Wireless Wide-Area Networks for Internet of Things

An Air Interface Protocol for IoT and a Simultaneous Access Channel for Uplink IoT Communication

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This article proposes an Internet of Things (IoT) wide-area communication system concept deployed within the operator's licensed macrocellular band, suitable for low-energy, low-complexity IoT modules with low-priority and infrequent IoT traffic. This article also proposes a simplified air interface protocol for IoT and a simultaneous access channel for uplink (UL) IoT communication. The proposed system concept can be considered either as an enhancement or as an overlay to the existing cellular systems.

The IoT is expected to bring billions of dollars in business opportunities over the next decade. The current market for communication systems enabling IoT is highly fragmented, and the revenues are being shared among multiple incumbents operating primarily in the small- and medium-enterprise space. The IoT market is serviced mostly by wireless

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personal area network (WPAN) technologies for health, automation, and other personal area applications but also by wide-area technologies that are mostly proprietary and using unlicensed industrial, science, and medical bands for fleet management, asset tracking, pipeline monitoring, and other such wide-area applications. Proprietary solutions (e.g., [1]) use dedicated networks catering to IoT services. The benefits of these solutions are their cost, range, power consumption, and robustness; however, these proprietary solutions require separate deployment from existing macrocellular networks, resulting in capital expenditure (Capex) and operating expense (Opex) costs. Most of the proprietary solutions are not optimized for spectral efficiency and will likely congest unlicensed bands and trigger complaints from existing users as the IoT communication demands increase.

Many of the wide-area applications for IoT [2] are enterprise-centric and offer an appealing market opportunity to wireless operators who are looking to enhance their revenues by entering the IoT market. Because of the expected boom in IoT with smart cities, power grid management, and such wide-area applications, there is a strong interest in developing wide-area solutions within the Third Generation Partnership Project (3GPP) and in forums such as OneM2M [3]. For IoT devices, in addition to the desired property of low power/energy consumption, the hardware must be inexpensive and reliable and have a long lifetime. In many cases, it must be capable of operating in rugged environments. Ease of use is another important factor for IoT devices, with minimal or no calibration or synchronization requirements. IoT devices must be able to tolerate frequency/time drift within a predetermined range and also support simple subscriber identification (ID). Furthermore, the traffic properties of IoT devices are wide ranging, from static, infrequent, delay tolerant, and small packets to mobile, frequent, delay sensitive, and large packets.

As mentioned earlier, it is clear that the requirements to support IoT communications are substantially different from the design paradigm for current macrocellular networks optimized for human communications. The challenges in deploying current macrocellular networks [e.g., general packet radio service (GPRS), high-speed packet access (HSPA), and long-term evolution (LTE)] for IoT are the tight synchronization requirement and high signaling overhead not suited to energy-constrained devices. Therefore, the requirements for IoT communications may be best supported by a new architecture and lightweight protocol structure rather than an evolution of the current cellular architecture and protocols.

Enhancing the existing LTE standard for meeting the needs of IoT devices that generate machine-type communications (MTC) traffic is an ongoing activity in 3GPP forums [4], [5]. The topics addressed in 3GPP forums for supporting MTC include overload control and signaling reduction, and those being addressed in 3GPP Release 12 and beyond include support for small data transmission, device power consumption optimization, etc. The current standards modifications for MTC may not sufficiently address an optimal MTC solution for large-scale wide-area deployments of IoT. The OneM2M forum is a wireless industry initiative to define a system, architecture, protocols, and services for IoT. The forum has wide membership and is making substantial progress toward its goals. The Weightless special interest group [6] has also developed an air interface protocol for IoT in wide-area communication, with a commercial solution operating in white space frequencies [7] available now.

Enhancing the existing LTE standard for meeting the needs of IoT devices that generate MTC traffic is an ongoing activity in the 3GPP forums.

A hierarchical network architecture for scalable connectivity to flexibly support the wide array of requirements to support IoT communications resulting from a wide range of use cases for IoT is proposed in [2]. Furthermore, research has addressed the need for a simplified protocol stack for supporting IoT transmissions in wide-area networks. In [8], the use of the LTE smartphone as a gateway to IoT devices is proposed, with constrained application protocol (CoAP) as the session layer protocol along with user datagram protocol (UDP) at the transport layer. CoAP is designed to suit the energy constraints and the low processing power of IoT devices. CoAP is a protocol with low message overhead, along with support for retransmissions, congestion control, and multicast. In [9], an MTC facilitator function is introduced in the eNodeB to act as an intermediary between an MTC device with a simplified protocol stack [no packet data convergence protocol (PDCP) or radio link control (RLC) layers] and the eNodeB. Although this solution reduces the protocol complexity at the MTC device, it does not provide a reliable transport mechanism as suggested with the use of CoAP.

Research on the physical layer design for MTC is also in progress [10], [11]. To circumvent the congestion arising from IoT devices in the existing cellular systems, one can consider contention-based radio access mechanisms. However, a contention-based access mechanism, if not properly configured, may cause many collisions. In [12], a coded expanded random access method has been proposed. In this method, a contention window is used, during which the IoT devices contend for the resources that are available in a noncontention window. Contention-based access for MTC in 3GPP LTE has been presented in [13], wherein the base station (BS) can broadcast a resource grant for multiple IoT devices to contend. The IoT devices also include their temporary identity assigned by the network when the data are transmitted over the resource. The temporary identity is protected by robust coding for reliable detection at the BS. If the BS detects a collision, a dedicated resource grant is given to the IoT devices in the next instant. Radio resource requests for small and sporadic packet transmissions from many IoT devices can overload the physical resource dedicated for the random access channel.

