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Analysing the Real-Time-Capability of Wide Area Communication in Smart Grids

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***Abstract*—Current developments towards *Cyber-Physical Energy Systems* (CPES) [1] requires the close integration of traditional power grids and appropriate *Information and Communication Technology* (ICT) infrastructures. Driven by additional requirements of future monitoring and control, increasing amounts of data have to be handled to ensure safe operation of the power grid and to maintain frequency stability. Therefore an appropriate ICT infrastructure becomes crucial for enabling fast and reliable transmission of time critical messages such as switching commands.**
This paper provides an evaluation on the real-time capability of the communication network in three scenarios analysing different levels of the power grid infrastructure: within the substation, between neighbouring substations and between a substation and the control centre. Communication is modelled according to the standard IEC 61850 using both simulation and the analytical approach of Network Calculus. Thus, we determine mean values as well as worst-case bounds on the delay of messages, evaluating the impact of varying network and traffic conditions. The results highlight the applicability of IEC 61850-based communication as a holistic solution for the power grid, supporting advanced tele protection and remote control applications.

I. Introduction

The energy system is about to change dramatically: from centralized power generation in large scale power plants to supply-dependent generation by a high number of small renewable, *Distributed Energy Resources* (DER). At the same time, the amount of energy trade increases as a result of liberalizing the energy market. Moreover, in the near future considerable numbers of electrical vehicles will be plugged to the power grid and approaches like demand side management will be introduced. These developments are about to drastically alter the character of energy transmission, from strictly hierarchical energy flows to bi-directional flows. Compared to conventional power plants, feed-in from DERs is fluctuating and less predictable, yielding extra stress on the power grid, which might compromise frequency stability. To countervail this development, the state of the power grid must be monitored closely and corresponding corrective measures have to be taken within the range of milliseconds [2]. This in turn necessitates reliable communication and the introduction of smart devices, inducing large amounts of information to be transmitted and processed. Aiming at reducing infrastructure investment costs and ensuring interoperability, standard hardware and protocols are to be considered for application in the power grids' communication networks. Features such as demand side management are additional, beneficial services of future Smart Grids, whereas monitoring and control are highly critical for stable operation of power grids and thus require specified delay bounds to be fulfilled. To deal with these increased demands, substations and the grid's control centre will need to apply data-centre-like ICT infrastructure. Moreover, high-performance wide area communication networks need to ensure reliable transmission of time-critical messages over long distances between the control centre and remote substations. This paper provides a perspective on possible communication solutions both on substation and wide area level. In order to evaluate the applicability of the proposed communication solution, we determine average and worst-case delays, considering a variety of conditions regarding link capacity, traffic load and inter arrival times (IAT).
The remainder of this paper is structured as follows: First, Section II provides an overview on communication in *Substation Automation Systems* (SAS). Here, the IEC 61850 is an important standard, which is currently being enhanced to wide area communication, and thus will be detailed in Subsection II-A. Afterwards, Subsections II-B and II-C introduce the reference network and detail related work on evaluating Smart Grid communication. In Section III three different scenarios will be introduced, followed by the corresponding evaluation results in Section IV. Finally, Section V closes this paper with a conclusion and an outlook on future work.

II. Communication in Power Grids

Communication in power grids can be divided into different hierarchical levels (cf. Figure 1): On the very top substations communicate with each other and a central control centre using *Wide Area Networks* (WAN). Inter-substation communication might serve for future applications such as tele protection, using measurement data from neighbouring substations. Control centres on the other hand depend on real-time information from the substations in order to obtain data as part of the *Supervisory Control and Data Acquisition* (SCADA) for operating and monitoring the power grid.

