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A Novel Scheme for Performance Evaluation of an IEC 61850-Based Active Distribution System Substation

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ABSTRACT With the integration of Distributed Energy Resources (DERs) into the distribution networks, the Active Distribution Network Management is becoming quite challenging. The DERs are integrated into the distribution networks through distribution substations. For achieving greater control and ease of operation substations are being automated by employing substation communication network based on standardized communication. IEC 61850 standard has emerged as the most popular standard due to its object-oriented modeling and interoperability features. To ensure smooth and efficient operation of substation automation system, the performance requirements for intra substation communication needs to be evaluated. This paper presents modelling of data traffic in the substation according to IEC 61850 and provides validation through simulation as well as through experimental setup. In the experimental setup, a real bay is replicated in the laboratory for performance validation. The scheme has been validated for VLAN and priority tagging implementation with the obtained simulation results.

INDEX TERMS Active distribution system (ADS), IEC 61850, substation communication network (SCN), GOOSE.

I. INTRODUCTION

With the growing concern over fossil fuel depletion and hazardous effects of carbon and sulphur pollutants emitted from conventional power plants, there is an increased demand of renewable power generation. Apart from their power utilization in generation and transmission levels, the Distributed Energy Resources (DERs) are being increasingly proliferated into the distribution system as well [1]–[4]. They have impacted the monitoring, protection and control of primary, secondary as well as the tertiary distribution level. This proliferation of DERs into the distribution system is through the substations and have resulted into bidirectional power flows in distribution networks [5]. This has even impacted the inherent radiality of distribution feeders. The resulted distribution network is more commonly termed as Active Distribution System (ADS) [6].

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The management and control of DERs is achieved through Active Distribution System Management (ADSM) by optimally managing the DERs in the distribution system by taking into consideration, the market constraints, operational uncertainties and optimal power flow [7]. The DERs in ADS are connected via substations. The growth of advanced communication technologies and deployment of Intelligent Electronic Devices (IEDs) impacted the Substation Automation System (SAS) more deeply than ever before [8]. In order to have an interoperable and standardized communication architecture for the SAS, IEC 61850 has emerged as one of the promising solutions. The IEC 61850 standard, a global standard for substation automation, published by International Electrotechnical Commission (IEC) Technical Committee 57 (TC57) in 2003 promises to resolve issues related to substation monitoring, protection, control and above all, the issue of interoperability among different vendor specific IEDs [9]. In order to achieve performance of automation applications, IEC 61850 defines various messages mapped

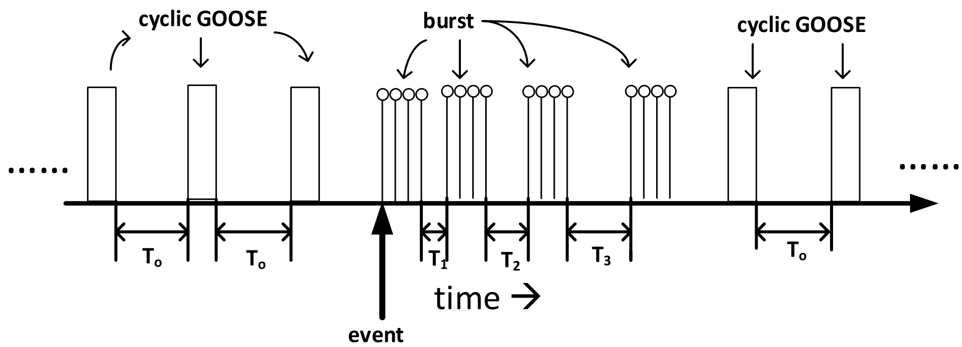

FIGURE 1. **GOOSE message retransmission in IEC 61850.**

to OSI seven-layer communication model. For time-critical events such as protection of electrical equipment and status of breakers, generic object-oriented substation event (GOOSE) messages are exchanged. For periodic messages, sampled value (SV) messages are sent from the conventional CT/PT via merging unit through process bus between devices by means of Ethernet switches.

These standardized information flows and messages (GOOSE, SV and status updates) are in the form of traffic flows in an ADS substation and are required to be modelled for studying the performance requirements of an ADS substation. In order to assess and improve overall performance of Substation Communication Network (SCN) various researchers have presented simulations-based results. A reliable, fast, deterministic SCN architecture for time critical and real-time functions in a substation has been proposed and its performance evaluation has been carried out in Riverbed Modeler for assessing the proposed SCN in terms of latency, throughput, transmission rates for different network configuration [10]. In another work, IEC 61850 based IED models are proposed and their performance evaluation study in a SCN has been carried out using Riverbed Modeler [11], [12]. In a similar work, performance evaluation and reliability assessment of SCN has been carried out by authors in [13]. Mathematical modeling for traffic flows in an SCN and their performance assessment viz. analytical models and stochastic models has been carried out in literature. Authors in [14] presented analytical modeling for traffic flow of SCN and the performance evaluation based on maximum message delay and traffic load distribution. Analysis and stochastic modeling of data flow in an SCN has been carried out in [15]. The performance evaluation based on the proposed traffic models is done using Riverbed Modeler.