In this article, we propose an IoT wide-area communication system concept to enable the wireless operators to efficiently use their licensed macrocellular spectrum and enhance their existing wireless infrastructure for building new vertical markets for IoT applications and services. The proposed system concept may be deployed as an overlay to the existing macrocellular access network (AN). The system concept presented in this article proposes a dedicated air interface for IoT traffic, operating within the resource constraints of an existing wideband wireless technology such as LTE, particularly serving traffic generated by low-energy, low-cost IoT modules. To support the IoT system concept, a separate lightweight air interface protocol for IoT that will best serve the needs of the emerging boom in IoT is necessary. With the proposed IoT wide-area communication system, a wireless operator can deploy energy-efficient IoT modules that are designed to operate in their licensed macrocellular spectrum, without the need for a smartphone as a gateway. The operator can optimize the performance of IoT system independently of the conventional macrocellular system, while operating within the licensed macrocellular system band with other person-oriented communications.

IoT System for Wide-Area Networks

Figures 1 and 2 illustrate the proposed IoT wide-area communication system that can be operator controlled end to end. A generic narrowband IoT communication module, referred to in the rest of the article as the *IoT module* for brevity, that is suited for low-energy operation and capable of operating within the existing cellular spectrum is shown in Figure 1. The narrowband transceiver in the IoT module may be configured to have a wide operating range or may be factory configured to operate within a constrained region

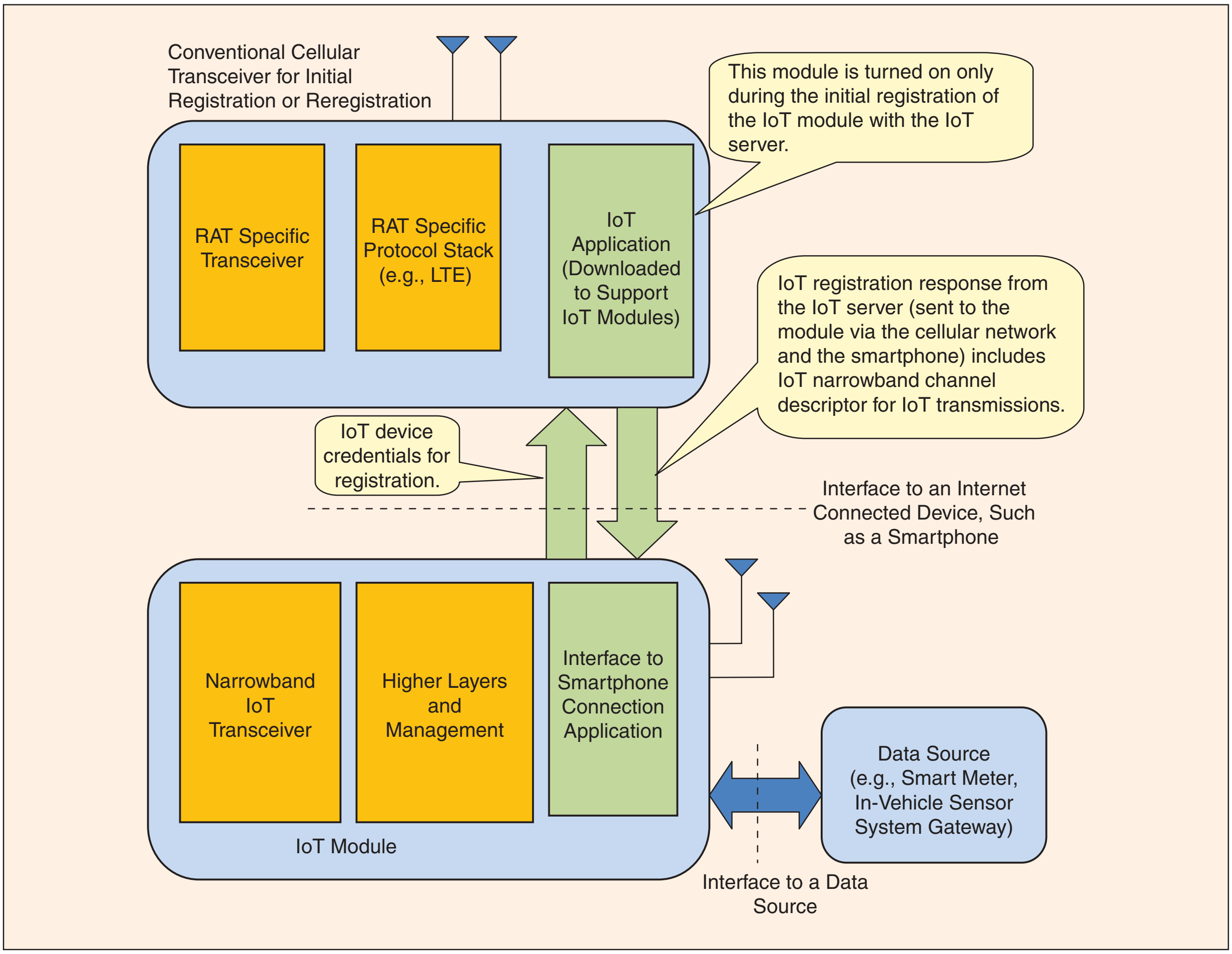

FIGURE 1 The IoT module for the wide-area communication system.

of the operator's licensed spectrum. The narrowband specification for a given IoT module may be determined by the operator to match the allocation of resources within the licensed cellular band for IoT use, after which the IoT transceiver operates only over the assigned narrowband. The IoT module may employ the simultaneous access channel mechanism described in [11]. The IoT module's transceiver aligns the UL transmission timing with the AN timing by simply measuring the downlink (DL) timing over narrowband IoT DL transmissions. The higher layers of the protocol stack for the IoT module are described later in the article.

