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A Review of the Methods Used to Model Traffic Flow in a Substation Communication Network

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ABSTRACT A significant component in electrical power systems are substations, in which the substation communication network is essential. Due to the evolving nature of communication protocols, and the introduction of the IEC 61 850 standard, substation communication networks can provide fast and reliable information transmission. Such improvements in transmission allow for improved protection and control of the power system network. A well-designed substation communication network can be achieved with the use of appropriate modeling, and as a result, this paper aims the review the methods in which parts of, or the entire substation communication network can be modeled. Modeling methods aim to determine various parameters of a substation communication network design, which include the traffic load distribution, and various message delays under different network conditions that may be experienced. In order for modeling to be carried out, a general structure of a substation communication network must be defined, which is laid out by the IEC 61 850 standard. The findings of the review in this paper show that there are various methods in which a substation communication network can be modeled, which include analytical modeling, software-based modeling, hardware/experimental modeling, and time-series based modeling. However, each method enables for different parameters to be found, with some of the methods having drawbacks including a limited network model size, and inability to find certain necessary parameters. The methods reviewed in this paper can be used and expanded on to create useful and accurate models of a substation communication network.

INDEX TERMS Ethernet networks, IEC 61850, network modeling, SCADA, substation automation system (SAS), substation communication network (SCN), SCN structure and architecture.

ABBREVIATIONS

Active Distribution Network	ADN
Auto Correlation Function	ACF
Auto Regressive Moving Average	ARMA
Breaker Intelligent Electronic Device	BIED
End-to-End	ETE
Finite State Machine	FSM
First in First Out	FIFO
Fractional Auto Regressive Integrated Moving Average	FARIMA
Generic Object-Oriented Substation Event	GOOSE
Intelligent Electronic Device	IED
Long-Range Dependence	LRD
Manufacturing Message Specification	MMS
Merging Unit	MU
Optimized Network Engineering Tool	OPNET
Partial Auto Correlation Function	PACF
Precision Time Protocol	PTP
Priority Queuing	PQ
Protection and Control	P&C
Rapid Spanning Tree Protocol	RSTP
Sampled Value	SV
Simple Network Time Protocol	SNTP
Substation Automation System	SAS
Substation Communication Network	SCN
Supervisory Control and Data Acquisition	SCADA
Switch Intelligent Electronic	SIED
System Integrity Protection Schemes	SIPS
Transmission Control Protocol	TCP
Virtual Local-Area Network	VLAN

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I. INTRODUCTION

Electrical power systems are essential in modern society, as they enable the continuous and reliable availability of electrical power, which is of paramount importance to many industries requiring electricity to operate. Substations are critical nodes in an electrical power system. The substation automation system (SAS) uses information retrieved from the power system in order to ensure proper operation and management of the power system network [1], [2]. The functions of the SAS include the protection, monitoring and control of both the primary equipment in substations, as well as their associated feeders [2]–[4]. Protection is a major component, as failure of protective equipment in a substation to operate under fault conditions can lead to severe damage to equipment, danger to human life and instability [5].

Software-based substation automation systems, developments in microprocessor-based intelligent electronic devices (IEDs) and the introduction of the IEC 61850 standard for communication systems in substations have led to a decrease in the use of rigid parallel copper wiring, as it is replaced with an Ethernet-based communication network [1], [3]. The large changes in the communication networks employed have led to an increasing dependency of the SAS on the substation communication network (SCN) [2], [3], [6]. As a result, improved operation and management of the SAS can be achieved through the correct design and maintenance of an SCN, allowing for fast and reliable information transmission [3]. Hence, the modeling of SCNs in a simple and reliable manner is essential, allowing for the evaluation of network performance under different network conditions and the determination of whether or not the SCN meets the network performance requirements [3].

The traffic load distribution, and the maximum message delay under different network schemes and equipment selections can be used to analyze the performance of an SCN design [3]. The IEC 61850-5 standard specifies that the requirements for message transmission time for a SAS must be maintained under any possible operating condition or contingency inside the substation [7]. Modeling of the communication network allows for the dynamic performance of the communication in the SAS to be determined and any issues that may occur to be found and rectified.

Due to the developing nature of substation automation, and the importance of the subsequent communication network, there are various survey and research papers that investigate the IEC 61850 standard. M. Aftab *et al.* [8] provide a holistic overview of the IEC 61850 standard, with discussions on the background of the standard, the functions and requirements a system must have to meet the standard, performance evaluation of communication networks using the standard and applications fields in which the standard may be applied. Although the paper [8] does consider performance evaluation of SCNs, with methods of modeling discussed briefly, the paper does not contain an in-depth and critical review of the methods available in literature.

In another paper, M. Aftab *et al.* [9] review the communication technologies that can be employed in active distribution networks (ADNs). Notably, one section of the technologies employed falls under the IEC 61850 standard. As a result, the research scholars in [9] provide an overview of the standard, as well as a discussion around performance evaluation metrics in ADNs. Methods for performance evaluation are very briefly discussed, but only software-based tools are mentioned [9].

V. Mathebula *et al.* [10] provide a reliability review of mission critical safety functions in an IEC 61850 based SAS. The paper provides a comprehensive overview of substation automation systems that utilise the IEC 61850 standard, as well as a discussion around their reliability [10]. However, the paper does not discuss the performance evaluation of IEC 61850 based SCNs or methods in which traffic flow in the networks can be modeled to evaluate the performance of the network [10].

As a result, this paper aims to provide a comprehensive review, evaluation, and comparison of the methods in which the traffic flow in a substation communication network can be modeled. Although these methods have been briefly reviewed in other papers, a comprehensive review and analysis has not yet been presented. A brief overview and description of the IEC 61850 communication standard is provided in section II. Section III of this paper reviews the general structure of an SCN, which relates to the models reviewed. Additionally, a review of redundancy and architectures that can be used in an SCN, as well as the use of SCADA systems is also presented in section III. As previously mentioned, the traffic load distribution and maximum message delays are essential parameters in the analysis of an SCN; hence, section IV aims to briefly discuss these parameters and their relevance in a communication network. The review of the various modeling methods, which include analytical models, software-based models, hardware/experimental models, and time-series based models is contained in section V, with a comparison of the modeling methods detailed in section VI. Finally, a conclusion, as well as suggestions for the expansion of the literature, is provided in section VII.

II. THE IEC 61850 COMMUNICATION STANDARD

The IEC 61850 standard was developed to allow for interoperability between devices made by different manufacturers. The guidelines allow for peer-to-peer communication between IEDs in the substation [11]–[13]. One of the main aims of the standard is to solve interconnectivity issues that arise from the use of IEDs from different manufacturers [10], [13]–[15]. This is achieved through the adoption of an abstract architectural construct, which is in the form of data objects and services that do not depend on the underlying protocols [10], [14], [15]. This means that the IEC 61850 standard specifies a communication protocol that allows for IEDs from different manufacturers to communicate using a standardized and beneficial method of communication. There are various benefits and features which the standard provides, which include [4], [10], [11], [14]–[16]:

- Fast transmission of Generic Object-Oriented Substation Events utilizing the peer-to-peer mechanism which the standard enables.
- The data definition in the communication network is based on object-oriented modeling.
- Standardized data modeling.
- The system scalability is independent of the manufacturers of the system's devices.
- Switched Ethernet technology forms the basis of the standardized high-level communication services.
- The application of the appropriate bus topology allows for a communication network with increased reliability.
- The specified architectures are simple and cost-effective.
- Communication extendibility and data integrity.

More specific to the application of this paper, the IEC 61850 standard specifies the medium of communication and provides a set of functions, formats and layers which define how signals or information is to be transferred between substation devices [5]. Substation devices generally include IEDS that are used for protection, control and monitoring in a substation.There are various message classes that are specified for use in the standard, which include message databases such as; client-server messaging, Generic Object-Oriented Substation Event (GOOSE), Manufacturing Message Specification (MMS), and Sampled Values (SV) [5], [17]. The functionality of these message classes include [14], [16], [18], [19]:

- Client/server messaging is communication between IEDs and the supervisory control and data acquisition system (SCADA) and usually consists of request/response sequences.
- GOOSE messaging is a service that is commonly used to transfer time-critical information with a very fast speed. The time-critical information that can be transferred using GOOSE messaging includes trips between IEDs, status changes, releases, and blockings. These are examples of events in a substation. GOOSE messaging supports peer-to-peer communication.
- The MMS protocol is generally to transfer data between the station level IEDs, and the control and protection IEDs, which are in the bay level.
- Sampled value messages are used in order to transfer current and voltage sample information. The information being transmitted is transmitted quickly in a synchronized stream of samples.

