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Robust Cellular Connection-Based Smart Street Lighting System for Supporting Strategic IoT Smart City Applications

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ABSTRACT:

The Smart city incorporates information and communication technology (ICT) and the internet of things (IoT) services to enhance the efficiency of the resident-related city operations and services. Smart lighting systems are evolving as an essential infrastructure that can support a wide range of existing and future smart city application. Each smart streetlight is transformed into multi-sensor-equipped smart node. Such a sensor (hub) node capable of capturing and transmitting/receiving real-time data (digitally controllable nodes). A smart streetlight has sensors embedded and connected to the cloud. Globally, many cities are in the replacement phase of the legacy streetlights by low-power light-emitting diodes (LEDs) to reduce energy utilization, expenses, and carbon footprint. In addition, some of these cities are installing intelligent controls with these smart streetlights, enabling a robust smart connected outdoor lighting network that can serve as the foundation for future smart city infrastructure. A smart connected lighting network employs sensors, smart light controller (LC), communication network, data collection, and cloud software to enable remote control and monitoring of LED streetlights over the Internet.

This paper reports the performance of commercial point-to point (P2P) 4G long term evolution (LTE) cellular networks when used to provide robust connectivity among massive number of smart streetlight hub nodes and the cloud. Each smart streetlight hub node is assumed to be running simultaneously few basic lighting control services as well as smart city applications. Smart city applications range from strategic applications to relaxed latency applications. Strategic applications necessitate strict latency and reliability requirements, particularly, HD IP video surveillance cameras, however, the relaxed latency applications do not demand such strict requirements, for instance, the smart meter applications.

The Control Center (CC) located at the cloud is the lighting infrastructure management module, which commands/ configures each streetlight (e.g., light-on, light-off, dimming) and monitors the infrastructure operating conditions for maintenance functions. The information exchange between the CC and each streetlight takes place via a communication network. This network must provide adequate coverage throughout the whole area where the streetlights are deployed. A smart LED has embedded sensors along with smart LC (to activate the commands received by the CC and transmit the required information) and connectivity to the cloud.

I. Introduction

Many cities around the globe are in the process of replacing legacy streetlights with low-power LEDs in order to reduce energy use, costs, and carbon footprint. Some of these cities are also installing networking and intelligent controls with these LED streetlights, enabling a powerful smart connected outdoor lighting network that can serve as the foundation for future smart city infrastructure [1-4]. A smart connected lighting network uses wireless networking, smart light controller (LC), data collection and cloud software to enable remote control and monitoring of LED streetlights over the Internet.

Smart connected LED streetlights can support a wide range of sensors and smart city services utilizing the communications and power connections available on each light pole. Because light poles are located throughout a city, they are considered ideal spots for a wide array of sensors. For instance, an environmental sensor, public Wi-Fi access point, an electric vehicle (EV) charger or a security camera can easily be mounted on a street pole. Each streetlight is then turned into multi-sensor-equipped smart node, a ***sensor 'hub' node***, capable of capturing and transmitting/receiving real-time data (digitally controllable nodes). LED and smart streetlights are expected to reach 85% and 24% of the total streetlight market, respectively, by 2028. This will total a $50.4 billion market opportunity over the next decade [1]. Streetlights are now viewed as a critical asset to releasing billions of dollars in smart city potential [1].

A smart streetlight 'Hub' Node (HN) is defined here as a Light pole-mounted LTE enabled smart IoT module that houses and provides power and connectivity to compact multifunction sensors, where multiple sensors are integrated and packed into the module to monitor and detect multiple variables simultaneously. Hub nodes also have on-board 4G LTE cellular modems that provide each with a direct cellular connection to the cloud via the mobile carrier wireless network. They also have enhanced on-board processing for edge computing. HNs can also provide power and communications for additional advanced lighting and smart city sensors and IoT devices as the city's needs grow and change.

Specifically, each smart HN is initially expected to be equipped with fewer sensors to support basic lighting control services such as switch power to luminaire, control LED driver (On/Off/Dim) - and more sensors will be gradually added over time to support a multitude of overlaid smart city services and applications. Thus, each smart streetlight HN is expected to be running simultaneously many applications (multi-bearer devices) with diverging performance requirements ranging from mission-critical applications with stringent latency and reliability requirements (such as traffic light control and public safety HD cameras) to those that require support of massive number of connected devices with relaxed latency and reliability requirements.

