Utilizing LTE QoS Features to Provide Reliable Access Network for Cyber-Physical Systems

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Abstract—**Cyber-physical systems (CPSs) are a new paradigm of control systems where control, communication, and computation fields intersect. Applications of such systems are expected to play an important role in many domains in the future. This includes critical domains such as transportation and health domains. Hence, it is quite important for such systems to operate reliable. Moreover, many CPS applications are characterized by having different modes of operation along with different corresponding traffic patterns and communication requirements. All this requires reliable communication networks that provide not only quality of service (QoS) support but also flexibility to adapt according to the varying communication requirements of the application/user. On the other hand, recent cellular standards such as Long Term Evolution (LTE) offer higher QoS control compared to earlier cellular standards with the ability to differentiate traffic at both the service and user levels. In this paper, we evaluate the ability of LTE cellular technology under certain QoS and load conditions to provide reliable communications for CPS applications characterized by possessing different modes of operation along with different corresponding traffic patterns and communication requirements. Our evaluation results indicate the ability of LTE cellular technology to provide reliable and adaptable communications for CPSs when QoS is provided.**

I. INTRODUCTION

Intelligent control systems that are able to interact with physical processes and span wide geographical areas represent the expected evolution of the current and mostly local control systems. These systems are a composite of different technologies in the control, communication, and computation fields. A commonly used term to refer to such systems in the literature is cyber-physical systems (CPSs) [1], [2]. CPSs target, beside the normal monitoring and controlling functionalities, the optimization of the overall system with explicit computation capabilities between the different units. Over the last decade, many CPSs have been proposed along with studies estimating their traffic characteristics and/or communication requirements. One of the main requirements for CPSs as indicated in [3], [4], [5] is reliability. System reliability, as defined in [6], is the ability of the system to perform its tasks for a specific time and under the stated conditions. Moreover, the lack of timing predictability in existing best effort communication networks and the need for reliable communication networks to realize CPSs, especially in critical domains, were highlighted in [1], [4], [7]. Reliability of the communication network is usually represented in terms of the provided QoS by the network. As defined in [8], [9], QoS is the user satisfaction determined by the collective impact of service performance. Practically, QoS is a set of performance metrics such as latency, provided bandwidth or data rate, and packet loss rate. On the other hand, the wide spread of cellular communication with wide area coverage, ease of deployment, and low costs represents an attractive access network for CPSs. In this paper we limit the scope to LTE cellular technology (4G) only. Even though LTE technology has a very comprehensive inbuilt QoS features, they are not accessible in todays LTE enabled cellular networks by the users because of provider policies and, consequently, are not fully utilized. Our target is to evaluate the provided reliability by it under certain conditions regarding network load, provided QoS, and communication requirements of the CPS application. Hence, in this paper, the performance of one of the CPS applications with different communication requirements with regards to latency, data rate, and used transport protocol is evaluated over an LTE network and under specific load and QoS conditions.

The rest of this paper is organized as follows: In Section II, a summary of related work is given. In Section III we provide an overview about CPS and an example of a CPS application characterized by different modes of operation. Section IV illustrates the general architecture of LTE networks and their QoS features. The test setup used for the performance evaluation and the analysis of the obtained results are presented in Section V. In Section VI, we conclude the paper.

II. RELATED WORK

The need to provide reliable communication for CPSs has been considered in a number of papers. In [10], a preliminary wireless system for CPSs targeting low latency communication was proposed. A hybrid communication technology, combining power line carrier and zigbee technologies, to provide reliable communications in electric vehicle charging systems, was presented in [11]. Challenges of reliable communication for vehicular Ad hoc networks for intelligent transportation systems have been investigated in [12]. Transport protocols with improved reliability for CPSs were proposed in [13], [14]. In addition, the utilization of existing wireless communication technologies for CPSs has been either proposed or investigated. In [15], issues arising from LTE scheduling for M2M communications were inspected. The experienced time delay over LTE with regards to the requirements of future smart grids was presented in [16]. Utilization of wireless communication networks for monitoring of overhead transmission

