Performance of LTE for Smart Grid Communications

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Abstract. The next generation power grid (the "Smart Grid") aims to minimize environmental impact, enhance markets, improve reliability and service, and reduce costs and improve efficiency of electricity distribution. One of the main protocol frameworks used in Smart Grids is IEC 61850. Together with the Manufacturing Message Specification (MMS) protocol, IEC 61850 ensures interoperability within the Smart Grid by standardizing the data models and services to support Smart Grid communications, most notably, smart metering and remote control. Long Term Evolution (LTE) is a fourth-generation (4G) cellular communications standard that provides high-capacity, low-latency, secure and reliable data-packet switching. This paper investigates whether LTE can be used in combination with IEC 61850 and MMS to support smart metering and remote control communications at a desirable quality of service level. Using ns-3 simulation models, it is shown that LTE can indeed satisfy the main IEC 61850 and MMS performance requirements for these two applications.

Keywords: Smart grid communications, IEC 61850, LTE, simulation models, ns-3, quality-of-service.

1 Introduction

The current power grid is evolving towards a so-called "Smart Grid", which promises to efficiently deliver electricity in a sustainable, economic and secure way. The current power grid infrastructure has existed for several decades, but cannot cope anymore with the emerging challenges. For example, the European 20-20-20 targets [1] aim to (1) reduce green house gas emission by 20% in 2020 (80% in 2050), (2) increase share of renewables in EU energy consumption to 20%, and (3) achieve an energy-efficiency target of 20%. In order to meet these targets, more use of Distributed Energy Resources (DERs) that run on renewable energy, such as solar or wind has to be integrated, which does impose new challenges for the grid. These challenges together with factors, such as the need for higher resiliency against failures, better security and protection, etc., drive the grid towards a modernized infrastructure and bring new benefits to both utilities and customers. In order to realize this objective,

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Smart Grid requires bidirectional communication between the components within the grid, such as power plants, substations and control centres.

In this paper we explore the requirements for smart grid communications, and investigate the potential of integrating two already standardized communication systems to fulfil these requirements. For the lower communication layers we propose to use LTE (Long-Term Evolution) [2] for 4G cellular communications. As application-level protocol we consider IEC 61850, which has been defined for interoperability among intelligent electronic devices (IED's) in smart grids. We investigate how LTE and IEC 61850 [3] can be integrated to support two key applications in smart grids, i.e., smart metering and remote control. The main contributions of this paper lie in (1) a clear specification of the performance requirements, (2) the establishment of a new architecture, that integrates IEC 61850 and LTE, and (3) a simulation-based performance evaluation.

This paper is organized as follows. Section 2 addresses background information on LTE, IEC 61850 and MMS. Section 3 then discusses the performance requirements, whereas Section 4 proposes a new overall integrated architecture. A detailed performance evaluation is reported in Section 5. Section 6 concludes the paper and provides recommendations for future work.

2 IEC 61850, MMS and LTE

The **International Electrotechnical Commission** (**IEC**) **61850** protocol [3] is an open standardized, extensible protocol that can be applied for the support of smart metering services. It has originally been defined to solve the interoperability problem among different Intelligent Electronic Devices (IEDs) from different manufacturers within a substation. In addition to that, IEC 61850 also defines a set of abstract remote control communication services for exchanging information among components of a Power Utility Automation System. These services are denoted as Abstract Communication Service Interface (ACSI) services and are described in [4]. Examples of such services are, e.g., retrieving the self-description of a device, the fast and reliable peer-to-peer exchange of status information, the reporting of any set of data (attributes) and/or sequences of events, the logging and retrieving of any set of data, the transmission of sampled values from sensors, time synchronization, file transfer, and online (re)configuration.

Within IEC 61850, IED functions are decomposed into core logical functions called Logical Nodes (LNs). Several LNs can be grouped into a Logical Device (LD), which provides the communication access point for IEDs. The LDs are hosted by a single IED. By standardizing the common information model for each LN and for their associated services, IEC 61850 is able to provide the interoperability among IEDs of different manufacturers in the substation automation systems.

By specifying a set of abstract services and objects, IEC 61850 allows the user to design different applications without relying on the specific protocols. As a consequence, the data models defined in IEC 61850 can be used for a diverse set of communication solutions. IEC 61850 has been extended outside the scope of substation automation systems to cover Remote Terminal Units (RTUs), Distributed Energy Resources (DERs), electric vehicles (EVs), and the communication to the control centre. Therefore, it can potentially be applied to support (smart) metering and remote control communication services within the distribution network.

