International Journal of Computing and Network Technology
ISSN (2210-1519)
Int. J. Com. Net. Tech. 7, No. 3 (Sept.-2019)

http://dx-doi.org/10.12785/ijcnt/070301

Commercial 4G LTE Networks for Supporting Evolving Smart Grid Applications

Ahmed Hassebo[1]* and Sumeet Chaudhary[2]

[1.2]Department of electrical and computer engineering, Purdue University Northwest, Westville, IN, USA

Received: 2. Jun. 2019, Accepted: 13 Augs. 2019, Published: 1 Sept. 2019

Abstract: Cell based Machine-to-Machine (M2M) infrastructure is one of the key internet of things (IoT) empowering advances with immense market potential for cell specialist organizations sending 4G long haul development (LTE) systems. The motivation for this paper is to investigate whether current commercial 4G LTE systems can possibly bolster a portion of the evolving strategic IoT applications. To accomplish this goal, we propose and devise a basic hybrid LTE uplink (UL) scheduling algorithm that uses a common LTE's dynamic scheduling for supporting human to human (H2H) applications just as M2M applications and Semi-Persistent Scheduling (SPS) for strategic IoT services that consistently require steady radio resources sharing regularly. The simulation results show that present public 4G LTE networks can possibly sufficiently bolster a portion of the developing strategic smart grid applications including Phasor Measurement Units (PMUs), with a constraint latency as low as 20 ms and extraordinary reliability .

Keywords: M2M communications, H2H communications, IoT, 4G LTE, SPS, and PMU.

1. Introduction:

The recent breakthroughs in the Internet of Things (IoT) applications and services, including smart healthcare, intelligent transportation systems (ITS), smart grid, and smart homes, have made this technology an integral part of our daily lives. Soon, IoT will facilitate billions of sensors, actuators, and smart devices to be interconnected and managed remotely via the Internet. One of the critical IoT enabling technologies with huge market potential for cellular service providers deploying Long Term Evolution (LTE) networks is the Cellular-based (M2M) communications. There is an emerging consensus that Fourth Generation (4G) and 5G cellular technologies will provide the global mobile connectivity to the anticipated tens of billions of things/devices that will be attached to the Internet.

The low cost and easy availability of the commercial LTE cellular networks are being exploited by many vital utilities and service industries to provide connections to users, sensors, and smart M2M devices on their networks [1]. Most of the emerging IoT applications have stringent requirements in terms of reliability and end-to-end (E2E) delay bound. The delay bound specified for each application refers to the device-to-device latencies caused due to the delay resulting from the application-level processing time and communication latency [2]. Each IoT application has distinct performance requirements in terms of latency, availability, and reliability. Typically, the most dominant network traffic in most of these applications is uplink traffic (much higher than downlink(DL) traffic)

Thus, efficient LTE UL scheduling algorithms at the base station ("Evolved NodeB (eNB)" per 3GPP standards) are more critical for M2M applications. Originally, LTE was not intended for IoT applications, as the traffic generated by M2M devices (running IoT applications) have characteristics that are different from those produced by the traditional Human-to-Human (H2H)-based voice/video and data communications. Additionally, the massive deployment of M2M devices and the limitedly available radio spectrum, the problem of efficient radio resources management (RRM) and UL scheduling poses as road-blocks in the adoption of LTE for M2M communications

Existing LTE quality of service (QoS) standard and UL scheduling algorithms were mainly optimized for H2H services and cannot accommodate such a wide range of diverging performance requirements of these M2M-based IoT applications (N. Abu-Ali, 2014). Though 4G

E-mail address: ahassebo@pnw.edu and schaudhaery@pnw.edu

LTE networks can support very low Packet Loss Ratio (PLR) at the physical layer, such reliability, however, comes at the expense of increased latency from tens to hundreds of ms due to the aggressive use of retransmission mechanisms. Current 4G LTE technologies may satisfy a single performance metric of these mission critical applications, but not the simultaneous support of ultra-high reliability and low latency as well as high data rates.

Numerous QoS aware LTE UL scheduling algorithms for supporting M2M applications, as well as H2H services, have been reported in the literature [4-17]. However, most of these algorithms cannot support mission-critical IoT applications, as they are not latency-aware [1]. Additionally, these algorithms are simplified and do not fully conform to LTE's signaling and QoS standards. For instance, a common practice is an assumption that the time domain UL scheduler located at the eNB prioritizes user equipment (UEs)/M2M devices connection requests based on the head-of-line (HOL) packet waiting time at the UE/device transmission buffer. However, as will be detailed below, LTE standard can't support a mechanism that could allow the UEs/devices to communicate with the eNB uplink scheduler about the waiting time of uplink packets residing in their transmission buffers

The recent emergence of Ultra-Reliable Low-Latency Communication (URLLC) paradigm has enabled a new range of mission-critical applications and services including industrial automation, real-time operation, and control of the smart grid, inter-vehicular communications for improved safety and self-driving vehicles (5G Ultra-reliable low-latency communications , 2018). URLLC and its supporting 5G NR technologies might become a commercial reality in the future.

Thus, deploying viable mission-critical IoT applications will have to be postponed until URLLC and 5G NR technologies are commercially feasible. Because IoT applications, specifically mission-critical, will have a significant impact on the welfare of all humanity, the immediate or near-term deployments of these applications is of utmost importance. It is the purpose of this paper to explore whether current commercial 4G LTE cellular networks have the potential to support some of the emerging mission-critical IoT applications. Smart grid is selected in this work as an illustrative IoT example as it is considered to be one of the most demanding IoT applications. Smart grids are required to support mission-critical applications that have stringent requirements in terms of E2E latency and reliability (e.g., real-time system protection and control utilizing PMU devices). And, at the same time, support a massive number of connected M2M devices with relaxed latency and reliability requirements (e.g., smart meters), as depicted in figure 1.

