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Real-Time Analysis of Time-Critical Messages in IEC 61850 Electrical Substation Communication Systems

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Abstract: IEC 61850 is a standard for the design and operation of electrical Substation Automation Systems (SAS) that defines how data may be transferred among Intelligent Electronic Devices (IEDs). The defined data models can be mapped into application protocols, such as SV or GOOSE, which may run upon high speed Ethernet LANs bridged by IEEE 802.1Q compliant switches. The communication system must cope with the timing requirements associated to protective relaying strategies. Given the time constrained nature of SAS applications, a thorough analysis of its timing behavior is required. In this paper, we propose an analytical model for the timing assessment of SV and GOOSE message exchanges in an IEC 61850 process bus. The proposed model allows the communication timing assessment, by analyzing the response time of each message stream of the SAS. This feature is an advantage for the expansion of the SAS, as it allows the evaluation at design time of the maximum number of IEDs that can be supported by the underlying communication system. The results from the proposed analytical model were validated for a typical IEC 61850 communication scenario, both through simulation and through an experimental assessment with IEC 61850 compliant equipment.

Keywords: substation automation system; smart grid communication; IEC 61850; real-time; SV and GOOSE application protocols

1. Introduction

Electrical power is a vital element of our society. The system in charge of guaranteeing an uninterrupted power supply is the Electric Power System (EPS). In an EPS, the electrical power is transported from generation plants to load centers through a set of transmission networks. Substations play an important role, transforming voltage values to levels considered suitable for transmission, distribution and consumption processes [1].

Due to several factors, such as the growing demand for electrical power and the difficulties to expand the available transmission networks, an EPS may be sporadically required to operate at its capacity bound, increasing the chance for blackouts due to external system disturbances. Consequently, it is necessary to rely upon specialized control and supervision schemes spread throughout the EPS, to ensure the required responsiveness to such disturbances. Typically, control and supervision schemes are implemented at the substation level, making them one of the most automated parts of the EPS, named as Substation Automation Systems (SAS). In an SAS, the easiness to integrate Intelligent

Electronic Devices (IEDs) provided by different manufacturers is an important requirement. The IEC 61850 standard directly targets this integration, establishing guidelines for the interoperability among components of an SAS [2].

Whenever designing an EPS communication system, a major challenge is to ensure that the system operation meets its timing and reliability requirements. The analysis of the timing constraints associated to IEC 61850 message exchanges is required for the assessment of the EPS operation, especially in what concerns those involved in the control and protection of the SAS. Examples of critical messages are SV (Sampled Values) and GOOSE (Generic Object Oriented Substation Events) messages [1]. Therefore, the availability during the system design phase of analytical and/or simulation tools that enable the timing assessment of message exchanges is highly desirable.

In this paper is presented an analytical assessment tool that is based on legacy response time analysis research works [3–6] previously proposed for the analysis of CAN (Controller Area Network) communication. This is a novel approach for the timing assessment of SV and GOOSE message streams supported by an IEC 61850 process bus. The use of adequate analytical models may both enable the response time analysis and scalability analysis of deployed IEC 61850 communication systems. These two features may represent an important advantage during the system design and setup times.

The analytical model proposed in this paper was experimentally validated using both a simulation model and a specifically built prototype of a small-size SAS bay. The performed comparison highlights its ability to map real IEC 61850 implementations.

This paper is divided in seven sections. Section 2 describes the basics of the IEC 61850 standard and discusses relevant related works. Section 3 presents the proposed analytical model that enables the assessment of the worst-case message communication delay within the context of IEC 61850 process bus communications. Section 4 exemplifies a potential use of the proposed analytical model, by applying it for the timing assessment of an IEC 61850 process bus under high communication load. Section 5 describes the usage of a specific IEC 61850 simulation model and also of an experimental prototype specifically built to validate the proposed analytical model. Section 6 extends the response time analysis introduced in Section 3 assuming a PTP (Precision Time Protocol) background traffic and also a process bus with gigabit Ethernet capability. Finally, Section 7 provides some conclusions and addresses some relevant future work directions.

2. Background

2.1. IEC 61850 and Process Bus Protocols

Due to a large number of devices that need to be interconnected within a typical SAS and also due to the need to support a broad range of applications, the usage of standardized interconnection procedures is required to enforce the system interoperability. This was the main purpose of the IEC 61850 standard [7–9]. Among other characteristics, this standard allows the modeling of complex IED functions as a set of simpler functions, called Logical Nodes (LN). Another important contribution is an information model that defines both the data to be communicated between functions and the communication services, specifying how the information model should be transmitted among IEDs.

The IEC 61850 standard defines a networking architecture for SAS with three automation levels—station, bay and process—connected through two communication buses (Figure 1) [8,10,11]. The first—station bus—carries messages among the Supervision, Control and Data Acquisition (SCADA) systems, substation operators and protection relays. This bus is used for monitoring and control operations. The second—process bus—interconnects instrument transformers, Merging Units (MUs) and protection relay devices.

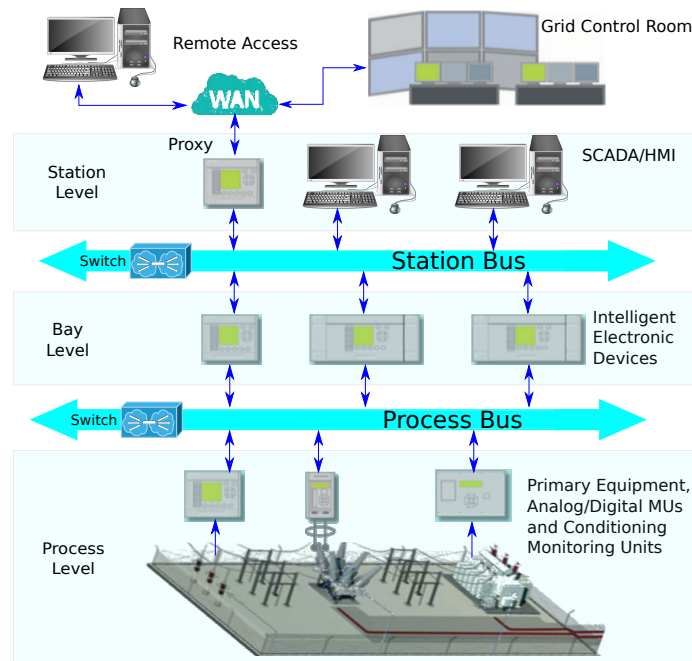


Figure 1. IEC 61850 automation levels [12].

Two of the protocols that can be used within this context are SV and GOOSE, predominantly used for process bus transactions. These protocols are described, respectively, in parts 8 and 9 of the IEC 61850 standard [9,11]. They operate in a publisher-subscriber model and implement just the application, data link, and physical layers of the communication stack. While GOOSE is typically used to transfer information closely related to monitoring and control functions (circuit breaker status etc.), SV is used to transfer numerical samples of current and voltage signals.

The SV protocol works on a periodic information transmission model, regularly sending messages at a fixed rate. For protection purposes, the default rate is 4000 or 4800 messages per second for, respectively, 50 or 60 Hz power systems. On the other hand, the GOOSE protocol operates in a sporadic information transmission model, where a continuous flow of data is maintained among LNs to increase communication reliability. Each message in a GOOSE transmission sequence has an attribute called Time allowed To Live (TTL) that informs the receiver about the maximum time to wait for the next transmission. As shown in Figure 2, upon the occurrence of a relevant event (e.g., circuit breaker tripped), this time interval is immediately reduced to a minimum configured value (T_L). Subsequently, the TTL of these messages will be increased at each transmission, until reaching the initial steady state periodicity value (T_S).

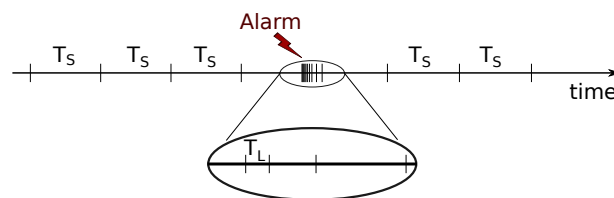


Figure 2. Example of sporadic behavior of GOOSE messages.

IEC 61850 standard specifies the timing constraints for messages typically used in substations (Table 1). GOOSE and SV messages are assumed as time critical messages, having the tightest deadlines (maximum allowed transfer time) among all IEC 61850 messages, corresponding to 3 ms.

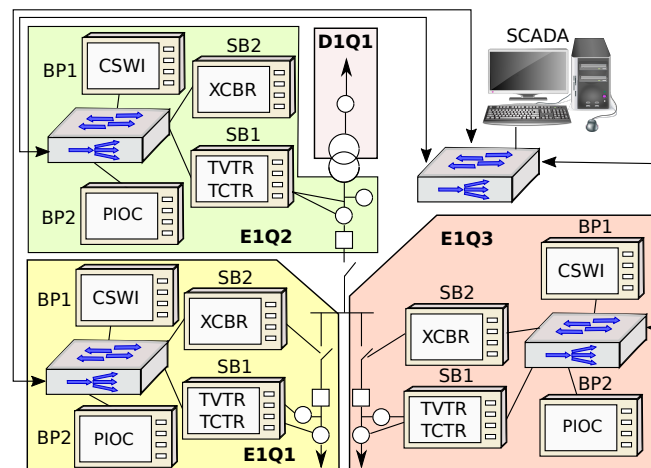
Table 1. Time constraints for IEC 61850 process bus messages.