The standard divides the SCN into three levels, which are the process level, the bay level, and the substation, or station level [11], [20]–[23]. More detail on the three levels specified is provided in section III of this report, in which the general structure of an SCN based on the IEC 61850 standard is discussed in depth. Fig. 1 shows the mapping of various message types to the OSI layered communication stack. The IEC 61850 standard uses mainstream technology for the communication stack, as the stack is structured according to the OSI model [11], [13], [18]. The OSI model has 7 layers, and as a result, the stack structure consists of Ethernet in layers 1 and 2, TCP/ICP in layers 3 and 4, and MMS in layers 5 to 7. Time-critical messages, which include SV and GOOSE messages, are mapped to the Ethernet linked layer in order to allow for fast communication of messages in real-time using peer-to-peer communication; however, client/server communication is mapped to layer 7, which is the MMS application layer [11], [17], [18]. The time-critical nature of SV and GOOSE messages means that they are expected to have fast and reliable synchronous message transmission, meeting the high requirements associated [11], [10].

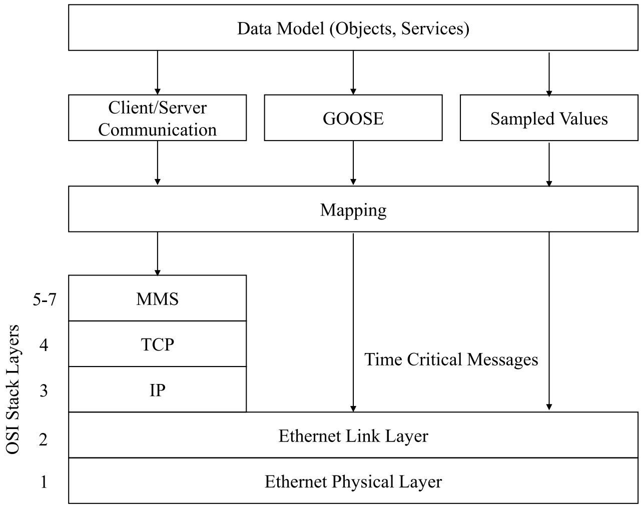

FIGURE 1. Mapping data model and communication services – OSI layered model [1], [11], [15], [17]–[19].

III. THE STRUCTURE OF AN SCN

Fig. 2 shows the general structure of an SCN based on the IEC 61850 standard. The figure indicates that the IEDs in the bay level, used for control, monitoring and protection, are connected with the station level devices through the station bus. A single protection & control (P&C) IED can also be used in the bay level. A P&C IED allows for the integration of the protection and control functionalities required in the bay unit of a substation [7], [18], [24], [25]. Simple network time protocol (SNTP) messages are used in order to achieve time synchronization of the sequence events in the station bus network. In addition to SNTP messages, the station bus also carries GOOSE and MMS messages [3], [26].

Additionally, the bay level IEDs are connected to the switchyard devices through the process bus [11], [22], [24]. Merging units (MUs) are IEDs, used to convert signals from instrument transformers to IEC 61850 telegrams [11], [18]. The breaker or switch (BIED, SIED) IEDs provide the process bus functionality for the switchgear. In general, the process bus network carries generic object-oriented substation events (GOOSE), sampled value (SV), and manufacturing message specifications (MMS) messages and protocols [3].

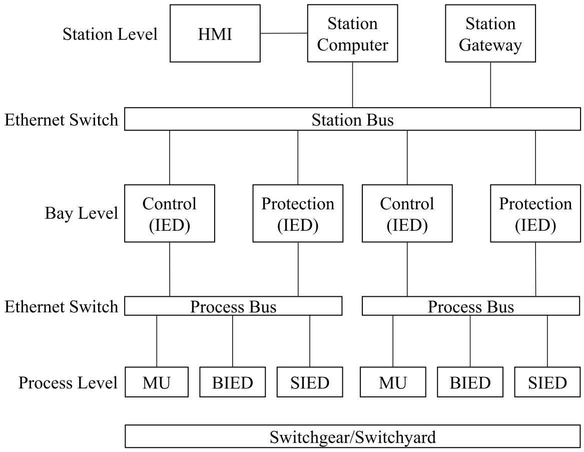

FIGURE 2. General Structure of an SCN [3], [11], [18], [19], [25], [26].

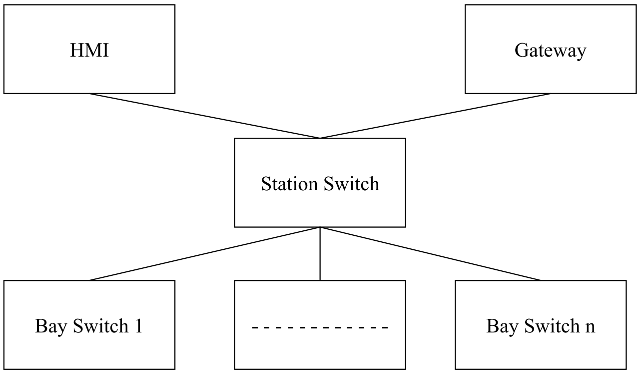

FIGURE 3. Star type architecture - SCN [10], [21], [23], [30].

Additionally, the sampled values in the process bus network are synchronized by precision time protocol (PTP) messages. GOOSE, SV and PTP messages all make use of connectionless multicast transmission, the conversion of many signals to one [3], [27]. For this purpose, it is useful to be able to limit the broadcast domain and separate different types of traffic; this can be done through the use of virtual local-area networks (VLANs) [3]. However, connectionless multicast transmission is not used for the transmission of MMS messages. Instead, connection-oriented transmission control protocol (TCP) is utilized as the MMS protocol is usually used to transfer data between the bay level IEDs and the station bus. The TCP protocol provides inter-network, connection-oriented end-to-end packet delivery, ensuring reliability [3], [19].

In general, the station and process buses in an SCN consist of an Ethernet switch. These allow for the VLANs in the SCN to be set up and enables the SCN to support the features of the SAS, which are distributed to multiple IEDs. The logical architecture of the SCN is designed with consideration for reliability and fast deterministic delivery requirements of messages used in the control and protection functions of the substation [1]. The structure of the SCN shown in Fig. 2 allows for optimal communication between devices in the network, as well as communication to the control centre. A SAS based on the IEC 61850 standards uses server/client configuration, which allows for shorter transmission times of substation messages on event occurring or request [10], [16]. As a result of this, time-critical applications such as protection functions benefit from the use of IEC 61850 based SAS's as they require messages to be transmitted immediately when an event occurs [10], [16].

As already discussed, the IEC 61850 standard divides an SCN into a station level, a bay level, and a process level. These levels are connected by the communication network, and as a result, it is essential to consider the architecture of the communication network. As the communication network is a major part of the SAS, the architecture has an impact on the performance and cost of the SAS [10], [21]. The reliability, survivability, availability, and response time are important features of an SCN, which can be affected by the design of the communication network architecture. The SCN architecture is not standardized in the IEC 61850 standard; however, cascade star, star, ring, star-ring and redundant ring architectures are recognized as the general SCN architectures by the Institute of Electrical and Electronic Engineers/Power System Relaying Committee (IEEE/PSRC) [10], [28], [29].

Fig. 3 shows the implementation of the star architecture in an SCN. The figure shows that the bay level switches are all connected to the station level by individual links and that the station level consists of a single centralized switch [21], [22], [29]. Each bay level switch is further connected to the IEDs in that bay. However, as there is only a single central station switch, it becomes a point of failure for the entire SCN [21], [22], [29]. As a result, the star architecture has no redundancy and offers the least reliability [10], [22], [29], [30]. Therefore, despite the fact that the star architecture is easy to maintain and offers the lowest network latency, it is only suitable for monitoring [10], [22].

Fig. 4 shows the implementation of the ring architecture in an SCN. The ring architecture provides inherent redundancy using the Rapid Spanning Tree Protocol (RSTP) or priority protocols as it is connected in a ring of switches. This means that there is no single point of failure [10], [21], [22], [25], [26]. However, despite the inherent redundancy that the ring architecture provides, when the failure of one link or switch occurs, time for network reconfiguration is required [10], [22].

The SAS's reliability, survivability and availability can be enhanced by redundancy in the communication system. Many redundant SCN architectures can be developed from the star and ring architectures. Additionally, IEDs which have parallel communication ports also improve redundancy in the communication network [21]. The IEC 61850 standard specifies that inoperability can be achieved with a communication architecture design that has no single point of failure [10], [22], [25], [28]. As a result of the importance of

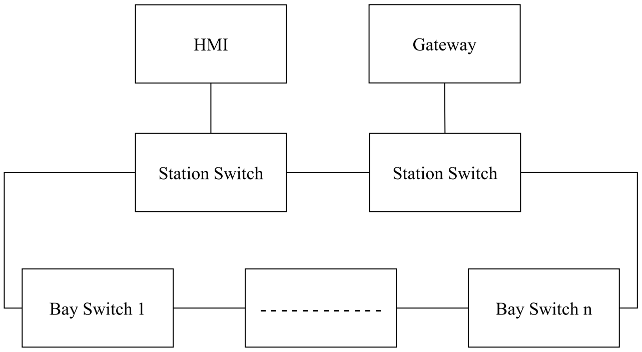

FIGURE 4. **Ring type architecture - SCN [10], [21], [23], [30].**

the SCN architecture, the design of the architecture should consider [10], [21], [22]:

- Interoperability.
- Maintainability.
- Dependability.
- Latency delays.
- Redundancy in the design.
- Bandwidth.
- Network segmentation.
- Network convergence.
- Scalability and expandability.