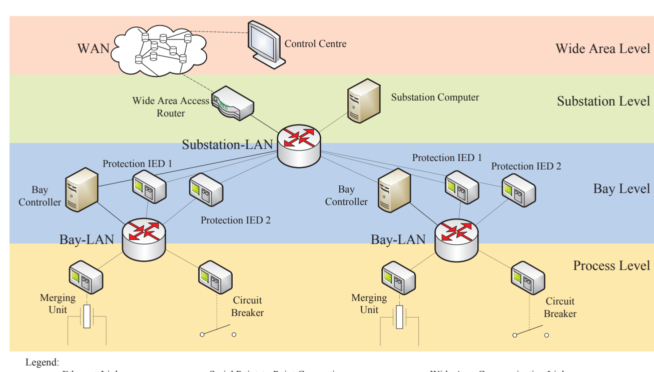


Fig. 1: Hierarchy of Power Grid Communication

Each substation consists of a substation computer (SC), a router for wide area connection and several bays for connecting primary equipment. The SC serves as a central controller for the substation, collecting data from the bays, providing a human machine interface and triggering station-wide actions e.g. interlocking or synchronised switching. To obtain necessary data and transmit switching commands, the SC and the router communicate with bay controllers (BC) and protection devices (PD), situated within each bay, via the substation's *Local Area Network* (LAN). Comparable to the function of the SC on substation level, the BC serves as a central control instance for its respective bay. Besides BC and PDs, each bay comprises merging units (MU) and circuit breakers (CB). MUs collect data from measurement transformers at fixed sample rates and forward it to the BC and the PDs. Subsequently, communication is required on bay level as well.

A. Standard IEC 61850

The Standard IEC 61850 [3] was developed by the *International Electrotechnical Commission* (IEC) Technical Committee (TC) 57 aiming at achieving standardised communication within substations using interoperable hardware, such as *Intelligent Electronic Devices* (IED). Recently IEC 61850 advances to an overall standard for Smart Grid communication, being also applied for inter-substation (IEC 61850-90-1 [4]) and substation-to-control centre communication (IEC 61850-90-2 [5]) as well as for connecting electric vehicles and DERs. In general, the standard covers a wide range of aspects, including communication topologies and services as well as a complete data model, describing everything from physical devices to single data attributes. In order to achieve openness for future communication technologies and protocols the communication services are defined using an abstract description technique. Yet, it also provides mappings to specific communication protocols, being based on standard protocols e.g. Ethernet and TCP/IP.

1) Communication Services: The IEC 61850 defines three major communication services, which will be detailed in the following. *Sampled Values* (SV) and *Generic Object Oriented Substation Event* (GOOSE) are used mainly on bay level and serve for transmitting measurement values respectively status and event messages. Due to their time-criticality, they apply directly to the MAC layer, using IEEE 802.1Q for prioritisation. In contrast, the *Manufacturing Message Specification* (MMS) applies client-server communication on basis of the TCP/IP protocol stack. MMS messages are mainly used for configuration, but are also applicable for requesting and reporting measurement or status values on substation and wide area level. Moreover, they might also be considered for issuing switching commands from the substation controller or the control centre.

2) Wide Area Communication: Both technical reports IEC 61850-90-1 [4] and -90-2 [5] define two approaches for wide area communication on basis of IEC 61850, a tunneling and a gateway approach. In case of the gateway approach each substation uses a gateway for connecting the respective substation to the WAN and handling all wide area communication. It acts as a proxy within the substation, receiving for example requests on the substation LAN and adapting them for transmission over low data rate WAN links. In turn incoming traffic from other substations is also processed by the gateway, reformatted and forwarded to the actual receiver within the substation. In contrast the tunnelling approach is designed for high data rate communication links, enabling information to be transmitted directly through a "tunnel" to the target substation or the control centre. Moreover additional data models are introduced by the technical reports, e.g. for tele-protection.

3) Time Requirements: The standard IEC 61850 comprises requirements concerning the delay of messages and the synchronization of measurements, being defined in part IEC 61850-5. On average, maximum permissible delay times range from a few microseconds to one second, except for certain management functions like network or configuration management, which are less time critical. Control messages, spontaneous status updates and messages for automatic switching sequences need to be transmitted within 100 ms. In case of protection functions, the whole sequence from fault detection to tripping has to be completed within 10 to 100 ms, depending on the specific protection function. This bound covers the actual protection logic as well as communication. For current differential line protection the technical report IEC 61850-90-1 specifies communication delays in the range of 10 to 40 ms to be permitted.