Due to the massive volume of sensors and their data, robust connectivity technology is a prerequisite for success - coverage and reliability across the entire city is the key to a viable deployment of smart connected streetlight infrastructure and launching any successful smart city. Because cabling such a massive number of sensors and devices is cost prohibitive, wireless technology is the key and sole viable solution to the deployment of IoT-based networked intelligent street lighting systems. Most of the advertised smart connected lighting systems, however, utilize proprietary gateways to provide connectivity between smaller segments of streetlights and the gateway via low-bandwidth communications, such as a power line communication (PLC) or a local RF mesh network. However, this proprietary infrastructure is expensive and has limited utility [5].

Commercial Point-to-Point (P2P) Fourth Generation (4G) Long Term Evolution (LTE) is currently considered the most viable cellular technology that can provide the required direct connectivity between smart streetlights HNs and the cloud (via mounting LTE cellular modem on each light pole), which eliminates the need for proprietary gateways. The LTE cellular modem can be configured, depending on the applications, to support low or high data throughput. Although Low-power wide area (LPWA) cellular technology standard including narrowband LTE (NB-LTE) and LTE for Machines (LTE-M) are more cost effective, they are only suited to meet very basic data requirements for IoT applications with limited data needs and relaxed latency - and can't support a multitude of overlaid smart city applications.

Cellular-based Machine-to-Machine (M2M) communications is one of the key IoT enabling technologies with huge market potential for cellular service providers deploying LTE networks [6-9]. LTE, however, was originally designed and optimized to support traditional Human-to-Human (H2H)-based voice, video and data applications and was not intended for the support of M2M/smart city IoT applications, specifically mission-critical ones. Numerous quality of service (QoS)-based LTE Up Link (UL) scheduling algorithms for supporting M2M applications have been reported in the literature [6-15]. Most of these algorithms, however, were mainly optimized for M2M devices that support only a single-application (single-bearer devices), don't fully conform to LTE's signaling and QoS standards and were not intended for the support of mission critical IoT application, as they are not latency-aware [9].

Because the proposed smart streetlight HNs are running simultaneously few/many applications (multi-bearer devices), each with its own distinct set of performance and QoS requirements in terms of reliability, latency and bandwidth; adopting commercial 4G LTE to support such a massive number of streetlights HNs will certainly pose additional new challenges to the problem of radio resource management (RRM), specifically, LTE UL dynamic scheduling. To the best of our knowledge, there is almost no work available in literature that examines the feasibility or quantifies the performance of P2P 4G LTE-based smart connected streetlight systems. There are only few white papers and technical reports that present various deployment options [1-5].

This paper assesses the feasibility and quantifies the performance of commercial P2P 4G LTE cellular networks when used to provide robust connectivity between a massive number of smart streetlight hub nodes and the cloud. Each smart streetlight HN is assumed to be running simultaneously few basic lighting control services as well as smart city services and applications. These applications have diverging performance requirements ranging from mission-critical applications with stringent latency and reliability requirements (with particular emphasis on HD IP video surveillance cameras) to those that require support of massive number of connected devices with relaxed latency and reliability requirements. Because the aggregate UL traffic load of most of these IoT applications is typically higher than that of downlink (DL), we focus our analysis only on LTE UL performance.

To achieve our objective, we present a simple LTE UL scheduling strategy that fully conforms to LTE's signaling and QoS standards and builds upon two sequential scheduling algorithms, that is, intra-HN scheduling and inter-HN scheduling. The numerical results of this work can be used as initial guidelines to help industry and city officials, who are planning to rollout Smart connected streetlights network, in selecting the appropriate wireless connectivity technology.

The rest of this paper is organized as follows. Section II presents an overview of LTE QoS model and signaling mechanisms. Section III presents the system model. The Proposed inter-streetlight HNs and intra-streetlight HNs UL Scheduling Algorithms are presented in Section IV. The simulation results are illustrateed in Section V. Finally, conclusions are presented in Section VI.

II. OVERVIEW OF LTE QOS MODEL AND SIGNALING MECHANISMS

LTE QoS model is based on the logical concept of an "EPS bearer", which refers to a logical IP transmission path between the user equipment (UE) and the mobile core (4G evolved packet core (EPC)). An EPS bearer uniquely identifies packet flows (connection request/IoT application) that receive the same packet forwarding treatment between the UE and EPC. Each bearer (IoT application) is assigned one and only one QoS class identifier (QCI) by the network, which is always chosen based on the bearer priority, bearer packet delay budget (PDB) and bearer acceptable packet-error-loss rate.

