Wireless Wide Area Networks for Internet of Things

Chandra S. Bontu*, Shalini Periyalwar†, Mark Pecen†, Jim Womack◊
Advanced Technology, BlackBerry
*4000 Innovation Drive, Ottawa, Canada K2K 3K1, E-Mail: cbontu@blackberry.com
†176 Columbia Street West, Waterloo, Canada N2L 3L3, E-Mail: shperiyalwar, mpecen@blackberry.com
◊5000 Riverside Drive, Irving, Texas, USA 75039, E-Mail: jwomack@blackberry.com

Abstract — This paper proposes an IoT Wide Area Communication System concept deployed within the operator's licensed macrocellular band, sutiable for low energy, low complexity IoT modules with low priority and infrequent IoT traffic. The paper proposes a simplified air interface protocol for IoT. Some performance results for the simultaneous access channel used for the IoT physical layer are provided.

Keywords: Internet of Things, Machine Type Communications, Simultaneous access, Multi-user detection.

I. INTRODUCTION

The Internet of Things (IoT) is expected to bring billions of dollars in business opportunity 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 Personal Area Network (WPAN) technologies for health, automation and other personal area applications, but also by wide area technologies that are mostly proprietary and utilizing unlicensed ISM 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 cost, range, power consumption and robustness; however, these proprietary solutions require separate deployment from existing macrocellular networks, resulting in Capex and 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. Due to 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 3GPP and in forums such as OneM2M. Enhancing the existing LTE standard for meeting needs of IoT devices that generate Machine Type Communications (MTC) is an ongoing activity in 3GPP forums [3][4]. 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.

For IoT devices, in addition to the desired property of low power/energy consumption, the hardware must be cheap, reliable and have a long lifetime, and in many cases 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. Further, 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.

From the above, 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., GPRS, HSDPA, LTE) for IoT is the tight synchronization requirement and high signaling overhead not suited to energy constrained UEs. The current standards direction for MTC may not sufficiently address an optimal MTC solution for large scale wide area deployments of IoT.

The OneM2M Forum [5] is an ETSI initiative to define a system, architecture, protocols and services for IoT. The forum has wide membership and is making substantial progress towards its goals. The Weightless SIG [6] has also developed an air interface protocol for IoT in wide area communication, with a commercial solution operating in white space frequencies [7] being available now.

In academic literature, [2] proposes 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. Further, some 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 CoAP as the session layer protocol along with UDP at the transport layer. Constrained Application Protocol (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 PDCP or RLC layers) and the eNodeB. While 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 physical layer design for machine type communications is also in progress [8][11].

In this paper, we propose an IoT Wide Area Communication System concept to enable the wireless operators to efficiently utilize their licensed macrocellular spectrum and enhancing 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. The system concept presented in this paper proposes low energy, low cost IoT modules and a dedicated air interface for IoT traffic, operating within the resource constraints of an existing wideband wireless technology such as LTE. 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.

II. IoT System for Wide Area Networks

A. System Description

Fig. 1 and Fig. 2 illustrate the proposed IoT Wide Area Communication System that can be operator controlled end-to-end. A generic narrowband RAT agnostic IoT communication module, referred to in the rest of the paper 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 Fig. 1. The narrow band 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 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 narrow band. The IoT module may employ the simultaneous access channel mechanism described in [11]. The IoT module's transceiver aligns with the access network timing by simply monitoring the downlink timing from the base station transmitter measured on a downlink control channel. The higher layers of the protocol stack for the IoT module are described later in the paper.

The IoT module interfaces with an IoT data source such as a smart meter. The IoT Module is equipped with a 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 to a) provide the device credentials (e.g., like BBM PIN) to the smartphone for registration and b) receive the narrow band channel descriptor assignment from the network operator for IoT transmissions. This channel descriptor may be provided by the macrocellular access network to the IoT server, which then sends the descriptor to the IoT module, following registration.