B. New England Test System (NETS)

The IEEE-39 bus 10 generator network, also known as *New England Test System* (NETS, cp. Figure 3) is a reference system which is commonly used by power engineers for studying frequency stability. In this work it has been used as a basis for analysing wide area communication. For modelling an appropriate communication network architecture on top of the NETS, we assume point-to-point fibre optic cables - carried along the power lines - to connect the routers within the substations. Within this WAN data is transmitted on basis of the *Synchronous Digital Hierarchy* (SDH) protocol, considering *Optical Carrier* specification 1 (OC-1) with a data rate of 51.84 Mbps as reference case. On the local level, each substation consists of transformer and line bays, which are mapped by corresponding IEDs and interconnected by Ethernet-based LANs.

C. Related Work

The performance of Smart Grid communication has been evaluated in several previous publications, taking into account different approaches. In [6] a simulation approach using the OPNET Modeler is applied for analysing communication delays of IEC 61850-based SAS. Empirical results on the performance of IEC 61850 traffic on process level are presented in [7]. A testbed is used in [2] for studying the real-time capability of the TCP/IP based Distributed Network Protocol 3.0 (DNP3) in different Smart Grid scenarios. In [8] communication delays on bay level of substations are evaluated, comparing simulation and analytical results. A hybrid approach for co-simulating power grid and communication network is introduced in [9] and applied for analysing wide area communication within power grids in [10]. In [11] Network Calculus is proposed for analysing substation communication, yet only simulation results are presented. In comparison to these approaches, this paper covers a wide range of power grid related application scenarios, applying simulation and analytical modelling.

III. Communication Scenarios within the Power Grid

In the following we present three different scenarios, ranging from intra-substation communication in Scenario 1 to inter-

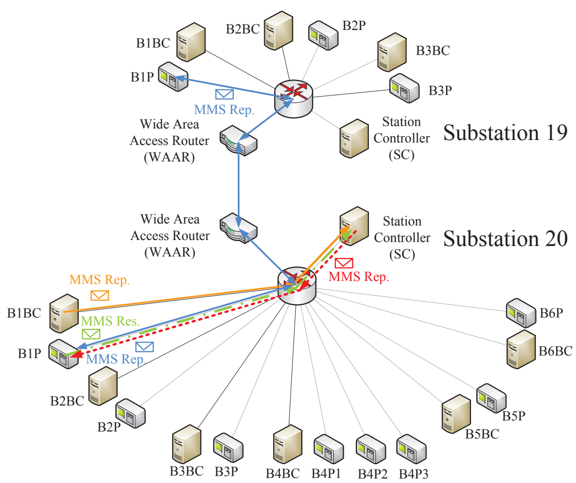


Fig. 2: Scenario 1 and 2: Topology and Traffic Flows

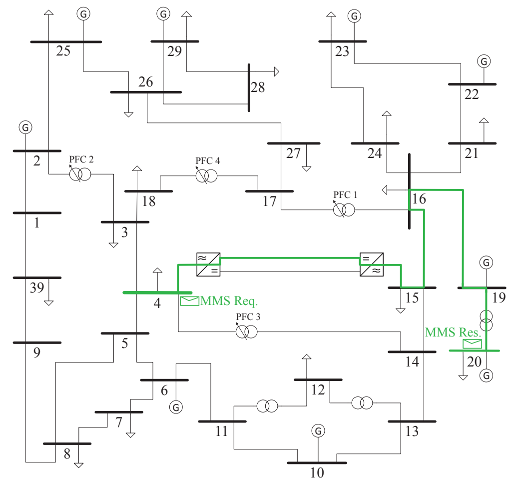


Fig. 3: Scenario 3: Topology of NETS and Traffic Flows

substation and substation-control centre communication in Scenario 2 respectively 3. In this way, we are able to derive delay bounds for various protection and control applications.

