

Proceeding Paper

Real-Time Cyber–Physical Power System Testbed for International Electrotechnical Commission 61850 Generic Object-Oriented Substation Event Transfer Time Measurements [†]

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Abstract: Towards the decarbonisation of the power system, digital substations have gradually increased in smart grids, where Ethernet cables have replaced large quantities of copper wires. With this transition, the standardised communication protocols through the LAN network play a central role in exchanging information and data between the physical power system and the control centres. One of the well-known protocols in the digital substations is IEC 61850 GOOSE (Generic Object-Oriented Substation Event), which is used to share time-critical information related to protection, automation, and control. The transmission time of this protocol affects power system operation and raises various issues, such as communication latencies and incorrect information. Therefore, it is necessary to consider the protocol transmission time for further protection and control mechanisms to ensure the stability and efficiency of the power system. For this purpose, this paper contributes the implementation of a cyber–physical power system (CPPS) testbed to measure the transfer time of IEC 61850 GOOSE under the real-time domain using the real-time simulator, Typhoon HIL, and its toolchains. This paper can benefit scholars and researchers in the relevant domains in implementing a CPPS testbed and an approach for transfer time measurement of communication protocols within the laboratory, eliminating the need for real-world substation devices.

Keywords: cyber–physical power system; communication protocol; GOOSE; IEC 61850; real-time simulation; Typhoon HIL



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1. Introduction

The design of upcoming power systems has been experiencing significant challenges as it moves from the traditional centralised method of electricity generation to a decentralised system [1,2]. This transition enables the development of flexible, low-carbon energy and power systems [3]. In addition, the use of numerous interactive distributed units creates new technical difficulties with the implementation of various smart grid concepts, such as virtual power plants (VPPs) [4], microgrids [5], and digital substations [6]. The consistent improvement in communication technologies, in terms of speed, reliability, and adaptability, has facilitated the conversion of conventional substation wiring into a fully digital environment.

Digital substations offer significant advantages compared to their traditional counterparts [7]. The availability of high-bandwidth communication enables the transmission of

large amounts of data over a single Ethernet cable, reducing the large amount of copper wiring in the substation [8]. To facilitate this transition to digital substations, there is a need for a universal communication standard that enhances interoperability and ensures the system's sustainability. As a result, the IEC 61850 standard was established to provide comprehensive models for power system devices across different vendors.

The IEC 61850 communication includes time-critical services that use GOOSE messages to transfer data and is usually associated with protective relaying activities. The popularity of this protocol has expanded in recent years [9]. For example, in [10], the authors proposed the conventional protective relay testing and the performance testing of IEC 61850-based relays to evaluate GOOSE message performance over traditional hardwired testing. Accordingly, functional testing has proved that GOOSE provides a very flexible, fast, high-priority, and reliable method for exchanging substation events among IEDs for interlocking and protection purposes. Similarly, another paper [11] proposed a methodology for the real-time implementation of a communication-dependent, logically selective, adaptive protection algorithm for AC microgrids using hardware-in-the-loop IEC 61850 GOOSE protocol testing. The authors in this paper agreed that the whole process of fault detection, isolation, and adaptive setting using Ethernet communication is possible within the standard low-voltage ride-through curve, which maintains the seamless transition to the islanded mode. Furthermore, in [12], Sidhu et al. provided a step-by-step configuration process comprising IEC 61850 data modelling, datasets of GOOSE within individual IEDs, and system integration of GOOSE.