A supervisory control and data acquisition (SCADA) system enables the monitoring and control of systems and processes that are geographically dispersed [31]. The SCADA system is a centralized system, from which information for an entire substation can be obtained [31], [32]. Increased productivity and cost-saving are some of the benefits that can be obtained from a SCADA system, as it allows for the early detection and analysis of faults, also enabling improved maintenance [31], [32]. The substation SCADA system, coupled with the SAS creates a comprehensive method in which to monitor and control the system, providing protection, control, automation, monitoring and communication abilities [32]. As discussed previously, a substation network often consists of IEDs, transformers (from which merging units collect analogue values), switchgear, and cables and communication links [27]. On account of the benefits a SCADA system provides, modern substations often use a SCADA system in conjunction with the SAS. However, the focus of this paper is specifically to review the modeling methods of an SCN in order to assist in the development of a fast and reliable SAS. As a result of this, section V presents the methods to model the communication networks, with a more in depth analysis of the use of SCADA systems falling out of the scope of this paper.

IV. SCN TRAFFIC LOAD DISTRIBUTION AND MESSAGE TRANSMISSION TIME IN AN SCN

The traffic load in a portion of a communication network gives an indication of the rate at which packets are transmitted in the proximity of a given node. In simpler terms, network or data traffic considers the amount of data which is transmitting across a network at a given point in time [33]. When there is more traffic in the network, larger queuing delays are experienced [33]. The traffic load distribution provides an indication of how the traffic is distributed in the network and allows for the identification of switches with high traffic load [3].

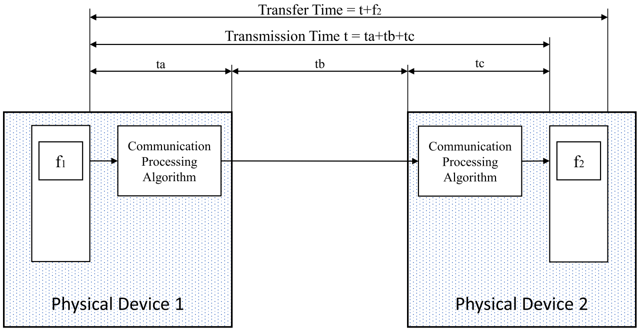

FIGURE 5. **Transmission time of a GOOSE message between IEDs [11], [10], [34].**

The substation architecture, as well as the processing time of the communication devices, determines the message transmission time in an SCN [10], [11], [34]. The factors affecting the transmission time are shown in Fig. 5. In Fig. 5, t_b is dependent on the network architecture. This network architecture delay gives an indication of the total latency caused by the network queuing and processing time at each substation communication device along the message path. The architecture latency is representative of the end-to-end (ETE) performance of the SCN. Fig. 5 reiterates the importance of the SCN in a SAS [10], [11], [34].

V. METHODS TO MODEL TRAFFIC FLOW IN AN SCN

As SCNs are an extremely important part of a substation, and significantly affect the SAS, the design of SCNs must be reviewed to ensure that they produce a fast and reliable form of transmission for messages required in the SAS. The analysis of the performance of an SCN can be carried out through the modeling of the communication network. The distribution of the traffic load, as well as the maximum message delay, are notable parameters in the analysis of the communication network's performance. This section of this paper aims to investigate the methods that can be used to model SCNs and obtain various parameters.

A. ANALYTICAL MODELING – NETWORK CALCULUS AND PATH FLOW MODEL

Reference [3] provides an analytical method that can be used to model the traffic flow in an SCN. The analytical traffic-flow model proposed can be applied to find various network parameters, which include the traffic load distribution, as well as the maximum message delay. The research scholars in [3] initially propose a physical connection model for the ports in the SCN, as well as logical connection models for both the VLAN and TCP mechanisms in the SCN, generated from a model representing the general structure

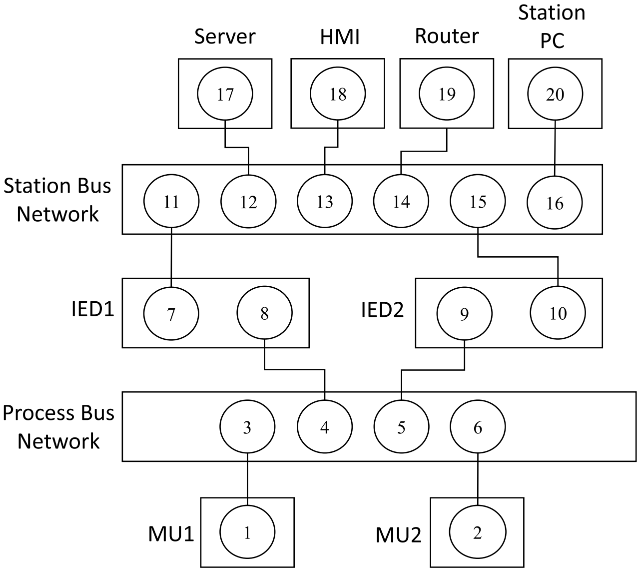

FIGURE 6. General Structure of an SCN used for analytical modeling [3].

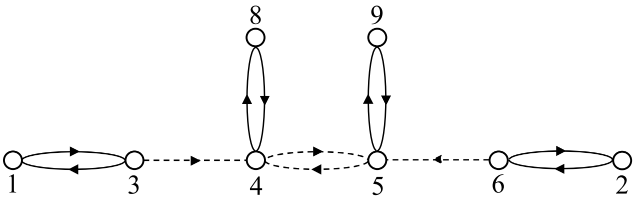

FIGURE 7. Flow diagram of the process bus network [3].

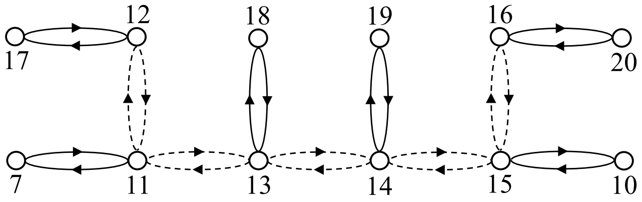

FIGURE 8. Flow diagram of the station bus network [3].

of an SCN [3]. Fig. 6 shows an example of the model of the general structure used. This is analogous to the general structure described in section III. However, the ports and physical connections of the components and levels of the substation communication network are labelled, which aids in the development of the matrix models for the analytical method proposed, as well as the flow diagrams for both the process and station buses generated from the matrices, seen in Fig. 7 and Fig. 8.

The physical connection model proposed uses a matrix **A** to represent the physical connections, in which **A** is a $P \times P$ matrix, where P is the number of physical ports in the SCN. In the matrix, element A_{ij} is equal to a 1 if there is a physical connection directed from port j to port i, and is 0 otherwise [3]. The formation of such a matrix can be represented by the diagrams in Fig. 7 and Fig. 8, in which the solid arcs represent the physical connections.

Similarly, the logical connection model for the VLAN mechanism proposed uses a matrix **C** to represent the logical connections, in which **C** is a $P \times P$ matrix. In the matrix, element $\boldsymbol{C_{ij}}$ is equal to a 1 if there is a logical connection (dashed arc in Fig. 7 and Fig. 8) directed from port $\boldsymbol{j}$ to port $\boldsymbol{i}$, and is 0 otherwise [3]. The **C** matrix is formed with the use of another two matrices in which the VLAN IDs and port-based VLAN IDs are considered [3]. Lastly, as part of the logical connection model for the TCP mechanism, it is proposed that a $P \times P$ matrix $\boldsymbol{C^{a,b}}$ can be found to denote the logical connection for the message sent from port a to port b [3]. The $\boldsymbol{C^{a,b}}$ matrix is found using other matrices, in which the TCP established communication connection relationship, and the subordinate relationship between ports and switches are considered [3].

In addition to the physical and logical connection models generated, the analytical modeling that [3] proposes also requires the formation of a source and a service model of the traffic flow in the SCN. Ports which are intended to send messages are traffic-flow sources, for which a source model is developed. The source flow model allows for the properties of the traffic-flow sources to be described [3], [35], [36]. The triggering relationships between GOOSE flows, the message rate, message length, the data rate of traffic flows and correspondence between a port and the messages it sends are some of the properties that the source model aims to describe [3], [35], [36]. Conversely, the service model aims to describe the service that traffic flow receives from the switches [3], [35], [36]. The network calculus theorem is used to develop both the source and service models of the SCN.