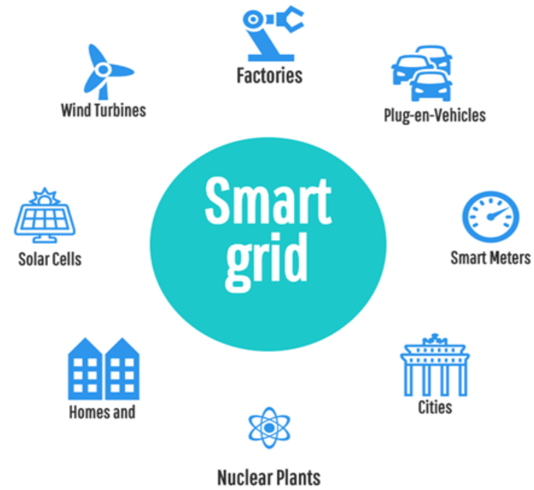


Figure 1. Smart grid applications.

Phasor Measure Units (PMUs) are devices deployed throughout the power grid (mainly within Substations) that provide synchronized measurements for the amplitude and angle of sinusoidal voltage and current waveform. These synchronized measurements provide accurate system state measurements in real-time and are expected to be massively deployed for real-time wide-area monitoring and control (WAMC) of the next-generation power grid. The information generated within the WAMC is used for mission-critical smart grid applications including state estimation, control, and protection of the power grid.

To achieve our objective, we propose and devise a simple hybrid LTE UL scheduling algorithm that utilizes a typical LTE's dynamic scheduling for supporting H2H services as well as M2M applications and Semi-Persistent Scheduling (SPS) for mission-critical IoT applications. These applications have a strong requirement for persistent radio resource allocation at regular intervals (similar to supporting voice in LTE networks). Specifically, we present a detailed LTE UL performance analysis that fully conforms to 4G LTE signaling and QoS standards to credibly assess the feasibility of commercial 4G LTE cellular networks to support such a diverse set of emerging smart grid applications as well as typical H2H services.

The simulation results have shown that current commercial 4G LTE systems can support a few of the neoteric mission-critical smart grid applications, including PMUs, with Packet Delay Budget (PDB) requirement as low as 20 ms. If achieving PLR $< 10^{-6}$ is the criteria for ultra-high reliability, then commercial 4G LTE systems can't simultaneously meet both ultra-high reliability and low latency.

2. Overview of LTE Signaling Mechanism and QoS Model

A. Signaling Mechanism

LTE standards define two MAC layer signaling messages, Buffer Status Report (BSR), and Scheduling Request (SR), to request resources from the evolved node base station (eNB). At the beginning of the scheduling process, UE/device sends SR (during its specific SR opportunity) on the Physical Uplink Control Channel (PUCCH) to inform the eNB that this UE/device has data to transmit. Each UE/device periodically gets an opportunity to send SR. Each UE is assigned a specific offset within an SR period. Following this, the UE must wait for its specific offset sub-frame to transmit its SR [19-21]. The offset is already assigned by the eNB during the RRC connection setup [20].

LTE standard (Release 8) identifies five different SR periods of 5, 10, 20, 40, or 80 ms [20]. Consequently, shorter periods of 1 ms and 2 ms were introduced in Release 9. In this work, an SR period of 10 ms was assumed so that SR offsets are within the 0-9 ms range. Note that the SR does not contain information about the UE/device buffer status (volume of data). As a result, the scheduler at the eNB does not have a detailed knowledge of buffer content. Therefore, the eNB must blindly assign the initial resources (uplink grant). In this work, it is assumed that, for the initial UL grant, the scheduler assigns a fixed size of bytes for each UE/device. Subsequently, these are converted to 1, 2, 3 RBs in the frequency domain, depending upon the UL channel conditions.

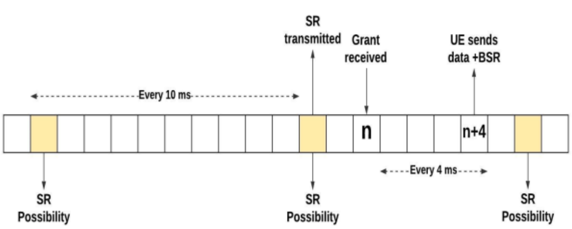


Figure 2. SR mechanism

On the other hand, the BSR allows the UE/device to communicate with the eNB and pass information about the amount of buffered data as well as their priority. As the UE/device may have quite a few radio bearers (QCIs) in its buffer, a considerable signaling overhead might be required to keep the eNB informed of the status of such massive radio bearers (logical channels). To reduce the signaling overhead, the LTE standard has introduced the concept of a Logical Channel Group (LCG). This approach maps a group of logical channels (with similar QoS requirements) to one of only four groups, with different priority levels. The mapping of radio bearers to an LCG is set up during RRC configuration. An LCG is a group of logical channels identified by a unique 2-bit LCG ID. Thus, the UE/device reports to the eNB the size of the buffer awaiting transmission per-LCG. The eNB responds with per-LCG grant to UE/device.

RRC configures two BSR Timers: Periodic BSR-Timer and retransmit-BSR-Timer (RETX_BSR_TIMER). The UE/ device generates three different types of BSRs: Regular BSR, Periodic BSR, and Padding BSR.

a) Regular BSR is generated at sub-frame n provided that the queue was empty in sub-frame (n-1) and new packets arrive in sub-frame n, or when a new data arrives in UL buffer provided that this new data has higher priority than the one already waiting in the buffer, or when the UE/device sends a BSR but never receives a grant and the RETX_ BSR-TIMER expires, a new BSR is triggered. The Timer is started when a BSR is sent and stopped when a grant is received. The time ranges from 320 ms up to 10.24 seconds. When a regular BSR is generated, a SR is transmitted at the next available SR opportunity unless resources are granted to the UE between the BSR generation and the opportunity to transmit SR (Ahmadi, 2014).

