interface to the Unified Data Repository (UDR): NFs use the NEF to expose their capabilities and events to other NFs, including secure exposure to support 3rd party, Application Functions, Edge Computing, and etcetera. The NEF can access the UDR located in the same PLMN as the NEF
  - Secure provision of information from external application to 3GPP network, to enable AFs to securely provide information to the 3GPP network. The NEF may authenticate, authorize, and assist in throttling AFs
  - Translation of internal-external information exchanged with the AF and information exchanged with the internal NF. In particular, NEF handles masking of network and user sensitive information to external AF's according to the network policy
  - Receives information from other NFs based on exposed capabilities, and stores the information as structured data via a standardized interface to the UDM. The NEF can then be accessed and re-exposed to other NFs and AFs, and also used for other purposes such as analytics
  - May support a PFD function, which will store and retrieve PFD(s) in the UDR, and provide PFD(s) to the SMF

- *NF Repository Function (NRF):* The NRF supports the service discovery function, maintains the NF profile of all available NF instances. In the case of network slicing, multiple NRFs may be deployed at different levels, or, in the case of roaming, multiple NRFs may be deployed in the different networks

- *Network Slice Selection Function (NSSF):* The NSSF selects the set of Network Slice instances to serve the UE. It also determines the allowed and configured Network Slice Selection Assistance Information (NSSAI), and if necessary, maps to the Subscribed S-NSSAIs, and determines the AMF Set to be used (or a candidate list) to serve the UE

- *Policy Control Function (PCF):* Reference 3GPP TS 23.503. The PCF supports the unified policy framework to govern network behaviour, provides policy rules to Control Plane functions to enforce them. It accesses relevant subscription information for policy decisions in the UDR

- *Session Management Function (SMF):* The SMF is responsible for session establishment, modification and release, including maintaining the tunnel between the UPF and the AN node. It allocates and manages UE IP addresses, including authorization

- *Unified Data Management (UDM):* The UDM is responsible for generating 3GPP AKA authentication credentials and for handling user identification, for example, storing and managing SUPI for each subscriber in the 5G System. It is also responsible for Generation of 3GPP AKA Authentication Credentials. The UDM performs access authorization based on subscription data, and supports session/service continuity. It manages UE Serving NF Registration. It also provides support for MT-SMS delivery, SMS management, and Lawful Intercept (LI)

- *Unified Data Repository (UDR):* The UDR supports storage and retrieval of data for other NFs, including subscription data by the UDM, policy data by the PDV, structured data for exposure, and application data

- *User Plane Function (UPF):* The UPF is the generic data plane element in the 5G system. Its responsibilities include:

    - Packet routing and forwarding (e.g., support of Uplink classifier to route traffic flows to an instance of a data network, support of Branching point to support multi-homed PDU Session)
    - Anchor point for Intra-/Inter-RAT mobility (when applicable)
    - External PDU Session point of interconnect to Data Network
    - Packet inspection (e.g. Application detection based on service data flow template and the optional PFDs received from the SMF in addition).
    - User Plane part of policy rule enforcement, e.g. Gating, Redirection, Traffic steering)
    - Lawful intercept (UP collection)
    - Traffic usage reporting
    - QoS handling for user plane, e.g. UL/DL rate enforcement, Reflective QoS marking in DL
    - Uplink Traffic verification (SDF to QoS Flow mapping)
    - Transport level packet marking in the uplink and downlink
    - Downlink packet buffering and downlink data notification triggering
    - Sending and forwarding of one or more "end marker" to the source NG-RAN node
    - ARP proxying as specified in IETF RFC 1027 [53] and / or IPv6 Neighbour Solicitation Proxying as specified in IETF RFC 4861 [54] functionality for the Ethernet PDUs. The UPF responds to the ARP and / or the IPv6 Neighbour Solicitation Request by providing the MAC address corresponding to the IP address sent in the request

- *Application Function (AF):* The AF interacts with the 3GPP Core Network to provide services for applications. An AF may interact directly with other relevant NFs (if the AF is trusted), or may interact with them via the NEF (if untrusted). The AF may also support policy control by interacting with the Policy framework

- *5G-Equipment Identity Register (5G-EIR):* The 5G-EIR is an optional NF that checks the status of the Permanent Equipment Identifier (PEI) to determine if it has been blacklisted. For Release 15, the only recognized PEI format is IMEI

- *Security Edge Protection Proxy (SEPP):* The SEPP is a non-transparent proxy that performs topology hiding, and message filtering and policing on inter-PLMN control plane interfaces

- *Short Message Service Function (SMSF):* The SMSF supports SMS over NAS. It checks SMS subscriptions and routes SMS messages. It also generates CDRs for SMS messages, and performs LI

- *Non-3GPP Interworking Function (N3IWF):* The N3IWF supports the interworking of 3GPP networks with non-3GPP access networks. The N3IWF:
  - establishes the IPsec tunnel with the UE
  - terminates the tunnel to the UE over NWu, and relays authentication information to the 5G Core over N2
  - terminates the N2 and N3 interfaces with the 5G CP and UP, respectively
  - relays uplink and downlink CP signaling between the UE and AMF, via N1
  - handles N2 signaling from the SMF (via the AMF), related to PDU sessions and QoS
  - establishes the IPsec Security Association to support PDU session traffic
  - relays uplink and downlink UP packets between the UE and the UPF
  - enforces QoS, including UP packet marking in the uplink
  - acts as the local mobility anchor within the untrusted non-3GPP access network
  - supports AMF selection
- *Location Management Function (LMF):* The LMF supports location determination for the UE. It obtains downlink location measurements or estimates from the UE, uplink location measurements from the NG RAN. It also obtains non-UE associated location assistance data from the NG-RAN
- *Network Data Analytics Function (NWDAF*): The NWDAF provides slice specific network data analytics to a NF that is subscribed to the NWDAF for that slice. In Rel-15, the PCF and NSSF may subscribe and consume network analytics from the NWDAF

5.3.6 DIFFERENT DEPLOYMENT OPTIONS WITH EPC AND 5GC

5G is currently under standardization in 3GPP where multiple UE connectivity options have been defined for the Radio Access Network, therefore, LTE and/or NR in combination with the Packet Core, and also EPC and 5GC.

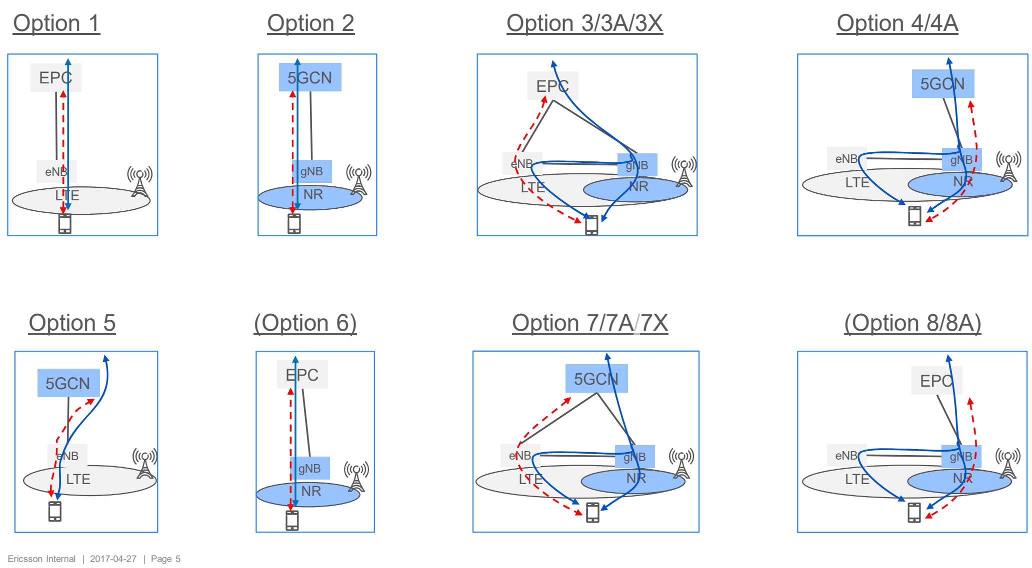


Figure 5.51. 3GPP UE Connectivity Options.

- Option 1 is legacy EPC and LTE and is only listed for reference
- Option 2 is standalone NR connected to 5GC
- Option 3 is non-standalone LTE/NR based on LTE-anchored dual connectivity with NR and using NR only for user plane. LTE is connected to EPC
- Option 4 is non-standalone LTE/NR based on NR-anchored dual connectivity with LTE and using LTE only for user plane. NR is connected to 5GC
- Option 5 is standalone LTE connected to 5GC
- Option 6 is standalone NR connected to EPC
- Option 7 is non-standalone LTE/NR based on LTE-anchored dual connectivity with NR and using NR only for user plane. LTE is connected to 5GC
- Option 8 is non-standalone LTE/NR based on NR-anchored dual connectivity with LTE and using LTE only for user plane. NR is connected to EPC
- Options 6 and 8 are not prioritized in 3GPP for further standardization

In addition to the UE connectivity options listed above, there are in some cases also different sub-options (called 3a, 3x, 4a, 7a, 7x). The main difference for these sub-options is how the terminal (UE) user plane connectivity to the CN and AN is defined. For example, in option 3 the user plane is between EPC and LTE eNB while in option 3a user plane can also be between EPC and NR gNB.

The UE connectivity sub-options represent a momentary view of how a UE is connected to the network. This can change over time for a UE connection depending on for example, radio coverage and applications used in the UE. The mentioned options and sub-options were introduced in the NG-RAN study phase but in the normative phase have been replaced by different radio bearer alternatives corresponding to the different options/sub-options.

UE connectivity option 3 is a fast path to introduce 5G RAN connected to EPC. It is based on tight interworking between LTE and NR within 5G RAN, re-using the EPC – LTE RAN interfaces S1-MME and S1-U with some smaller changes. Providing 5G RAN support has some moderate impact to EPC. Specifications on stage 2 and stage 3 level for Option 3 were completed by 3GPP in December 2017 in Rel-15.

When UE is connected to 5GC (i.e., using UE connectivity options 2, 4, 5 and 7) the different options do not impact how a UE is handled in the 5GC. The same 5GC to 5G RAN interfaces are used, these are newly specified by 3GPP in Rel-15 with completion in June 2018.

The initial 5G migration should be done via EPC and Non-Standalone NR (option 3), where the extensive LTE coverage and the use of the LTE control plane makes it almost seamless to the end user entering and exiting NR coverage.

5GC with Standalone NR systems (option 2) can be deployed as small 5G systems with limited coverage. Deployment of 5GC/option 2 for the generic MBB use case should be when continuous coverage for both uplink and downlink can be provided for NR.

A possible extension step to 5GC with Standalone NR (option 2) is 5GC/NR-anchored Dual Connectivity (option 4) with the motive to aggregate more bandwidth (from LTE) for devices that are camping on a relatively narrow NR-carrier. 5GC/LTE-anchored Dual Connectivity (option 7) and Stand-alone LTE with 5GC (option 5) can be additions to option 2 or migration paths from option 3, reusing the radio network deployment with a new core network.

5.3.6.1 5G ENABLED EPC (OPTION 3)

This section provides additional information about EPC supporting Option 3/3a/3x, describing background, key functions, characteristics and addressed use cases.

5.3.6.1.1 OVERVIEW OF 5G ENABLED EPC (OPTION 3)

In March 2017, the 3GPP organization signed off a 6-months accelerated work plan to enable trials and deployments in 2019 instead of 2020. This was initiated by some 40 Tier 1 mobile operators and network vendors. Here, two distinct and different architectures, separated by time, emerged – 5G Enabled EPC and 5GC.

The 5G Enabled EPC is motivated by the need of shortest time-to-5G-service by reusing and complementing the already existing Evolved Packet Core (EPC) infrastructure — therefore, 4G — while supporting the performance and characteristics of 5G Radio Access and devices – up to 20/10 Gbps Downlink/Uplink per device is targeted by 3GPP.

The eNB serves as the UE anchoring point and handles related control signaling for both LTE and 5G New Radio (NR) services. The eNB acts as the Radio Access Network master node towards the gNB, over an X2-C interface. Communication with MME is still made over S1'C. Both X2-C and S1'-C are based on the reuse of the S1-MME and X2 protocols and procedures, with certain 5G additions.

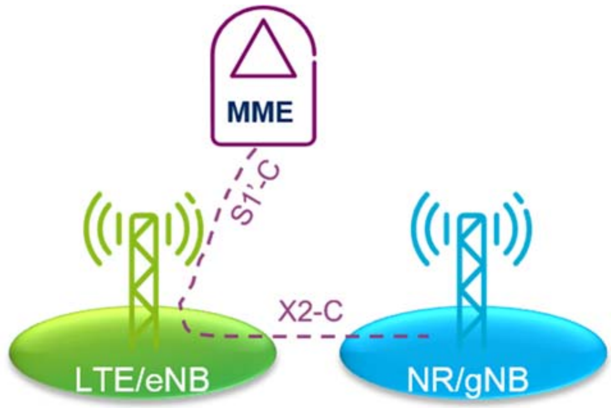


Figure 5.52. NR communication with MME via X2-C and S1'-C.

Three user plane paths models are defined:

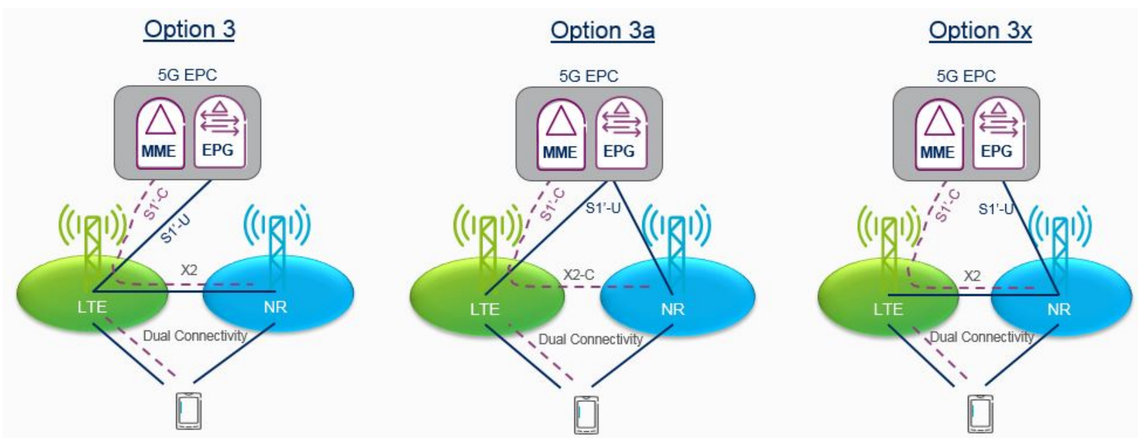


Figure 5.53. Three User Plane Path Models to Support Data Connectivity of UE to EPC.

The choice of Option 1/3/3a/3x and related user plane path(s) is dynamically made by the eNB for each session and for each user, based on eNB local configurations and selection algorithms using load measurements data and session types.

5G Enabled EPC is fully interworking with existing GSM and WCDMA/HSPA networks.

On the device side, a new generation of devices is needed to work with the higher speeds and the additional, new radio frequency bands. These devices are normally backward compatible with existing LTE/EPC as well as GSM, WCDMA/HSPA and Circuit-Switched services (although some of these may not support GSM, WCDMA/HSPA for low-cost reasons). The present and older generations of devices not supporting 5G, may enter 5G Enabled EPC but will then only use LTE access and services (Option 1 mode of operation as described in section 1.2).

IMS services are supported, including VoLTE. Since Voice over NR (VoNR) is not supported in 3GPP for 5G Enabled EPC, the eNB steers voice traffic to LTE only (Option 1 mode of operation).

5.3.6.1.2 BENEFITS OF 5G ENABLED EPC (OPTION 3)

5G Enabled EPC satisfies the basic needs of 5G operation including high speed, slicing and backward compatibility. And this by reusing existing EPC investments with 5G-additions. However, 5GC takes a more general approach to longer-term future orientation satisfying the expected market needs beyond 2020.

And when 5GC is eventually introduced, 5G Enabled EPC will still be used for several more years in parallel, to serve the large volumes of existing devices and related network areas.

5.3.7 5G INTERWORKING WITH NON-3GPP ACCESS NETWORKS

One of the objectives of the 5G Next Generation Network is to support non-3GPP access networks (e.g., WLAN), via a common control plane architecture. The ultimate intent is to support multiple non-3GPP access mechanisms in a much more general and extensible way than in previous 3GPP releases.

This work has been distributed over 3GPP Releases 15 and 16. While prior 3GPP releases have supported both trusted (e.g., non-3GPP access controlled by the 3GPP Network Operator), and untrusted, or "standalone" non-3GPP access (e.g., the WLAN is outside the NG-RAN), only untrusted non-3GPP access is supported in Release 15.

For simplicity, this document will only describe the simple, non-roaming case, illustrated in Figure 5.54.

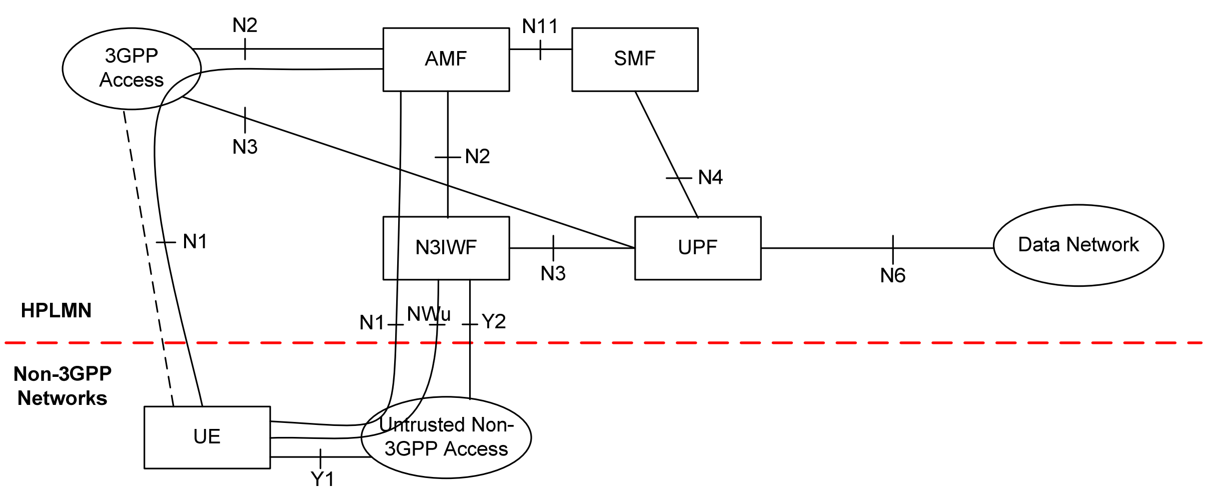


Figure 5.4. Non-roaming Architecture for 5G Core Network with Non-3GPP Access.[134]

In all cases, roaming or non-roaming, the non-3GPP access network interacts with the NGC via the Non-3GPP Interworking Function (N3IWF), using the N2 (for control plane functions), and N3 (user plane) reference points. After attachment, the UE supports NAS signalling with the 5G Core network via an N1 reference point. Note that when a UE is connected via a NG-RAN and a standalone non-3GPP access network, it will maintain a separate N1 reference point instances simultaneously, one with each network. In the case illustrated in Figure 5.54, where the N3IWF is located in the same PLMN as the 3GPP RAN, the UE will be served by the same, single AMF for both connections.

[134] 3GPP TS 23.501.

Several other configurations are also supported, including several roaming scenarios, and scenarios where the N3IWF is not located within the same PLMN as the 3GPP RAN. These other configurations, as well as the simple non-roaming scenario shown above, are described fully in 3GPP TS 23.501.