In the aforementioned papers, the authors emphasised the importance of the IEC 61850 GOOSE communication protocol in the control and protection of digital substations. Therefore, it is necessary to consider the time transmission of GOOSE to ensure the accuracy of the proposed control and protection mechanisms. Since conventional power systems have transformed into cyber-physical systems (CPS), the cyber-physical power system (CPPS) testbed is considered a valuable solution. Indeed, the CPPS has the ability to integrate communication protocols and advanced control and protection algorithms [11]. For example, the authors in [13] used a CPPS testbed to verify the monitoring and wide-area control. Additionally, with the advent of simulation modelling, the appearance of real-time simulators such as RTDS, Typhoon HIL, or OPAL-RT enhanced the simulation capabilities to replicate the realistic power system behaviours and characteristics [14]. Leveraging these real-time simulators, the authors in [15] proposed a CPPS testbed for optimal power flow study using Typhoon HIL. The communication protocols were also involved in this research paper, demonstrating practical scenarios in grid operations. Similarly, other researchers have leveraged CPPS to advance power system security and control, highlighting its versatility across different areas of power system research [16]. A key advantage emphasised in these studies is CPPS's ability to operate in real-time environments, effectively simulating real-world scenarios without the need for costly infrastructure (such as RTUs, PMUs, or digital protection relays), making it a cost-effective and scalable approach for power system experimentation and development [2,17]. Therefore, there is an urgent need to deploy the CPPS testbed for further research and studies in control and protection domains.

To address this need, this paper proposes a CPPS testbed to implement an IEC 61850 GOOSE communication protocol under real-time simulation, aiming to measure its transfer time within a laboratory environment. The main contributions of this paper can be summarised as follows:

- A construction methodology for the CPPS testbed is proposed using a real-time simulator, Typhoon HIL. This testbed is used to mimic the actual operations of power systems such as a manual open/close circuit breaker or an automatic tripping protection relay under fault scenarios.
- The communication protocol, IEC 61850 GOOSE, is integrated into the CPPS testbed. The deployment of this protocol within the laboratory environment opens a new horizon for the further testing of control and protection mechanisms.

- The methodology of transmission time estimation of IEC 61850 GOOSE is provided in this paper. One-way and round-trip transfer time experiments are conducted to verify the working conditions of the laboratory for further studies in the control and protection domains.

The remaining sections of the paper are organised as follows. Section 2 provides the theoretical background of the IEC 61850 GOOSE communication protocol. In this section, the structure of the GOOSE message and the transfer time measurement based on international standards are provided. Then, the methodology of CPPS testbed implementation and the time measurement approach are provided in Section 3. Section 4 describes the experimental cases with relevant hardware and software in a laboratory environment. Finally, the last section, Section 5, summarises the main contribution of the work that was carried out.

2. Theory Background

2.1. IEC 61850 GOOSE

The IEC 61850 device model begins with a physical device connected to the network and is defined by its network address [18]. Within each physical device, one or more logical devices may provide a common interface between various physical devices in the substation and the SCADA system. Each logical device contains one or more logical nodes and functional units within a logical device [19]. A logical node is a named grouping of data and associated services and is logically related to the power system function. The IEC 61850 defines a standardised way of addressing data objects. Figure 1 shows the default addressing scheme that includes the following:

- LDName—stands for logical device name.
- LNRef—stands for Logical Node name.
- DataObjectName—the data objects within a logical node represent the information that is exchanged between devices.
- DataAttributeName—describes the properties of the data objects. These attributes may include data type, measurement range, and accuracy.
- FC—stands for function code defining the type of message being sent, such as a control command or status update.

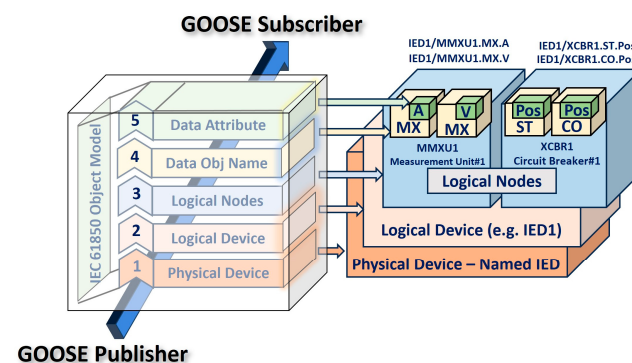


Figure 1. Default naming scheme of IEC 61850 GOOSE.

The IEC 61850 GOOSE protocol specifies that engineers and vendors use Substation Configuration Language (SCL), which was developed to configure the settings and format the functions within a particular IED [20].