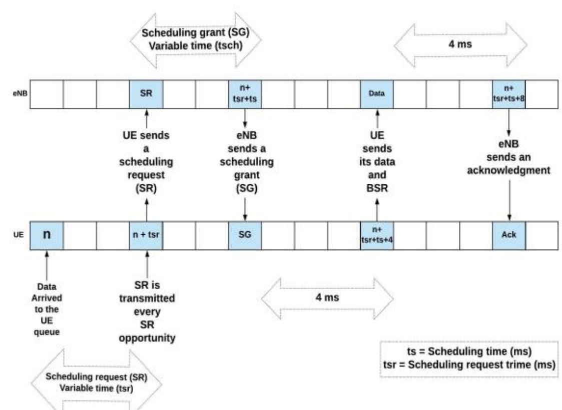


Figure 3. BSR mechanism

b) Periodic BSR is generated every n subframes. Each UE/device keeps a periodic BSR Timer. When the periodic BSR-Timer expires, a new BSR is triggered. The time, which is configured by RRC, ranges from 5 ms up to 2.56 seconds; and

c) Padding BSR, in a given cycle, if the resources allocated by the eNB to the UE/device are more than the aggregate data size in its transmit buffer, the unused space is referred to as "padding". If this padding space is large enough to accommodate a BSR then the UE can transmit a padding BSR. A BSR period of 5 ms is assumed in this work.

Note that if either a Regular or Periodic BSR is triggered it will be sent at the next earliest sub-frame in which the UE receives an UL grant from eNB along with data provided that there is enough room for both the data and the BSR. These BSRs have higher priority than the data. Figures 4-a and 4-b respectively show Two formats for the BSR based on its data structure: 1) a short BSR: is one-byte Mac Control Element (CE) where the UE/device can report the amount of data in UL buffer only for one specific LCG; and 2) a long BSR: is a 3 bytes MAC CE where the UE/device can report the amount of data in UL buffer for all four LCGs as well as their priority.

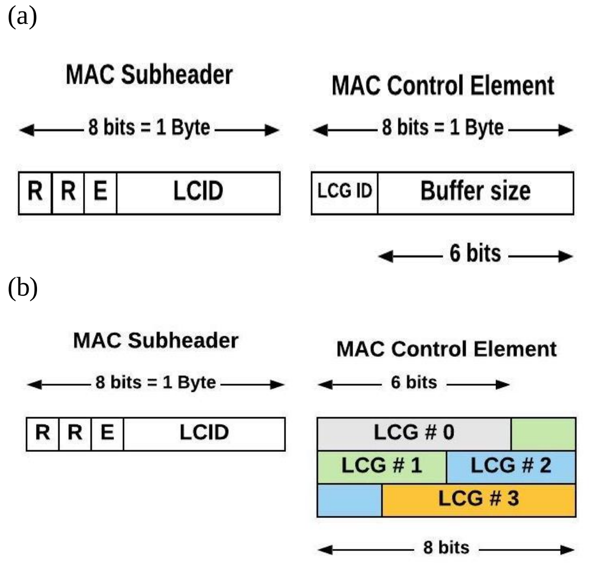


Figure 4. BSR format. (a) Short BSR and (b) Long BSR

B. QoS Model

The QoS model is based on the logical concept of an “EPS bearer,” where “bearer” denotes a reasonable IP transmission route between the UE and the mobile core network with explicit QoS parameters (capacity, delay, packet loss error rate, etc.). A unique QoS class identifier (QCI) is assigned to each bearer by the network and is composed of a radio bearer and a mobility tunnel. Bearers are composed of two categories: guaranteed bit- rate (GBR) and non- guaranteed bit- rate (non-GBR) bearers. A GBR bearer is characterized by a guaranteed bit-rate (GBR) and maximum bit-rate (MBR). UE shares an Aggregate Maximum Bit Rate (AMBR) in case of multiple non-GBR bearers in the same UE. As shown in Table I, the 3GPP specifications define nine standard QCIs, each QCI is characterized by bearer type (GBR versus non-GBR), priority, packet delay, and packet error loss rate.

TABLE I. QCI TABLE

QCI	Bearer Type	Priority	PDB (ms)	PLR	Example
1	GBR	2	100	10^{-2}	VoIP call
2		4	150	10^{-3}	Video call
3		3	50	10^{-6}	RT Gaming
4		5	300	10^{-3}	Vid stream
5	Non-GBR	1	100	10^{-6}	IMS Signal
6		6	300	10^{-3}	Video
7		7	100	10^{-6}	Gaming
8		8	300	10^{-6}	Buffer Streaming
9		9	300	10^{-6}	

3. THE SYSTEM MODEL

In this paper, we considered A 20 MHz LTE type-I system. As shown in Figure 5, a 2.5 km radius single cell base station is communicating with numerous fixed smart devices (experience a time invariant channel) and mobile UEs concurrently. These devices/UEs are randomly distributed in the cell coverage. In the simulation environment settings, M2M devices are abstract devices, which might denote any measurement, controlling, and regulation function(s) for any IoT application including strategic services. In order to implement the simulation environment, we assumed that each UE/device within the cell has its own channel conditions, and the eNB has perfect knowledge about channel conditions.

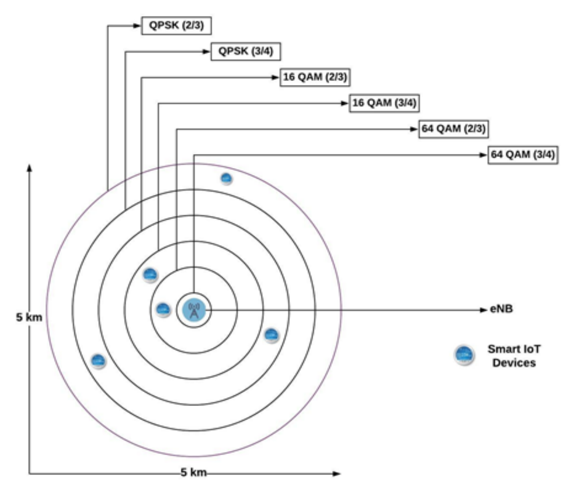


Figure 5. The modeled system

As shown in Table II, M2M applications are modelled using four different smart grid applications. APP1, APP2, and APP3, are strategic applications with strict Packet Delay Budget (PDB) and extraordinary reliability requirements. On the other hand, APP4 models an application with relaxed latency and reliability requirements, e.g., smart meters (SMs). Mission-critical APP1 models PMUs, which generate fixed length messages at regular intervals (constant bit rate). Note that the PDB value specified in table II is defined as the time interval between the times the packet entered the device transmit buffer to the time when the packet was transmitted to the eNB (i.e., it is not an E2E latency).