The IoT module interfaces with an IoT data source such as a smart meter. The IoT module is equipped with an IoT smartphone application, which interfaces with the corresponding IoT application installed in the smartphone to communicate with the IoT module. The IoT module interfaces with the smartphone operating on the existing radio access technology to 1) provide the IoT module and/or source credentials [e.g., a BlackBerry Messenger personal ID number (PIN)] to the IoT server for registration and 2) receive the narrowband channel descriptor assignment from the network operator for IoT transmissions. This channel descriptor may be provided by the macrocellular AN to the IoT server, which then sends the descriptor to the IoT module, following registration. The communication between the cellular packet core and the IoT server is facilitated by an interworking function (IWF) entity.

Figure 2 provides an overview of the proposed system for supporting traffic arising from IoT sources in wide-area communication. The IoT server shown in Figure 2 may be within the operator's own network. The data source shown in may be a simple sensor on a street light or an aggregation point for several IoT sources in a hierarchical network. In step 1 of Figure 2, the IoT module is shown being used in conjunction with a smartphone for initial registration and identity assignment on the operator's network. At this time, the IoT module is not communicating with the IoT data source. Once its identity is established and the network handshake is completed with the aid of the smartphone, the module is deployed on a street light, meter, car, or similar entity. As shown in step 2, the IoT module then operates independently of the smartphone, only to send and receive information on a narrowband channel.

Since many wide-area applications (smart cities, utilities, etc.) are enterprise driven, it is possible for a wireless operator contracting with the customer to complete the setup described earlier using smartphones operating on their network. Any further reconfiguration of the IoT module is conducted via in-band signaling between the IoT module and the network.

Figure 3 shows the setup procedure for the IoT module. The setup procedure begins with the initiation of the registration process for the IoT module and/or source with the IoT server and the macrocellular AN. The geolocation of the IoT module (e.g., using smartphone's global positioning system location) can be appended (by the IoT application on the smartphone) to the IoT registration request that is sent to the IoT server. The registration request may include the IoT module ID (e.g., PIN), its personality (stationary or mobile), and other such parameters. Following the initiation of the IoT module registration process via the smartphone, the IoT server may contact the smartphone operator's AN to query the configured IoT channels. If there are no IoT channels configured by the AN, the

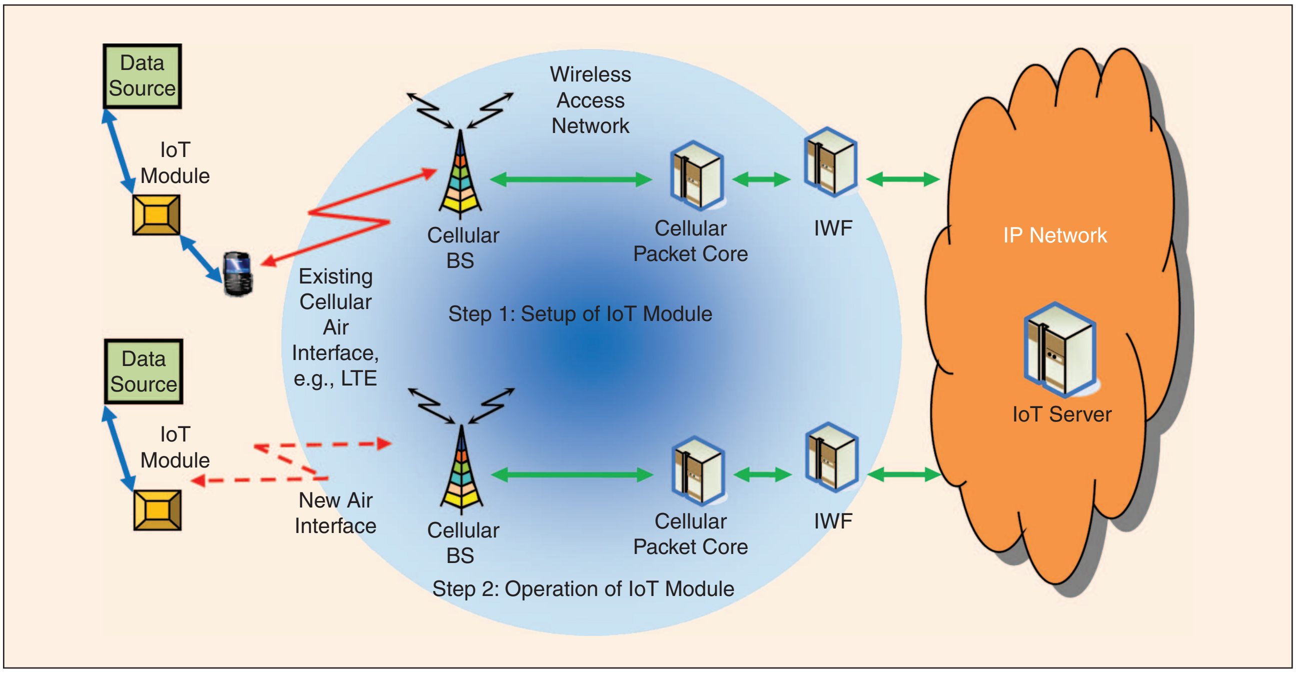

FIGURE 2 The IoT wide-area communication system: initial setup and operation.