Manufacturer-specific IED configuration tools are used to convert the functionality, communication mechanism, and parameters of an entire IED into a hierarchy of SCL system files. The “.scd” file extension is used for SCL files, which contain the description of the substation configuration data in XML format. The “.scd” file defines the logical nodes, data classes, and data objects within the substation, along with their attributes and relationships. In addition, this type of format serves as a blueprint for the configuration of

the communication network and system in the substation, and the engineering tools and IEDs use it to understand and interpret the data exchanged in the system.

The IEC 61850 GOOSE protocol specifies transmission times based on various operation applications. As outlined in [21], these transmission time requirements are summarised in Table 1. For critical operations like interlocking or trip signals, which necessitate a rapid response, the protocol mandates a maximum transmission time of 10 milliseconds. This ensures the reliable and timely exchange of fast messages, essential for the proper functioning of time-sensitive protection and control operations.

Table 1. Transmission time requirements for substation operations.

Type	Performance Class	Application Type	Max Transmission Time
Type 1A—Trip	P1	Interlocking, inter trip, logic discrimination	10 ms
Type 1B—“Others”	P1	Interaction of the automation system	100 ms
Type 2	P2	Status monitoring, control commands	100 ms
Type 3	P1	Historical data, event logging	500 ms

2.2. IEC 61850 GOOSE Transfer Time

The idea of transfer time, as described in IEC 61850-5 [21], is used to ensure adequate transmission time between two devices [22]. Part 5 of this standard provides a diagram, as shown in Figure 2a, that depicts the transfer time for transmitting a message from one device to another.

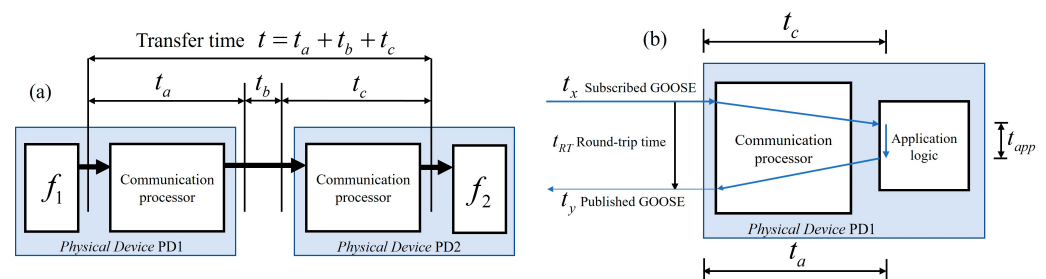


Figure 2. (a) GOOSE transfer time and (b) GOOSE round-trip time.

The measurement of data transfer is calculated from the moment the sender (physical device 1, PD1) sends the data to the point that the receiver (physical device 2, PD2) receives it. This duration is the transfer time, which includes t_a and t_c , the time taken by the communication processors at both ends to encode and decode the data, and t_b , the time taken for the data to travel over the network.

2.3. IEC 61850 GOOSE Round-Trip Time

The internal data of commercial devices are typically inaccessible to end users, which makes it challenging to measure transfer time according to IEC 61850-5 specifications [22]. However, by following the transfer time definition provided in the standard, various tests can be performed to assess the performance of devices that comply with IEC 61850.

The round-trip time specified in IEC 61850-10 [23], as shown in Figure 2b, can be used to measure the transfer time. According to this standard, the time between receiving a subscribed GOOSE message (t_x) and publishing a GOOSE message (t_y) on the network determines the round-trip time, t_{RT} . It is noticed that while this definition is similar, it deviates from the standard use of round-trip time in the networking community.

2.4. Ping-Pong Test

As shown in Figure 3, the ping-pong test is performed by two devices that publish and subscribe to GOOSE messages to measure the round-trip time between the two devices. In this test, the Test Set (TS) device, device A, publishes a message to the Device Under Test (DUT), device B. Device B then responds by publishing a message that device A subscribes to. According to IEC 61850-10, this test focuses on measuring the round-trip time and is intended as a benchmark for comparing the performance of different IEDs.