At application level, the **Manufacturing Message Specification** (MMS) [5] (and IEC 61850-8-1) has been chosen, since after some small modifications, it does provide (1) smart metering and remote control communication services, and (2) the required complex information models that support the mapping of IEC 61850 abstract objects. Another advantage of using MMS is that it provides high flexibility by supporting both TCP/IP and OSI communication profiles.

Long Term Evolution (LTE) [2] is a fourth generation (4G) communication technology standardized by the 3rd Generation Partnership Project (3GPP). It is capable of providing high data rates as well as support of high-speed mobility. It has a completely packet-switched core network architecture. Compared to UMTS, the LTE system uses new access schemes on the air interface: Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) in the uplink, which brings flexibility in scheduling as well as power efficiency. LTE features low latency in both the control plane and user plane. The success and rapid roll-out of LTE in many countries have led to an increased interest to use this networking technology for, among others, smart metering, distribution automation, fault location, etc., within electricity distribution networks. Therefore, LTE is a promising choice as the Wide Area Network (WAN) communication technology to support IEC 61850 MMS-based smart metering and remote control services.

Few research studies focussed on the performance of LTE when applied in Smart Grids, cf. [6]. However, to the best of our knowledge, there has been **no previous work** that specifies how IEC 61850 MMS, in combination with LTE, can be used for smart metering and remote control communication services. There are a number of logical nodes defined in IEC 61850 that represent different functions of an IED within the substation domain, however, there is no specification on how the logical nodes can be used for smart metering and remote control applications. In addition, there has been no previous work that discusses how the IEC 61850 MMS used for smart metering and remote control communications can be integrated with an LTE system.

In this paper we propose a solution to integrate the IEC 61850 MMS used for smart metering and remote control application with the LTE communication system. The performance of the integrated solution is evaluated using extensive simulations, performed with the ns-3 simulation environment [7], [8]. The following questions are addressed:

1. What are the performance requirements of IEC 61850 MMS on the LTE system when used to support smart metering and remote control communication services for the smart grid?
2. Can LTE be used and integrated with IEC 61850 MMS to support smart metering and remote control communication services in smart grids (functionally and performance-wise)?

3 Functional and Performance Requirements

Smart metering is the first application that utilizes a two-way communication channel to provide reliability, robustness and efficiency to the smart grid; it lays a foundation for future applications to be built. Utility companies are moving towards advanced metering infrastructure (AMI) with the widespread roll-out of smart meters, which features two-way communication that does not only allow utilities to perform automated readout functions (like its predecessor Automatic Meter Reading (AMR)) but also allows the control of smart meters, cf. [9].

IEC 61850 was specified to provide interoperability inside the Substation Automation System (SAS) by providing abstract definitions of the data items and services that are not depending on any underlying protocol. The abstract data and object models of IEC 61850 allow all IEDs to present data using identical structures that are directly related to their power system functions, cf. IEC 62351-4. However, while the abstract models are critical to achieve a high level of interoperability, these models need to be operated upon by a set protocols that are practically relevant for the power industry. Therefore, one of the main requirements on an underlying communication system, like LTE, is the capability of supporting IEC 61850 abstract objects and services mapping. The requirements that need to be satisfied by the integrated solution are listed below.

Architecture. The architecture that specifies how the IC 61850 communication system can be integrated with LTE is not available and therefore it needs to be specified.

Integration of IEC 61850 MMS and LTE communication protocol stacks. The integration of these two communication protocol stacks is not available and therefore it needs to be specified.

IEC 61850 LN information objects for smart metering and remote control communication services. The IEC 61850 LNs that can be used for smart metering and remote control communications are not available and therefore they need to be specified.

Scalability. This challenge applies more to smart metering services, since it is expected that over 200 million smart meters will be deployed in Europe between 2011 and 2020, which will have a massive demand for the network. The large number of smart meters also affects the performance of the used communication systems.

Latency (delay). For a smart metering service it is preferable to collect meter data in real-time, because utilities can correctly predict the load profile, perform load forecasting, dynamic balancing between generation and consumption, support real-time pricing and demand response, etc. In general, with the meter data collected in real-time, the stability and intelligence of the grid are greatly improved.

Moreover, latency is the most important requirement for remote control communication since receiving a late control command may seriously affect the safe operation of the electricity grid. According to IEC 61850-5 [10], the most important performance requirement that was mentioned is transfer time. Transfer time is specified as the complete transmission time of a message including the handling at both ends (sender, receiver). For smart metering services the end-to-end delay requirement ranges from 500ms to 1000ms, while for remote control communication services it ranges from 100ms to 1000ms, cf. [10]. In this research, we concentrate on the 100ms transfer time requirement for remote control communication services and on the 500ms requirement for the smart metering communication services.

