Enabling IEC 61850 Communication Services over Public LTE Infrastructure

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***Abstract*—Ongoing IEC 61850 standardization activities aim at improved grid reliability through advanced monitoring and remote control services in medium- and low-voltage. However, extending energy automation beyond the substation boundaries introduces the need for timely and reliable information exchange over wide areas. LTE appears as a promising solution since it supports extensive coverage, low latency, high throughput and Quality-of-Service (QoS) differentiation. In this paper, the feasibility of implementing IEC 61850 over public LTE infrastructure is investigated. Since standard LTE cannot meet the stringent latency requirements of such services, a new LTE QoS class is introduced along with a new LTE scheduler that prioritizes automation traffic with respect to background human-centric traffic. Two representative automation services are considered, a centralized (MMS) and a distributed one (GOOSE), and the achievable latency/throughput performance is evaluated on a radio system simulator platform. Simulations of realistic overload scenarios demonstrate that properly designed LTE schedulers can successfully meet the performance requirements of IEC 61850 services with negligible impact on background traffic.**

I. Introduction

The transformation of the existing power distribution grid into a smart grid is hindered by the lack of a scalable and reliable wide-area communication network that would enable advanced automation services [1]. The IEC 61850 standard for power utility automation defines the communication between Intelligent Electronic Devices (IEDs) within a substation and the corresponding system requirements [2]. The ongoing modernization of the power grid extends the scope of IEC 61850 to wide-area control services. Such services require an efficient long-range communication platform that ensures extensive and timely information exchange among IEDs, substations, remote control centers and Distributed Energy Resources (DERs) [3].

LTE technology is emerging as a promising candidate to satisfy the communication requirements of advanced smart grid applications, e.g., inter-substation communication, outage management, DERs integration. Utilities can easily use the existing LTE infrastructure to significantly reduce the investment/deployment costs. LTE could potentially support remote automation services in the distribution grid given that its coverage extends to wide geographical regions. In addition to low latency, LTE offers high data rates and system reliability, enabling currently unrealizable critical control tasks. However, LTE was not initially designed for smart grid applications, but for human-centric communications. Smart grid data characteristics (sporadic nature, uplink-based) are different than those generated by broadband services originally thought for LTE, and hence LTE needs to be optimized for energy traffic flows.

In this paper, we investigate up to which extent public LTE infrastructure can support real-time automation services in distribution grid. We present the technical challenges introduced by IEC 61850 standard for wide-area substation automation tasks and discuss the ability of LTE to meet the latency and throughput requirements of control traffic. We focus on two representative automation services, namely i) client-server scenarios, where IEDs periodically report measurements to a remote controller, based on IEC 61850 Manufacturing Messaging Specification (MMS) protocol, and ii) event-driven peer-to-peer communications among IEDs, based on IEC 61850 Generic Object Oriented Substation Event (GOOSE) protocol.

In [4], the applicability of WiFi for intra-substation communication is studied. However, its relatively short range is not adequate for inter-substation communication between IEDs located in remote areas. Existing LTE implementations have difficulties to meet the energy automation requirements [5]. We address this issue by prioritizing energy data flows over conventional LTE traffic in network-overload scenarios. In this context, the role of scheduler is significant to resolve the contention. In static allocation schemes [6], no resource contention is taking place; however, such schemes are rendered inefficient in terms of spectrum utilization. The downlink performance of LTE round-robin scheduler in network-underload was investigated in [7] for IEC 61850 MMS services. Instead, here we propose a channel-aware adaptive scheduling scheme to address the most challenging uplink scenario, where traffic overload naturally arises due to the scarcity of uplink resources [8]. In [9], an LTE scheduler is analytically designed to maximize the control traffic rate. Instead, we propose an adaptive scheduling scheme that dynamically allocates contiguous uplink resources and prioritizes smart grid traffic to guarantee its strict latency and throughput requirements.

