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Research Article

Communication Delay Modeling for Wide Area Measurement System in Smart Grid Internet of Things Networks

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We present communication frameworks, models, and protocols of smart grid Internet of Things (IoT) networks based on the IEEE and IEC standards. The measurement, control, and monitoring of grid being achieved through phasor measurement unit (PMU) based wide area measurement (WAM) framework. The WAM framework applied the IEEE standard C37.118 phasor exchange protocol to collect grid data from various substation devices. The existing frameworks include the IEC 61850 protocol and programmable logic controllers (PLCs) based supervisory control and data acquisition (SCADA) system. These protocols have been selected as per the smart grid configuration and communication design. However, the existing frameworks have severe synchronization errors due to the communication delays of IoT networks in the smart grid. Therefore, this article designs the timing mechanism and a delay model to reduce the timing delay and boost real-time measurement, monitoring, and control performance of the smart grid WAM applications. The result shows that the proposed model outperformed the existing WAM system.

1. Introduction

The electrical substation is a standout among the most critical parts of the electrical transmission and distribution frameworks. As indicated by [1], the substations are classified into switchyard substation, client substation, framework substation, and conveyance substation. The switchyard substations are situated at generations, which interface the generators to the utility matrices that give the off-site capacity to the plants. Generator switchyards tend to have substantial establishments that are commonly built and developed by the power plant operators and are liable to arranging, financing, and development accomplishments not quite the same as those of predictable substation projects—the substation functions as the essential source of electric power supply for heavy consumers such as factories. The specific necessities and business case, for this kind of usages, rely more on the customer's essentials than utility needs. In the meantime, the intelligent grid substations are network connected from the generation to the distribution through a communication framework to maintain the power grid intelligent devices and sensors deployed at the various components. The main purpose of the network-connected framework is to collect the grid data from various substation components, so that

the power grid becomes smart with the facility of ICT infrastructure. To accomplish the smart grid operation, the communication infrastructure plays a massive role in connecting, monitoring, and controlling. The communication infrastructure plays a massive role in connecting, monitoring, and controlling the smart grid system. Communication infrastructure is the key factor to have real-time accessibility on the grid. This is because proper communication architecture can deliver a large amount of operation data, communications, processing, and control for the remote monitoring for grids and the consumptions through the communication infrastructure. Figure 1 presents a hierarchical distributed communication infrastructure for the smart grid that includes smart homes and the communication architecture from the perspective of generation, transmission, distribution, and consumption [2]. The architecture considers SCADA, PMUs, massive-scale SMs, and SMDs to obtain and measure the voltage amplitude, current phasor, and power quality of generation and distribution information at a high sampling level of effectiveness in controlling, estimating, and ongoing checking of the keen matrix. SCADA is one of the mainstream frameworks that use its uncommon convention and equipment configuration to control and estimate the substation framework. The PLC-based SCADA system has been implemented in the existing power grid automation.

For the automation purpose the various components of substations have been connected to the wide area measurement system. Choosing the right convention and correspondence system is essential to accomplish the best level of effectiveness in controlling, estimating, and ongoing checking of the keen matrix. SCADA is one of the mainstream frameworks that use its uncommon convention and equipment configuration to control and estimate the substation framework.

The existing automation architecture is based on PLCs with the SCADA system. This SCADA framework incorporates the IEDs, the correspondence protocols like IEC 61850 that have detailed data demonstrating the information out of devices that use this protocol. The IEC 61850's strategy transport embraced connecting estimations devices, similar to instrument transformers, actuators, protection systems, and circuit breakers, to the IEDs of the sound amid an essential station. Indeed, these devices are associated with the controller of the inlet by cable connections. The IEC 61850 randomly proposes a captivated technique bus to curtail the cabling and upkeep cost. In any case, the quality does not maintain with the devoted topology of the bus bay: one technique transport will interconnect all the circle devices of the station, or a process bus per bay will connect the devices specifically.

The main contribution of this paper is as below:

(1) The communication framework and the delay modeling with the timing mechanism

(2) The key determinant performance factors are total measured delay, and real-time delays are modeled and analyzed the performance focusing propagation delays, receive delays, initial delays, skews, and phasor offsets parameters

(3) The comparison evaluation with the C37.118 standard

2. Smart Grid Communication Systems and Protocols

The IEC 61850 communication protocol has expressively improved the substation automation system (SAS), by introducing the control structure in a communication framework to measure, control, and monitoring [3]. The IEC 61850 protocol suits two arranged communication phases: the substation bay and the system bay that reliably communicates the SCADA framework to the strait embellishment of the basic substation. The instrumentations are transformers; the protection unit and MU to IEDs are connected to the system bay. The two foundations have specific necessities, and consequently, the advances and plans need to send the two bays are routinely intriguing. Conventionally, the substation bay is executed utilizing a performing fiber optical gigabit Ethernet, with ring topology to redesign the receptiveness of the correspondence. The strategic bay needs to deal with a more significant proportion of information starting from transformers or merging unit (MU) that sent on the substation. Generally, a high-speed gigabit Ethernet (1/10) network system is incorporated to accomplish the communication infrastructure. The IEC 61850-9-2 LE represents a course of action of guidelines to empower the interfacing of instruments and MUs to the bay system [4]. The IEC 61850-9-2LE discusses the rate of SV that is focused on protection applications: the estimation contraptions reliable with this profile need to test the current or the voltage multiple times for each system cycle (50 Hz in EU, 60 Hz in the USA). The instruments made for also asking for applications, like quality control monitoring, test the characteristics multiple times for the lattice cycle. The MUs should be synchronized with one another to achieve precision underneath four μs. The synchronization of the equipment should be set up using a 1-PPS committed banner, generally using a GPS recipient and enclosed to each contraption [5]. A progressive package number is utilized to recover the testing cycle of each instrument. In any case, the progressing standard for the propelled substations for this standard perseveres through the synchronization challenges.