The traffic flow can be described by a cumulative function using the network calculus theorem. The basic concepts of the network calculus theorem are the arrival and service curves [3]. Reference [3] proposes that a matrix **S** can be used in order to create a source model for the SCN. Matrix **S** is a $P \times D$ matrix, in which P is the total number of ports, and D is the total number of messages in an SCN [3]. The corresponding relationship between messages sent and their sources is described by matrix **S**. When considering the **S** matrix, the element S_{ij} is equal to a_j if port i is the source of message j. The research carried out in [3] suggests that the transmission characteristics of the various messages in the source model should also be considered. These considerations include the fact that SV flows have a fixed data rate, fixed intervals are used when sending PTP and SNTP messages (meaning the SV source model is the same as the PTP and the SNTP messages source model) and that only in the steady-state period does the GOOSE flow i have a fixed data rate [3]. The steady-state period represents the period in which no fault or warning event occurs. In the steady-state period, the lowest data rate of GOOSE flow is utilized; however, when an event occurs, the related GOOSE flow changes to the highest data flow rate [3]. The data rate then declines exponentially; however, the change in rate creates a traffic burst for a very short period of time [3]. Lastly, time-driven MMS flow also has the same source model as that of SV flow, as MMS messages are configured by a time-driven or an event-driven mode [3].

The service model proposed by [3] suggests that the queue scheduling policies must be taken into account in order for the model to be developed. The priority queuing (PQ) and the first in first out (FIFO) queue scheduling policies are the two most important that must be considered [3]. The PQ policy indicates that packets are served in order of priority (higher priority packets first), whereas the FIFO policy indicates that packets are served in order of arrival. These queue scheduling policies are commonly used to improve the quality of service as well as to achieve congestion control [3]. The service policy of packets depends on the priority of the packets received. In the case of packets of different priorities, the service policy between packets is PQ, whereas, when considering packets that have the same priority, the FIFO service policy is used [3].

Having developed the connection, supply, and service models, [3] proposes a traffic-flow calculation algorithm, which can be used to obtain the distribution of messages, the traffic load and the maximum message delay. The message delay is found using an algorithm developed, which makes use of the various matrices found in the models developed. The source model matrix, **S**, is used in the traffic load distribution algorithm. The traffic load distribution can be calculated under different conditions by considering the GOOSE triggering relationship as part of the development of the load distribution calculation algorithm. An example of such a condition is a single-phase short circuit [3]. The delay of messages in a switch can be divided into four types, which are the transmission delay, the packet receiving delay, the processing delay, and the queuing delay [3]. These four types of delay are important when considering the maximum message delay. The packet receiving delay, and the processing delay are both in the range of a few microseconds and can be considered to be approximately 3 μs [3], [37]. Additionally, the fixed arrival and service curves proposed in the network calculus theorem can be used in order to calculate the upper bound of the transmission and queuing delay, which is also referred to as the maximum message delay [3]. As with the traffic load distribution, the GOOSE triggering relationship can be applied to the algorithm to calculate the maximum message delay under certain conditions [3]. When finding the maximum message delay an assumption, that all triggered GOOSE flows burst at the same time, is made; however, this is not the case due to the network delay. This assumption leads to a longer delay than is seen in practical simulations, and as a result, the calculation provides a conservative analysis of the network performance [3].

The analytical modeling method proposed by [3] also allows for the consideration of the network performance under various scenarios. These scenarios are the minimum load scenario, the maximum load scenario, and the typical event scenario.

The minimum load scenario occurs when the SCN is in steady-state, and the GOOSE flow has a fixed minimum data rate [3]. This scenario is the most common operating state for the SCN. The traffic load distribution in the minimum load scenario can be used in order to set the network monitoring threshold. Traffic load lower than this threshold at some point in the network could indicate that a packet loss fault or link disconnection has occurred [3].

The maximum load scenario occurs in the opposite case, when all of the GOOSE flows are in bursting period, indicating the maximum traffic load distribution of an SCN. The maximum traffic load that a link may withstand can be found using the maximum load scenario; however, this scenario may not exist practically. The maximum load scenario is essential for equipment selection and the design of the network [3].

Lastly, when there is an occurrence of events or faults in a primary system, it is defined to be the typical event scenario. The network performance under conditions in which faults or alarms occur can be analyzed with the application of the traffic-flow model and calculation algorithm to a typical event scenario. [3]. The analysis, as previously mentioned, is carried out with the prediction of the maximum message delay and the traffic load distribution.

B. ANALYTICAL MODELING – ADAPTED NETWORK CALCULUS AND PATH FLOW MODEL

Reference [38] aims to extend and simplify the analytical model proposed and developed by [3]. The proposed adaptation of the network calculus and path flow model also discusses the minimum load, maximum load, and typical event scenario; however, a fourth scenario, called the network abnormal flow calculation scenario is added. This scenario considers abnormal states of the network due to anomalies that are caused by the communication network itself. Corresponding flow characteristics are seen from many of the abnormal states, which include network jams and switch failure [38]. Calculations performed based on this scenario allow for thresholds to be set in the protection being used to monitor network anomalies [38].

The method proposed by [38] requires three characteristics of the message source to be defined when developing the model, which are, the number of each type of message packet the source sends, the length of each message package type, and the transmitting frequency of each message packet type [38]. The format of the packets of each message type allows for two vectors to be formed, F_{d*1} and S_{d*1}. These vectors consider the transmitting time interval and the packet length of each packet respectively. They are arranged according to the sequential order of the message source in a digital substation in which the total packet types is d [38].

Initially, [3] proposed the formation of the physical and logical connection models, as well as the supply and service models to find the traffic load distribution as well as the message delay. Reference [38] also defines the physical and logical connection models and in doing so, defines a message transmission path model. This does not differ from the method developed in [3]; there is merely a separation of the calculation carried out into an extra model. However, [38] later defines a message transmission path matrix, as well as a message flow distribution model, and a message flow calculation flowchart, which differ from the work done in [3]. The method proposed by [38] allows for the message flow to be calculated; however, the method does not propose a way to find the message transmission time delay, which is an important aspect in SCN design and modeling.

C. ANALYTICAL MODELING – STOCHASTIC NETWORK CALCULUS AND TRAFFIC FLOW MODEL

P. Xie *et al.* [39] propose another analytical model, from which the parameters of an SCN can be analyzed. The method uses the mapping relationship between the input and output nodes in order to describe the transmission process of traffic flow in a branch. Additionally, the transmission performance of an SCN is analyzed with the use of a stochastic network calculus theory [39].

Various models are used to form the final analytical model of the network. The first model is the network topology model, in which the corresponding relationship between the nodes and branches is expressed using matrix **A**. Matrix **A** is a $N_n \times (K + M)$ matrix, where N_n is the total number of input nodes, K is the number of single input branches, and M is the number of multi-input branches [39]. The value of each element in matrix **A** is as follows:

- $a_{ij} = 1$ when N_i is the input node of b_j.
- $a_{ij} = -1$ when N_i is the output node of b_j.
- $a_{ij} = 0$ in all other cases.

The arrival curve of the input traffic flow, as well as the service curve that is provided by the nodes in the branch are used in order to determine the output of branch i [39].

The second model proposed is an analytical traffic-flow distribution model. The traffic load of a specific layer or level in the substation communication network can be modelled making use of matrix **A** previously defined, as well as the departure curves of the traffic flow, and the service curves of the nodes [39]. However, various matrix operations are required in order to develop the model using the method proposed by [39].

The third and final model developed in the proposed method is the analytical fault event model. This model investigates three different matrix configurations depending on the fault scenario which could occur. This first scenario is a break in the path of traffic flow transmission. When this scenario occurs, the output node of the link can no longer receive data from the sending node. As a result of this, the -1 element in matrix **A** (defined in the network topology model) corresponding to the output on which the fault has occurred, is no longer included [39]. The second fault condition considered is the dislocation of the branch output node. This fault scenario occurs when the output of a branch no longer corresponds to the correct output node. Matrix **A** is adjusted to represent the fault conditions that occur in this scenario [39]. The final fault scenario accounted for in the model is a fault that occurs due to transmission data mistakes. The output of the branches are adjusted using a vector ε_k to represent this fault scenario [39].

Reference [39] also proposed the use of the stochastic network calculus theory in conjunction with the previously mentioned models. This theory has two key concepts, which are the Stochastic Arrival Curve and the Stochastic Service Curve. From this, an arrival curve of traffic flow, and a service curve of traffic flow can be developed for the SCN being investigated. GOOSE and SV messages are the main message types considered in the arrival curve proposed by [39] when calculating and analyzing the network's communication performance. The method proposed allows for the traffic distribution in the SCN to be analyzed in various scenarios. These include steady-state conditions, conditions in which there are primary faults, and finally, conditions in which there are secondary faults, which include low traffic load scenarios and message content faults. Additionally, the analytical model and network calculus theory proposed allows for the transmission delay of the traffic to be analyzed [39].

D. A BOUNDED MODEL OF COMMUNICATION DELAYS IN SIPS AND NETWORK CALCULUS THEORY

C. Huang *et al.* [40] investigate a method that can be used to analyze the data latency of system integrity protection schemes (SIPS). The method investigated involves the use of a bounded model for communication delay. SIPS are required to be developed to allow for both time-critical and reliable operation, and as a result, the consideration of delays is essential. Idealistic parameters are, in most cases, unfavourable for SIPS design considerations [40]. The research scholars in [40] consider the division of system integrity protection into two categories based on different protection scopes, which are wide-area protection and substation-area protection [40]. The wide-area network considers the protection of the power system against system-wide disturbances [40]. A bounded model is used in order to model the communication delay over regional and backbone networks in the wide-area protection network.