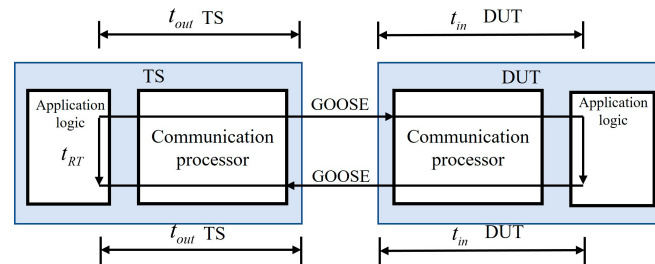


Figure 3. Ping-pong test.

3. Implementation of Cyber–Physical Power System Testbed and Methodology of Transfer Time Measurement

3.1. CPPS Testbed Implementation

Figure 4 illustrates the architecture of the CPPS testbed that relies on communication between two real-time simulators. The real-time simulator has the capability to communicate with external devices via LAN Ethernet [24]. In recent years, there have been many studies utilising real-time simulators to transmit communication signals to external devices [2]. For example, the author in [25] proposed an approach consisting of using the OPAL-RT platform to interact with protection relays. In the same manner, the authors in this paper utilise two real-time simulators to develop a CPPS testbed to simulate the behaviour of the real-world substations in the virtual environment.

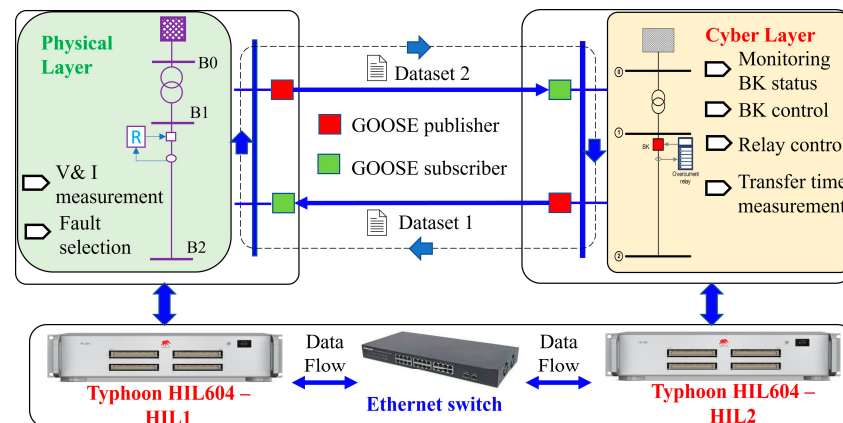


Figure 4. CPPS framework.

The CPPS testbed contains two layers: the physical layer and the cyber layer. The physical layer sends the information and data of physical devices, while the cyber layer provides the control feedback. In this setup, the CPPS is designed to replicate the specific operations in substations regarding the protection relay and circuit breaker (BK), as detailed in Table 2.

Table 2. Operations in CPPS testbed.

Operation	GOOSE Publisher	GOOSE Subscriber	Transfer Type
When a fault occurs, the tripping signal from the relay causes the BK to open, and the BK status is sent from the substation to the control centre.	Physical layer	Cyber layer	One-way transfer
The control centre sends a reset signal for the protection relay in the test system, which clears the tripping signal and takes the BK return to the closed state. In addition, the BK can be manually opened or closed by command from the control centre.	Cyber layer	Physical layer	Round-trip transfer
The control centre updates the status of the BK accordingly.	Physical layer	Cyber layer	

3.2. Transfer Time Measurement

To measure the transmission time of GOOSE messages within the communication system, the authors employed a timer with a specified execution time, T_S . This execution time represents the duration required to solve a system of complex equations and produce the output results, and is synchronised with the real-world clock. The operating principle of detecting logic state changes in the transmitted signal is straightforward; the timer is activated upon the sender's detection of a state change. It remains active until the signal is successfully recorded at the receiver, marking the end of the transmission process. The transfer time is equal to the product of the T_S and n points at the counter.