Even though a large amount of research has been done to evaluate the performance of SCN based on simulations and mathematical modeling, an experimental validation for performance evaluation of different types of messages in a SCN is required. This paper proposes experimental validation for performance assessment of different message types defined in IEC 61850-5 has been presented for an ADS substation. Firstly, these different types of message are modeled using stochastic modeling approach and then the traffic is set for Riverbed Modeler simulations. Exhaustive results for performance evaluation have been presented. Secondly, a real bay in a SCN is replicated in the laboratory and performance evaluation based on End to End (E2E) delay is done. Lastly, a detailed comparison has been presented which is found to be in validation to the simulation results.

The organization for rest of the paper is as follows, Section II presents mathematical modeling of data flow in a SAS. Section III presents simulation of an ADS substation architecture and its performance evaluation on Riverbed Modeler. Hardware implementation of a real bay in a laboratory and its performance validation has been presented in Section IV. Finally, Section V presents conclusion.

II. MODELING OF DATA FLOW IN SAS

IEC 61850-5 specifies 7 different message types and performance classes in SAS. This section discusses the theoretical modeling of the different type of messages in SAS.

A. TYPE 1 - FAST MESSAGES

This category of messages contains a single point status data or command such as "trip", "close", "start", "stop" or "block". The messages carrying the "trip" command is further named as Type 1A, while other fast messages are named as Type 1B. The Type 1A message have stringent timing requirements and are most important than other fast type of messages.

Whenever a fault occurs, protection devices respond to the fault by generating burst of Type 1A GOOSE messages. The occurrence of fault changes the periodic heartbeat nature of GOOSE message into burst mode. In burst mode, the transmission interval of GOOSE increases sequentially such that after the certain time of trigger of the event, the retransmission time changes back to normal periodic nature as shown in Fig.1. As an event occurs (such as a fault) the retransmission time of GOOSE message is changed from T_o to T_1, T_2, T_3, ...T_n such that $T_1 < T_2 < T_3 < \ldots < T_n$. The sequential increase in retransmission time ends until T_n reaches to T_o. The gradual increase in retransmission time in bursts is adopted in order to increase reliability of the network, since the Type 1A GOOSE message conveys critical commands.

In an ON/OFF model of GOOSE traffic, burst data has self-similar and independent nature with a sequentially increasing retransmission time. When the state is ON, the traffic can be modelled by a heavy tailed function which can model a fixed rate of data in a time period. Thus, Weibull Distribution Process has been selected to model the ON state. In literature, Pareto distribution has been used to model the ON state for a single data source [15]. However, due to inherent nature of Pareto distribution for independent and identically distributed interarrival times, it does not fit for modeling the ON state of bursty GOOSE message which typically has a sequentially increasing retransmission time and thus does not have an identically distributed interarrival time. The Weibull distribution function is given by (1)

$$F(t) = 1 - e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \quad t > 0 \tag{1}$$

where, α and β are scale and location parameters respectively. The OFF state obeys a negative exponential distribution and thus has been model using Poisson distribution. In Poisson process the interarrival times are exponentially distributed with rate parameter of λ. The Poisson distribution is given by (2)

$$\mathrm{P} = \frac{(\lambda \mathrm{t})^{\mathrm{k}} \mathrm{e}^{\lambda t}}{\mathrm{k}!} \tag{2}$$

where, λ is the arrival rate of packets and k is the packet count arrived in time interval t.

B. TYPE 2- MEDIUM SPEED MESSAGES

This category of messages contains transmission of normal state information which contains the important message but the time for transmission i noncritical. These messages include a time tag field from the sender, and the receiver is expected to react normally after an inherent time delay computed from the time tag. The medium speed message category contains client-server type of messages which are either periodic MMS messages or event triggered MMS messages.

The periodic MMS messages are continuously transmitted over the network and are cyclic in nature. The event triggered MMS messages are independent in nature and can occur at any time when an event occurs. However, the time criticality for such messages is medium and thus are classified as medium speed messages. In order to model the traffic of event triggered MMS messages, a distribution function for independent traffic is required. This has been done using a negative exponential distribution function such as a Poisson process given by (2).

C. TYPE 3- LOW SPEED MESSAGES AND TYPE 7- COMMAND MESSAGES

This category includes messages which are used for slow auto-control functions, event record transmission, reading/changing set point values etc. Generally, slow speed functions such as transmitting non-electrical parameters like pressure, temperature. Also, the Type 7 messages used to send control commands to provide access control are same as Type 3 messages with an additional feature of password protection. Thus, Type 7 messages are also considered as Type 3 messages while presenting traffic modeling. The traffic modeling for this class of messages can be modelled on similar lines as Type 2 messages by a negative exponential distribution such as Poisson process.

D. TYPE 4- RAW DATA MESSAGES

This category of messages includes cyclic/periodic sampling messages from the instrument transformers. They contain continuous synchronized data streams generated in a SAS. The SV message generated from the MU IED which is transmitted to P&C IED is a typical example of cyclic raw data message. These messages are time driven data of fixed length, i.e. the triggering of message occurs at same time interval and size of message is decided in advance. The cyclic/periodic data can be modeled as in [15], given by (3);

$$\begin{aligned} M_c &= f(L_c, N_c, D_c) \\ N_c &= f_o \\ D_c &= S_c + E_c + R_c \end{aligned} \tag{3}$$

where Lc is the size of cyclic data, Nc is the number of cyclic data arrived per unit time, Dc is end to end time delay of a packet i.e sum of Ethernet delay Ec, sender delay Sc, and receiver delay Rc.