5.3.8 NETWORK SLICING

It is often desirable to partition a single network into a number of segregated logical networks, each optimized for a particular type of service, or dedicated to a particular customer or application. In GPRS networks, this was accomplished by pairing a UE's Packet Data Network (PDN) with a particular SGSN by using an Access Point Name (APN). This concept was extended and enhanced for 4G networks in Release 13 via Dedicated Core Networks (DÉCOR), and further extended in Release 14 via Enhanced Dedicated Core Networks (eDECOR), pairing the UE's Packet Data Unit (PDU) sessions with a particular MME.

Both of these schemes were overlays on an existing architecture that was not initially intended to partition the network in this way, and both present limitations (beyond the scope of this paper). As discussed in previous sections, the 5G Next Generation System (NGS) has been designed to support this capability as part of its intrinsic framework, via the mechanism of 5G Network Slicing.

Several "service based" network slices have been conceived by 3GPP:

- Enhanced Mobile Broadband (EMBB), intended to be capable of providing very high per-user throughput
- IoT, intended to support very large numbers of connections, possibly with very limited throughput
- Ultra-reliable Low Latency Communications (URLLC), intended to support critical low-latency applications

Since the initial conception of network slicing, the industry view has broadened to include supporting logical networks dedicated to a particular customer (e.g., an enterprise), to Mobile Virtual Network Operators (MVNOs), to individual applications, and to other use cases that could make use of a separate logical network.

In the 5G NGS, different applications on the UE may each be mapped to different, distinct network slices. A UE may simultaneously support mapping of up to eight distinct slices, where a slice is (minimally) defined as an SMF and a UPF (though other NFs may also be included).

All of a particular UE's active slices share the same AMF, but each slice will likely be mapped to a different SMF and to a different UPF. Consequently, in the event that the AMF initially assigned cannot support all the requested slices, a different AMF that can support them will be assigned. While all of a UE's access and mobility characteristics will be the same for all applications, each application may have different, unique session management, different policies, different user plane characteristics, and etcetera.

Figure 5.55 illustrates the Release 15 network slicing architecture. It shows two UEs, one connected to the internet for a commercial application, the other running a private enterprise application connected to an enterprise network/application server, and a car running two different IoT applications, each mapped to a different slice.

Figure 5.55 also shows a network-wide UDM, and a global NSSF and NRF.

Note that slices 3 and 4 in the figure, both assigned to the car, share the same AMF (since only one AMF can be assigned to serve all the slices for a given UE), and share a PCF and NRF that are common to the slices serving the car. In addition to the common NRF serving slices 3 and 4, both slices 3 and 4 each have a slice-specific PCF that serves the slice's SMF. In this way, there can be global policies applying to the entire network, another set of policies that apply to all the slices serving the UE (via the assigned AMF), and slice-specific policies for each slice (via the slice's SMF).

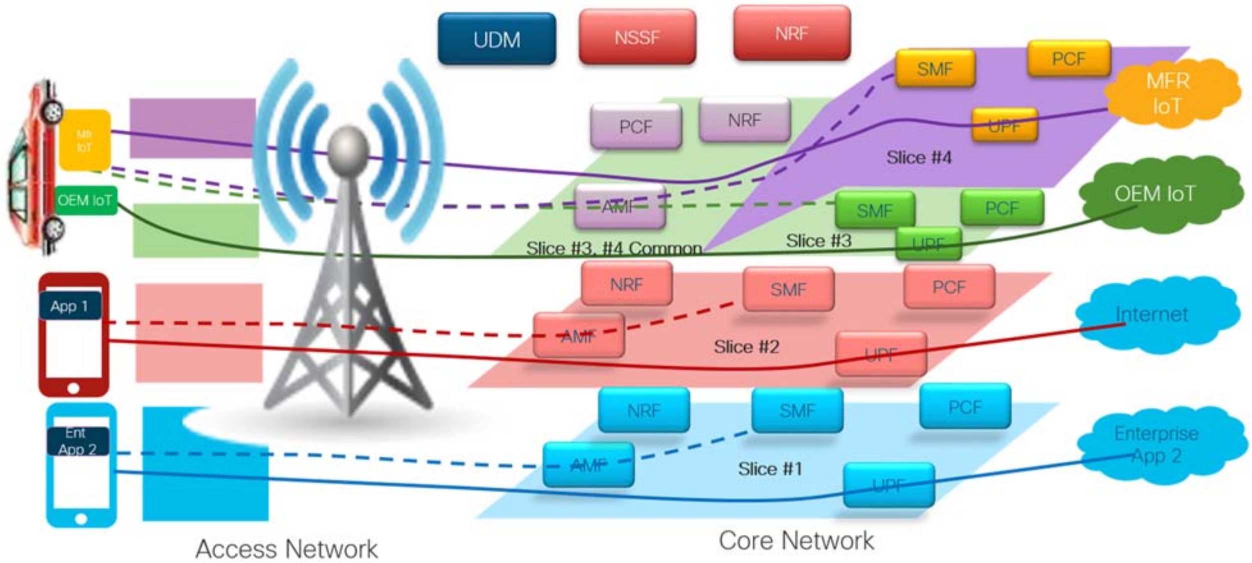


Figure 5.55. Release 15 Network Slicing Architecture.

Some characteristics of Release 15 network slices are as follows:

- Flexible policy for binding of applications to network slices. These policies can be provided to the UE during registration, or may be configured on the UE directly. Binding policies can be changed after registration via Non-Access Stratum (NAS) signaling procedures between the UE and the AMF
- Policies for slice selection may be centralized in the NSSF (see Section 5.3.1 of this white paper), or may be configured in each AMF
- Discovery of slice-specific NFs is enabled via the NRF. As shown in figure 5.55, the Release 15 architecture supports a global, network-wide NRF, as well as slice-specific NRFs, per slice. By having an NRF specifically assigned to a particular slice, NF discovery for NFs assigned to that slice can be made invisible to other slices
- The concept of network slicing can be extended through the access network and RAN. Slice IDs of each PDU session are provided to the RAN to enable it to share resources, per slice, according to policy

Network Slicing is described in 3GPP TS 23.501.

5.3.9 SUBSCRIPTION AUTHENTICATION IN 5GC

The subscription authentication architecture in 5GC has been defined aiming for the following main goals:

- Support additional types of subscription identifiers and authentication mechanisms (compared with EPC where only SIM-based IMSI/AKA mechanisms are supported)

- Enable a unified authentication architecture for both 3GPP and non-3GPP accesses (compared with EPC where different authentication architectures for 3GPP and non-3GPP accesses are defined)
- Increase the Home Network (HN) control of the execution of the authentication process (compared with EPC where for 3GPP access the MME authenticates the UE locally at the VPLMN)

Figure 5.56 depicts the authentication architecture in 5GC compared with the one in EPC.

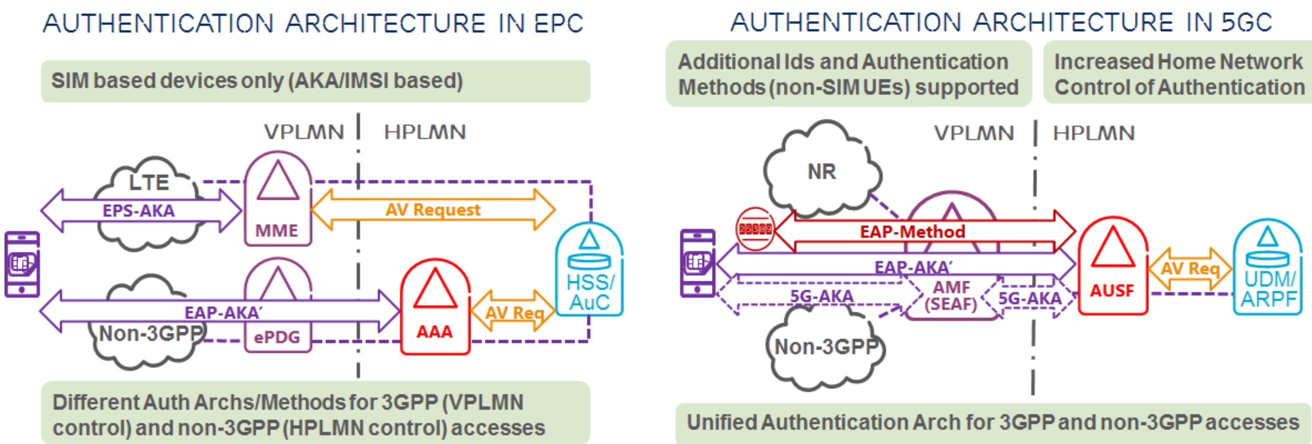


Figure 5.56. Comparison of 5GC and ePC Authentication Architectures.

In order to integrate the support for IMSI/AKA based authentication with the support of alternative subscription identifiers and authentication methods in a unified and access agnostic manner, 3GPP has defined therefore a unified authentication architecture for the 5GC based on the Extensible Authentication Protocol (EAP) framework.

The EAP framework enables the control of the authentication execution in an EAP Authentication Server at the HN, played by an Authentication Server Function (AUSF). The subscription authentication runs end-to-end between the UE and the AUSF in the HN even if the user is roaming. The role of the EAP Authenticator is played by a SEcurity Anchor Function (SEAF) supported by the AMF in the 5GC.

Multiple authentication methods are defined to be used over the EAP framework including EAP-AKA' (Authentication and Key Agreement) supporting Subscriber Identity Module/AKA (SIM/AKA) based identification/authentication and EAP-Transport Layer Security (TLS) supporting devices that will not use International Mobile Security Identity/Subscriber Identity Module (IMSI/SIM) based identification/authentication schemes.

In addition to the support of EAP framework for devices supporting SIM/AKA based identification/authentication schemes, 3GPP has agreed to also allow the execution of 5G-AKA, an evolution of the EPS-AKA mechanism which allows an increased HN control of authentication in par with EAP principles. With 5G-AKA, the authentication result is only partially verified at the Access and mobility Management Function/SEAF (AMF/SEAF), full validation of the challenge response from the UE is done at the AUSF in the HN.

UDM within the HN supports the AUSF deciding the authentication method applicable for a particular subscription (i.e. EAP-AKA' vs 5G-AKA, AKA vs other EAP method). When SIM/AKA based authentication is used, AKA authentication vectors will be generated by the Unstructured Data Management (UDM) acting as Authentication credential Repository and Processing Function (ARPF).

UDM can be additionally used to further increase the HN control of authentication by linking subsequent procedures for a subscriber (e.g., UE registration within the 5GC) with the authentication status of a particular subscriber. Thus, the HN would be able to reject attempts for registration and service requests within the 5GC if the UE was not properly authenticated in the first place according to the HN policy.

Support for EAP-AKA' and 5G-AKA is mandatory for UE and AMF in 3GPP Rel-15. AUSF and UDM may support only one of these methods. Support for EAP-TLS is defined as an informative Annex in 3GPP Rel-15.

EAP based methods and 5G-AKA can be executed both over 3GPP and non-3GPP accesses. Non-3GPP access networks are connected to the 5GC via a Non-3GPP InterWorking Function (N3IWF) which interfaces the AMF and UPF via N2 and N3 interfaces, respectively. Furthermore, a UE that accesses the 5GC over a standalone non-3GPP access supports NAS signaling with the 5GC using the same N1 reference point as in 3GPP access.

First, the UE establishes an IPSec tunnel with the N3IWF to attach to the 5GC over untrusted non-3GPP access using a vendor-specific EAP method called "EAP-5G". "EAP-5G" method is used between the UE and the N3IWF only for encapsulating Network Access Server (NAS) messages (not for subscription authentication). Subscription authentication, is executed between the UE and AUSF using an EAP based method or 5G-AKA as described above. The NAS authentication messages (EAP or 5G-AKA) are encapsulated within EAP/5G-NAS packets.

Finally, 3GPP has also evolved the subscription authentication mechanism used in EPC where at the establishment of PDU sessions, the UE transfers Password Authentication Protocol/Challenge Handshake Authentication Protocol (PAP/CHAP) usernames and passwords using the Protocol Configuration Options (PCO) information element via NAS signaling to the PDN-GW which then runs them through an external AAA server for authentication/authorization.

In the 5GC, it is proposed to enhance this mechanism in order to support more advanced authentication methods using also the EAP framework. The SMF will act as EAP authenticator role in this case, exchanging EAP packages with the UE using the SMF NAS containers transparently to the AMF. The SMF will also communicate with an AAA server external to the 5GC (i.e., at the DN) via the UPF or using a direct connection when available.

The subscription identifiers and credentials used for this secondary authentication are different from those used during authentication at registration in the AMF/SEAF and AUSF.

The subscription identifiers and credentials used for this secondary authentication are different from those used during authentication at registration in the AMF/SEAF and AUSF.

5.3.10 5G CORE QUALITY OF SERVICE (QOS) MECHANISM

QoS mechanisms have been in focus in several releases of 3GPP specifications, although the use of the GPRS and EPS QoS framework has primarily been limited to differentiate voice services from mobile broadband data, and to offer relative differentiation across mobile broadband subscription types whenever resources are scarce. With 5GS aiming to address the variety of connectivity needs in the industry digitalization as well as the ambition to define a QoS usable for any access technology connected to 5GC (i.e., 3GPP access, non-3GPP access), improvements to the QoS framework have been introduced in the 5GS standardization.

A wide use of the QoS capabilities of the 3GPP system has been hampered by the complexity in configuring the QoS parameters and the limited predictability of the effect of QoS differentiation that has been primarily jsufficient for a relative differentiation of flows. Fuelled by the critical communication 5G use cases, the 5G QoS framework has on one hand leveraged on the EPS QoS principles but also addressed some of the limitations present in the earlier 3GPP releases.

The 5G principles for classification and marking of User Plane traffic and mapping of QoS Flows to (R)AN resources is illustrated in Figure 5.57.

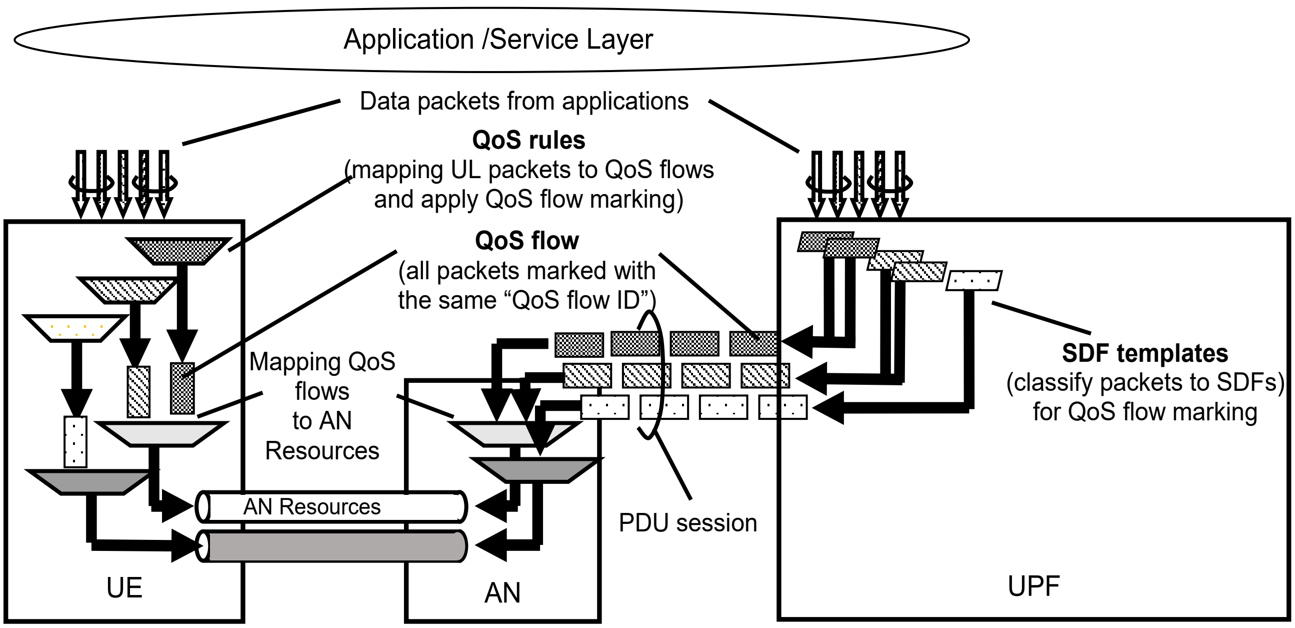


Figure 5.57. The Principles for Classification, User Plane Marking and Differentiation in 5GC.

Incoming application data packets are classified based on the QoS and service requirements of the Service Data Flows of the application. The Session Management Function (SMF) assigns the QoS Flow ID (QFI) and derives its QoS profile from the information provided by the PCF. The SMF provides:

- QFI together with the QoS profile to the (R)AN
- QoS flow marking (i.e., the QFI) and the necessary information to enable classification, bandwidth enforcement and marking of User Plane traffic to the UPF
- QoS rules enabling classification and marking of UL User Plane traffic to the UE

Comparing the 5G QoS framework with the legacy EPS and GPRS QoS frameworks, the following can be noted:

- As in EPS, the 5G QoS framework is network controlled, meaning that the QoS treatment given to an application data is authorized through the Policy and Charging Control (PCC) framework
- To circumvent the limitation imposed by the number of default and dedicated bearers present in EPS due to the 1:1 relation between EPS bearers and Data Radio Bearers (DRB), a clearer

separation of concerns has been introduced in the 5GS between the CN and the AN. In 5GS, the responsibility of the CN is to classify the application data into "QoS Flows" (rather than EPS bearers) and assign a treatment to a QoS Flow, described by a QoS profile. The Access Network (AN) is in turn responsible to enforce the differentiation described by the QoS profile assigned to the QoS Flow. This allows the AN to multiplex multiple QoS Flows into a single DRB

- QoS flows are identified by the QoS Flow ID (QFI) and each UP packet of the QoS flow is marked by the UPF with the QFI value. The QFI value may implicitly describe the QoS treatment of the QoS Flow or explicitly signaled QoS parameters and characteristics may be associated to the QoS flow
- New QoS parameters and characteristics are introduced, aimed to improve the predictability and the effect of the QoS differentiation specially to fulfill the requirements of ultra-reliable low latency communication

A method to reduce the signaling to the UE for UL data classification, Reflective QoS, is introduced, allowing a simple principle for applying the same QoS differentiation to application data in DL and UL.

With the changes and additions introduced in 3GPP Release 15 QoS framework, the 5G system is therefore well prepared to deliver differentiated and prioritized connectivity services to meet the requirements of evolved mobile broadband and critical communication services.

5.3.11 5G POLICY FRAMEWORK

The reference architecture of policy and charging control framework for the 5G System is comprises the functions of the Policy Control Function (PCF), the Session Management Function (SMF), the User Plane Function (UPF), the Access and Mobility Management Function (AMF), the Network Exposure Functionality (NEF), the Network Data Analytics Function (NWDAF), the Charging Function (CHF), the Application Function (AF) and UDR (Unified Data Repository).The interaction between network functions is represented in two ways, both of which are shown in Figures 5.58 and 5.59.

- A service-based representation, where network functions enable other authorized network functions to access their services. This representation also includes point-to-point reference points where necessary
- A reference point representation, which shows that interactions exist between those network functions for which a reference point is depicted between them

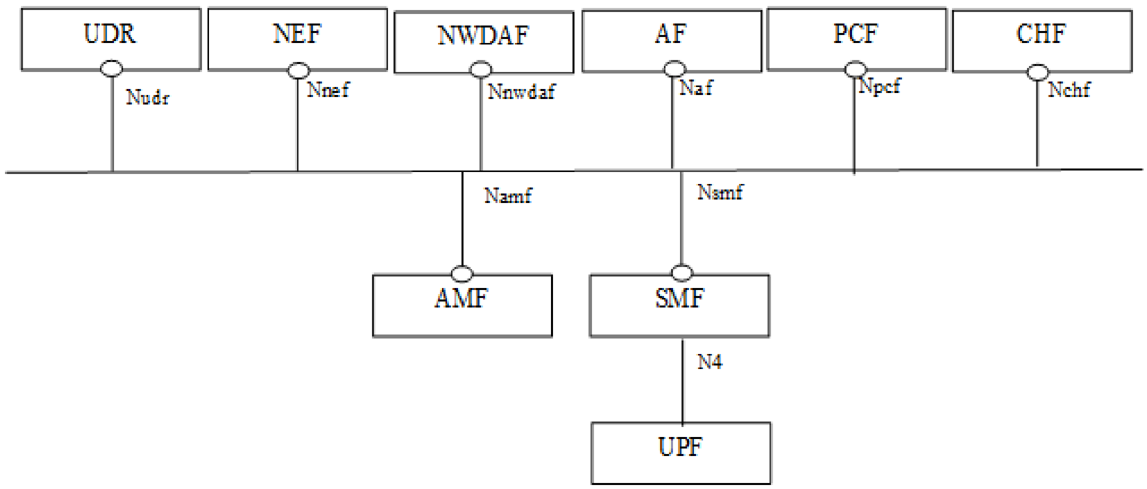


Figure 5.58. Overall Non-roaming Reference Architecture of Policy and Charging Control Framework for the 5G System (service-based representation).