The main contribution of this work is the design of an appropriate LTE scheduler to support IEC 61850 services. We further extend existing bibliography via i) a characterization of the performance constraints that energy automation tasks introduce in the LTE scheduling process, and ii) an analysis of

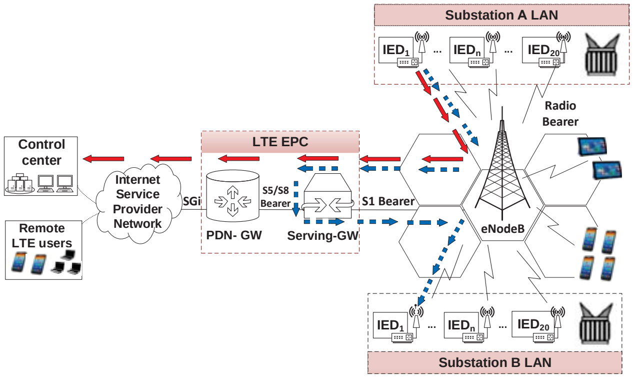

Fig. 1. Centralized/distributed architecture for energy automation services in the distribution grid. A regular LTE cellular deployment with a hexagonal grid is considered, where smart grid communications are based on IEC 61850 MMS (solid arrows) and GOOSE messages (dashed arrows) respectively.

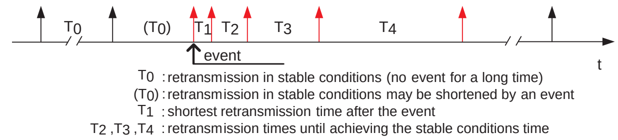

Fig. 2. Under stable conditions, GOOSE messages follow a periodic traffic pattern, but are generated in bursts in case of an event. GOOSE message retransmissions then occur in short but increasing time intervals [2].

TABLE I
PERFORMANCE REQUIREMENTS OF CONTROL TRAFFIC [11]

	Min throughput	Max delay
Centralized automation using MMS	2 kbit/s	100 ms
Distributed automation using GOOSE	70 kbit/s	50 ms

the impact of energy traffic prioritization on the performance of the human-centric and real-time LTE services.

The structure of the paper is as follows. Section II describes the considered automation scenarios and their communication requirements. Section III presents the implementation details that enable integration of IEC 61850 and LTE and presents an LTE scheduling scheme to provide QoS guarantees for energy automation services over public LTE infrastructure. Section IV validates the feasibility of the proposed integration scheme in overload through Ericsson's radio system platform. Our concluding remarks are presented in Section V.

II. Smart Grid Automation Scenarios and Communication Requirements

Next-generation power systems will incorporate numerous renewable DERs and control centers that remotely control distant IEDs. In this context, the IEC 61850 standard has to be extended to enable automation applications beyond the substation premises.

Two representative scenarios of energy automation services are depicted in Fig. 1. In the figure, solid arrows correspond to a state-of-the-art centralized architecture where MMS traffic is exchanged between the IEDs and the control center. The IEDs are equipped with LTE radio interfaces for direct communication with the eNodeB and belong to the same substation Local Area Network (LAN). A connection-oriented communication is established, where the backward-compatible IEC 61850 methods with MMS over TCP/IP are used [10]. Focusing on event reporting use cases, we consider a scenario where real-time power quality measurements are periodically sent to a remote controller for system situational awareness. In turn, this information is used to detect out-of-step conditions (e.g., excessive/increasing phase angle), issue alarms and initiate control actions to rectify the fault and/or isolate the system.