Quality of Service (QoS). This challenge applies more to remote control communication services. Since such services are considered very critical, it might be needed to prioritize these services. In a public, shared LTE network, many different background traffic types are supported. Therefore, the remote control communication should be distinguished and assigned higher priority in order to guarantee its performance requirements.

Reliability. The communication system needs to be reliable such that all the IEC 61850 related information is exchanged successfully.

Security. The communicated IEC 61850 related information needs to be protected from security attacks. Therefore security services, such as authentication, confidentiality and integrity are needed.

4 Integration of LTE with IEC 61850 Communication System

We concisely present the integration of LTE and the IEC 61850 communication system such that the requirements discussed in Section 3 are fulfilled. For conciseness, not all requirements will be used. In particular, we focus on: (1) defining an architecture, (2) integrating the IEC 61850 MMS and LTE communication protocol stacks, (3) defining the IEC 61850 LN information objects used for smart metering and remote control communications, (4) the verification of the latency requirements, and (5) the verification of the prioritization requirement assuming that the QoS related performance bottleneck is the LTE eNodeB used on the downlink communication path (eNodeB towards the mobile devices). The two performance requirements ((4) and (5)) will be addressed in Section 5.

Although important, scalability, reliability and security requirements are not further considered in this paper, for two reasons: (1) the LTE system is designed in such a way that it is considered to be scalable and reliable when used to support services like smart metering and remote control communications, (2) IEC 61850 can be used in combination with IEC 62351 for security support [11].

4.1 Overall Architecture

The architecture that can be used for the integration of the LTE and the IEC 61850 communication systems applied to support smart metering and remote control communication services is visualized in Fig. 1 (more details can be found in [12] and [13]). The key entities in this architecture are as follows:

The **MMS server** represents the IED's located in the smart grid distribution network that need to be controlled. The MMS server can represent an individual Distributed Energy Resource, a micro-grid or a home-grid. A micro-grid is composed of home-grids, individual DERs and a Regional Control and Management Centre

(RCMC) that is controlling and managing these home-grids and individual DERs. The home-grid is composed of in-home private DERs, smart household appliances, and a Home Control and Management (HCMC) that is controlling and managing these devices. The MMS server supports in addition to the MMS server functionality also the following communication protocol stacks: IEC 61850, IEC 62351 and LTE.

The **MMS client** and **MDMS (Meter Data Management System) Host** represents the control centre. Between the MMS client and MMS server there is always an application association. For one application association, the MMS entity that sends an initiation-request to establish the association will be the MMS client and the other one is the MMS server. One MMS client can establish multiple application associations with different MMS servers. After an application association has been established, the MMS client can send requests to read, write or delete variables at the MMS servers. The MDMS Host functionality is used by the smart meter service and represents the meter data management system. The MDMS Host, similar to the MMS client, can establish multiple application associations with different Smart Meters or DC Smart Meters. In addition to the MMS client and MDMS Host functionalities, the control centre supports also the communication protocol stacks for IEC 61850, IEC 62351, LTE.

The **Smart Meter** represents either an individual Smart Meter functionality, i.e., a Smart Meter associated with one apartment, or a Data Concentrator Smart Meter that aggregates the Smart Meter related information associated with all the apartments located in a building.

4.2 Integrating IEC 61850 MMS and LTE Communication Protocol Stacks

The IEC 61850-based smart metering and remote control communication services have to meet several communication requirements defined in IEC 61850-5, cf. [10].

Most importantly, the core ACSI services, like smart metering and remote control communication services are mapped to the MMS protocol, which supports both the TCP/IP and the OSI communication profiles. Therefore, it is required that the underlying integrated communication system supports at least one of these two communication profiles. This means that each of the entities specified in Fig. 1 that support the IEC 61850 MMS module, i.e., Smart Meter, DC Smart Meter, MMS Client and MMDS Host, needs to support at least the TCP/IP communication protocol stack. In addition, these entities will also need to support the adaptation protocol layers required when MMS is mapped over the TCP/IP communication profiles, cf. Fig. 2.

4.3 IEC 61850 LN Information Objects

In smart metering and remote control communication services used in Smart Grid distribution networks, there are four types of equipment that need to be modelled:

- Distributed energy resources (DER): such as PV panels and energy stores.
- Smart household appliances: such as TV sets, electric heaters, or a refrigerator.
- Home Control and Management Centre (HCMC): that can reside in a MMS server.