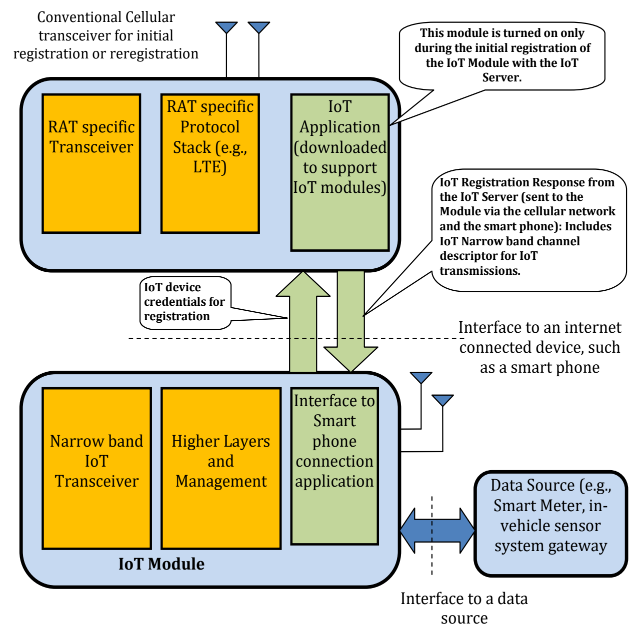

Fig. 1. RAT agnostic IoT Module for Wide Area Communication System

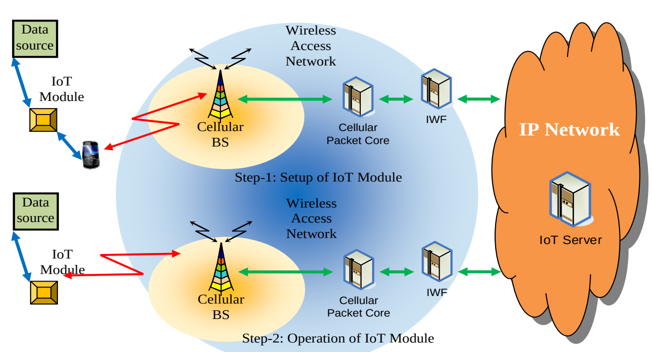

Fig. 2. IoT Wide Area Communication System: Initial Setup and Operation

Fig. 2 provides the overview of the proposed system for supporting traffic arising from IoT sources in wide area communication. The IoT server shown in Fig. 2 may be within the operator's own network. The data source shown in Fig. 2 may be a simple sensor on a street light or may alternately be an aggregation point for several IoT sources in a hierarchical network. In Step 1 of Fig. 2 above, 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 such entity. As shown in Step 2 of Fig. 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 enterprise customer to complete the setup described above 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.

Fig. 3 below shows the setup procedure for the IoT module. The setup procedure begins with the initiation of the registration process for the IoT device with the IoT server and the macrocellular access network. The geo location of the IoT module (e.g., using smartphone's GPS 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 device 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 Access Network (AN) to query the configured IoT channels. If there are no IoT channels configured by the AN, the AN may configure new IoT channels at the base station 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 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 (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.

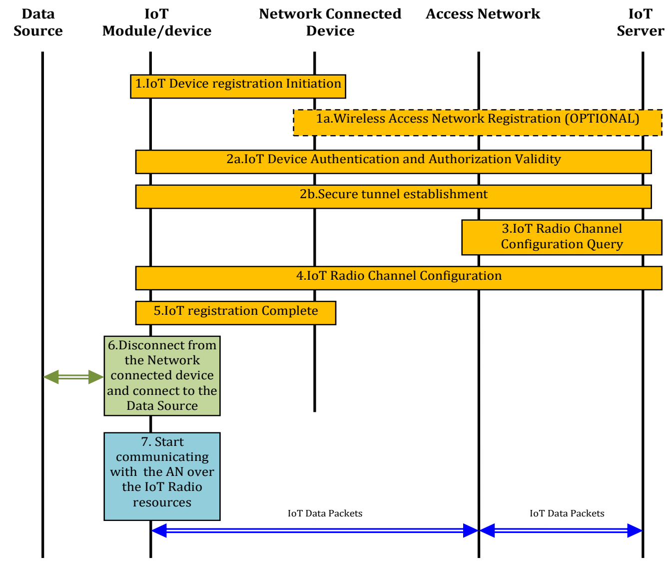

Fig. 3. IoT Module Setup Procedure

III. SIMPLIFIED PROTOCOL STACK

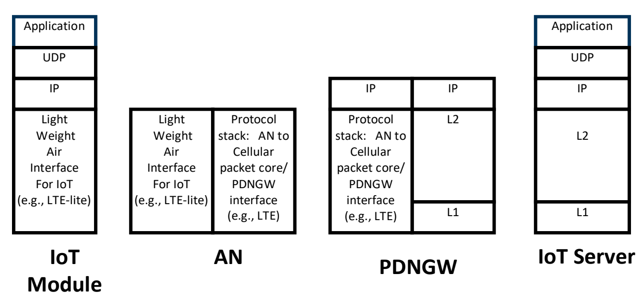

Fig. 4. Protocol Stack for IoT Air Interface

A protocol stack is proposed in Fig. 4 for the IoT air interface supporting IoT services. In this case, UDP is preferred over TCP 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 Access Network (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 the AN has an added requirement to decode these simultaneous quasi or asynchronous transmissions from the IoT devices.