It is worth noting that the modeling of the substation-area protection discussed in the paper is of relevance to this review. The researchers [40] make use of the network calculus theory in order to model the SCN network traffic. The choice of the network calculus theory for modeling was informed by the concept that the network calculus theory allows for focus on performance guarantees, rather than the average values that are dealt with in classical queuing theory [40]. The research scholars in [40] use the arrival and service curves, the fundamental aspects of the network calculus theorem, in order to determine the delay and back-log bound of the network traffic. For this, the constraints on the arrival and service processes, considering the average traffic rate, maximum instantaneous burst, minimum service rate and latency parameter, are used [40].

The paper uses the network calculus theorem in order to propose a method that allows for delay bound analysis to be performed on SCNs in which priority-based queuing is used in order to schedule different types of messages in the network [40]. The researchers suggest that various results or properties can be obtained from the network calculus theory employed, from which delay bound analysis can be performed. The properties that are readily available from the network calculus theory are as follows [40]:

1. The superposition property.
2. The leftover service property under priority scheduling.
3. The leftover service property under FIFO scheduling.
4. The output property.
5. The concatenation property.

The delay and back-log service guarantee analysis property is also essential for delay bound analysis of the SCN traffic. As would be anticipated, the arrival and services curves of GOOSE and SV messages are given the highest priorities in the model developed [40]. Additionally, the lengths and frequencies of the messages, as well as the switch port rate, are also considered in the proposed method [40]. The model allows for SV message delays in a substation, as well as GOOSE message delays between two substations to be analyzed under different network traffic loads [40]. The research scholars in [40] see the use of the network calculus theorem which provides bounded analysis as an essential method, due to the requirement that all time-critical messages must be delivered within the maximum allowable message delays [40].

E. OPNET MODELING OF IEDS

T. Sidhu *et al.* [7] proposes a method of modeling IEC 61850-based IEDs and setting up a platform for SCN performance studies using the optimized network engineering tool (OPNET) modeler. The creation of IED models allows for the specific characteristics of a SAS network to be represented and modeled. As mentioned previously, the general structure of an SCN in a SAS has three main levels, two of which are the station and the process levels [7]. The research scholars in [7] propose the modeling of three different types of IEDs that are seen in the general structure of an SCN described previously, which are merging unit IEDs, breaker IEDs, and combined protection and control (P&C) IEDs. The IEC 61850 guideline specified communication stack is used in order to develop the model proposed by reference [7]. This involves the classification of messages into seven categories, following which, the performance requirements of the messages are used in order to map the messages into different communication stacks [7].

An object-oriented modeling approach is used by the OPNET modeler. As previously discussed, IEDs and switches are examples of network devices in an SCN and are called node models when modeled using the OPNET modeler. Modules that are connected through packet streams or static wires make up the node models, and each of the modules is assigned to a process module. This configuration allows for the required behaviours to be achieved [7], [21]. Additionally, a finite state machine (FSM) approach is used by the OPNET process model, which allows for the implementation of resources, protocols, algorithms, applications, and queuing policies [7], [21]. The states and transitions of the FSM are used to graphically define the progression of a process in response to events.

The modeling of the MU IEDs proposed by [7] is based on IEC 61850-9-1. The default destination address is determined by the Ethernet broadcast address; however, the model does support both unicast and multicast transmission. The packet size, sample rate, address, start time, stop time and multicast group address can be specified to configure the model of the MU IED proposed by [7]. The communication stack of the proposed MU IED model contains an application layer, Ethernet layer and physical layer. The various layers allow for the configuration of the model to meet the requirements of the system as well as the various standards [7]. The use of the bus or star topology in the model allows for different methods of connection between the MU IEDs and the P&C IEDs. The process bus is used to connect the MU IEDs to the P&C IEDs in the bus topology [7].

The circuit breaker IED has important functionalities in the SCN, which are the receiving of the trip messages, the sending of a GOOSE event to the other protection IEDs, as well as the station PC, and the calculation of the end-to-end (ETE) delay, [7]. The ETE delay can be defined as the amount of delay between the creation of the message, which is at the application layer of the source IED, and the arrival of the message at the receiving IED's application layer. As with the MU IED model, the GOOSE message package size, the address, and the transmission type can be configured in the circuit breaker IED model [7]. The GOOSE message is sent automatically when a trip or control command is received, and as a result, it is not necessary to set the start time of the message. As GOOSE messages are time-critical, the priority of the messages must be considered when creating the model [7]. Additionally, the fact that the breaker IED has to exchange messages with both the protection IEDs, as well as the station PC must also be taken into account, meaning the breaker IED must be modeled to support client-server communication [7].

The modeling of the P&C IED proposed using the OPNET modeler is very similar to that of the breaker IED. However, it should be noted that when connected in the bus topology, the P&C IED model must have two bus communication ports as it must communicate with both the process and station bus. Two ports are also required in the star topology [7]. Background traffic flow to the station PC or server can also be generated by the P&C IED model, if it is configured to provide this function. In fault mode, the IED model sends multicast trip messages at a specified time to the corresponding breaker IEDs [7]. The model also requires the address, destination address and multicast group address to be configured for the model to operate correctly.

With the creation and configuration of the IED models in OPNET, the software allows the SAS communication network being researched to be modeled. The research carried out by [7] focuses on the ETE delay for critical messages. The ETE delay is a critical statistic when evaluating the performance of the SCN. Reference [7] shows that the ETE delays can be found using different operating conditions, including different LAN speeds, different sampling rates and, priority tagging.

The research scholars in [21] also proposed the OPNET simulation software as a method of modeling a substation communication system in order to analyze the performance. Paper [21] reviews various different architectures that can be employed in a substation automation system, which include the star architecture, the ring architecture and various adaptations of the star and ring architectures, which add redundancy and as a result, reliability [21]. Paper [21] also discusses the object-oriented modeling approach that is used by the OPNET modeling software, as well as the fact that the process model in the modeler uses an FSM approach. Ultimately the research scholars in [21] proposed a method in which to find the ETE time-delay of an SCN under different conditions, which included various LAN speeds, priority tagging, and different VLAN sampling rates.

The research provided in paper [1] also proposed a method to find the ETE time-delay of a specific SCN architecture using the OPNET modeler in order to analyze the performance of the SCN architecture. The research is carried out by the same authors that proposed the work in paper [21]; however, [1] investigates additional aspects in the design of an SCN architecture, which include, redundant paths, provision for local data concentrators, no single point of failure, the absence of gateways for inter IED communication, enhanced reliability and finally, cost. With a design carried out focused on these aspects, the SCN architecture proposed by [1] was simulated using the OPNET modeler, focusing on the ETE delay performance of the proposed network. The performance analysis under various configurations was considered, including different transmission rates, normal and heavy background network traffic, normal and fault conditions, priority tagging and different VLAN configurations [1]. These conditions include those used in [21], as well as additional ones in order to review the performance of the SCN architecture designed.

F. USING ETHERNET CARDS TO MEASURE PROCESS BUS PERFORMANCE

As mentioned previously, it is essential to analyze the performance of an SCN in order for the successful design and implementation to be carried out. The dynamic performance of the communication in the SAS can be determined through modeling, allowing for any issues that may occur to be found and rectified. Reference [41] proposed a different method, using experimental modeling to find the latency introduced by Ethernet switches in the sample value process bus.

The method involves the use of an Ethernet capture card to measure the delay of SV messages. The sampling of the merging unit, as well as the time-stamping unit in the Ethernet capture card are synchronized by the same one pulse per second source [41]. As the synchronizing signal is transported through cables and media or level converters, the propagation delay must be estimated when assessing the performance of the process bus. This propagation delay is usually less than 20 ns for cables with a length of less than 20 m. The error in the frame arrival time-stamps of the Ethernet card, as well as the absolute time error, must also be considered when conducting the experimental testing [41]. Two experiments were proposed using the method. In the first experiment proposed, three ports on the Ethernet capture card were used in order to directly capture SV frames from three merging unit cards. With one of the merging unit cards generating the one pulse per second clock for the other merging unit cards as well as the Ethernet capture card [41]. The second experiment proposed used two Ethernet switches between the merging units and the Ethernet capture card, allowing the network latency under this condition to be found. The second experiment allows for a larger substation network to be represented [41].

G. HARDWARE AND EXPERIMENTAL MODELING

Reference [37] proposes the use of a process bus test-bed to create a hardware/experimental model for the process bus of an SCN, which differs from the analytical and simulation-based models previously discussed. Although simulation models allow for much larger substation communication networks to be modelled, [37] suggests that the quality of the simulation models largely influence the results. Detailed-event based models may not be available for use in simulation software as industrial Ethernet switches rated for substation use have not been widely used in the past [37].

The process bus model formed includes the exchange of the measured transformer data between the process and bay levels, as well as the exchange of control data between the process and bay levels in the SCN [37]. A very similar method to that proposed in [41] was used to find the latency of frames. This method again involved the use of an Ethernet capture card; however, an Ethernet tap was also used. The Ethernet tap is placed between the message source and the first Ethernet switch. As a result of this arrangement, any source of Ethernet traffic can be used, and the frame latency is the time difference between the frame being received from the tap, and the frame received from the switch. The setup proposed is shown in Fig. 9.

