# Simulation Models for IEC 61850 Communication in Electrical Substations Using GOOSE and SMV Time-critical Messages

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***Abstract*—IEC 61850 is a communication standard for electrical Substation Automation Systems (SAS). It defines both the information model and services used for communication between Intelligent Electronic Devices (IEDs) in a substation. The adoption of this standard brings several advantages for the design and operation of substations. The abstract data models defined in IEC 61850 can be mapped upon application protocols, such as MMS, GOOSE or SMV. These protocols can run upon TCP/IP networks or upon specific high speed Ethernet LANs, in order to match the timing requirements associated to protective relaying mechanisms. For the specific case of GOOSE messages, the standard specifies the use of VLANs (Virtual LANs) with priority tagging (IEEE 802.1q) to implement separate virtual networks with the appropriate message priority levels, in order to ensure the specified response times. The lack of adequate simulation models that enable the response time assessment of both SMV and GOOSE messages is one of the shortcomings of available simulation tools. In this paper, we propose simulation models for the IEC 61850 communication standard, targeting application that use GOOSE and SMV messages. This simulation models has been built upon OMNeT++/INET. The simulation results obtained from a typical IEC 61850 communication scenario show the effectiveness of the developed models. Some of these results have been experimentally validated.**

***Index Terms*—IEC 61850, smart grid, GOOSE, SMV, OMNeT++, real-time communication, substation automation systems**

## I. Introduction

Electric Power Systems (EPS) are considered to be one of the largest machines built by humans, not only for its geographic dimension, but also for its synchronism. Maintaining such a system in operation is not a trivial task and the most efficient way to accomplish it is dividing it into regions through electrical substations. Within substations, electrical power is manipulated in order to obtain acceptable voltage levels for transmission, distribution and consumption processes.

Electrical substations are typically formed by electromagnetic machines responsible for voltage and power management (Fig. 1). Power Transformers and Instrumentation Transformers (IT) are examples of these kind of machines. There are also devices (such as protection relays, switchgear, circuit breakers, etc.) used for the protection and control of EPS operation. Some further elements such as cables and network devices (switches, workstations, etc.) assist in the interconnection and supervision of substation infrastructure.

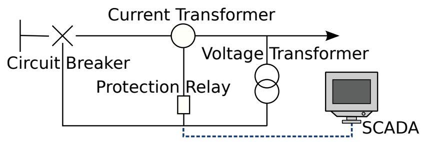


Figure 1. Basic layout of substation automation and protection system.

In order (i) to ensure high availability of electrical power, (ii) to reduce the service restoration time after failures and (iii) to reduce the manpower costs, electricity business agents pursue the automation of some of the operations performed by electrical substations. Within this context, Intelligent Electronic Devices (IED) are key elements for the fulfillment of these targets and consequently of a smart grid. IEC 61850 standard boosts the achievement of these goals by defining both the information model and the communication services used in EPS's automation systems, particularly in electrical substations.

One of the critical aspects for the automation of EPS is the timely transmission of time critical information, such as status changes, blockings, releases or trips between IEDs. The IEC 61850 standard defines two types of time-critical communication services: GOOSE (Generic Object Oriented Substation Event) is used for the transfer of sporadic time-critical data, usually associated to protective relaying activities; SMV (Sampled Measure Value) is used for the transfer of periodic time-critical data, such as the transfer of synchronized streams of current or voltage samples. Therefore, the assessment of the timing requirements associated to both GOOSE and SMV messages is of critical importance for the analysis of the operation of EPS critical tasks, such as control and protection tasks [1], [2].

As a complement, there is also the need to evaluate the reliability and safety of these communication processes. Therefore it is highly desirable to have adequate simulation tools for the assessment of EPS operation, specially during product development and human resources training phases [3], [4].

In this paper, we propose a set of new simulation models for communication in electrical substation, that enable the timing assessment of GOOSE and SMV messages exchanged through an IEC 61850 based substation process bus. These simulation models have been developed using the OMNeT++/INET framework. The validation of the proposed simulation models have been made both by the simulation of a typical SAS scenario, and by its comparison with the results obtained from an experimental setup.

The main contributions of this paper are:

- A set of simulation models that fully implement both the IEC 61850 application layer protocols and a link layer message prioritization compliant with IEEE 802.1q;
- An extension of simulation models offered by the OMNeT++/INET framework to support GOOSE and SMV messages. These extensions allow the configuration of all parameters defined by IEC 61850, and can be freely downloaded from [5];
- The proposed simulation models have been validated by a set of experiments using real IEC 61850 based equipment.