The QCI is a scalar that is used within the access network to identify the QoS characteristics that the EPC is expected to provide for the IP service data flows [10-11]. LTE standards define nine standardized QCIs, each with its corresponding standardized characteristics including bearer type (GBR versus non-GBR), priority, PDB, and packet-error-loss rate [10-11]**.** There are two types of bearers: guaranteed bit- rate (GBR) and non-guaranteed bit- rate (non-GBR) bearers. A GBR bearer has a guaranteed bit-rate (GBR) and maximum bit-rate (MBR) while more than one non-GBR bearer belonging to the same UE/device shares an Aggregate Maximum Bit Rate (AMBR).

LTE standard defines two signaling messages, Buffer Status Report (BSR) and Scheduling Request (SR), which are used by the UE/device to request resources from the 4G enhanced base station (eNB). When a UE/device has data to transmit, it sends SR (during its pre-allocated slot) to the eNB on the Physical Uplink Control Channel (PUCCH). During the RRC connection setup, each UE/device is assigned a specific offset sub-frame within an SR period, and it must wait for its specific sub-frame to transmit its SR [16-18].

LTE standard (Release 8) specifies five different SR periods of 5, 10, 20, 40, or 80 ms [17] and shorter periods of 1 ms and 2 ms have been introduced in Release 9. In this work we assume SR period of 10 ms such that SR offsets are within the range 0-9 ms. Note that the SR does not contain information about the UE/device buffer status. Hence, the scheduler at the eNB must blindly assign initial resources (uplink grant) without detailed knowledge of buffer content. In this work we assume that the scheduler assigns a fixed size of bytes for each UE/device for the initial UL grant, which is converted to the appropriate number of physical resource blocks (PRBs) in the frequency domain, depending upon the UL channel conditions [10].

The UE/device utilizes the BSR to inform the eNB about the amount of buffered data as well as their priority. Because a UE/device may have quite a few radio bearers in its buffer, keeping the eNB informed of the status of such a large number of radio bearers (logical channels) will require considerable signaling overhead. The approach of a Logical Channel Group (LCG) was introduced by the LTE standard to reduce the signaling overhead. This approach maps a group of logical channels (with similar QoS requirements) to one of only four groups, each of which has a different priority level. An LCG is a group of logical channels identified by a unique 2-bit LCG ID. The mapping of a radio bearer (or logical channel) to a Logical Channel Group is done at radio bearer setup time by the eNB based on the corresponding QoS attributes of the radio bearers such as QCI.

The UE/device utilizes a long BSR to inform the eNB about the buffer size of each LCG (up to four LCGs), each of which has a different priority level (a short BSR is used if the UE/device queue has only one LCG). The scheduler utilizes the sum of all LCG buffers (total queue size) for allocating the radio resource to the

UE/device. Consideration of per-LCG priority and requirements are considered, but the radio resources are ultimately allocated per UE/device and are not allocated per-LCG or per radio bearer.

III. THE SYSTEM MODEL

This work assumes a 20 MHz LTE Frequency Division Duplex (FDD) system. A single cell eNB with 5-km radius is simultaneously communicating with 800-fixed smart streetlight HNs (experience a time invariant channel) that are randomly distributed around the cell coverage. The modeled system is intended for a residential/commercial area where the lights are on average 15-50 m apart. In the simulation environment setting, these 800-streetlight sensor HNs are abstract smart IoT devices and might represent measurement and/or monitoring and control functions for any IoT application including mission critical. Each streetlight HN is assumed to have its own channel conditions, and the eNB is assumed to have a perfect knowledge about channel conditions.

Since single carrier frequency division multiple access (SC-FDMA) scheme is the typical scheme utilized in LTE's UL direction, the Physical Resource Blocks (PRBs) allocated to a single user/HN in the UL direction must be adjacent to each other (contiguity constraint). A PRB is the minimum resource allocation unit. It contains 12 adjacent subcarriers (180 kHz) in the frequency domain and 1.0 ms (whole sub-frame) in the time domain. For the dynamic scheduling, the resource allocation is computed by the eNB every sub-frame (1.0 ms) and signaled to the devices via UL resource grants, which include the contiguous set of PRBs allocated to the terminal/HN along with the modulation and coding scheme (MCS) [10-11]. The simulation parameters utilized here are summarized in table I.