TABLE II. M2M TRAFFIC CHARACTERISTICS

M2M Apps	Packet Size (Byte)	Inter arrival time (ms)	# devices	PDB (ms)	Uplink Load (Mbps)
APP 1	100 Fixed	20 Fixed	600	20	24
App 2	A mean 100 Exp.	20 Exp.	600	40	24
App 3	A mean 100 Exp.	40 Exp.	600	60	12
App 4	125 Fixed	(100 - 500) Unif.	600	500	1.2 - 6

PMUs continuously generate 100 bytes fixed length packets (including IP and UDP overhead) at regular interval of 10 ms, 16.6 ms, 20 ms and 100 ms (Basu, 2016). These intervals are determined by the sampling rate at which the measurements are scheduled. These intervals are different based on the requirements of the control applications and the frequency of the power cycle. Values of 100 Hz, 60 Hz, 50 Hz, and 10 Hz are currently used (Basu, 2016). This work assumes a 50 Hz for both the power cycle and phasor sampling period. PMUs latency requirements reported in the literature, varies between 8 ms and 100 ms (61850-5, 2003) ((SUNSEED), 2015). This is synchronous with the real-time control system requirements.

Mission critical APP2 and APP3 modelled as Event-Driven applications in which data is sent to the server only when an event occurs in the monitored environment and are provisioned using typical dynamic scheduling. As shown in Table II, their packet sizes as well as inter-arrival times are distributed according to an exponential distribution with a mean of 100 bytes. The lowest priority App4 simulates Time-Driven application (SMs), where SM devices send data to the server at regular time intervals. The transmission interval of each Time-Driven device was uniformly distributed between 50 and 500 ms. All devices send their payloads (including the 28 bytes IP/UDP header) in an unsynchronized manner. Traffic parameters used to model typical H2H services are shown in table III.

TABLE III. H2H TRAFFIC CHARACTERISTICS

H2H Apps	Inter arrival time dist.	# Users	Data Rate (Kbps)	Uplink Load (Mbps)
Voice	Two states Markov	30	12.2	0.366
Video	Truncated Pareto	30	64	1.92
BE	Self-Similar	30	400	12

Uplink LTE utilizes a single carrier frequency division multiple access (SC-FDMA), a UE/device is granted an adjacent number of resource blocks (RBs). An RB contains 12 contiguous subcarriers (180 kHz) in the frequency domain and 1 ms (whole sub-frame) in the time domain. For the dynamic scheduling, every sub-frame, eNB computed the resource allocation for the UEs/devices and then signaled it to the UEs/devices via UL resource grants. These grants include a contiguous set of RBs allocated to the UE/device along with the modulation and coding scheme (MCS) as depicted in table IV.

TABLE IV. MCS ZONES

Modulation Rate	Coding Rate	SNR (dB)	RB Rate (kbps)	RB Rate (Bytes)
64 - QAM	(3/4)	22	756	94.5
64 - QAM	(2/3)	14.1	672	84
16 - QAM	(3/4)	10.3	504	63
16 - QAM	(2/3)	5.9	448	56
QPSK	(3/4)	4.3	252	31.5
QPSK	(2/3)	6.7	224	28

The simulation parameters utilized in this paper are summarized in table V.

TABLE V. SIMULATION PARAMETERS

Simulation Parameter	Value
System Bandwidth	20 MHz
Number RBs	100 RB
Number of Subcarriers	1200
OFDM symbols	14
Cyclic prefix	Normal
Simulation Time	1 Seconds
No. of M2M devices	2400
No. of H2H users	30
Number of MCS-Zones	6 zones
Modulation Schemes	64 - QAM, 16 - QAM and QPSK
Coding Schemes	(3/4) and (2/3)
Channel Model	FGN Multipath Fading model
Pathloss Model	$L(d) = 128.7 + 10\log(d)$
Carrier Frequency	2 GHz
Flows per user/device	3 Connections per H2H user 1 connection per M2M device

4. PROPOSED HYBRID UL SCHEDULING ALGORITHM

Since the focus is on commercially deployed 4G LTE systems, the proposed UL scheduling algorithm must fully conform to 4G LTE signaling and QoS standards. Thus, improvements introduced beyond Release 8 standards are not considered in this work. The hybrid-scheduling algorithm utilizes a typical LTE's dynamic scheduling for supporting H2H services as well as M2M applications (App2, APP3, and APP4) and Semi-Persistent Scheduling (SPS) for mission-critical IoT applications that always require persistent radio resource allocation at a regular interval (M2M APP1/PMUs).

A. Semi-Persistent Scheduling

The UE/device is typically dynamically scheduled on a per sub-frame basis, with the control information signaled on the Physical Downlink Control Channel (PDCCH). In this case, the UE/device is addressed using the cell radio network temporary identifier (C-RNTI). On the other hand, the UE/device may also receive a semi-persistent grant/allocation where the UE/device is addressed using the SPS-RNTI. In this case, the scheduling control information is signaled once via the PDCCH. The UE/device is pre-configured by the eNB with an SPS-RNTI and a periodicity. Once pre-configured, and the UE/device receives an allocation using the SPS-RNTI (instead of the typical C-RNTI), then this one allocation would repeat according to the pre-configured periodicity (Ahmadi, 2014). This same configuration is used until modified or released. Thus, the UE/device is not required to request resources each sub-frame, saving substantial control plane overhead.