Message Type	Example Application	Time Constraint
1A—Fast messages, trip	Circuit breaker commands and states (GOOSE)	≤ 3 ms
1B—Fast messages, other	The same as above	≤ 20 ms
2—Medium speed messages	RMS values calculated from type 4 messages	≤ 100 ms
3—Low speed messages	Alarms, non-electrical measurements, configurations	≤ 500 ms
4—Raw data messages	Digital representation of electrical measurement (SV)	≤ 3 ms
5—File transfer functions	Files of data for recording settings	≤ 1000 ms
6—Time synchronization messages	IED internal clock synchronization	none

Both GOOSE and SV run on the top of the Ethernet standard (IEEE 802.3). IEC 61850 also proposes the usage of IEEE 802.1Q upon IEEE 802.3 to deal with timing constraints in process bus applications. IEEE 802.1Q allows both (i) processing of messages with priority-based scheduling policies, and (ii) segmentation of the process bus into virtual local area networks (VLAN) to upper-bound the diffusion domain of both broadcast and multicast messages.

2.2. T1-1 Substation Reference Case Study

A relevant case study for the analysis of an SAS process bus operation has been described in Part 5 of the IEC-61850 standard as the T1-1 substation (Figure 3). This case study is normally used as a reference for a substation that transforms voltage levels from 220 kV to 132 kV [13–15].

**Figure 3.** Diagram of the T1-1 substation scenario.

In the example of Figure 3, it is assumed that the switch connected to the SCADA complies with the IEEE 802.1Q standard and is able to configure multiple VLANs in order to logically isolate each feeder bay. Consequently, there will be no data transmission between different bays. Therefore, the following description may refer to the traffic of any of the bays of the T1-1 architecture (E1Q1, E1Q2 or E1Q3).

In each bay, a star topology has been selected to interconnect the SAS devices. There is one MU (SB1) that is an IED able to generate SV messages, and three Protection & Control (P&C) IEDs (BP1, BP2 and SB2), able to generate GOOSE messages. In Figure 3, the names inside each device indicate the LN assigned to them. SB1 devices are intended to measure electrical parameters, and each one of them is composed of both a TVTR (Voltage transformer) and a TCTR (Current transformer) LNs. BP1 devices are responsible for the interlocking logic and are composed of a CSWI (Switch controller) LN. BP2 is responsible for the protection and is formed by a PIOC (Over current protection) LN. Finally, SB2 is responsible for the commands, and it is composed of an XCBR (Circuit Breaker) LN.

Table 2 presents the assumed network configurations for this T1-1 case study. While the new edition of IEC 61850 foresees the usage of Gigabit Ethernet, the bandwidth of the channel has been

set to 100 Mbps which is a de facto speed value used in digital substations deployed projects [16,17]. In Section 6, this assumption will be relaxed by simulation, analyzing a 1 Gigabit Ethernet process bus system.

The sizes of GOOSE and SV messages are set, respectively, to 160 and 140 bytes. While the standard allows larger messages, these values can be considered as typical maximum values for a T1-1 case study. It is important to note that P&C devices can operate in two modes: safe and emergency. When operating in emergency mode, these devices generate a traffic load of GOOSE messages 32 times greater than when operating in safe mode.

Table 2. Network characterization for the T1-1 case study.

Network Parameters	Values
Channel bandwidth	100 Mbps
Number of bays	3 (E1Q1, E1Q2, E1Q3)
P&C devices per bay	3 (BP1, BP2, SB2)
MUs per bay	1 (SB1)
GOOSE frame size	160 bytes
GOOSE frame period	Safe operation: 992 ms (≈ 1 frame/s) Emergency operation: 31 ms (≈ 32 frames/s)
Maximum bitrate per P&C device	Safe operation: 1.29 kbps Emergency operation: 41.29 kbps
SV frame size	140 bytes
SV frame period	208.33 μ s (4800 frames/s)
Maximum bitrate per MU	5376.09 kbps

A typical operation scenario was defined to support the assessment of the timing behavior for the message exchanges. Figure 4 illustrates the sequence of events for a specific feeder bay of this T1-1 case study: In safe operating conditions, SB1 transmits voltage and current samples for protection applications using multicast messages according to the SV protocol; that is, 4800 messages per second, containing information of four voltage-current pairs. At instant ①, an electrical fault (e.g., over-current) occurs in the bay. In event ②, the LN PIOC of BP2 receives and processes the message from SB1 reporting an “emergency” value. As a result, in event ③, a sequence of GOOSE messages notifying this event is forwarded by BP2. In event ④, the LN CSWI of BP1 processes these messages. Another sequence of GOOSE messages is then transmitted by CSWI as represented in event ⑤. In event ⑥, these messages are processed by the LN XCBR of SB2, in order to open the circuit breaker of the affected bay. Once performed the relay opening operation, in event ⑦, a new sequence of GOOSE messages will be generated by SB2. In event ⑧, CSWI processes these messages to become aware of the contact status change.

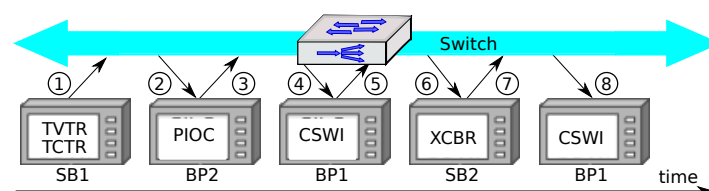


Figure 4. Intrabay sequence of events among protection and control IEDs.

2.3. Related Work

Three main approaches can be found in the literature about how to deal with the timing assessment of IEC 61850 process bus communication: analytical models, simulation approaches and experimental studies mixing prototypes and multi-vendor equipments.

In order to assess the service provided by the communication network, analytical models usually consider worst-case operational conditions. However, depending on the application, the use of

analytical models may increase the complexity of the analysis and introduce an excessive level of pessimism. Stochastic approaches [18,19], for example, have been used to quantify communication delays in SAS. In [18], assuming a specific service model, a network calculus-based algorithm is proposed to evaluate the maximum delay of messages in an SAS communication bus. Results were compared against experimental measurements acquired from real equipments. The assessment results showed some level of pessimism, and also a dependence on the adopted arrival and service probabilistic distribution functions. In [19], the authors propose a different network calculus-based algorithm to model the communication delay for a substation-area protection scheme. The results were compared with data obtained from a simulation platform developed in OPNET. In [20], the authors use timed automata and model checking to perform formal verification of the IEC 61850 real-time communication requirements.

On the other hand, the use of simulation approaches allows the assessment of multiple substation scenarios at a relatively small cost and risk. However, it must be carefully considered that simulation models are prone to excessive simplifications. Therefore, the selection of adequate simulation models is a crucial step to obtain reliable results. In [13–15] some specific simulation platforms are presented. Ref. [13] proposes simulation models for the OMNeT++/INETMANET framework to support IEC 61850 based communication. An interface to incorporate messages from external networks as part of the simulator was also developed. Ref. [14] proposes the modeling of a Phasor Measurement Unit and also presented simulation models of IEDs for the OMNeT++/INET platforms. Ref. [15] proposes simulation models for SAS devices using the OPNET tool. Ref. [21] adopts the OPNET simulator configured to assess the use of Constrained Application Protocol (CoAP) in an IEC 61850-based SAS. The work in [22] targets Distributed Automation Systems (DAS) addressing the autonomous execution of distributed applications, enabling IEDs to handle dynamic topologies and establishing data flows between independent IEDs. To assess the proposed approach, a case study has been setup and implemented through a simulated DAS.

Finally, lessons learned from experimental assessments with real equipments provide also important inputs to understand typical SAS behaviors. However, the use of experimental assessments usually faces scalability problems, in what concerns the number of considered IEDs, and can hardly replicate real conditions in complex operational scenarios. In [23], electrical signal generators, IED emulators and network traffic capture boards were used to study the interaction between time synchronization protocols and IEC 61850 communication protocols. Other works, as in [24], used the so-called Real-Time Digital Simulator (RTDS) to assess the behavior of SAS close to real situations. Ref. [25] describes a specific calibration setup composed of analog signal generators, hardware for SV capture and analog-to-digital converters.

The use of specific hardware setups combined with numerical simulations can be used to assess complex systems, using techniques known as hardware-in-the-loop simulation. As an example, due to the higher complexity of protection and communication systems of IEC 61850-9-2LE substations, in [26] is proposed the use of this simulation technique in a laboratory test bed for analyzing the performance of complex substation topologies that are prone to faults.

In [27,28], methodologies with some similarities to the one proposed in this paper are proposed. In [27], the authors analyzed a bay of an IEEE-39 bus system model consisting of one bay controller, one circuit breaker, 2 MUs, and 2 protection relays. The assessment of the GOOSE and SV protocols in this bay was done both through simulation using OPNET and through analytical measures using network calculus-based equations. An atypical configuration for SV messages in protection applications, which is not compliant with the recommendations of IEC61850-9-2LE, was used. Furthermore, although being stated that the system uses 802.1Q, the paper does not describe how VLANs and priorities were configured and managed.

In [28], the network delays in a multi-hop process bus substation network are also characterized through analytical and simulation models. However, as almost all above-mentioned works [13–15,19,23–25,28], the focus lies upon the modeling of communication interactions from the

application layer perspective, disregarding existing data link layer communication services, such as VLANs and prioritization mechanisms. In particular, such works typically ignore the behavior of IEEE 802.1Q standard services, which are of critical importance for the study of IEC 61850 communications.