E. TYPE 5- FILE TRANSFER MESSAGES

This category of message contains bulk of data consisting of recorded files, information files, setting files which are transmitted as and when required by a receiver in a randomly selected time. The data is split into smaller blocks to allow other network activities to occur in between and to ease continuous traffic in the network. A typical FTP message in a SAS belongs to Type 5 message class. In order to model the FTP traffic (or Type 5 message traffic), a stochastic process is selected since the occurrence of FTP type message is random in nature. This has been modelled by exponential probability distribution function given by (4)

$$F(t) = e^{-lt} \tag{4}$$

where l is the rate parameter, and the time interval between two consecutive packets obey a negative exponential distribution of 1/l i.e. the interarrival time is inverse of the rate parameter.

F. TYPE 6- TIME SYNCHRONIZATION MESSAGES

This category of message contains the synchronization messages for the internal clocks of IEDs in an SAS. These messages are periodic in nature and their periodicity is determined based on the accuracy for the application. However, time synchronization message accuracy must be an order above the accuracy required by the functional requirements of the application.

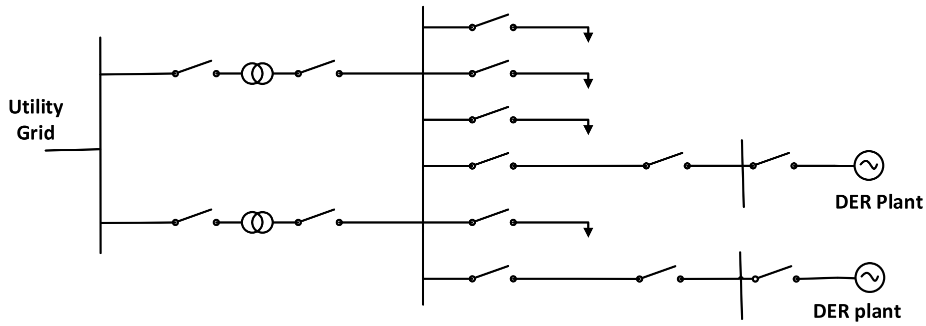

FIGURE 2. Single line diagram of a ADS substation test system.

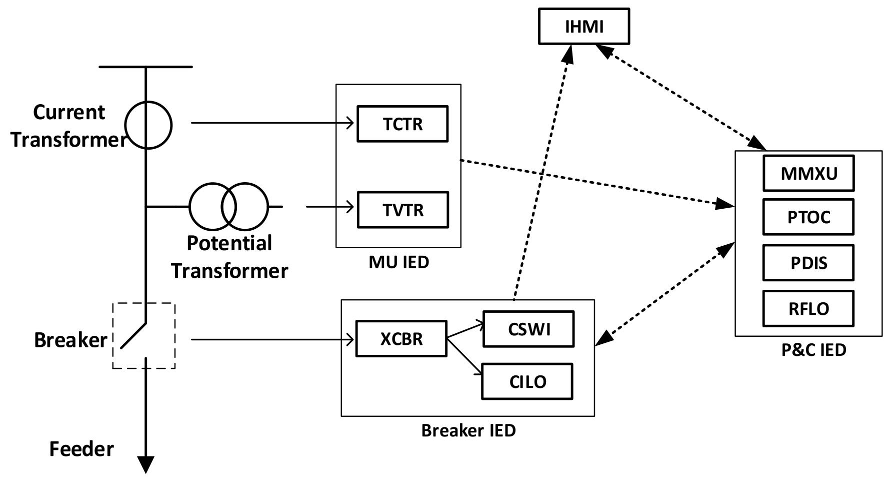

FIGURE 3. IEC 61850 logical node representation for a bay in a substation.

III. MODELLING SIMULATION OF SCN

A SAS communication architecture of an ADS substation consists of various bays such as transformer bay, bus section bay or a feeder bay and is represented in Fig. 2. These bays in the SAS are modeled with three different types of IEDs namely, Merging Unit (MU) IED, Breaker IED and Protection and Control (P&C) IED. MU is the main equipment in process level, which receives current and voltage samples from non-conventional instrument transformers and then convert them to digital data packets and communicate to other IEDs, as per communication mechanisms described in IEC 61850-9-2LE [10]. The SV data generated from MUs is time stamped and synchronized using time synchronization source in the substation. A synchronizing accuracy of $1\mu s$ is required by the 'IEC 61850-9-2 LE' process-bus implementation guidelines to synchronize the MUs in SAS. Breaker IED represents the circuit breaker controlling device, control and monitor the status and condition of breaker and also acts as a sink for tripping, close and interlocking commands. P&C IEDs normally receive the SVs data packets from MU IEDs and implement protection and control functions by exchanging appropriate data with other IEDs.