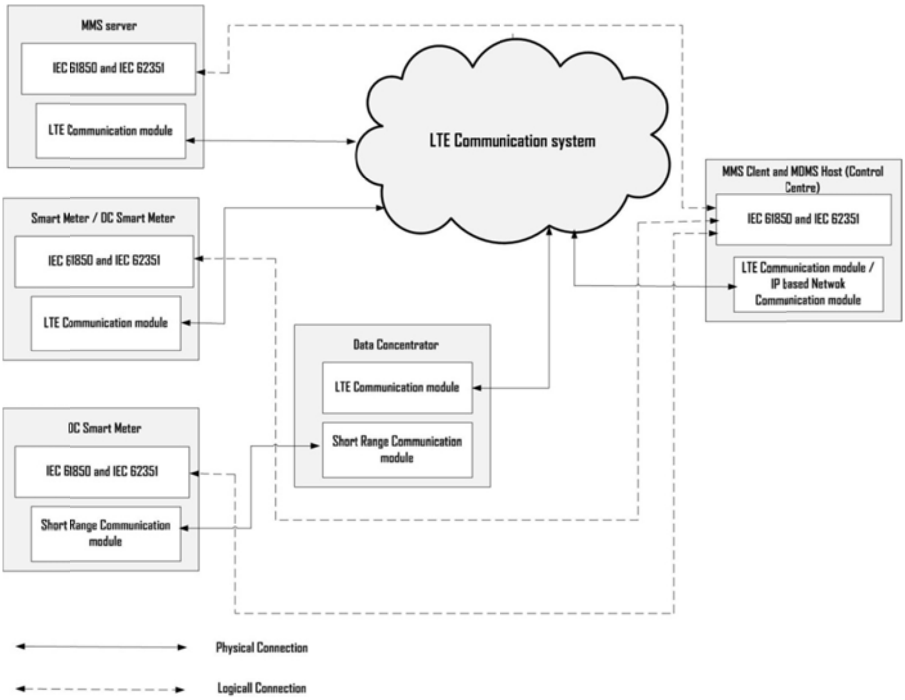

Fig. 1. Visualization of the architecture of the LTE and IEC 61850 MMS integrated solution

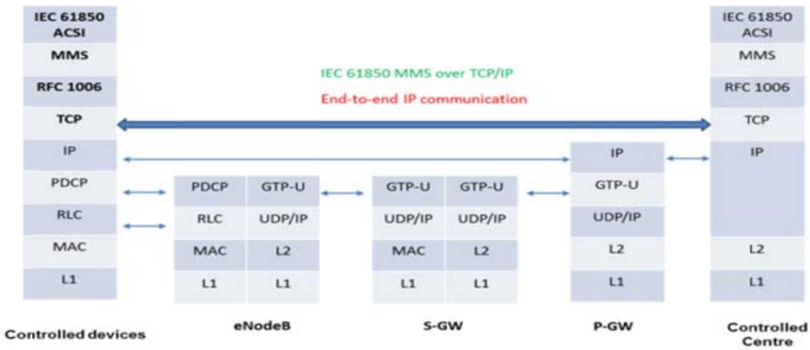

Fig. 2. Integrated LTE and IEC 61850 MMS communication protocol stacks

– Remote Control and Management Centre (RCMC): that can reside in a MMS server.

DERs can be modeled using the existing LNs defined in IEC 61850-7-420 and in IEC 61850-90-7 and IEC 61850-90-8. **Smart household appliances** are new devices that need to be modeled according to IEC 61850. Therefore, in addition to existing LNs also new LNs need to be specified. Two of the existing LNs, i.e., MMXN, MMTN, cf.

IEC 61850-7-4 [14], can be used for this purpose. Furthermore, for monitoring the devices in terms of product information, IEC 61850 defines the LN LPHD [14] that consist of the physical information of the equipment and is mandatory for all IEDs. Similarly, for monitoring other operational parameters such as temperature, pressure, heat of the devices, IEC 61850 also provisions the corresponding LNs STMP, MPRS and MHE [15]. An important feature of smart home appliances that is associated with the energy tuning needs cannot be modeled by any existing LN. Energy tuning is associated with the operational status and operating mode, i.e., whether the appliance is working autonomously or following a schedule or being controlled by the user. In the context of this research we defined in [16], [17] a new LN that can be used for modeling the energy tuning and is denoted as ZAPL (Z type APpLiances). **Home control and management centre (HCMC)** is an entity that can use existing IEC 61850 services to manage and control in-home DERs and smart household appliances. **Remote Control and Management Centre (RCMC)** is an entity used for regional areas, like neighborhoods, that can manage and control the HCMC. Currently, there are no LNs specified in IEC 61850 that can be used for this purpose. Therefore, a new LN, denoted as ZHCM (Z type Home Control and Management centre), has been specified in the context of this research, cf. [16], [17]. Notice that the new defined LNs, ZAPL and ZHCM, have been submitted by Alliander as standardization inputs to the Dutch NEC57 committee, which is a part of the IEC 61850 standardization group, where they are currently being discussed.