A significant simplification of the IoT system design relative to conventional macrocellular systems is that we propose to have 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 Long Term Evolution (LTE), 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 ETSI) terminology, as an example. The description covers the UL transmission mechanisms only. It is straightforward to extend the presented mechanisms to downlink (DL).

A. Radio Resources for IoT Transmission in LTE

In keeping with the LTE air interface definition, we consider simultaneous OFDM transmission from multiple IoT devices over the same frequency–time resources. As illustrated in Fig. 5 below, 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 Radio Resource Unit (RRU) for UL IoT transmissions, with 1.25 KHz spacing. Subframes in which these resources are available may alternately be broadcast by a cellular access network on the downlink for IoT modules that may be capable of dynamic reconfiguration of resources. Guard time $\boldsymbol{\Delta_{GT}}$ and a guard band $\boldsymbol{\Delta_{GB}}$ are provisioned based on the deployment scenario, to accommodate the quasi synchronous 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.

A. New Uplink Physical, Transport and Logical channels in LTE

To support the desired requirements of quasi synchronous operation and simultaneous use of an uplink resource, we introduced a new uplink physical channel to achieve quasi-synchronous simultaneous uplink access [11]. The Physical Uplink Simultaneous Access Shared CHannel (PUSSCH) shown in Fig. 6 below, enables a simultaneous-access shared channel capable uplink receiver to detect individual data packets from simultaneously transmitting IoT modules. The PUSSCH maps to the UL-SSCH transport channel at the MAC layer, which operates in parallel to the existing macrocellular UL-SCH in LTE, also shown in Fig. 6.

A new logical channel, the Common Traffic Channel (CTCH), is introduced as illustrated in Fig. 6. As depicted, the CTCH data is transmitted on Transparent Mode (TM) or Un-acknowledged Mode (UM). The CTCH data is mapped to either Up Link Simultaneous-access Shared Channel (ULSSCH). The data packets which are larger may be transmitted using the UM mode.

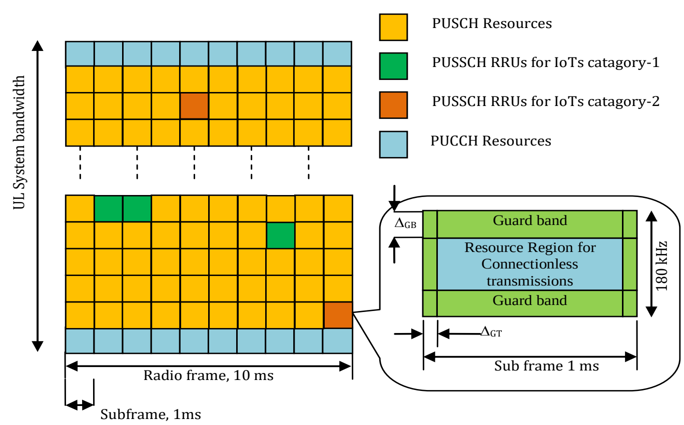

Fig. 5. Radio Resource Grants for ULSSCH IoT Transmissions in a 10 MHz LTE Uplink Band