As illustrated in Figure 5a, the one-way transfer time needs to be precisely measured between two points: point 1 and point 4. Point 1 is the sender transmission stack and point 2 is after the execution of the receiver transmission stack, when the GOOSE message is transmitted onto the network. This timing ensures accuracy, as point 2 aligns with the moment the message is effectively placed onto the network. Similarly, for the client, measurement occurs between point 3, before the receiver transmission stack is initiated, and point 4, after the stack has been fully executed.

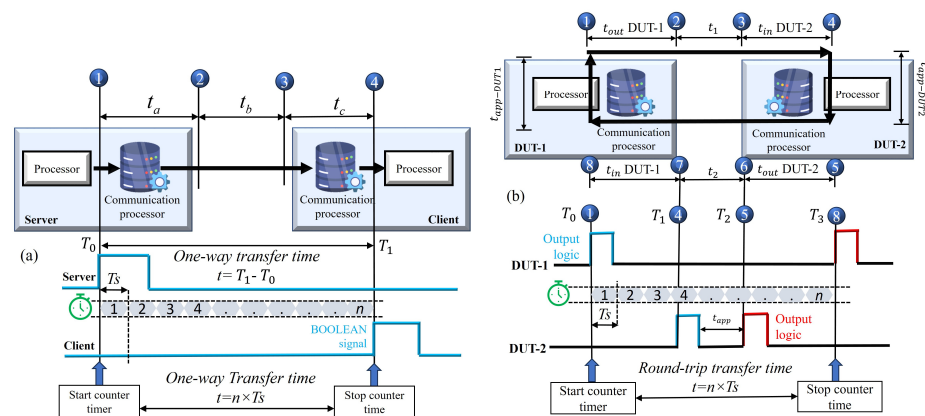


Figure 5. IEC 61850 GOOSE transfer time measurement using timer counter. (a) One-way transfer and (b) round-trip transfer.

For the round-trip transmission time depicted in Figure 5b, the evaluation includes measuring the time interval between two distinct points: point 1 and point 8. This includes two primary segments: points 1 to 4, reflecting the transfer time from DUT-1 to DUT-2, and points 5 to 8, which represent the reverse journey from DUT-2 back to DUT-1. These segments encapsulate the complete transmission process between two devices. Additionally, points 4 to 5 denote the time required for application communication within the devices

themselves. In addition, Algorithm 1 is provided to measure round-trip time based on commands of open and close BK at the cyber layer.

Algorithm 1: GOOSE round-trip time measurement

Inputs:

```

Ts ← Execution rate
Co ← Open BK = 0/Close BK = 1           [BK control = GOOSE send]
SBC ← BK opened = 0/BK closed = 1      [BK status = GOOSE receive]
Clock ← Clock off = 0/Clock on = 1     [Enable/Disable Clock]
en ← Encounter
t_Rt ← GOOSE round-trip time
for i in n = 1, 2...N do:               [N point of measurement]
    if (Clock = 1) and (Co = 1):        [Condition to enable the counter]
        en = 1;
    else
        en = 0;
    end if
    count = 0;
    if en = 1 and SBC = 1:              [Condition to measure t_Rt]
        count = count + 1;
        t_Rt = count * Ts;
    else
        count = 0;
    end if
    Max = 0;
    if t_Rt(t - 1) > t_Rt(t)
        c = 1;
    else
        c = 0;
    end if
    Max = Max + t_Rt(t - 1)*c          [Maintain t_Rt]
end

```

Outputs:

N measured values of GOOSE round-trip time

4. Experimental Case

The experimental cases of the CPPS testbed are conducted at DIgEnSys-Lab at the Department of Electrical Engineering, Information Technology, and Cybernetics at the University of South-Eastern Norway (USN) at the campus in Porsgrunn, Norway (<https://fglongattlab.fglongatt.org>). The laboratory setup is shown in Figure 6. The experiment involved the use of two digital real-time simulators, Typhoon HIL version HIL 604s, each with eight computing cores, two ARM cores, and a combination of digital and analogue input/output. The CPPS testbed is modelled and visualised on two corresponding PCs. One PC was responsible for managing the physical layer, while the other PC was responsible for the cyber layer. Both PCs operate on Windows 10. All devices were connected through a LAN in the laboratory. GOOSE block [16] executes the communication between two layers in the Typhoon HIL environment.