5 Performance Evaluation

This section describes the simulation experiments that have been performed to verify whether the latency and prioritization requirements are satisfied by the LTE and IEC 61850 MMS integrated solution. These experiments have been performed using the ns-3 simulation environment, thereby using the LTE LENA models [7], [8]. Two sets of simulation experiments have been performed, focusing on remote control communication services and smart metering services, respectively. More elaborate results can be found in [12] and [13].

5.1 Remote Control Communications

The simulation topology used during these experiments is based on the architecture shown in Fig. 1. However, of all the entities in Fig. 1, only the MMS client, MMS server and the LTE communication system are used in the simulations. Furthermore, the LTE communication system uses only one eNodeB (i.e., base station) and EPC (Evolved Packet Core) uses only one S-GW/P-GW (Serving Gateway/Packet Data Network Gateway) entity. In addition to these entities, the simulation topology includes typical UE (User Equipment) nodes and servers that are able to generate and use traffic that is non IEC 61850-based; we denote this as background traffic.

The system parameters, as used in the simulations, are summarized in Table 1. All the parameters are typical for LTE release 8, which is implemented in the ns-3 LENA

M5 simulation environment, cf. [8]. An important functionality that needs to be mentioned is the MAC (Medium Access Control) scheduling mechanism, which can be used to implement the prioritization of IEC 61850-based traffic over background traffic. In particular, two types of MAC (Medium Access Control) scheduling mechanisms are supported: Round Robin (RR) and Priority-aware Round Robin (PrioRR). The RR scheduler, cf. [13], divides the network resources among the active flows, i.e., the logical channels with non-empty queue. The PrioRR scheduler is specified in detail in [13] and is based on the RR scheduling mechanism, however in such a way that available resource blocks are assigned to flows with a higher priority first.

The used model for the MMS protocol stack is based on [5] (and IEC 61850-8-1) and its implementation in ns-3 is described in [12]. The LTE background traffic is generated using the traffic mix models specified in [18], [19], as given in Table 2.

Table 1. System parameters as used in all simulation studies

Parameters	Values
Uplink bandwidth	5MHz (25 RBs)
Downlink bandwidth	5MHz (25 RBs)
Uplink EARFCN	21100 band 7 (2535MHz),
Downlink EARFCN	3100 band 7 (2655MHz),
CQI generation period	10ms
Transmission mode	MIMO 2x2
UE transmission power	26dBm
UE noise figure	5dB
eNB transmission power	49dBm
eNB noise figure	5dB
Cell radius	2000m (typical sub-urban case)

The following performance metrics are evaluated. The **average delays** specify the averages of the MMS traffic delays. There are two types of MMS traffic delays:

- Initiation delay: time from the start of the connection setup until the Initiate-Response is received at the client;
- Request (polling) delay: time from the start of the polling request until a response is received at the client.

The **Cumulative Distribution Function** of the request delay is used in order to observe the maximum delay value measured during the simulation experiments and to compute delay variance (jitter). The **throughput** (bits/second) shows how much data is successfully transmitted over the LTE network. It is calculated as the total data received in the downlink over the simulation time. The **downlink packet loss ratio (PLR)** shows the reliability of the communication link and is calculated as:

$$\mathrm{PLR(DL)} = \frac{packets\_sent\_by\_eNB - packets\_received\_by\_UE}{packets\_sent\_by\_eNB}\ .$$

Throughput and packet loss ratio are measured at the PDCP (Packet Data Convergence Protocol) layer, while delay is measured at the application layer, see [12], [13]. In order to evaluate the impact of integrating IEC 61850 MMS remote control communication traffic in a public LTE network, **different traffic mixes** will be used with the percentage of background traffic over remote control communication traffic, such as 80/20, 60/40. In each experiment with a specific traffic mix, the number of MMS nodes and background nodes will be increased but the traffic mix (percentages) is maintained. For the MMS traffic, we assume that the control centre (MMS client) sends a control request to the MMS nodes (MMS servers) and waits for the response. If the response is positive then the control centre sends a new control request. For the background traffic, the traffic mix follows the mix of 5 different traffic types with the percentage of nodes defined in Table 2. The ns-3 implementation of the models used to generate background and MMS traffic is described in [12].