The IEEE C37.118 standard uses synchrophasors in estimating smart grid devices and components. This is to manage the synchrophasor estimation. At the required significances, the configuration parameters analyses in different conditions and displays immaterial precision [5]. The standard depicts by class P suggests security applications require helpful reaction time. Anyway, class M gives the base element of accuracy for the estimation applications, which do not require an intelligent reaction time yet perfect precision over class P. The contrasts between the two classes are recognizable in the execution of work in progress changes of amplitudes or stages. For this kind of test, the implementation required for the P class, concerning reaction time, is on an elementary level higher than M class and is accessible on the detailing pace of synchrophasors in any case, and it relies just upon the straightforward rehash of the framework [3, 6]. The circled current and voltage transformers should completely synchronize. The IEEE C37.118 synchronization calculation involves a synchronization exactness of end

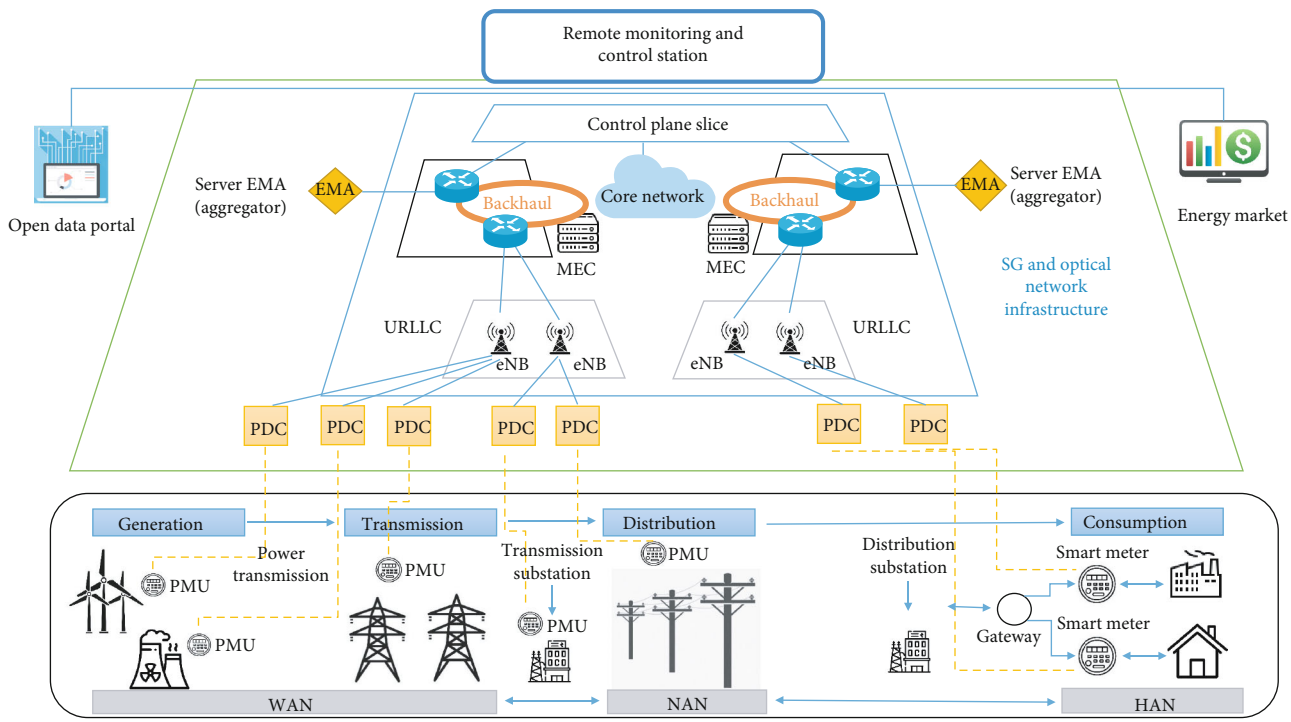

Figure 1: A hierarchical distributed communication infrastructure: where energy management agent (EMA), eNB is the macrocell base station, SM denoted massive scale, SMD states the supervisory control and data acquisition measurement devices, N3 is the communication interface between the router and macrocell base station, URLLC is the ultrareliable, MU is the merging unit, and low-latency communications, MEC used for mobile edge computing [2].

gadgets underneath the microsecond, enough to estimate the synchrophasors. Moreover, the voltage and current on the framework ought to be assessed on different occasions for each cycle (50 Hz), to give an adequate number of tests. Right now, the estimation focus point can make up to two megabits for every second of development, which the system structure ought to precisely sensible with no adversity came in liberal stacked conditions.

IEEE C37.118 is messages that are structured with the data of information, configuration, header, and control message. Information messages are utilized to send supportable estimations. Data from different PMUs are transmitted in a special message related to a particular timestamp [7, 8]. Configuration messages are machine-arranged and contain information about the game-plan parts and data sorts. Configuration messages are of three explicit categories: CFG-1, CFG-2, and CFG-3. CFG-1 finds out for kind of data and point of confinement of PMU/PDU. CFG-2 displays the synchrophasor estimations, which are starting at now being transmitted/declared. In any case, CFG-3 resembles CFG-2, yet contains some extra flexibility and information about PMU qualities and estimations. Header messages contain expressive information sent by the PMU by techniques for PDC. Request messages are used to control the endeavor of contraption sending synchrophasor estimations. Like this, data, configuration, and request messages are passed on in machine-clear methodology while the header explains information in the fathomable connection. Moreover, data, configuration, and header are sent by the data sources while control messages are received by the data sources. The IEEE C37.118 correspondence design is introduced in Figure 2 [8]. IEEE C37.118 encounters the nonattendance of standard data names checks autodisclosure and self-depiction without learning of configuration message, customization weakens interoperability and joining support, and no apparent security framework or even more all it depends on GPS for the outside timestamps [9–16].

3. Recent Issues and Challenges of Communication Systems in Smart Grid

The significant advancement has been accomplished for the communication infrastructure with the special technologies that include artificial intelligence, Internet of Things (IoT), 4G, and 5G data access [15–29]. This advancement enriched the communication infrastructure for smart grid protection, measurement, and control system in a sophisticated manner. However, the smart grid maintains high-level communication with specific devices with the applications to support substation automation. The above discussion can be discussed with the specific illustration of WAM for SCADA and PMU system issues. The issues and the challenges of SCADA and PMU based WAM system for substation automation are discussed below.

3.1. Issues and Challenges of PLC and SCADA System for the Digital Substation. The network infrastructure of the WAM system is designed with the consideration of multiple device