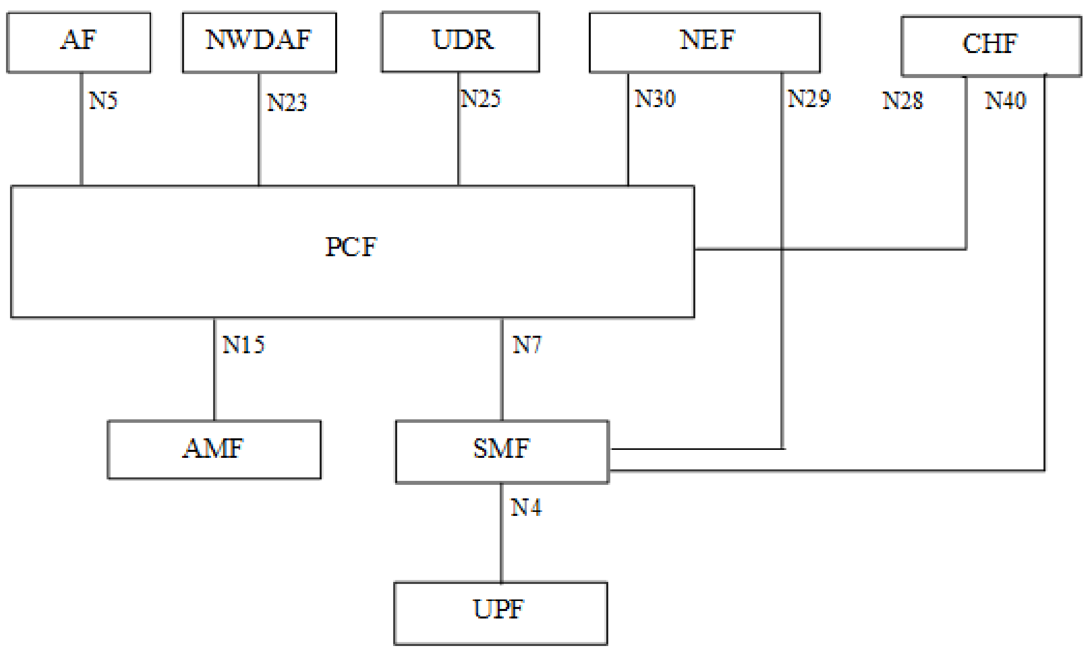


Figure 5.59. Overall Non-roaming Reference Architecture of Policy and Charging Control Framework for the 5G System (reference point representation).

5.4 RELEASE 16

Release 16 is primarily focused on fixing NR, enhancing NR and enabling new services on NR. The primary features being developed are MIMO enhancements to increase efficiency in the mmWave bands, expanding V2X beyond what is currently available using LTE, NR positioning enhancements to meet both commercial and regulatory requirements for voice services, enhancements to base station interference mitigation, improvements in UE power savings, added Industrial IoT features, improvements to HO performance, studies on operation above 52.6 GHz., SON improvements, NR CA and dual connectivity improvements, defining UE testing in mmWave bands, NR in unlicensed bands and solutions for in-band backhaul. Table 5.33 provides more detail on the approved Rel-16 3GPP study items and work items.

Table 5.33. 3GPP Release 16 Approved Study Items and Work Items.

New Release 16 SID/WIDs	**Description**
NR MIMO Enhancements approved RP-181453	Rel-15 NR includes a number of MIMO features that facilitate utilization of a large number of antenna elements at the base station for both sub-6GHz and over-6GHz frequency bands. Some of these features are primarily based on Rel-14 LTE while others are introduced due to several newly identified deployment scenarios such as multi-panel arrays and hybrid analog-digital for high frequency bands. In particular, the following MIMO features are included: limited support for multi-TRP/panel operation, flexible CSI acquisition and beam management, Type I (low-resolution) and II (high-resolution) codebooks supporting up to 32 ports, and flexible RS for MIMO transmission (especially CSI-RS, DMRS, and SRS). Equipped with such features, NR MIMO can differentiate itself from LTE MIMO at least in the following aspects. First, Type II codebook can offer substantial (at least 30 percent) gain in average user throughput over the best of Rel-14 LTE. Second, flexible CSI acquisition and RS design permit scalability for future enhancements. Third, NR MIMO accommodates operation in high frequency bands (>6GHz) via beam management. Overall, the Rel-15 MIMO features offer ample foundation for four further potential enhancements which can be unlocked in Rel-16 NR. First, although Type II CSI specified in Rel-15 offers large gain over advanced CSI of Rel-14 LTE, there is still some significant, yet attainable, performance gap from near-ideal CSI especially for multi-user (MU)-MIMO. Second, although Rel-15 NR MIMO provisionally accommodates multi-TRP/panel operation, the supported features are limited to standard-transparent transmission operations and small number of TRPs/panels. Third, although specification support for multi-beam operation has been largely specified in Rel-15 (targeting over-6GHz frequency band operation), some aspects such as beam failure recovery and enabling schemes for DL/UL beam selection are fairly basic and can potentially be improved for increased robustness, lower overhead, and/or lower latency. Fourth, there is a need for enhancement to allow full power transmission in case of uplink transmission with multiple power amplifiers.
NR V2X SID RP-181480	To expand the 3GPP platform to the automotive industry, the initial standard on support of V2V services was completed in September 2016. Enhancements focusing on additional V2X operation scenarios leveraging the cellular infrastructure were completed in March 2017 as 3GPP V2X phase 1 for inclusion in Rel-14 LTE. In Rel-14 LTE V2X, a basic set of requirements for V2X service in TR 22.885 has been supported, which are considered sufficient for basic road safety service. Vehicles (i.e., UEs supporting V2X applications) can exchange their own status information through sidelink, such as position, speed and heading, with other nearby vehicles, infrastructure nodes and/or pedestrians. 3GPP V2X phase 2 in Rel-15 introduces a number of new features in sidelink, including: carrier aggregation, high order modulation, latency reduction, and feasibility study on both

	transmission diversity and short TTI in sidelink. All these enhanced features in 3GPP V2X phase 2 are primarily based on LTE and require co-existing with Rel-14 UE in same resource pool. SA1 has completed enhancement of 3GPP support for V2X services (eV2X services). The consolidated requirements for each use case group are captured in TR 22.886, and a set of the normative requirements is defined in TS 22.186. SA1 has identified 25 use cases for advanced V2X services and they are categorized into four use case groups: vehicles platooning, extended sensors, advanced driving and remote driving. The detailed description of each use case group is provided: **Vehicles Platooning** enables the vehicles to dynamically form a platoon travelling together. All the vehicles in the platoon obtain information from the leading vehicle to manage this platoon. This information allows the vehicles to drive closer than normal in a coordinated manner, by going to the same direction and travelling together. **Extended Sensors** enables the exchange of raw or processed data gathered through local sensors or live video images among vehicles, road site units, devices of pedestrian and V2X application servers. The vehicles can increase the perception of their environemnt beyond of what their own sensors can detect and have a more broad and holistic view of the local situation. High data rate is one of the key characteristics. **Advanced Driving** enables semi-automated or full-automated driving. Each vehicle and/or RSU shares its own perception data obtained from its local sensors with vehicles in proximity and that allows vehicles to synchronize and coordinate their trajectories or manoeuvres. Each vehicle shares its driving intention with vehicles in proximity too. **Remote Driving** enables a remote driver or a V2X application to operate a remote vehicle for those passengers who cannot drive by themselves or remote vehicles located in dangerous environments. For a case where variation is limited and routes are predictable, such as public transportation, driving based on cloud computing can be used. High reliability and low latency are the main requirements. NR V2X is not intended to replace the services offered by LTE V2X instead NR V2X complements LTE V2X for advanced V2X services and support interworking with LTE V2X. NR V2X is destined as 3GPP V2X phase 3 and would support advanced V2X services beyond services supported in LTE Rel-15 V2X. NR V2X system is expected have a flexible design in support of services with low latency and high reliability requirements. NR system also expects to have higher system capacity and better coverage. The flexibility of NR sidelink framework would allow easy extension of NR system to support the future development of further advanced V2X services and other services.
NR Positioning SID RP-181399	The objective of this study item is to evaluate potential solutions to address NR positioning requirements as defined in TR 38.913, TS 22.261, TR 22.872 and TR 22.804 while considering E911 requirements by analyzing positioning accuracy (including latitude, longitude and altitude), availability, reliability, latency, network synchronization requirements and/or UE/gNB complexity to perform positioning, and taking into account a preference to

	maximize synergy where possible with existing positioning support for E-UTRAN. This SI covers RAT dependent, RAT independent, and hybrid of those positioning technologies (hybrid of RAT-dependent positioning techniques as well as hybrid of RAT-dependent and RAT-independent positioning technologies). This study item will study both NR-based RAT-dependent as well as RAT-independent and hybrid positioning methods to address regulatory as well as commercial use cases. NR design targets for commercial positioning use cases include: 1. Support for range of accuracy levels, latency levels and device categories 2. Support accuracy and latency as defined in TR 22.862 for some use cases 3. Reduced network complexity 3. Reduced device cost 4. Reduced device power consumption 5. Efficient signalling over the air interface and in the network 6. Support for hybrid positioning methods 7. Scalability (support for large number of devices) 8. High security 9. High availability 10. Support UE speed as defined in TR 22.862
NR Cross Link Interference and Remote Interference Management SID RP-181430/1431	This is to study mechanisms to mitigate the impact of remote base station interference in unpaired spectrum focusing on synchronized macro cells with semi-static DL/UL configuration in co-channel. In NR deployment on lower TDD frequency, the impact of the troposphere bending will continue to exist if no special mechanisms are introduced. Though the design of the frame structure in NR is already considered as much more flexible GP to leave larger room for avoiding the remote interference, it is necessary to study mechanisms for identifying when or for how long will be enough for GP to be configured, as well as corresponding gNB's behavior and inter-gNB's coordination procedure.
NR UE Power Consumption Improvement SID RP-181463	The objective is to study UE power saving framework taking into consideration latency, performance and network impact. The objective of the UE power saving study includes the following: 1) Identify techniques for UE power saving with focus in RRC_CONNECTED mode 2) Study the UE power consumption reduction in RRM measurements in synchronous and asynchronous network deployment 3) Study the enhancement of higher layer procedures for UE power saving a) Study the enhancement of UE paging procedure based on the additional power saving signal/channel/procedure b) Study the enhancement of UE power saving procedure in supporting efficient transition from RRC_CONNECTED to RRC_IDLE/RRC_INACTIVE mode

<table>
<tr><th></th><th></th></tr>
<tr><td>NR Support for Industrial IoT (URLCC related) SID

RP-181479/1451</td><td>In Rel-15, the basic support for URLLC was introduced with TTI structures for low latency as well as methods for improved reliability. Further use cases with tighter requirements have been identified as an important area for NR evolution.
Rel-15 enabled use case improvements
Such as AR/VR (Entertainment industry)
New Rel-16 use cases with higher requirements
Factory automation
Transport Industry
Electrical Power Distribution
For these use cases, improved areas have been identified for /L2 and L3, including support of TSN (Time Sensitive Networking). TSG SA WG1 has been also addressing the requirements for enhanced URLLC work, as captured in TS 22.804.

The objective of this study item is to investigate enhancements to URLLC, considering both FR1 and FR2 as well as TDD and FDD, with the already existing solutions for NR as the baseline.</td></tr>
<tr><td>NR Mobility Enhancement WID

RP-181433</td><td>3GPP has completed the basic feature for new radio (NR) systems in Rel-15 specification. However, due to lack of time in Rel-15 time frame, only basic handover is introduced. The basic handover is mainly based on LTE handover mechanism in which network controls UE mobility based on UE measurement reporting. In the basic handover, similar to LTE, source gNB triggers handover by sending HO request to target gNB and after receiving ACK from the target gNB, the source gNB initiates handover by sending HO command with target cell configuration. The UE sends PRACH to the target cell after RRC reconfiguration is applied with target cell configuration.

In fact, handover in NR high frequency range with beamforming may increase interruption time in comparison to LTE due to beam sweep delay. Reliability reduces for the same reason due to beamforming characteristics and provides smaller coverage. When the UE moves or rotates, the UE can experience very fast signal degradation. Another challenge is due to very different channel condition between LoS and non LoS in NR. It is observed that pathloss fluctuation can be tens of dB different in signal strength in beams or between LOS and non-LOS. It may result in higher handover failure and large Ping-Pong rate. Therefore, handover becomes more challenging in NR environment than in LTE.

Furthermore, in NR, 0ms interruption is one of the requirements to provide seamless handover UE experience. Mobility performance is one of the most important performance metrics for NR. Therefore, it is important to identify handover solution to achieve high handover performance with 0ms interruption, low latency and high reliability. In Rel-15 NR, 0ms interruption time can be achievable by using intra-cell using beam mobility and addition/release of SCell for CA operation. However, there is demand to achieve 0ms</td></tr>
</table>

	interruption time in more scenarios especially in URLLC type of service which requires 1ms of end-to-end delay in some scenarios. Therefore, the use cases and requirements in Rel-16 should be: to reduce HO/ SCG change interruption time, and; to improve HO reliability. The mobility enhancements should be applied to both inter-/intra-frequency HO/SCG change. The mobility enhancements should not be limited to the high frequency range although challenges/channel characteristic in high/med frequency should be considered. Solutions to reduce HO/ SCG change interruption time and to improve HO reliability is also beneficial to high speed trains and aerial use cases where the channel situation becomes challenging in terms of HO performance.
NR Study on Operations Above 52.6GHz SID RP-181435	NR Rel-15 WI defines operation for frequencies up to 52.6GHz. The physical layer channels were designed to be optimized for uses under 52.6 GHz and with the potential to be used for above 52.6 GHz. However, frequencies above 52.6 GHz are faced with more difficult challenges, such as higher phase noise, extreme propagation loss due to high atmospheric absorption, lower power amplifier efficiency, and strong power spectral density regulatory requirements, compared to lower frequency bands. Additionally, the frequency ranges above 52.6 GHz potentially contains larger spectrum allocations and larger bandwidths that are not available for bands lower than 52.6 GHz and should support widely ranging use cases, such as V2X, IAB, NR licensed and unlicensed, and non-terrestrial operations. Other aspects for NR operation in above 52.6 GHz bands are co-existence with other RATs such as IEEE 802.11ad/ay systems. With the aim of enabling and optimizing 3GPP NR systems for operation in above 52.6 GHz, as originally planned during the NR SI, 3GPP should further work on physical layer channels including potential introduction of new waveform, procedures, and requirements, and etcetera, where the operation is applicable for operations in licensed and unlicensed spectrum, to WAN operation, private networks, Integrated Access Backhaul (IAB), ITS application using vehicular communications (V2X), and etcetera. This study item studies general aspects of NR operation in above 52.6 GHz such as target spectrum range, use cases, requirements, and etcetera, which can facilitate 3GPP's future relevant work.
RAN-Centric Data Collection and Utilization for NR SID RP-181456	In order to optimize system performance in scenarios where UEs are served by different 3GPP RATs, SON mechanisms need to be designed to enable self-organization in the presence of LTE and NR radio accesses. One example of such scenarios is EN-DC, where the UE is served via radio links hosted by LTE and NR base stations. In such cases coordination between involved eNBs and gNBs is needed. On the other hand, in new RAN architecture in NR (e.g., CU/DU), more powerful storage and

	computing capability of new RAN, as well as emerging technologies in industry (for example, Machine Learning), provide new opportunity for data collection and utilization. Furthermore, in LTE, due to the lack of a whole picture from the very beginning, features of the SON family were studied and specified separately although they are inter-related with each other, for example, MDT and RACH optimisation, MDT and layer 2 measurements, load balancing and handover optimisation. For NR, there is an opportunity to have a fresh start with a complete picture of how to collect information to better serve SON-oriented solutions, RRM enhancement and other applications. Therefore, RAN-centric data collection and utilization should be thoroughly studied and investigated in NR. LTE solutions already defined for SON and MDT should be taken into account in this SI and study on SON and MDT use cases will focus on the differences arising from the new scenarios or features of NR compared to LTE. Furthermore, use of machine learning to predict future QoS would be beneficial for V2X and may require special L1/L2/RRM reporting. Additionally, more and finer granularity (therefore, beam basis) of measurement can be achieved in NR. NR measurements are performed based on SSB, which corresponds to each beam. However, LTE measurements are performed based on SS, which corresponds to each cell.
WID CA and DC Enhancements for NR RP-181469	The objective of this work item is to investigate enhancements to DC and CA. The following topics are included in the WID: 1. Support of asynchronous and synchronous NR-NR Dual Connectivity 2. Early Measurement reporting**:** Early and fast reporting of measurements information availability from neighbor and serving cells to reduce delay setting up MR-DC and/or CA 3. Efficient and low latency serving cell configuration/activation/setup**:** Minimizing signaling overhead and latency needed for initial cell setup, additional cell setup and additional cell activation for data transmission 4. Fast recovery**:** Support fast recovery of MCG link e.g. by utilizing the SCG link and split SRBs for recovery during MCG failure while operating under MR-DC.
Study on radiated test methodology for the verification of multi-antenna reception performance of NR UEs RP-181402	The objective of this Study Item is to define metrics and end-to-end testing methodology for the verification of radiated multi-antenna reception performance of NR UEs in FR1 and FR2 and the associated measurement uncertainty budgets. What kinds of performance metrics are feasible and necessary to better characterize the end-user performance should also be studied. It is anticipated that the multi-antenna UE reception testing methodologies for FR1 and FR2 will be different. The development proceeds within the following scope:

	In general- • The study is based on key performance metrics identified by operators, network infrastructure vendors, and UE vendors • For the following device types: - Smartphones - Tablets - Wearable devices - Other UE types are not precluded for discussion as a second priority • The development of test methodology aspects shall initially focus on the smartphone device type • The test methodology shall include both NSA and SA • Utilizing the free space (FS) testing configuration is the first priority • A second priority is the study of head/hand/body blocking and its impact on test methods – this will be in collaboration with CTIA who plan to study these aspects • Up to spatial multiplexing rank 4 scenarios for FR1 and up to spatial multiplexing rank 2 scenarios for FR2 • A study to define the environmental conditions is needed - Noise-limited and interference-limited (with spatial interference emulation) scenarios shall be considered - Considering the definition of interference conditions for example, colored by in- channel frequency allocation, space and time • Maintaining alignment with the corresponding baseband demodulation test case parameters in [TS38.101-4] as much as possible • Using the channel models defined in [TR38.901] as well as the associated aspects related to channel modeling in [TR38.810] as the basis of the emulated propagation environment • For setups intended for measurements of UE characteristics in non-standalone (NSA) mode, an LTE link antenna setup is used to configure the NR link • Define the applicable test methodology verification procedures • Develop the preliminary uncertainty assessment for the methodology • For any alternate method(s) identified, verify equivalence per agreed criteria and quantify impact on the measurement uncertainty assessment • Develop channel model and emulated environment validation procedure to ensure correct implementation • For testing methodology in FR1 - Use the reference MPAC MIMO OTA methodology and the harmonized RTS methodology in TR37.977, extend the applicability of the LTE MIMO OTA methodology to NR FR1