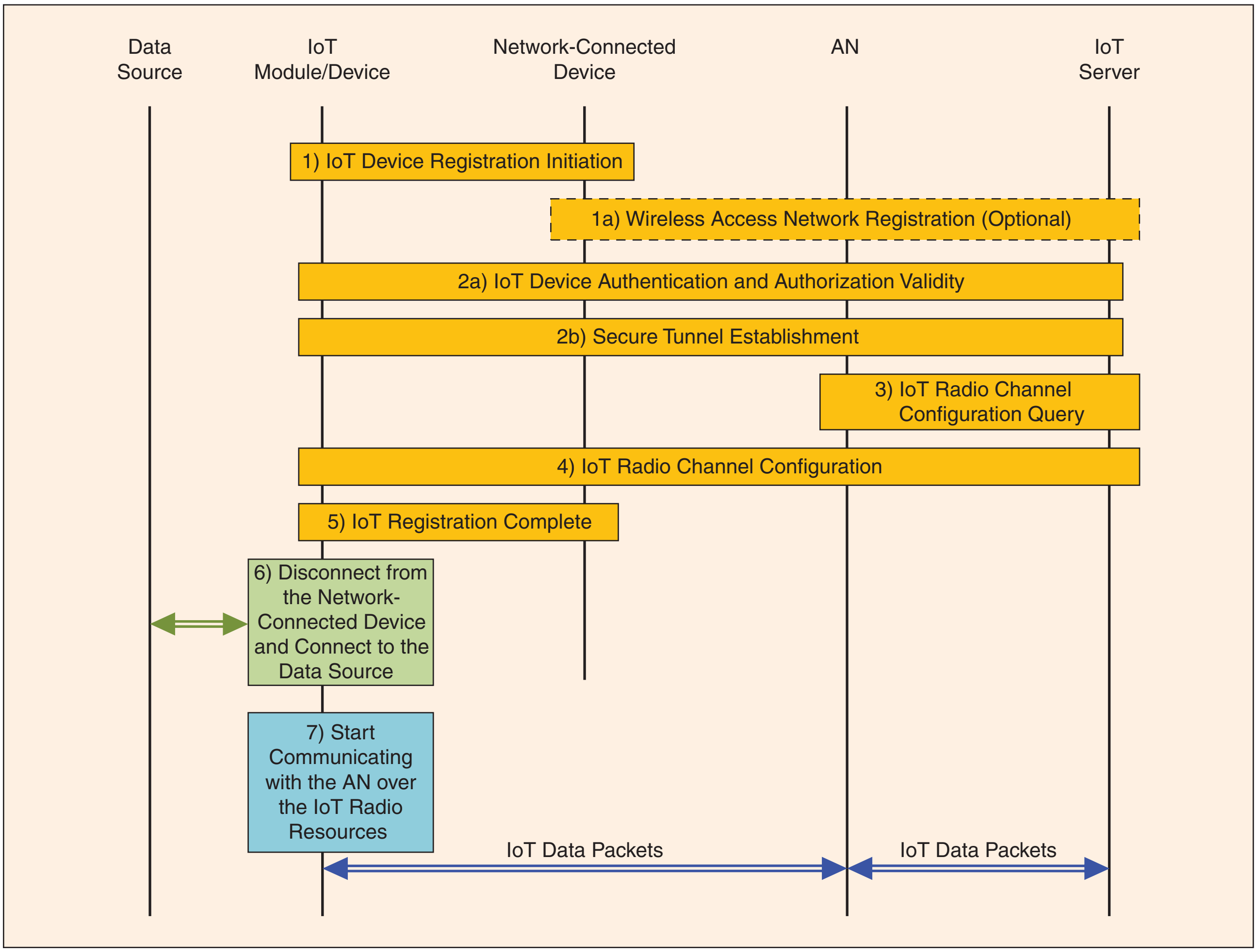

FIGURE 3 The IoT module setup procedure.

AN may configure new IoT channels at the BS in the IoT's coverage area. Furthermore, if there is a need to reconfigure IoT channels to meet the demand for IoT traffic, new IoT channels may be added by the AN. The AN will also assign an IoT access ID for use in the AN and include that ID in its response to the IoT server. This ID is included in the medium access control (MAC) header by the IoT module or AN whenever a data packet is transmitted.

Subsequently, the IoT server provides the IoT module configuration details as assigned by the AN, to the IoT module via the smartphone. The configuration details include the IoT access ID and the IoT channel descriptor (i.e., the carrier frequency, resource allocation region, power level, etc.).

Once the IoT module registration is completed with the help of the smartphone operating over the operator's cellular network, the IoT module is connected to the IoT data source and transmits test packets originating from the data source over the allocated resources in the macrocellular network. Once the test packets are acknowledged by the IoT server, the setup is complete, and at this time, the smartphone is disconnected from the IoT module. The IoT module is now ready to transmit/receive data packets using the AN's radio resources as indicated by the IoT server.

Simplified Protocol Stack

A protocol stack is proposed in Figure 4 for the IoT air interface supporting IoT services. In this case, UDP is preferred over transmission control protocol for the complexity- and energy-constrained IoT module. The session layer (not shown) may use CoAP. The air interface between the IoT module and the AN may use new protocols to conserve battery power at the IoT module and also reduce the signaling overhead at each layer of the protocol stack. The proposed protocol stack should allow the IoT modules to transmit the data with very low overhead. Furthermore, the IoT module should be able to send the data packet without the need for strict UL synchronization. It will be an added advantage if multiple IoT modules can transmit the data packets using the same radio resources. Thus,