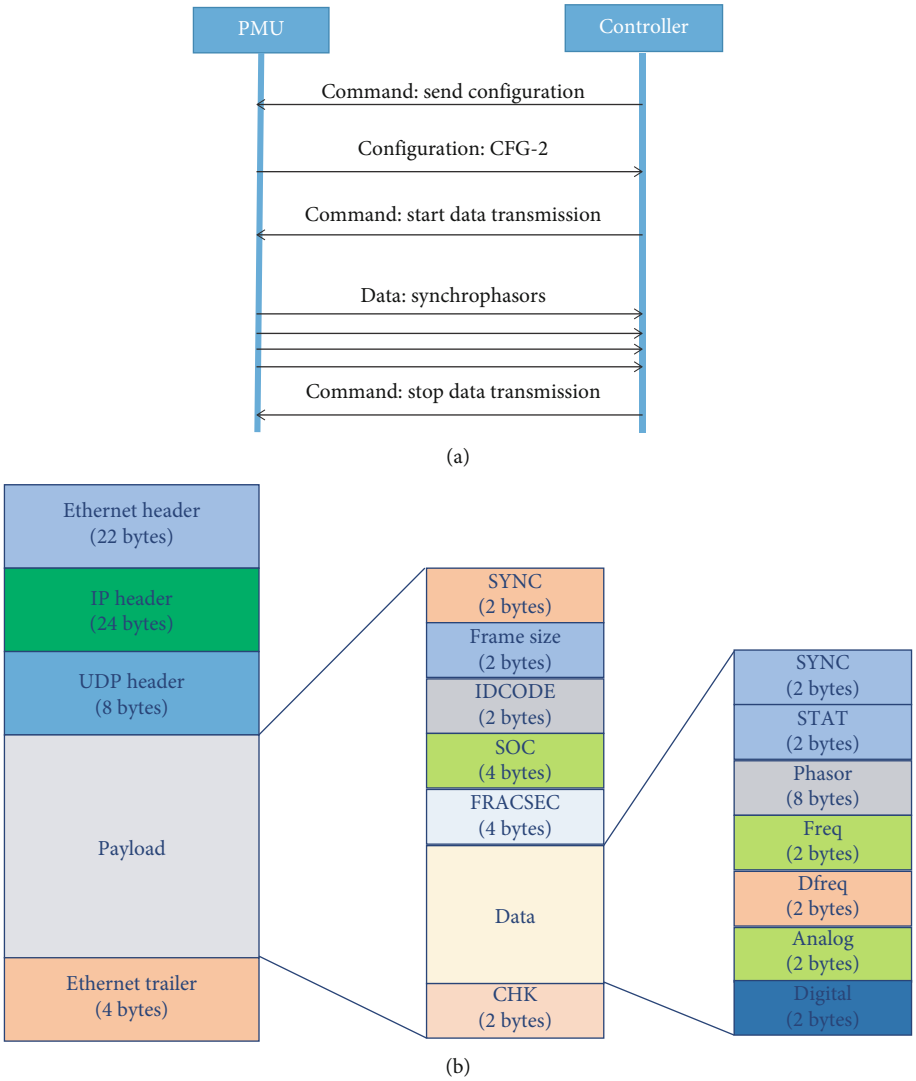

Figure 2: Functionalities of IEEE C37.118 protocol (a) and data structure (b) [8].

associations to access substation devices, reduce maintenance cost, and support the execution of additional substation mechanization applications [25–29]. The coordination of sequential protocol substation devices onto an Ethernet structure is a significant test. There are different devices called Terminal Servers, Serial Device Servers, or Console Servers. These devices symbolize short sequential data messages into TCP/IP bundles to send over Ethernet, and each sequential stream is related to a reliable TCP/IP session. Terminal Servers may be connected to be worked at the client or server zone to change over Serial-IP streams back to the sequential plan. Then again, some expert servers or remote PCs may interface clearly to Serial-IP streams over IP/Ethernet affiliations. The execution over wide area networks (WANs) can be an issue with Serial-IP organize fuse in perspective on limited information exchange limit, e.g., 56 kbps or fragmentary T1 (under 1.5 Mbps) layout hand-off or gave electronic organizations. Various SCADA has that usage serial remote devices have short reviewing breaks; except for on the off chance that they get a response from a remote IED in less than 100 milliseconds, they may expect a framework issue. Some Serial-IP frameworks cannot dependably achieve this low dormancy. One segment that impacts orchestrate torpidity can be the traditional overhead of TCP/IP epitome. As showed up in Figure 3, sequential SCADA messages may be only two or three bytes in length; anyway, TCP/IP tradition headers increase the length of the Serial-IP packages by demand of degree. This can be relieved with a SCADA frame forwarding technique that uses layout hand-off-based embodiment with only two or three bytes of the header to multiplex sequential SCADA development on a WAN framework. SCADA frames implemented together using IP-based WAN infrastructure. The SCADA frame forwarding packet formats have been designed with the link header, IP header, TCP header, message and data information field, and FCS. This frame forwarding is used to reduce the overhead by saving 90% of bandwidth and also reduce the latency on the wide area network.

Generically, cybersecurity is another essential requirement from the extruders hacking for the entire internal

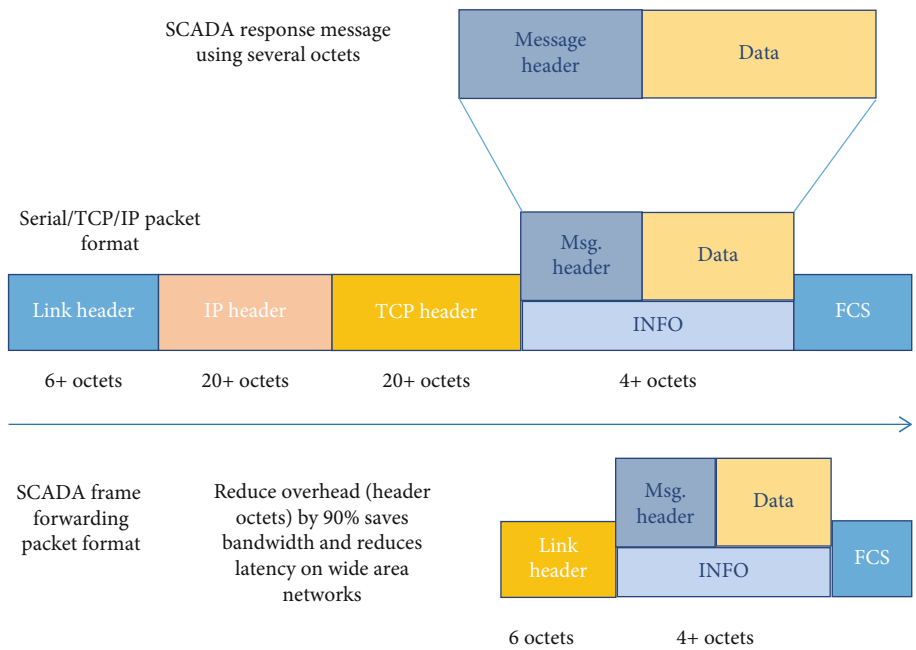

Figure 3: Serial IP protocol overhead vs. SCADA frame forwarding [29–31] (reproduced under the Creative Commons Attribution License/public domain).

systems and smart grid processes. Researchers have been emphasizing the effort on cybersecurity-related projects to comply with current industry standards. Another critical issue is network reliability. For the high network, reliability is required in SCADA and other operational systems in grid operations. In addition, substation networking becomes advanced and integrated. Therefore, the network outages can affect many systems and control elements that need to be minimized.