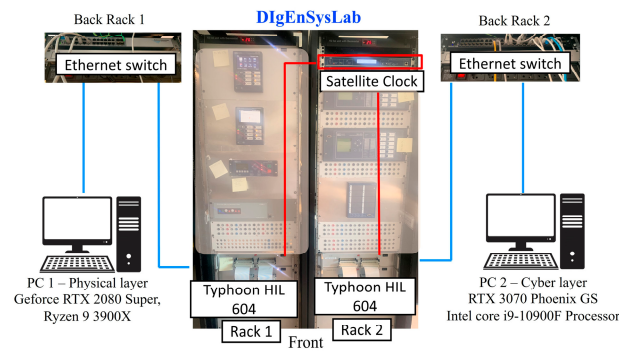


Figure 6. Laboratory setup for CPPS with blue line as Ethernet cable and red line for coaxial cable.

4.1. Test System

The physical layer includes the test model, which is a modified model of the three-phase radial Feeder 1 of the distribution benchmark network, and the CIGRE European Medium Voltage, which was proposed by CIGRE Task Force C6.04.02 [8], as shown in Figure 7. The nondirectional overcurrent protection relay located at transmission line B1–B2 is the instantaneous overcurrent protection relay. The configuration of the relay is provided in [17,26].

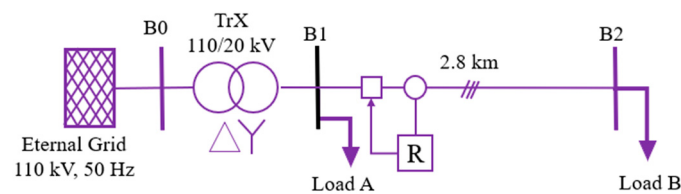


Figure 7. Test system.

4.2. GOOSE Configuration

To implement communication between the two layers, it is necessary to configure the dataset for data transfer. In this paper, the authors used SEL acSELerator Architect Software, Version 2.3.11.2125 [27], which is a Schweitzer Engineering Laboratories (SEL) product, to configure the GOOSE message. The GOOSE files are then exported in a .scd format and imported into GOOSE blocks in the two models. The configuration of the GOOSE files is shown in Table 3.

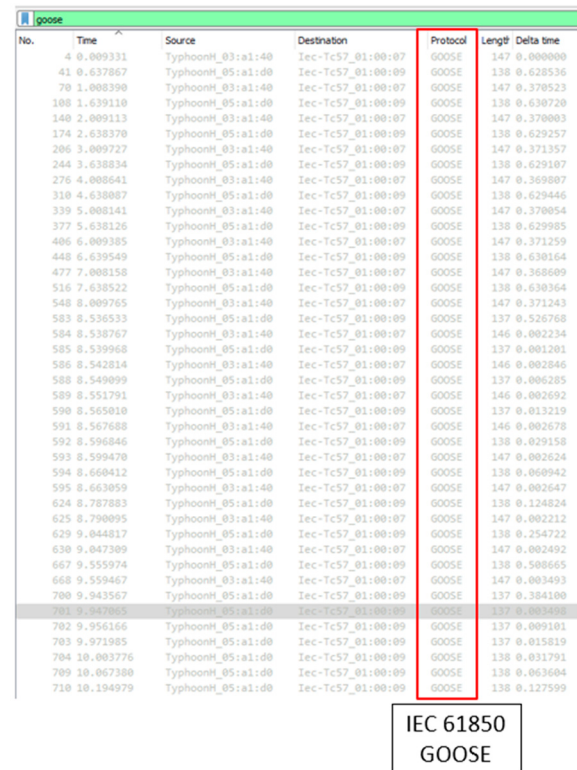
Table 3. GOOSE configuration.