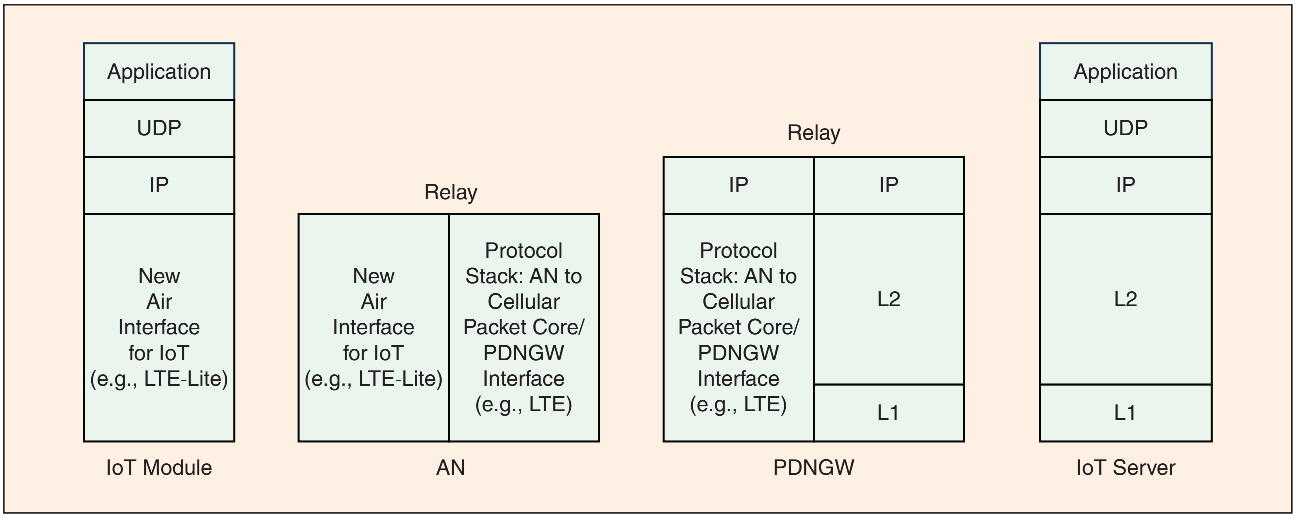

FIGURE 4 The protocol stack for IoT air interface.

the AN has an added requirement to decode these simultaneous quasisynchronous transmissions from the IoT modules.

A significant simplification of the proposed IoT system design relative to conventional macrocellular systems is that there is no separate control plane and associated control channel signaling. The control signaling is kept minimal, and any such signaling is achieved through in-band transmissions in the user plane protocol.

To accommodate this proposed protocol stack, new mechanisms are to be defined with respect to the existing macrocellular standards. The intention is to fit the proposed air interface to collaboratively function with the conventional access air interface. For example, in 3GPP LTE advanced, new logical, transport, and physical channels need to be defined for IoT.

The following sections detail the accommodation of the proposed air interface in LTE, following 3GPP (or, in general, European Telecommunications Standards Institute) terminology, as an example. The description covers the UL transmission mechanisms only. It is straightforward to extend the presented mechanisms to DL.

Radio Resources for IoT Transmission

In keeping with the LTE air interface definition, we consider simultaneous orthogonal frequency-division multiplexing (OFDM) transmission from multiple IoT modules over the same frequency–time resources. As illustrated in Figure 5,

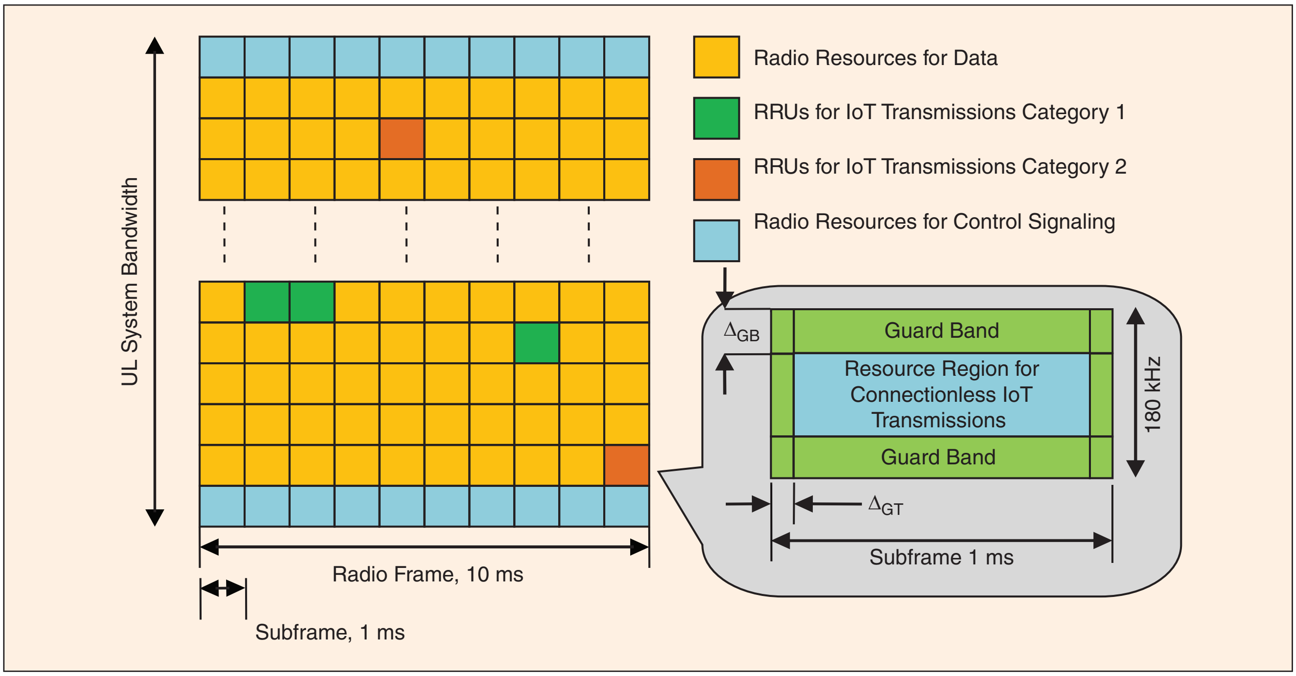

FIGURE 5 The radio resource grants for IoT transmissions in a 10-MHz LTE UL band.