	- Use the performance metric based on the LTE MIMO OTA performance metrics in TS37.144 and CTIA MIMO OTA Test Plan as a starting point such that - The DUT configuration, DUT positions (FS DMP, FS DML, FS DMSU), and DUT azimuth positions should be reused where possible - Support up to 100 MHz CBW - Support UE operating frequency in the range of 450 MHz – 6000 MHz • For testing methodology in FR2 - Define the test scenario(s) in terms of the assumptions of the number of emulated gNB sources, BS antenna patterns, channel model, and DUT positions. Ensure the applicability of the testing methodology to NR FR2: - Support up to 400 MHz CBW - Support UE operating frequency in the range of 24250 MHz – 52600 MHz • MIMO throughput under static geometry environment is the first priority • MIMO throughput under dynamic geometry environment is the second priority • Extension of Rel-15 RRM tests to include dynamic geometry • Test scenario definition is based on key performance metrics identified by operators, network infrastructure vendors, and UE vendors • Noise-limited environmental condition is the first priority
	This study item will identify and evaluate solutions for supporting wireless backhaul/relays in NR, including specification impact for potential enhancements to the physical and higher layer design for NR to meet requirements for efficient operation of integrated backhaul and access links.
Study on NR-based Access to Unlicensed Spectrum RP-181339/1019	As the cellular industry enters its next phase of evolution with the study of a wider bandwidth waveform under the NR project, it is also time to incorporate those lessons into the evolution of the LAA feature. We call this "NR-based access to unlicensed spectrum". NR-based unlicensed access, with underlying unlicensed band CCs with wider bandwidth (for example, 80 or 100MHz), will also reduce the implementation complexity for both eNB and UE, compared to carriers of smaller bandwidth, when moving to address larger amount of spectrum, something that we consider inevitable for those scenarios where multi-Gbps data rates need to be achieved. In line with NR development and in order to maximize the applicability of NR-based unlicensed access, we consider it beneficial in studying solutions applicable to sub7 unlicensed bands (for example, 5GHz, 6GHz). In the same vein, the study should look into scenarios and solutions where NR-LAA is anchored to a legacy LTE carrier by dual-connectivity (DC) similar to the NSA mode of regular NR operation, as well as CA based aggregation with a 5G NR anchor. Furthermore, it is beneficial to consider standalone operation of NR in unlicensed spectrum at an early stage. As already considered in RP-141646 in some regions in the world, unlicensed technologies need to abide by certain regulations, for example, Listen-Before-Talk (LBT). Fair coexistence

	between cellular operations and other technologies such as Wi-Fi, in its different versions, as well as between cellular operators themselves, is necessary. Even in countries without LBT, regulatory requirements exist to attempt to minimize interference with other users of the unlicensed spectrum. However, it is not enough to minimize interference simply for regulatory aspects. It is thus essential to ensure that a NR-based unlicensed access wideband system operates as a "good neighbor" towards all forms of legacy systems. This is a study to determine a single global solution for NR-based access to unlicensed spectrum, to be compatible with the NR concepts
Solutions for NR to Support Non-Terrestrial Networks RP-181370	The objectives for this study item, based on the outcomes of the TR 38.811, are to study a set of necessary features/adaptations enabling the operation of NR protocol in non-terrestrial networks for 3GPP Rel-16 with a priority on satellite access. UAS (including HAPS) based access could be considered as a special case of non-terrestrial access with lower delay/Doppler value and variation rate. ***Physical layer*** Consolidation of potential impacts as initially identified in TR 38.811 and identification of related solutions if needed : • Physical layer control procedures (e.g. CSI feedback, power control) • Uplink Timing advance/RACH procedure including PRACH sequence/format/message • Making retransmission mechanisms at the physical layer more delay-tolerant as appropriate. This may also include capability to deactivate the HARQ mechanisms Performance assessment of NR in selected deployment scenarios (LEO based satellite access, GEO based satellite access) through link level (Radio link) and system level (cell) simulations. ***Layer 2 and above, and RAN architecture*** Study the following aspects and identify related solutions if needed: • Propagation delay: Identify timing requirements and solutions on layer 2 aspects, MAC, RLC, RRC, to support non-terrestrial network propagation delays considering FDD and TDD duplexing mode. This includes radio link management [RAN2] • Handover: Study and identify mobility requirements and necessary measurements that may be needed for handovers between some non-terrestrial space-borne vehicles (such as Non-Geo stationary satellites) that move at much higher speed but over predictable paths [RAN2, RAN1] • Architecture: Identify needs for the 5G's Radio Access Network architecture to support non-terrestrial networks (for example, handling of network identities) [RAN3] ◦ Paging: procedure adaptations in case of moving satellite foot prints or cells

Study on Communication for Automation in Vertical Domains	• Identify stage 1 potential requirements based on existing work in IEC on dependable communication (for example, IEC 61907) as used, for instance, in industrial automation • Identify stage 1 potential requirements resulting from common usage of the network, for instance assurance of network operation (SLA) to the user through network monitoring • New use cases (including, for example, rail-based mass transit, industrial automation), also based on input from relevant vertical interest organisation (for example, UITP, CCBG, ZVEI, CENELEC) • Note: this study will only address use cases that are not already covered in TR 22.889 • Identify stage 1 potential security requirements based on work already done, e.g. IEC 62443, NERC CIP, and IEC 62351
Study on Enhancements to the Service-Based 5G System Architecture	On network architecture, functions and interfaces: • Identify and document existing media handling functions that need to be ported to the 5G architecture • Map media related SA1 use cases to the 5G network architecture • Study implications of the 5G architecture on PSS and MBMS services • Identify media related interface and their network terminating functions in the 5G architecture • Identify network media processing and handling functions that need to be defined as part of the 5G system • Study how to utilise the service-based architecture for example, via NEF (Network Exposure Function) to obtain UE information that can be used in service personalisation (for example, for ad insertion, personalised media and etcetera • On device/UE architecture, functions and APIs • Study and Identify media handling functions in the device/UE related to the 5G architecture • Study and identify device APIs and network interfaces • Address interfaces to network functions identified in the network aspects of the study • Develop media-related reference device/UE device architectures
Study on MBMS User Services for IoT	The objective of this study is to investigate and make recommendations on MBMS User Service profiles and optimizations to provide for IoT: 1. Study and evaluate MBMS User Services and the associated service delivery and management framework in the context of deployment scenarios and requirements for Massive IoT in 3GPP TR 22.861 (stage-1) and MBMS user service for IoT UEs using power saving functions in 3GPP TS 23.682 defines in clause 4.5.18 (stage-3) 2. Identification of constraints for IoT devices in the reception of application content via MBMS User Service mechanisms, possibly identifying different classes of devices with

	differentiated constraints and needs and addressing different use cases and application services • Power consumption models for IoT services for MBMS User and Bearer Services • Processing and storage constraints for IoT devices 3. Study and evaluate potential MBMS service layer optimizations and profiles, based on the current protocols and procedures, including delivery methods, service announcement, associated procedures and security considerations. 4. Identification of potential normative work on new or modified functionality for the MBMS service layer, xMB interface, MBMS bearer service, MBMS-APIs, and security aspects.
Study on Media Handling Aspects of Conversational Services in 5G Systems	The objective is to study media handling aspects of conversational services in 5G, taking as baseline the Stage-1 requirements developed by SA1 in TS 22.261, as well as the Stage-2 architecture for 5G systems developed by SA2 in TS 23.501. In particular, the following areas will be investigated: 1. Investigate media handling aspects of the 5G system architecture in relation to 3GPP conversational services, e.g., Multimedia Telephony Service over IMS (MTSI) in TS 26.114 and IMS-based Telepresence Service in TS 26.223 2. Identify relevance and potential reuse of components in existing 3GPP conversational services (for example, MTSI, IMS-based telepresence, etc.) in the context of 5G systems and related Stage-2 architecture, for example, use of MTSI features for supporting voice and video calls, use of MTSI, MS-MTSI and IMS-telepresence features for supporting multi-party conferencing, and applicability of existing QoE monitoring and QoS handling mechanisms 3. Study potential enhancements to existing 3GPP conversational services (for example, MTSI, IMS-based telepresence, and etcetera) towards better fulfilling the Stage-1 requirements in TS 22.261, for example, in terms of criteria such as latency and bandwidth efficiency, while also taking into consideration the Stage-2 architecture for 5G systems 4. In case existing codecs are unable to address 5G application requirements, new media codec requirements for 3GPP conversational services may be developed 5. Investigate the need for, and potential use of, new QoS media handling mechanisms in 5G systems such as traffic classification and codec-aware network elements in the context of 3GPP conversational services
Study on Architecture Enhancements for 3GPP Support of	The objectives of this study are to identify and evaluate potential architecture enhancements of EPS and 5G System design needed to support advanced V2X services identified in TR 22.886, based on vehicular services requirements defined in SA1 V2X

Advanced V2X Services	(TS 22.185) and eV2X (TS 22.186) and determine which of the solutions can proceed to normative specifications. The detailed objectives are as follows: 1. Investigate and evaluate the possible reuse/enhancement of existing functionalities and architectures (e.g. NR, E-UTRA, NG-RAN, E-UTRAN, 5G CN, EPC) in order to support advanced V2X services, including but not limited to: • platooning, extended sensor sharing, ranging to enhance positioning accuracy and other network based positioning enhancements, advanced driving, and remote driving. 2. Identify which of the solutions for architecture enhancements could proceed to normative specifications.
Study on the Wireless and Wireline Convergence for the 5G System Architecture	The objective of this study is to enhance the common 5G core network defined in phase 1 in order to natively support non-3GPP access networks, specifically wireline access networks. The key areas of the investigation are: • Support of wireline access networks - Definition of the 5G Core network (CN) and wireline access functional split - Investigation on whether enhancements are needed to interfaces (e.g. N1, N2, N3) used to connect wireline access network to the converged 5G CN Note 1: The area of investigation for authentication and security will be limited to the part relevant to SA2 scope and responsibility. • Use of a common framework for authentication and security, policy and QoS, Network Slicing and investigation on whether enhancements are needed • Study on how to support CPE/Residential Gateway capable of connecting via wireline / wireless access to the 5G CN as a 3GPP UE • Study on how to support end user devices, with or without UICC, connected to the convergent 5G CN from behind a CPE/Residential Gateway • Identification of the impacts on mobility, session management and interaction with Access Traffic Steering, Switching and Splitting for UEs accessing the 5G convergent network and investigation on whether enhancements are needed Note 2: The study of Access Traffic Steering, Switching and Splitting is not in the scope of this SID • Study on how to support CPE/Residential Gateway capable of connecting simultaneously via both 5G RAN and wireline access to 5G CN; Note 3: The above scenario is referred as Hybrid Access in Broadband Forum (BBF TR-348).

	The study will consider information provided by the BBF and may identify specific areas which will be further studied in 3GPP, or where that study / specification should be under BBF responsibility.
Study on Encrypted Traffic Detection and Verification	1) Identify the scenarios to be addressed by the study, considering SA1 requirements for the 5GS 2) Study encrypted traffic detection and verification, which may include: • how to use PFDF to provision the information to PCEF for encrypted traffic detection and verification • potential detection and verification mechanisms in core network, excluding heuristics and similar solutions out of scope of 3GPP • handling of IPv4, IPv6, and non-IP data 3) Evaluate solutions to determine which solution(s) can be used for EPS, 5GS, or both SA3 will be involved as needed depending on the solutions proposed, in order to consider the security aspects and impacts.
Study of Enablers for Network Automation for 5G	Operators have traditionally been collecting information about their network and more and more such collected information is being mined. Network Data Analytics (NWDA) is introduced in the 5G phase1 to automatically provide slice specific network data analytics to the network. In Rel-15, NWDA only notifies or publishes slice-specific network status analytic information to the PCF(s) that are subscribed to it. However, other network functions may also benefit from NWDA reporting. In order to improve the NWDA work initiated in Rel-15, it looks beneficial to further investigate solutions for supporting network automation deployment. With information exposure across technical domains for context mining. The work will study the necessary data to expose to NWDA and the necessary NWDA outputs in order to at least support (non-exhaustive list): • Customized mobility management per UE for example, paging enhancements and mobility pattern • 5G QoS enhancement for example, 5G QoS target fulfilment verification and QoS profile for non-standardized 5QI • Dynamic traffic steering and splitting, UPF selection, UE traffic routing policies based on UE's service usage behaviour • Service classification-based resource management for example, background data transfer for MNO and 3rd party service provider and TV content

<table>
<tr><td></td><td>No algorithms or NWDA internal behaviour is to be specified, which is out of the scope of 3GPP and the SID will focus on how to collect data and how to feedback network data analytics to the network.

During the study phase, other SDOs/organizations (as appropriate) may need to be consulted to ensure and evaluate the performance applicability and any solutions implications and any overlapping on their areas.</td></tr>
<tr><td>Study on Access Traffic Steering, Switch and Splitting Support in the 5G System Architecture</td><td>The objective of this SID is to study for the following aspects for UEs, that can connect to both 3GPP and non-3GPP accesses in the 5G system:

• How the 5G Core network and the 5G UE can support multi-access traffic steering (as defined in clause 3.1 in TR23.799) between 3GPP and non-3GPP accesses
• How the 5G Core network and the 5G UE can support multi-access traffic switching (as defined in clause 3.1 in TR23.799) between 3GPP and non-3GPP accesses. This includes the conditions that can trigger the switching of data traffic to a new access type
• How the 5G Core network and the 5G UE can support multi-access traffic splitting (as defined in clause 3.1 in TR23.799) between 3GPP and non-3GPP accesses (multi access PDU session). This includes the conditions that can trigger the splitting of data traffic across multiple accesses
• How the multi-access traffic steering, switching and splitting (ATSSS) can be considered by the charging framework in order e.g. to enable the network operator to differentiate charging for data traffic that is switched and/or split between 3GPP and non-3GPP accesses
• It is clarified that this SID will not address the charging framework and it will only consider what information needs to be provided to the charging framework in order to charge traffic that is switched and/or split between 3GPP and non-3GPP accesses
• How the 5G core network can support multi-access PDU sessions, therefore, PDU sessions whose traffic can be sent over 3GPP access, or over NON-3GPP access, or both.

This study will also define potential policy requirements that should be fulfilled for multi-access traffic steering, switching and splitting (ATSSS).</td></tr>
<tr><td>Study on Enhancements to IMS for New Real-Time Communication Services</td><td>The objective of this study is to develop high-level use cases and identify the related potential requirements to enable IMS network to support new RTC services.

The study will for example consider the following scenarios:

• large scale one to many asymmetric communication (e.g. live broadcast video service in a stadium, concert, or other events) with efficient media negotiation
• remote control of video client (for example, camera) functions not specifically related to the video stream therefore, Pan, Tilt and Zoom (PTZ)</td></tr>
</table>

	• fast IMS call setup time for Group Communication • enhancements on voice & video communications for supporting AR/VR • network slicing for IMS • video sharing between UEs in V2X (i.e. VaD)
Study on 5G Message Service for MIoT	The objectives of this study item is to develop use cases of message communication for MIoT, identify 5G message service requirements, and identify potential requirements on 5G system. The study will have gap analysis between the new requirements of message communication for MIoT and the existing operator's message services/3GPP network capabilities. The use cases in this study will include but are not limited to the following scenarios: • Light-weight message communication • Ultra-low delay and high reliability message communication • Group message communication • Multicast and broadcast message communication

Study on Business Role Models for Network Slicing	The objective of this study is to examine the business role models for network slicing in order to identify potential requirements that will enable a 3GPP system to adequately support those models. The following topics will be studied:
	
	• Business role models for network slicing, (for example, monitor, limited control, enhanced control, private slice)
	• Trust relationships between MNOs and slice tenants under various business role models
	• Security relationships between
	  o a UE and a private slice,
	  o a private slice and the network, and
	  o a private slice and other slices in the same network
	• Relationship of business/stakeholder/management role models with slice characteristics (for example, slice scalability, slice flexibility, slice performance)
	• 3GPP enhancements needed to support the business/stakeholder/management role models for slices

Study on Cellular IoT support and evolution for the 5G System	Objective I: Enable CIoT/MTC functionalities in 5G CN The objective is to study how to support identified CioT/MTC functionalities in 5G CN with potential connectivity to WB-EUTRA (eMTC) and/or NB-IoT for 5GS capable devices. How to enable the following CIoT/MTC functionalities needs to be evaluated and studied in 5G CN, if needed:

	• Equivalent overall functionalities as provided by SCEF for CIoT/MTC • Monitoring • Small data transmission (infrequent and frequent small data transmission including frequent small data transmission from tracking devices) • Additional power saving functions unless those are supported for 5G system in Rel-15 • Non-IP Data Delivery • Overload control (as relevant in 5G CN) • Support of Coverage enhancement including adaptations in 5G CN required to support latencies • Equivalent to Group communication and messaging • Reliable communication via functionality equivalent to SCEF • Inter-RAT mobility support to/from NB-IoT • High latency communication • Include location services procedures for IoT in 5G location services • Any modifications in the EPC-5GC interworking "baseline" specific to CIOT NOTE: Attach without PDN connection and non-IP PDN Connection type is already supported in 5G CN (TS 23.501). Ensure that regulatory requirements can be fulfilled at the same level as in EPC. Objective II: Co-existence and migration from EPC based eMTC/NB-IoT to 5GCN. Study solutions for coexistence and migration from EPC towards 5G CN for eMTC/NB-IoT. This objective will study solutions where the same service is offered to some UEs connected to EPC and some UEs connected to 5G CN for example, using SCEF and equivalent functionalities in 5GCN. Solutions that assume that 5G CN needs to support EPC NAS Signalling for legacy IoT devices access are not considered. Objective III: 5G System enhancements to address 5G service requirements (based on TS 22.261 and TR 38.913). To study system architecture enhancements to address related service requirements defined in TS 22.261 and RAN requirements defined in TR 38.913 and how to enable them in 5G CN, if needed. At least the following service requirements have been identified: • Enable the association between subscription and address/number of an IoT device within same operator and in between different operators • Restricted Registration procedure to allow IoT device remote provisioning Any system implications for the RAN will be coordinated with RAN WGs.
	The objectives of this normative work are to specify the stage 1 requirements for new functionalities for the following UEs in order to support the legacy regulatory policy and to

Enhancements of Public Warning System	provide the requirements for devices whose user interface or display method is not suitable to show text-based PWS messages. • UEs with no user interface over direct network connection • Remote UEs with no user interface over indirect network connection • Relay UE for indirect network connection of remote UEs • UEs with different user interface In addition, another objective is to specify the stage 1 requirements that address the improvement of the understandability of a PWS message to help the following users recognize what happens from a PWS message that they receive: • Users with disabilities such as vision impairment; and • Users who internationally travel or live in other country than their mother country without knowledge of the local language. The new requirements that are to be introduced in 3GPP TS 22.268 are based on the results of the study FS_ePWS specified in 3GPP TR 22.869. This work item will not introduce new functionality for US WEA and Japan ETWS.
Study on Multimedia Priority Service (MPS) Phase 2	This study will identify use cases and the associated potential new stage 1 requirements beyond those documented in TR 22.953. Example use cases to be studied include: • MPS for Data Transport Service (DTS): MPS DTS communications invoked from a subscribed UE, a subscribed IoT device, and from an Enterprise network • MPS for Video: MPS for conversational video, streaming video, and video teleconferencing invoked from a subscribed UE and MPS for video teleconferencing invoked from a Video Server by the Host • MPS for Text Messaging: MPS for text messaging (for example, based on IMS/SIP messaging) invoked from a subscribed UE and from a subscribed IoT device. The study will also consider evolution aspects for MPS support in 5G. This includes: • Support of MPS communications in a 5G multiple accesses and core network environment • Support of MPS in a mixed LTE and 5G NR environment • Security considerations Note: Although MPS may use some common priority mechanisms used by MCData and MCVideo, MPS has some unique service requirements that are different from MCData and MCVideo. Specifically, MPS is supported using operator's commercial services (voice, video and data) with priority.
	The objectives of the study are to address the questions of why, when, where, and how, as detailed in the Justification part of the present SID.