An envisaged architecture that could enable localized control interactions is depicted with dashed arrows in Fig. 1. Moving beyond the state-of-the-art, we consider a distributed automation scenario that relies on peer-to-peer communications. In particular, we propose a system model where there is no centralized decision logic that coordinates the substations based on information collected from the entire grid. Instead, decision making is distributed among the substations that coordinate directly, so that delay is minimized. The required communication may take place either through the eNodeB as depicted in the figure or via the Device-to-Device paradigm. Establishing a peer-to-peer network over LTE facilitates time-critical GOOSE messages to be exchanged between neighboring IEDs that belong to the same or different substation LANs. Generally, this network topology captures use cases where distributed event-driven communication is required. GOOSE services provide fast transmission of substation events, such as protection commands/alarms, and enable localized decision-making. As illustrated in Fig. 2, once an event occurs, a specific retransmission scheme of identical GOOSE messages is applied; thus, with high probability, any GOOSE message will be eventually received by the intended IED.

Table I summarizes the performance requirements for centralized and distributed grid topologies, as these have been identified by the EIT research activity "LTE for Smart Energy" [11]. Our objective is to address the implementation challenges so that LTE meets these requirements, as discussed next.

III. LTE Scheduling for Energy Automation

In this section, we propose a novel LTE scheduler that enables IEC 61850 communication services. The IEC 61850 standard was initially defined for local intra-substation automation services using switched Ethernet in the data link layer [2]. However, to extend the reach of automation information beyond substation boundaries, IEC 61850 packets would have to be translated to a different wide-area protocol through supporting routing mechanisms. Thus, the set of IEC 61850 services have to be compatible with the LTE radio protocol architecture. Since LTE was not initially designed to support energy automation tasks, adaptation protocols have to be introduced above the transport layer in the OSI reference model, as illustrated in Fig. 3.

LTE standard defines different QoS classes to support a diverse set of services. This class-based QoS mechanism relies on the concepts of data flows and bearers. Data flows are mapped to bearers, a set of multiple QoS requirements which are indicated by the QoS Class Identifier (QCI). As illustrated

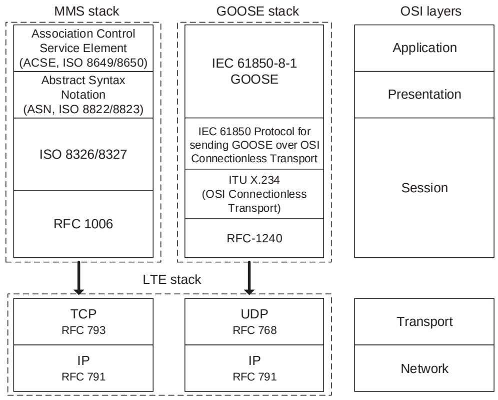

Fig. 3. MMS and GOOSE protocol stacks and their association with OSI layers [2], [10]. Adaptation protocols are added to ensure seamless integration with LTE radio protocol stack.

TABLE II
STANDARDIZED [12] AND EXTENDED QCI CHARACTERISTICS

QCI	Resource type	Priority	Packet delay budget (ms)	Packet loss rate	Example services
1	Guaranteed Bit Rate	2	100	10^{-2}	Conversational Voice
2		4	150	10^{-3}	Conversational Video (Live Streaming)
3		3	50	10^{-3}	Real Time Gaming
4		5	300	10^{-6}	Non-Conversational Video (Buffered Streaming)
5	Non-Guaranteed Bit Rate	1	100	10^{-6}	IMS Signaling
6		6	300	10^{-6}	Video (Buffered Streaming), TCP-based (e.g. www, e-mail, ftp, p2p file sharing, etc.)
7		7	100	10^{-3}	Voice, Video (Live Streaming), Interactive Gaming
8		8	300	10^{-6}	Video (Buffered Streaming), TCP-based (e.g. www, e-mail, ftp, p2p file sharing, etc.)
9		9			
10	Guaranteed Bit Rate	Highest	100, 50	10^{-6}	IEC communication services (MMS, GOOSE)

in Table II, a set of nine QCI profiles has been prescribed in 3GPP specifications which target at human-based services. We now propose the extension of the standardized QoS-based LTE mechanism with the introduction of an additional QoS class of highest priority for IEC 61850 MMS and GOOSE services, based on the performance requirements in Table I. QoS provisioning is then achieved through the establishment of dedicated bearers exclusively used by IEC 61850 traffic. This QoS-differentiation mechanism ensures different packet-forwarding treatment (i.e., scheduling and queue management, resource allocation) between automation and other types of traffic. Based on QCI value, the LTE scheduler could schedule traffic flows so as to achieve the corresponding QoS targets.