This document is organized as follows: **Section II** provides a brief background about the IEC 61850 standard and the main network technology components used in SAS. **Section III** presents an overview of related works. **Section IV** describes some characteristics that must be considered to obtain a valid representation of both IEDs and switches used in process bus for SAS. **Section V** introduces the substation scenario used in this paper for simulation purposes, discusses the laboratory experiments and compares the results obtained from both techniques. Finally, **final remarks** are presented.

## II. Background

### A. IEC 61850

The integration of IEDs provided by different manufacturers is one of the challenges faced by electrical substation designers. To assist in this process, the International Electrotechnical Commission published the IEC 61850 standard, which establishes guidelines to achieve interoperability in the communication networks of SAS [3]. One of the main contributions of the IEC 61850 standard is the definition of the information model that must be used by substation devices for their communication.

The modeling process defined by the standard aims to represent the complex functions of the IED (also named as Physical Devices - PHD) as a set of simpler functions called Logical Nodes (LN). This LNs, in turn, can be grouped to form complex entities called Logical Device (LD) [6]. The standard also specifies communication services (data read/write, event reporting, logging, etc.), which describe the mechanisms used to transmit information between IEDs [7]. More precisely, the standard defines the data to be communicated (information model) and the way in which this data should be communicated (communication services). Fig. 2 shows an IED according to the vision of the information model specified by IEC 61850.

In addition to the information model and the communication services, the IEC 61850 standard also defines a communication architecture divided into two buses (Fig. 3) [8]. The first – **Station Bus** – is used for monitoring and control operations

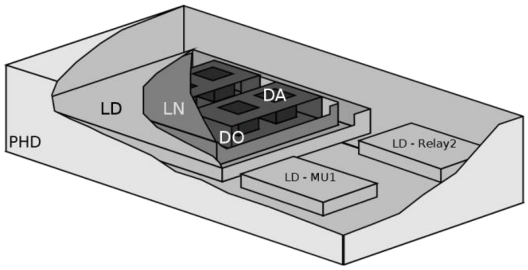


Figure 2. IED information model.

of substations. This bus carries messages among the substation operators (SCADA) and protection relays. The second – **Process Bus** – interconnects Instrument Transformers (IT) and protection relays, reducing the construction and maintenance costs associated with traditional wired connections [9].

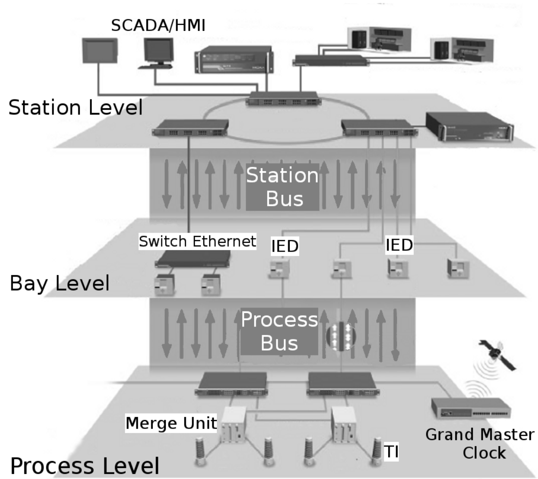


Figure 3. IEC 61850 substation architecture.

### B. Process Bus Communication Protocols

To achieve interoperability, the IEC 61850 standard uses the OSI Reference Model (RM-OSI) as the basis of its communication protocol suite [10]. There are three main application protocols used in the IEC 61850 environment: MMS (Manufacturing Message Specification), GOOSE and SMV (Fig. 4). The MMS protocol is mapped into a seven-layer communication stack and it is mainly used for Station Bus transactions. It operates as a client-server protocol, and optionally provide real-time communication mechanisms. On the other hand, GOOSE and SMV protocols, use just the three lower layers of RM-OSI, reducing message overheads and simplifying communication between IEDs. These two protocols operate with the publisher-subscriber model and are predominantly used for Process Bus transactions.

The IEC 61850 document is organized into ten main parts. Parts 8 and 9 are important for the Process Bus definition, which is the focus of this paper. Specifically, Part 8 describes the GOOSE protocol and Part 9 describes the SMV protocol. The former is used to transmit information closely related to monitoring and control functions (circuit breaker states, etc.),

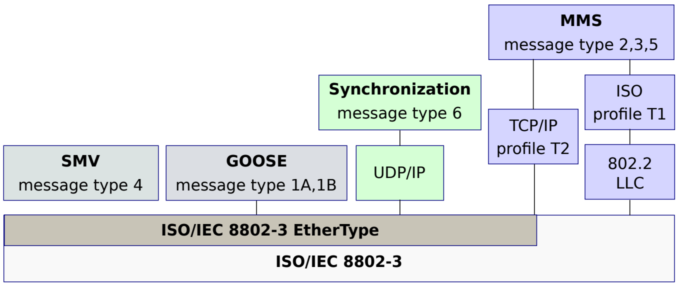


Figure 4. IEC 61850 and RM-OSI protocol communication mapping.

while the latter is used for transmission of digital samples of current and voltage signals.