In this paper, we aim to explore the advantages of using a combination of these methodologies, in order to obtain a more accurate assessment of the messages' timing behavior for different IEC 61850 based communication scenarios.

3. Analytical Model for IEC 61850 Process Bus

This section introduces a worst-case response time analysis tool that can be used for the assessment of typical SAS communications compliant with the IEC 61850 standard.

3.1. Real-Time Scheduling Concepts and Notation

A real-time task is an abstraction used in real-time scheduling theory [29], which corresponds to some entity that can be scheduled for execution according to a predefined policy. In the context of an IEC 61850 process bus, a real-time task may correspond to a GOOSE or an SV message stream. In this case, the resource shared by the message streams is the transmission medium or, in the case of switched networks, the transmission queue at the switch. An SV message stream can be modeled as a periodic task. On the other hand, a GOOSE message stream may correspond to a sporadic task which, in real-time scheduling theory, consists of an aperiodic task with a minimal interarrival time.

A basic way of modeling a real-time system and assessing the feasibility to meet its deadlines is by performing this related schedulability analysis. Real-time systems usually follow a priority-based scheduling, where the access to the shared resource can be preemptive or non-preemptive. Considering that, when a message is being transmitted, it occupies the channel until the end of its transmission, the IEC 61850 process bus shall be modeled as non-preemptive scheduling system.

In this particular case study involving an SAS, the main real-time scheduling attributes of the message streams and their notations are highlighted in Table 3.

In Table 3, the value of i refers to the index of the message stream, where all the messages share the same attributes. For example, C_i refers to the longest transmission time of message stream i , but it also refers to the longest transmission time of all messages in stream i .

3.2. Message Priority Assignment Policy for Substation T1-1

Among the priority-based scheduling methods, those using static priority assignments have been widely adopted by industry due to its easy implementation, low execution overhead and greater predictability in case of failures [29]. Static approaches follow basically three steps. First, at design time, priorities are assigned to the message streams according to some specific policy. Then, a schedulability test is applied to verify whether each message stream will meet or not its deadlines. If all message streams meet individual deadlines, then it is said that the system is schedulable or feasible. Finally, at runtime, a scheduler triggers the transmission of a message from the stream that has the highest priority among those that have a message ready to be transmitted. In the case of substation T1-1, the IEEE 802.1Q compliant switch has the responsibility for implementing the priority scheduler that will schedule the GOOSE and SV messages.

For the first of the three aforementioned steps, the Rate Monotonic algorithm (RM) will be used in this paper. It is well-known that there is no optimal priority assignment policy when the system is non-preemptive and the tasks have arbitrary deadlines (deadlines that can be greater than the periods) [5]. The basic idea of the RM assignment policy is to assign higher priorities to the message streams with lower periods.

Table 3. Real-time attributes and their notation.

Symbol	Meaning
C_i	computing time —is the worst-case time required to transmit a message from message stream i . This transmission time may be calculated using the maximum message size (in bits), divided by the network bandwidth (in bps).
T_i	period —is the interarrival time between messages of a periodic message stream i , where the arrival time corresponds to the moment when the message is inserted in the transmission queue of the IED or switch.
J_i	delay jitter —is a measure of the delay variation, and can be defined as the difference between the highest and the lowest time required for the insertion of a message from stream i in the transmission queue of the devices.
D_i	deadline —corresponds to the maximum time interval within which a message from stream i must be delivered at its destination. In the case of GOOSE streams, D_i depends on the system operating state. In the steady state, the deadline value is equal to the message stream period; in an emergency state, this value corresponds to the minimum between TTL and the timing constraint defined by a message class 1A, that is, $\min(TTL, 3ms)$. In the case of SV streams, according to IEC 61850, D_i corresponds to 3ms.
P_i	priority —is the priority assigned to message stream i , where the highest number corresponds to the higher priority level.
R_i	worst-case response time —is the longest time required for a message of the stream i to be delivered at its destination, measured from its release time.
B_i	blocking time —represents the time a message from stream i is retained in the transmission buffer because another message of lower priority is already occupying the shared channel.
U_i	utilization factor (or utilization) —is the fraction of time during which the shared resource is being used by a message stream i , given by C_i/T_i .
τ_{bit}	bit time —is the time required to transmit one bit through the communication channel, corresponding to 10 ns for a network with a bandwidth of 100 Mbps.
$hp(i)$	Set of message streams with higher priority than stream i .
$ep(i)$	Set of message streams with equal priority than stream i .

The assessment of a real-time system must be made under worst-case operation scenarios. Table 4 presents the message streams parameters of a T1-1 bay, when the system changes from “alert” to “emergency” state. This is the moment when GOOSE message streams shorten their periods to the minimum configured value, thus increasing the network load to its maximum (see Table 2). The first column of Table 4 refers to the message streams names that will be used throughout this work. The numbers in the second column refer to the events shown in Figure 4.

Table 4. T1-1 system message stream parameters for 100 Mbps and 1 Gbps Ethernet.

Msg Stream	Source	Message Type	P_i	T_i (μs)	D_i (μs)	C_i (μs)		J_i (μs)		U_i (%)	
						100 Mbps	1 Gbps	100 Mbps	1 Gbps	100 Mbps	1 Gbps
T_7	① SB1(MU)	SV	7	208.33	3000	12.16	1.216	1.0	0.2	5.84	0.584
T_6	③ BP2(Relay)	Protection GOOSE	6	31,000	3000	13.76	1.376	1.0	0.2	0.04	0.004
T_5	⑤ BP1(Relay)	Interlocking GOOSE	5	31,000	3000	13.76	1.376	1.0	0.2	0.04	0.004
T_4	⑦ SB2(Relay)	Command GOOSE	4	31,000	3000	13.76	1.376	1.0	0.2	0.04	0.004

According to the IEEE 802.1Q standard, compliant switches have eight priority levels, where 0 indicates the lowest and 7 the highest priority level. Thus, applying a RM scheduling policy, the highest priority level in the system was assigned to SV streams from SB1 (T_7). The three GOOSE message streams have the same periodicity and therefore priorities were sequentially assigned following the chronological order of events occurred during the over-current fault described in Figure 4, as follows: priority 6 assigned to GOOSE message streams produced by BP2 protection devices (T_6); priority 5 assigned to GOOSE message streams produced by BP1 interlocking devices (T_5); and priority 4 assigned to GOOSE message streams produced by SB2 command devices (T_4). It is

important to highlight that this priority assignment do not reflect the relative importance of tasks: When the schedulability test is positive, all the message streams will meet their deadlines, even the lowest priority stream.

Table 4 shows the C_i value for each of the T1-1 process bus message streams under analysis. These C_i values already include the Inter Frame Gap (IFG) value specified by the IEEE 802.3 protocol, which is a time interval after a message transmission during which the channel must remain free. The IFG value corresponds to the time required to transmit 96 bits in the communication channel. Thus, assuming a 100 Mbps Ethernet, for a τ_{bit} of 10 ns, IFG is equal to 960 ns. In this sense, for an SV message, with a size of 140 bytes, $C_i = 140 \times 8 \times 10 \text{ ns} + 960 \text{ ns}$, resulting in $C_i = 12.16 \mu\text{s}$. Similarly, for a GOOSE message of 160 bytes, this calculation results in $C_i = 13.76 \mu\text{s}$.

Another value that appears in Table 4 corresponds to the delay jitter. As the typical delay jitter for Ethernet switch queues has values around 100 ns, it was adopted the value of 1000 ns for a worst-case jitter value (J_i) of the message streams for a 100 Mbps Ethernet, and 200 ns for a 1 Gbps Ethernet [30].

It is important to note that GOOSE message streams are treated as periodic tasks. This approach, although pessimistic, is usual in real-time scheduling theory due to its simplicity when handling sporadic tasks. According to this, a real-time sporadic task can be modeled as a real-time periodic task with a period equal to the minimum interarrival time between two consecutive instances. Consequently, in Table 4, GOOSE sporadic message streams will be handled with a periodicity of 31,000 μs . This value was selected to match the minimum TTL values reported on the equipment manuals used in the experimental assessment [31,32] (see Section 5.2).

In this case study, it is assumed that there is no background traffic in the process bus of T1-1 substation, for example, generated by PTP message streams. The rationale behind this assumption was that this type of traffic can be avoided in the SAS process bus by using VLANs, and segregating the network traffic into synchronization traffic and protection/automation traffic. Nevertheless, this assumption will be relaxed in Section 6, where we illustrate how to integrate the PTP background traffic in the schedulability analysis.