Fig. 4 illustrates the proposed uplink scheduling framework. Consider C traffic classes, where a smaller class index corresponds to higher priority traffic, as presented in Table II. We model class i arrivals as a Poisson process of rate λ_i and are characterized by a payload size which is an exponential random variable with mean b_i bytes. In LTE, the available bandwidth can be seen as a time-frequency grid of physical resource blocks (RBs). Two time-consecutive RBs form an RB pair, the minimum scheduling unit that can be allocated to a class in every Transmission Time Interval (TTI). We denote by $\mathcal{N}$ the set of available RB pairs in every TTI. Uplink resource allocation needs to conform to the contiguity

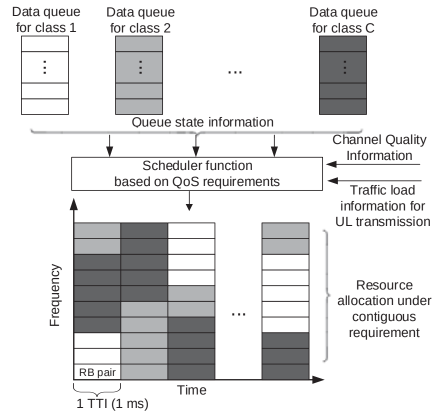

Fig. 4. A generic view of the LTE uplink scheduler. In each Transmission Time Interval (TTI), multiple adjacent resource block (RB) pairs can be assigned to a number of performance classes.

constraint, i.e., adjacent RB pairs have to be allocated to each performance class [8]. Let x_i^n be the decision variable that indicates whether RB pair $n \in \mathcal{N}$ is assigned to class i and let $\boldsymbol{x}_i = \{x_i^n : n \in \mathcal{N}\}$ denote the corresponding allocation vector. Then, for the service rate of class i, R_i, according to Shannon-Hartley theorem, we have

$$R_i\left(\boldsymbol{x}_i\right) = \sum_{n \in \mathcal{N}} x_i^n \frac{B}{|\mathcal{N}|} \log_2\left(1 + \mathrm{SINR}_{i,n}\right), \tag{1}$$

where B is the total available system bandwidth, and $\mathrm{SINR}_{i,n}$ is the average Signal to Interference and Noise Ratio for the RB pair n for class i. The latter information is generally available through reporting mechanisms (Channel Quality and Traffic Load Information) provided by LTE [8]. Based on the above, the service time of class i, S_i, follows an exponential distribution with a mean value of $s_i = b_i/R_i$. Thus, we may model the system as C M/M/1 queues, where each queue holds the traffic of the respective class, and the resulting average delay $T_i\left(\boldsymbol{x}_i\right)$ is given by [13]

$$T_i\left(\boldsymbol{x}_i\right) = \frac{\lambda_i b_i^2}{R_i\left(\boldsymbol{x}_i\right)\left(R_i\left(\boldsymbol{x}_i\right) - \lambda_i b_i\right)} + \frac{b_i}{R_i\left(\boldsymbol{x}_i\right)}. \tag{2}$$