To increase the communication reliability, the GOOSE protocol specifies a periodic information transmission that maintains a continuous flow of data among LNs. Each message in the transmission sequence has an attribute called Time allowed To Live (TTL) that informs the receiver about the maximum time that it must wait before the arrival of the next message. As shown in Fig 5, upon the occurrence of a relevant event (e.g. circuit breaker state change), this time is immediately reduced to a minimum configured value ($P_l$) and gradually restored to its initial ($P_s$) value. If a message does not arrive before the expiration of TTL, the receiver must assume that the connection was lost.

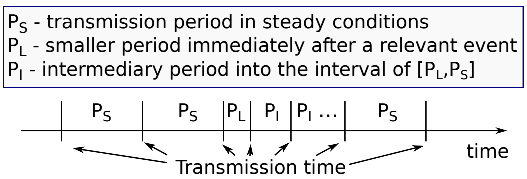


Figure 5. GOOSE temporal behavior.

Although both protocols being defined with a publish-subscriber model, the main difference is that GOOSE repeats the same information in several consecutive messages, while in SMV, consecutive messages do not contain the same information. As a consequence, for the SMV protocol, the publisher adds a time stamp to each message enabling the subscriber to check its temporal correction (deadline fulfillment). Another difference is that SMV periodically send messages at a fixed rate, whose value depends on the frequency of the power system (4800 and 4000 message per second, for 60 Hz and 50 Hz power systems, respectively) [11].

IEC 61850 standard completes its information model specifying the time constraints for messages typically used in major substation's operations. Table I shows seven types of messages along with their respective time constraints, where GOOSE messages are classified as type 1A or 1B, and SMV messages are classified as type 4. It is worth noting that GOOSE and SMV have the smaller required transmission times among all IEC 61850 types of message.

### C. Ethernet Technology for Process Bus Communication

IEC 61850 uses IEEE 802.1q upon IEEE 802.3 (switched Ethernet) standards to deal with time constraints in Process Bus applications. IEEE 802.1q allows both: (i) processing of messages with priority-based scheduling policies, and (ii) segmentation of local area networks (LAN) into virtual networks (VLAN) to upper-bound the diffusion domain of broadcast and multicast messages. Additionally, in order to ensure real-time deterministic communication [12], it is mandatory to have Ethernet switches compliant with the IEEE 802.1q standard.

Table I
IEC 61850 MESSAGE TYPES AND TIME CONSTRAINTS.

| Message type | Time requirement | Comm. Bus | Example application |
|---|---|---|---|
| **1A** – Fast messages, trip | Transmission time $\leq$ 3ms | Process bus | Circuit breaker commands (trip, close, reclose, start, stop, block), states etc. |
| **1B** – Fast messages, others | Transmission time $\leq$ 20ms | | |
| **2** – Medium speed messages | Transmission time $\leq$ 100ms | Process and Station Bus | RMS values calculated from type 4 messages. |
| **3** – Low speed messages | Transmission time $\leq$ 500ms | Process and Station bus | Alarms, configurations, non-electrical measurand, etc. |
| **4** – Raw data messages | Transmission time $\leq 208.3\mu s$ [a] | Process bus | Digital representation of electrical measurand (SMV) |
| **5** – File transfer functions | Transmission time $\leq$ 1000ms | Process and Station bus | Files of data for recording, settings, etc. |
| **6** – Time synchronization messages | N/A | Process and Station Bus | IED internal clock synchronization |
| **7** – Command message with access control | N/A | Station bus | Based on type 3 message with additional password verification procedures |

[a] SMV transmission period for protection applications in 60Hz grids.

Fig. 6 shows the basic structure of SMV and GOOSE messages, with respect to IEEE 802.3 and IEEE 802.1q standards. It is important to note the presence of the VLAN TCI field, which has twelve bits to identify the destination VLAN and three bits to indicate the level of priority at which the message must be handled by the receiver.

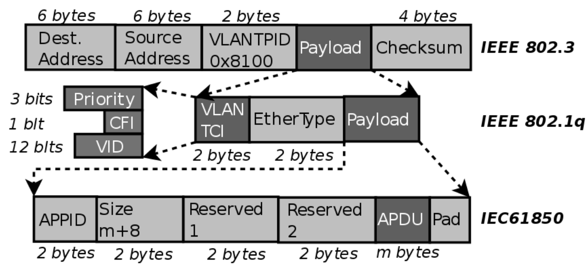


Figure 6. Process bus communication protocols encapsulation.