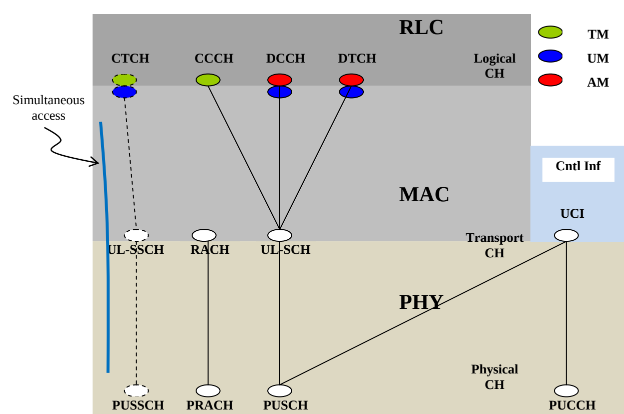

Fig. 6. Channel mapping for IoT Air Interface

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

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

B. PUSSCH payload format

Fig. 7 depicts the PUSSCH structure. The MAC PDU is appended with a MAC header which consists of a temporary IoT device ID and a new data indicator (NDI) bit. The temporary device ID assigned by the AN may be appended to physical layer payload or inserted in the MAC header The New Data Indicator (NDI) field indicates whether the PUSSCH contains new data or retransmitted data. The NDI bit may be set to 0 or 1 to indicate an original transmission or a retransmission respectively (for example, to support HARQ operation). A CRC is calculated and appended to this payload (together with the IoT device ID and the NDI bit) to form an MAC PDU. The MAC PDU thus formed is rate-1/2 convolutional coded and symbol mapped to QPSK symbols to generate a PHY PDU. A preamble sequence of 24 symbols is appended to the PHY PDU before transmitting the burst over the air. The preamble/ pilot sequence for the ℓth IoT device, $\boldsymbol{P}^{\ell}$ is picked from a set of sequences with good auto-correlation 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 after appending CP. The position of the preamble symbols within the PHY SDU for the ℓth IoT device, α^{ℓ} is randomly selected.

The MAC 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 doesn't require segmentation or if the data is 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.

IV. Resource Assignment for Uplink Simultaneous Access

RRUs from the configured RRU-sets can be pre-assigned for IoT devices by assigning the preamble for each IoT device. However, the radio resources are wasted when the IoT device doesn't transmit a data packet for a while. Alternatively, all the IoT devices can contend for the available preambles. In this contention scheme, the network-registered IoT devices 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 device monitors the DL subframes for the receive status. The packet is retransmitted based on the receive (RX) status broadcasted by the AN.

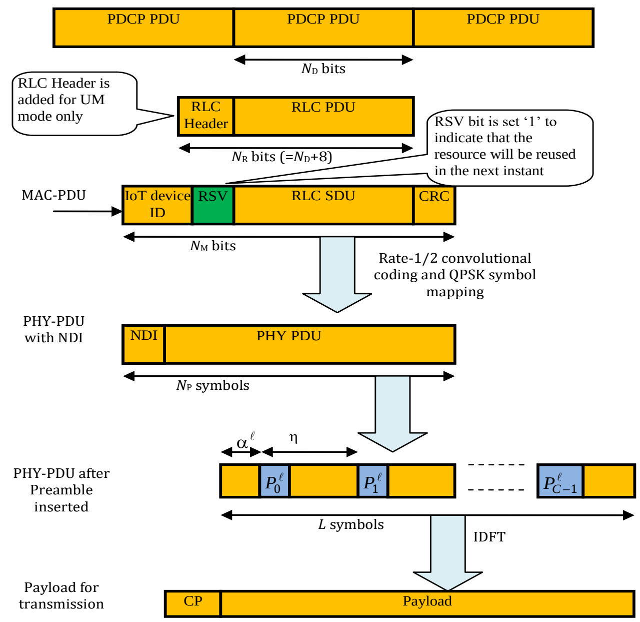

Fig. 7. PUSSCH Payload Transmission Format

V. Performance Results

The performance of the proposed system is evaluated through computer simulations. In the simulations, we assume a packet of length, 96 symbols: 24 symbols of preamble and 72 symbols of data. The modulation scheme used by all the user terminals is QPSK. The 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 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 BS. 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 quasi-static, i.e. an independent channel weight is generated for each packet transmission. The average received power at the BS from each IoT device is assumed to be the same.

The transmission timing of the data packets is randomly selected for each packet or each packet burst from 0 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 UTs. For example if the expected PHY payload size is 54 octets (which fits in 3 data packets), then three consecutive resource units are assigned to the IoT Modules.

Error! Reference source not found. depicts the average 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. These simulation results demonstrate that the AN can successfully separate the simultaneous data transmissions on the same resources from different IoT devices.