Our objective is the maximization of overall system throughput subject to the resource contiguity, throughput and delay constraints. If n_i^a and n_i^b denote the first and last RB allocated to user i, uplink scheduling can be formulated as the following optimization problem:

$$\max_{\boldsymbol{x}_i} \quad \sum_{i=1}^{C} \sum_{n \in \mathcal{N}} R_i\left(\boldsymbol{x}_i\right) \tag{3a}$$

$$\text{s.t.} \quad \sum_{i=1}^{C} x_i^n \leq 1\,, \;\; \forall n \in \mathcal{N}\,, \quad x_i^n \in \{0,1\}\,, \tag{3b}$$

$$\sum_{n=n_i^a}^{n_i^b} x_i^n = n_i^b - n_i^a + 1\,, \;\; \forall i\,, \;\; x_i^{n_i^a} = x_i^{n_i^b} = 1\,, \tag{3c}$$

$$R_i(\boldsymbol{x}_i) \geq R_{i,\min}\,, \quad \forall i\,, \tag{3d}$$

$$T_{i,\text{total}}(\boldsymbol{x}_i) \leq \tau_i\,, \quad \forall i\,. \tag{3e}$$

Constraint (3b) ensures that each RB pair is allocated to at most one traffic class. Constraint (3c) ensures the RB pair contiguity constraint of LTE uplink [5]. Constraint (3d) implies that the throughput lower bound, $R_{i,\text{min}}$ has to be met for each class i. Constraint (3e) captures the requirement that the overall transfer time for class i should be at most τ_i. As illustrated in Fig. 1, the delay of the core LTE network domain, T_{core}, has to be taken into account; hence, the actual average latency for message delivery is

$$T_{i,\text{total}}\left(\boldsymbol{x}_i\right) = T_{\text{core}} + T_i\left(\boldsymbol{x}_i\right). \tag{4}$$

Solving problem (3) is particularly challenging. First, the decision variables x_i^n are binary constrained. Second, the presence of the decision variables in the denominator of the performance constraints results in a nonlinear problem [14]. Third, the contiguous RB pair allocation constraint renders the problem NP-hard [5].

Due to mathematical intractability of solving efficiently problem (3), we propose a dynamic heuristic scheduling scheme. The heuristic algorithm is executed on a per-TTI basis following a QoS-, queue- and channel-aware policy. In every TTI, the scheduler calculates the SINR values based on the buffer status report and channel quality information. Priority handling is performed by assigning RB pairs in sequential order from the higher-priority to lower-priority classes. In particular, starting from the highest priority class, the initial number of RB pairs to be allocated for class i is set to 1. The proposed heuristic scheduler then estimates the achieved throughput R_i and the response time T_i. If R_i and the overall transfer time $T_{i,\text{total}}$ do not meet the respective requirements $R_{i,\text{min}}$ and τ_i, an additional, neighboring RB pair is allocated. The scheduler keeps increasing the number of allocated RB pairs, which results in an increase of R_i and a corresponding decrease of T_i, until the requirements of the throughput and latency are both met. Iteratively, the scheduler proceeds by processing the following traffic flows that are characterized with lower priority. Finally, once the allocation is performed, the system updates all the relevant parameters. Note that in every TTI, the proposed scheduler dynamically assigns resources to meet the QoS requirements.

In the following section, we analyze the performance of our proposed heuristic scheduler and quantify the impact of smart grid prioritization on the background LTE real-time traffic.

IV. Numerical Results

To evaluate the performance of the proposed LTE scheduler, we consider realistic overload scenarios where LTE subscribers generate background traffic within the eNodeB coverage area and compete with the IEDs for the available resources. Such scenarios would arise in practice, if public LTE infrastructure was shared by smart grid and conventional traffic. For the simulation of LTE, we have used Ericsson's radio simulation platform. We simulate the full LTE protocol stack and traffic generated by typical mobile applications, e.g., web browsing (HTTP), Voice-over-IP (VoIP), video streaming and file transfer (FTP). Starting from a medium-load scenario, new users appear in the system according to a Poisson process with the arrival intensities selected so as to drive the system to overload and network capacity reaches its maximum. Network performance is then evaluated when the system operates close to its capacity limits. Regarding MMS and GOOSE traffic, we consider traffic patterns that follow IEC 61850 specifications, as described in Section II. Table III summarizes the basic parameters used in our simulations. For benchmarking purposes, we evaluate also the performance of the native LTE scheduler. In particular,