## III. Related work

In the literature, it can be found three main approaches to deal with the assessment of IEC 61850 based Process Bus communication: analytical studies, simulation approaches using available simulation tools and experimental studies with real equipment and prototypes. Each approach has its own advantages and disadvantages.

Analytical studies usually consider the SAS's worst case operation behavior to assess the service provided by the communication networks. However, depending on the application, this type of analysis can introduce an excessive level of pessimism, thus unnecessarily restricting the design and installation of network devices. In [13]–[15], are described algorithms for traffic flow calculation, which evaluates the maximum delay suffered by messages, in particular switched communication networks. Additionally, in [16], some analytical models are proposed considering that some traffic flows are events generated by humans, which are not generally the case in modern substations.

On the other hand, evaluation techniques using real equipment or prototypes can hardly reproduce complex operation scenarios of real substations, especially those requiring a large number of devices. In [17], specific hardware (electric signal generators, IED emulators and network traffic capture board) is used to study the interaction between time synchronization protocols and IEC 61850 communication protocols. Other works, as in [18], use the so-called Real-Time Digital Simulator (RTDS) to study the behavior of SAS in close to real situations.

Finally, using available simulation techniques allows the assessment of multiple substation scenarios at relatively small cost and risk. However, the availability of adequate simulation models becomes a crucial step to obtain reliable results. In [19]–[21] are presented simulation platforms for the study of some particular features of IEC 61850. [19] proposes both simulation models for the OMNeT++/INETMANET framework to support IEC 61850 based communication, and a specific interface to manage messages coming from external networks and incorporate them into the simulated environment. [20] presents also simulation models of IEDs for the OMNeT++/INET. The modeling of a device known as Phasor Measurement Unit is detailed. [21] proposes simulation models for SAS devices using the OPNET tool. The author shows the flexibility of the simulation technique applying different network architectures and bandwidths to the same scenario. It is worth noting that some of these works use messaging frequency and size that are not in accordance with those specified by IEC 61850.

A shortcoming of these studies is that they focus on the modeling of communication interactions at the application layer, disregarding existing data link layer communication services, such as VLAN and prioritization mechanisms. In particular, these works ignore the modeling of IEEE 802.1q standard services and Ethernet switches, which are essential for the study of IEC 61850 communication for substation.

In this paper, we seek to overcome this inefficiency by defining adequate simulation models that implement the core of VLANs and the IEEE 802.1q mechanisms.

## IV. IED Modelling Principles

### A. P&C IED and MU IED models

The IEC 61850 standard classifies the substation automation equipment according to the three automation levels (Fig. 3). These equipment can also be classified according to the type of handled messages. For the case of Process Bus, assuming that IEDs performing Protection and Control functions (P&C) do not perform monitoring functions (Merging Units - MU), and vice versa, it is also possible to consider that there are two types of devices: (i) those that handle SMV messages and (ii) those that handle GOOSE messages.

Some further considerations are assumed for the proposed IEDs models:

- IEDs that are part of the P&C group, generate and process GOOSE messages. These IEDs do not generate SMV messages, but are able to process them every time they receive one of those messages.
- IEDs that are part of the MU group just generate SMV messages. That is, these devices do not process any other kind of message (not even SMV messages).
- The two types of IEDs are modeled from the communication point of view, thus avoiding details on the hardware operation (such as the frequency of the processor, type of analog-digital converter etc.).

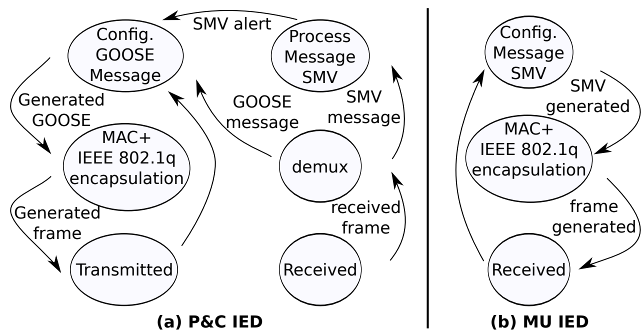


Figure 7. IED state machine for the simulation model.

As GOOSE and SMV messages are directly mapped upon the IEEE 802.3 standard, the procedures for generation and reception of messages are structured according the RM-OSI architecture. Consequently, to maintain compliance with IEC 61850, these models were implemented with functions for the application, data link and physical layers. The functions performed by each of these three layers are discussed below.