We evaluate the impact of varying IATs and traffic loads on the performance of the three traffic flows, described before, reflecting increasing real-time requirements and data volumes in Smart Grids. Here, we use "traffic load" to refer to different packet sizes of MMS reports and responses, as shown in Table I. Packet sizes are based on common header sizes of the TCP/IP protocol stack, MMS header fields defined in [3] and increasing numbers of transmitted data items. As a reference case we assume IATs of 50 ms and Traffic 1 (c.f. Table I).

With regard to wide area communication, we apply the tunnelling approach, described previously.

A. Scenario 1: Intra-Substation Communication

In this scenario communication within an exemplary substation from the NETS is analysed, focussing on data exchange between the SC and bay level devices via the substation LAN. We choose substation 20 as a medium size substation, containing six bays, including line and transformer bays. Regarding the topology of the substation LAN, we suppose bay and substation level devices to be connected to a central Ethernet switch using 100 Mbps standard Ethernet links with an average propagation delay of 1 ms between the switch and all other devices. The switch is assumed to have a processing rate of 500.000 packets/s, which equals to a mean processing delay of 2 µs.

We assume communication on substation level to comprise five different types of traffic flows as described in the following and shown in Table I. MMS reports are sent in fixed intervals from all BCs to the SC, providing measurement and status data

Messages Types	Route	Packet Size [Bit]	IAT
MMS report	SC $\leftrightarrow$ B1BC	Traffic 1: 4784 Traffic 2: 7824 Traffic 3: 10864	deterministic
MMS request	SC $\rightarrow$ B1P	Traffic 1-3: 1776	exponentially distributed
MMS response	SC $\leftrightarrow$ B1P	Traffic 1: 824 Traffic 2: 1320 Traffic 3: 1880	exponentially distributed
MMS request	SC $\rightarrow$ B1BC	Traffic 1-3: 1776	exponentially distributed
MMS response	SC $\leftrightarrow$ B1BC	Traffic 1: 824 Traffic 2: 1320 Traffic 3: 1880	exponentially distributed

TABLE I: Traffic Flows in Substation 20

from each bay to the SC. In addition, the SC randomly queries status information from the protection IEDs using MMS requests and corresponding MMS responses. Furthermore, the SC is able to trigger station-wide control actions such as interlocking or synchronous switching, wherefore MMS requests are sent to the BCs. The execution of these commands is confirmed using MMS responses.

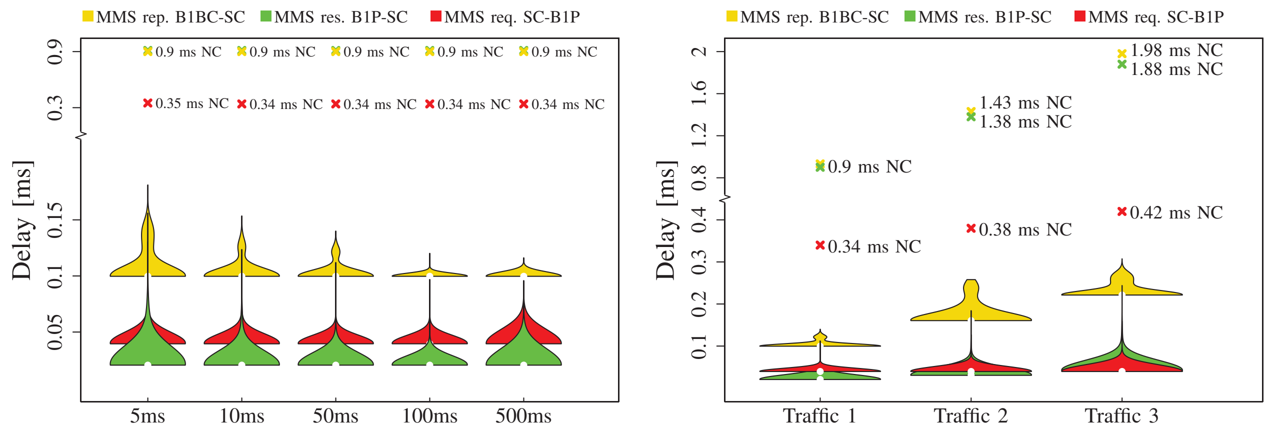
While all traffic flows described above have been modelled and analysed, we present results for three representative traffic flows (highlighted in Table I)