TABLE III
Simulation settings overview

Parameter	Value/Description
System bandwidth	5 MHz
Number of subcarriers per RB	12
RB bandwidth	180 kHz
Transmission Time Interval	1 ms
Transmission mode	MIMO 2x2
{User, eNodeB} transmission power	{24, 43} dBm
{User, eNodeB} noise figure	{9, 5} dB
IEDs in a substation LAN	20
Channel Model	Suburban
User distribution	Uniform
{EPC, Internet} delay	10 ms

TABLE IV
Simulation parameters for MMS scenario

	Traffic Type				
	Web	VoIP	Video	FTP	MMS
Initial number of active users/IEDs	3	3	1	2	2
Arrival intensity	2.0	3.0	0.75	4.0	1.0
Number of active devices in overload	27	34	15	25	20

- The dashed curves correspond to simulations where both background LTE and smart grid flows are mapped to the same default bearer and resource allocation is performed with the proportional-fair scheduling policy. This captures the default network configuration with no special handling of smart grid with respect to other LTE traffic.
- The solid curves depict the performance of the proposed scheme where a dedicated bearer is established for the control traffic flow, with QoS requirements specified in Table I. Smart grid control traffic is prioritized over conventional LTE which is mapped to the default bearer.

A comparative study of the two approaches is performed in terms of latency and throughput, aiming to verify whether the performance requirements for each scenario are satisfied with the proposed QoS-differentiation scheduling scheme.

A. Scenario 1: Centralized scenario

Table IV provides the details of the simulated client-server scenario. We assume that remote control traffic between the IEDs and the control center follows a periodic traffic pattern with constant inter-arrival times of 6 ms and a payload of 150 bytes. These traffic characteristics are typical for control tasks [11]. In overload all IEDs that belong to the same substation LAN are active and send data to the control center.

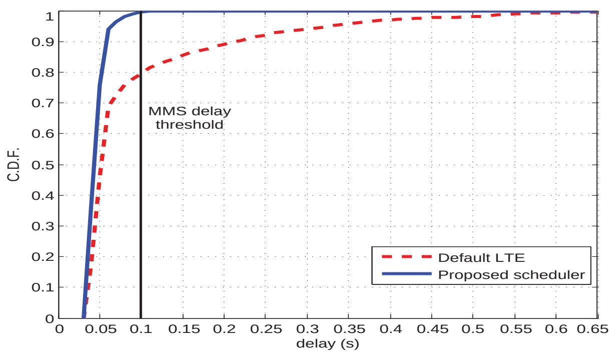

Fig. 5. CDF of delay for MMS traffic.

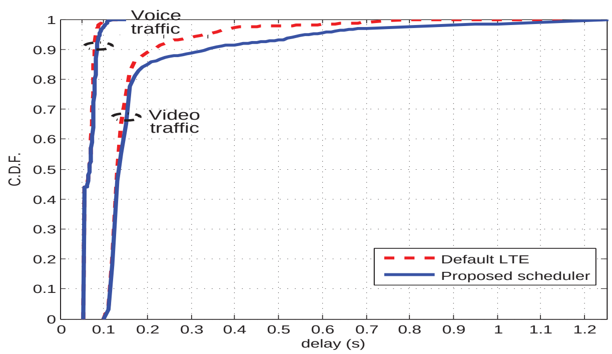

Fig. 6. CDF of background voice and video delay in presence of MMS traffic.

Fig. 5 presents the CDF of the delay experienced by MMS messages, measured at the control center. The proposed scheduler outperforms the conventional LTE one. In particular, our scheduler guarantees that even in overload only 0.5% of the messages experience delay slightly above the maximum acceptable threshold of 100 ms whereas the corresponding percentage for the native LTE scheduler is 21.8%. Naturally, this improvement causes some performance degradation to background traffic. Since user Quality of Experience (QoE) should not be sacrificed, we quantify the impact of smart grid traffic prioritization on delay-sensitive applications.