Study on Supporting 256-bit Algorithms for 5G	WHY: assessing of threats and potential countermeasures; comparing of countermeasures in the 5G system. WHEN: establishing timelines for the introduction of countermeasures, in particular the increase of key lengths to 256 bits. Aligning with the timeline for strengthening asymmetric cryptographic algorithms used in 5G systems. WHERE: establishing which parts of the 5G system will be affected and in which way. HOW: More detail is given here: The following are key components of the proposed migration to 256-bit session keys in the context of 5G networks that need to be examined: • Study the addition of full entropy 256 bit keys in the 5G key hierarchy, beginning with the permanent pre-shared key. Study modifying the derivation algorithms in order to derive child keys from the 256-bit master key instead of the 128-bit key. • Integrity protection: Currently, the integrity protection MAC-I that is appended to CP and UP messages is only 32 bits. This study will determine whether a longer MAC is appropriate for 5G. Note that the higher data rates achievable in 5G should be able to accommodate a reasonable MAC-I size increase without suffering significant performance degradation. It is also to be studied whether an integrity algorithm different from the ones standardized for 5G phase 1 needs to be developed. • Coexistence of different size keys: In 3GPP networks, 256-bit keys in 5G will need to coexist with 128-bit keys in legacy networks or earlier 5G phases. This entails storage of keys and separate key derivation algorithms both on the UE and in the core network. • Determine the desired number of 256-bit algorithms, for example, if two 256-bit AKA key generation algorithm sets are needed • Determine the desired performance aspects for the new 256-bit algorithms considering software and hardware aspects • Key size negotiation: The security specification should be flexible so as to be easily adapted or upgraded in the future, particularly taking into consideration roaming situations. • Key management, key distribution and key refresh: It is studied whether the current methods for distribution and refresh of security keys are equally applicable to larger key sizes and can remain the same. • Encryption and integrity algorithms: accommodating 256-bit session/intermediate keys in 5G, may, in some cases, simply entail using larger-key versions of current algorithms, while in other cases new algorithms may need to be chosen altogether. • Determine suitable requirements for the needed algorithms for use with 256-bit keys and ask ETSI SAGE to provide those algorithms.
Study on Enhancements to the	The objectives of this study are to enhance service-based architecture used for location service in 5G system, and corresponding Network Functions, procedures, to meet the full set of requirements defined in SA1 (e.g. TS 22.261 and TS 22.071)

5GC Location Services	1. For those requirements to be fulfilled aforementioned: • Identify new functionalities and their assignments to different NFs (for example, which new functionality is needed, and how to assign new functionality to the LMF, AMF, GMLC, and etcetera) • Detailed end to end procedures, for example, 5GC-MT Location request, 5GC location reporting procedures, and eteterca • Evaluate benefits and disadvantages of different assignments of new functionality • Both non-roaming and roaming scenarios should be considered • Both non 3GPP access and 3GPP access should be considered 2. How to support location service in 5GS and EPS interworking scenario, for example, how to respond MT-LR during inter NR and LTE handover procedure, and as well as in non-3GPP access and 3GPP access interworking scenarios. Key Issues, solutions for those objectives will be investigated and evaluated during the study. Solutions in Rel-16 should avoid or minimize impact to reference point protocols that are defined by non-3GPP organizations; should be backward compatible with Rel-15 UEs, and should minimize impacts to N2 interface, and the existing network functions (NF) in 5GC. This study will consider un-trusted non-3GPP access and 3GPP access first from the perspective of UE access (though can allow non-3GPP access to be used for UE location determination). After the architecture for connecting trusted non-3GPP access to 5GC has been specified, the study will also consider how to support location services for trusted non-3GPP access.
Study on Enhancement of Network Slicing	The objectives of this Rel-16 SA2 study are to address the network slicing open issues which are left over from Rel-15: • Identify, prioritize and study the practical non-roaming and roaming deployment scenarios and system impacts when the 5GS is not able to support all possible combination of S-NSSAIs for the UE, and the isolation aspects among Network Slices • Study the possible enhancement for the Network Slicing interworking with EPC for Connected and Idle modes • Study how to provide Network Slice Access authentication and authorization specific for the Network Slice Access authorization that uses User Identities and Credentials different from the 3GPP SUPI and that takes place after the primary authentication which is still required between the UE and the 5GS for PLMN access authorization and authentication
Study on Security Aspects of the 5G	The objective of this study item is to investigate the following security aspects related to SBA in 3GPP Rel-15: • NF-NRF Authentication during NF registration and service discovery • NF-NRF Authorization during NF registration and service discovery

Service Based Architecture	• NF-NF Authentication during service access • NF-NF Authorization during service access • Security for inter-PLMN signalling (N32 reference point), considering intermediaries in the form of IPX providers in between different PLMNs • SEPP security policies that determine the application layer protection to be applied • Confidentiality as well as integrity and replay protection for messages exchanged between NFs
Mission Critical Services Security Enhancements	This work item will address the SA3 normative security work for the mission critical architecture based on the output of SA6 as specified in TS 23.179, TS 23.280, TS 23.281 and TS 23.282 and 23.283 including: • Mission critical PTT, MCPTT functional architecture and information flows • Mission critical data, MCData Functional architecture and information flows • Mission critical Video, MCVideo Functional architecture and information flows • Interconnect, mission critical interconnection between MCPTT systems, with a scope that includes the mission critical services of MCPTT, MCVideo and MCData • Interworking, mission critical interworking between MC systems and LMR systems which includes MCPTT and MCData (SDS only) services • Migration, mission critical migration between MCPTT systems, which includes the mission critical services of MCPTT, MCVideo and MCData • MONASTERY, mission critical future railway architecture for MCPTT, MCData and MCVideo • MBMS, usage of the Multimedia Broadcast/Multicast Service for MC communication services The Stage 2 security architecture previously defined in Rel-15 shall form the basis of the Rel-16 architecture to maintain cohesion, integration and backward compatibility across Mission Critical services.

6. CONCLUSIONS

3GPP Releases 14 through 16 mark an important transition for mobile communications. LTE, first defined in 3G Releases 8 and 9, reaches its culmination with Release 14, completing the work begun on LTE Advanced Pro in Release 13. Release 14 also contained a number of 5G-like capabilities in the context of a 4G network architecture. These included an OAM framework designed to support virtualized network functions, as well as control/user plane separation and enhanced dedicated core networks (eDECOR).

Releases 15 and 16 introduce the 5G Next Generation System, which marks a radical departure from 4G and all other previous networks. Besides specifying the 5G New Radio and RAN (with support for new frequency bands including mmWave frequencies up to 100 GHz), Release 15 defines a new, service-based network architecture that is designed with: network function virtualization in mind; support for features including automation and orchestration, network discovery; support for multiple access mechanisms with a common control structure (including bringing in non-3GPP access networks); and network slicing to create multiple logical networks on a single physical network.

Important Release 14 LTE RAN features are described in Section 3 of this paper, including MIMO enhancements, enhanced LAA, Narrowband IoT, the generalized V2X framework, enhancements to eMBMS, and enhanced dedicated core networks (eDECOR). Section 3 also describes the UTRAN/HSPA+ enhancements included in Release 14, and then describes the network services-related enhancements including Control and User Plane Separation, mission critical/public safety improvements, improvements for TV service and VoLTE.

Section 4 describes the progress to date of the ITU in defining IMT-2020 5G requirements, including the status of the System Architecture studies (Rel-14), the normative specs (Rel-15) and Phase II (Rel-16) requirements.

Sections 5.1-5.3 provide details of Release 15, including the 5G RAN and New Radio requirements and specifications, LTE/E-UTRAN Enhancements, and descriptions of the Next Generation System architecture and features. Descriptions of all the newly defined Network Functions are included, as well as descriptions of the various standalone and non-standalone deployment options, the common mechanism for integrating non-3GPP access networks, network slicing, subscription and authentication, QoS, and the policy framework. Section 5.4 describes progress towards Release 16.

In addition to the detailed treatment of the standards, this paper presents a view of the progress of the industry with respect to mobile networks, with a primary focus on 4G and 5G networks. An extensive section outlining the progress made by 5G Americas members in developing and deploying 4G networks and 5G demonstrations trials and products is also included in the Appendix.

7. APPENDIX

APPENDIX A: RELEASE 15 RELEASE INDEPENDENT BANDS

3GPP divided the NR bands into two major categories called FR1 and FR2. Where:

Table 7.1 Major Categories of NR Spectrum Bands.

Frequency range designation	Corresponding frequency range
FR1	450 MHz – 6000 MHz
FR2	24250 MHz – 52600 MHz

There is considerable interest in the industry to be able to repurpose existing LTE bands for NR. In December 2017, 3GPP published the first version of NR containing 18 unique frequency bands. The vast majority of the bands are below 6 GHz and they closely mirror the existing LTE bands. The three bands above 6 GHz were the 24 GHz, 28 GHz and 39 GHz bands.

In Table 7.2, there are 6 bands shown in bold face type that were included in the WID but weren't far enough along in development to be included in the first release.

3GPP adopted a new nomenclature for New Radio frequency bands; LTE uses the designation of Band XX whereas New Radio places an 'n' in front of the band number. For example, LTE uses band 71 and NR uses n71 to designate the same set of frequency ranges.

Table 7.2. NR Operating Bands in FR1.

NR Operating Band	Uplink (UL) operating band BS receive UE transmit			Downlink (DL) operating band BS transmit UE receive			Duplex Mode
	F_{UL_low}	–	F_{UL_high}	F_{DL_low}	–	F_{DL_high}	
n1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD
n2	1850 MHz	–	1910 MHz	1930 MHz	–	1990 MHz	FDD
n3	1710 MHz	–	1785 MHz	1805 MHz	–	1880 MHz	FDD
n5	824 MHz	–	849 MHz	869 MHz	–	894MHz	FDD
n7	2500 MHz	–	2570 MHz	2620 MHz	–	2690 MHz	FDD
n8	880 MHz	–	915 MHz	925 MHz	–	960 MHz	FDD
n13	700 Mhz			700 Mhz			[FDD]
n20	832 MHz	–	862 MHz	791 MHz	–	821 MHz	FDD
n25	1900 MHz			1900 MHz			[FDD]
n26	800 Mhz			800 MHz			[FDD]
n28	703 MHz	–	748 MHz	758 MHz	–	803 MHz	FDD
n34	2000 MHz			2000 MHz			[TDD]
n38	2570 MHz	–	2620 MHz	2570 MHz	–	2620 MHz	TDD
n39	1800 MHz			1800 MHz			[TDD]
n40	2300 MHz			2300 MHz			[TDD]
n41	2496 MHz	–	2690 MHz	2496 MHz	–	2690 MHz	TDD
n50	1432 MHz	–	1517 MHz	1432 MHz	–	1517 MHz	TDD
n51	1427 MHz	–	1432 MHz	1427 MHz	–	1432 MHz	TDD
n66	1710 MHz	–	1780 MHz	2110 MHz	–	2200 MHz	FDD
n70	1695 MHz	–	1710 MHz	1995 MHz	–	2020 MHz	FDD
n71	663 MHz	–	698 MHz	617 MHz	–	652 MHz	FDD
n74	1427 MHz	–	1470 MHz	1475 MHz	–	1518 MHz	FDD
n75	N/A			1432 MHz	–	1517 MHz	SDL
n76	N/A			1427 MHz	–	1432 MHz	SDL
n77	3300 MHz	–	4200 MHz	3300 MHz	–	4200 MHz	TDD
n78	3300 MHz	–	3800 MHz	3300 MHz	–	3800 MHz	TDD
n79	4400 MHz	–	5000 MHz	4400 MHz	–	5000 MHz	TDD
n80	1710 MHz	–	1785 MHz	N/A			SUL
n81	880 MHz	–	915 MHz	N/A			SUL
n82	832 MHz	–	862 MHz	N/A			SUL
n83	703 MHz	–	748 MHz	N/A			SUL
n84	1920 MHz	–	1980 MHz	N/A			SUL

Table 7.3. NR Operating Bands in FR2.

NR Operating Band	Uplink (UL) operating band BS receive UE transmit			Downlink (DL) operating band BS transmit UE receive			Duplex Mode
	F_{UL_low}	–	F_{UL_high}	F_{DL_low}	–	F_{DL_high}	
n257	26500 MHz	–	29500 MHz	26500 MHz	–	29500 MHz	TDD
n258	24250 MHz	–	27500 MHz	24250 MHz	–	27500 MHz	TDD
n260	37000 MHz	–	40000 MHz	37000 MHz	–	40000 MHz	TDD

NR Non-standalone mode uses Dual connectivity which requires the UE to transmit on both the NR and the LTE carrier. Dual Connectivity requires the pairing of an anchor LTE carrier with a secondary NR carrier. The dual connectivity combinations pair one or more aggregated LTE carriers with one or more aggregated NR carrier. The number of permutations is too large to include in this report and those that 3GPP is currently developing can be found in the WID (RP-181474) and the approved combinations are found in TS 38.101-3.

APPENDIX B: MEMBER PROGRESS

AT&T

AT&T Inc. is a premier communication holding company and one of the most honored companies in the world. Its subsidiaries and affiliates – AT&T operating companies – are the providers of AT&T services in the United States and internationally. With a powerful array of network resources, AT&T helps millions around the globe connect with leading entertainment, mobile, high speed internet and voice services. AT&T is building a truly modern media company that will create the best entertainment and communications experiences in the world. The recently completed acquisition of Time Warner brings together the three key elements in media and entertainment that are required to transform how video is distributed, paid for, consumed and created:

- Premium Content: No one does premium content better than the terrific talent at HBO, Turner and Warner Bros. Add in targeted content such as Bleacher Report, Boomerang and FilmStruck, and AT&T's investment in Otter Media's properties, and we have a robust content portfolio that can drive viewer engagement to new levels.
- Direct to Consumer (D2C) Distribution: AT&T's more than 170 million unique D2C connections across its wireless, video and broadband businesses provide valuable subscriber insights to better inform how we deliver advertising, what content we distribute and how we distribute that content. And we also have an opportunity to significantly grow our D2C streaming services such as HBO NOW, DIRECTV NOW and Boomerang.
- High-Speed Networks: The more customers engage with premium content the more access they will need to network bandwidth. And demand will only continue to grow with 4K and virtual reality. That's why we're investing heavily in 5G wireless and our fiber network to ensure our customers will always have a great viewing experience whenever they want to watch their favorite content.

AT&T is comprised of four distinct business units:

- AT&T Communications provides mobile, broadband, video and other communications services to U.S.-based consumers and more than 3 million companies – from the smallest business to nearly all the Fortune 1000 – with highly secure, smart solutions.
- WarnerMedia consists of HBO, Turner and Warner Bros.
- AT&T Latin America provides mobile services in Mexico to consumers and businesses, plus pay-TV service across 11 countries in South America and the Caribbean.
- Xandr provides marketers with advanced advertising solutions using valuable customer insights from AT&T’s TV, mobile and broadband services, combined with extensive ad inventory from Turner’s cable networks and AT&T’s pay-TV services.

AT&T also offers the best global coverage of any U.S. wireless provider*. AT&T is the world’s largest provider of pay TV. AT&T’s GigaPower service provides customers with ultra-fast internet speeds up to 1 gigabit per second in 26 major markets nationwide thus far with more to come. The company’s suite of IP-based business communications services is one of the most advanced in the world.

AT&T has a long history of innovation in wireless communications. AT&T and Ameritech Mobile Communications launched the nation’s first commercial cellular telephone service in Chicago on Oct. 13, 1983. AT&T's wireless network is based on the 3rd Generation Partnership Project (3GPP) family of technologies that includes LTE and HSPA+ mobile broadband. The 3GPP family of technologies is the most open and widely-used wireless network platforms in the world. This means that AT&T customers benefit from broader global roaming capability, more efficient research and development, the best options in cutting-edge devices, and smoother evolution to newer technologies. AT&T has a continuing commitment to bring together policymakers, academia, and industry through promoting standards and security for next-generation 5G mobile networks.

AT&T builds its networks for speed, performance and reliability to support services such as video. Network radio components are placed near the antennas which minimizes power loss. This translates into fast speeds and great reliability across AT&T's 4G LTE network. The network is designed with its core elements distributed across the country, meaning data traffic gets on the Internet faster, which increases mobile data speeds.

AT&T also launched one of the world's first virtualized core network platforms. The launch of virtualized core network platforms and NFV/SDN has enabled AT&T to rapidly deploy additional mobile core sites and expand its mobile core network within the US, as well as build out mobile cores in Mexico and in Europe.

AT&T's virtualized core network functions are deployed onto AT&T Integrated Cloud (AIC) locations across the globe. Running virtual core network functions on AIC enables AT&T to gather and analyze extremely large volumes of network data which enhances its Big Data based intelligence capabilities. The ability to grow the mobile core in an agile manner using NFV/SDN is a key enabler for new services, IoT growth, and 5G.

And AT&T is reinventing the cloud to boost the potential of self-driving cars, augmented and virtual reality, robotic manufacturing, and more. AT&T is embracing a model called edge computing (EC) to move the data crunching from the device to the cloud. Driving it will be single-digit millisecond latency that only tomorrow's 5G can deliver. And powering it all will be AT&T's software-defined network, the most advanced of its kind in the networking industry.

In early 2016, AT&T began its' 5G millimeter wave (mmWave) fixed wireless trials in Austin, Texas. AT&T structured its trials in such a way that continues to contribute to the international 5G standards development and pivot to compliant commercial deployments as standards were set by 3GPP. AT&T's fundamental technology approach to 5G is unique. Built on its industry-leading positions in SDN, data analytics, security and open source software, the approach will help deliver a cost-effective wireless experience that can quickly adapt to new consumer and business demands.

In September 2018, in Waco, Texas, working with key technology collaborators, AT&T made the world's first wireless 5G data transfer over millimeter wave using standards-based, production equipment with a mobile form factor device. Not a lab. Not preproduction hardware. Not emulators. And fully compliant with global standards.

AT&T's 5G deployment strategy will include using millimeter wave spectrum to deploy 5G in pockets of dense areas – where demand on our network is high and extra capacity and coverage is needed most. In other parts of urban areas and in suburban and rural areas, AT&T plans to deploy 5G on mid and low-band spectrum. AT&T has been encouraged by the performance of mmWave in their 5G trials and found that it performs better than expected and is successful in delivering ultra-high wireless speeds under a variety of conditions.

In addition, our foundational 5G Evolution technology is now live in more than 200 markets, reaching 400+ markets in 2018. 5G Evolution markets are locations where AT&T has deployed the latest technologies that enable peak theoretical wireless speeds of at least 400 megabits per second on capable devices.

AT&T plans to introduce mobile 5G in parts of twelve cities in 2018 - Houston, Jacksonville, Louisville, New Orleans, San Antonio, Atlanta, Charlotte, Dallas, Indianapolis, Oklahoma City, Raleigh, and Waco.

Looking forward to early 2019, AT&T will keep the 5G momentum going and plan to introduce mobile 5G in parts of Las Vegas, Los Angeles, Nashville, Orlando, San Diego, San Francisco, and San Jose. From these 19 cities, AT&T will continue to expand.

Since 2011, the AT&T Foundry has collaborated with customers to combine their innovative ideas with our network capabilities, then rapidly create and test prototypes for deployable products and solutions. Soon AT&T will start creating 5G-enabled technologies with the potential to disrupt entire industries at our AT&T Foundry innovation center in Plano. So whether it's moving personalized shopping experiences closer to customers or allowing surgeons to perform operations from a remote location, AT&T will be at the forefront of bringing these 5G-enabled industry capabilities to market faster.

AT&T is implementing a variety of LTE-Advanced features within its network and will continue to add more over the next few years to take full advantage of its rich functionality. These features include carrier aggregation, high-order MIMO and self-optimizing networks, to name a few.