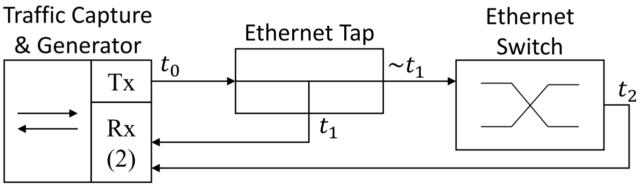

FIGURE 9. **Measurement of the frame latency [37].**

Additionally, [37] proposes the use of a much larger test network than was seen in [41]. Reference [37] also proposes hardware/experimental model setups that allow for interaction testing to be performed. The testing of these models considered two types of interaction, the effect that high-volume SV traffic has on management and GOOSE signalling, as well as the complement, the effect that management and GOOSE messages have on the delivery of SV messages [37].

H. TIME-SERIES MODELING

R. Feizimirkhani *et al.* [42] discuss a manner in which GOOSE messages between IEDS in smart grids can be modeled, making use of a time-series modeling method. The paper, mentioning the randomness that exists in data behaviour in power grids, indicates that a stochastic or probability model is useful for the representation of such data [42]. As a result, data-driven Auto Regressive Moving Average (ARMA) models can be used as a time-series method for characterization and modeling of the traffic [42]. The research conducted is discussed through a case study to which the modeling method is applied. The case study scenario utilised is of some importance as the reactive power absorbed or injected into the grid can be independently controlled by different nodes, with a centralized supervisor not required [42]. In a similar manner, the voltage and/ or reactive power can be controlled within specified boundaries in a smart grid, making use of distributed and cooperative algorithms [42], [43]. As a result of the benefits of the voltage and reactive power control, the implementation of the algorithms required is expected to continue. As a result, the communication network and connected devices must be able to adapt, allowing for the implementation of the algorithms. The case study discussed by the research scholars [42] consists of two renewable energy generating units (used in order to compensate the reactive power of a load unit), and each unit has an IED, which communicates through a VLAN. Additionally, MATLAB/Simulink is utilised in order to form a co-simulation platform allowing for the electrical and communication grid to be modeled. This co-simulation model allows for the reactive power variation data flow traffic, which is transmitted through IEC 61850 based GOOSE messaging to be obtained [42], [44]. The paper focuses on the modeling of the variation in the number of data packets which flows through the communication channel over time [42].

A sample realization of n observed samples, measured over equal time-spaces, can be measured from an infinite population of the samples in question, $y_1, y_2, \ldots, y_n$ using time-series modeling [42]. The modeling scenario proposed, which allows the SCN data flow to be modeled, considers the cumulative number of packets which are passed between the PV and load unit IEDs in the case study used. The linear relationship which exists through current values, historical data and exogenous factors can be investigated by making use of time-series modeling and analysing methods. Exogenous factors refer to external factors, factors that are outside of the system. The Box-Jenkins model, a widely used method for mathematical representation of time series analysis, is applied to the ARMA model proposed by the researchers [42]. The Box-Jenkins methodology is applied to the ARMA modeling in five steps, namely [42]:

1. Data preprocessing.
2. Model-identification.
3. Estimation of the model parameters.
4. Diagnostic verification of the model.
5. Possibility forecasting.

The research scholars in [42] progress to discuss the application of the ARMA model proposed to the specific case study described. This deals with the implementation of the ARMA model over the data traffic obtained from the co-simulation. The application of the ARMA model is discussed in five steps [42]:

1. Data preparation – The ARMA model must only be applied to stationary time series, which are assumed to be in a specific form of statistical equilibrium. The statistical equilibrium implies that the time series vary over time in a stable manner about a fixed mean. As non-stationary characteristics are almost always present in practical time series, the non-stationary behaviour must be removed [42]. The paper discusses various methods (tools) which can be used for this purpose, including detrending, dissimilarity and deseasonality [42]. These tools remove characteristics such as dependence on time, long-range dependence (LRD) and seasonal patterns [42].
2. Model Identification – The estimated Auto Correlation Function (ACF) and estimated Partial Auto Correlation Function (PACF) can be used to measure the statistical relationships that exist within a series, allowing for the correct type of ARMA model with the best orders to be determined [42]. Identification of the most applicable model and orders is important as the application of these provides a stochastic data model, which has a simple polynomial form [42].
3. Parameter estimation – The estimated model can be evaluated for statistical adequacy using various diagnostic tests suggested in the Box-Jenkins method. If the estimated model is deemed unsuitable through the diagnostic tests performed, the identification and estimation stages are repeated. The cycle is repeated until a model performs suitably in the diagnostic tests run, as the future behaviours of the time series being analysed can be forecast through the use of a satisfactory model [42].
4. Model Implementation – The model implementation stage used by the researchers [42] allows for the ARMA model proposed to be applied to the sampled data over the simulation network developed. An important step in the implementation process is the determination of the correct sampling period [42]. Fig 10. shows a flowchart of the ARMA modeling procedure proposed by the research scholars in [42]. The figure provides a graphical representation of the first four steps in the application of the Box-Jenkins model that have been discussed.
5. Mathematical expression – The originally measured traffic can be reconstructed through the use of the ARMA model.

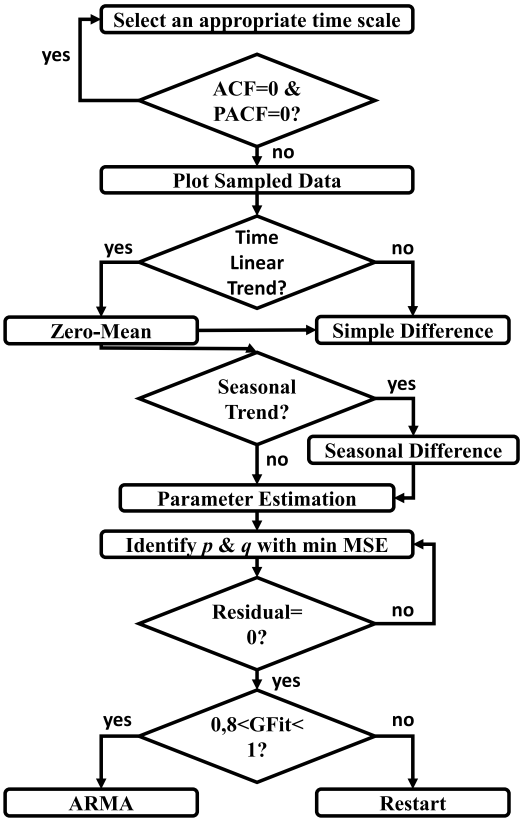

FIGURE 10. **Flowchart of the ARMA modeling procedure [42].**

This is done through the application of the inverse operations, to those that were applied to the originally measured traffic [42].

Finally, the research scholars in [42] also investigate the effect that three main communication channel parameters; packet loss, channel speed and cable length, have on the traffic model. Various values were used for each parameter, allowing for an investigation into the sensitivity of the ARMA models to variations in some of the communication network parameters [42]. The number of packets with respect to time in the communication network is presented in the paper, giving an indication of traffic flow and traffic load distribution [42].

I. FARIMA BASED THRESHOLD MODEL FOR DATA CHARACTERIZATION

W. Hao and Q. Yang [45] propose a method of characterizing data traffic in intelligent SCNs with the use of a FARIMA based threshold model, based on real data measurements. Additionally, the paper [45] aims to predict the data traffic behaviour with the bounding thresholds against time, with the use of a filtering algorithm. Initially, a brief review of intelligent substations based on the IEC 61850 standards, as well as a discussion of the characteristics of SCN data traffic is provided. As SCNs are required for the intelligent functionality of electrical substations, and diverse communication patterns are exhibited by SCN data traffic, the characteristics of the SCN data are essential and are utilised in the model developed [45]–[47]. SCN data traffic can be considered with the following characteristics [45], [48]:

1. Self-similarity and long-range dependence.
2. Smoothness.
3. Multi-fractal.
4. Periodic.
5. Irregularity.

The Fractional Auto Regressive Integrated Moving Average (FARIMA) model proposed by the research scholars in [45], is an alternative model structure to the ARMA model used by the researchers in [42]. As a result, similarities between the methods can be noted, such as the use of the Auto Correlation and Partial Auto Correlation Functions. Additionally, the Hurst parameter is found, which can be used to indicate the degree of auto correlation [45]. The paper briefly proposes the formulation of an optimized FARIMA model, as well as a threshold model for different confidence levels. A threshold model for the communication network traffic flow can be developed under different confidence levels with the use of different experimental data obtained from the communication network in an intelligent substation [45]. With the development of the final threshold model, SCN data traffic flow under normal operating conditions can be characterized [45].