- **Application layer**: For the generation role, this layer is in charge of defining the elements and values that make up GOOSE or SMV messages. For the reception role, this layer analyzes the content of the messages and determines the behavior of the IED.
- **Data link layer**: For the generation role (handling data coming from the application layer), this layer is responsible for encapsulating data in IEEE 802.1q frames. For the reception role (messages coming from the physical layer), the data link layer identifies the MAC address to verify if the message is addressed to the IED and then extract its contents. At this point, the data link layer executes the demultiplexing function (demux) for determining whether the message should be handled as an SMV or GOOSE message by the application layer.
- **Physical layer**: This layer takes care of the point to point connection among the network IEDs (and possibly

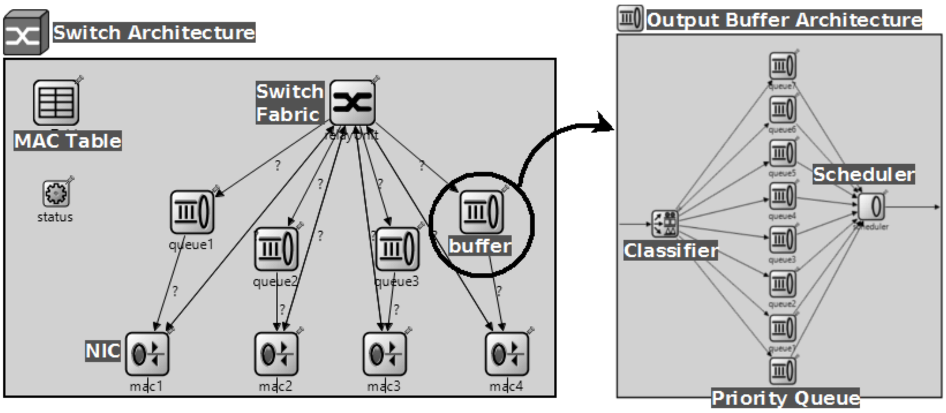


Figure 8. Switch model in OMNeT++/INET.

between an IED and a switch). At this layer, the data transmission configuration parameters can be defined, such as full-duplex communication parameters, buffer sizes, etc.

Fig. 7 illustrates the state diagram of simulation models for IED of type P&C (Fig. 7(a)) and MU (Fig. 7(b)), which were implemented upon the OMNeT++/INET simulation environment. These models are available for download from [5].

### B. Switch model

A switch simulation model was also developed, in compliance with the IEEE 802.3 and IEEE 802.1q standards. In the proposed simulation model, are included mechanisms to support fixed priority scheduling policies, targeting the performance classes described in Table I.

The OMNeT++/INET implementation for the switch simulation model contains three main elements: (i) Network Interface Card (NIC), (ii) Switch fabric and (iii) output buffers. In this model, there is a NIC and eight buffers (one for each IEEE 802.1q priority level) for every Ethernet port.

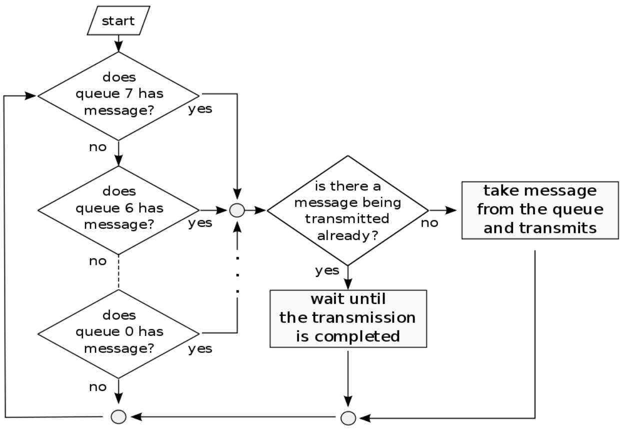


Figure 9. Fixed priority scheduling algorithm implemented within the switch model.

When a message is received by one of the Ethernet ports (NIC) of the switch, it is directed to the **switch fabric** to determine which port must be used for the message to arrive at its destination. Thereafter, the message is routed to the **classifier module** (contained in the corresponding output buffer), which organize the message in one of eight **output queues** according to its priority level (7 and 0 are the highest and lowest priority levels, respectively). Finally, the **scheduler module** checks the availability of messages in each output queue and processes them with the specified order. The architecture of the switch simulation model is presented in Fig. 8, while the algorithm used by the scheduler for message processing is illustrated in Fig. 9.