B. Scenario 2: Inter-Substation Communication

The second scenario deals with the delay of data transmission between two neighbouring substations, for which we selected substation 19 and 20 of the NETS. IEC 61850-90-1 describes the application of inter-substation communication for advanced protection functions such as distance line protection with blocking / permissive overreach tele-protection scheme or current differential line protection. Here, we focus on the exchange of information between two current differential line protection IEDs, located in substation 19 and 20. Differential line protection uses current measurements from both ends of the power line to determine deviations and thus detect faults. Therefore, an overall worst-case bound consists of the delay for transmitting measurement values via the WAN and the delay of the local switching command using the GOOSE service. In contrast to IEC 61850-90-1, in which the transmission of SV between substations is conceived, we propose the application of MMS for this purpose, considering the ease of addressing.

C. Scenario 3: Substation-Control Centre Communication

In contrast to the previous scenario, this analysis focusses on wide area communication between substations and a control centre. We assume the control centre to be situated at node 4 of the NETS due to its central location and dense connectivity. We assume every substation to regularly transmit measurement values to the control centre using MMS reports, so that an up-to-date global view of the power grid is obtained at the control centre. In addition, we define groups of substations, which will be addressed simultaneously in case of global intervention by the control centre. In the following we consider an incident during which the control centre communicates with four of these groups. Corresponding commands are sent out by the control centre using



(a) Influence of Inter Arrival Time (IAT) (b) Variation of Traffic Load

Fig. 4: Scenario 1: Network Calculus and Simulation Results for MMS Communication within Substation 20

MMS requests. Subsequently, after executing the command each substation transmits a MMS response to the control centre. A summary of all traffic flows in wide area communication is given in Table II. In the following, we present results for the traffic flows between substation 20 and the control centre, which are illustrated in Figure 3 along with the complete topology of the NETS. One major issue of this scenario is studying whether time-critical issues can be handled by the control centre using remote switching commands. In particular, this approach could become highly valuable for simultaneous control of several substations.

Messages Types	Route	Packet Size [Bit]	IAT
MMS report	CC ← all substations	Traffic 1: 4784 Traffic 2: 7824 Traffic 3: 10864	deterministic
MMS request	CC → S6-S9,S16, S20,S21-S24,S26-S29	Traffic 1-3: 1776	exponentially distributed
MMS response	CC → S6-S9,S16,S19, S20,S21-S24,S26-S29	Traffic 1: 824 Traffic 2: 1320 Traffic 3: 1880	exponentially distributed

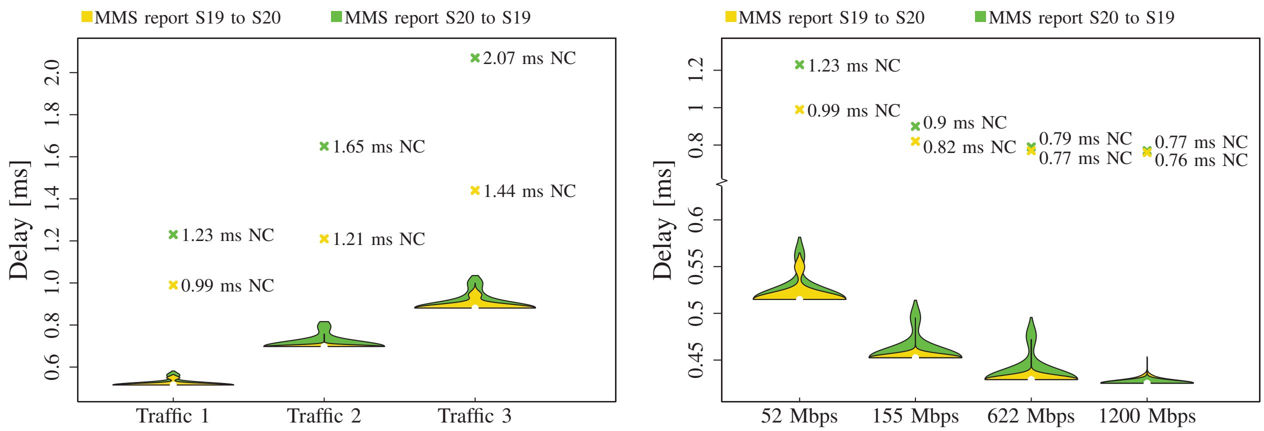
TABLE II: Wide Area Traffic Flows and Packet Sizes