THE INTENTION IS TO FIT THE PROPOSED IoT AIR INTERFACE TO COLLABORATIVELY FUNCTION WITH THE CONVENTIONAL AIR INTERFACE IN 3GPP LTE, NEW LOGICAL, TRANSPORT AND PHYSICAL CHANNELS NEED TO BE DEFINED FOR IoT.

for example, in a 10-MHz LTE system, some of the frequency–time resources can be allocated by the AN to small packet transmissions. A bandwidth of 180 kHz in a subframe of 1 ms (which correspond to a resource block in LTE) forms a basic unit of radio resource for this purpose, referred to as a *radio resource unit* (RRU) for UL IoT transmissions, with 1.25-kHz subcarrier spacing. The subframes in which these resources are available may alternately be broadcast by a cellular AN on the DL for IoT modules that may be capable of dynamic reconfiguration of resources. Guard time Δ_{GT} and a guard band Δ_{GB} are provisioned based on the deployment scenario, to accommodate the quasisynchronous access mode for IoT use. Note that while 180 KHz is introduced for illustration purposes, any other basic unit can be suitably assigned. Different sets of resources may be assigned for different IoT services.

New UL Physical, Transport, and Logical Channels

To support the desired requirements of quasisynchronous operation and simultaneous use of a UL resource, a new UL physical channel is introduced [11]. The physical UL simultaneous access shared channel (PUSSCH) shown in Figure 6 enables a simultaneous-access shared channel capable UL receiver to detect individual data packets from simultaneously transmitting IoT modules. The PUSSCH maps to the UL simultaneous-access shared channel (UL-SSCH) transport channel at the MAC layer, which operates in parallel to the existing macrocellular UL shared channel (UL-SCH) in LTE, also shown in Figure 6.

A new logical channel, the common traffic channel (CTCH), is introduced as illustrated in Figure 6. As depicted, the CTCH data are transmitted on transparent mode or unacknowledged mode (UM). The CTCH data are mapped to either UL-SSCH. The larger data packets may be transmitted using the UM.

One of the DL RRUs may be assigned to transmit the various control commands or packets to the IoT modules. The UL timing is adjusted based on the DL receive timing.

The receiver [11] at the AN uses a multiuser (MU) detection technique to detect the individual bursts. The detection process involves the estimation of the relative time offsets between the IoT module packet transmissions, the estimation of the channel weights for each of these transmissions, and the data detection.

PUSSCH Payload Format

Figure 7 depicts the PUSSCH structure. The RLC payload data unit (PDU) is appended with a MAC header, which consists of a temporary IoT module ID and a reserve (RSV) bit. A cyclic redundancy check is calculated and appended to this payload to form an MAC PDU. The MAC PDU thus formed is rate-1/2 convolutional coded and symbol mapped to quaternary phase-shift keying (QPSK) symbols to generate a PHY PDU. A new data indicator (NDI) bit is appended to the PHY PDU. The NDI field indicates whether the PUSSCH contains new data or retransmitted data. The NDI bit may be set to zero or one to indicate an original transmission or a retransmission, respectively, [e.g., to support hybrid automatic repeat request (HARQ) operation]. A preamble sequence of 24 symbols is added to the PHY PDU before transmitting the burst over the air. The preamble/pilot sequence for the lth IoT module, $P^l = \{P_0^l, P_1^l, \ldots, P_{C-1}^l\}$, is picked from a set of sequences with good autocorrelation and cross-correlation properties (in the time and/or frequency domain). The physical layer payload is mapped to the allocated subcarriers and transmitted in the time domain [by performing inverse discrete Fourier transform (IDFT)] after appending a cyclic prefix (CP). The position of the preamble symbols within the PHY PDU for the lth IoT

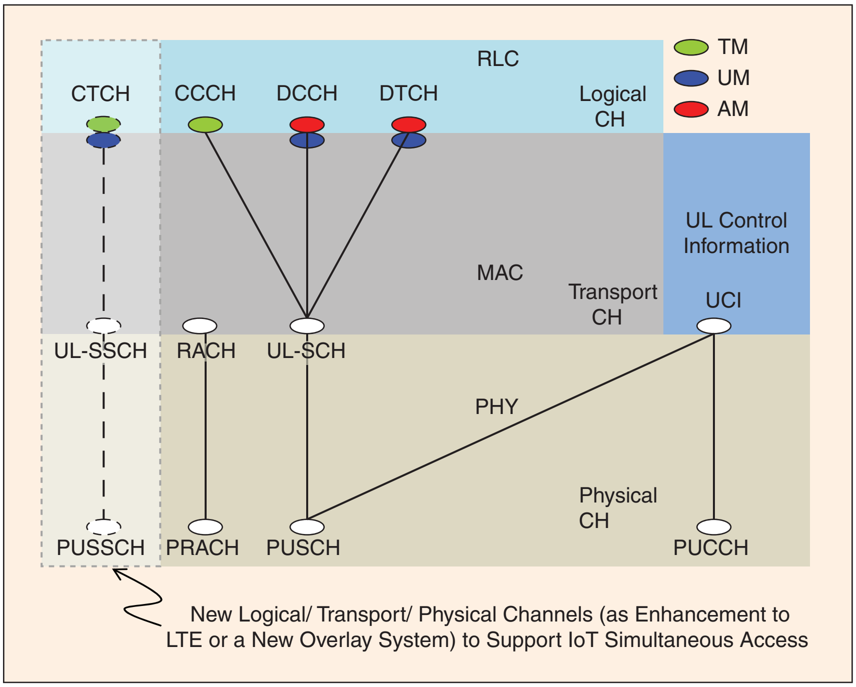

FIGURE 6 UL channel mapping for the IoT air interface.