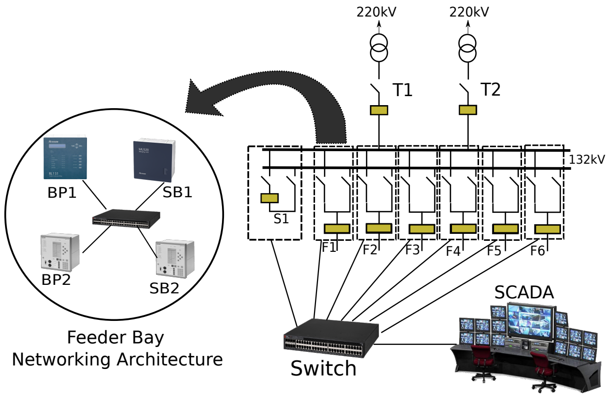


Figure 10. D2-1 substation one-line diagram.

## V. Simulation and Experimental Results

### A. Reference IEC 61850 Architecture

A relevant communication scenario was then built, considering the most important features of the substation operation, especially the volume and type of traffic, required to validate the components of the simulation model. The D2-1 reference substation configuration (as defined by IEC 61850) was selected as the case of study to analyze the behavior of an SAS Process Bus. The selection criteria were primarily its simplicity and the fact that this configuration has been widely used by other academic papers [19]–[21], and therefore, it becomes easy to compare the obtained results with the results from other research works. Fig. 10 shows the single line diagram of the substation along with the SAS.

A star topology was selected to interconnect the SAS communication network devices. Devices with a SB1 name represents those intended to measure electrical parameters (MU), while the BP1, BP2 and SB2 devices represent devices for protection and control functions (P&C). In Fig. 11, the names inside each device indicate LN assigned to them.

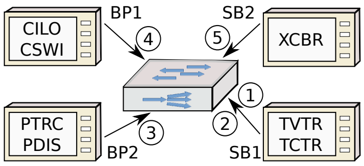


Figure 11. Intrabay defined sequence of events.

After defining the communication architecture of the SAS, a communication scenario was defined for assessing the temporal behavior of messages in the communication bus. Fig. 11 illustrates the sequence of events for an affected feeder bay of substation D2-1:

① In safe operating conditions, the IEDs with SB1 name (i.e. those of the MU type) transmit voltage and current samples using multicast messages in accordance with the SMV protocol [11]; that is, 4800 messages per second, containing information of four voltage-current pairs.

② An electrical fault (over-current, for example) is generated in one feeder bay, and the corresponding Logical Node PDIS (contained in the IED BP2) receives and process the message from the Merging Unit (SB1) detecting "emergency" currents and voltages values.

③ A sequence of multicast GOOSE messages, notifying the event at the substation, is forwarded from the LN PDIS. Despite being received by every device, only LN CSWI (contained in the IED BP1) will process this message.

④ Next, another sequence of multicast GOOSE messages is then transmitted from LN CSWI. This message is processed by LN XCBR (from IED SB2), in order to perform the opening/closing of the circuit breaker on the affected feeder bay.

⑤ Once performed the opening operation, a new sequence of multicast GOOSE messages is generated from LN XCBR. LN CSWI process this message to aware about the contact state change.

It is worth noting that the listed events show just a intra-bay interaction, i.e there are no messages from other bays. Therefore the analysis can be applied for any of them.

## B. Simulation Results

Simulations were performed using the D2-1 substation reference architecture, aiming to validate the simulation models developed for the SAS Process Bus. In the simulations, two network infrastructures are used: The first one considers that each bay has a dedicated switch and there is an additional central switch to interconnect all bays. The other infrastructure considers a single central switch to connect all substation devices. In this second scenario, called the "low-footprint scenario", VLANs were created to separate data streams according to their bay of origin.

As the events defined for this case of study implement just an intrabay data stream, the maximum amount of MU devices that a bay can support (according to the time constraints of the messages) was also investigated. In addition to this simulation assessment, some experiments with real equipment were also implemented to replicate one of the bays of the D2-1 reference architecture. The comparison of both simulation and experimental results is shown at the end of this section. Table II presents the SAS message characteristics, that were used for all the assessments. The end-to-end transmission time (end-to-end delay of the messages) was used as the main performance metric to perform these experiments.

Message priorities were assigned according to the Deadline Monotonic policy (DM) [22], which is considered an optimal fixed priority scheme for scheduling periodical tasks with deadline values smaller than or equal to their period. The highest priority of the system (7) was assigned to the SMV messages generated by an SB1 device. Note that also according to the type of message processed by every node, the network traffic was divided into two VLANs (VLAN2 for GOOSE and VLAN1 for SMV messages, respectively). Thus, as BP2 device (protection relay) belongs to both VLANs and receives every transmitted message, the switch port where it is connected to can suffer from the congestion and message delays in the system.