IV. Real-Time Capability Analysis of the Network

In the following we present our evaluation of communication delays based on the comparison of the analytical approach of Network Calculus (NC) and OPNET simulations. NC has been first introduced by Cruz [12] and allows the computation of upper bounds on the performance of communication networks. Therefore arrival and service curves - describing the characteristics of incoming traffic flows respectively the service offered by a network node - are (de-)convolved using Min-Plus-Algebra in order to determine upper bounds on the delay, the backlog (i.e. buffer size), and the departures at certain nodes respectively throughout the whole network. As a precondition for computing end-to-end bounds, the service curves of a given path have to be concatenated for deriving an end-to-end service curve. The service curves of communication links and routers are modelled using rate-latency curves $\beta(t) = R[t - T]^+$ with R being the data or processing rate and T modelling the propagation delay or constant queueing delay. Arrivals are described by curves in the form $\alpha(t) = b + rt$, where b is the burst packet size of each traffic flow and $r = \frac{b}{IAT}$.
Complementing NC's worst-case bounds, we use simulations to obtain a detailed view of the network and to deduce mean and maximum delays. We ran simulations in OPNET Modeler with 500 seeds of the *Random Number Generator* (RNG) per configuration and a simulation time of 5 minutes.
The results, shown in Figures 4 to 6, can be interpreted as follows: Delays, determined in simulations, are depicted using so-called violin plots [13]. Each violin holds all delays found in simulation, weighted by the frequency of their occurrence: the more frequent a certain delay, the wider the corresponding part of the violin. Here, different colours indicate different message types. Above each violin, associated NC bounds are shown, marked by an 'x' and the corresponding numerical value.