3.3. Real-Time Scheduling Analysis

The response time analysis for a non-preemptive fixed-priority system, as proposed in [3–5], can be adapted to estimate the maximum response time of message exchanges in an IEC 61850 process bus communication system Equation (1).

$$R_i = \max_{q=0 \dots Q_i-1} R_i(q) \quad (1)$$

where

$$R_i(q) = J_i + w_i(q) - qT_i + C_i \quad (1a)$$

$$Q_i = \left\lceil \frac{t_i + J_i}{T_i} \right\rceil \quad (1b)$$

$$t_i^{n+1} = B_i + \sum_{\forall j \in hp(i) \cup ep(i)} \left\lceil \frac{t_i^n + J_j}{T_j} \right\rceil C_j \quad (1c)$$

and

$$w_i^{n+1}(q) = B_i + qC_i + \sum_{\forall j \in hp(i)} \left\lceil \frac{w_i^n + J_j + \tau_{bit}}{T_j} \right\rceil C_j \quad (1d)$$

In parts (1b) and (1c) of Equation (1), term t_i represents the i -busy-period, that is, the window of time within which messages with priority higher than or equal to message i (that is, $hp(i) \cup ep(i)$) are being continuously transmitted. As the task model of the system is non-preemptive and admits arbitrary deadlines, in order to determine R_i , it is necessary to analyze multiple instances of a message

i within the busy period. These instances are represented by the term q and form a finite set bounded by the value of Q_i Equation (1b).

In part (1d), the term w_i represents the delay that a message from stream i suffers before its execution. This term includes the interference caused by messages from streams of higher priority and a block term B_i caused by a given message from a lower priority stream that was already using the communication bus before the message from stream i has been released.

For the calculation of both terms t_i and w_i , it is considered that equations are monotonically increasing and, therefore, they can be iteratively solved, until their convergence. In the procedure proposed by [5], $B_i + qC_i$ is assumed as the initial value of w_i and C_i as the initial value for t_i .

3.4. Worst-Case Response Time Analysis Results

Assuming values of Table 4, Equation (1) may be used to verify the schedulability of the T1-1 set of message streams from the point of view of the switch ports. By demonstrating that this message stream set is schedulable, it can be concluded if the system meets (or not) the timing requirements of the supported SAS applications.

It is important to note that as the system is non-preemptive, a message can be only blocked once by a lower priority message, and therefore it is necessary to assume a worst-case blocking time. For the particular case of the T1-1 set of message streams, as \mathcal{T}_6 , \mathcal{T}_5 and \mathcal{T}_4 have the same C_i (see Table 4), the respective blocking times are similar. For this reason, and for the sake of simplicity, in the following analysis it is assumed that \mathcal{T}_4 is always the message stream that blocks other streams, as shown below.

Message stream \mathcal{T}_7 (SV messages sent by SB1)

Calculation of Q_7 : starting with C_7 as the initial value of t_7 and assuming $B_7 = 13.76 \mu s$, whose value corresponds to the computation time of \mathcal{T}_4 , we have:

$$t_7^1 = B_7 + \left\lceil \frac{t_7^0 + J_7}{T_7} \right\rceil C_7 \quad \therefore \quad t_7^1 = 13.76 + \left\lceil \frac{12.16 + 1}{208.33} \right\rceil 12.16 = 25.92$$

Iterating again:

$$t_7^2 = 13.76 + \left\lceil \frac{25.92 + 1}{208.33} \right\rceil 12.16 = 25.92$$

Therefore, 7-busy-period value converged in 25.92 μs . By applying Equation (1b):

$$Q_7 = \left\lceil \frac{t_7 + J_7}{T_7} \right\rceil \quad \therefore \quad Q_7 = \left\lceil \frac{25.92 + 1}{208.33} \right\rceil = 1$$

The value of $Q_7 = 1$ indicates that the q value in Equation (1) is equal to 0. Therefore, in order to obtain the worst-case response time for \mathcal{T}_7 , it is enough to examine its first instance within the 7-busy period.

Calculation of R_7 : Since \mathcal{T}_7 is the highest priority message stream, in Equation (1d) there is no element in $hp(i)$. Because $q = 0$, this equation can be simplified to $w_7^{n+1}(0) = B_7$. Therefore, $w_7(0)$ converges to 13.76 μs . Through Equation (1a), $R_7(0) = 1 + 13.76 + 12.16 = 26.92 \mu s$. As this worst-case response time is smaller than the deadline D_7 (3000 μs), we conclude that \mathcal{T}_7 is schedulable and it will always meet its deadline.

Message stream \mathcal{T}_6 (GOOSE messages sent by BP2)

Calculation of Q_6 : starting with C_6 as the initial value of t_6 , and assuming $B_6 = C_4$, we have:

$$t_6^1 = B_6 + \left\lceil \frac{t_6^0 + J_7}{T_7} \right\rceil C_7 + \left\lceil \frac{t_6^0 + J_6}{T_6} \right\rceil C_6 \quad \therefore \quad t_6^1 = 13.76 + \left\lceil \frac{13.76 + 1}{208.33} \right\rceil 12.16 + \left\lceil \frac{13.76 + 1}{31,000} \right\rceil 13.76 = 39.68 \mu s$$

Iterating again:

$$t_6^2 = 13.76 + \left\lceil \frac{39.68 + 1}{208.33} \right\rceil 12.16 + \left\lceil \frac{39.68 + 1}{31,000} \right\rceil 13.76 = 39.68 \mu\text{s}$$

This iteration converges with the value of 6-busy-period equal to 39.68 μs , then:

$$Q_6 = \left\lceil \frac{t_6 + J_6}{T_6} \right\rceil \quad \therefore \quad Q_6 = \left\lceil \frac{39.68 + 1}{31,000} \right\rceil = 1$$

This value of Q indicates that the q value in Equation (1) is equal to 0 and it is enough to examine the first instance of T_6 within the 6-busy period.

Calculation of R_6 : starting with B_6 as the initial value of $w_6^0(0)$, this results in $w_6^0(0) = 13.76 \mu\text{s}$. By applying Equation (1d):

$$w_6^1(0) = 13.76 + \left\lceil \frac{13.76 + 1 + 0.01}{208.33} \right\rceil 12.16 = 25.92 \mu\text{s} \quad \therefore \quad w_6^2(0) = 13.76 + \left\lceil \frac{25.92 + 1 + 0.01}{208.33} \right\rceil 12.16 = 25.92 \mu\text{s}$$

As $w_6(0)$ converges in 25.92 μs , then $R_6(0) = 1 + 25.92 + 13.76 = 40.68 \mu\text{s}$. This time value is smaller than D_6 (3000 μs) and therefore this message stream is always schedulable.

Applying similar reasoning, the worst-case response times can be evaluated for all the T1-1 set of message streams (the complete scheduling calculation is provided as Supplementary Material available online). Table 5 summarizes these values. Since $R_i \leq D_i, \forall i \in \text{message streams set}$, we may conclude that this set of message streams is schedulable according to the RM policy. Moreover, it can be observed that all R_i obtained by the response time analysis are much smaller than the corresponding D_i . This situation occurs because the analyzed system has a lot of slack time. This can be corroborated by direct inspection of Table 4, where the total utilization of the system (sum of column U_i) is rather small, being less than 6%, leaving a large margin for the system expansion. This expansion can be achieved, for example, by increasing the number of devices in the bay. The analytical tool presented in this section may become highly useful for the scalability analysis of a process bus based on IEC 61850. In the next section we will present an example of a typical scalability analysis that can be made.

Table 5. T1-1 system message scheduling analysis results.

\mathcal{R}_7 (SB1)	\mathcal{R}_6 (BP2)	\mathcal{R}_5 (BP1)	\mathcal{R}_4 (SB2)
26.92 μs	40.68 μs	54.44 μs	54.44 μs

4. Scalability of T1-1 Networks

The IEEE 802.1Q standard provides a limited number of just 8 different priorities. This restriction may lead to the case where different message streams with the same priority have messages waiting to be transmitted in the switch queue. In the case study of Section 3, this situation was intentionally avoided by keeping the load on the bus at a low value and assigning different priorities to T1-1 network message streams. Consequently, the output buffers of the switch never had more than one message with the same priority ready to be transmitted. This is a convenient solution for small scale systems. However, whenever the complexity of an SAS bay increases, it will be unavoidable to have more than one IED sending messages with the same priority.

As an example, assume now that in the T1-1 scenario of Section 3 there are N MU devices sending SV messages at a rate of 5376.09 kbps, and three P&C devices, each one sending GOOSE messages at a rate of 41.29 kbps (see Table 2). A naive test to find the maximum number of MU devices that the system would be able to support, would divide the bus bandwidth by the MU transmission rate, that is:

$$N \leq \left\lfloor \frac{100,000 - (3 * 41.29) \text{ kbps}}{5376.09 \text{ kbps}} \right\rfloor \quad \therefore \quad N \leq \lfloor 18.58 \rfloor \quad \therefore \quad N \leq 18$$

This type of test may become very optimistic, whenever different periodicities are used to send messages by multiple SV and GOOSE message streams. A more adequate test to find an upper bound value for N would be based on the concept of total utilization, which consists in accounting the sum of the utilization of the individual message streams in the system:

$$\sum_{\forall i \in \text{task set}} \frac{C_i}{T_i} \leq 1 \quad \therefore N \times \frac{12.16}{208.33} + 3 \times \frac{13.76}{31,000} \leq 1 \quad \therefore N \leq 17.11$$

As N must be an integer number, $N = \lfloor 17.11 \rfloor = 17$. However, it is important to point out that this is just a “necessary but not sufficient” test. Again, this type of utilization-based tests only defines an upper bound for the number of MUs, being unable to provide the exact maximum number. What this type of necessary test points out is that the T1-1 system is not schedulable for more than 17 MUs. However, it is not able to confirm if a system with 17 or less MUs is schedulable or not.