In November 2017, AT&T launched the first commercial deployment of LTE-LAA technology in Indianapolis. With LTE-LAA, the network has peak theoretical wireless speeds reaching up to 1 gigabit per second on capable devices. AT&T has identified three new cities to get 5G in 2018, and has launched LTE-LAA in parts of eight new markets: four in Texas—Austin, Dallas, Houston and San Antonio—along with markets in Little Rock, Arkansas; San Jose, California; Tampa, Florida; and Tuscaloosa, Alabama. That brings AT&T's total LTE-LAA markets to 15; AT&T previously launched LTE-LAA in parts of Boston, Chicago, Indianapolis, Los Angeles, San Francisco, Sacramento, California, and McAllen, Texas.

AT&T launched HD Voice service utilizing Voice over LTE technology in the U.S. during 2014, following on with Wi-Fi Calling, Advanced Messaging and Video Calling. They are also working with Verizon to offer Voice over LTE interoperability between their customers.

In 2017, AT&T launched a trial of Project AirGig technology in Georgia with Georgia Power and have been encouraged by the results. In that trial, AT&T provided a fixed wireless application to a number of participating homes. It used a combination of mmWave and LTE spectrum.

Over the past 5 years, AT&T invested nearly $145 billion in our wireless and wireline networks, including capital investments and acquisition of wireless spectrum and operations. During this same period, AT&T invested more in the U.S. than any other public company. AT&T's wireless network now covers more than 99% of Americans, AT&T's fiber network is one of the nation's largest and AT&T connects more IoT devices than any other provider in North America. Additionally, more than 3 million businesses, from the largest global companies to small businesses, turn to AT&T.

** Global coverage claims based on offering discounted voice and data roaming; LTE roaming; voice roaming; and world-capable smartphone and tablets in more countries than any other U.S. based carrier. International service required. Coverage not available in all areas. Coverage may vary per country and be limited/restricted in some countries.*

CABLE & WIRELESS

Cable & Wireless Communications, a subsidiary of Liberty Latin America, is a full-service communications and entertainment provider and delivers market-leading basic and enhanced video, broadband internet and fixed-line telephony to over 1.6 million service subscribers (RGUs) represented by more than 910,000 customers as well as mobile voice and data services to approximately 3.4 million mobile subscribers as of March 31, 2018. In addition, through its business division, C&W provides data center hosting, domestic and international managed network services, and customized IT service solutions, utilizing cloud technology to serve business and government customers.

C&W also operates a state-of-the-art submarine fiber network – the most extensive in the region – connecting over 40 markets.

C&W primarily operates under the consumer brands Flow, Mas Movil, and BTC which are located in the Caribbean, Panama and Bahamas, respectively.

Cable & Wireless has deployed LTE technology on most of its mobile markets, starting the deployment of LTE-Advanced in 2016; currently Cable & Wireless has LTE-Advanced networks in Jamaica, Bahamas, Cayman Islands, British Virgin Islands, Anguilla, Dominica, Antigua and Barbados.

During the year 2017, Cable & Wireless trialed LTE-TDD in 3GPP Band 42 (3500 MHz) in Antigua, successfully testing downlink carrier aggregation with TM3/TM4 4x4 MIMO and 256QAM and achieving ~880 Mbps peak throughput per Category 18 UE on real life conditions.

During the same year, in partnership with Ericsson, 5G NR over 28 GHz was tested across the island, measuring the real performance of the system under different environmental and weather conditions. Results are being used to evaluate the different applications that this technology could have in the Caribbean markets.

In Panama, VoWiFi was launched in 2016, and during 2018, VoLTE was introduced allowing the customers to get the benefit of better voice quality and lower call setup times provided by VoLTE technology.

CISCO

Cisco is the worldwide leader in IT that helps companies seize the opportunities of tomorrow by proving that amazing things can happen when you connect the previously unconnected. At Cisco customers come first and an integral part of our DNA is creating long-lasting customer partnerships and working with them to identify their needs and provide solutions that support their success. We are an industry leader in enabling Service Provider and Enterprise digital transformation associated with 5G that allows for monetization of new services while driving efficient operations.

The Cisco Open Network Architecture provides a cross-domain platform to deliver business transformation through network agility. Cisco Open Network Architecture for service providers is a comprehensive open, extensible and modular framework for delivering simplification, automation and virtualization within the End to End Network. This architecture consists of three key functional layers that are tightly integrated with security, policy, and analytics:

- **Infrastructure** – foundational layer providing physical and virtual compute, network, and storage functions. Examples: routing, switching, mobile core, mobile backhaul, aggregation and video processing
- **Network Abstraction** – orchestration for comprehensive lifecycle service automation; telemetry and analytics for programmability. Examples: physical/virtual services orchestration, streaming telemetry, network analytics

- **Cloud-based Services** – Multi-cloud, policy-based consumer, business, IoT, video, mobility services that drive new revenue. Examples: 5G fixed mobile broadband, connected car, virtual managed services (VPN, security), residential video

A Service Creation function which includes design, assurance, and catalog provides a wrapper across these layers for simplified cloud deployment.

Cisco's market presence is the culmination of a deep understanding of the emerging needs of our service provider customers by providing complete solutions to address real business challenges and opportunity. This includes leadership not only in IP transport, but also Mobile Services Core, SON, Policy, IoT, video, and security.

The Cisco® mobile software portfolio is a key building block of the Cisco Open Network Architecture programmable framework. It provides new monetization opportunities while optimizing networks for the fullest utilization.

- **Cisco Ultra Services Platform** providing industry leading fully orchestrated VPC for the greatest elasticity and scale.
- **Cisco Policy Suite for Service Providers** provides next-gen policy management to deliver customized user experiences.
- **Cisco SON** provides real-time intelligence into the Radio Access Network (RAN) for optimized performance.
- Mobile Backhaul with the Cisco ASR Series Aggregation Services Routers are hardened, high-speed, low-power-consumption routers optimized ideal for mobile backhaul, business services, and residential voice, video, and data ("triple-play") applications
- The ASR 9000 Series Aggregation Services Routers provide a programmable and scalable network edge that are the cornerstone of modern edge and carrier Ethernet networks. They offer high platform density, low power consumption, and virtualization capabilities.
- Security Solutions such as Firepower 9300, 4100, 2100 provide critical security of traffic across the network

Cisco is deployed globally by more than 350 service providers in more than 75 countries.

Some recent customer success stories include:

- Ultra-Services Platform launched for 5G and Mobile Cloud
- CenturyLink, Inc. introduces Smart Spaces, a location-based, mobile engagement, analytics and marketing Internet of Things (IoT) solution
- 3Italia (H3G) – Ericsson and Cisco partner to protect the mobile packet core for improved performance and service stability
- Cisco and Samsung Team With Verizon To Deliver First Interconnected Multi-Vendor 5G Trials

COMMSCOPE

CommScope is a global leader in wired and wireless network infrastructure, supplying all the integral building blocks for base station sites, converged networks and indoor coverage and capacity. CommScope products support current 3GPP releases and product roadmaps and will continue to be developed to ensure future compliance to 3GPP specifications. CommScope also is a leading global provider of wireless network planning, installation and optimization products and services.

CommScope's wireless solutions address all areas of RF path and coverage needs for UMTS, LTE and LTE-Advanced networks. The company's RF solutions enable operators to synchronize investments with revenue, using scalable deployment strategies and technologies; accelerate payback by expanding macro and small cell coverage effectively; and manage coverage, capacity and interference in key areas such as urban settings, indoors, and along transportation corridors.

The CommScope Mobility Solutions portfolio includes:

- Macro cell solutions for wireless tower sites and on rooftops including antennas, RF conditioning, backhaul and enclosures
- Metro cell concealment solutions for street poles and on other urban structures that help speed deployments
- DAS and small cell solutions for enhancing cellular coverage and capacity in challenging network conditions such as commercial buildings, urban areas, stadiums and transportation systems
- Spectrum management solutions

CommScope works closely with service providers so that they are ready to address the bandwidth and service needs of their customers now and in the future. To that end, CommScope continues to evolve its wireless solutions portfolio to add network capacity, reduce latency, decrease complexity and improve efficiency. CommScope most recently has announced:

A Spectrum Access System (SAS) solution and proprietary environmental sensing capability (ESC) network for the Citizens Broadband Radio Service (CBRS). CommScope is a member of the CBRS Alliance and on the board of directors of the Wireless Innovations Forum.

- The commercial deployment of its OneCell C-RAN Small Cell solution in a mid-sized UK stadium.
- The expansion of its Metro Cell Concealment Solutions portfolio with options for discretely housing RF equipment at the bottom, middle or top of poles, while still meeting the equipment's thermal requirements.
- New ultra-wideband, MIMO base station antennas that support spectrum in 600 and 1400 MHz, part of the company's evolving antenna portfolio.
- A new In-building Wireless Sales Specialist authorization in its PartnerPRO Network, which enables qualified cabling installer partners to offer CommScope's innovative digital DAS solutions to customers.

CommScope also supports the evolution to 5G as a board member of 5G Americas, and also participates in 5G industry consortiums such as the Platforms for Advanced Wireless Research (US), NGMN (Germany), 5Tonic (Spain), 5GMF (Japan) and U5GIG (United Arab Emirates).

ERICSSON

Ericsson is a world leader in communications technology and services. With a long history of innovating new technologies within telecoms, the company is at the forefront of developing the emerging 5G.

5G systems are wider than previous generations, with support for network slicing, wireless and wired access, transport, cloud, applications, management and orchestration. Moreover, 5G will meet the needs of diverse verticals – like railways, public safety, industry automation, vehicle-to-vehicle and utilities – all with their own specific requirements implemented in the same network.

Together with a global network of operator, industry and academic partners, not the least in North America, Ericsson has been able to help build an understanding of what 5G is and is capable of, while developing and proving the needed technologies both for advanced LTE and for 5G (3GPP Releases 14, 15 and 16). Trials are ongoing with operators around the globe on 5G architectures including 5G NR access, core, and network slicing.

In 2016, Ericsson announced the first 5G NR radio, the AIR 6468, part of Ericsson Radio System, designed for compatibility with the coming 5G NR standard while also supporting advanced LTE capabilities from 3GPP Release 14. AIR 6468 also pioneers the new eCPRI interface for future fronthaul applications.

The company followed up in 2017 with the launch of a full 5G platform that supports evolution from today's networks into future standardized standalone and non-standalone 5G networks. Operators and industry trials across Europe, Asia, and the Americas have shown 5G networks delivering capabilities in a wide range of use cases from fixed wireless access, augmented and virtual reality to self-driving vehicles, connected drones, smart factories and remote surgery. Trials activities and Ericsson's leading role in projects like METIS II, mmMagic and 5TONIC feed forward into making future 5G standards robust and achievable.

Ericsson is a leading contributor within 3GPP and other major standardization organizations, not least in 5G, with awards from Global Telecom, LTE Asia, and LTE and 5G World recognizing the company's outstanding contribution to 5G standardization.

In 2017, Ericsson filed a 5G Foundation patent application that incorporates numerous Ericsson inventions into a complete architecture for the 5G network standard. With its pioneering 5G patent application the company intends to lay the foundation for all future mobile networks. The application combines the work of 130 Ericsson inventors into the largest patent in cellular communications in terms of number of inventors, anywhere in the world.

Operators need solutions that they can deploy within today's networks to manage the growth of current services as they prepare for 5G. Ericsson has focused on providing future-proof designs that can take advantage of 5G and IoT technology concepts and reap the benefits of the technology now. The same platform is designed to evolve into 5G to help the industry open new revenue opportunities and offer new levels of experience for mobile users everywhere.

INTEL CORPORATION

As Intel works to expand the boundaries of technology to make the most amazing experiences possible, the company is working with partners globally on the enablement of 5G. In support of 5G development, Intel is actively engaged in accelerating 5G standards development, trials with operators, and technology providers around the world and platform development. The company has made early investments in cloud and core networks, radio technologies and compute platforms, and other technologies that are key to enabling the next-generation of communications and computing and critical to ensuring end-to-end compatibility, interoperability, security, and optimization for greater speed and reduced latency.

Platforms: Intel debuted its Mobile Trial Platform 2016 and had continued advancements including the Intel® 5G Mobile Trial Platform, which provides a high level of flexibility and processing power for the early development and testing of 5G technologies, and the Automotive Trial Platform which recently demonstrated, in partnership with NTT DoCoMo and Toyota, the world's first interoperable 5G trial mobile network - testing at 28GHz frequency and realizing data transfer rates of over 1Gbps in a moving car.

Modems: Intel introduced, in 2016 the world's first global 5G modem supporting both sub-6GHz and mmWave bands and, in 2017, Intel introduced the Intel® XMM™ 8000 series its portfolio of new commercial modems to accelerate the 5G future. This portfolio of commercial 5G ready modems will enable a range of devices to connect to 5G networks – from PCs and phones to fixed wireless consumer premise equipment (CPE) and even vehicles. Complementing the 5G modem is the 5G RFIC, working in the 3.3 to 4.2 GHz and 20 GHz bands and supporting 50 MHz to 800 MHz transmission with 2x2 and 4x4 MIMO.

Networks: Intel also has an extensive and growing portfolio of products and technologies that deliver solutions to help communication service providers transform their networks—bringing advanced performance and intelligence from the core of the data center to the network edge. Intel's commitment to network transformation is long and deep – with years invested in delivering reference architectures, growing a strong ecosystem, and partnering with end-users. As a data company, the creation of a new generation of highly agile, open, and programmable cloud-ready networks utilizing technologies such as network slicing, flexible RAN architectures, small cells and multi-access edge computing (MEC) is key to realizing new services and applications in wireless networks.

Standards: Intel is also a leading contributor to the 3GPP standards in the evolution of LTE Advanced and 5G technologies. The overall focus of Intel's 3GPP Standards team has been the continuation of Release 15 and the beginning of Release 16 technology development. In a march to provide increased capabilities for mobile computing, Intel has been actively addressing several areas in 3GPP RAN1-4 that includes 5G NR, LTE-Advanced Pro, MTC in various modes, LAA & LWA enhancements in unlicensed spectrum, multimedia delivery, positioning and eMBB enhancements. Intel has been highly involved in the execution of Release 15 5G standards development.

KATHREIN

Kathrein is recognized as the worldwide leader in professional antenna systems (ABI Research 2014, 2015) with global headquarters located in Rosenheim, Germany. Kathrein's RF solutions ensure the highest quality and enable operators to expand macro and small cell coverage and capacity for wireless densification. Quality has played a major role since our inception almost a century ago and is the primary focus for the company. Due to this key principle, Kathrein products and solutions are well regarded for their durability, maturity, sophisticated design, and sustainability.

Kathrein's technicians, engineers and scientists drive innovation for densification on the road to 5G. To maintain its market leadership, Kathrein annually invests 7.5% of revenue back into Research & Development, which is represented in over 1,000 actively used patents, patents pending and utility models. Kathrein generates more than 60% of revenues annually with products which are less than two years old.

Kathrein's leadership is established not only in mobile communication solutions, but also in Satellite, RFID, Broadcast, and Connected Car solutions. Kathrein is an active member in many of the standards bodies for LTE, and 5G.

- The Kathrein Communication Products Portfolio optimizes networks for full utilization and monetization for carriers around the globe.
- Kathrein's Small Cell site solutions optimize network performance and accelerate deployments. Encompassing RF delivery, equipment housing, and concealment, Kathrein Small Cell antennas improve performance of the RF air link, expedite construction, and enable faster zoning approvals, thereby decreasing CapEx and OpEx and improving time to revenue.
- As the innovation and technology leader in the field of base station antennas for mobile cellular networks, Kathrein manufactures over a million antenna systems per year. Our customer base includes all major system manufacturers as well as hundreds of network operators worldwide.
- Kathrein is the world leader in Active Antenna solutions with AIR21/32 expertise. Kathrein continues to invest in active antennas, to include massive MIMO and mmWave platforms.
- Kathrein has been involved in 5G mmWave trials with OEMs in North America, Europe and South Korea. A mmWave repeater solution is in development to economically extend coverage and performance with equipment that is waveform agnostic.
- The product range in the mobile communications segment extends from 25 to 6,000 MHz, featuring directional and omni-directional antennas tailored to specific customer needs, as well as special antennas for buses and trains and for ground-to-air communications. Kathrein's extensive product range features over 250 types for technologies such as CDMA, GSM, UMTS, LTE, LAA, CBRS, WIMAX and WLAN.

Learn more here: https://youtu.be/v7YxhAAZItE

MAVENIR

Mavenir is purpose-built to redefine mobile network economics for Communication Service Providers (CSPs). Our innovative solutions pave the way to 5G with 100 percent software-based, end-to-end, Cloud Native network solutions. Leveraging industry-leading firsts in VoLTE, VoWiFi, Advanced Messaging (RCS), Multi-ID, vEPC and Cloud RAN, Mavenir accelerates network transformation for more than 250+ CSP customers in over 130 countries, serving over 50 percent of the world's subscribers.

Three key focus areas this year have been driving further evolution of the packet core, virtualization of the Radio Access Network (RAN), and innovation in voice, video and messaging services:

Packet Core Evolution: Mavenir has developed an innovative microservice-based cloud-native virtualized packet core that is natively extensible from LTE to emerging 5G architectural standards. The resultant approach provides cost-efficient support for a wide range of LTE, 5G and mobile edge computing on a small form factor, with zero touch orchestration.

RAN Virtualization: Mavenir has taken a lead in developing a virtualized, flexible Radio Access Network (RAN) in place for today's 4G networks that is adaptive and responsive as infrastructure needs evolve to

5G. By adopting such a solution, Mobile Operators could realize 49 percent savings in capex and 31 percent annual savings in OPEX [Senza Fili].

Service Innovation: Mavenir has developed innovative solutions for RCS with monetization opportunities such as chatbots, enterprise services, content delivery, all enabled by a Messaging as a Platform (MaaP) solution, and Multi-ID, a virtual line service which leverages the benefits of IP-based 4G/LTE networks to bring the experience of web-based services to the telecom world.

Here are some highlights of Mavenir's advancement of 5G and LTE this year:

- Mavenir joins the xRAN foundation to help promote a software-based, extensible Radio Access Network (xRAN) and standardize critical elements of the xRAN architecture – February 2017
- Mavenir unveils its RCS Cloud Platform, providing both an RCS Platform and a Global RCS Interconnection Hub to enable RCS Services on behalf of Operators Globally – March 2017
- TMC names Mavenir's RCS Cloud Platform as 2017 Communications Solutions Products of the Year award winner – July 2017
- Mavenir launches Multi-ID cloud communications platform, an industry first for innovation in voice, video and messaging – June 2017
- TMC names Mavenir's RCS Cloud Platform as 2017 Communications Solutions Products of the Year award winner – July 2017
- Announces its 5G Core Network and virtualized Cloud RAN solutions; Network trials and PoCs in progress in several countries – September 2017
- Key Revenue Generation Services - T-Mobile US adds more than 250 thousand additional subscribers each paying $10 per month in the first three months after launch of DIGITS (powered by Mavenir's Multi-ID) – August 2017
- Mavenir's innovative Multi-ID cloud communications platform named Best Telecom Service Innovation at the 5G Asia Awards. – October 2017
- Announces Virtualized Network Slicing Suite for 4G/5G providing end-to-end network slicing for radio, core and applications, both in 4G and 5G networks – November 2017

As the industry's only 100 percent software-based, end-to-end, Cloud Native network solutions provider Mavenir continues to embrace disruptive, innovative technology architectures and business models that drive service agility, flexibility, and velocity. With solutions that propel Cloud Native evolution to achieve web-scale economics, Mavenir offers solutions to CSPs for cost reduction, revenue generation and revenue protection across LTE and 5G networks.

NOKIA

We create the technology to connect the world. Powered by the research and innovation of Nokia Bell Labs, we serve communications service providers, governments, large enterprises and consumers, with the industry's most complete, end-to-end portfolio of products, services and licensing. From the enabling infrastructure for 5G and the Internet of Things, to emerging applications in digital health, we are shaping the future of technology to transform the human experience. nokia.com

Nokia 5G

Nokia is a world leader in the development of 5G, the next-generation wireless technology that will enable a whole range of new services, from enhanced mobile broadband to advanced automation in industry. Via its 5G-ready hardware and software products, Nokia is at the forefront of making 5G a commercial reality and is already shipping its 5G-ready AirScale and cloud-native core platforms.