J. RIVERBED (OPNET) MODELING OF SAS COMPONENTS AS WELL AS A METHOD FOR EXPERIMENTAL VALIDATION OF RESULTS

T. Ustun *et al.* [49] propose a method for both modeling and experimental validation of the results obtained, for the performance analysis of different types of messages utilised in an active distribution system (ADS) substation. The different types of messages considered are defined by the IEC 61850-5 standard, and are as follows [49]:

1. Type 1 – fast messages
2. Type 2 – medium speed messages.
3. Type 3 and 7 messages are grouped, which include low speed and command messages respectively.
4. Type 4 – raw data messages.
5. Type 5 – file transfer messages.
6. Type 6 – time synchronization messages.

An in-depth description of the communication links and data transfer between devices in a SAS is provided by the research scholars in [49]. Additionally, a software approach to the modeling of the traffic flow in an SCN is proposed, with the use of the Riverbed Modeler being discussed in the paper [49]. The Riverbed Modeler, which was previously the OPENT modeler, allows for the modeling of the various components contained in the SAS, including the P&C IEDs, MU IEDs, breaker IEDs, Ethernet switches and fiber optic links. The simulation requires that appropriate nodes are selected to model the IEDs being investigated. As a result, a node which accommodates the communication stack for MMS based messages is used for the modeling of MU IEDs, and a node which has dual capability of two communication stacks is utilised for the P&C IED as well as the breaker IED [49]. This is due to the fact that the P&C and breaker IEDs need to be modeled allowing for relation to both the publishing and subscribing of GOOSE messages, as well as client-server type communication, the latter of which requires complete TCP/IP implementation [49].

The various assumptions made in the development of the simulation model are also described by the research scholars. The model of the Ethernet switch selected should be able to support a full-duplex of communication links at the desired speeds [49]. The software modeling method proposed allows for the performance evaluation of the SCN with the use of the ETE delay metric. This evaluation can be performed under various network conditions, which include the use of VLANs and a priority tagging scheme. The difference in results under the various conditions can be analysed to determine the best configuration for the SCN [49].

Additionally, the research scholars in [49] also propose a method to produce a hardware replication of a real substation bay in a laboratory. In this setup, the Ostinato software is used in order to generate a fixed amount of background traffic and achieve realistic results from the experimental setup [49]. As in the experimental setup proposed in [37], the use of a network (Ethernet) tap is proposed in [49], allowing for the duplication and monitoring of signals. Wireshark, a packet capture software is utilised to capture GOOSE messages in the breaker IED. Additionally, the researchers [49] propose the further use of software in order to replicate the behaviour of P&C and breaker IEDs on computer systems in the laboratory. With the correct hardware configuration, performance evaluation of both VLAN and priority tagging configurations can be performed [49].

K. MATHEMATICAL AND OPNET SIMULATION BASED MODELING

Z. Zhang *et al.* [50] acknowledge the IEC 61850-5 classification of the seven different message types; however, for the purpose of the modeling method proposed, the reachers classify substation messages into three types, which are cyclic data, stochastic data and burst data. The data types are classified as follows [50]:

- Cyclic data flow is generated through the periodic sampling of current and voltage transformers.
- Stochastic data is data which is generated through substation events, such as trip messages. It is typical event-driven data.
- Burst data contains information which belongs to GOOSE messages, such as information regarding protection actions and changing the status of breakers.

Cyclic data, which includes high priority SV messages, as well as medium speed GOOSE messages, is typical time-driven data that is of a fixed length. This indicates that the packet size can be decided in advance and that the messages are triggered at the same time [50]. The time-dependent nature of cyclic data allows it to be mathematically modeled considering the size of the data, the amount of cyclic data which arrives per unit time (the numeric equivalent to the sampling frequency of the IEDs), and the time delay of the messages [50]. The time delay is considered to be made up of the sum of the Ethernet delay, the pretreatment time of the sender and the postproceeding time of the receiver [50]. The maximum delay times specified by the IEC 61850 standards can be considered using the mathematical model.

The stochastic data considered in the paper is divided into two types, which are classified as follows [50]:

1. Type 1 – These messages include trip messages, switch operation messages and transformer tap modulation data.
2. Type 2 – These messages include event log checking and protection setting modification data.

The research scholars in [50] propose the modeling of the arrival of stochastic data traffic with the use of the Poisson process. The Poisson process is chosen as the packet data is generated in a random time period with a probability P. The amount of packets arriving in two mutually exclusive time periods is independent as packets which arrive one after another have no correlation. Additionally, packet size can vary with time, or it could be fixed [50]. The nature of the arrival of the stochastic data indicates the suitability of the Poisson process.

Burst data, during a random time, is dependent on events that have previously occurred and are also generated with a probability λ. When a substation event (fault) occurs, the messages change to burst mode, from the original cyclic mode [50]. This change results in burst data flow. The generation of burst data causes a large amount of network traffic in a short space of time, leaving the network free for long periods once the transmission of the data packets is complete. As a result of this nature, burst data flow can be said to have long-range dependence and self-similarity characteristics, presenting the same burstiness at different time scales [50], [51]. The research scholars discuss that self-similarity of data flow in a network can described with the use of the ON/OFF model and heavy-tailed distribution. The ON/OFF model allows for the representation of data sources whose state repeatedly change between sending messages and not sending messages. In the ON state of the model, it is assumed that data is generated at a constant rate, whereas it is assumed that no data is generated in the OFF state [50], [52], [53]. Due to the described nature of burst traffic flow, the ON/OFF state model and Pareto distribution are used for the mathematical model proposed. The amount of data for different types of messages can be found using the models, constituting the analysis of data flow for a typical substation presented by the researchers [50]. In addition to the mathematical models presented, the paper also provides modeling with the use of the OPNET simulator, which investigates Ethernet delays under different network configurations (with and without VLANs), as well as different SCN architectures [50].

L. ADDITIONAL MODELING METHODS PROPOSED IN LITERATURE

The research scholars in [54] again use the OPNET modeler; however, one of their main goals was to determine whether the real-time demands of a SAS can be met using Ethernet. This entails the investigation of Ethernet's performance characteristics in a substation communication network. Prior to the simulation, reference [54] investigated various issues that involved the simulation of communication networks and the measurement of Ethernet's performance. These issues were protocol, disturbances, performance requirements, substation topology and message rate, and switched Ethernet characteristics. The research conducted using the OPNET modeler found that the real-time demands of a SAS can be met with the use of switched Ethernet, as it has sufficient performance requirements to successfully operate in an SCN [54]. This was tested through the examination of Ethernet's capabilities as a common network, handling multiple coexisting traffic types. This investigation found that various substation automation configurations could be successfully implemented with the use of a switch-based fast Ethernet network [54]. The use of UDP/IP is also investigated in the research carried out in [54].

VI. DISCUSSION AND COMPARISON OF THE METHODS REVIEWED

The analytical modeling methods reviewed in this paper all use linear algebra (matrix operations) and the network calculus theorem in order to model substation communication networks. The main findings of the methods reviewed are the traffic load distribution, and the maximum message delay. These network parameters are discussed in section IV of this paper and are essential to the successful operation of the communication network. In general, when analytical modeling methods are considered, various sub-models are developed using the arrival and service curve models for traffic flow in the network. These are used in all of the analytical modeling methods reviewed and form part of the network calculus theorem. The largest differences between the methods are the parameters which the methods are able to model, and under which conditions the parameters can be found.

The network calculus and path flow model aims to create a source model which describes the triggering relationships between GOOSE flows, the message rate, message length, the data rate of traffic flows and correspondence between a port and the messages. Additionally, the service model developed in the method takes into account the queuing and scheduling policies in the network. These sub-models allow for the traffic load distribution, as well as the maximum message delay to be found in three scenarios, namely the minimum load scenario, the maximum load scenario, and the typical event scenario. However, the method assumes that all GOOSE flows burst at the same time, providing a conservative, and likely higher maximum message delay than seen in simulation, and practically. This method can be adapted and simplified, allowing for an additional scenario to be added, which is an abnormal flow scenario. However, although the adapted network calculus and path flow method is very similar to the original method, the simplifications and adaptions mean that the maximum message delay can no longer be solved for, which is an essential parameter in communication network modeling. Lastly, the stochastic network calculus and traffic flow model method differs slightly from the first two analytical methods reviewed. Although one of the main aims of the method is also to find the traffic load distribution and maximum message delay, the method also considers the analysis of fault events that may occur in the communication network. The fault events considered are breaks in the traffic path/flow of transmission, the dislocation of the branch output node, and transmission data mistakes. Additionally, instead of investigating the network parameters under the minimum, maximum and typical event scenarios, the method investigates steady-state, as well as primary and secondary fault conditions.

The simulation methods reviewed all made use of the OPNET modeler. Notably, besides the modeling of SCNs for design and analysis, the OPNET modeler can also be used in order to confirm the suitability of Ethernet to the communication network. One of the main tasks in the simulation of the communication network using the OPNET modeler is the creation of models for the IEDs in the network. The software uses an object-oriented modeling approach, and an FSM approach is used by the process model, allowing for the implementation of resources, protocols, algorithms, applications and queuing policies. In general, when creating an IED model, the packet size, sample rate, address, start time, stop time and multicast group address must be specified to configure the model of the IED. Ultimately, the results of the simulation model focus on the ETE delay for critical messages (the maximum message delay, as discussed in the analytical modeling). However, the operating conditions in which the ETE delay can be found vary extensively from the analytical methods reviewed. The different operating conditions in which the SCN can be simulated include, different LAN speeds, different sampling rates, different transmission rates, normal and heavy background network traffic, normal and fault conditions, priority tagging and different VLAN configurations. Additionally, the architecture of the SCN can be easily adjusted.