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lines in power grids was proposed in [17]. Furthermore, traffic characteristics for a number of CPS applications have been also investigated. In [18], the general characteristics of some M2M applications have been presented. A number of smart grid applications along with their traffic characteristics and communication needs were investigated in [19]. Based on [17], the data requirements of the different sensors used for such overhead transmission lines monitoring system were presented in [20]. The above mentioned work addresses providing reliable communications for CPS either by 1) suggesting new communication protocols and systems which, beside being proposed for specific CPS applications, might take long time and require standardizations to be realized. 2) considering only the communication latency and overhead under normal base station (BS) traffic loads. 3) investigating the communication requirements of future CPS applications without relating them to the capabilities of existing communication technologies. In this work, we suggest the use of the existing LTE technology for CPSs rather than proposing new communication solutions. Unlike the above mentioned investigations of LTE, we evaluate its communication reliability with and without QoS support and under two traffic load conditions of the BS (minimal traffic load where only the data of interest are transmitted and full traffic load where other data of high volume beside the one of interest are transmitted). Moreover, we relate the provided reliability to the communication requirements of one exemplary CPS application.

III. CYBER-PHYSICAL SYSTEMS OVERVIEW

In this section, a brief description about the general architecture and the traffic characteristics of one exemplary CPS application are provided.

A. *General Architecture*

A CPS can be viewed as a group of interconnected autonomous components or units where services of each unit are visible to the other units of the system. Communications within each unit of the system is usually realized by local control networks while the communication between the units is realized over the Internet protocol. The general architecture of a CPS is shown in fig. 1. Here the different units cooperate and adapt their behavior to optimize the overall system operation. A single CPS unit, as depicted in the lower part of fig. 1, usually consists of the following entities: a computational entity to monitor and control the physical process, sensing and actuating entities to interact with the physical process, and finally the physical process.

B. *Traffic characteristics*

The wide variety of CPSs applications and their different traffic characteristics impose a challenge to consider all of them here. In addition, some of these applications, as indicated in section I, might possess varying traffic characteristics. As a result, we consider only one CPS application, namely, a wide area supervision system (WASS) for monitoring of overhead transmission lines in power grids. Overhead transmission lines, as shown in fig. 2, connect the generation plants along with the substations in the transmission domain to deliver power from the generation domain to the distribution domain of the power grid. These transmission lines usually span large distances that might reach up to 50 km and require support towers every 0.5 or 1 km depending on the terrains [17]. A WASS uses different types of sensors which are usually distributed in close proximity to the towers where data aggregation and transmission is handled by a more powerful node called data aggregation node (DAN). The DAN uses additional communication interface, beside the one employed to collect the data from the sensors, with a longer transmission range to send the collected information to nearby DANs, substations, or to the main monitoring center (MMC). The different sensor types for WASS along with their data requirements in terms of the data size per data point per sensing channel are provided in Table I. 5 modes of operation (traffic generation patterns) for each of the DANs were proposed in [17]. In the normal mode of operation, the sensed data is collected periodically and transmitted to the MMC with loose upper limit on network latency for data validity. In the urgent and user defined modes of operation, the sensed data might need to be collected at a higher frequency than in the normal mode and the transmission of the collected data might also need to be done at an equal frequency of the data collection. In addition, the MMC might request transmission of stored raw data (unprocessed data) over previous time intervals when abnormalities are detected. Finally in the backup mode, backups of sensor measurements with large data volumes are sent to the MMC.