- Nokia is fully focused on applying the 3GPP-compliant 5G New Radio standard and is involved in more than 50 customer trials of the technology around the world, ahead of expected commercial launches between 2019 and 2020.
    - Nokia launched 5G FIRST at MWC 2017. 5G FIRST builds on 5G-ready commercial Nokia AirScale and AirFrame platforms to deliver a complete and versatile solution to operators to commence immediate evaluation and implementation. In September 2017, Nokia announced that 5G FIRST would be extended to support 5GNR, thus broadening the ability to provide end-to-end technology to customers for mobile broadband use cases.
- Nokia is also active within the broad industry ecosystem, working closely with chipset and device manufacturers alike, as well as working with all initial 5G frequency bands, including 3.5GHz, mmWave bands, 28GHz, and 39GHz.
- Nokia is the only vendor working on 5G implementation with major operators in the 'lead' 5G countries, including the US, Japan, South Korea and China. Nokia sees a strong appetite for 5G in these countries, pointing to an acceleration of 5G trials in 2018 and meaningful rollouts in 2019.
    - Nokia announced in January 2018 it is to provide 5G baseband technology to Japan's largest mobile operator, NTT DOCOMO to integrate 3GPP-compliant 5G New Radio-based hardware into NTT DOCOMO's network, enabling it to commence a smooth evolution from 4G/LTE to 5G. This will enable NTT DOCOMO to launch its 5G mobile service by 2020.
- Nokia also supplies 18 of the 20 top LTE operators and 14 of 20 top TD-LTE operators.

QUALCOMM

Qualcomm Incorporated is a world leader in 3G, 4G, Wi-Fi, Bluetooth, and next-generation wireless technologies. For over three decades, Qualcomm ideas and inventions have driven the evolution of mobile, linking people everywhere more closely to information, entertainment and each another. Today, Qualcomm and its subsidiaries are helping shape this new, interconnected world by engineering ground-breaking mobile chipsets and software, developing technologies and creating solutions to tackle the growing demand for mobile data.

Qualcomm Technologies has been instrumental in driving the 3G/4G evolution, and now, Qualcomm is leading the world to 5G. Qualcomm is pioneering 5G technologies today to enable a truly connected world, transforming the way people live, work, and play. Qualcomm's vision for a 5G unifying connectivity fabric will take on a significantly larger role than previously generations: empowering a variety of industries to benefit from 5G as a platform for their services. Qualcomm is fueling progress across an array of world-changing use cases and ushering in a better future. Qualcomm is:

- Leading the path to 5G through R&D and technology development, including collaborations with infrastructure vendors, operators and OEMs on early interoperability testing and other 5G initiatives.
- Engaging in early trials and verification of key 5G technology components to support the technical work required for 3GPP standardization (starting from Release 15).
- Driving 5G commercialization in close alignment with 3GPP, in order to enable rapid adoption of standards-compliant and forward-compatible 5G infrastructure and devices.

Here are some of Qualcomm Technologies' recent key milestones in the advancement of 5G and LTE Advanced/LTE Advanced Pro:

- Announced that 18 global operators have selected Qualcomm Snapdragon X50 5G modem for mobile 5G NR standard-compliant (3GPP Rel.15+) trials in 2018, and that 19 global device OEMs have selected Qualcomm Snapdragon X50 5G NR modem family for device launches in 2019 – February, 2018.

- Announced third generation Gigabit LTE modem – the Qualcomm Snapdragon X24 LTE modem – first LTE (3GPP Rel-14) Category 20 modem with support for download speeds up to 2.0 Gbps – February, 2018.

- Demonstrated the next phase of 5G NR, driving 5G NR evolution and expansion in 3GPP Release-16+, including first demonstration of wireless PROFINET Industrial Ethernet over 5G NR for Industrial IoT use cases utilizing 5G NR URLLC – February, 2018.

- Achieved 5G NR multi-band interoperable testing with Nokia – compliant with 3GPP standard (Rel-15) and in collaboration with Nokia, BT/EE, Deutsche Telekom, Elisa, KT, LGU+, NTT DOCOMO, Optus, SKT, Telia and Vodafone Group – February, 2018.

- Achieved first 5G NR multi-band (mmWave and sub-6 GHz) interoperable testing with Ericsson – compliant with 3GPP standard (Rel-15) and in collaboration with AT&T, NTT DOCOMO, Orange, SK Telecom, Sprint, Telstra, T-Mobile US, Verizon, and Vodafone – December, 2017.

- Completed first 3GPP 5G NR global standard (Rel-15 phase1) in collaboration with global mobile industry, setting the stage for full-scale development of 5G NR for large-scale trials and commercial deployments as early as in 2019 – December, 2017.

- Achieved first 5G NR sub-6 GHz interoperable testing with ZTE and China Mobile, based on 3GPP standard (Rel-15) – November, 2017.

- Achieved first announced 5G data connection on a 5G modem chipset for mobile devices, utilizing the Qualcomm Snapdragon X50 5G modem and operating at mmWave spectrum bands – October, 2017.

- Announced 5G NR mmWave prototype system based on 3GPP standard (3GPP Rel-15), including an optimized mmWave RF Front-end design in a smartphone form-factor to test and trial real-world mobile conditions – September, 2017.

- First to announce Cellular-V2X chipset and Reference Design to support automotive road safety, helping to pave a path for the future of autonomous driving – September, 2017.

- Announced Cellular-V2X testing and trials in collaboration with Audi, Ford, LG, and more. – 2017.

- Announced first 5G NR multi-mode chipset solution – the Qualcomm Snapdragon X50 5G modem family – with first commercial products featuring Snapdragon X50 5G NR modems expected to be available in 1H-2019 – February, 2017

- Led industry-wide effort to accelerate the 5G NR standardization schedule to enable large-scale trials and deployments as early as 2019 – February, 2017.

- Unveiled first Private LTE-based trial network customized for Industrial IoT in collaboration with GE and Nokia – February, 2017.

- Announced second generation Gigabit LTE modem – the Qualcomm Snapdragon X20 LTE modem – first LTE (3GPP Rel-13) Category 18 modem with support for download speeds up to 1.2 Gbps – February, 2017.

- First to demonstrate 5G NR connection based on work in 3GPP (Rel-14/15), utilizing Qualcomm Technologies' sub-6 GHz 5G NR prototype system – February, 2017.

- Delivered the first commercial Gigabit LTE network with Telstra, Ericsson, and NETGEAR in Australia – an essential anchor to the 5G mobile experience – January, 2017.

- First to announce collaborations with global operators on standard-compliant 5G NR trials, including SKT, AT&T, China Mobile, NTT DOCOMO, Telstra and Vodafone - December, 2016 through February, 2017.

- First to announce 5G NR Spectrum Sharing prototype system to test, demonstrate and trial new 5G spectrum sharing technologies – November, 2016.

- First to announce 5G modem – the Qualcomm Snapdragon X50 5G modem – October, 2016.
- Founding member of 5G Automotive Association (5GAA) to evolve, test and promote communications solutions for connected driving; Qualcomm Technologies' Dino Flore appointed as Director General of the Association – September, 2016.

- First to announce 5G NR sub-6 GHz prototype system and trial platform to test, demonstrate, and trial 5G design to drive 3GPP 5G NR standardization (3GPP Rel-15) – June, 2016.

- Announced the 6th generation Snapdragon X16 LTE modem, the first commercially announced Gigabit Class LTE chipset designed to deliver fiber-like LTE Category 16 download speeds of up to 1 Gbps, and is the mobile industry's first announced LTE Advanced Pro modem with support for Licensed Assisted Access (3GPP Rel-13) – February, 2016.

- Qualcomm Research demonstrates robust 5G mmWave design for 5G (3GPP Rel-15) – November, 2015.

- Qualcomm announces new modem solutions designed to support reliable, global connectivity to the Internet of Things; new MDM9207-1 enables scalable, power-efficient and cost-optimized Cat 1 LTE connectivity and MDM9206 provides a path to LTE eMTC and NB-IoT standards (3GPP Rel-13) – October 2015.

Being a key contributor to 3GPP, Qualcomm Technologies not only excels in pioneering new technologies but also making them a commercial reality through proof of concept development, prototyping and finally delivering commercial chipset solutions.

SAMSUNG

Samsung inspires the world and shapes the future with transformative ideas and technologies. The company is redefining the worlds of TVs, smartphones, wearable devices, tablets, digital appliances, network systems, memory, system LSI, and LED solutions.

Samsung Networks is leading the charge on wireless innovation with our partners. Our Wi-Fi, LTE and 5G technologies solve real-world issues for mobile network operators and enterprises, giving them solutions that generate new opportunities and improved user experiences.

Samsung is an active and leading member of the 5G standards bodies including 3GPP and the ITU-R IMT-2020 study groups. Samsung's contributions across all of the standards areas are a demonstration of our commitment to guiding the mobile industry forward and devoting our technical excellence to the development of 5G and other future technologies.

Samsung is committed to help commercial network operators lay a 5G foundation to create the next generation of technology and services.

Samsung has been driving 5G progress a number of ways:

- Samsung was the first to use millimeter wave mobile broadband for next generation 5G mobile systems to increase mobile network speeds.

- Samsung developed the world's 1st adaptive array transceiver technology in 2013 to overcome the radio propagation loss.

- Samsung pioneered a waveform design which combined two air interface components FQAM and FBMC in 2014 which allows the support of heterogeneous services with a diverse set of requirements to be supported with efficient use of wireless spectrum.

- 5G cell-edge performance requirements lead Samsung to utilize Sliding-Window Superposition Coding (SWSC) scheme to achieve optimal ML decoding performance in 2014.

- Samsung was the first to show 5G data transmission at highway speeds, demonstrating data speeds that were 30 times faster than 4G LTE. Achieving industry bests in 2014 at Everland Speedway in South Korea with 7.5Gbps performance in a stationary setting and 1.2Gbps in a moving vehicle traveling over 100 Kilometers per hour.

- In 2015, Samsung demonstrated another 5G corner stone in signal quality with full-dimensional multiple-input, multiple-output (FD-MIMO) that cut interference and overlapping simultaneous transmissions to other receivers and increases the power of the signal that reaches the target.

- Samsung was able to bring 5G to two real world situations, an indoor to outdoor scenario and to a mobility scenario in 2016. Using Verizon's FIOS wired network and Samsung's 5G Hybrid Adaptive Array antenna radio technology high-quality 5G wireless signals with low latency, high throughput transmission of various data including 4K UHD video content was demonstrated.

Recently, Samsung has achieved progress with 5G and 4G LTE.

- Samsung and Verizon completed deployment of 5G systems in five U.S. cities in preparation of 5G customer trials.

- Samsung and Cisco team with Verizon successfully deployed the first multi-vendor end-to-end trial network in Detroit, Michigan.

- Samsung participated in AT&T's expanded fixed and mobile wireless tests which included Samsung's end-to-end 5G solutions and products delivered to homes and business in South Bend, Indiana.

- Samsung and Sprint tested Massive-MIMO in a real-world application using 20MHz channel of 2.5 GHz spectrum to help Sprint dramatically boost LTE Plus wireless capacity and coverage and offer Gigabit LTE service to its customers.

- Samsung and Charter are collaborating on 5G and 4G LTE wireless networks lab and field trials at various locations in the U.S.

- Samsung and SK Telecom successfully completed the world's first 4G LTE and 5G end-to-end network interworking trial in a real outdoor environment in Seoul. The companies used the current 4G LTE commercial network in the 2.6GHz band and newly built 5G networks using frequencies of 3.5GHz and 28GHz, as well as virtualized core and a test device that supports both 4G and 5G technologies.

- Samsung and KDDI successfully tested 5G on a high-speed train, achieving 1.7Gbps while traveling over 60mph. This paves the way for superior passenger infotainment, vastly improved on-board Wi-Fi and increased security and analytics.

Samsung Electronics uniquely combines the infrastructure and devices solutions for building future networks. Samsung will continue to utilize the R&D talents and engineering knowledge in both the mobile communications and network business units to deliver successful end-to-end solutions at an industry leading pace.

SHAW COMMUNICATIONS

Shaw Communications Inc. is a leading Canadian connectivity company. The Wireline division consists of Consumer and Business services. Consumer serves residential customers with broadband Internet, Shaw Go WiFi, video and digital phone. Business provides business customers with Internet, data, WiFi, digital phone and video services. The Wireless division provides wireless voice and LTE-Advanced data services through an expanding and improving mobile wireless network infrastructure.

Notable network milestones for Shaw include:

- We completed LTE-Advanced network upgrades across our footprint and refarmed a portion of our AWS-1 spectrum so that existing and BYOD customers with LTE-capable phones can now get an LTE experience on our network, where previously they had only 3G service. We have also begun launching VoLTE across select handsets within our lineup.
- We are in the early stages of deploying our 700 MHz spectrum. Once deployed, this spectrum will add to our spectrum mix by improving our network quality and coverage.
- In May, we completed some initial 5G technical trials. Conducted in collaboration with Nokia, CableLabs and Rohde & Schwarz, Shaw's trials leveraged 28GHz mmWave and 3.5GHz spectrum and demonstrated the significant and sustained speeds for the next generation of wireless technology.
- Shaw's leadership in WiFi continues to position us well for wireless growth and 5G deployment. Shaw owns and operates the country's largest WiFi network, with over 100 thousand hotspots across Western Canada.
- Through mutually-beneficial partnerships with cities and towns across Western Canada, we've been able to expand our WiFi footprint, while providing municipalities with a free Guest WiFi access to offer their citizens. Earlier this year, we announced a partnership with the City of Vancouver which has allowed us to expand our footprint in one of Canada's largest cities while making their municipal WiFi network one of the largest in North America.

Shaw's wireline network has never been stronger. Our Hybrid Fibre-Coax network is well positioned to deliver the converged wireline-wireless connectivity that will drive our customers' needs in the future, and we continue to make significant investments to be ready to capitalize on emerging technology to support the launch of 5G.

SPRINT

Sprint (NYSE: S) is a communications services company that creates more and better ways to connect its customers to the things they care about most. Sprint served 54 million connections as of September 30, 2017 and is widely recognized for developing, engineering and deploying innovative technologies, including the first wireless 4G service from a national carrier in the United States; leading no-contract brands including Virgin Mobile USA, Boost Mobile, and Assurance Wireless; instant national and international push-to-talk capabilities; and a global Tier 1 Internet backbone. You can learn more and visit Sprint at www.sprint.com or www.facebook.com/sprint and www.twitter.com/sprint.

Today the Sprint LTE network covers 306 million people. Sprint's LTE Plus Network, available in 250 markets, takes advantage some of the world's most advanced technologies in wireless – carrier aggregation for higher speeds, 8T8R radios for enhanced coverage, and multi-antenna processing techniques like

MIMO for higher capacity, along with tri-band LTE devices to deliver the consistent reliability, capacity and speed that its customers demand.

Recent notable network milestones for Sprint include:

- Development of the world's first all-wireless small cell, Sprint Magic Box, a revolutionary plug–and–play LTE small cell that dramatically improves data coverage and increases speeds on average by 200 percent.

- First U.S. carrier to conduct TDD-LTE Massive MIMO field trials using 2.5 GHz spectrum and 64T64R radios in preparation for commercial deployment in 2018.

- Drove the development of High Performance User Equipment (HPUE) in 3GPP Release 14 in December 2016.

- Expansion of the HPUE ecosystem with 12 devices launched in 2017.

- First carrier to demonstrate Gigabit Class LTE on a live commercial network in New Orleans during an NBA basketball game.

- Sprint includes 2.5 GHz spectrum as part of 3GPP Release 15 in March 2017 for completion in June 2018.

- Sprint, Qualcomm Technologies and SoftBank announce agreement to jointly develop 3GPP 5G New Radio (NR) for 2.5 GHz with anticipated deployment of commercial 5G network in late 2019.

Looking ahead Sprint will accelerate its network investment in fiscal year 2018 to build a competitive, capacity-rich network by leveraging its deep 2.5 GHz spectrum holdings and executing its Densification and Optimization strategy. Sprint is focused on building a strong foundation for 5G by densifying its network with more cell site solutions across its 2.5 GHz, 1.9 GHz and 800 MHz spectrum bands.

T-MOBILE

T-Mobile US, Inc. built the nation's fastest LTE network to handle customers' unlimited data demands while preparing and planning for the future. T-Mobile continues to increase and expand the speed and capacity of our network to better serve our customers. Our advancements in network technology and our spectrum resources ensure we can continue to increase the breadth and depth of our network.

T-Mobile rapidly deployed its 4G LTE network across America by completing several major deployments across various spectrum bands in 2017, most recently aggressively deploying its newly acquired 600 MHz spectrum, bringing coverage to entirely new places. Since 2015, the Un-carrier has nearly tripled its LTE coverage and now covers 322 million people, nearly every American.

Key Network Milestones

2016:

- At the end of 3Q 2016, T-Mobile had further deployed Wideband LTE[1], which increases bandwidth and capacity on its LTE network, to cover more than 231 million people; in addition to the deployment of its Extended Range LTE[6] (700 MHz A-Block spectrum), now covering more than 225 million people in 366 markets

- In support Internet of Things and machine-to-machine customers, T-Mobile announced it would maintain its 2G network through 2020
- T-Mobile led the industry with new technology advancements like Enhanced Voice Services[2](EVS), 4x4 MIMO [3] , and 256 QAM [4] – in fact, here's all of T-Mobile's network "firsts"
- T-Mobile improved and expanded Binge On, technology which allows customers on qualifying plans to stream video data without hitting their data bucket, to more than 100 streaming partners
- Internationally, T-Mobile gave customers unlimited high-speed data while traveling in Europe and South America until 2017, and added roaming in Cuba
- Introduced T-Mobile ONE and One Plus – the wireless industry's first truly all-in unlimited plan

2017:

- April: T-Mobile acquires 45% of all 600 MHz spectrum sold in the FCC auction – covering 100% of the US and Puerto Rico. T-Mobile won 31 MHz of 600 MHz spectrum nationwide on average
- June: First national wireless provider to make LTE-U available to customers
- June: T-Mobile completed the nation's first mobile broadband data session live in the field using License Assisted Access (LAA)[5]on its commercial network, showing 741 Mbps download speeds
- July: First wireless provider in North America to successfully complete Narrowband IoT field tests on a live commercial network in Las Vegas using just 200 KHz of T-Mobile's AWS spectrum
- July: T-Mobile and the City of Las Vegas announced a partnership to deploy IoT technology throughout the city – including Narrowband IoT
- August: first major wireless provider in the world to place no. 1 in every category of the OpenSignal State of Mobile Networks report
- August: Two months after T-Mobile received the spectrum licenses from the FCC, it lit up the world's first 600 MHz LTE sites in Cheyenne, Wyoming
- September: First ever 600 MHz capable device available at T-Mobile
- September: T-Mobile unveils its roadmap to nationwide Narrowband IoT in 2018

2018:

- At the end of 1Q 2018, T-Mobile had enhanced coverage breadth and depth of its 4G LTE network, expanding its 4G LTE network coverage to 322 million people, and remained the fastest 4G LTE network for download and upload speeds for the seventeenth consecutive quarter
- January: To further broaden LTE footprint in Iowa and western Illinois, T-Mobile closes on its agreement to purchase the remaining interest of Iowa Wireless from Aureon.
- February: First lab and field tests of NB-IoT in guard bands
- February: T-Mobile and Nokia achieve 1.3 Gbps in the lab using commercial technology with License Assisted Access
- February: T-Mobile expands its deployment of the combination of LTE – Advanced technologies – 4x4 MIMO, carrier aggregation and 256 QAM – to nearly 5,000 cities and towns
- February: T-Mobile continues rapid deployment of 600 MHz LTE, announces 600 MHz LTE in 738 cities and towns across 30 states
- May: T-Mobile completes nation's first 3GPP standards based mmWave over the air uplink/dowlink 5G data transmission

About T-Mobile US, Inc.: As America's Un-carrier, T-Mobile US, Inc. (NASDAQ: TMUS) is redefining the way consumers and businesses buy wireless services through leading product and service innovation.