Fig. 6 depicts the CDF of the delay for real-time voice and video services in presence of MMS traffic. As a result of MMS traffic prioritization, a slight increase in the delay of the voice frames (up to 20 ms) is observed. However, this would not be noticeable by end users. Typically, delays of up to 150 ms do not affect significantly call quality and hence are considered acceptable for VoIP [15]. Video streaming delay increases by up to 0.5 sec with respect to the default LTE scheme. The performance degradation is higher compared to the voice traffic. However, since 95% of video frames are delivered with a delay of less than 0.6 sec, QoE can be considered acceptable.

Fig. 7 illustrates the CDF of the throughput for MMS control traffic. When the proposed priority-scheduling approach is applied, the throughput measured at the control center satisfies the requirement of 2 kbit/s per connection. On the other hand, with the default network configuration, 4% of the MMS traffic throughput is below the threshold.

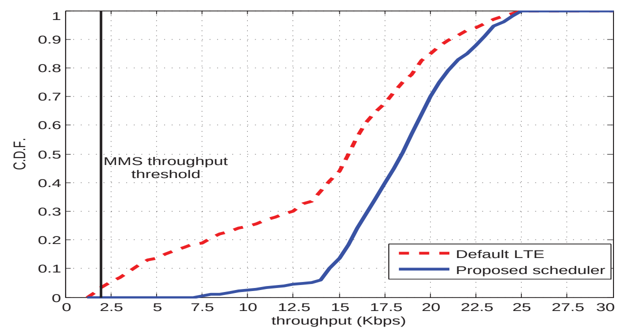

Fig. 7. CDF of throughput for MMS traffic.

TABLE V
GOOSE TRAFFIC CHARACTERISTICS

Parameter	Value/Description
Payload	250 bytes
Retransmission $\{T_0, T_1\}$	$\{0.5$ sec, 1 ms$\}$
Retransmission T_N	$T_N = 2^{N-1}T_1$, for $N \geq 2$

B. Scenario 2: Distributed scenario

In the peer-to-peer scenario, the GOOSE traffic pattern has two modes. Under stable operating conditions, each IED periodically reports its state via GOOSE messages to other IEDs, within the same or different substation LANs. Once an event is detected, the retransmission period is shortened, which results to a GOOSE burst. The generation of a GOOSE traffic burst can be modeled as a Poisson process. Table V summarizes the characteristics of GOOSE traffic in both stable and burst operation modes, according to Fig. 2. We assume also that in overload all IEDs belonging to the two substation LANs identify the event and eventually switch to burst mode. The details of the simulated scenario are described in Table VI. Note that due to the increased traffic load of GOOSE, overload is reached with a lower number of background LTE users.

Fig. 8 depicts the CDF of the delay experienced by GOOSE messages, measured in the receiving IED. The proposed priority-scheduling scheme outperforms the default one. Despite the intense traffic conditions imposed by the GOOSE bursts, 77.6% of the messages experience delays below the maximum allowed threshold of 50 ms, whereas less than 2% require more than 60 ms. The corresponding values under the default LTE scheme are 66.4% and 10%.

Fig. 9 illustrates the impact of GOOSE traffic prioritization on the performance of background real-time voice and video services. Compared to the first scenario, the impact on voice applications is higher mainly due to the stringent QoS requirements and the bursty nature of GOOSE traffic. Voice users would experience a delay increase of up to 30 ms with respect to the default scheme. However, the resulting delay level is totally acceptable, being significantly lower than the threshold of 150 ms and would not lead to dropped calls. For video users, the respective delay increases up to 0.85 sec. The overall delay levels are now higher with respect to Fig. 6, reaching up to 2.6 sec. Moreover, 77% of video frames are now transmitted with less than 0.6 sec delay. Thus, the video quality can still be considered acceptable; however, the performance deterioration may lead to some unsatisfied video users. Note that here