Experimental modeling was reviewed as a method to determine the essential performance parameters of an SCN. The main aim of the experimental modeling was to find the latency introduced by Ethernet switches in the SCN. This was done through the use of Ethernet capture cards; however, the error in the frame arrival time-stamps, as well as the absolute time error must be taken into account when carrying out the experimental modeling. The use of an Ethernet tap in conjunction with an Ethernet card allows for any source of Ethernet traffic to be used, and the method allows for interaction testing to be performed. The interaction tests include the effect that high-volume SV traffic has on management and

TABLE 1. Modeling methods and applications.

Ref.	Year	Modeling Method	Application
[54]	2002	OPNET Modeling	Software-based verification of the suitability of Ethernet for use in SCNs.
[7]	2007	OPNET Modeling of IEDS	Software-based modeling of IEC 61850-based IEDs, switches and links. IEDs in all substation levels can be modeled. Various architectures can be modeled.
[21]	2008	OPNET Modeling of IEDS	Software-based modeling of IEC 61850-based IEDs, switches and links. IEDs in all substation levels can be modeled. Various architectures can be modeled.
[1]	2010	OPNET Modeling of IEDS	Software-based modeling of IEC 61850-based IEDs, switches and links. IEDs in all substation levels can be modeled. Various architectures can be modeled.
[41]	2012	Ethernet Capture Cards	Practical method to determine process bus performance. SV delay can be measured in small experimental systems.
[37]	2013	Hardware and Experimental Modeling	Practical method to determine process bus performance. Additionally, interaction testing can also be performed. Restricted to small test models.
[3]	2015	Analytical Modeling – Network Calculus Theorem	Modeling of entire SCN, including process bus, station bus and IEDs under minimum load, maximum load, and typical event scenarios.
[39]	2016	Analytical Modeling – Network Calculus Theorem	Modeling of entire SCN, including process bus, station bus and IEDs in steady-state and fault conditions.
[40]	2016	Bounded Analytical Modeling – Network Calculus Theorem	Modeling of entire SCN to find SV and GOOSE delays with focus on delay bound analysis.
[38]	2017	Analytical Modeling – Network Calculus Theorem	Modeling of entire SCN, including process bus, station bus and IEDs under minimum load, maximum load, typical event, and abnormal flow calculation scenarios.
[50]	2017	Mathematical and OPNET Modeling	Modeling of cyclic, stochastic, and burst data flow in an SCN. These message classifications include the IEC 61850-5 message types.
[45]	2018	Time-Series Modeling (FARIMA)	Characterization of data traffic in smart substation communication networks. Prediction of data traffic behaviour. Requires experimental data.
[42]	2018	Time-Series Modeling (ARMA)	Modeling of GOOSE messages between IEDs in a smart grid. Requires a co-simulation model.
[49]	2019	Riverbed (OPNET) Modeling and Experimental Validation of Results	Simulation and experimental modeling of the different IEC 61850-5 messages times in an SCN. Benefits and applications of both OPNET and experimental modeling.

GOOSE signalling, as well as the complement, the effect that management and GOOSE messages have on the delivery of SV messages.

Lastly, time-series based modeling methods were also reviewed as a method in which traffic flow in a substation communication network can be modeled. These make use of the ARMA and FARIMA models to model traffic flow. However, the development of such models is an iterative process if the original model does not meet certain diagnostic checks. Additionally, experimental or simulated data is also required for use in these methods. The amount of data (number of packets) versus time is presented using this method, providing an indication of traffic flow and traffic load in the communication network.

All four types of modelling methods have certain advantages; however, certain methods are able to provide additional parameter identification in additional scenarios.

TABLE 2. Modeling methods and advantages and disadvantages.

Ref.	Year	Key Results	Merits/Demerits
[54]	2002	• Maximum message (ETE) delay • Suitability of the use of Ethernet in SCNs	The researchers use OPNET to verify the suitability of Ethernet for use in SCNs. This study provides a specific application of the OPNET modeler.
[7]	2007	• Maximum message (ETE) delay	Simple modeling of the network; however, only ETE delay can be analyzed. Additionally, the accuracy of the models must be considered. Various network configurations can be easily analyzed.
[21]	2008	• Maximum message (ETE) delay	Simple modeling of the network; however, only ETE delay can be analyzed. Additionally, the accuracy of the models must be considered. Various network configurations can be easily analyzed.
[1]	2010	• Maximum message (ETE) delay	Simple modeling of the network; however, only ETE delay can be analyzed. Additionally, the accuracy of the models must be considered. Various network configurations can be easily analyzed.
[41]	2012	• Maximum message (ETE) delay	The ETE time delay can be accurately analyzed; however, the size of the network model is limited, and the method can be expensive.
[37]	2013	• Maximum message (ETE) delay	The ETE time delay can be accurately analyzed; however, the size of the network model is limited, and the method can be expensive. Although, the use of this method allows for larger models than the Ethernet capture card method.
[3]	2015	• Traffic load distribution • Maximum message (ETE) delay	Both the traffic load distribution and maximum message delay can be found; however, the method requires complex calculus and linear algebra operations.
[39]	2016	• Traffic load distribution • Maximum message (ETE) delay • Analysis of fault conditions	Both the traffic load distribution and maximum message delay can be found, with the ability to also analyze fault conditions. However, the method requires complex calculus and linear algebra operations.
[40]	2016	• Maximum message (ETE) delay	The research scholars consider the bounded analytical analysis to be important as the maximum bound can be determined; however, the method requires complex calculus operations.
[38]	2017	• Traffic load distribution	Simplified use of the network calculus theorem; however, maximum message delay cannot be found.
[50]	2017	• Traffic load distribution. • Maximum message (ETE) delay	The amounts of different messages (traffic load) can be analyzed using a mathematical model, and the ETE delay can be analyzed using the mathematical model and the OPNET model. However, the use of two methods complicates and lengthens the modeling and evaluation process.
[45]	2018	• Characterization of traffic flow	The traffic flow can be characterized; however, the iterative process may make the modeling method cumbersome. Additionally, experimental data is required.
[42]	2018	• Number of messages (traffic load	The traffic load can be analyzed; however, the iterative process may

TABLE 2. *(Continued)* Modeling methods and advantages and disadvantages.

TABLE 2. ***(Continued)*** **Modeling methods and advantages and disadvantages.**

		distribution)	make the modeling method cumbersome. Additionally, a co-simulation is required.
[49]	2019	• Maximum message (ETE) delay	The maximum message delay can be found through simulation and experimental hardware modeling. This method limits inaccuracies but is longer and more resource-intensive.

The analytical modeling methods provide accurate models that allow for the traffic load distribution to be analyzed, which was not a focus in either the simulation or experimental modeling methods. However, the analytical methods require various matrix and calculus operations, adding to their complexity. Simulation methods, using the OPNET modeler, are arguably simpler to implement; however, they only allow for the ETE delay to be found. Even so, the simulation modeling method is extremely beneficial, as a large array of network conditions can be analyzed. One of the major considerations of the OPNET simulation method should be the accuracy of the models, as industrial Ethernet switches rated for substation use have not been widely used in the past, meaning detailed-event based models may not be available for use in the simulation software. While experimental modeling means the substation equipment can be physically analyzed, there are limitations on the size of the network that can be modeled easily. Additionally, experimental modelling is largely dependent on the accuracy of the equipment used, and as a result, can be an expensive method to use. Lastly, time-series based modeling allows for the traffic load distribution to be analyzed; however, the possible iterative nature of the process could make it cumbersome. Table 1 and Table 2 provide summaries of all the modeling methods, displaying applications, key results and the advantages and disadvantages of the methods.

VII. CONCLUSION

The objective of this paper was to review the methods in which the traffic flow in a substation communication network can be modeled. Due to the development of software-based substation automation systems, microprocessor-based intelligent electronic devices and the introduction of the IEC 61850 standard for communication systems, Ethernet communication systems are being more commonly used in substation communication networks, leading to an increased dependency of the substation automation system on the communication network. The review carried out in this paper found that there are various methods in which the traffic flow in a substation communication network can be modeled. These methods include analytical, simulation, experimental, and time-series based modeling methods. Simulation-based modeling was found to be a very useful tool, as the end-to-end message delay can be simulated in various network conditions; however, analytical modeling is more useful for representing the traffic load distribution.

This paper reviews the current methods that can be used to model the traffic flow in a substation communication network. However, this work can be used in order to develop additional models or extend the current ones discussed. The development of substation communication networks to produce fast and reliable substation automation systems is likely to continue, and as a result, the further development of simple ways in which the communication networks can be modeled is of paramount importance.

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