Table I. Simulation Parameters

Simulation Parameter	Value
System Bandwidth	20 MHz
# RBs	100
# Subcarriers	1200
Cyclic prefix	Normal
# of HNs	2348 (HNs)
# 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
Connections per UE/device	3 Connections per device (MB)

As listed in Table II, we selected four basic lighting control services and smart city IoT applications that span a wide range of use cases ranging from mission-critical applications with stringent latency and reliability requirements to those that require support of massive number of connected IoT devices with relaxed latency and reliability requirements. APP1 (HD IP video surveillance cameras) and APP2 model mission critical use cases with strict latency requirements (< 50 ms). APP3 (basic lighting control services) and APP4 (smart meters) model use cases with relaxed latency and reliability requirements. Note that the PDB values listed in Table II are defined here 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 end-to-end latency).

Table II. Traffic Characteristics

Apps	# of HNs	Mean Packet Size (Byte)	Mean Inter Arrival Time (ms)	Data Rate (kbps)	Total Load (Mbps)	PDB (ms)
App1	26	Max 1500 with Mean 1400 (Pareto)	11 (T Pareto)	1018.2	26.47	50
	26		22 (T Pareto)	509.1	13.23	
App2	748	50 (Exp)	20 (Exp)	20	14.96	20
App3	800	50 (Exp)	100 (Exp)	4	3.20	200
App4	748	100 (Unif)	100 (Unif)	8	5.98	500

To support basic lighting control services such as on-off commands, dimming, and scheduling, a motion detector sensor (for instance, Passive Infrared or Ultrasonic sensors) is mounted on each of the 800-streetlight hub nodes. The motion sensor detects pedestrians, vehicles and cyclists within the range of each streetlight, and then signals to the cloud server. The video surveillance cameras are mounted on just 52 streetlight HNs (only 52 HNs were chosen so that the aggregate 800 HN traffic demands do not overly exceed the total UL traffic demand that can be supported by a 20 MHz LTE system; see Table II). Each of the remaining 748-streetlight hub nodes supports three applications, APP2, App3, and App4. Note that each of the 52 video hub nodes supports only two applications, APP1, and APP3. Thus, the total number of IoT applications supported by the 800 sensor hub nodes = (748 hub nodes * 3 AAPs/node) + (52 hub nodes * 2 AAPs/node) = 2,348 IoT Applications.

We assume that IP cameras have DSP capabilities to support real-time video analytics on the camera. Once IP video surveillance cameras have connectivity to the cloud server, they can be remotely configured and managed from a central command center at the cloud. To capture a video feed, the IP camera must be configured for resolution, frame rate, and server IP address. To efficiently utilize the scarce radio link bandwidth, the frame rate and resolution could change at anytime.

We choose H.265 as the video compression codec as it reduces the bandwidth by about half. To address the problem of how the video stream handles changes in scene complexity, we further assume the use of smart codecs, which allows cameras to intelligently adapt compression for significant bandwidth reduction. Variable bit rate (VBR) is selected as the video streaming mode in order to accommodate the use of smart codecs. VBR allows the bit rate to vary but maintains a constant video quality level.

Because how video is streamed has a major impact on quality and bandwidth, we assume two different streaming scenarios. Under the first scenario, cameras record locally to, for instance, an SD card at full mainstream resolution but use a second sub-stream that is much lower resolution and frame rate for remote access, which is good enough to check on the camera or change a configuration. In the second scenario, large amounts of HD video streaming at full resolution captured by the wireless cameras are directly uploaded via UL 4G cellular modem to a control center at the cloud where the acquired videos can be archived, analyzed, and/or distributed. Almost every security camera has both the mainstream and sub-stream.

An Elementary Stream (ES) is the output of an MPEG/H.264/H.265 encoder and typically contains compressed digital video, compressed digital audio, digital data, and digital control data. To transmit these ESs across channel, they are first converted into Packetized Elementary Stream (PES) packets. These variable sizes PES packets are then encapsulated into a second stream of fixed smaller sized packets called Transport Stream (TS) packets, 188 bytes long (4 bytes header and 184 bytes of payload). These TS packets are what are actually transmitted across the IP network. This TS stream is then loaded into IP packets (Transport Stream over IP (TSoIP)). Assuming that IP packets have a 1500 byte MTU, and since TS packets are fixed at 188 bytes, only 7 TS packets can be encapsulated into an IP packet. The resulting IP packet is 1316 bytes, not including headers.