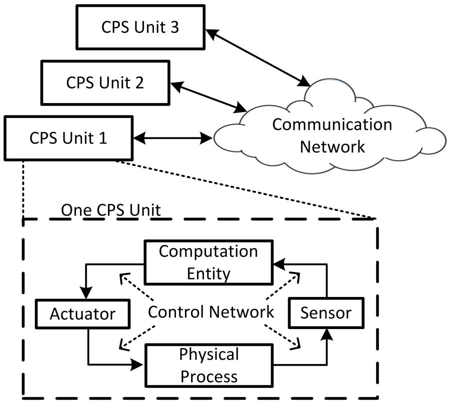

Fig. 1. General architecture of CPSs [21]

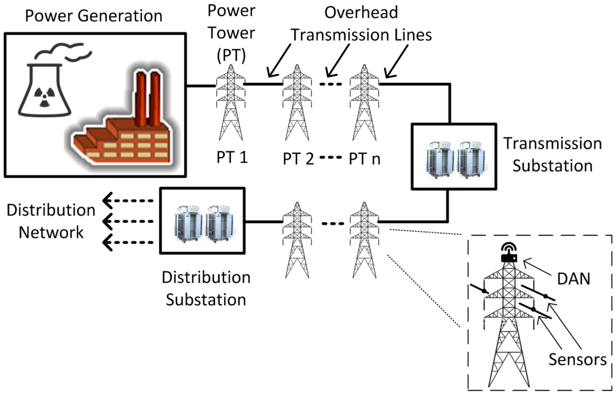

Fig. 2. Example of overhead transmission line system with WASS units[17]

TABLE I. WASS SENSOR TYPES AND THEIR DATA REQUIREMENTS [20]

Sensor Type	**Measurement**	**Data size (bytes/data point)**	**Data points**	**No. of channels**	**Sensing frequency (Hz)**
Magnetic field sensor	Current	4	1	2	10
	Magnetic field	16	4	2	10
	Power quality	16	4	2	10
Temperature sensor	Temperature	4	1	1	1
Strain sensor	Extension and strain	8	2	2	0.2
Accelerometers	Inclination	16	4	2	0.2
	Cable position	8	2	2	0.2

IV. BACKGROUND OF LTE

LTE network architecture and its QoS features are briefly presented in this section.

A. LTE Network Architecture

As shown in fig. 3, the LTE (Long Term Evolution) network, also called the evolved packet system (EPS), consists of two main parts. The first part is the radio access network (RAN) which is a group of inter-connected cellular BSs called evolved NodeBs (eNBs) that connect the user equipments (UEs) to the LTE network. The second part is the evolved packet core (EPC) which connects the UE to either another UE or another packet data network (PDN). The EPC consists of a number of entities including the mobility management entity (MME), the home subscriber server (HSS), the packet data network gateway (P-GW), and the serving gateway (S-GW). The different interfaces connecting these entities are also illustrated in fig. 3.