Our advanced nationwide 4G LTE network delivers outstanding wireless experiences to 74.0 million customers who are unwilling to compromise on quality and value. Based in Bellevue, Washington, T-Mobile US provides services through its subsidiaries and operates its flagship brands, T-Mobile and MetroPCS. For more information, please visit http://www.t-mobile.com.

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[1] Wideband LTE –T-Mobile refers to carrier bandwidth of 15+15 MHz or greater in a particular market, allowing for faster speeds and greater capacity. Wider carrier bandwidths (of which 20+20MHz is the LTE maximum, after which you'd need carrier aggregation) are basic LTE features and have been a part of 3GPP standards since the beginning, i.e., Release-8.

[2] Enhanced Voice Services (EVS) Codec was completed in 3GPP Release 12. EVS is the first 3GPP conversational codec offering up to 20 kHz audio bandwidth, delivering speech quality that matches other audio input such as stored music, while offering high robustness to delay jitter and packet losses.

[3]4x4 MIMO – 4-layer spatial multiplexing was introduced since 3GPP Rel-8, but it's use with TM3/4 had been limited to only UE categories 5 and 8 due to lack of signaling to indicate the used number of layers. In September 2015, 3GPP enhanced the support of 4-layer MIMO with TM3/4 to be able to work with UE categories 6 and above from Rel-10 onwards. T-Mobile's 4x4 MIMO deployment is based on this enhancement.

[4] 256 QAM - Downlink 256 QAM was introduced in 3GPP Rel-12 in order to improve spectral efficiency.

[5] 3GPP specified LAA for downlink operation in Release 13 and is further working on specifying LAA for uplink operation in Release 14. LAA provides operators and consumers with an additional mechanism to utilize unlicensed spectrum for improved user experience, while coexisting with other Wi-Fi and other technologies in the 5GHz unlicensed band.

[6] Extended Range LTE – T-Mobile refers to deployment of low-band spectrum / POPs, most recently 600 MHz and 700, allowing for better breadth as well as in-building coverage

APPENDIX C: ACRONYMS

3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation Mobile Networks
5GC	Fifth Generation Core
5GEIR	5G Equipment Indentity Register
5QI	5G QoS Indentifier
64QAM	64-Quadrature Amplitude ModulationUL
AAA	Authentication, Authorization & Account
AAS	Active Antenna Systems
ACDC	Application Specific Congestion Control for Data Communication
ACS	Adjacent Channel Selectivity
ADC	Application Detection and Control
AESE	Architecture Enhancements for Service Capability Exposure
AF	Application Function
AKA	Authentication & Key Agreement
AMF	Access and Mobility Management Function
ANR	Automatic Neighbor Relation
API	Application Program Interface
APN	Access Point Name
APs	Access Points
ARP	Allocation Retention & Priority
ARPF	Authentication Credential Repository & Processing Function
AUSF	Authentication Server Function
BBU	BaseBand Unit
BF	Beamforming
BL	Bandwidth Reduced Low Complexity
BM-SC	Broadcast Multicast Service Center
BPF	Beamforming Processing Function
BS	Base Station
BSR	Buffer Status Report
BSSID	Basic Service Set Identification
CA	Carrier Aggregation
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenses
CCA	Clear Channel Assessments
CDMA	Code Division Multiple Access
CELL_PCH	Cell Paging CHannel
CELL_FACH	Cell Forward Access CHannel
CHF	Charging Function
CHAP	Challenge Handshake Authentication Protocol
CIOT	Cellular IoT
CM	Configuration Management
CM	Cubic Metric
CMS	Communication and Media Solutions
cMTC	Critical Machine Type Communications
CN	Core Network
CoMP	Coordinated Multi-Point Transmission and Reception
CRI	CSI-RS Resource Indicator
CS	Circuit Switched
CSI	Channel State Information
CSI-RS	Channel-State Information Reference Symbol
CTIA	Cellular Telecommunication Industry Association
CU	Control/ User Plane OR Central Unit
CUPS	Control and User Plane Separation
CP	Control Plane
CUPS	Control and User Plane Separation
D2D	Device-to-Device

DAI	Downlink Assignment Index
DASH	Dynamic Adaptive Streaming Over HTTP
DB	Database/ Dual Band
DB-DC	Dual Band Dual Cell
DC	Dual Connectivity
DC-HSPA	Dual Cell High Speed Packet Access
DCN	Dedicated Core Network
DDN	Downlink Data Notification
DCF	Distributed Coordination Function
DCI	Downlink Control Indicator
DC-HSPA	Dual Carrier-High Speed Packet Access
DCN/DECOR	Dedicated Core Network
DÉCOR	Dedicated Core Networks
DFS	Dynamic Frequency Selection
DL	Downlink
DM	Domain Manager
DMRS	Demodulation Reference Signal
DN	Data Network
DPDK	Data Plane Development Kit
DU	Distributed Unit
DRB	Data Radio Bearer
DRB	Data Resource Bearer
DRS	Discovery Reference Signals
DSCP	Differentiated Services Codepoint
DRX	Discontinuous Reception
DSMIPv6	Dual Stack-Mobile Internet Protocol version 6
DTLS	Datagram Transport Layer Security
DTX	Discontinuous Transmissions
DU	Distributed Unit
EAP	Extensive Authentication Protocol
EBF	Elevation Beam Forming
EC	Enhanced Coverage
ECGI	E-UTRAN Cell Global Identifier
ECM-IDLE	EPS Connection Management IDLE
ED	Energy Detection
eDEC	Enhanced Dedicated Core
eDECOR	Enhanced Dedicated Core Network
eLAA	Enhanced LAA
eLWA	Enhanced LWA
EIRP	Equivalent Isotropic Radiated Power
EIS	Equivalent Isotropic Sensitivity
EM	Element Manager
eMBB	Enhanced Mobile Broadband
eMBMS	Evolved Multimedia Broadcast Multicast Service
EMTC	Enhanced Machine Type Communication
EN-DC	E-UTRAN New Radio Dual Connectivity
eNodeB	Evolved NodeB
EPC	Evolved Packet Core also known as System Architecture Evolution (SAE)
EPC/SAE	Evolved Packet Core/System Architecture Evolutions
ePDG	Evolved Packet Data Gateway
EPDCCH	Enhanced Physical Downlink Control Channel
EPS	Evolved Packet System
E-RNTI	E-DCH Radio Network Transaction Identifier
ETSI	European Telecommunications Standards Institute
E-UTRAN	Evolved Universal Terrestrial Radio Access Network (based on OFDMA)
EVS	Enhanced Voice Services
EVR	Error Vector Magnitude
eV2X	Enhanced V2X
FCC	Federal Communications Commission
FCAPS	Fault, Configuration, Accounting, Performance, Security

FD	Frequency Division
FD	Full Dimension as in FD-MIMO
FDD	Frequency Division Duplex
F-DPCH	Fractional Dedicated Physical Channel
Fe	Further Enhancements
FeICIC	Further Enhanced Inter-Cell Interference Coordination
FFS	Further Study
FM	Fault Management
FNPRM	Further Notice of Proposed Rule Making
FOMA	Freedom of Mobile Multimedia Access
FTA	Free-To-Air
FTL	Frequency Tracking Loop
FTV	Free-to-View
GBR	Guaranteed Bit Rate
GCS AS	Group Communication System Application Server
GGSNs	Gateway GPRS Support Nodes
GHz	Gigahertz
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GROUPE	Group Based Enhancement
GTP	General Packet Radio Service Tunneling Protocol
GTP-C	GPRS Tunneling Protocol - Control
GTP-U	GPRS Tunneling Protocol User Plane
GUMMEI	Globally Unique Mobility Management Entity Identifier
GUTI	Globally Unique Temporary Identify
GW	GateWay
GWCN	GateWay Core Network
HARQ	Hybrid Automatic Repeat Request
HESSID	Homogeneous Extended Service Set IDentification
HLCom	High Latency Communications
HLR	Home Location Register
HO	Handover
HPLMNs	Home Public Land Mobile Networks
H-RNTI	HS-DSCH Radio Network Transaction Identifier
HN	Home Network
HSDPA	High Speed Downlink Packet Access
HS-DSCH	High Speed Downlink Shared Channel
HSPA	High Speed Packet Access
HSPA+	High Speed Packet Access Plus (also known as HSPA Evolution or Evolved HSPA)
HS-SCCH	High Speed Shared Control Channel
HSS	Home Subscriber Server
HSUPA	High Speed Uplink Packet Access
IC	Interference Cancellation
ICIC	Inter-Cell Interference Coordination
ICS	IMS Centralized Services
ICSCF	Interrogating Cell Session Control Fun -ction
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
IFOM	Internet Protocol Flow Mobility and seamless WLAN Offload
IMPI	IP Multimedia Private Identity
IMPU	IP Multimedia Public User identity
IMS	Internet Protocol Multimedia Subsystem
IMSI	International Mobile Subscriber Identity
IMT	International Mobile Telecommunications
InH	Indoor Hotspot
Inter-RAT	Inter- Radio Access Technology
IoT	Internet of Things
ISD	Inter-Site Distance
ISG	Information Services Group
ISO	International Standards Organization

ILPC	Inner Loop Power Control
IP	Internet Protocol
IRC	Interference Rejection Combining
ITU	International Telecommunications Union
ITU-T	ITU-Telecommunication Standardization Bureau
KPIs	Key Performance Indicators
LAA	Licensed Assisted Access
LBT	Listen-Before-Talk
L-CWIC	Linear - CodeWord level successive - Interference Cancellation
LCM	Life Cycle Management
LI	Lawful Intercept
LIR	Location Information Request
LSA	Licensed Shared Access
LPWA	Low Power Wide Area
LTE	Long Term Evolution
LTE-U	LTE for Unlicensed Spectrum
4G LTE	Fourth-Generation Long Term Evolution
LWA	LTE Wireless Local Area Network Aggregation
LWIP	LTE-WLAN Radio Level Integration with IPsec Tunnel
LWIPEP	LWIP Encapsulation Protocol
M2M	Machine-to-Machine
MA	Multiple Access
MANO	Management Nodes
MBMS	Multimedia Broadcast Multicast Services
MBMS-GW	Multimedia Broadcast Multicast Services – Gateway
MBR	Maximum Bit Rate
MBS	Metropolitan Beacon System
MBSFN	Multicast Broadcast Single Frequency Networks
MCE	Multi-cell/Multicast Coordination Entity
MCG	MeNB Cell Group
MCCH	Multicast Control CHannel
MCL	Maximum Coupling Loss
MCPTT	Mission Critical Push-to-Talk
MCOT	Maximum Channel Occupancy Times
MDT	Mobile Data Terminal
MGCF	Media Gateway Control Function
MEC	Mobile Edge Computing
MMEGI	MME Group Identity
MeNB	Macro Evolved NodeB
MIMO	Multiple-Input Multiple-Output
MIOT	Massive Internet of Things
MLB	Mobility Load Balancing
MME	Mobility Management Entity
MMSE	Minimum Mean Square Error
mMTC	Massive Machine Type Communications
mmWave	Millimeter Wave
MNO	Mobile Network Operator
MO	Mobile Originated
MOCN	Multi-Operator Core Network
MOI	Management Object Instance
MONTE	Monitoring Enhancement
MPDCCH	MTC Physical Downlink Control CHannel
MPS	Multimedia Priority Service
MRO	Mobility Robustness Optimization
MSC-S/MGW	Mobile Switching Center – Server/Media Getaway
MT	Mobile Terminated
MTC	Machine Type Communications
MTC-M2M	Machine Type Communications/Machine-to-Machine
MTC_SIB	Machine Type Communication System Information Block
MU-MIMO	Multi-User Multiple-Input Multiple-Output

MUST	Multi-User Superposition Transmission
MWC	Mobile World Congress
NAIC	Network Assisted Interference Cancellation
NAS	Non-Access Stratum
NAS	Network Access Sever
NBIFOM	Network-Based Internet Protocol Flow Mobility
NB-IoT	Narrowband IoT
NE-DC	NR E-UTRA Dual Connectivity
NFC	Near Field Communications
NG	Next Generation
NGAP	NG Application Protocol
NGC	Next Generation Core
NGMN	Next Generation Mobile Networks Alliance
NG- RAN	Next Generation Radio Access Network
NGS	Next Generation System
NFV	Network Function Virtualization
NM	Network Management
NPBCH	Narrowband Physical Broadcast Channel
NPDCCH	Narrowband Physical Downlink Control CHannel
NPDSCH	Narrowband Physical Downlink Shared CHannel
NPRACH	Narrowband Physical Random-Access CHannel
NPUSCH	Narrowband Physical Uplink Shared CHannel
NPSS	Narrowband Primary Synchronization Signal
NSA	Non-Standalone
NSD	Network Service Descriptors
NSSS	Narrowband Secondary Synchronization Signal
NRS	Narrowband Reference Signal
NR	New Radio
NSWO	Non-Seamless WLAN Offload
NWDAF	Network Data Analytics Function
OAM	Operations, Administration and Maintenance
OCC	Optical Communication Channel
OCS	Online Charging System
OFCS	Offline Charging System
OFDM	Orthogonal Frequency Division Multiplexing
OEMs	Original Equipment Manufacturers
OMA	Open Mobile Alliance
OoBTC	Out-of-Band Transcoder Control
OPEX	Operating Expenses
OTA	Over-The-Air
OTDOA	Observed Time Difference of Arrival
OTT	Over-the-Top
PAP	Password Authentication Protocol
PAPR	Peak-to-Average-Power Ratio
PAR	Packet Arrival Rate
PBCH	Primary Broadcast Channel
PCC	Policy and Charging Control
PCEF	Policy and Charging Enforcement Function
PCF	Policy Control Function
PCell	Primary Cell
PCI	Physical Cell ID
PCF	Policy Control Function
PCRF	Policy Control and Charging Rules Function
PC-SCF	Proxy Call Session Control Function
PCO	Protocol Configuration Options
PDCCH	Physical Downlink Control CHannel
PDCP	Packet Data Convergence Protocol
PDN	Public Data Network
PDR	Packet Drop Rate
PDN-GW	Packet Data Network Gateway
PDSCH	Physical Downlink Shared Channel
PDU	Packet Data Unit/ Protocol Data Unit
P-GW	Public Data Network Gateway
PHR	Power Head Room
PLMN	Public Land Mobile Network

PM	Performance Management
PMCH	Physical Multicast Channel
PPF	Packet Processing Function
PRACH	Physical Random-Access CHannel
PS	Packet Switched
PSCell	Primary SCell
PSID	Public Service ID
PSM	Power Saving Mode
P-TMSI	Packet Temporary Subscriber Identity Mode
PO	Paging Occasions
ProSe	Proximity Services
ProSe/D2D	Proximity Services / Device to Device
PSD	Power Spectral Density
PSM	Power Saving Mode
PSS/SSS	Primary Synchronization Signal/Secondary Synchronization Signal
PTT	Push-to-Talk
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QCI	QoS Class Identifier
QFI	QoS Flow ID
QoE	Quality of Experience
QoS	Quality of Service
RACH	Random Access Channel
RADIUS AAA	Remote Authentication Dial In User Service for Authentication, Authorization, and Accounting management for computers to connect and use a network service
RAN	Radio Access Network
RATG	Radio Access Technique Group
RAU	Routing Area Update
RCF	Radio Control Function
RE	Resource Element
REST	Representation State Transfer
RESTful	Representation State Transfer based
RLC	Radio Link Control
RLF	Radio Link Failure
RMa	Rural Macro
R-ML	Reduced Complexity ML
RNC	Radio Network Controller
ROHC	Robust Header Compression
RNTP	Relative Narrowband Tx Power
RPF	Repetition Factor
RRC	Radio Resource Control
RRH/RRU/RU	Remote Radio Head/Remote Radio Unit/Radio Unit
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSU	Road Side Unit
RTP	Real-time Transport Protocol
RV	Redundancy Version
Rx	Receive
RXU	Receiver Units
SA	System Architecture/ Stand Alone
SAND	Server and Network Assisted DASH
SBI	Service Based Interface
SC	Service Continuity
SC-FDMA	Synchronization Channel-Frequency Division Multiple Access
SCG	SeNB Cell Group
SCG	Secondary Cell Group
SCM	Security Context Management
SCEF	Service Capability Exposure Function
SD	Interface between PCRF and TDF
SDN	Software-Defined Networking
SDOs	Standards Development Organization
SDS	Short Data Service

SDU	Service Data Unit
SEA	Security Anchor Function
SEM	Spectrum Emissions Mask
SEPP	Security Edge Protection Proxy
SeGW	Security Gateway
SFN	Single Frequency Network
SGSNs	Serving GPRS Support Nodes
SGW	Serving Gateway
SIB	System Information Block
SIM	Subscriber Identity Module
SIPTO	Selected Internet Protocol Traffic Offload
SLIC	Symbol Level - Interference Cancellation
SM	Spatial Multiplexing
SMi	Suburban Micro
SMARTER	Services and Markets Technology Enablers
SMF	Session Management Control Function
SMSF	Short Message Service Function
SN	Sequence Number
SON	Self-Optimizing or Self-Organizing Network
SRB	Signaling Resource Bearer
SRS	Sounding Reference Signal
SRVCC	Single Radio Voice Call Continuity
SSID	Service Set Identification
STA	Station
TA	Tracking Area
TAB	Transceiver Array Boundary
TAS	Telephony Application Server
TAU	Tracking Area Update
TBS	Transport Block Size/Terrestrial Beacon System
TC	Traffic Class
TCCE	TETRA and Critical Communications Evolution
TDD	Time Division Duplex
TDF	Traffic Detection Function
TD-LTE	Time Division LTE
TETRA	Terrestrial Trunked Radio
ToS	Type of Service
TPC	Transmit Power Control
TPR	Technical Performance Requirement
TrFO	Transcoder Free Operation
TRP	Transmission Reception Point
TLS	Transport Layer Security
TSN	Time Sensitive Networking
TTI	Transmit Time Travel
Tx	Transmit
TXU	Transmitter Unit
UDM	Unified Data Management
UDR	United Data Repository
UE	User Equipment
UHF	Ultra-High Frequency
UIC	International Union of Railways
UL	Uplink
Uma	Urban Macro
UMi	Urban Micro
UMTS	Universal Mobile Telecommunication System (also known as WCDMA)
UP	User Plane
UPCON	User Plane Congestion Management
UPGW	User Plane Gateway
UPF	User-Plane Function
UPT	User Perceived Throughput
UpPTS	Uplink Pilot Timeslot
URA_PCH	UTRAN Registration Area Paging Channel
URLLC	Ultra-Reliable Low Latency Communications
USIM	Universal Subscriber Identity Module
UTDOA	Uplink Time Difference of Arrival

UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network
V2X	Vehicle-to-Everything
VCC	Voice Call Continuity
VNF	Virtualization of Network Functions
VoLTE	Voice-over-LTE
VoNR	Voice-over-New Radio
ViLTE	Video over LTE
WI	Work Item
WID	Work Item Description
WebRTC	Web Real-Time Communication
wIMPU	wildcard IMS Public Identity
WLAN	Wireless Local Area Network
WT	WLAN Termination
XnAP	Xn Application Protocol
Xw-C	Xw Control Plane Interface
Xw-AP	Xw Application Protocol
Xw-U	Xw User Plane Interface

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The mission of 5G Americas is to advocate for and foster the advancement of 5G and the transformation of LTE networks throughout the Americas region. 5G Americas is invested in developing a connected wireless community for the many economic and social benefits this will bring to all those living in the region.

5G Americas' Board of Governors members include AT&T, Cable & Wireless, Cisco, CommScope, Ericsson, Intel, Kathrein, Mavenir, Nokia, Qualcomm Incorporated, Samsung, Shaw Communications Inc., Sprint, T-Mobile USA, Inc., Telefónica and WOM.

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