The semi-persistent scheduling implies that the eNB can change the resource allocation type or location if required, for instance, for link adaptation. If a dynamic grant is received in the sub-frame marked for SPS data, the UE/device uses the radio resource indicated by dynamic scheduling at that sub-frame and does not use the radio resource configured by SPS. The dynamic grant takes precedence (Ahmadi, 2014).

It is assumed that each PMU device is configured with SPS-RNTI. Depending on the device location, eNB assigns a fixed number of RBs (e.g., 1, 2, 3 or 4) which is/are equivalent to the fixed PMU packet size (100 bytes), and periodicity of 20 sub-frames. Because there are 600 PMU devices, therefore, we divided them into 20 groups, each group of 30 devices. These devices were configured with a specific offset within the 20 sub-frames period such that it must wait for its specific offset sub-frame to transmit its data. Since the PMU devices are fixed, the RB allocations and MCSs remain fixed for the current SPS configuration. If any radio link condition changes, a new allocation (SPS configuration) will have to be sent on PDCCH. Any HARQ re-transmission will be separately scheduled using normal dynamic scheduling (Ahmadi, 2014).

B. Dynamic Scheduling

The classic approach of mapping M2M applications to a newly introduced set of QCIs (radio bearers) necessitates introducing new LCGs, which requires modifications/ changes to the current LTE signaling mechanisms and QoS standards. Thus, we do not pursue this approach. The eNB RRM module is a critical component of the scheduling process since it performs the bearer control function that configures parameters that are specific to the uplink bearers. The RRM bearer control function manages the UE/device queue length via the PDCP discard timer, which is configured based on the PDB associated with each Application. Therefore, if there are any packets delayed beyond the allowed PDB limits, while waiting to be scheduled, are dropped.

The dynamic scheduling algorithm works as follows and as summarized in table VI.

1) Assign each M2M or H2H application (connection request) to one and only one of the nine LTE standardized QCIs (radio bearer).

2) RRM groups the data and signaling bearers having common QoS requirements into LCGs (up to four per UE/device).

3) Assume the following grouping:

- LCG 0 (data radio bearers (DRBs) with QCI 5 and QCI 3 for time-critical M2M APP1, respectively)
- LCG 1 (DRB with QCI 1 for voice call and QCI 2 for M2M APP2)
- LCG 2 (GBR DRB with QCI 4 for H2H video and QCI 7 for M2M app3)
- LCG 3 (non-GBR DRBs with QCI 6, and QCI 9 for best effort traffic and M2M APP4, respectively).

Note that within LCG 0, DRB of M2M APP1 has higher priority than that of M2M APP2 As shown in figure (6).

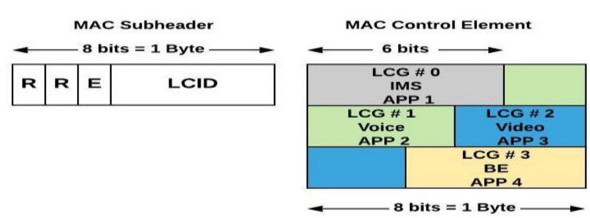


Figure 6. Mapping of QCI bearers to LCG

4) A classic UL scheduler orders UEs/devices connection requests based on the priority of the QCI mapped to a given application connection. The problem with this approach is that the UE/device reports to the eNB the size of the buffer awaiting transmission per LCG (group of QCIs). The eNB responds with per-LCG grant to UE/device. This kind of grouping permits the scheduling rules to be applied per LCG rather than per bearer/QCI. However, in the proposed algorithm, because RRM configures the Priority, PDB, and Prioritized Bit Rate (PBR) is done per uplink bearer, not per UE/device. UE/device utilizes these parameters to distribute the received uplink grant from eNB among bearers within LCG.

5) The PBR is allocated in proportion to the GBR rates. The principals of a token bucket algorithm is used to

calculate the number of tokens credited to a given bearer, where every bearer is credited a number of tokens equivalent to PBR. Within a LCG, RRM allocates priority to the bearer as per the QCI priority. The received grant is allocated to the bearer with highest priority (M2M APP1) until all tokens are consumed, followed by another bearer in priority (M2M APP2) until tokens of all bearers in LCG 0 are served. Same steps are repeated within LCG 1, LCG 2, and finally within the lowest priority LCG 3, until either all resources are allocated, or bearers are served.

TABLE VI. THE PROPOSED ALGORITHM

The

1. *Map each M2M and H2H connection to QCI as given in table I.*
2. *Assign connections with the same characteristics to the same LCG in the long BSR.*
3.
   a) *LCG0 contains (IMS and M2M App1)*
   b) *LCG1 contains (Voice and M2M App2)*
   c) *LCG2 contains (Video and M2M App3)*
   d) *LCG3 contains (BE and M2M App4)*
4. *UL scheduler order the connections based on their priority.*
5. *After the eNB assign the UL grant to the UE, UE should divide the grant among its bearers according to the PBR which is a fraction of GBR.*

The key shortcoming of this simple approach, which strictly follow the 4G LTE signaling and QoS standards, is that the eNB RRM knows the radio bearers contained in the group and their priorities but does not have status of an individual bearer. LTE standard does not support a mechanism that enables the UEs/devices to inform the eNB UL scheduler about the waiting time of uplink packets residing in their transmission buffers. Thus, for a given bearer (QCI), there are many M2M and H2H connection requests competing for transmission order and resources. There is no way to sort out these connection requests because they have the same QCI. This problem is more detrimental for the highest priority QCIs that support mission critical M2M applications.

This problem can be addressed if the UE/device transmits to eNB a second BSR that contains HOL packet delay per bearer, as has been reported in (Afrin, Brown, & Khan, A packet age based LTE uplink packet scheduler for M2M traffic, 2013), but once again the LTE signaling and QoS standards must be modified. The dynamic scheduling in this work addresses this problem by multiplying each UE/device connection request that have the same priority (QCI) by the following metric: (R_i/H_i), where (R_i) is the present data rate to be assigned to (UE_i or $device_i$) this cycle and (H_i) is the average assigned rate that is already granted to (UE_i or $device_i$) over the past 100 cycles. Multiplying by this metric only enhances fairness among M2M devices and UEs but does not address the critical timing problem.