Table 2. Background traffic mix

Application	Traffic category	Percentage
VoIP	Real-time	30%
FTP	Best effort	10%
HTTP	Interactive	20%
Video streaming	Streaming	20%
Gaming	Interactive real-time	20%

For each traffic mix experiment type, two different sets of experiments will be conducted, one using the RR and the other using the PrioRR MAC scheduler. In the normal (non-overloaded) experiments the total traffic load is increased up to 80% of the maximum cell capacity in the downlink direction. The maximum cell capacity in the downlink direction is defined as the capacity where the downlink throughput is not anymore increasing when the traffic load is constantly increasing. In all the performed simulations, 95% confidence intervals are computed (and shown) using on average 20 simulation runs.

For the 80/20 traffic mix, we start with the number of background nodes of 10. Subsequently, we calculated the number of MMS nodes (MMS servers) such that the MMS traffic load is equal to approximately 20% of the total traffic load generated by both MMS nodes and background (UE) nodes. Then we increase the number of background nodes in steps of 10. The number of MMS nodes will be increased to meet the condition such that the traffic mix is always 80/20.

Since we only focus on the downlink path from the control centre to the MMS server nodes, only the results associated with downlink communication path are collected and analyzed. It is important to notice that in case the total traffic load on the downlink direction is lower than 80% of the maximum cell capacity in the downlink direction, all active flows can be served within 1 (or very few) TTI (Transmission Time Intervals; 1 TTI = 1ms), regardless of what scheduler is used.

Throughput. Fig. 3 shows the average throughput results that include the overall average throughput, background average throughput and MMS (i.e., remote Control

Communications) throughput, when the RR and the PriorRR MAC schedulers are used. Since the total traffic load on the downlink direction is lower than 80% of the maximum cell capacity in the downlink direction, it is to be expected that most of the packets are delivered successfully. Therefore, approximately equal throughput results are obtained for the scenarios that use the RR or PrioRR MAC schedulers.

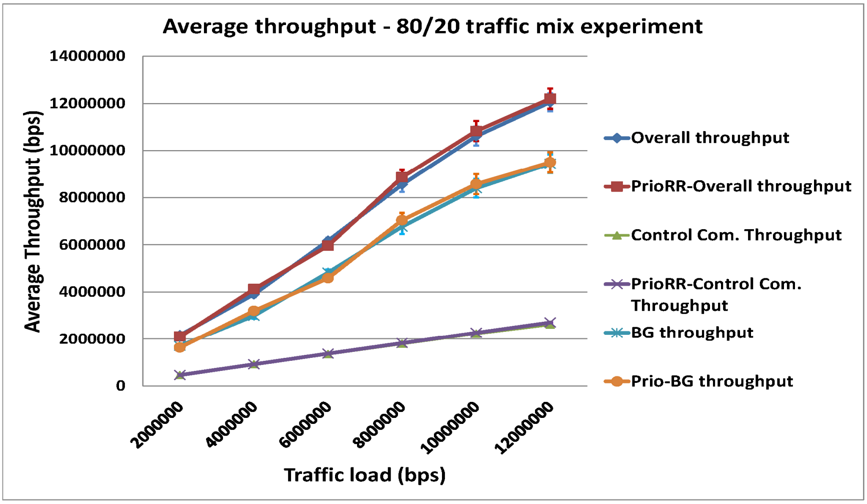

Fig. 3. Throughput performance in 80/20 traffic mix experiment with both Round Robin and Priority-aware Round Robin schedulers

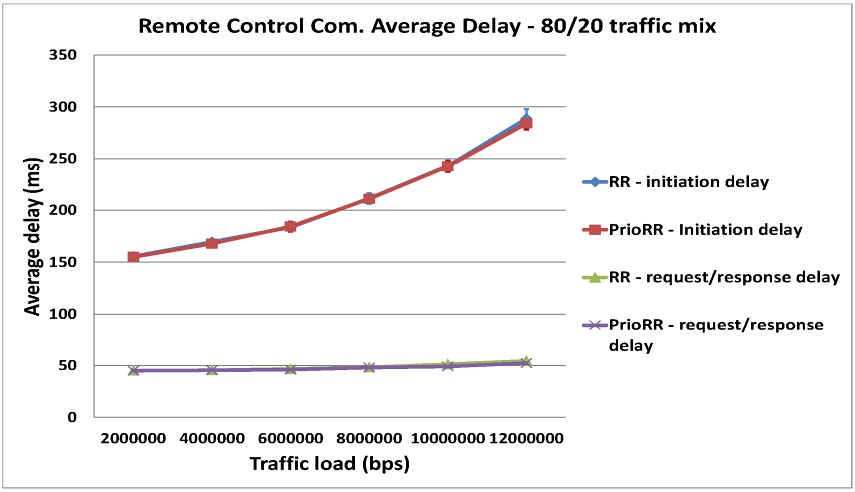

Fig. 4. Remote control communication average delays in 80/20 traffic mix experiment