The MU IED produces the voltage and current samples and therefore comprises of TCTR, TVTR logical nodes. A MU IED normally sends the samples values to P&C IEDs and other IEDs, as required by the application, in the same LAN by direct mapping on to Ethernet layer. Breaker IED is modeled with LNs such as XCBR, XSWI and XFUS. XCBR is used to model circuit breaker with short circuit breaking capability, whereas XSWI is used to model switches without short circuit breaking capability. P&C IED receives the measurement data from the MU IED and exchange data with other IEDs for control and protection functions. The P&C IED comprises of LNs corresponding to the protection and control functions such as PDIF, PDIS, PTOC etc. and LNs MMXU for receiving SVs. Fig. 3 shows the LN description of different IEDs at a feeder bay.

The modeling of various components of a SAS i.e. P&C IEDs, MU IEDs, breaker IEDs, Ethernet switches and fiber optic links is done using Riverbed Modeler. The MU IED sends sample values which are directly mapped to the data link layer of the TCP/IP model. To model the MU IED node in Riverbed Modeler the '*ethernet_station_adv*' node is considered which accommodates the communication stack for MMS based messages. The P&C IED and the breaker IED are related with publishing and subscribing GOOSE messages and also for client server type communication which requires complete TCP/IP implementation. This is possible

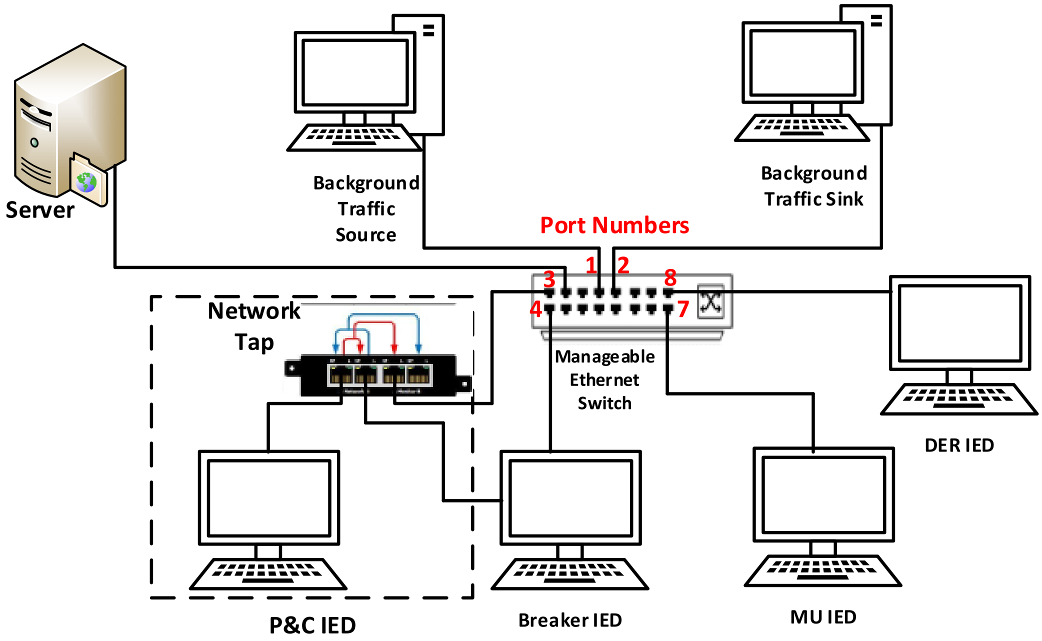

FIGURE 4. Functional diagram of laboratory setup.

only when a node has dual capability of two communication stacks. Thus, a modified '*ethernet_wkstn*' node is used for the simulation. The message flows in simulation are based on following assumptions.

1. The SV messages along with the status update messages, which is MMS based, start flowing at t = 3s. Since these messages are mapped as TCP over IP and travels continuously and are thus modeled as cyclic data.
2. At t = 5s a fault occurs in feeder 2 of the SCN. The trip message is generated from the P&C IED which is send to breaker IED for appropriate tripping action. The breaker IED generates GOOSE messages, which provides acknowledgement to the P&C IED and also to server. However, the GOOSE packet has its specific destination MAC to identify the P&C IED which is responsible for generating the trip command.
3. To maintain proper log of actions taken a FTP file transfer message begins at t = 10 sec and remains till end of simulation. This message needs to travel to destination which may or may not be in same network and hence provided with an IP header.
4. Another status update messages from DER control IED to Distribution System Operator (DSO), which continuously updates the status of DERs.

The ethernet switch selected is *ethernet32_switch_adv* which supports a full duplex communication of 10/100 Mbps ethernet links. The application was defined in *Application_Config* object and is used by *Profile_Config* node for configuring profiles for SCN. The performance evaluation for the communication network is presented with and without VLAN and priority tagging scheme. A VLAN scheme provides a virtual local area network within the same LAN. Devices which remain in same VLAN can broadcast their messages and receive them with less time delay. This VLAN scheme can be very advantageous in case of a large network consisting of many nodes. This helps in efficient utilization of network resources. The scheme of prioritizing the packets sent over the network on the switch is known as priority tagging. The data packets are given priority of 0-7 as least to most. As the packet arrives in the buffer of switch, it gets automatically arranged in the priority order and travels to destination. The GOOSE messages are highly time critical messages and are given highest priority at the switch level.

TABLE 1. Average E2E delay for ADS SCN.