5. Simulation Results

In the simulation, we have utilized two significant performance metrics: (1) the packet loss ratio (PLR) (2) the average communication link UL latency. To enumerate the communication link reliability measured between the communication source and destination, PLR is the most frequently utilized parameter in communication systems ((SUNSEED), 2015). In this paper, the PLR will be defined for a given M2M application since every M2M service has its own distinct performance requirements. PLR is defined as follows:

$$\text{PLR} = \frac{\#\text{ of packets generated by the Source} - \#\text{ of received packets with } T<PDB}{\#\text{ of packets generated by the Source}} \quad (1)$$

The UL latency is defined as the time interim between the time when the packet arrived at the device transmission buffer to the time when the packet was transmitted to the eNB (i.e., it is just from the device to the eNB and does not include processing delay; not an E2E latency). The simulation results will be compared with a typical reference model, e.g., proportional fairness (PF).

Figure 7 shows the average UL latency (300 devices per M2M application for a total of 1200 M2M devices) of the hybrid (dynamic QCI-based scheduling and SPS algorithms) model versus PF model. As anticipated, the UL latencies for both dynamic and SPS are less than those of the PF for all M2M applications. It can also be realized from Figure 7 that the UL latency for 300 PMUs (APP1) is about 50% of its 20 ms PDB. However, the UL latency for each of the other 2 mission critical applications (APP2 and APP3) is almost within the PDB range of 40 ms and 60 ms, respectively.

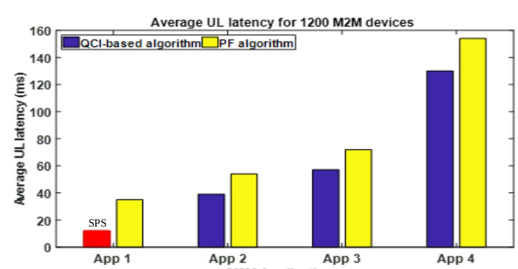


Figure 7. Comparison between QCI-based and SPS-based scheduling and PF

Figure 8 shows the average UL latency for 300 devices (same as Figure 7 but on a different scale) and 600 devices per M2M application for a total of 1200 and 2400 M2M devices, respectively. As the number of devices increase up to 600 per application, none of the strategic smart grid applications can meet its own PDB requirement. The UL latency for 600 PMUs (APP1) is almost twice of that of the allowed 20 ms PDB.

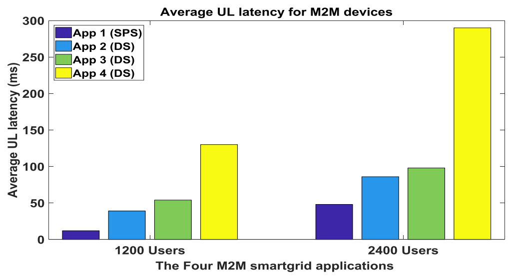


Figure 8. Average UL latency for each of the four M2M applications

Figure 8 depicts the average UL latency against the total quantity of M2M devices for all the four applications. As can be indicated from the Figure, the UL latency of the PMUs (APP1) is within the 20 ms PDB if the total number of devices does not exceed 1400 (350 PMU devices). The UL latency for each of the other two-time critical applications (APP2 and APP3) can meet the required 40 ms and 60 ms PDBs but for lower number of 1200 devices. As the number of total devices increase above 1500, the UL latencies for all applications increase rapidly and their performances are no longer satisfactory.

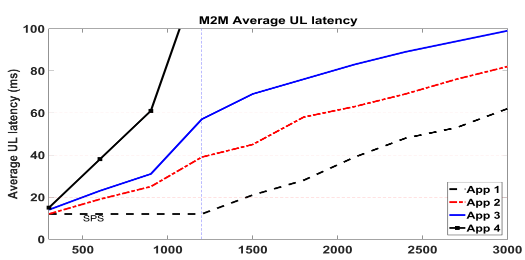


Figure 9. Average UL latency vs. number of M2M devices

Figure 10 illustrates the PLR against the total amount of M2M devices for all the four services. As can be seen from the Figure, the PLR of the PMUs can be as low as 10^{-6} but only if the total of devices does not exceed 800 devices (200 PMU devices). This is a significant result as it clearly validates that strategic APP1 (PMUs) may satisfy just a distinct performance metric (meets PDB latency requirement) for 350 PMU devices (see Figure 9). To simultaneously support both high-reliability (10^{-6} PLR) and low latency, the number of supported devices drops to 200 PMUs. Same trend is applicable to both APP2 and APP3.

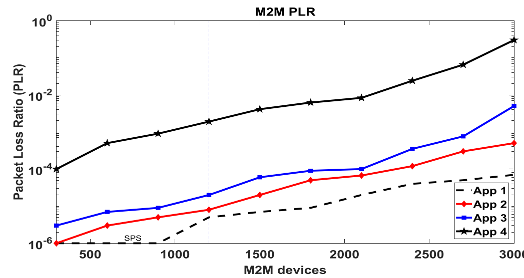


Figure 10. PLR vs. number of M2M devices

Figure 11 demonstrates the average UL latency versus the total number of H2H users for the three H2H services. It can be perceived from the Figure that Voice and video services can each scarcely meet its corresponding PDB for a total number of 30 H2H users and only 1200 M2M devices. Figure 12 shows the average UL latency versus the PMU packet size for 300 and 600 PMU devices. As can be seen from the Figure, for a total of 300 PMU devices, PMUs can't meet its 20 ms PDB as the packet size exceeds 140 bytes. As the number of PMU devices increase up to 600, the maximum packet size that cam meet the 20 ms PDB is about 60 bytes.