Figure 5 illustrates a timeline for the execution of this system assuming 17 MUs (note that the timeline presented is optimistic because it does not account for jitter values). For the sake of convenience, the 17 MU message streams are represented as a single stream called \mathcal{T}_7' . This task has the same period and deadline of \mathcal{T}_7 but its maximum transmission time is equivalent to $17 * 12.16 \mu\text{s}$, that is, $C_7' = 206.72 \mu\text{s}$. In the timeline, it is also assumed the critical instant concept [3], where all streams (\mathcal{T}_7' , \mathcal{T}_6 , \mathcal{T}_5 and \mathcal{T}_4) are simultaneously released at time instant 0.

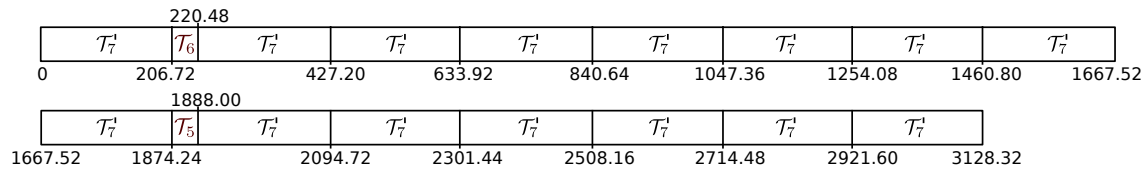


Figure 5. Execution scale of a T1-1 system with 17 MU IEDs (scale unit in μs).

\mathcal{T}_7' finishes its first instance at $t = 206.72 \mu\text{s}$ and then \mathcal{T}_6 executes until $t = 220.48 \mu\text{s}$. The second instance of \mathcal{T}_7' had arrived at $t = 208.33 \mu\text{s}$, but since the system is not preemptive, it is blocked by \mathcal{T}_6 . This \mathcal{T}_7' instance and subsequent sequence of instances arrive and run consecutively until $t = 1874.24 \mu\text{s}$. Then \mathcal{T}_5 executes until $t = 1888.00 \mu\text{s}$. The tenth instance of \mathcal{T}_7' had arrived at $t = 1875.24 \mu\text{s}$ but it had to wait for the completion of \mathcal{T}_5 . Again, a sequence of instances of \mathcal{T}_7' arrives and runs consecutively until $t = 3128.32 \mu\text{s}$. As \mathcal{T}_4 were not able to execute until its deadline ($t = 3000 \mu\text{s}$), the system is not schedulable. This behavior highlights the “necessary but not sufficient” label of utilization-based tests, which are not able to guarantee the schedulability of the system.

Instead, by using response time analysis based tests, it would be possible to show that this system is not feasible with 17 MUs, but feasible with 16 MUs. In this sense, it is necessary to test every message stream of the system. For the sake of convenience, we will just illustrate the results for \mathcal{T}_4 . Now, $C_7' = 16 * 12.16 \mu\text{s} = 194.56 \mu\text{s}$. Thus, for the Q_4 calculation, applying Equation (1c): $t_4^1 = \lceil (13.76 + 1) / 208.33 \rceil 194.56 + 3 * \lceil (13.76 + 1) / (31,000) \rceil 13.76 = 235.84 \mu\text{s}$. The next iterations result in $t_4^2 = 430.40 \mu\text{s}$ $\therefore t_4^3 = 624.96 \mu\text{s}$ $\therefore t_4^4 = 819.52 \mu\text{s}$ $\therefore t_4^5 = 819.52 \mu\text{s}$. Then, using Equation (1b): $Q_4 = \lceil (819.52 + 1) / 31,000 \rceil = 1$. As $Q_4 = 1$, for the R_4 calculation, it is enough to analyze just the first instance of \mathcal{T}_4 . By applying Equation (1d): $w_4^1(0) = \lceil (13.76 + 1 + 0.01) / 208.33 \rceil 194.56 + 2 * \lceil (13.76 + 1 + 0.01) / (31,000) \rceil 13.76 = 222.08 \mu\text{s}$. The next iterations result in $w_4^2(0) = 416.64 \mu\text{s}$ $\therefore w_4^3(0) = 611.20 \mu\text{s}$ $\therefore w_4^4(0) = 611.20 \mu\text{s}$. Therefore $R_4 = 1 + 611.20 + 13.76 = 625.96 \mu\text{s}$.

These results show that \mathcal{T}_4 is schedulable when the T1-1 system has 16 MUs. In this configuration, the system has a total utilization of: $\mathcal{U} = 16 * (12.16 / 208.33) + 3 * (13.76 / 31,000) = 0.94$, which characterizes a system with high network load.

5. Simulation and Experimental Assessment of Similar T1-1 Case Studies

In this section, the worst-case response time analysis tool is validated by comparison with both simulation and experimental setups. Initially, it is presented the simulation setup configured as a small-size SAS bay with VLANs. In the sequence, results from an experimental setup with the same configuration are compared with results obtained through both simulation and analytical assessments.

5.1. Simulation Assessment

The same scenario presented in Figure 4 was assessed using a set of simulation models developed for the OMNeT++ and INET frameworks, previously presented in [33] and available in [34]. In addition to the simulation models originally available in OMNeT++, a set of specific models were developed for the simulation of elements of an SAS control bus. The conformance statements of this simulator are presented in Appendix A.

Figure 6 depicts the three main developed components: Merge Unit Node, Switch Node and Protection and Control IED. The main communication flow is also illustrated in the figure, where SV messages generated by MU IEDs are classified within the switch, forwarded to their respective priority queues and scheduled to be sent to P&C IEDs. These P&C devices, besides being able to process SV messages, they can also generate and process GOOSE messages during emergency operations.

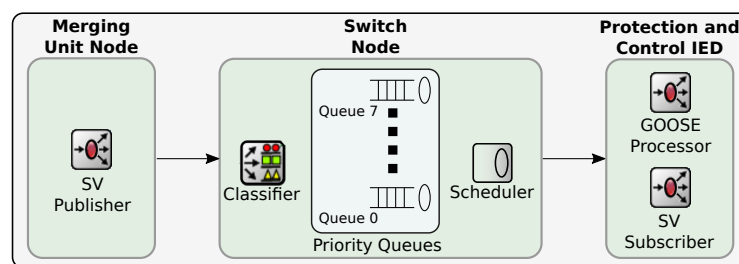


Figure 6. Main developed simulation models.

The switch simulation model was also developed according to the protocol requirements specified by the IEEE 802.3 and IEEE 802.1Q standards, focusing on full-duplex operation mode, VLAN configuration and message prioritization. The switch was configured with SB1, BP1, SB2 and BP2 devices connected to port 0, 1, 2 and 3, respectively. Two VLANs were created, with port 0 associated with VLAN1, ports 1 and 2 to VLAN2, and port 3 allocated to both VLAN1 and VLAN2 (Figure 7).

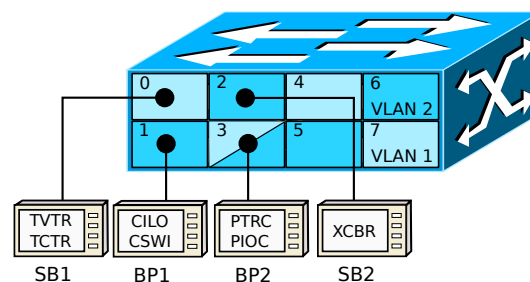


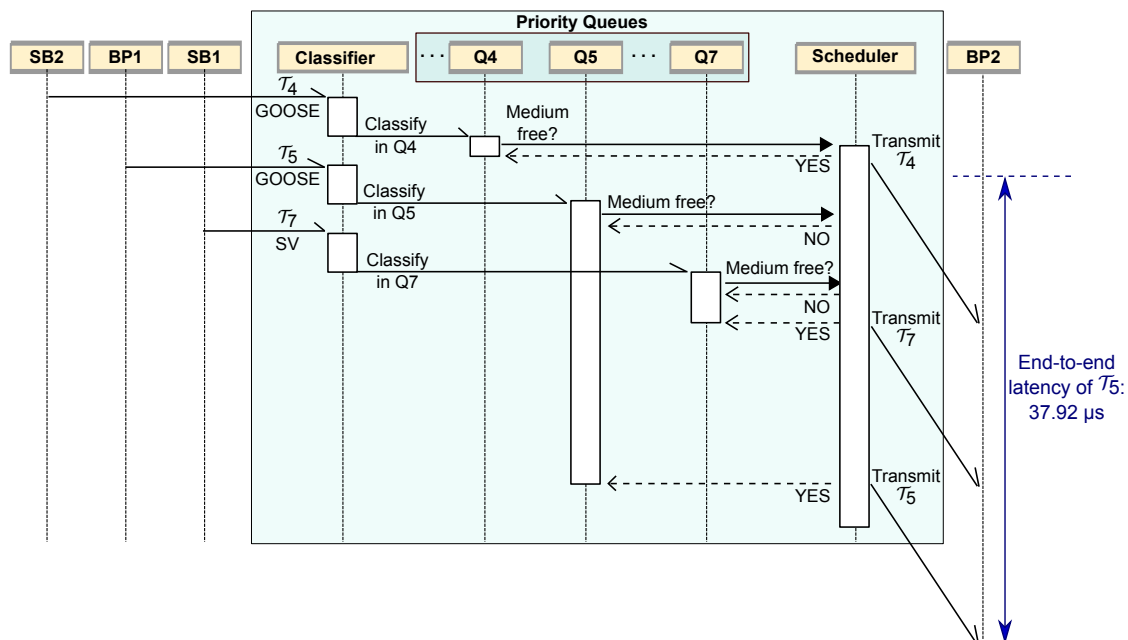
Figure 7. Switch virtual local area networks (VLANs) and port configuration.