Average E2E Delay		
Without VLAN	With VLAN Scheme	With Priority Tagging Scheme
0.1423 ms	0.0442 ms	0.0601 ms

The ADS SCN has been modelled in Riverbed Modeler with the help of aforementioned appropriate nodes. It consists of various feeders which are connected to either load or are supplied through a DER. The simulation is configured as per the aforementioned assumptions and traffic was set in the simulation. The IEC 61850 messages are configured according to the data flow modeling in previous section and size of messages (i.e. frame format) is set according to [15].

The performance evaluation was carried for three cases, namely Case I: Without VLAN, Case II: With VLAN scheme, and Case III: With priority tagging scheme. The average E2E delay of GOOSE messages for the three cases has been tabulated in Table 1.

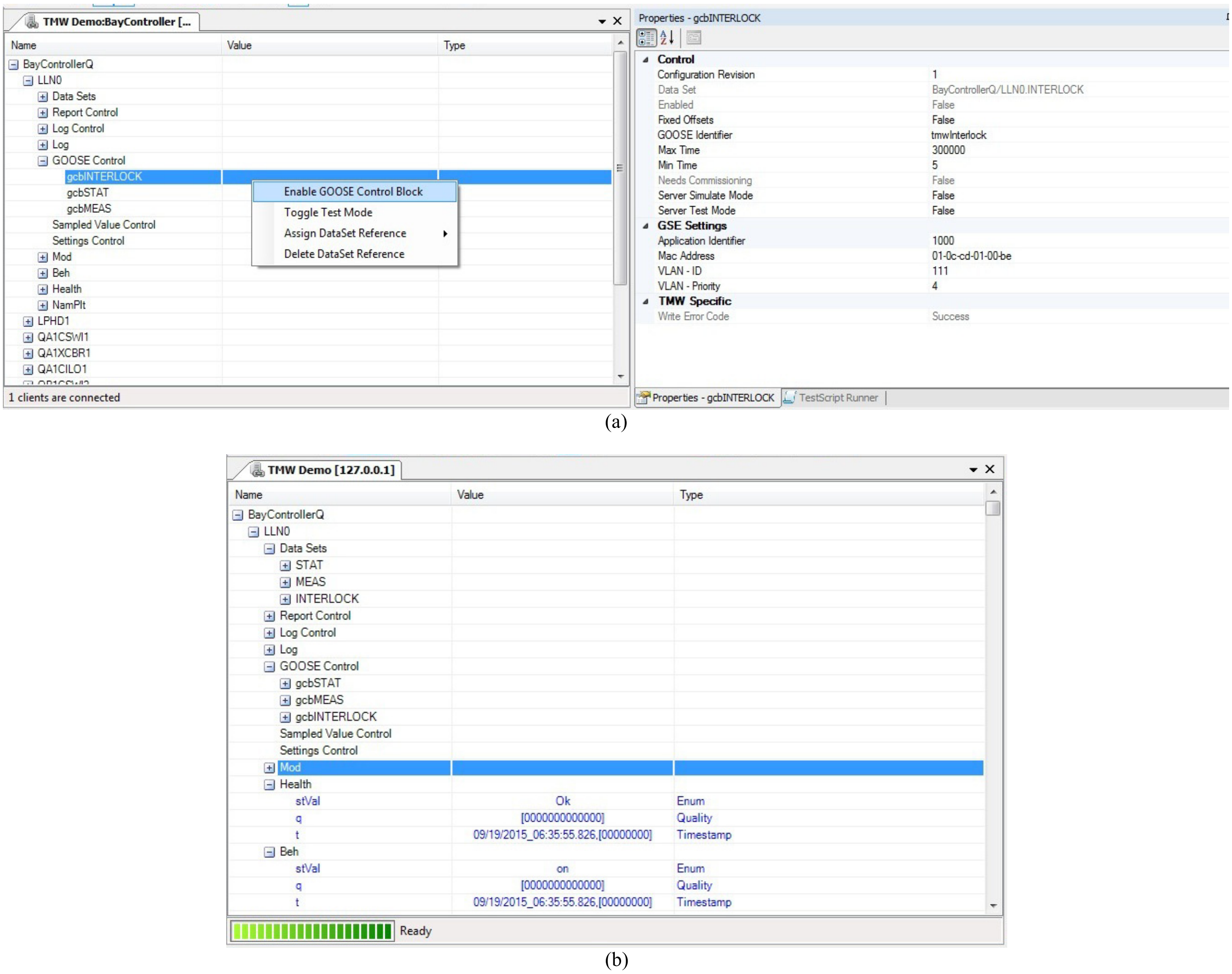

FIGURE 5. (a) Settings for anvil as GOOSE publisher. (b) Settings for hammer as GOOSE subscriber.