Note that encapsulating TS packets into the IP packet increases the rate of the TS stream as a result of the addition of headers (RTP/UDP/IP/MAC headers). We assume that half of the video surveillance cameras (26 cameras) are 1MP (1280*720) IP cameras that consume about 1 Mb/s per camera (assuming H.265 encoder) at full resolution (for the mainstream). Each of the remaining 26 surveillance cameras is assumed to be using a second sub-stream with lower resolution and frame rate, resulting in a digital bandwidth of about 500 Kb/s per camera.

IV. Streetlight Sensor Hub Node-based UL Scheduling Algorithm

LTE dynamic scheduling process is typically divided into 2 sequential phases: Time Domain (TD) scheduler followed by Frequency Domain (FD) scheduler [10-11]. Based on a priority metric, the TD scheduler selects a group of streetlight HNs for scheduling in the following cycle. The FD scheduler then gets the prioritized list and, based on the received BSR and channel quality of each HN, determines the number of PRBs that will be assigned to each listed HN.

In order to support the different QoS requirements of the 4 IoT applications, we assume that each IoT application (connection request/flow) is mapped into one of the nine LTE standardized QCIs (radio bearers). The data and signaling bearers with similar QoS requirements are then grouped by RRM (radio resource management module) into LCGs (up to four per HN). The following grouping are assumed (see Fig. 1): LCG 0 (data radio bearers (DRBs) with QCI 5 for time-critical IoT APP2), LCG 1 (DRB with QCI 3 for time-critical APP1), LCG 2 (non-GBR DRB with QCI 7 for APP3), and LCG 3 (non-GBR DRB with QCI 9 for APP4). It is important to emphasize that while per-LCG/bearer characteristics and requirements are taken into account, the scheduling decisions/radio resources, however, are ultimately made/allocated on a per hub node basis (not on a per LCG/bearer basis).

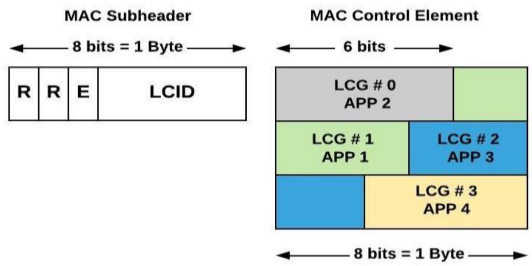

Fig.1. Mapping of QCI bearers to LCG

The TD scheduler utilized here prioritizes HNs based on typical dynamic weighted priority metric values generated for each active HN. The metric value of each active HN takes into consideration the collective QCI weights of its individual radio bearers (number of IoT applications supported by the HN) as well as its BSR queue size. The QCI weight assigned to an individual bearer is based on the bearer priority, bearer packet delay budget, and bearer acceptable packet loss rate. For the case of multi-bearer HNs considered here, the dynamic weighted priority metric for HN i at time t, $P_i(t)$, is given by [11]:

$$\mathbf{P_i(t)} = \frac{\mathbf{BSR_i(t)}}{\mathbf{BSR_{max}}} \sum\nolimits_{\mathbf{n}} \mathbf{W_{i,n}} \qquad (1)$$

BSR_i (t) is the BSR index of HN i at time t (range of pending data volume in the device buffer as defined in LTE standard [13]), BSR_{MAX} is the maximum BSR index = 63, and $W_{i,n}$ is the QCI weight of bearer n of HN i. Note that n =2 for each of the 52 streetlight HNs that support surveillance camera applications. Otherwise, n = 3 for each of the remaining 748 streetlight HNs. Equation (1) is also applicable in the case of a single-bearer HN (a HN that supports only one IoT application) but the summation of the n QCI weights is replaced with just a single bearer QCI weight.