As a consequence of the segmentation of the network and the use of messages with multicast destination address, each P&C device processes GOOSE messages from two different sources with the exception of BP2, which belongs to both VLANs. This device, in addition to processing GOOSE messages, also processes SV messages from SB1. Table 6 summarizes the source/destination of each message stream and its corresponding VLAN. As BP2 is configured as processor of SV messages, instead of generator, it does not generate SV messages, just process the ones generated by SB1. For this reason, SB1 and port 0 do not appear as a destination and output port of BP2 in this table.

Table 6. T1-1 communication with VLAN tagging.

Source/Input Port	Message Type	VLAN	Destination/Output Port
SB1 (\mathcal{T}_7)/0	SV	1	BP2/3
BP2 (\mathcal{T}_6)/3		1 and 2	BP1/1 and SB2/2
BP1 (\mathcal{T}_5)/1	GOOSE	2	SB2/2 and BP2/3
SB2 (\mathcal{T}_4)/2		2	BP1/1 and BP2/3

The communication snapshot illustrated in Figure 8 represents a message exchange scenario that highlights the worst-case end-to-end communication delay for a GOOSE message sent by BP1 (\mathcal{T}_5) that was obtained during the simulations. This scenario give emphasis to a situation where message \mathcal{T}_5 arrives at the output port 3 of the switch, but a lower priority GOOSE message (\mathcal{T}_4) sent by SB2 already is occupying the communication channel. During the interval that \mathcal{T}_5 is blocked, a SV message of higher priority \mathcal{T}_7 arrives at the output port 3 and is also blocked by \mathcal{T}_4 . When the \mathcal{T}_4 message ends, the switch starts sending \mathcal{T}_7 . The switch only starts transmitting \mathcal{T}_5 after the end of \mathcal{T}_7 . For this specific communication-case scenario, where \mathcal{T}_5 receives a blocking from \mathcal{T}_4 and an interference from \mathcal{T}_7 , it was obtained in the simulator the maximum measured response time of 37.92 μs .

**Figure 8.** A scenario extracted from the simulator in which a GOOSE message sent by BP1 message reaches its maximum end-to-end latency.

In this snapshot, the IEDs were configured to have buffers that allow the switch to retransmit a message whenever the channel is released (while respecting the IFG time interval). Therefore, the interferences and blockages between messages in the switch are not affected by the IED processing times. The simulation results are illustrated in Table 7.

Table 7. Maximum response times obtained by simulation.

\mathcal{R}_7 (SB1)	\mathcal{R}_6 (BP2)	\mathcal{R}_5 (BP1)	\mathcal{R}_4 (SB2)
25.38 μs	25.92 μs	37.92 μs	38.4 μs

When comparing these results with the worst-case analytical results from Table 5, it can be observed that the analytically-obtained results incorporate some pessimism and may consider the

occurrence of interferences and blocking that could have been avoided through a careful configuration of VLANs.

To better understand the traffic behavior of the switch, it is important to detail its operational model (see Table 6). \mathcal{T}_7 , \mathcal{T}_5 and \mathcal{T}_4 compete for the output queue of port 3, \mathcal{T}_6 and \mathcal{T}_4 compete for the output queue of port 1, and \mathcal{T}_6 and \mathcal{T}_5 compete for the output queue of port 2. Consequently, analyzing this information, it can be stated that: (i) \mathcal{T}_6 never receives any interference from \mathcal{T}_7 ; (ii) \mathcal{T}_5 never receives simultaneous interference from \mathcal{T}_6 and \mathcal{T}_7 (either it receives interference from \mathcal{T}_7 on port 3 or from \mathcal{T}_6 without being blocked by \mathcal{T}_4 on port 2); and (iii) \mathcal{T}_4 never receives simultaneous interference from \mathcal{T}_5 , \mathcal{T}_6 and \mathcal{T}_7 (just either from \mathcal{T}_5 and \mathcal{T}_7 on port 3, or from \mathcal{T}_6 on port 1).

Therefore, in order to build an analytical model that reflects this specific VLAN configuration, the following actions can be considered. Assuming item (i), \mathcal{T}_7 is no longer part of $hp(6)$, then $R_6 = R_6 - C_7$. Considering item (ii), it is assumed that \mathcal{T}_6 is no longer part of $hp(5)$, thus $R_5 = R_5 - C_6$. Finally, considering item (iii), it is assumed that \mathcal{T}_4 receives interferences only from both \mathcal{T}_5 and \mathcal{T}_7 , then $R_4 = R_4 - C_6$. Table 8 highlights the results from the analytical model assuming the relaxations due to this specific VLANs configuration.

Table 8. Worst-case response times obtained by the analytical model with VLANs.

\mathcal{R}_7 (SB1)	\mathcal{R}_6 (BP2)	\mathcal{R}_5 (BP1)	\mathcal{R}_4 (SB2)
26.92 μ s	28.52 μ s	40.68 μ s	40.68 μ s

The vicinity of the results obtained from both the analytical model and the simulator is a strong indication that both were correctly designed to reflect the SAS behavior.

5.2. Experimental Assessment

Finally, we present some experimental assessment results, obtained from a specifically-built experimental setup. The target of this experimental assessment was to validate the results obtained when using the analytical model and the simulation tool.

Figure 9 illustrates the implemented setup, which mimics the substation bay illustrated in Figure 4, configured with the same VLANs (Figure 7). The set of used equipments considers two bay controllers compliant with IEC 61850 and supplied by different manufacturers [31,32], an eight ports switch compliant with IEEE 802.1Q, a GPS clock with synchronization output compliant with various standards (IRIG-B, PTP etc.), and a computer for the emulation of GOOSE messages. During the experiments, the computer was also used for capture and record the network traffic for further analysis.

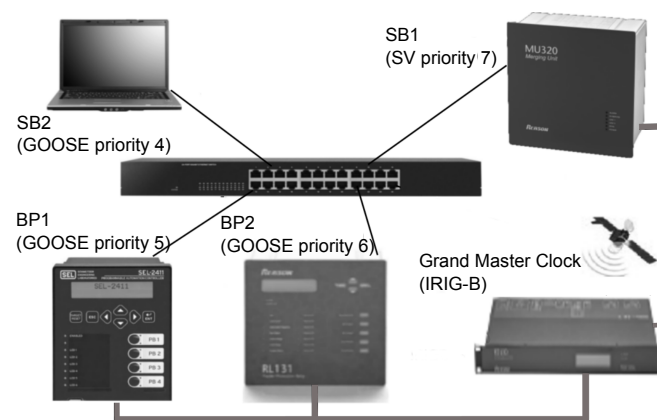


Figure 9. Bay laboratory architecture.

The following assumptions were made in the experiments:

- The equipments were synchronized by using IRIG-B; and synchronization messages do not affect the GOOSE and SV messages exchanged over the process bus.
- A signal generator was connected to the analog input channels of MU (SB1) simulating the voltages and currents values of the EPS.
- The events were recorded by the equipments in the form of log, SoE (Sequence of Events) and COMTRADE files. These files kept the time stamps related to the occurrence of all the events.
- The message processing time of each equipment was considered according to the values reported by the manufacturers. These processing time values needed to be subtracted from the end-to-end delays obtained during experiments.

The following steps were executed in order to assess the timing behavior of the network.

- With the equipments powered on, one digital output of the GPS clock was activated in order to trigger the transmission of all SV and GOOSE messages. This strategy intended to replicate the worst-case scenario envisioned by the analytical tool where all messages arrived at the switch at the same time.
- After five minutes of steady state operation, the signal generator was programmed to inject an over current signal to one of the analog input channels of the MU (SB1). With this, the Over Current protection function of the BP2 relay was triggered, and a trip message was sent to the rest of the network. This event also triggered the SoE and the COMTRADE recorder of the BP2 device.
- Once the BP1 device received the alarm message from BP2, one of its LEDs lighted up, thus the event could be identified within the corresponding SoE file. Next, the BP1 device changed the value of the monitored variable, allowing the circuit breaker trip by the SB2 device.
- Once the SB2 device has received the alarm messages from BP1, it recorded the event within a PCAP file generated by the Wireshark [35] instance running in the device. The circuit breaker is simulated by a variable within the SB2 device. From this point, the acknowledgement of the events goes in the opposite direction (i.e., from SB2 to BP1, from BP1 to BP2 and so on).
- After ten minutes of operation, the GPS clock disabled (via one of its digital outputs) the transmission of all GOOSE and SV messages, thus slowing down the activity in the network. Ten seconds later, the GPS clock enables the transmission of messages starting the process all over again.

The previously described steps were executed during two hours and the maximum end-to-end delay values were obtained by correlating the inputs and outputs of events registered within the log, SoE and COMTRADE files of each device.

Table 9 highlights a comparison among the three techniques used for the SAS communication assessment. The difference mentioned in the last line of this table refers to the variation between the lowest and highest values obtained for each message stream. The analytical approach presents slightly longer times for the maximum delays. This is an expected result because it is well known that prototype measurements and simulation approaches can present optimistic results and should not be used to determine worst-case response times. The reason is that, no matter how long these experiments take place, there is no guarantee that the worst-case of a code execution branch would occur.