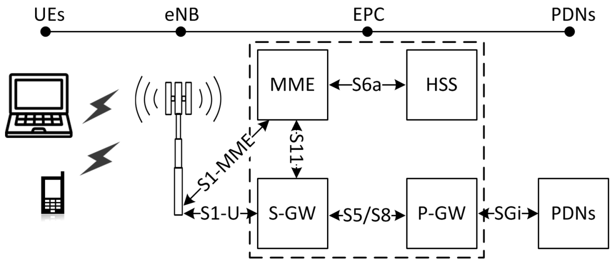

Fig. 3. General architecture of LTE networks

B. LTE QoS Features

In LTE, QoS parameters are applied to bearers, where a bearer is a virtual connection between the UE and the P-GW that determines the network configuration used to carry a set of user traffic. A bearer, commonly known as an EPS bearer, consists of three parts, the radio bearer between the UE and the eNB, the S1 bearer between the eNB and the S-GW, and the S5/S8 bearer between the S-GW and the P-GW. Upon UE connection for the first time, the LTE network assigns a default bearer along with an IP address to the UE. As the default bearer does not provide any QoS (only best effort), the LTE network establishes additional bearers, called dedicated bearers, when higher QoS than best effort is needed to carry the user traffic. In order to differentiate the user traffic and to provide different QoS levels using the bearers concept, LTE networks implement what is called packet filters, also known as traffic flow templates (TFTs). The TFT filters the user traffic into different service data flows (SDFs) based on one or more of the following: the IP address of the source, the IP address of the destination, the MAC (media access control) address of the source, the MAC address of the destination, and the protocol number. A packet filter is an uplink (UL) filter when applied at the UE while it is a downlink (DL) filter when applied at the P-GW. To illustrate this better, we consider fig. 4. As we can see, the user IP traffic consisting of 3 IP flows first arrives at the P-GW. After that, the IP flows are compared with the user TFTs at the P-GW and filtered into different SDFs. Based on the required QoS for each SDF, SDF 1 and 2 are carried over the dedicated bearer while SDF 3 is carried over the default bearer. Finally, these data flows are delivered to the UE and forwarded to their corresponding applications. The parameters used to determine the QoS [22] are the following:

- QoS class indicator (QCI): a scalar with a value ranging from 1 to 9 and determines the QoS characteristics values such as priority, packet delay budget, etc.
- Allocation and retention priority (ARP): a metric that determines the priority of the EPS bearer during congestion periods.
- Maximum bit rate (MBR): a parameter that specifies the maximum allowable bandwidth for an EPS bearer
- Guaranteed bit rate (GBR): a parameter that specifies the minimum guaranteed bandwidth for an EPS bearer.
- Access point name-aggregate maximum bit rate (APN-AMBR): a parameter that indicates the maximum allowable bandwidth for all non-GBR bearers connected to a UE and belong to one PDN.
- UE aggregate maximum bit rate (UE-AMBR): a parameter that indicates the maximum allowable bandwidth for all non-GBR bearers connected to a UE from different PDNs.

The QoS parameters are mainly set by the entities that perform the packet filtering (UE and the P-GW), for example, the P-GW set all the QoS parameters except the UE-AMBR. fig. 4 illustrates where the different QoS parameters are set and/or enforced by the different entities of the LTE system.

V. PERFORMANCE EVALUATION

The performance evaluation of the WASS using LTE network is presented in this section. We first introduce the test setup used and its lab realization. After that, we analyze the obtained results.

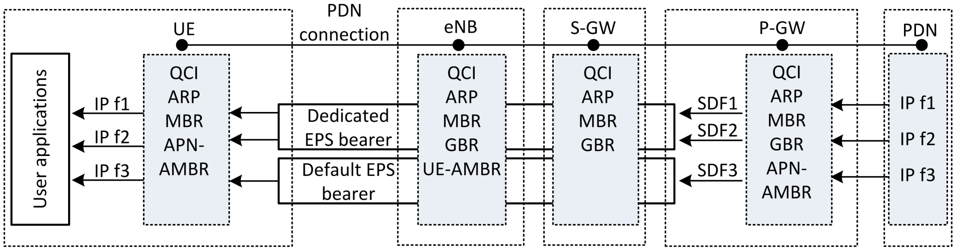

Fig. 4. LTE bearers and QoS parameters [23]

A. *Test Setup*

In this test setup, shown in fig. 5, we consider a number of wireless sensor nodes conducting different types of measurements such as current, magnetic field, temperature, etc., in the vicinity of a power transmission tower. The sensors send their measurements wirelessly to a DNA which, in turn, sends the collected data directly to the MMC using an LTE network. As our focus is on the reliability of the communication network rather than the efficient aggregation and processing of the data, we assume that the DAN sends the data as soon as it collects them. The lab realization of the above setup, as illustrated in fig. 6, use a cellular network emulator, namely Anritsu MD8475A, to emulate the LTE network in a controlled lab environment. The LTE emulator connects to a 2G/3G/4G router over the radio interface and to a data sink over a 1 Gbit/s Ethernet connection. As the performance bottleneck of cellular networks usually comes from the RAN, we limit our evaluation to this part of the LTE network. A test access point (TAP), commonly known as a network TAP, was used to capture and analyze the arrived traffic to the data sink. We also used two traffic generators that generate traffic in accordance to the urgent and the backup modes of the WASS mentioned in Section III-B, where the urgent mode traffic is characterized by varying communication requirements with regards to the communication latency, the desired throughput, and the used transport protocol. The LTE network parameters used in the emulator are listed in table II.