IV. HARDWARE REPLICATION OF A REAL SUBSTATION BAY IN LABORATORY

A. SETUP DESCRIPTION

The single line diagram of an ADS substation is shown in Fig. 1. In order to evaluate the real-time performance of the simulated network in previous section, a hardware evaluation of replication of a real bay of an ADS substation is performed. A feeder section, namely F2, is replicated for experimental evaluation of network performance. It comprises of a MU IED, P&C IED, Breaker IED and a DER IED connected through a manageable ethernet switch. The DER IED collectively represents the traffic flowing through the DER Controller IED, Breaker IED at the PCC, MU IED at the CT/PT of DER node. In order to achieve realistic and true results, a lumpsum amount of traffic representing the collective traffic in the substation except the traffic of the replicated feeder, is also connected to the switch. This is done by generating a fixed amount of customized background traffic via Ostinato software. Thus two additional computers, running Ostinato software, for background traffic source and sink is connected to the ethernet switch. The experimental replication of a real bay in laboratory is demonstrated in Fig. 4.

The real time experimental performance evaluation of ADS substation is carried out by measuring the E2E latency in the IEC 61850 messages. Since, GOOSE messages are most time critical and hence their E2E latency is computed in the hardware experiment. This is done via duplicating the generated GOOSE message at the P&C IED for a fault arising in the substation. This duplication is carried out through a network tap used in the experimental setup. A network tap consists of live ports and monitor ports. Any incoming signal/ message is duplicated and sent onto the live and monitor port simultaneously. Thus, a time tagged GOOSE message generated from the P&C IED is sent to the Breaker IED via two network routes. One is directly through the live port of the network port i.e. port A and other through traversing the feeder bay switch i.e. port B. Since the feeder bay switch mimics, the traffic criterion of a real switch in the ADS substation, the generated GOOSE message travels through it and reaches the Breaker IED, supporting dual LAN ports

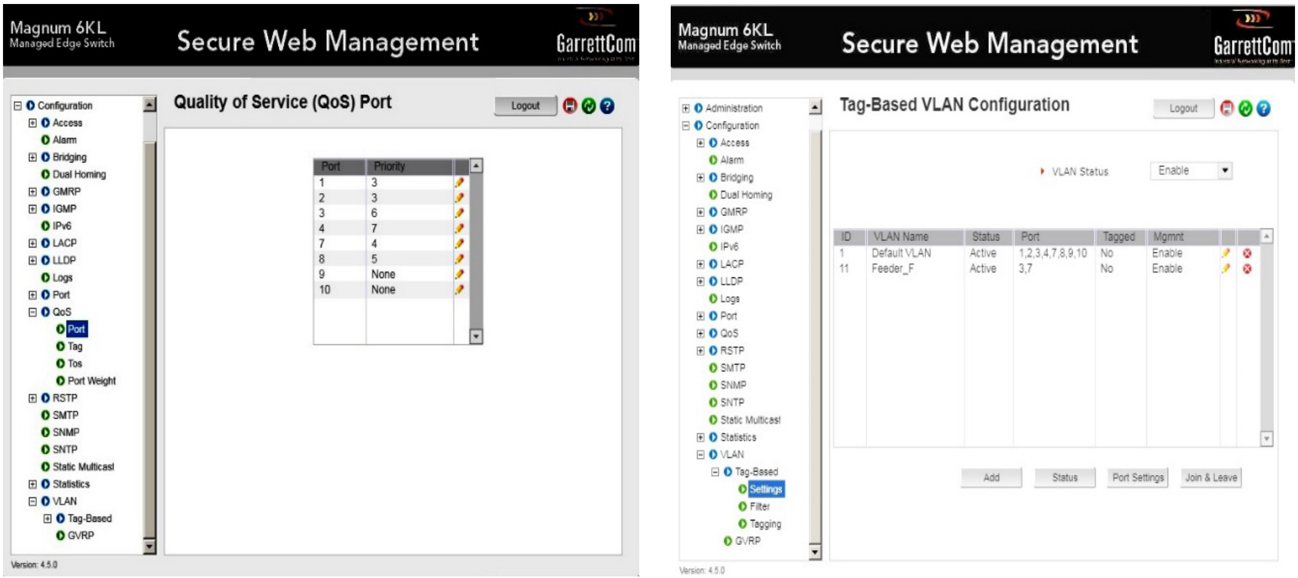

FIGURE 6. Configuration panel for VLAN and priority tagging in manageable ethernet switch.

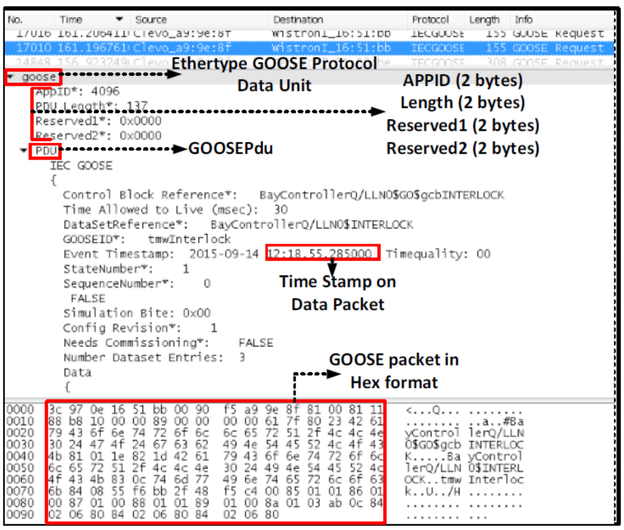

FIGURE 7. Captured GOOSE packet.