A. *Scenario 1: Intra-Substation Communication*

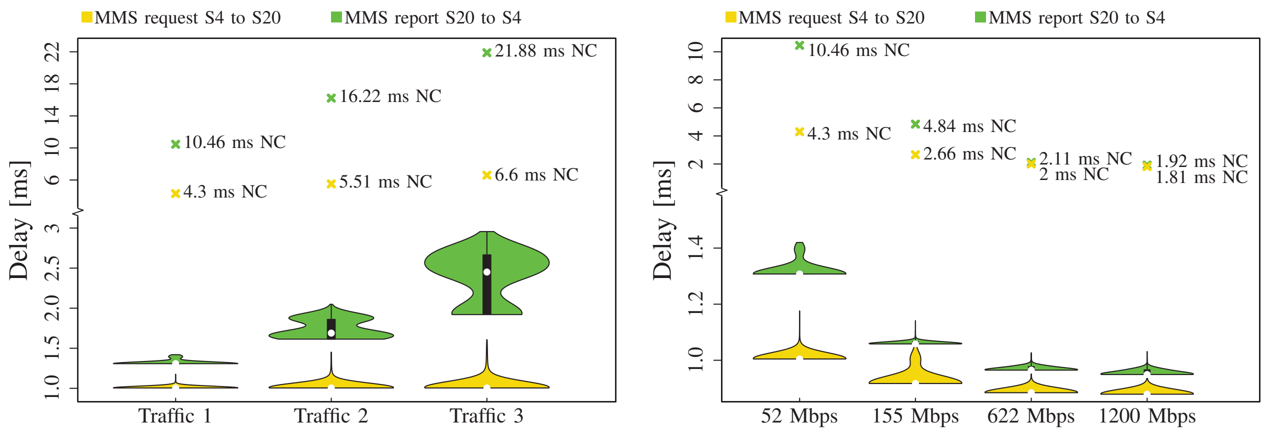
The following analysis focusses on the communication delay of MMS messages on substation level, using substation 20 of the NETS as an example. Figure 4a shows decreasing maximum delay values in simulation - according to the peaks of the violins - for all three message types, while increasing the IAT from 5 to 500 ms. In contrast mean delays as well as NC' delay bounds, are reduced only slightly in the range of 10 µs. For example, the maximum delay of MMS reports from the bay controller B1BC to the SC declines from 0.18 ms to 0.12 ms, whereas the mean delay remains in the range of 0.10 ms. By comparison, NC provides an upper bound of about 0.90 ms. As for MMS responses to the SC and MMS requests to the protection IED B1P, the same development can be observed. Interestingly, MMS requests exhibit larger mean delays compared to MMS responses, whereas the peak delay in simulation is higher for MMS responses. This observation is supported by the comparison of the delay bounds, gained by NC computation. This result can be attributed to the following effect: MMS requests require longer transmission times due to their larger packet size compared to MMS responses. However, MMS responses and requests are transmitted in opposite directions, whereat MMS responses are interfered by more traffic flows, which results in higher peak delays.
Next, we increase the traffic load (c.f. Figure 4b), resulting in a considerable rise of delay times. In case of MMS reports the reference maximum delay of 0.14 ms has more than doubled (0.31 ms). The same accounts for the NC bound, which rises from 0.9 ms to 1.98 ms. A similar development can be observed for the delay of MMS responses. In contrast the mean delay of MMS requests barely increases, since their packet size remains unchanged. Yet, the impact of MMS reports' and MMS



(a) Variation of Traffic Load

(b) Influence of Wide Area Link Capacity

Fig. 5: Scenario 2: Network Calculus and Simulation Results for MMS Communication between Substation 19 and 20



(a) Variation of Traffic Load

(b) Influence of Wide Area Link Capacity

Fig. 6: Scenario 3: Network Calculus and Simulation Results for MMS Communication between S20 and CC (4)

responses' higher traffic load on the delay of MMS requests is encountered, regarding the rise of maximum delay and NC' delay bound.

Altogether, the variation of packet sizes clearly affects communication delay, while different IAT have only minor impact. Delay requirements of 100 ms defined for typical SC applications can be met at all times and even time-critical switching commands with bounds of 10 ms can be fulfilled without difficulty, leaving room for additional processing time. While there is a clear gap between the maximum simulation delay and NC's upper delay bound, both techniques show comparable trends.

B. *Scenario 2: Inter-Substation Communication*

In this scenario we evaluate the performance of inter-substation communication based on the example of current differential line tele-protection IEDs, while varying IAT, traffic load and the capacity of WAN links. Similarly to intra-substation communication, the delay of MMS reports from substation 20 to 19 and vice versa barely responds to the variation of IAT, wherefore it is not discussed in detail.

By contrast, with rising traffic loads the upper delay bounds of both traffic flows significantly increase for MMS reports from substation 20 to 19 (from 1.23 ms to 2.07 ms) as well as in opposite direction. Other than in simulation, this gap even widens, as can be seen in Figure 5a. Yet, also in simulation, the mean and maximum delay of messages from substation 20 to 19 (peak delay: 0.58 ms to 1.04 ms) - and vice versa - rises.

Finally, Figure 5b shows communication delays for data rates from 51.84 Mbps up to 1244.16 Mbps on WAN links, complying with OC-1, -3, -12 and -24. With the increase of the data rate, mean and peak delays, found in simulation, decrease due to faster message transmission. For example the peak delay of MMS reports from substation 20 to 19 reduces from 0.90 ms to 0.45 ms. The same accounts for NC's upper bound which diminishes from 1.23 ms to 0.77 ms for this traffic flow. In addition, the bounds of both traffic flows converge for increasing link capacities, since disturbance by other traffic flows is reduced due to faster transmission speed.