3.2. Issues and Challenges of IEC 61850-90-5 Communication System. The current communication convention IEC 61850 for substation computerization inside the grid framework today is being utilized with the help of up to 12 RS232/485 and 6 Ethernet ports, SCADA server (see Figure 4). Although there are timing and control issues inside the present framework applications, the framework has been confronting difficulties utilizing IEC 61850. One point to be communicated about is that the usage of IEC 61850 inside a repetition setting, at both the gear and correspondences levels, and its impact on the general inertness of a framework, including the potential effect and issues concerning control and assurance in such an excess domain. One must ensure that the methodology will give appropriate reaction times and adaptability for future expansion (s), without precluding the adaptability to deal with considerably further developed conceivable control outcomes that may be required during a future keen network.

The IEC 61850-90-5 is inherited from the IEC 61850 main version that had been implemented for substation digitalization. The IEC 61850 is a network correspondence convention that will, in general, show power framework parts, thought of interconnected administrations, and correspondence conventions just as frameworks. It was sketched out because of the interoperability and combination between power control structure, device configurations, self-association, and item autorevelation, the persistent quality framework through retransmission, reduced substation cost through multicast, and multicast, and multicast, and multicast remote network communication system, and reinforce for the machine-to-machine interchanges. Even though IEC 61850 furthermore has weaknesses, including the nonappearance of security constituent and confined correspondence, IEC 61850-90-5 gets all of the features of IEC 61850 while in like manner vanquishing its constraints. The critical differences between IEC 61850 and IEC 61850-90-5 showed up in Figure 5. IEC 61850-90–5 joins a security segment considering Group Domain of Interpretation (GDOI) and besides allows the transmission of time-essential shows over wide-area organizes by relying upon transport and framework layer conventions.

3.3. Issues and Challenges of IEEE C37.118 Protocol with SCADA and WAM System. Using high-level data-efficient communication system, many smart grids established the communication framework and IEEE C37.118 and SCADA. It is identified that the existing grid system uses fiber optic-WiMAX technologies as the backbone of AMI traffic is to control and access between the control center and the grid [16]. Using WiMAX provides a high communication data rate from the control center to the smart grid substations. On the other hand, researchers also investigated LTE-based fiber-optic technology to provide high communication data rates from the control center to the smart grid substations [17, 29, 30, 32–37]. Depending on the GPS timestamps, the nonappearance of GPS lopsidedness influences the accuracy

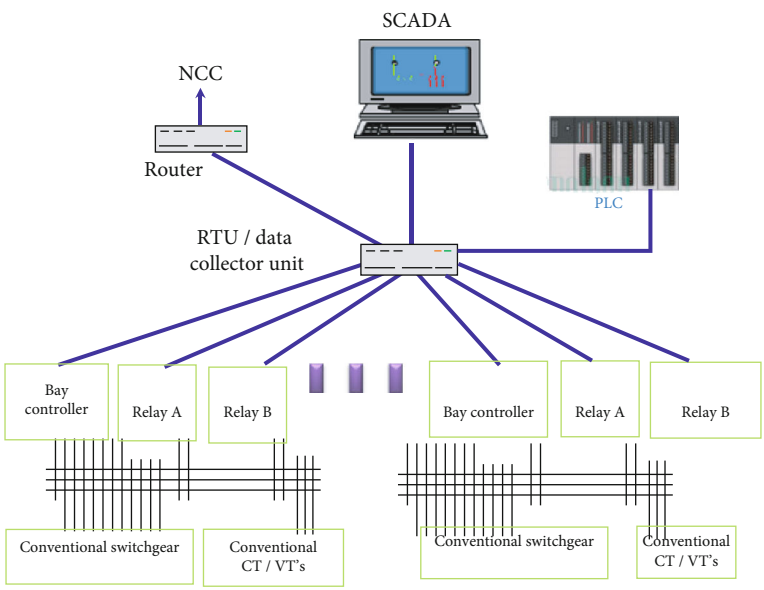

Figure 4: Diagram of IEC 61850 in SCADA system.

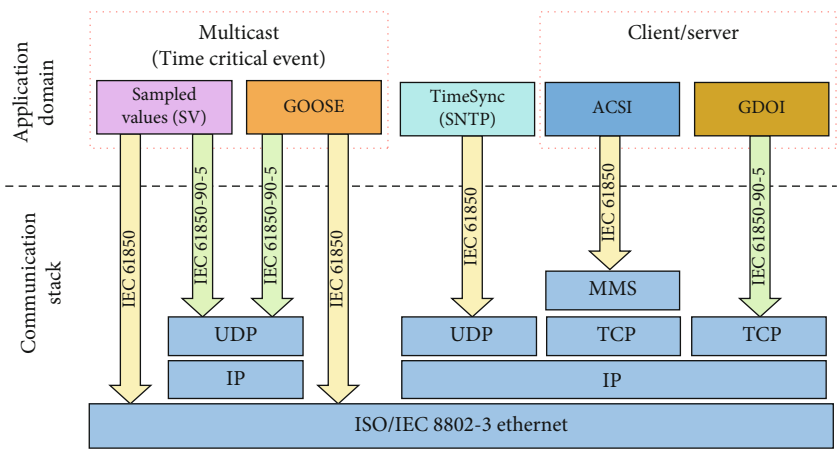

Figure 5: Difference between IEC 61850 and IEC 61850-90-5 protocol stack [14].

of the lattice-observing framework because of offbeat and mistake events in estimating the ongoing information [17, 18, 38, 39]. The nonattendance of standard data names stays away from autorevelation and self-association without the learning of configuration messages: vender specific features and customization cripple interoperability and blend support. There is no inherent security component to ensure digital assault [4, 12, 16–18, 27, 30, 33]. The other significant issue is the implementation of the PMUs using GPS in the smart grid. The study suggests that if the GPS connectivity is missing a little longer, the measurement and control will be complicated; therefore, the effect will be on the efficiency.

However, it is observed that latency, phasor delays, and internal processing delays are still key concerns in smart grid communications. Therefore, delay modeling is critical to calibrate the existing WAM systems for smart grid applications [30, 34–37, 39]. The next section will discuss and propose the communication delay modeling by focusing and consider the few delay parameters that can be calibrated to the existing system to enhance the grid measurement performance.