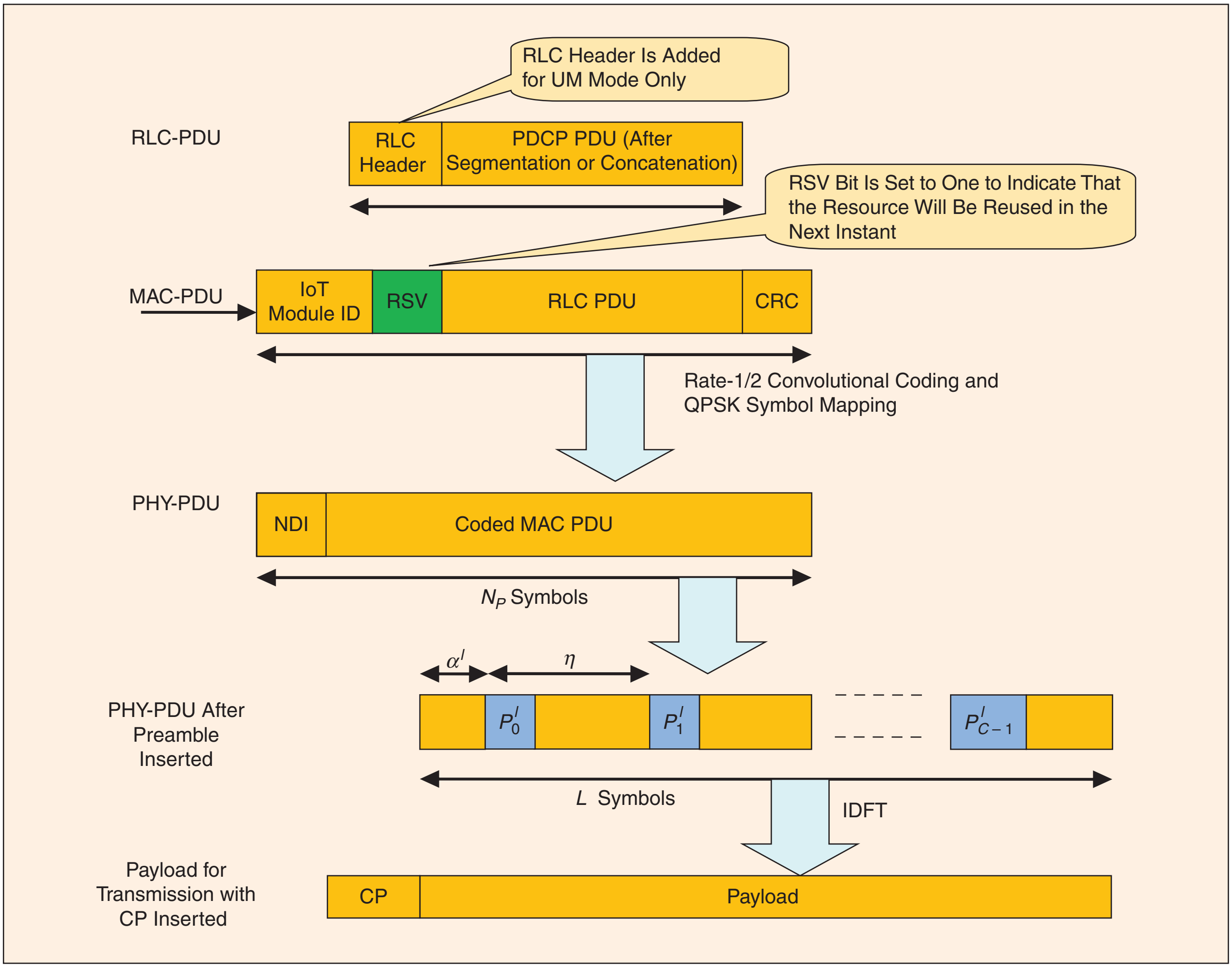

FIGURE 7 The PUSSCH payload transmission format.

module, α^l is randomly selected as illustrated in Figure 7. In the proposed simultaneous access mechanism, an UL radio resource for the lth IoT module can be defined by the selected preamble sequence P^l and the position of P_0^l within the OFDM burst, α^l, where $0 \leq \alpha^l \leq \eta - 1$. The RSV bit in the MAC header is used by the IoT module to reserve the current UL radio resource for the next UL opportunity.

As illustrated in Figure 7, the MAC service data unit (SDU) is formed by attaching an RLC header to the RLC PDU. The RLC header is not required if the RLC PDU is small and does not require segmentation or if the data are being transmitted in transparent mode. Further, a control channel (not shown) may be embedded into the data PDUs as a means of in-band control signaling, thus avoiding the need for a separate set of control channels.

Resource Assignment for UL Simultaneous Access

UL radio resources [defined by the set (P^l, α^l)] from the configured RRU-sets can be preassigned for IoT modules by assigning the preamble for each IoT module. However, the radio resources are wasted when the IoT module does not transmit a data packet for a while. Alternatively, all of the IoT modules can contend for the available preambles. In this contention scheme, the network-registered IoT modules, which intend to send data packets, will randomly pick a RRU and an associated unused preamble and transmit via the PUSSCH to the serving cell. The preamble is appended with the data, and the preamble is placed at one of the randomly selected positions. The AN will attempt to decode the transmitted data packet. After the transmission, the IoT module monitors the DL subframes for the receive status. The packet is retransmitted based on the receive (RX) status broadcasted by the AN.