Average Delay. Fig. 4 illustrates the average delay when the RR and PrioRR schedulers are used. Due to the fact that the total traffic load on the downlink direction is lower than 80% of the maximum cell capacity in the downlink direction, all active flows can be served within 1 (or very few) TTI, regardless of what scheduler is used. This also means that approximately equal average delay results are obtained for the scenarios that use the RR or PrioRR MAC schedulers. In Fig. 4, two types of average delays are shown: the initiation delay and the request delay. The initiation delay is seen when setting up the connection and establishing the application association between the MMS client and server. The request-response delay is the delay perceived in normal operation. Fig. 5 shows the CDF of the Control communication request-response delay, when the RR scheduler is used. From Fig. 5 it can be observed that the latency requirement of 100ms, see Section 3, is always satisfied.

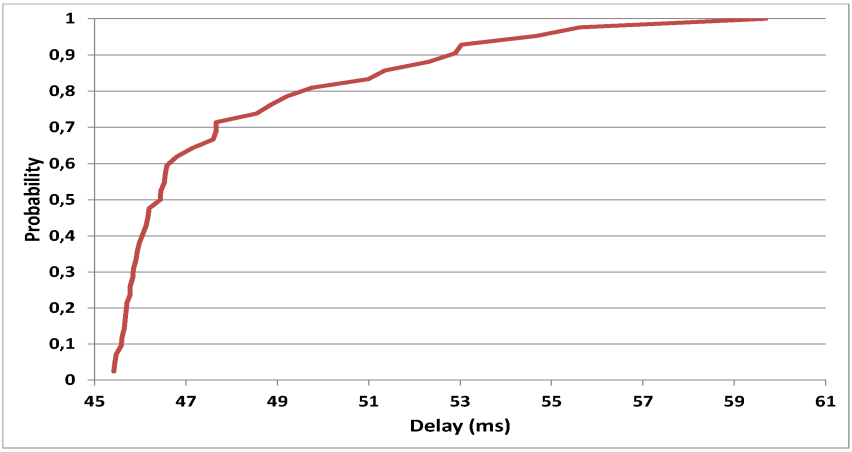

Fig. 5. CDF of Remote control communication request delay in 80/20 traffic mix experiment

Packet Loss Ratio. Fig. 6 illustrates the packet loss ratio (PLR) when the total traffic load increases. Since the total traffic load on the downlink direction is lower than the 80% of the maximum cell capacity in the downlink direction, the PLR results are approximately equal for the RR and PrioRR. When the traffic load increases, due to limited available radio resources, the PLR increases as expected.

Discussion. In this section only a subset of the remote control communication experiments have been presented. The complete set of experiments can be found in [13]. All the experiments show that the integration of IEC 61850 MMS and LTE is not only possible, it also provides a good performance in terms of delay, throughput and packet loss. When the traffic load generated does not exceed the maximum cell capacity in the downlink direction, the request/response delay is only 50% (50 ms) of the delay requirement specified by IEC 61850 for the medium-speed automatic control interactions. Furthermore, the traffic overload simulation experiments, which due to paper size limitations, are not presented in this paper but can be found in [13], show that when the generated traffic load exceeds the cell capacity in the downlink direction, the PrioRR MAC scheduler does provide a much better delay and throughput performance for the remote control communication traffic. However, the trade-off is that the performance of other less-important background traffic is reduced. Moreover, in overload situations, independently of which MAC scheduler is used, the request/response delay is lower than the delay requirement specified by IEC 61850.