4. Proposed Delay Modeling for the Smart Grid Applications

A crucial prerequisite for every data transmission of the smart grid communication system's proper operation is timing and phase synchronization. The method by which a receiver finds the correct pulse width of time at which to sample the incoming signal is known as timing synchronization. Phase synchronization is the process by which a receiver adjusts the frequency and phase of its local carrier oscillator to match that of the transmitter. However, due to the synchronization issue of the existing IEEE C37.118 in the WAM system timing synchronization requires delay

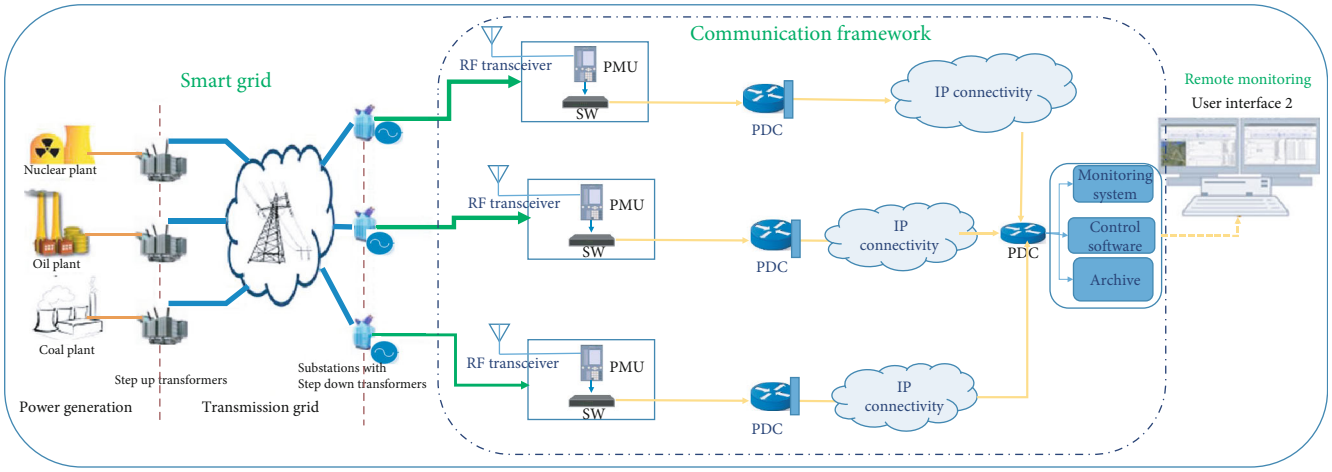

Figure 6: Communication diagram for wide area measurement (WAM) system, where an external timing source is used using GPS system for each of the PMUs in the set of substations, and PDCs are connected to monitor the smart grid remotely.

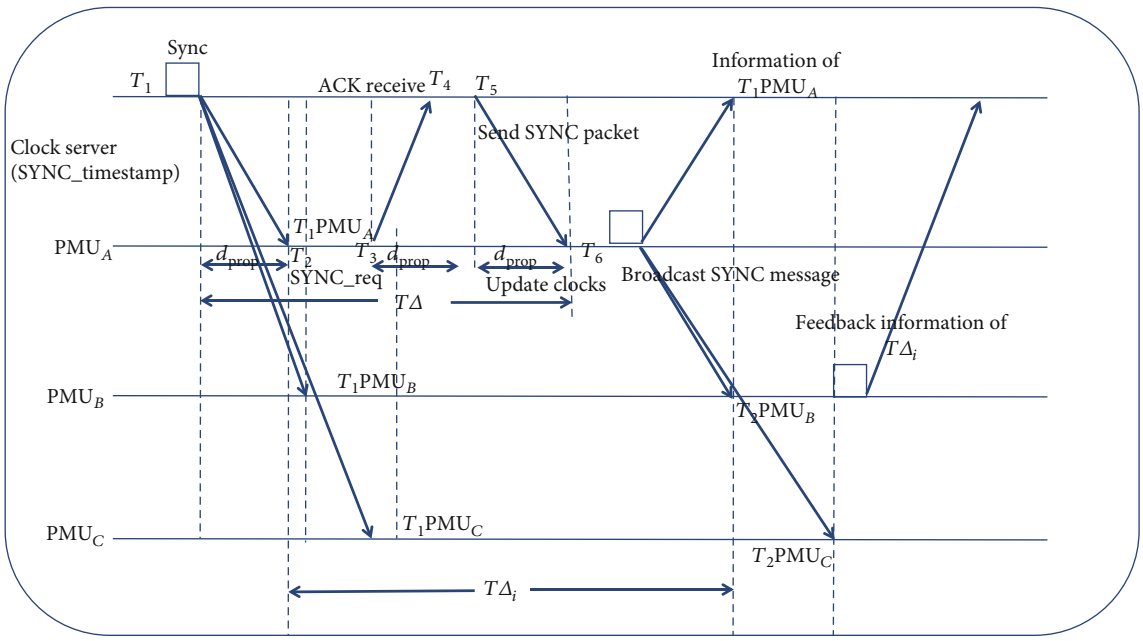

Figure 7: The timing diagram for the delay measurement and modeling [4, 16, 29, 33].

modeling. In order to delay modeling, a timing synchronization diagram is designed along with the network architecture. The communication delay is modeled using the following proposed timing diagram of existing, where the number of PMU, PDC, and the external timestamp source is considered (see Figure 6). Figure 7 demonstrates the timing diagram [4]. The timing diagram is used for the proposed delay modeling.

The delay is estimated from the above timing diagram, the time differences between the external timing source to all PMUs, PDCs, and the entire WAM communication system. To measure the total delay of the system, the first need is to consider small partial delays, propagation delays, receive delays and the phase errors, and the skew errors. The following equation is for the entire timing measurement where all sorts of delays are considered. The list of symbols that are used in Figure 7, and Eqn. (1) to Eqn. (6) are defined in Table 1.

$$T^{\text{timing\_signal}}_{\text{PMU}A\longrightarrow i} = \Phi^{\text{skew\_error}}_{\text{PMU}A\longrightarrow i}\left\{T_1^{\text{PMU}_{A\longrightarrow i}} + \frac{\alpha}{2} + \frac{\rho^{\text{PMU}_{A\longrightarrow i}}_{\text{prop\_uplink}} - \rho^{\text{PMU}_{A\longrightarrow i}}_{\text{prop\_downlink}}}{2}\right\} + \widehat{T}^{\text{phase\_error}}_{\text{PMU}_{A\longrightarrow i}} + \frac{\bar{\mathscr{D}}^{\text{delay}}_{\text{PMU}_A} - \bar{\mathscr{D}}^{\text{delay}}_{\text{PMU}_i}}{2}, \tag{1}$$

$$\bar{\mathscr{D}}^{\text{total\_delay}}_{A\longrightarrow i} = \left[\left(\bar{\rho}^{\text{PMU}_{A\longrightarrow i}}_{\text{prop}} - \mathscr{D}^{\text{PMU}_{A\longrightarrow B}}_{\text{rec},i}\right) + \left(\mathscr{D}^{\text{PMU}_{A\longrightarrow i}}_{\text{rec},i} - \mathscr{D}^{\text{PMU}_{B\longrightarrow C}}_{\text{rec},i}\right) + \left(\mathscr{D}^{\text{PMU}_{A\longrightarrow i}}_{\text{rec},i} - \mathscr{D}^{\text{PMU}_{i\longrightarrow A}}_{\text{rec},i}\right)\right]. \tag{2}$$

Table 1: Definition of the symbols that are used in Eqn. (1) to Eqn. (6).