Performance Results

The performance of the proposed system is evaluated through computer simulations. In the simulations, we assumed a data packet consisting of 96 symbols: a preamble of length 24 symbols, and user data of 72 symbols. The modulation and forward error correction (FEC) schemes used by all the user terminals are QPSK and rate-1/2 convolutional code, respectively. The

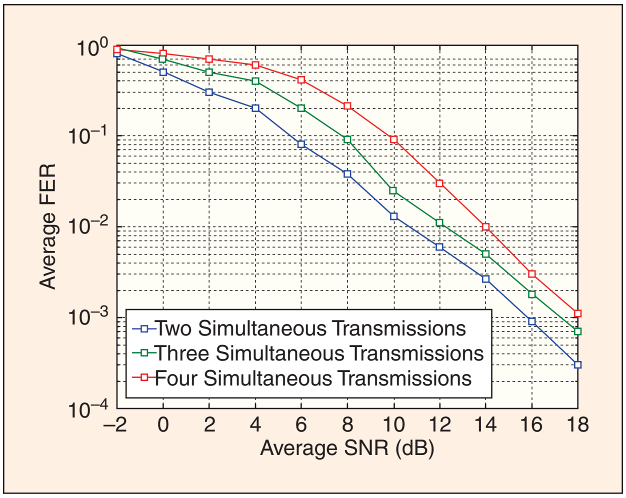

FIGURE 8 System UL FER performance.

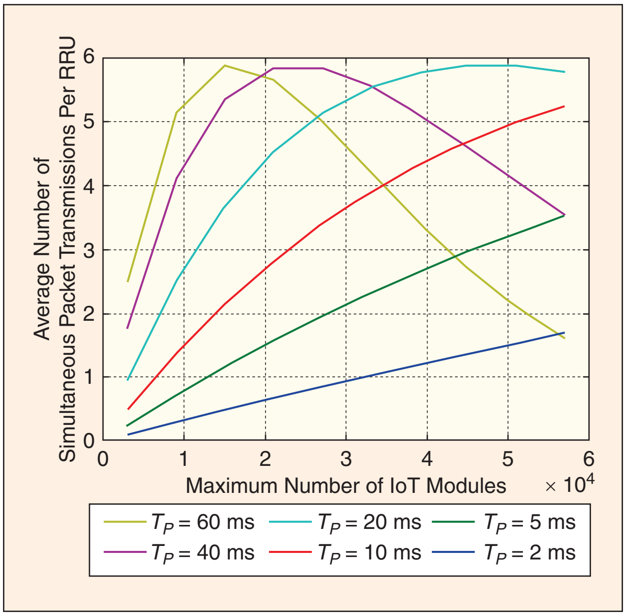

FIGURE 9 The performance of the simultaneous access contention mechanism.

preamble is a 24-symbol Zadoff–Chu sequence, which is created from 29 length Zadoff–Chu sequence truncated to 24 symbols. The roots used to generate these Zadoff–Chu sequences are 5, 7, 13, and 19. The roots are selected such that the roots and differences of the roots are prime compared to the length of the sequence. The transmit power of the preamble and data symbols is assumed to be equal in our evaluation.

In the simulations, we assume two receive antennas at the AN. The number N of IoT modules that are simultaneously transmitting are fixed for each simulation run and are varied across $N = 2$, 3, and 4. For simplicity, the channel is assumed to be constant over one packet transmission, i.e., over 180 kHz in 1 ms. Further the channel model assumed is quasistatic, i.e., an independent channel weight is generated for each packet transmission. The average received power at the AN from each IoT module is assumed to be the same.

The transmission timing of the data packets is randomly selected for each packet or each packet burst from zero to the duration of the CP. This allows us to simulate a large range of timing offset among the packets from different users. The packet burst consists of multiple packets transmitted consecutively by the IoT modules. For example, if the expected PHY payload size is 54 octets (which fits in three data packets), then three consecutive subframes are assigned to the IoT modules.

Figure 8 depicts the average packet or frame error rate (FER) as a function of average signal to noise ratio (SNR). The SNR is defined as the average received power at the AN for each IoT transmission to the receiver's thermal noise power level. The channel estimation and data detection mechanisms used are described in [11]. These simulation results demonstrate that the AN can successfully separate the simultaneous data transmissions on the same resources from different IoT modules.

Figure 9 shows the simulation results when many IoT modules contend for the UL radio resources. Here we assume that the RRUs for the IoT transmissions are allocated periodically with a period of T_P. The number of IoT modules that are actively transmitting in a PUSCCH resource is approximated by a binomial distribution, with a probability $\rho = 1/T'$, where $T' = T/T_P$. T is assumed to be 60 s. This model is extracted from the simulation methodology described in [14]. The average number IoT modules that can communicate with the AN without collisions are calculated for the different number of IoT modules in the system. The number of preambles and preamble offset combinations are set at 16 for this analysis. The maximum number of IoT modules are varied from 3,000 to 60,000 for various values of T_P. For large values of T_P (say, > 20 ms), the number of simultaneous successful transmissions drop rapidly as the number of IoT modules increase. The reason for this behavior is that as the number of IoT modules increase, the probability of collision (i.e., more than one IoT module selects the same preamble sequence and preamble offset) increases.

Conclusion

This article addressed an IoT wide-area communication system concept and protocol that can be deployed within the operator's licensed macrocellular band, functioning alongside person-oriented communications. The system concept presented in this article is dedicated to low-energy, low-complexity IoT modules with low priority and infrequent IoT traffic. To support the IoT system concept, it is proposed that a separate lightweight air interface protocol for IoT that will best serve the needs of the emerging boom in IoT is necessary. This article attempted to illustrate such a protocol within the construct of an LTE protocol architecture. Performance results for the proposed simultaneous access channel used for the UL IoT communication are provided. Further simplification of the protocol stack and extension of the protocol for different classes of IoT traffic is possible and is a topic of future work. The authors hope that the article will motivate further research along the lines of developing a new architecture and lightweight protocol structure for IoT communications that fit into current licensed bands and work alongside current cellular architecture and protocols.

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