Table II
D2-1 COMMUNICATION AND ELECTRICAL CHARACTERISTICS.

| **Electrical characteristics** | | | |
|---|---|---|---|
| | **Feeder** | **Transformer** | **Section** |
| **Number of bays** | 6 | 2 | 1 |
| **MU per bay** | 1 | 1 | 1 |
| **P&C per bay** | 3 | 3 | 3 |

| **Communication characteristics** | | |
|---|---|---|
| | **GOOSE** | **SMV** |
| **Transmission period** | Stable operation: 992ms<br>After event: 31ms | 208.3$\mu$s<br>(4800 frames/s) |
| **Message size** | 160 bytes (typical size according [23]) | |
| **Transmission time** | 13.71$\mu$s time at 100Mbps | |

| **Timing characteristics** | | | | |
|---|---|---|---|---|
| **Message type** | **Priority** | **VLAN** | **Source node** | **Destination** |
| SMV | 7 | 1 | SB1 | BP2 |
| GOOSE | 6 | 2 | BP2 | BP1,SB2 |
| | 5 | | BP1 | BP2,SB2 |
| | 4 | | SB2 | BP1,BP2 |

### *B.1 Simulation results considering the Low-footprint Architecture*

Table III shows the comparison of simulation results using the proposed network architecture. The simulation time was fixed at 100 seconds and 4 critical events were simulated (one every 20 seconds). Note that the values of end-to-end delays are independent of the type of architecture used whenever VLAN resources and priorities are used. Fig. 12 illustrates with higher detail the delay for a GOOSE message, where sequence of events is explained below.

1) Arrival of a GOOSE message with priority 4. This message is generated by an SB2 device and arrive to the output buffer of the switch where the device BP2 (protection relay) is connected (port 3).

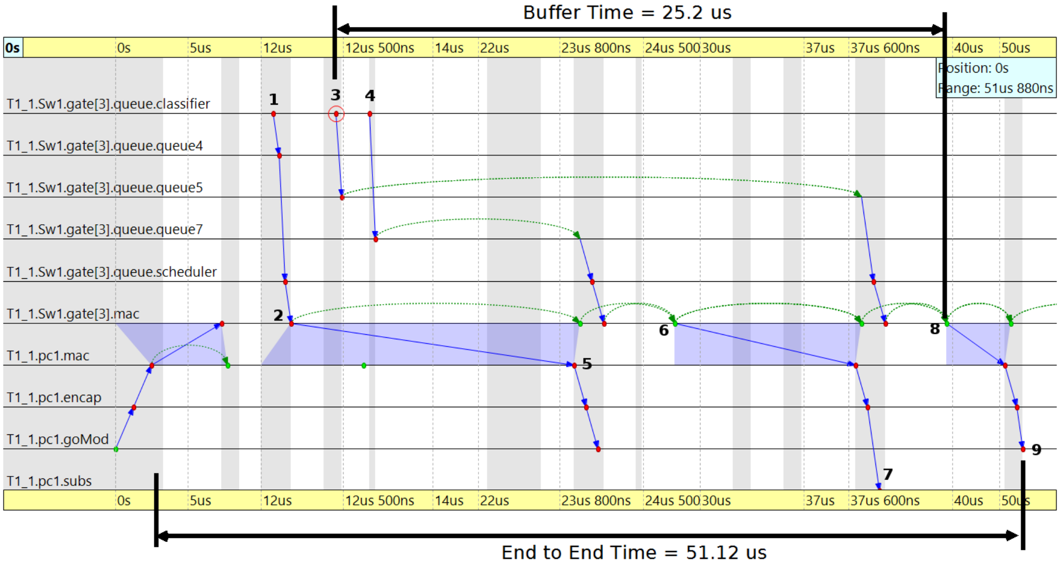


Figure 12. Maximum end-to-end delay situation.

2) Start of transmission of message from SB2 through port 3 of the switch. Arrival of the GOOSE message with priority 5 generated by BP1 device. As a message from IED SB2 is already occupying the channel, the IED BP1 message waits in the output queue, suffering delay due to blocking [22].
3) Arrival of the SMV message with priority 7 generated by SB1 device. As the message from IED SB2 is already occupying the channel, the IED SB1 message waits in the output queue, suffering delay due to blocking.
4) Completion of the message transmission from IED SB2. The maximum end-to-end delay of this message was about 23.8 $\mu$s, including the IED and switch processing time (not shown in Fig. 12).
5) Start of transmission of message SMV from SB1 IED. As the message from BP1 IED has a lower priority, this message waits in the outgoing queue even though it has arrived before the SMV message. Such characteristic evidences the inexistence of priority inversion [22] in the system when priority assignment is used: the message from BP1 IED suffers only delays due to interference from messages with higher priorities.
6) Completion of transmission of the message from IED SB1.
7) Start of transmission of message from BP1 IED.
8) Completion of transmission of the message from IED BP1. The maximum end-to-end delay for this message was about 51.12 $\mu$s