Symbol	Definition
Sync_start	Synchronization start message frame
Ack	Acknowledgement
$T^{\text{timing\_signal}}_{\text{PMU}A\longrightarrow i}$	Timing signal of PMU A to the ith number
$\Phi^{\text{skew\_error}}_{\text{PMU}A\longrightarrow i}$	Phase skew error of PMU A to the ith number
α	Initial receive delay
$\rho^{\text{PMU}_{A\longrightarrow i}}_{\text{prop\_uplink}}$	Propagation delay for uplink
$\rho^{\text{PMU}_{A\longrightarrow i}}_{\text{prop\_downlink}}$	Propagation delay for downlink
$\bar{\mathscr{D}}^{\text{delay}}_{\text{PMU}_A}$	Receive delay at PMU_A
$\bar{\mathscr{D}}^{\text{delay}}_{\text{PMU}_i}$	Receive delay at PMU_i
$\check{\Phi}^{\text{skew\_error}}_{\text{PMU}A\longrightarrow i}$	Total skew error
$\widehat{T}^{\text{phase\_error}}_{PMU_{A\longrightarrow i}}$	Total phase offset
$\gamma^{\text{desired\_delay}}_{\text{PMU}_{A\longrightarrow i}}$	Desired signal of PMU_A to PMU_i

The total skew or the related frequency error can be expressed in Eqn. (3).

$$\check{\Phi}^{\text{skew\_error}}_{\text{PMU}A\longrightarrow i} = T^{\text{timing\_signal}}_{\text{PMU}_A} - T^{\text{timing\_signal}}_{\text{PMU}_i}. \tag{3}$$

To measure the absolute delay of the entire communication system, the phase error needs to be estimated. Consequently, the total estimated phase errors can be expressed in Eqn. (4) considering Eqns. (1), (2), and (3). Therefore, the real-time delay can be modeled in Eqn. (5) using Eqn. (4),

$$\bar{\rho}^{\text{PMU}_{A\longrightarrow i}}_{\text{prop}} = \frac{\rho^{\text{PMU}_{A\longrightarrow i}}_{\text{prop\_uplink}} - \rho^{\text{PMU}_{A\longrightarrow i}}_{\text{prop\_downlink}}}{2}, \tag{4}$$

$$\widehat{T}^{\text{Measured\_delay}}_{\text{PMU}_{A\longrightarrow i}} \cong \frac{1}{M}\sum_{i=1}^{M} \widehat{T}^{phase_{error}}_{\text{PMU}_{A\longrightarrow i}} + \bar{\mathscr{D}}^{\text{total}_{\text{delay}}}_{A\longrightarrow i} + \check{\Phi}^{\text{skew}_{\text{error}}}_{\text{PMU}A\longrightarrow i}, \tag{5}$$

$$D^{\text{PMU}_{A\longrightarrow i}}_{\text{real-time\_delay}} = \gamma^{\text{desired\_delay}}_{\text{PMU}_{A\longrightarrow i}} - \widehat{T}^{\text{Measured}_{\text{delay}}}_{\text{PMU}_{A\longrightarrow i}}. \tag{6}$$

5. Result and Discussion

The performance analysis was accomplished by applying the Monte Carlo simulation approach in MATLAB [16, 38]. The performance of the proposed delay model is simulated and then compared with the existing IEEE C 37.118-based WAM system. The performance was measured with the integration of the proposed delay model into the existing IEEE C37.118 and then compared with IEEE C37.118 assessed without the proposed delay model. The total measured delay and the real-time delay are considered as the performance metric of delay measurement. The simulation scenario considered 50 PMUs, and the 50 PMUs, 20 PDCs, 20 trials, and the designed communication topology. The communication network is shown in Figure 8. The initial random receive delay reference was set to 15 μs, 20 μs, and 30 μs. The number of samples was 10,000. Setting the initial delay at 10 microseconds (μs) and the network bandwidth with an external timing server set to10 Mbps, the total delay is represented in Figure 8. In addition, with the setting of 30 μs initial delays, the total delay measurement is shown in Figure 9. It is visible that the total measured delay is marginally acceptable using the proposed model. However, the existing IEEE C37.118 shows the extra delays.

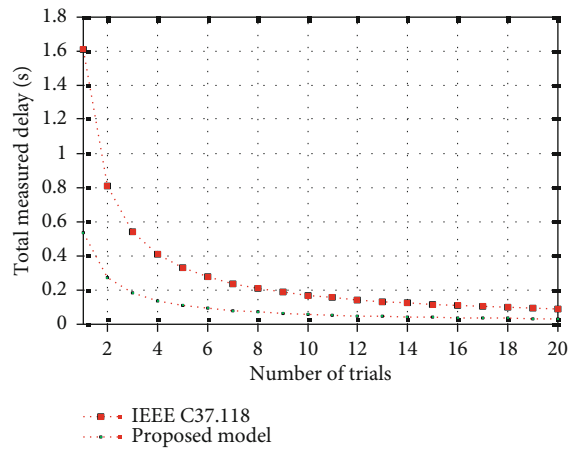

Figure 8: Total delay measurement in terms of number of trials at the initial 10 uc delay consideration.

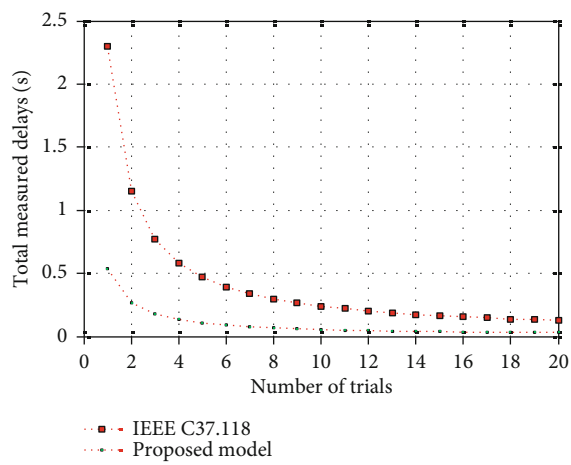

Figure 9: Total delay measurement in terms of number of trials at the initial 30 uc delay consideration.