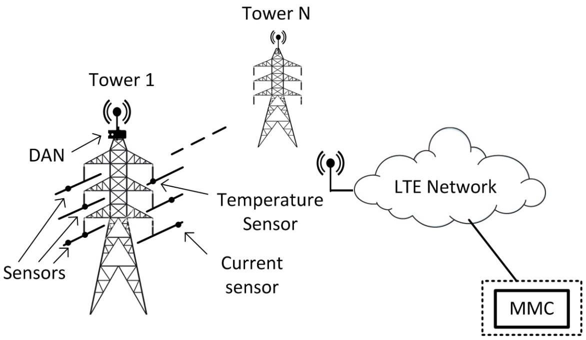

Fig. 5. Evaluation test setup

TABLE II. LTE NETWORK EMULATOR SETTINGS

Parameter	Selection
Duplex mode	Frequency division duplex (FDD)
Transmission mode (TM)	Single antenna (TM 1)
Downlink (DL) bandwidth	5 MHz
Uplink (UL) bandwidth	5 MHz
Modulation and Coding Scheme (MCS), (DL)	27
Modulation and Coding Scheme (MCS), (UL)	23
Number of Resource Blocks (NRB), (DL)	25
Number of Resource Blocks (NRB), (UL)	25

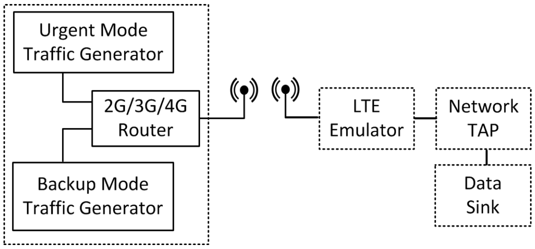

Fig. 6. Lab realization of test setup

B. *Analysis*

1) Scenario 1: In this scenario, the DAN sends current measurements that are collected from a magnetic field sensor to the MMC using UDP/IP protocols. The collection and transmission frequency of the data is set to 10 Hz (every 100 ms). The throughput of the urgent traffic for a period of 50 s and without QoS support is shown in fig. 7 (logarithmic values for both types of traffic were used). As it can be seen, once the backup traffic started and at a high volume, the throughput of the urgent traffic becomes intermittent and barley reaches its normal value. After that, we ran a second trial of this scenario, but with the urgent traffic differentiated and assigned a QCI of 3. The network resource type, priority, packet delay budget, and packet error loss rate of this QoS class, as provided in Table 6.1.7 in [22], are GBR, 3, 50 ms, and 10^{-3} correspondingly. In this trial, as shown in fig. 8 (using logarithmic values), the throughput of the urgent traffic remains almost constant even during the backup traffic transmission. We carried out similar trials to trial 1 and 2 to measure the maximum UL time delay experienced by the urgent traffic and the result is depicted in fig. 9. As we can observe, the maximum UL time delay with no QoS support reaches about 300 ms during active backup traffic. On the other hand, the maximum UL time delay experienced by the urgent traffic with QoS support was only 11 ms. The high values of the maximum UL time delay experienced during the backup traffic where no QoS was provided are mainly due to the capacity of the LTE eNB. By considering the UL MCS