GOOSE dataset 1	
appID	0 × 1000
VLAN ID	0 × 000
Min Time	4 ms
Max Time	1000 ms
Dataset	PIOC\$ST\$q (Relay reset signal) BKRC\$W\$ST\$stVal (BK Open/Close)
GOOSE dataset 2	
appID	0 × 1001
VLAN ID	0 × 001
Min Time	4 ms
Max Time	1000 ms
Dataset	BKRC\$WI\$ST\$stVal (BK status)

4.3. Results and Discussion

The GOOSE package is typically transferred in the LAN with its timestamps, and relevant information can be captured using network analyser software. The well-known

software Wireshark (Version 3.6.1) is a network sniffer tool that can capture network traffic through the host network interface card. Therefore, the GOOSE package can be captured using Wireshark, as shown in Figure 8.



No.	Time	Source	Destination	Protocol	Length	Delta time
4	0.009331	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.000000
41	0.637867	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.628536
70	1.008390	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.370523
108	1.639110	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.630720
140	2.009113	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.370003
174	2.638370	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.629257
206	3.009727	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.371357
244	3.638834	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.629107
276	4.008541	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.369807
310	4.638057	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.629446
339	5.008141	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.370054
377	5.638126	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.629985
406	6.009385	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.371259
448	6.639549	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.630164
477	7.008158	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.368609
516	7.638522	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.630364
548	8.009765	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.371243
583	8.536533	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	137	0.526768
584	8.538767	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	146	0.002234
585	8.539968	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	137	0.001201
586	8.542814	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	146	0.002646
588	8.549099	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	137	0.006285
589	8.551791	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	146	0.002692
590	8.565010	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	137	0.013219
591	8.567688	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	146	0.002678
592	8.596846	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.029158
593	8.599470	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.002624
594	8.60412	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.060942
595	8.663059	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.002647
624	8.787883	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.124824
625	8.790095	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.002212
629	9.044817	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.254722
630	9.047309	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.002492
667	9.555974	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.500065
668	9.559467	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.003493
700	9.943567	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	137	0.384100
701	9.947065	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	147	0.003496
702	9.956166	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	137	0.009101
703	9.971905	TyphoonH_03:a1:40	Iec-Tc57_01:00:07	GOOSE	137	0.015819
704	10.003776	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.031791
709	10.067308	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.063604
710	10.194979	TyphoonH_05:a1:d0	Iec-Tc57_01:00:09	GOOSE	138	0.127599

IEC 61850
GOOSE

Figure 8. IEC 61850 GOOSE captured by Wireshark during the experiments.

However, it is important to note that Wireshark timestamps in Windows environments are sourced from the WinPcap library, which is a Microsoft Windows package capture for software installed in Microsoft Windows computers. WinPcap consists of a driver for low-level network access and a library for accessing low-level network layers [28]. Consequently, utilising Wireshark to capture files and analyse timestamps could potentially result in inaccurate outcomes [29].

The transmission time is measured according to the CPPS testbed operations outlined in Table 2. The one-way transmission time follows the BK state sent from the physical layer to the cyber layer when the fault occurs. On the other hand, the ping-pong test based on BK control and status signal is conducted to correctly obtain the round-trip time of the GOOSE communication protocol between two real-time simulators. The acquisition time from the transmitted and received GOOSE signal is based on Algorithm 1. This algorithm is simulated through logical and computation blocks in Typhoon HIL and connected to the communication part in the control centre model. The execution time for the counter is selected as 20 μ s, and the transmission time is measured at 1000 points.

The GOOSE time measurement consists of 1000 samples over a duration of 25 min. These values are used for analysis to obtain the mean value of the transmission time as well as maximum and minimum values. The measurement time includes the processing time of the communication processor in a real-time simulator under LAN traffic in a laboratory environment.