Figure 10 shows the delay performance of the proposed model function of the number of occurrences and the exchanges of phasor signals among different PMUs and PDCs in the communication framework. This figure shows the actual delay in terms of asymmetric bandwidth rates; if the bandwidth increases from 1 Mbps to 10 Mbps, the communication delays are lower. For the convenience of the analysis, the receive delay processing time was varied from 10 μs to 30 μs, and the simulation processing time was assumed 1 hour. Therefore, the study suggests that the delays can be lower if the bandwidth reaches higher to higher. The observations of the proposed model result show that the communication delays are less than 0.5 seconds while bandwidth

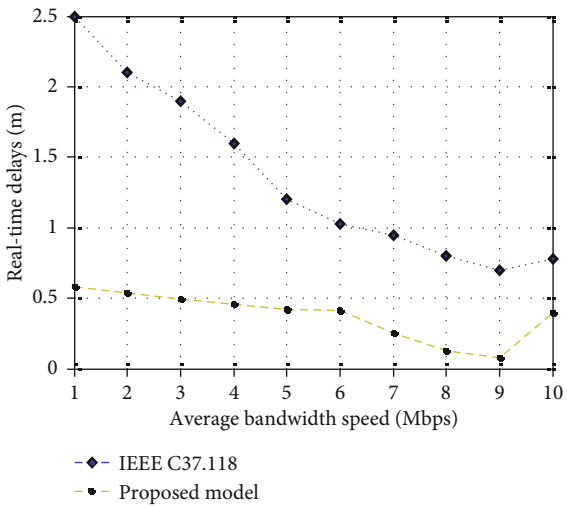

Figure 10: Real-time delay measurement in terms of average bandwidth speed.

reaches 5 Mbps, whereas the C37.118 has a communication delay of more than 1.7 seconds.

The proposed model performs better than the existing C37.118 IEEE synchrophasors standard because of the design consideration of the timing controlling and parameters of delay modeling of the communication framework. The main parameter selection considers the propagation delays, receive delays, frequency errors, and phase errors so that it can finally estimate the real-time precisely communication delays. Therefore, in terms of delay modeling, the proposed model performs better in comparison with the C37.118 IEEE standard.

6. Conclusions

This article has investigated the smart grid automation systems and their protocols. This is to trace out the traditional communication system's limitations and advantages in smart grids. The algorithms discussed the functionalities and characteristics. The main contributions of this paper are the proposed real-time delay measurement model and then the performance analyzing over the existing IEEE C37.118. The main achievement of the proposed model is the mitigation of the communication delays in the wide area measurement system. The result of the proposed model suggests that the unexpected delays can affect the efficiency of the smart grid application. The performance of the proposed model was found better in enhancing the precise real-time measurement and monitoring the prefault situation and the exigence occurrence of the smart grid applications. The future work of this study is to calibrate the delay parameter into the real-time smart grid WAM system.

Data Availability

The data used to support the findings of this study are available in the manuscript.

Conflicts of Interest

The authors declare no conflict of interest regarding this paper.

Authors' Contributions

Data, methodology, simulation, result analysis, software, validation, and manuscript writing are done by Mohammad Kamrul Hasan. Review and editing are done by Shayla Islam, Muhammad Shafiq, Fatima Rayan Awad Ahmed, Somya Khidir Mohmmed Ataelmanan, Nissrein Babiker Mohammed Babiker, and Khairul Azmi Abu Bakar.

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References

[1] J. D. McDonald, *Electric Power Substations Engineering*, CRC Press, 2017.

[2] J. S. Choi, "A hierarchical distributed energy management agent framework for smart homes, grids, and cities," *IEEE Communications Magazine*, vol. 57, no. 7, pp. 113–119, 2019.

[3] J. Claveria and A. Kalam, "The influence of IEC 61850 standard: implementation and development of a functional substation automation simulator," *Australian Journal of Electrical and Electronics Engineering*, vol. 17, no. 1, pp. 28–35, 2020.

[4] M. K. Hasan, S. H. Yousoff, M. M. Ahmed, A. H. A. Hashim, A. F. Ismail, and S. Islam, "Phase offset analysis of asymmetric communications infrastructure in smart grid," *Elektronika ir Elektrotechnika*, vol. 25, no. 2, pp. 67–71, 2019.

[5] A. Bhargav, S. Ahmad, S. Kumari, A. Sahu, S. Luthra, and A. Gupta, "Technical evaluation and optimization of phasor measurement unit using CSIR-NPL PMU calibrator system to ensure reliability," *MAPAN*, vol. 35, no. 1, pp. 117–124, 2020.

[6] D. Fan and V. Centeno, "Phasor-based synchronized frequency measurement in power systems," *IEEE Transactions on Power Delivery*, vol. 22, no. 4, pp. 2010–2016, 2007.

[7] K. E. Martin, "Synchro-phasor standards development-IEEE C37. 118 & IEC 61850," in *2011 44th Hawaii International Conference on System Sciences (HICSS)*, pp. 1–8, Kauai, HI, USA, January 2011.

[8] K. Narendra, *Role of phasor measurement unit (PMU) in wide area monitoring and control*, Erlphase Power Technology Ltd, Winnipeg, Canada, Tutorial-Cbip, 2007.

[9] L. Montini, T. Frost, G. Dowd, and V. Shankarkumar, "Precision time protocol version 2 (PTPv2) management information base," *Information Base (No. RFC 8173)*, IETF, 2017.

[10] S. Lee, S. Lee, and C. Hong, "An accuracy enhanced IEEE 1588 synchronization protocol for dynamically changing and asymmetric wireless links," *IEEE Communications Letters*, vol. 16, no. 2, pp. 190–192, 2012.

[11] M. K. Hasan, R. A. Saeed, R. A. Alsaqour, A. F. Ismail, H. A. Aisha, and S. Islam, "Cluster-based time synchronisation scheme for femtocell network," *International Journal of Mobile Communications*, vol. 13, no. 6, pp. 567–598, 2015.

[12] Y. Mostofi and D. C. Cox, "Mathematical analysis of the impact of timing synchronization errors on the performance of an OFDM system," *IEEE Transactions on Communications*, vol. 54, no. 2, pp. 226–230, 2006.

[13] R. Khan, K. McLaughlin, D. Laverty, and S. Sezer, "Analysis of IEEE C37.118 and IEC 61850-90-5 synchrophasor communication frameworks," *2016 IEEE Power and Energy Society General Meeting (PESGM)*, 2016, pp. 1–5, Boston, MA, USA, July 2016.