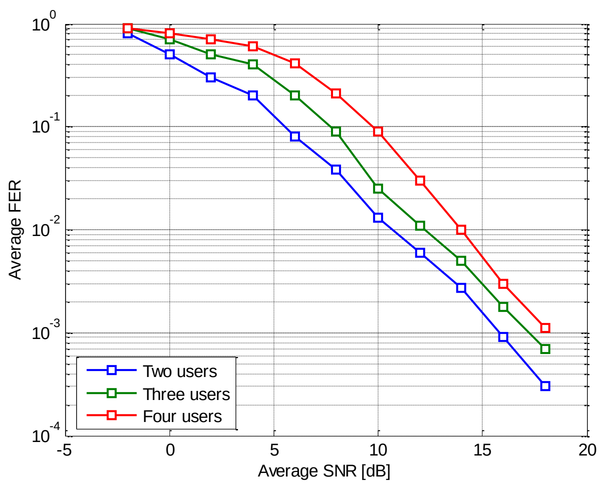

Fig. 8. System FER performance

Fig. 9 shows the simulation results when many IoT devices contend for the RRUs. Here we assume that the RRUs for the IoT transmissions are allocated periodically with a period of T_P. The number of IoT devices that are actively transmitting in a PUSCCH resource is approximated by a Binomial distribution, with the probability $p = 1/T'$, where $T' = T/T_P$. T is assumed to be 60 seconds. This model is extracted from the simulation methodology described in [12]. The average number IoT devices that can communicate with the AN without collisions are calculated for different number of IoT devices in the system. The number of preambles and preamble offset combinations are set at 16 for this analysis. The maximum number of IoT devices are varied from 3000 to 60000 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 devices increase. The reason for this behavior is that as the number of IoT devices increase, the probability collision increases.

VI. CONCLUSION

This paper has addressed an IoT Wide Area Communication System concept deployed within the operator's licensed macrocellular band, and functioning alongside person oriented communications. The system concept presented in this paper 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. The paper attempts to illustrate such a protocol within the construct of an LTE protocol architecture. Further performance results for the simultaneous access channel used for the IoT physical layer are provided. Further simplification of the protocol stack is possible and is a topic of future work.

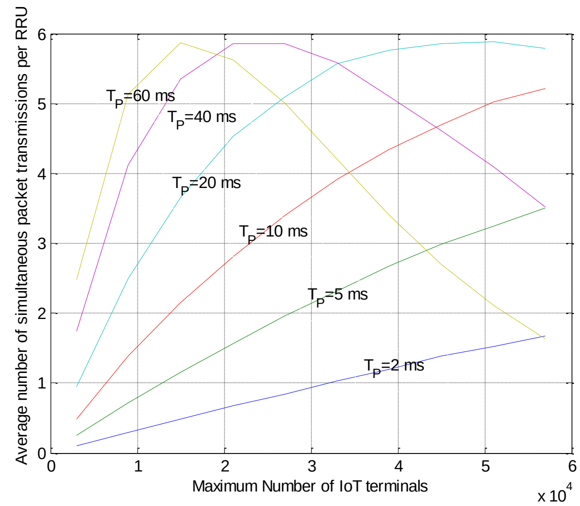

Fig. 9. Performance of the simultaneous access contention mechanism

.

REFERENCES

[1] http://www.plextek.com/design-services/industrial-a-automotive/metering-a-utilities.html

[2] G. Wu, S. Talwar, K. Johnsson, N. Himayat, K.D. Johnson, "M2M: From Mobile to Embedded Internet", *IEEE Communications Magazine*, April 2011, pp. 36-43.

[3] P. Jain, P. Hedman, H. Zisimopoulos, "Machine Type Communications in 3GPP Systems", *IEEE Commun. Mag*., Nov 2012, pp. 28-35.

[4] D. Astely, E. Dahlman, G. Fodor, S. Parkvall, and J. Sachs, "LTE Release 12 and Beyond", *IEEE Commun. Mag*., Jul 2013, pp. 154-160.

[5] OneM2M, http://onem2m.org/

[6] Weightless SIG http://www.weightless.org/

[7] Neul http://www.neul.com/neul/?page_id=3614

[8] L. Constantino, N. Buonaccorsi, C. Cicconetti, and R. Mambrini, "Performance Analysis of an LTE Gateway for the IoT, *IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2012 ,San Francisco, USA, pp. 1 – 6.

[9] V.B. Misic, J. Misic, and D. Nreandzic, Extending LTE to support Machine-Type Communications, *Workshop on Telecommunications: From Research to Standards*, pp.6977-6981.

[10] G. Wunder, "Challenges in Air Interface: Initial Waveform Results of 5GNOW", *FUNEMS2013*, July 3-5 2013, Lisbon, Portugal

[11] C. S. Bontu, J. Ghimire, S. Periyalwar, M. Pecen, Asynchronous Simultaneous Small Packet Transmission in Cellular Wireless System, GWS2013, June 24-27, 2013, Atlantic City, NJ, USA.

[12] 3GPP TS 37.868 V11.0.0 (2011-09): Study on RAN Improvements for Machine-type Communications; (Release 11).