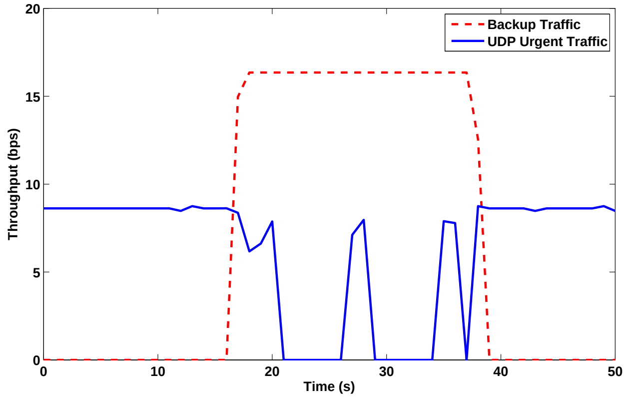

Fig. 7. Throughput of urgent traffic without QoS support

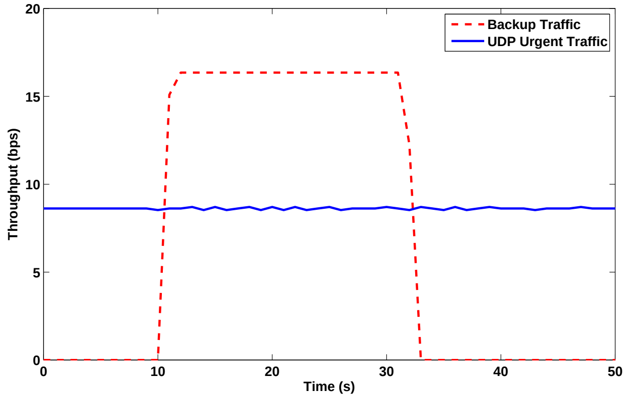

Fig. 8. Throughput of urgent traffic with QoS support

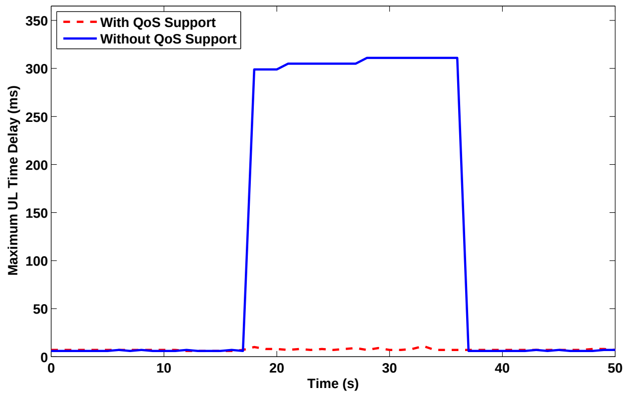

Fig. 9. Maximum UL time delay with and without QoS support

value in table II in this paper and using table 8.6.1-1 in [24], we obtain the corresponding transport block size (TBS) index value of 21. By using this value and the UL NRB value in Table II, we determine the corresponding TBS size value in table 7.1.7.2.1-1 in [24] with 12576 bits. Since we have only a single antenna rather than two, the number of UL transport blocks per 1 ms is equal to 1. Hence, the maximum physical data rate of the LTE eNB is given by:

$$Maximum\ data\ rate = TBS\ (bits) \times 1000\ (1/s) \approx 12\ Mbit/s \qquad (1)$$

On the other hand, the measured data rate at the network interface of the backup traffic generator was about 37 Mbit/s or 3.7 Mbit of backup traffic generated every 100 ms which is the interval between two consecutive urgent traffic packets. With no QoS support, there is no traffic differentiation and prioritization and the urgent traffic packets experience a high time delay prior transmission and is approximated by:

$$Time\ Delay = 3.7\ Mbits/(12\ Mbit/s) \approx 308\ ms \qquad (2)$$

It is clear that reliable communications provided by QoS is very essential to have reliable CPS that is able to function even if the access point (LTE eNB in this case) to the communication network or even the communication network itself become fully loaded.