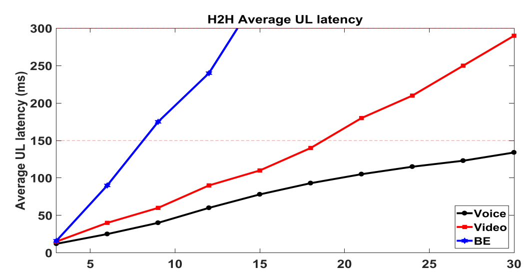


Figure 11. Average UL latency vs. number of H2H users for 1200 M2M devices

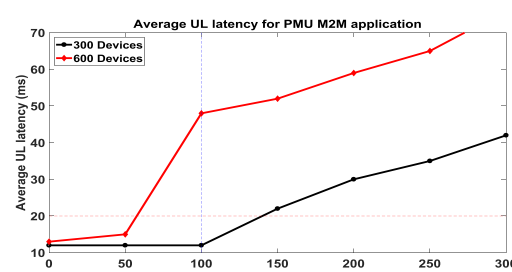


Figure 12. Average UL latency vs. PMU packet size

Figure 13 displays the average UL latency for H2H Voice and Video applications for the 30 UEs versus the total number of M2M devices. As can be seen for the Figure, both applications cannot meet their corresponding PDBs if the total numbers of M2M devices exceed 1200, in total agreement with the results of Figure 11.

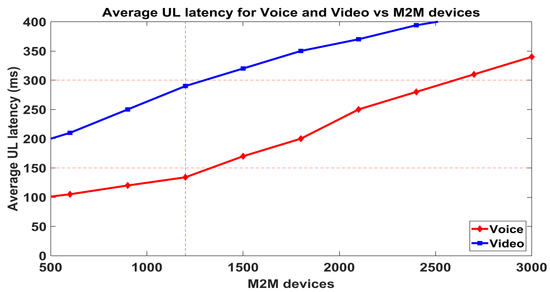


Figure 13. Average UL latency for Voice and Video versus number of M2M devices

6. Conclusion

This work has proposed and devised a simple hybrid LTE UL scheduling algorithm. This scheduling algorithm exploits a typical LTE's dynamic scheduling for supporting H2H applications as well as M2M applications. It also utilizes a Semi-Persistent Scheduling (SPS) to support mission-critical IoT applications that always require persistent radio resource allocation at a regular interval. The simulation results designate that existing commercial 4G LTE networks have the potential to adequately support some of the evolving strategic smart grid services including PMUs which necessitates 20 ms latency. The number of supported devices that can adequately meet such latency (PDB) requirements is about 300 devices per each of the four supported M2M applications along with few tens of H2H users.

To simultaneously meet high reliability (PLR = 10^{-6}) and low latency, the total number of supported PMU devices drops to almost one-half. If achieving PLR $< 10^{-6}$is the criteria for ultra-high reliability, then commercial 4G LTE networks cannot support both ultra-high reliability and low latency concurrently.

In this work, 20 ms PDB is assumed which only considers the communication link delay within the Radio Access Network (RAN), i.e., device-to-eNB. To be more realistic, E2E delay that takes into account application level processing latency as well as latency within the mobile core which would be in the range of about 50-100 ms. Thus, a more realistic estimate is to claim that current commercial 4G LTE networks have the potential to adequately support some of the developing strategic smart grid services (or any other similar IoT applications) including PMUs, with moderate E2E latency requirements in the range of 50-100 ms and high reliability.

The realistic results of this work can be utilized by industrial firms and utilities, which are planning to utilize commercial 4G LTE networks for supporting their private IoT services, as initial guidelines to ensure that LTE can support the performance requirements of these applications.

References

C. Beard, "High Reliability 4G and 5G Cellular Wireless Services for Smart Cities," in IEEE smart cities ISCW-KC-2016, Kansas city.

F. B. a. K. Basu, "Performance Evaluation of Time-Critical Smart Grid Applications," in Proceedings of the Eleventh International networking conference (INC), Frankfurt, 2016.

A. M. T. M. S. a. H. H. N. Abu-Ali, "Uplink Scheduling in LTE and LTE-Advanced:Tutorial, Survey and Evaluation Framework," IEEE COMMUNICATIONS SURVEYS & TUTORIALS, vol. 16, no. 3, pp. 1239-1265, 2014.

A. E. Mostafa and a. Y. Gadallah, "A statistical priority-based scheduling metric for M2M communications in LTE networks," IEEE Access, vol. 5, pp. 8106 - 8117, 2017.

A. S. Alexiou and a. A. Lioumpas, "Uplink scheduling for Machine-to-Machine communications in LTE-based cellular systems," in IEEE GLOBECOM Workshops (GC Wkshps), Houston, TX, USA, 2011.

N. Afrin, J. Brown and a. J. Y. Khan, "Performance analysis of an enhanced delay sensitive LTE uplink scheduler for M2M traffic," in Australasian Telecommunication Networks and Applications Conference (ATNAC), Christchurch, New Zealand, 2013.

A. E. a. Y. Gadallah, "BAT: A Balanced Alternating Technique for M2M Uplink Scheduling over LTE," in 81st Vehicular Technology Conference (VTC Spring), Glasgow, UK, 2015.

K. W. a. Y. T. Y. Hsu, "Enhanced cooperative access class barring and traffic adaptive radio resource management for M2M communications over LTE-A," in Asia-Pacific Signal and Information Processing Association Annual Summit and Conference, Kaohsiung, Taiwan, 2013.

S. Lien, K. Chen and a. Y. Lin, "Toward ubiquitous massive accesses in 3GPP machine-to-machine communications," IEEE Communications Magazine, vol. 49, no. 4, pp. 66 - 74, April 2011.

I. A. a. S. Venkatesan, "A QoE preserving M2M-aware hybrid scheduler for LTE uplink," in International Conference on Selected Topics in Mobile and Wireless Networking (MoWNeT), Montreal, QC, Canada, 2013.