Table 9. Maximum end-to-end delay from three evaluation methods.

	\mathcal{R}_7 (SB1)	\mathcal{R}_6 (BP2)	\mathcal{R}_5 (BP1)	\mathcal{R}_4 (SB2)
Experimental	26.50 μ s	26.00 μ s	39.80 μ s	38.50 μ s
Simulation	25.38 μ s	25.92 μ s	37.92 μ s	38.40 μ s
Analytical model	26.92 μ s	28.52 μ s	40.68 μ s	40.68 μ s
Difference	1.54 μ s	2.60 μ s	2.76 μ s	2.28 μ s

6. T1-1 Substation with Background PTP Traffic and 1 Gigabit Network Links

This section presents a simulation scenario involving a T1-1 substation architecture with IEDs in conformance with 1 Gigabit Ethernet and the addition of a timing synchronization background traffic, namely a stream of PTP (IEEE 1588) messages. The purpose of this section is to highlight the ability of the proposed response time analysis to handle different sets of message streams.

The PTP stream of sync messages produced by a Grand Master Clock is modeled as a background message stream (\mathcal{T}_3) with message size of 255 bytes, which is assumed as the maximum size of PTP Sync messages. Following the RM policy, the lowest priority was assigned to \mathcal{T}_3 . Table 10 illustrates the parameters for this new message stream. The parameters for other message streams (\mathcal{T}_7 , \mathcal{T}_6 , \mathcal{T}_5 and \mathcal{T}_4) are similar to the ones presented in Table 4.

Table 10. Precision Time Protocol (PTP) message stream parameters for 100 Mbps and 1 Gbps Ethernet.

Message Stream	Source	Message Type	P_i	T_i (μ s)	D_i (μ s)	C_i (μ s)		J_i (μ s)		U_i (%)	
						100 Mbps	1 Gbps	100 Mbps	1 Gbps	100 Mbps	1 Gbps
\mathcal{T}_3	Grand Master Clock	Sync PTP Message	3	1,000,000	250,000	21.36	2.136	1.0	0.2	0.00002	0.000002

The VLAN settings of Figure 7 and Table 6 were preserved. In addition, the traffic generated by the Grand Master Clock (\mathcal{T}_3) is associated to VLAN2. Thus, as occurred before with \mathcal{T}_4 , the stream \mathcal{T}_3 will never receive any interference from \mathcal{T}_6 in port 3, and also the maximum transmission duration of \mathcal{T}_3 will become the blocking time for the others higher priority message streams.

Table 11 presents both the simulated and analytical results. For the sake of comparability, this table also shows the results obtained with and without background traffic, and with megabit or gigabit links.

The obtained results illustrate that both analytical and simulation tools yield good performance in the response time analysis and proved to be flexible enough to accurately analyze different configurations of SAS systems.

Table 11. Results of a T1-1 system with 100 Mbps and 1 Gbps links both with and without PTP traffic.

		\mathcal{R}_7 (SB1)	\mathcal{R}_6 (BP2)	\mathcal{R}_5 (BP1)	\mathcal{R}_4 (SB2)	\mathcal{R}_3 (PTP)
100 Mb without PTP	Analytical	26.92 μ s	28.52 μ s	40.68 μ s	40.68 μ s	Not Applicable
	Simulation	25.38 μ s	25.92 μ s	37.92 μ s	38.40 μ s	Not Applicable
100 Mb with PTP	Analytical	36.30 μ s	37.90 μ s	50.10 μ s	63.80 μ s	63.80 μ s
	Simulation	35.51 μ s	35.60 μ s	49.23 μ s	62.47 μ s	62.84 μ s
1 Gb without PTP	Analytical	2.69 μ s	2.85 μ s	4.06 μ s	4.06 μ s	Not Applicable
	Simulation	2.42 μ s	2.52 μ s	3.62 μ s	3.78 μ s	Not Applicable
1 Gb with PTP	Analytical	3.55 μ s	3.71 μ s	4.93 μ s	6.30 μ s	6.30 μ s
	Simulation	3.46 μ s	3.45 μ s	4.82 μ s	6.20 μ s	6.28 μ s

7. Final Remarks

This paper highlights how the classical real-time scheduling theory can be used to analyze the communication response time in an SAS, in conformance with the IEC 61850 standard. The proposed analytical model allows the assessment of the worst-case response times of IEC 61850 process bus message streams. This is an innovative approach because, to the best of our knowledge, there is no other work in the literature providing a similar approach for the assessment of IEC 61850 process bus communication.

A simulation tool and an experimental setup were used to experimentally validate the proposed analytical model. The system was modeled and assessed assuming the use of VLANs and prioritization mechanisms of the IEEE 802.1Q. The following key conclusions can be summarized:

1. The combined use of analytical models and simulation tools during the system design phase may allow a systematic analysis of the process bus schedulability, even for high load communication scenarios. Similar tools may become mandatory for the assessment of future complex SAS configurations. It is possible to make a parallel with another area of application—the automobile industry. The adoption of similar analysis tools in the context of CAN networks leveraged the average bus utilization from around 35% to 80% due to the designers' confidence that the time constraints of all tasks would be met even for high load conditions [5].
2. The use of VLANs and prioritization mechanisms of the IEEE 802.1Q are mandatory for the proper configuration of a typical SAS process bus. Therefore, the used assessment tools must be able to consider this type of lower layers' features of the communication stack.
3. The use of analytical assessment tools will always provide slightly longer times for the worst-case response times, when compared to the maximum response times obtained by simulation or experimental setups. These last approaches usually present optimistic results because, no matter how long their experiments take place, there is no guarantee that the worst-case of a code execution branch would occur.

In the future, it is expected that more complex SAS configurations will require the use of analytical tools similar to the one proposed in this paper. Besides, techniques such as high-performance computing and computational intelligence will enable these systems to behave intelligently, handling more devices with lower response time and with the ability of making failure predictions in the system components.

A further continuation of this work is to handle GOOSE messages with a sporadic server, reducing the inherent pessimism of the analysis. Another alternative is to model and implement the IEC 61869 series standards in the simulator.

Supplementary Materials: The document “Complete IEC 61850 Response Time Analysis presented in Section 3.4” is available online at <http://www.mdpi.com/1996-1073/12/12/2272/s1>.

Author Contributions: H.L. conducted the literature review, designed both the simulator and the prototype, and performed the experiments. O.V. wrote the first version of this manuscript. C.M. and F.V. coordinated the research and conducted the analyses. All the authors contributed to the discussion of results and critical review of this manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

CAN	Controller Area Network
CSWI	Switch Controller LN
EPS	Electric Power System
FIFO	First In, First Out
GOOSE	Generic Object Oriented Substation Events
HMI	Human Machine Interface
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IFG	Inter Frame Gap
LAN	Local Area Network
LN	Logical Node
MU	Merging Unit
PIOC	Over Current Protection LN
P&C	Protection & Control
PTP	Precision Time Protocol
RM	Rate Monotonic

SAS	Substation Automation Systems
SCADA	Supervision, Control and Data Acquisition
SV	Sampled Values
TCTR	Current Transformer LN
TTL	Time allowed To Live
TVTR	Voltage Transformer LN
VLAN	Virtual Local Area Network
WAN	Wide Area Network
XCBR	Circuit Breaker LN

Appendix A. Conformance Statements of the Simulator for IEC 61850 Compliant SAS

In this appendix, we present the conformance statements of the proposed simulator that provide the required elements to assess IEC 61850 process bus deployments. A preliminary description of this simulator tool was presented in [33], and additional information about the simulator library and its corresponding source-code is available at [34].

Both parts 8-1 and 9-2 of the IEC 61850 standard provide tables named Protocol Implementation Conformance Statement (PICS), where the manufacturers document the communication capabilities of each developed device. Table A1 highlights the compliance with the IEC standard of the devices implemented in the proposed simulator.

Table A1. Simulator's A-Profile and T-Profile PICS support.

MU IEDs			
Abbreviation	Description	Subscriber	Publish
A1	Client/Server A-Profile	No	No
A2	SV A-Profile	Yes	Yes
T1	TCP/IP T-Profile	No	No
T1	SV T-Profile	Yes	Yes
	SendMSVMessage	Not applicable	Yes
P&C IEDs			
Abbreviation	Description	Subscriber	Publish
A1	Client/Server A-Profile	No	No
A2	GOOSE A-Profile	Yes	Yes
T1	TCP/IP T-Profile	No	No
T3	GOOSE T-Profile	Yes	Yes
T5	TimeSync T-Profile	No	No
GoCB	GOOSE Control Block	Not applicable	Yes
	GOOSE Services	Yes	Yes
	SendGooseMessage	Not applicable	Yes

While important, these conformance statements are not enough. Before asserting that a device is compliant with IEC 61850, it is necessary to perform a series of tests specified in Part 10 of the standard. The conformance tests propose several use cases and, in the context of this work, five tests for static requirements were implemented (Table A2). Four of them involve sending GOOSE messages (named Goo3, Goo4, Goo5 and GsePs1) and one of them involves SV messages (Sv1). For the sake of space limitation, these results are not discussed in this paper, but they are available in [34] along with the source code of the simulator.

Table A2. Conformance tests for static requirements.