2) Scenario 2: The use of either TCP or UDP to carry the traffic is an application dependent communication requirement. Hence, in this scenario we compare the throughput of the urgent traffic when it is carried by these two protocols under the QoS and load conditions specified in Scenario 1. Here, we consider the collection and transmission of temperature measurements generated by two temperature sensors at the frequency of 1 Hz (every 1 s). The data from one of the sensor is carried over UDP, while the data from the other sensor is carried over TCP. Both the UDP and TCP packets have the same size of 64 bytes (with enough payloads to carry the temperature measurements). As it can be observed from fig. 10, both types of urgent traffic (UDP traffic and TCP traffic) had the same and desired throughputs of 1 packet/s during the time intervals before the start of the backup traffic and after the activation of the dedicated bearers (starting QoS support). Where in the later interval, both types of urgent traffic were provided the same QoS (both were assigned a QCI of 3). During the time interval between the start of the backup traffic and before the activation of the dedicated bearers, the throughputs of both types of urgent traffic had degraded. It is also clear that the impact on the TCP traffic is much more than that on the UDP one. We carried an additional trial of this scenario where the UDP and TCP packets are generated at the same frequency used in trial 1 (1 Hz) and no QoS was provided for both, but for a longer time interval. As shown in fig. 11, the UDP traffic showed higher throughput compared to the TCP one over a 100 s period while the backup traffic was

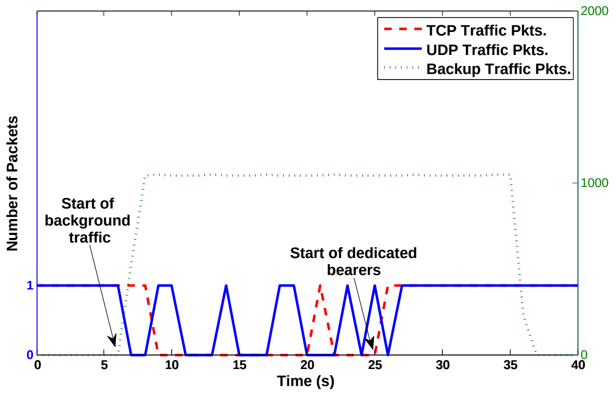

Fig. 10. No. of captured packets of UDP vs. TCP with and without QoS support

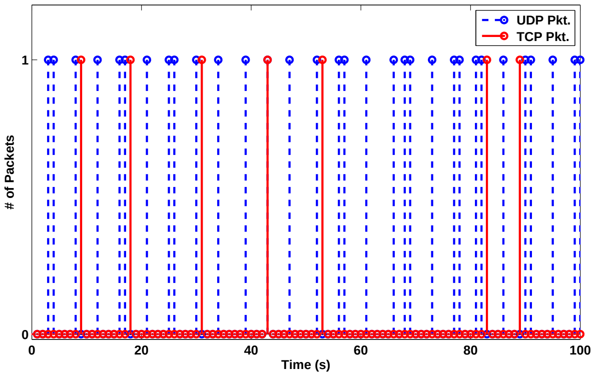

Fig. 11. No. of captured packets of UDP vs. TCP without QoS support and active backup traffic

active. Figures 10 and 11 indicate the higher reliability required with regards to certain communication requirements (such as the need to use TCP protocol) by the CPS application and the gained adaptability by the LTE network to such requirements when QoS is provided.

VI. CONCLUSION

In this paper we demonstrated the ability of LTE networks under specific load conditions to provide reliable communications to one exemplary CPS application and adapt to its different communication requirements when QoS is provided by the network. It was also clear the sever degradation in performance of the desired urgent traffic when the eNB was fully loaded and the QoS was not provided. Hence, one of the key factors to realize CPSs over LTE networks in specific, and over other communication networks in general, is to provide QoS support. It is also necessary to involve the end users/applications in QoS control. In this case, it is not only expected to provide better utilization of communication resources (based on the communication requirements of the CPS application), but also to provide higher flexibility to the CPS to utilize the same network connection for different modes of operation.

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