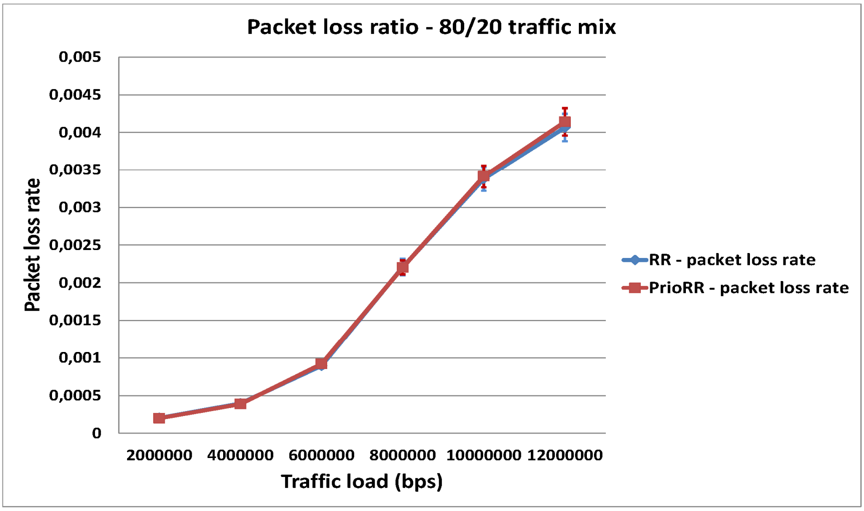

Fig. 6. Packet loss ratio in 80/20 traffic mix experiment

5.2 Smart Metering Experiments

The simulation topology is chosen as before, with the main difference that instead of using the MMS server, the Smart Meter entity is used, and instead of using the MMS client, the MDMS Host entity is used, cf. Fig. 1. Furthermore, in this set of experiments only the RR MAC scheduler is used. The simulation parameters and performance measures, including the background traffic, are similar to those used in Section 5.1, with the main difference that the cell radius is 800m, instead of the 2000m used previously (due to the smaller radio coverage cell area used for this MMS service). The traffic mix used in this set of experiments are the same as the ones used in Section 5.1. We only show simulation results on the MMS average delays for the 80/20 traffic mix. The complete set of experiments can be found in [12].

The delay performances of the smart meter initiation process and smart meter request (polling) process are illustrated in Fig. 7. From this figure, it can be observed that, as expected, both the average delays (initiation and polling) increase when the total traffic load increases. Furthermore, it can be observed that the average delay for the initiation process is much higher than the average polling delay. This is due to the fact that in the initiation process more MMS messages need to be exchanged in order to set up the connection and to establish the application association between the MMS client and server (initiate-request and initiate-response messages).

An important conclusion is that the obtained MMS average delay results, cf. Fig. 7, are below the latency (MMS transfer time) requirement of 500ms as specified in Section 3.

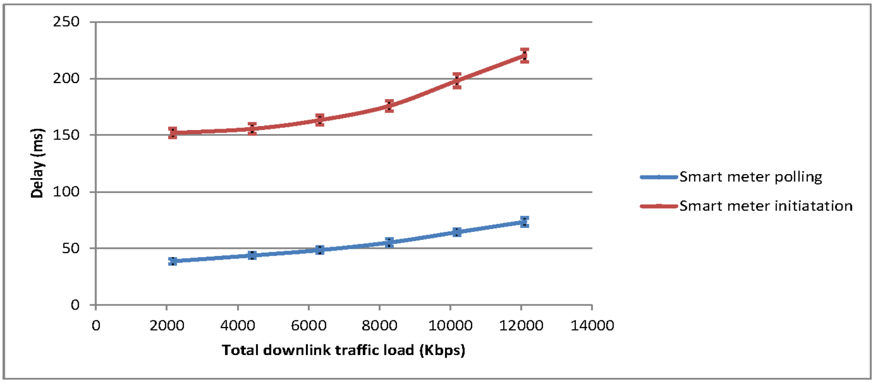

Fig. 7. MMS delay in 80/20 traffic mix experiment

6 Conclusions and Future Work

The smart grid is the next generation power grid, which aims to minimize environmental impact, enhance electricity markets, improve reliability and service, and reduce costs and improve efficiency. The most deployed communication protocol framework that can be used for the communication support in smart grids is the IEC 61850 MMS protocol framework. This paper proposes how LTE can be used and can be integrated with IEC 61850 MMS to support smart metering and remote control communications in smart grid distribution networks. In particular, this paper provides an overall architecture, the integration of the IEC 61850 MMS and LTE communication protocol stacks, the definition of IEC 61850 LN information objects used for smart metering and remote control communications, as well as a simulation-based validation of the performance requirements. Using ns-3 simulation experiments we have shown that LTE can satisfy these performance requirements on smart metering for remote control communication services.

Regarding recommendations for future work, additional simulation experiments could be done to verify the performance of IEC 61850 MMS over LTE when different types of background traffic mix are used, different LTE-based configuration parameters are used, or other IEC 61850 time-critical services are used.

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