[14] A. K. Das and S. Zeadally, "Data security in the smart grid environment," in *Pathways to a Smarter Power System*, pp. 371–395, Academic Press, 2019.

[15] D. Bian, M. Kuzlu, M. Pipattanasomporn, S. Rahman, and D. Shi, "Data security in the smart grid environment," *IET Communications*, vol. 13, no. 8, pp. 1025–1033, 2019.

[16] M. K. Hasan, M. M. Ahmed, A. H. A. Hashim, A. Razzaque, S. Islam, and B. Pandey, "A novel artificial intelligence based timing synchronization scheme for smart grid applications," *Wireless Personal Communications*, vol. 114, no. 2, pp. 1067–1084, 2020.

[17] J. Zhang, X. Luo, X. Fu, X. Wang, C. Guo, and Y. Bai, "Experimental study on the influence of satellite spoofing on power timing synchronization," *International Journal of Network Security*, vol. 22, no. 6, pp. 954–960, 2020.

[18] M. Z. Gunduz and R. Das, "Cyber-security on smart grid: threats and potential solutions," *Computer Networks*, vol. 169, article 107094, 2020.

[19] M. Shafiq, Z. Tian, A. K. Bashir, A. Jolfaei, and X. Yu, "Data mining and machine learning methods for sustainable smart cities traffic classification: a survey," *Sustainable Cities and Society*, vol. 60, article 102177, 2020.

[20] M. Shafiq, Z. Tian, A. K. Bashir, X. Du, and M. Guizani, "IoT malicious traffic identification using wrapper-based feature selection mechanisms," *Computers & Security*, vol. 94, article 101863, 2020.

[21] R. Ahmad, E. A. Sundararajan, N. E. Othman, and M. Ismail, "Handover in LTE-advanced wireless networks: state of art and survey of decision algorithm," *Telecommunication Systems*, vol. 66, no. 3, pp. 533–558, 2017.

[22] M. Shafiq, Z. Tian, Y. Sun, X. Du, and M. Guizani, "Selection of effective machine learning algorithm and Bot-IoT attacks traffic identification for internet of things in smart city," *Future Generation Computer Systems*, vol. 107, pp. 433–442, 2020.

[23] I. Shgluof, M. Ismail, and R. Nordin, "An enhanced system information acquisition scheme for CSG femtocells in 3GPP LTE/LTE a systems," *Wireless Personal Communications*, vol. 96, no. 3, pp. 3995–4011, 2017.

[24] M. Shafiq, Z. Tian, A. K. Bashir, X. Du, and M. Guizani, "Corrauc: a malicious bot-iot traffic detection method in iot network using machine learning techniques," *IEEE Internet of Things Journal*, vol. 8, no. 5, pp. 3242–3254, 2021.

[25] F. Yang and X. Zhang, "Performance analysis for OFDM smart-grid networks under AWSαSN with imperfect synchronization," in *ICC 2020-2020 IEEE International Conference on Communications (ICC)*, pp. 1–6, Dublin, Ireland, June 2020.

[26] M. Akhtaruzzaman, M. K. Hasan, S. R. Kabir, S. N. H. S. Abdullah, M. J. Sadeq, and E. Hossain, "HSIC bottleneck based distributed deep learning model for load forecasting in smart grid with a comprehensive survey," *IEEE Access*, vol. 8, pp. 222977–223008, 2020.

[27] M. K. Hasan, M. M. Ahmed, S. S. Musa et al., "An improved dynamic thermal current rating model for PMU-based wide area measurement framework for reliability analysis utilizing sensor cloud system," *IEEE Access*, vol. 9, pp. 14446–14458, 2021.

[28] A. H. Aman, N. Shaari, and R. Ibrahim, "Internet of things energy system: smart applications, technology advancement, and open issues," *International Journal of Energy Research*, vol. 45, no. 6, pp. 8389–8419, 2021.

[29] M. K. Hasan, M. M. Ahmed, A. F. Ismail, S. Islam, A. H. Hashim, and R. Hassan, "Timing synchronization framework for wide area measurement system in smart grid computing," in *2020 Global Conference on Wireless and Optical Technologies (GCWOT)*, pp. 1–5, Malaga, Spain, October 2020.

[30] M. K. Hasan, M. M. Ahmed, Z. Janin, S. Khan, A. H. Abdalla, and S. Islam, "Delay analysis of two-way synchronization scheme for phasor measurement unit based digital smart grid applications," in *2018 IEEE 5th International Conference on Smart Instrumentation, Measurement and Application (ICSIMA)*, pp. 1–6, Songkla, Thailand, November 2018.

[31] "Evolving to a strategic substation network architecture," June 2021, http://www.bomara.com/Garrett/wp_substation_architecture.htm.

[32] N. Nurelmadina, M. K. Hasan, I. Memon et al., "A systematic review on cognitive radio in low power wide area network for industrial IoT applications," *Sustainability*, vol. 13, no. 1, p. 338, 2021.

[33] K. Yu, M. Arifuzzaman, Z. Wen, D. Zhang, and T. Sato, "A key management scheme for secure communications of information centric advanced metering infrastructure in smart grid," *IEEE transactions on instrumentation and measurement*, vol. 64, no. 8, pp. 2072–2085, 2015.

[34] A. K. Ahasan Habib, S. M. Motakabber, M. I. Ibrahimy, and M. K. Hasan, "Active voltage balancing circuit using single switched-capacitor and series LC resonant energy carrier," *Electronics Letters*, vol. 56, no. 20, pp. 1036–1039, 2020.

[35] N. Fatima, T. A. Qasuria, and M. A. Ibrahim, "A brief review on smart grid residential network schemes," *Sains Malaysiana*, vol. 49, no. 12, pp. 2989–2996, 2020.

[36] A. Albayati, N. F. Abdullah, A. Abu-Samah, A. H. Mutlag, and R. Nordin, "A serverless advanced metering infrastructure based on fog-edge computing for a smart grid: a comparison study for energy sector in Iraq," *Energies*, vol. 13, no. 20, article 5460, 2020.

[37] N. Safitri and A. S. Yunus, "Integrated arrangement of advanced power electronics through hybrid smart grid system," *TELKOMNIKA*, vol. 18, no. 6, pp. 3202–3209, 2020.

[38] D. D. Chowdhury, "Synchronization for smart grid infrastructure," in *NextGen Network Synchronization*, pp. 181–207, Springer, Cham, 2021.

[39] M. Liu, I. Dassios, G. Tzounas, and F. Milano, "Model-independent derivative control delay compensation methods for power systems," *Energies*, vol. 13, no. 2, p. 342, 2020.