On the whole, similar behaviour of the traffic flows can be identified with both NC and simulation, despite of the deviation in the magnitude. The variation of traffic loads and link capacities considerably weakens respectively advances the performance of traffic flows, whereas IATs barely affect delay times. Taking into account GOOSE messages' NC bound of 0.12 ms [8], delivers an overall bound of 2.19 ms in the worst-case (Traffic 3, S20→S19). Even this NC bound is clearly below the bound of 10 to 40 ms required for current differential line tele-protection.

C. Scenario 3: Substation-Control Centre Communication

For the analysis of communication between the control centre and substation 20 we apply the same steps as in the previous scenario, evaluating the impact of different IAT, traffic loads and link capacities. Assessing the increase of the IAT, NC demonstrates MMS requests from the control centre to the substation and MMS reports in opposite direction to be barely influenced (reductions in the range of a few microseconds).
Regarding the increasing traffic loads in Figure 6a, we find that MMS reports' NC delay bound has more than doubled (21.88 ms). This trend is reflected by the simulation results. Yet, simulation provides a more detailed view on this issue, showing risen mean delays and significant variation of delay times for higher traffic loads. This large range of delay times might be a result of the increased probability of this traffic flow being interfered by other traffic flows due to its larger packet size. Compared to that, the mean delay of MMS requests to substation 20 remains nearly unchanged at approximately 1 ms, since the packet size has not changed. However the peak delay in simulation as well as NC' delay bound show a slight increase, as MMS requests are interfered by MMS reports more often.
In Figure 6b, both simulation and NC indicate significant impact of varied link capacity. In case of MMS reports transmitted to the control centre NC's upper delay bound drops from 10.46 ms to 1.92 ms, while the maximum delay in simulation reduces from 1.42 ms to 1.03 ms. Similar results can be observed for MMS requests to substation 20. However, with increasing data rates of the wide area communication links the deviation between the two traffic flows minimizes. One possible reason is the diminishing impact of transmission delay compared to propagation delay for high data rate links. While the propagation delay is the same for both message types, the transmission delay depends on the packet size and is therefore significantly higher for MMS reports. All in all, the worst case bounds, determined by NC, are not reached by the maximum delays in simulation in any case. Nevertheless, this scenario demonstrates remote control by the control centre to be applicable for triggering time-critical functions, since even rather pessimistic NC bounds for MMS requests from the control centre are below a limit of 10 ms in all cases. In particular, this might be an interesting solution, considering wide area communication links using OC-12 or -24 and thus achieving upper delay bounds of approximately 2 ms.

V. Conclusion and Future Work

In this paper we evaluated the performance of IEC 61850 based substation and wide area communication using simulation and analytical modelling to derive average and worst-case delays. While the variation of traffic loads and link capacities exhibits to have significant influence on the delay of traffic flows, IAT has shown only little impact on their performance. We concluded the substation LAN being able to handle even high amounts of measurement data and to transmit switching commands efficiently. While time-critical control mechanisms currently rely on local data, future applications are likely to consider wide area information and thus require fast data transmission between neighbouring substations. On the example of current differential line tele-protection, we prove the applicability of inter-substation communication for time-critical protection functions. Moreover, we were able to show that remote control of substations from the control centre can be established using high performance fibre connections, complying with strictest delay bounds of 10 ms. Yet, it has to be emphasized that higher traffic loads can increase the delay significantly. In contrast to IEC 61850-90-1 and -90-2, we propose the use of MMS messages for communication in WANs due to their ease of management and addressing. Furthermore, we highlighted NC and simulation results to show similar trends, despite of deviations in magnitude (about 10 ms).
In future work, we will refine our results by considering actual processing times of protection and control functions to provide a holistic view of the performance of the power grid's ICT infrastructure. Besides, the impact of security mechanisms such as message encryption will need to be considered for detailing the analysis of the real-time capability. Moreover, we aim at enhancing the reliability of the ICT infrastructure on substation and core network level by applying the concepts of Software-defined Networking.

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