Table III
MAXIMUM END-TO-END DELAY FOR STANDARD AND LOW-FOOTPRINT ARCHITECTURE.

| **IED source** | SB2 | BP1 | BP2 | SB1 |
|---|---|---|---|---|
| **End-to-end delay** | 51.1 $\mu s$ | 51.1 $\mu s$ | 37.0 $\mu s$ | 37.7 $\mu s$ |

Note that the IED processing time does not affect the blocking time or the interference suffered by a message on the switch. This occurs because the IEDs have buffers large enough to allow the switch to retransmit a message when the channel is released (while respecting the IFG time – Inter Frame Gap).

### *B.2 Extended simulation results with scalability analysis*

Table IV illustrates the maximum end-to-end delay values obtained when using 13 and 14 MU devices in a D2-1 substation bay. The MU devices have been configured to transmit 4800 messages per second, with messages size of 160 bytes. An important result to note is that 13 devices is the maximum number of devices that can be installed in the network, according to the simulation results. When 14 MU devices are considered, the deadline for SMV messages (208.3$\mu$s) is not always respected.

Table IV
MAXIMUM END-TO-END DELAY WITH EXTENDED SCENARIO.

| **MU quantity** | **Maximum end-to-end delay** |
|---|---|
| 13 | 201.6 $\mu s$ |
| 14 | 215.5 $\mu s$ |

## C. *Results from the Experimental Setup*

Fig. 13 illustrates the laboratory architecture used to experimentally validate the simulation results. This architecture mimics the substation bay illustrated in Fig. 11. The set of used equipment is described below:

- Two bay controllers compliant with IEC 61850;
- A switch with throughput of 48 Gbps and compliant with the IEEE Standard 802.1q;
- A GPS clock with synchronization output;
- A Merging Units capable of generating SMV messages;
- One computer with software for protocol analysis (sniffers);

The experimental results were compared against the simulation results and the comparison is reported in Table V. As

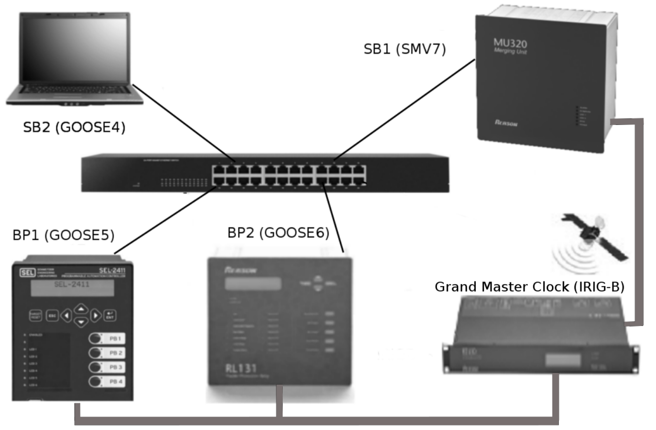

Figure 13. One bay laboratory architecture.

it would be expected, with the simulation platform is possible to run a larger number of events, facilitating the finding of worst-case operating points (with higher delays) more easily than using the experimental evaluation setup. Nevertheless, the closeness of the experimental vs simulation results presented in Table V is an indication of the validity of the simulation models proposed in this work.

Table V
END-TO-END DELAY: EXPERIMENTAL AND SIMULATED RESULTS.

| Message source | Max experimental end-to-end delay | Max simulated end-to-end delay | Difference |
|---|---|---|---|
| **SB2** | 48.5 $\mu$s | 51.1 $\mu$s | 5.1% |
| **BP1** | 50.5 $\mu$s | 51.1 $\mu$s | 1.2% |
| **BP2** | 32.5 $\mu$s | 37.0 $\mu$s | 12.0% |
| **SB1** | 32.5 $\mu$s | 37.7 $\mu$s | 13.7% |

## VI. FINAL REMARKS

The proposed IEC 61850 simulation models allow the assessment of communication scenarios at the data link layer with switches in compliance with the IEEE 802.1q. Therefore immediately bring some advantages, such as: (i) facilitating the scalability analysis of the network, allowing the designers to check how many IEDs can be added to the system; (ii) allowing the analysis of large and complex systems (with many IEDs and switches); and, finally, (iii) obtaining the accurate end-to-end delays more easily than with experiments with real equipment.

The obtained simulation results, validated through comparison with real equipment, indirectly demonstrate that the fixed priority scheduling algorithm, implemented in the switch, works as expected, avoiding the priority inversion phenomenon.

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