N. R. A. C. K. V. S. a. B. R. T. M. Giluka, "Class based dynamic priority scheduling for uplink to support M2M communications in LTE," in IEEE World Forum on Internet of Things (WF-IoT), Seoul, South Korea, 2014.

T. d. Andrade, C. Astudillo and a. N. d. Fonseca, "Impact of M2M Traffic on Human-type Communication Users on the LTE Uplink Channel," in 7th LATINCOM, Arequipa, Peru, 2015.

Y. H. C. X. a. L. H. S. Zhenqi, "Research on uplink scheduling algorithm of massive M2M and H2H services in LTE," in IET International Conference on Information and Communications Technologies (IETICT 2013), Beijing, China, 2013.

J. Brown and a. J. Y. Khan, "Predictive resource allocation in the LTE uplink for event based M2M applications," in IEEE International Conference on Communications Workshops (ICC), Budapest, Hungary, 2013.

A. A. a. G. Miao, "Lifetime-aware scheduling and power control for M2M communications in LTE networks," in Proceeding IEEE Vehicular Technology Conference (VTC-Spring), Glasgow, UK, 2015.

S. R. Y. J. N. H. a. M. Z. W. Y. B. Chen, "'an energy- efficient scheduling algorithm for real-time machine-to-machine (M2M) data reporting," in Proceedings of IEEE Global Communications Conference (GLOBECOM),, Austin, TX, USA, 2014.

A. A. a. A. Aghvami, "On Radio Resource Allocation in LTE Networks with Machine-to-Machine Communications," in IEEE 77th Vehicular Technology Conference (VTC Spring), Dresden, Germany, 2013.

"5G Ultra-reliable low-latency communications," IEEE Network Magazine (Special Issue), vol. 32, no. 2, 2018.

J. B. a. J. Y. Khan, "Performance analysis of an LTE TDD based smart grid communications network for uplink biased traffic," in IEEE Globecom Workshops, Anaheim, CA, USA, 2012.

3. T. V. 36.211, "Evolved Universal Terresterial Radio Access (E-UTRA): Physical channel and modulation Release 8," 2009-12.

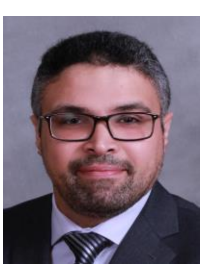
J. B. a. J. Y. Khan, "Performance comparison of LTE FDD and TDD based Smart Grid communications networks for uplink biased traffic," in IEEE Third International Conference on Smart Grid Communications (SmartGridComm), Tainan, Taiwan, 2012.

S. Ahmadi, LTE-Advanced A Practical Systems Approach to Understanding the3GPP LTE Releases 10 and 11 Radio access technologies, Elsevier, 2014.

I. 61850-5, "Communication networks and systems in substation- Part 5: Communication requirements for functions and device models," International Electrotechnical Commission, Geneva - Switzerland, 2003.

S. a. r. n. f. s. e. d. (SUNSEED), "D3.1 Traffic modelling, communication requirements … for real-time smart grid control. Version2.0," 2015.

N. Afrin, J. Brown and J. Y. Khan, "A packet age based LTE uplink packet scheduler for M2M traffic," in 7th International Conference on Signal Processing and Communication Systems (ICSPCS), Carrara, VIC, Australia, 2013.



Ahmed Hassebo is a visiting Assistant professor at Electrical and Computer Engineering department in Purdue University Northwest. Dr. Hassebo has been awarded MPhil and PhD degrees of EE from The City College of The City University of New York in 2016 and 2019, respectively. He also awarded the BSc of EE from Al-Azhar University, Egypt. His research interests including 4G/5G dynamic bandwidth allocation algorithms, and IoT mission critical applications.

Sumeet Chaudhary is a Visiting Assistant Professor in the Department of Electrical and Computer Engineering. He has earned his PhD. in Electrical Engineering from the University of Cincinnati. His dissertation involved developing a lightweight Electromagnetic Motor. The approach was to use composite manufacturing technology to reduce "touch labor" and produce a device which is simpler to manufacture than using conventional metal lamination techniques.

Appendix

In this appendix, we would like to elaborate in explaining the resource block (RB) assignment method. As given in step # 5 in table.

The eNodeB converts the incoming bursts of data from every single connection to the appropriate instantaneous data rate using the following equation.

$$\boldsymbol{R_i^{new}} = \left(\mathbf{1}\ \boldsymbol{e^{-\frac{t_i^k}{N}}}\right)\frac{\boldsymbol{l_i^k}}{\boldsymbol{t_i^k}}\ \boldsymbol{e^{-\frac{t_i^k}{N}}}\ \boldsymbol{R_i^{old}} \quad (1)$$

R_i^{new} is the instantaneous data rate for i^{th} connection l_i^k *and* t_i^k is the length of time of k^{th} packet of i^{th} flow. N is a constant between 100 and 500 ms, we use N = 300 ms.

After the instantaneous data rate was obtained, the required number of RBs per flow can be calculated using the following method depending on the MCS zone:

$$\boldsymbol{Req.RBs} = \sum_{i=1}^{72} \boldsymbol{floor}\left(\frac{\boldsymbol{Instantenous\ data\ rate}}{\boldsymbol{MCS\ Zone\ Rate}}\right) + \mathbf{1}\ (2)$$

$$\boldsymbol{MCS\ Rate} = \frac{\boldsymbol{\#\ OFDM\ sym}}{\boldsymbol{TTI}} * \frac{\boldsymbol{\#\ Subcarriers}}{\boldsymbol{RB}} * \frac{\boldsymbol{\#\ bits}}{\boldsymbol{Sym}} * \#\ \boldsymbol{RB}\ (3)$$

$\#\ OFDM\ sym$ = 14 OFDM symbols per TTI (i.e., subframe), where TTI = 1 ms.
$\#\ Subcarriers$ = 12 Subcarriers per RB.
$\#\ bits$ = Number of bits per symbol
Depends on the modulation scheme