The dynamic UL scheduler of streetlight HNs is based on two sequential schedulers, intra-HN scheduling and inter-HN scheduling [10-11].

i) Intra-HN scheduling:

The weighted priority of each HN with a non-zero queue load is calculated using Equation (1) above and all are sorted in decreasing order of weighted priority. The FD scheduler then allocates the appropriate number of PRBs (based on the received BSR and channel quality) to the selected list of HNs (intra-HN scheduling), continuing until all the list of devices are served or all the available PRBs in that sub-frame is exhausted, whichever comes first.

ii) Inter-HN scheduling:

Once the selected list of HNs get their assigned resources (via the uplink transmission resource grant message signaled on the PDCCH), each has to make an independent decision on how to efficiently distribute the assigned PRBs among its own LCGs/IoT applications (inter-HN scheduling), based on the priority and buffer size of each LCG. To achieve this objective, the LTE standard has introduced the concept of Logical Channel Prioritization (LCP), which will be used here [19-20]. The HN utilizes the LCP procedure (feature built in the device equipment) to efficiently construct its own MAC PDU. In the LCP procedure, which is based on the token bucket model, each logical channel/bearer is assigned a Priority Bit Rate (PBR) and a Bucket Size Duration (BSD).

RRM module configures the Priority, PBR, and BSD per uplink bearer. UE/HN uses these parameters to distribute the received uplink grant from eNB among bearers (IoT applications) within LCG. Within an LCG, RRM allocates priority to the bearer as per the QCI priority. The PBR is allocated in proportion to the GBR rates.

The PBR is the minimum data rate guaranteed for each bearer, which is proportional to its priority. The higher the channel priority is, the higher the value of PBR. Assigning a PBR for each logical channel guarantees that the order of their data transmission is based on the channel priority while concurrently avoiding starvation of lower priority ones. The upper bound in which a logical channel can accumulate the right to transmit is set by BSD. The maximum allowed accumulation cannot exceed the value set by the product: PBR*BSD, which is called a Bucket [19-20].

As shown in Figure 2, inter-UE/HN scheduling with LCP (constructing a MAC PDU) is implemented in two sequential phases [10, 20]. In the first phase, each radio bearer (logical channel) is served in decreasing order of priority, but only up to the data amount equivalent to the pre-assigned PBR value of the bearer. If any resources remain after all radio bearers have been served up to their PBR values, the second phase is triggered. In the second phase, all the radio bearers are served again in a strict decreasing priority order. In this phase, however, every radio bearer is either served until it has no more data to transmit or the assigned UL grant is exhausted, whichever comes first.

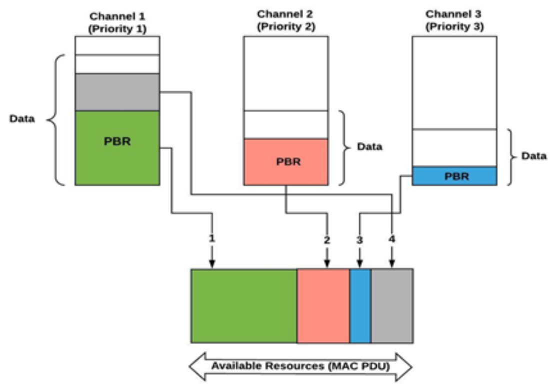

Fig.2. Logical Channel Prioritization (LCP)

V. Simulation Results

The Packet loss ratio (PLR) and the average communication link UL latency are the two key critical performance metrics for the two mission critical applications modeled here. The UL latency is defined here as the time interval between the times the packet entered the device transmission buffer to the time when the packet was transmitted to the eNB (i.e., it is not an E2E latency; just from the device to the eNB and does not include processing latency) [10]. The PLR is a typical parameter used in communication networks to quantify the communication link reliability measured on a particular protocol layer between the communication source and destination [10, 18]. The PLR is defined here for a given IoT application since every application has its own distinct performance requirements. PLR is defined as follows:

$$\mathbf{PLR} = \frac{\mathbf{\#\ of\ packets\ generated\ by\ the\ \ Source} - \mathbf{\#\ \ of\ received\ packets\ \ with\ T\ <\ PDB}}{\mathbf{\#\ of\ packets\ generated\ by\ the\ Source}}$$

Figure 3 shows the average UL latencies for both mission critical APP1 and APP2 versus the number of active streetlight hub nodes. As can be seen form the figure, as expected, the average UL latencies for both APPs increase with number of deployed streetlight HNs such that each APP can meet its own PDB requirement (50 ms/20 ms) for only a fraction of the total number of HNs supporting the APP. Figure 4 shows the percentage of streetlight HNs meeting their PDB requirements for each of the four IoT applications. As can be seen from the Figure, almost 90% and 100% of the total number of streetlights HNs running APP3 and APP4, respectively (with relaxed latency requirements), can meet their PDB requirements. On the other hand, as expected, the percentage of the streetlight HNs running mission critical APP1 (60%) and APP2 (50%) meeting their PDB requirements are significantly less.