TABLE VI
SIMULATION PARAMETERS FOR GOOSE SCENARIO

	Traffic Type				
	Web	VoIP	Video	FTP	GOOSE
Initial number of active users/IEDs	3	3	1	2	2
Arrival intensity	0.75	1.0	0.75	2.0	0.8
Number of active devices in overload	25	18	29	10	40

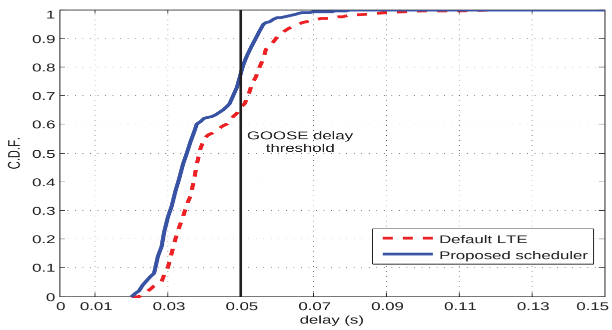

Fig. 8. CDF of delay for GOOSE traffic.

all types of background traffic are considered equivalent and hence are handled similarly. However, QoS differentiation can be extended to background traffic so as to reduce the impact of smart grid traffic prioritization on delay-sensitive services.

Fig. 10 shows the CDF of throughput for GOOSE control traffic for both simulation sets, measured in the receiving IED. As observed, by applying the proposed priority-scheduling approach, the achieved throughput improves significantly. In particular, only 4.8% of the throughput is below the threshold of 70 kbit/s whereas the corresponding percentage in the default scheme is 18%.

V. CONCLUSION

In this paper, we demonstrated how IEC 61850 standard can be implemented over LTE to extend energy automation services beyond the substation boundaries. Since such time critical applications are not adequately supported by current LTE implementations, we proposed a novel LTE scheduler that prioritizes automation traffic. Our extensive simulations in a realistic radio system simulator indicate that the proposed scheduler enables public LTE to efficiently support automation services with minimum impact on background traffic. The proposed scheduler could enhance the widely deployed LTE networks to support mission-critical machine-type communications and hence it enables a number of novel LTE use cases.

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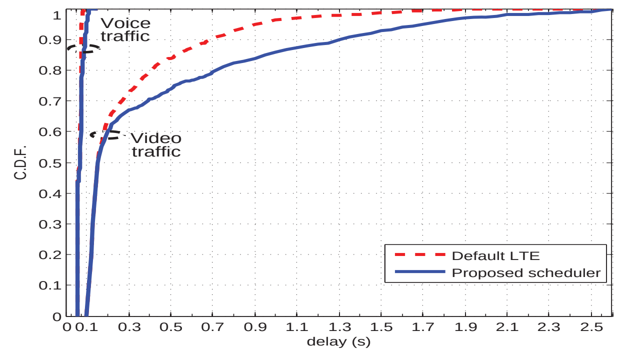

Fig. 9. CDF of background voice and video delay in presence of GOOSE traffic.

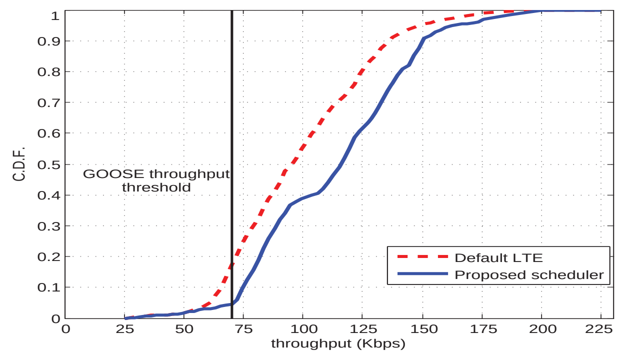

Fig. 10. CDF of throughput for GOOSE traffic.

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