(i.e. dual Network Interface Cards (NICs). The difference between the time tagged GOOSE messages arriving at the breaker IED gives the E2E delay value. The GOOSE messages are captured in the breaker IED via a packet capture software, Wireshark.

In case a fault occurs in any part of the substation, the P&C IED of the corresponding bay generates trip signals which travel to respective breaker IED in form of burst. These trip commands are type of stochastic data with a packet size of 204 bytes [15]. In order to mimic the real behavior of P&C IED and Breaker IED on computer systems in laboratory, a client server IEC 61850 testing software from Triangle Microworks is used. A GOOSE packet was sent from the P&C IED to the breaker IED via Anvil Software of Triangle Microworks [16]. Anvil and Hammer from Triangle Microworks, are test clients for IEC 61850 based testing. Anvil works as a test server for testing IEC 61850 messages and thus acts as GOOSE publisher. The configuration settings in the Goose control block (GOCB) field in Anvil was set to 'true' and maximum time for GOOSE message was set for 5 min. In order to make the anvil as a GOOSE client, the loop-back settings for GOOSE message was set to 'false'. Thus, this procedure configures the P&C IED setting for replicating a real IED on a computer system. The configuration carried out in Anvil is shown in Fig. 5(a).

The GOOSE packets generated at the P&C IED via Anvil software are subscribed at the breaker IED. This is done through invoking a IEC 61850 client software, Hammer. Hammer is a testing client for IEC 61850 messages. Hammer software exercises GOOSE subscriber option to receive the incoming GOOSE packets from a GOOSE publisher. The configuration of Hammer is done so as to receive the GOOSE packets from the Anvil software. The configuration and connection window of Hammer is shown in Fig. 5(b). Through this procedure, a computer system running Hammer software works as a replication of a breaker IED of a real bay.

The different types of message flows along with their data length in the hardware setup are tabulated in Table 2.

B. CONFIGURATION

The performance evaluation results for the replicated hardware setup was done by enabling VLAN and priority tagging. This is done in order to verify the results obtained in Riverbed simulation experimentally. The configuration for VLAN and priority tagging was done in the manageable ethernet switch.

1) PERFORMANCE EVALUATION FOR VLAN

The VLAN develops a virtual local area network for prioritized delivery of messages in the LAN. The configuration

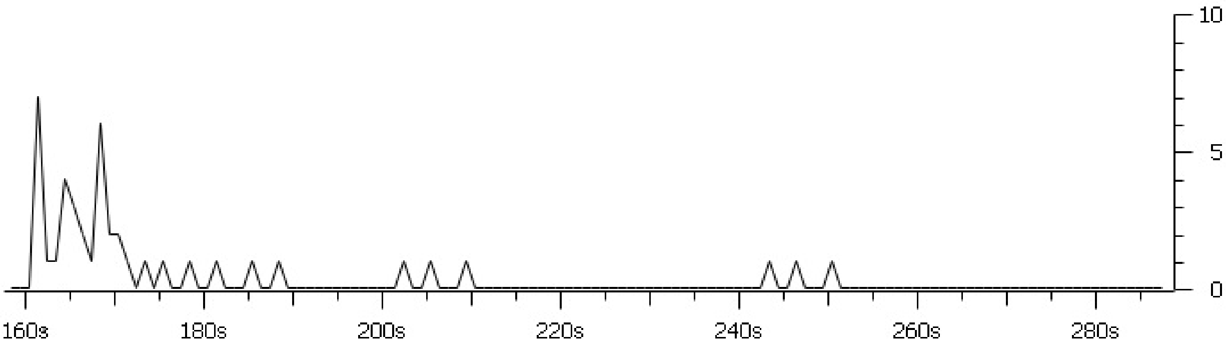

FIGURE 8. Waveform of captured GOOSE message.

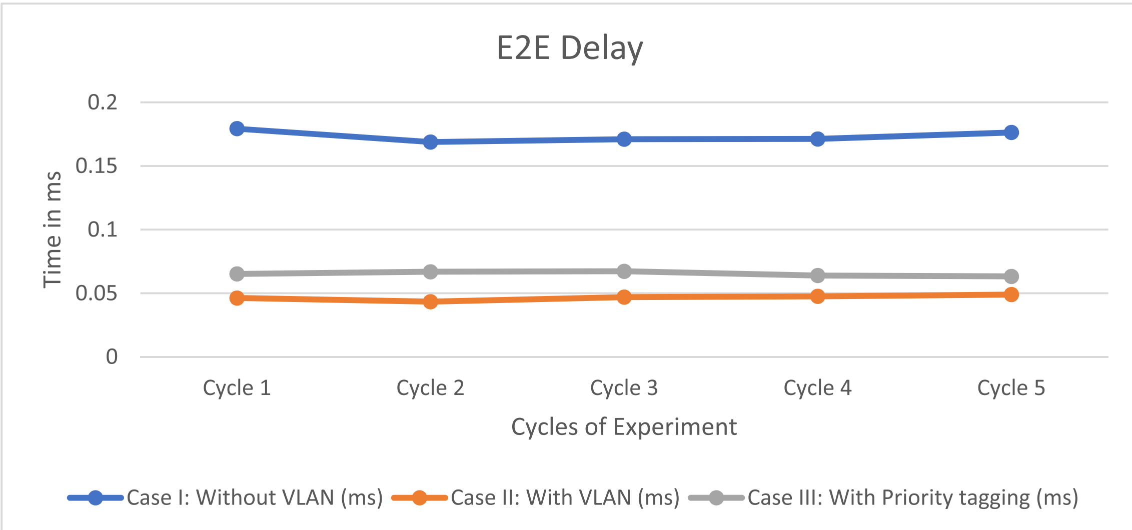

FIGURE 9. E2E delay for various cases.