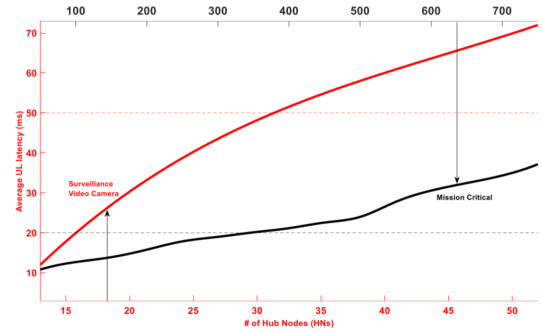

Fig.3. Average UL latencies for mission critical APP1 and APP2 versus the number of active streetlight hub nodes

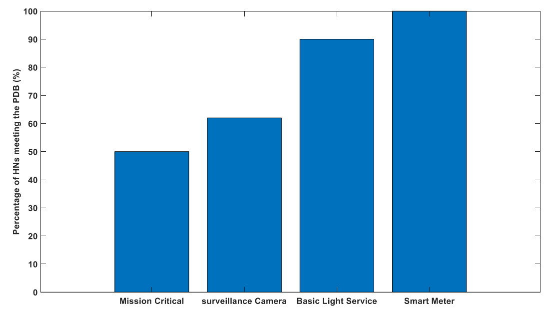

Fig.4. The percentage of streetlight HNs meeting their PDB requirements for each of the four IoT applications

Figure 5 shows the PLR for both mission critical APP1 and APP2 versus the number of active streetlight hub nodes. As can be seen from Figure 5, both APPs can meet an adequate reliability target, i.e., achieving a $\mathbf{10^{-6} < PLR < 10^{-5}}$ provided that the number of streetlight HNs supporting each APP can still meet its own PDB requirement (up to a maximum of 32 HNs for APP1 and 374 HNs for APP2). As the number of streetlight HNs supporting each APP exceeds the maximum number that meets the app's PDB requirement, the PLR starts to increase for both APPs but at a faster pace for APP1. It can also be seen from Figure 5 that none of the two APPs can meet the ultra-high reliability target, i.e., achieving a PLR < 10^{-6}. Because the video quality for H.264/H.265 (APP 1) is highly dependent on little or no packet loss, achieving a very low PLR, specifically for APP1 (HD IP video surveillance cameras), is a critical requirement.

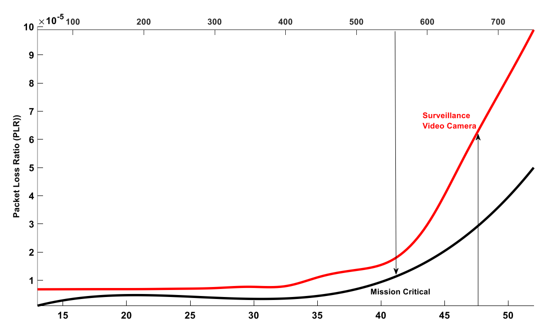

Fig.5. the PLR for both mission critical APP1 and APP2 versus the number of active streetlight hub nodes

VI. Conclusions

This paper has assessed the feasibility and quantified the performance of commercial P2P 4G LTE cellular networks when used to provide robust connectivity between a massive number of smart streetlight hub nodes and the cloud. A smart streetlight 'Hub' Node (HN) is defined here as a Light pole-mounted LTE enabled smart IoT module that houses and provides power and connectivity to compact multifunction sensors, where multiple sensors are integrated and packed into the module to monitor and detect multiple variables simultaneously. Each smart streetlight HN is assumed to be running few basic lighting control services as well as smart city services and applications, including mission-critical applications with strict latency and reliability requirements with particular emphasis on HD IP video surveillance cameras.

The simulation results indicate that current commercial 4G LTE systems have the potential to adequately support a massive number of smart streetlight HNs, where each is simultaneously running few basic lighting control and smart city services and applications, provided that these applications have relaxed latency (> 200 ms) and reliability requirements. On the other hand, if the applications supported by each HN include one or more mission-critical application(s) with strict latency (less than 50 ms) and reliability requirements, only a limited number of streetlight HNs can adequately be supported.

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