The measurement results from the experiments conducted in the CPPS testbed are presented and analysed using a histogram and box plot, as illustrated in Figure 9. Specifically, Figure 9a and 9b display the one-way and round-trip transmission times of GOOSE messages, respectively. For one-way transmission, the analysis indicates a mean transmission time of 7.28 ms. The recorded maximum and minimum transmission times are 10.6 ms and

5 ms, respectively. However, the most probable one-way transmission time is 6.5 ms, with a probability density of 0.29. For round-trip transmission, the analysis reveals an average transmission time of 19.68 ms, with a maximum of 32.32 ms and a minimum of 7.65 ms. The most probable round-trip time is 17.3 ms, with a probability density of 0.08.

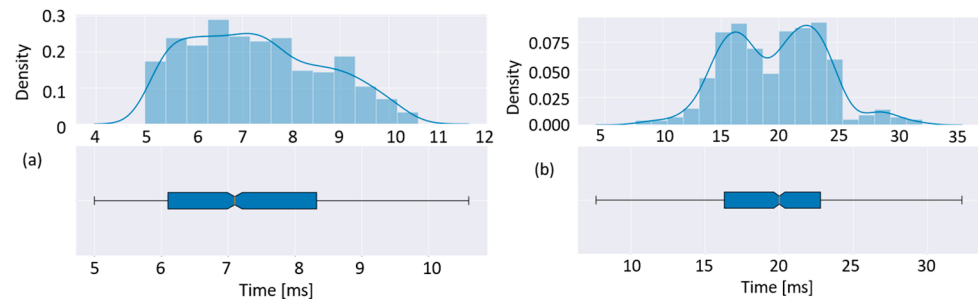


Figure 9. Histogram and box plot of IEC 61850 GOOSE transfer time. (a) One-way transfer and (b) round-trip transfer.

When compared to Table 1, which outlines the required transmission times for operational applications in the power system, the results show that both the mean and most probable one-way transmission times are under 10 ms. Similarly, for round-trip transmission, the mean value of 19.68 ms and the most probable value of 17.3 ms for the outbound and return journeys remain within acceptable limits (below 20 ms for round-trip transfer). These results demonstrate that the laboratory environment satisfies the requirements for researching communication protocols, as well as for control and protection systems in the power grid, particularly for fast message processing and other time-sensitive applications.

However, the observed maximum transmission times for both one-way and round-trip transmissions indicate that there is room for improvement. Increasing the transmission bandwidth and speed in the laboratory environment would help improve the transmission speed and ensure more consistent performance across all scenarios.

5. Conclusions

The shift towards digitalisation in power systems has led to an increase in digital substations, where traditional copper wiring is gradually being replaced by Ethernet cables. This transition has made standardised communication via Ethernet LAN an essential requirement. IEC 61850 is a commonly used communication protocol in these digital substations. The transfer time of this protocol is crucial because it directly affects the operation of substation components and can impact the wider area network. Therefore, it is essential to consider the transfer time of this protocol for further advance control and protection algorithm development. Within the Typhoon HIL framework associated with its toolchains, the lab-based environment is set up for the CPPS testbed to perform the specific operation in the power substation. The CPPS testbed can be used for further research in power system domains without the actual high-cost devices.

The transfer time of the IEC 61850 GOOSE message exchange between layers is measured using 1000 points over approximately 25 min. The presented results show mean transfer times of 7.28 ms and 19.68 ms for one-way and round-trip transfers, respectively. The measurement values obtained from both one-way and round-trip transmission experiments meet the fast message requirements essential for substation operations. This confirms that the laboratory environment is well-suited for conducting experiments and research related to further control and protection system development. Given the capabilities of the CPPS testbed and the potential for improving transmission times, the following suggestions for future work are proposed:

- Transmission time improvement: enhance Ethernet bandwidth and speed to ensure consistent and reliable communication protocols.

- In-depth research on communication latencies: conduct comprehensive studies to further analyse and understand the factors contributing to communication latencies within the system.
- Development of advanced control and protection strategies: utilise the CPPS testbed to explore and implement innovative control and protection strategies, leveraging its capabilities for improved performance and reliability in power system operations.

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