TABLE 2. Data flow summary of messages in an ADS SCN.

Type of Message	Source and Destination	Type	Size(bytes)
Sample Value	MU → P&C IED	Cyclic Raw Data	219
GOOSE	P&C →Breaker IED P&C → DER IED	Burst Data	144
File Transfer Message	To Server	Stochastic Data	1000
DER Status Update	DER IED →Server	Cyclic Data and Burst Data	144

is carried out in the manageable ethernet switch used in the experiment. The MU IED and the P&C IED in the replicated bay are configured to be in a VLAN with identifier 11. The default VLAN Id for all devices is 1 and thus all devices connected through the switch remains in default VLAN for receiving and sending messages. The MU IED and P&C IED are connected through port 3 and 7 of the manageable ethernet switch and thus these ports are configured with VLAN Id 11.

2) PERFORMANCE EVALUATION FOR PRIORITY TAGGING CONFIGURATION

The priority tagging is applied on definite switch ports to manage data queues on the switch based on the pre-set priority levels. In the experimental setup, the Breaker IED receives the GOOSE packet and is set for priority 7. The priority for MU IED which publishes SV is set to 4. The P&C IED is set to priority 6 as it publishes GOOSE messages. The DER IED provides the comprehensive data from the DER controller and Breaker at the PCC and is hence set to priority 5. The background traffic is having least priority among other IEDs and is set to 3. Table 3 gives the connection of various IEDs on manageable ethernet switch along with the priority values. The configuration is carried out in switch and the snapshot of configuration pane is shown in Fig. 6.

C. RESULTS AND DISCUSSION

The performance evaluation results of the ADS substation through the hardware replication of a bay according to the aforementioned configuration is carried out in laboratory environment. Several cycles of experiments were performed

TABLE 3. Priority tagging configuration for various IEDs.

Type of IED	Port No.	Priority
Breaker IED	4	7
MU IED	7	4
P&C IED	3	6
DER IED	8	5
Background Traffic	1,2	3

TABLE 4. Average E2E delay in various cases in an ADS SCN.

E2E Delay	Case I: Without VLAN (ms)	Case II: With VLAN (ms)	Case III: With Priority tagging (ms)
Cycle 1	0.1793	0.0462	0.0651
Cycle 2	0.1688	0.0433	0.0668
Cycle 3	0.1710	0.0469	0.0672
Cycle 4	0.1712	0.0475	0.0639
Cycle 5	0.1763	0.0489	0.0632
Average E2E Delay	0.1733	0.0465	0.0652

and the average E2E delay is computed through the time difference of captured data packets in Wireshark. The captured GOOSE packet along with its details is shown in Fig. 7.

The detailed explanation of GOOSE Application Protocol Data Unit is given in [17]. The heartbeat waveform of captured GOOSE packet arriving as burst form of data as discussed in Section II is as shown in Fig. 8.

The results for E2E delay in GOOSE message for various configurations such as, Without VLAN and priority tagging, With VLAN configured, with priority tagging configured are tabulated in Table 4.

The average E2E delay for normal condition is found to be approximately 173.3 μs. In Case II, impacts of VLAN on communication performance has been studied and it has been found that on including the MU IED and P&C IED within a same VLAN the E2E delay has been significantly reduced and average E2E delay with VLAN configuration is 46.5 μs. This can be accounted due to the fact that the VLAN is able to limit the SV traffic from the MU IED which has impacted the performance of the ADS SCN.

In Case III, the impact of priority tagging on the manageable ethernet switch has been studied. It is found by assigning the maximum priority to the time critical GOOSE messages, the E2E delay is reduced as compared to normal condition. The average E2E delay with priority tagging is found to be 65.2 μs. The comparative E2E delay for the three cases is shown in Fig. 9.

V. CONCLUSION

This paper presents mathematical modeling of data traffic in an ADS substation based on seven different types of IEC 61850 messages. Based on this modeling, a simulation analysis for performance evaluation of an ADS SCN is carried out for different cases. It can be concluded that VLAN based simulation and priority tagging scheme significantly improves the performance of the ADS SCN. This is due to the fact that it lowers the SV within the bay network and thus improves the performance by reducing E2E delay.

Also, a novel scheme for hardware validation of substation performance validation is carried out in the laboratory by replicating a real bay. This helps to obtain the real-time performance validation of an ADS SCN. The results obtained from hardware performance evaluation and through software simulation are found to be in conformance. The enhanced delays in experimental results can be accounted to the fact that the hardware performance evaluation is real time and hence introduces comparatively more delays.

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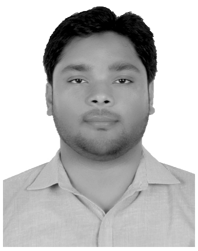

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