DUT	Test	Short Description
P&C generator	Goo3	Check if GOOSE messages are periodically published.
	Goo4	Check if GOOSE module has initial values correctly assigned.
	Goo5	Force a data value change and checks if GOOSE messages are sent as specified in the standard.
P&C processor	GsePs1	Send a GOOSE message with new data in the data-set and check if the received message is consistent.
MU generator and processor	Sv1	Generate SV messages and verify if the transmitted and received values are consistent.

References

- Mackiewicz, R. Overview of IEC 61850 and Benefits. In Proceedings of the Power Systems Conference and Exposition (PSCE '06), Atlanta, GA, USA, 29 October–1 November 2006; pp. 623–630. [\[CrossRef\]](#)
- Honeth, N.; Khurram, Z.; Zhao, P.; Nordstrom, L. Development of the IEC 61850-9-2 software merging unit IED test and training platform. In Proceedings of the 2013 IEEE Grenoble, PowerTech (POWERTECH), Grenoble, France, 16–20 June 2013; pp. 1–6. [\[CrossRef\]](#)
- Tindell, K.W.; Hansson, H.; Wellings, A.J. Analysing real-time communications: Controller area network (CAN). In Proceedings of the Real-Time Systems Symposium, San Juan, Puerto Rico, 7–9 December 1994; pp. 259–263. [\[CrossRef\]](#)
- Pinho, L.M.; Vasques, F. Timing Analysis of Reliable Real-Time Communication in CAN Networks. In Proceedings of the IEEE Computer Society 13th Euromicro Conference on Real-Time Systems, Delft, The Netherlands, 13–15 June 2001; pp. 103–112.
- Davis, R.I.; Burns, A.; Bril, R.J.; Lukkien, J.J. Controller Area Network (CAN) schedulability analysis: Refuted, revisited and revised. *Real Time Syst.* **2007**, *35*, 239–272. [\[CrossRef\]](#)
- Carreiro, F.B.; Moraes, R.; Fonseca, J.A.; Vasques, F. Real-time communication in unconstrained shared Ethernet networks: The virtual token-passing approach. In Proceedings of the 2005 IEEE Conference on Emerging Technologies and Factory Automation, Catania, Italy, 19–22 September 2005; Volume 1, pp. 8–432. [\[CrossRef\]](#)
- Communication networks and systems in substations. In *Part 80-1—Network Engineering Guidelines*; IEC: Geneva, Switzerland, 2013.
- Communication networks and systems in substations. In *Part 7-1—Basic Communication Structure Principles and Models*; IEC: Geneva, Switzerland, 2003.
- Communication networks and systems in substations. In *Part 8-1—Specific Communication Service Mapping (SCSM) Mappings to MMS*; ISO/IEC 9506-1; ISO/IEC 9506-2; ISO/IEC 8802-3; IEC: Geneva, Switzerland, 2004.
- Lei, H.; Singh, C.; Sprintson, A. Reliability Modeling and Analysis of IEC 61850 Based Substation Protection Systems. *IEEE Trans. Smart Grid* **2014**, *5*, 2194–2202. [\[CrossRef\]](#)
- Communication networks and systems in substations. In *Part 9-2—Specific Communication Service Mapping (SCSM)—Sampled Values over ISO/IEC 8802-3*; IEC: Geneva, Switzerland, 2004.
- Richards, S.; Arnaud, J. Digital Substation? The Next Generation Smart Substation for the Power Grid. *PAC World Magazine*, 14 July 2016.
- Juarez, J.; Rodriguez-Morcillo, C.; Rodriguez-Mondejar, J.A. Simulation of IEC 61850-based substations under OMNeT++. In Proceedings of the 5th International ICST Conference Simulation Tools and Techniques, Desenzano del Garda, Italy, 19–23 March 2012; pp. 319–326.
- Golshani, M.; Taylor, G.; Pisica, I. Simulation of power system substation communications architecture based on IEC 61850 dard. In Proceedings of the Power Engineering Conference (UPEC) 49th International Universities, Cluj-Napoca, Romania, 2–5 September 2014; pp. 1–6. [\[CrossRef\]](#)
- Sidhu, T.; Yin, Y. IED modelling for IEC 61850 based substation automation system performance simulation. In Proceedings of the Power Engineering Society General Meeting, Montreal, QC, Canada, 18–22 June 2006; p. 7. [\[CrossRef\]](#)

16. Altaher, A. Implementation of a Dependability Framework for Smart Substation Automation Systems: Application to Electric Energy Distribution. Ph.D. Thesis, Université Grenoble Alpes, Grenoble, France, 2018.
17. Kasarpatil, K.; Karadkar, T.; Dudwadkar, A. Digital Substation and Case Study of Tata Power. *Int. J. Emerg. Technol. Adv. Eng.* **2015**, *5*, 134–141.
18. Zhang, Y.; Cai, Z.; Li, X.; He, R. Analytical Modeling of Traffic Flow in the Substation Communication Network. *IEEE Trans. Power Deliv.* **2015**, *30*, 2119–2127. [[CrossRef](#)]
19. Huang, C.; Li, F.; Ding, T.; Jiang, Y.; Guo, J.; Liu, Y. A Bounded Model of the Communication Delay for System Integrity Protection Schemes. *IEEE Trans. Power Deliv.* **2016**, *31*, 1921–1933. [[CrossRef](#)]
20. Kunz, G.; Machado, J.; Perondi, E.; Vyatkin, V. A Formal Methodology for Accomplishing IEC 61850 Real-Time Communication Requirements. *IEEE Trans. Ind. Electron.* **2017**, *64*, 6582–6590. [[CrossRef](#)]
21. Shin, I.J.; Song, B.K.; Eom, D.S. International Electrotechnical Committee (IEC) 61850 Mapping with Constrained Application Protocol (CoAP) in Smart Grids Based European Telecommunications Standard Institute Machine-to-Machine (M2M) Environment. *Energies* **2017**, *10*, 393. [[CrossRef](#)]
22. Zhu, Z.; Xu, B.; Brunner, C.; Yip, T.; Chen, Y. IEC 61850 Configuration Solution to Distributed Intelligence in Distribution Grid Automation. *Energies* **2017**, *10*, 528. [[CrossRef](#)]
23. Ingram, D.; Schaub, P.; Taylor, R.; Campbell, D. System-Level Tests of Transformer Differential Protection Using an IEC 61850 Process Bus. *IEEE Trans. Power Deliv.* **2014**, *29*, 1382–1389. [[CrossRef](#)]
24. Manbachi, M.; Sadu, A.; Farhangi, H.; Monti, A.; Palizban, A.; Ponci, F.; Arzanpour, S. Real-Time Co-Simulation Platform for Smart Grid Volt-VAR Optimization Using IEC 61850. *IEEE Trans. Ind. Inf.* **2016**, *12*, 1392–1402. [[CrossRef](#)]
25. Agustoni, M.; Mortara, A. A Calibration Setup for IEC 61850-9-2 Devices. *IEEE Trans. Instrum. Measur.* **2017**, *66*, 1124–1130. [[CrossRef](#)]
26. Jurišić, G.; Havelka, J.; Capuder, T.; Sučić, S. Laboratory Test Bed for Analyzing Fault-Detection Reaction Times of Protection Relays in Different Substation Topologies. *Energies* **2018**, *11*, 2482. [[CrossRef](#)]
27. Georg, H.; Dorsch, N.; Putzke, M.; Wietfeld, C. Performance evaluation of time-critical communication networks for smart grids based on IEC 61850. In Proceedings of the IEEE INFOCOM, Turin, Italy, 14–19 April 2013; pp. 3417–3422.
28. Santos, A.; Soares, B.; Fan, C.; Kuipers, M.; Sabino, S.; Grilo, A.M.R.C.; Pereira, P.R.B.A.; Nunes, M.S.; Casaca, A. Characterization of Substation Process Bus Network Delays. *IEEE Trans. Ind. Inform.* **2018**, *14*, 2085–2094. [[CrossRef](#)]
29. Liu, J.W.S. *Real-Time Systems*; Prentice-Hall: Upper Saddle River, NJ, USA, 2000.
30. Kohler, D. A Practical Implementation of an IEEE1588 supporting Ethernet Switch. In Proceedings of the 2007 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control and Communication, Vienna, Austria, 1–3 October 2007; pp. 134–137. [[CrossRef](#)]
31. Schweitzer Engineering Laboratories Inc. *SEL-751A, Feeder Protection Relay, Instruction Manual*; SEL: Washington, DC, USA, 2012.
32. Reason Tecnologia SA. *RL131, Relé Multifunção para Proteção e Controle de Alimentador, Manual do Usuário*; Reason Tecnologia S.A.: Florianópolis, Brazil, 2013.
33. León, H.; Montez, C.; Stemmer, M.; Vasques, F. Simulation models for IEC 61850 communication in electrical substations using GOOSE and SMV time-critical messages. In Proceedings of the 2016 IEEE World Conference on Factory Communication Systems (WFCS), Aveiro, Portugal, 3–6 May 2016; pp. 1–8. [[CrossRef](#)]
34. IEC 61850 Process Bus Models for OMNeT++/INET. Available online: <https://github.com/hectordelahoz/ProcessBusIec61850> (accessed on 1 March 2019).
35. Sharp, R.; Warnicke, E. Wireshark User's Guide. Available online: https://www.wireshark.org/docs/wsug_html_chunked/ (accessed on 1 March 2019).

