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A Co-simulation Platform for Wireless LTE Networks in Smart Distribution Systems

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***Abstract*—Wireless long-term evolution (LTE) networks are considered as a viable option for deployment in smart distribution systems due to their reliability, scalability, and cost-effectiveness. Yet, co-simulation platforms with the ability to analyze the performance of wireless LTE networks are lacking in the existing literature. This paper, for the first time, presents a real-time co-simulation platform based on Typhoon HIL and OMNeT++ for wireless LTE networks in smart distribution systems. The performance of the wireless LTE networks in smart distribution systems is investigated using the proposed co-simulation platform. A case study related to distribution automation is used to demonstrate the usefulness of the proposed co-simulation platform for examining the performance of wireless LTE networks.**

***Index Terms*—Smart distribution systems, wireless LTE communication networks, co-simulation, distribution automation.**

I. Introduction

ELECTRIC distribution systems around the globe are undergoing a significant transformation to address global warming concerns and achieve ambitious decarbonization goals set by the governments. This transformation has resulted in the rapid installation of renewable energy resources, battery energy storage systems and electric vehicle charging stations. The integration of these assets poses various challenges to distribution systems such as thermal overloading, over-voltage and reverse power flow. In order to address these challenges, deployment of distribution management systems is imperative to achieve higher observability and real-time control of distribution systems.

Distribution management systems require reliable, scalable, and cost-effective communication networks with wide area coverage and low latency. Utilities traditionally relied on leased telephone networks to exchange information between various assets in the distribution systems and distribution system operators. Nevertheless, leased phone networks have been gradually phased-out over the past years. Wireless Long Term Evolution (LTE) communication networks are considered as a viable option for replacing leased phone networks in electric distribution systems considering the prohibitive cost of dedicated fiber-optic communications.

The application of the wireless LTE and fiber optic communications in distribution systems for differential protection and wide area control are compared in [1]. It is concluded that the latency in wireless LTE network is higher than fiber optics, but it still satisfies the protection and wide area control requirements. The feasibility of using wireless LTE networks for data transfer of phasor measurement units (PMU) and phasor data concetrators (PDC) in distribution systems is studied in [2] and compared with fiber optic communications. The worldwide interoperability for microwave access (WiMAX) and wireless LTE networks are examined in [3] for self-healing applications in distribution systems. An experimental testbed is used in [4] to examine the possibility of deploying wireless LTE networks in various applications in distribution systems.

Various technologies such as (asymmetric digital subscriber line) ADSL, fiber optics and wireless LTE networks are used in [5] to transfer data based on IEC 61850 protocol. The data transfer based on various energy protocols such as IEC 104, and IEC 61850 over wireless LTE networks are thoroughly examined in [6]. The cybersecurity requirements of wireless LTE networks for advanced metering infrastructure and demand side management in distribution systems are studied in [7] based on national institute of standards and technology (NIST)-7628 guideline. An experimental approach is used in [8] to test latency requirements of generic object-oriented substation event (GOOSE) messages in wireless LTE networks. Experiments are performed in [9] to evaluate the performance of wireless LTE networks for IEC 61850-90-5 protocol.

In the existing literature, there is a lack of co-simulation platforms with the ability to analyze the application of wireless LTE networks to smart distribution systems. This paper, for the first time, presents a co-simulation platform based on Typhoon HIL and OMNeT++ for the wireless LTE networks. The proposed co-simulation platform is employed to investigate the performance of the wireless LTE networks in smart distribution systems. The main contributions of this paper are as follows:

- A real-time co-simulation platform based on Typhoon HIL and OMNeT++ is developed for the first time for wireless LTE networks in smart distribution systems.
- The performance of wireless LTE Communications in monitoring and automation applications of smart distribution systems are investigated.

The remainder of the paper is organized as follows. The existing co-simulation platforms in the literature are reviewed in Section II and the benefits of the proposed co-simulation platform are highlighted. The components of the proposed co-simulation platform are explained in Section III. The simulation results are provided in Section IV before concluding the paper in Section V.

II. Existing Co-Simulation Platforms

Power systems are evolving into complex cyber-physical systems where the cyber and physical domains are increasingly intertwined. As such, there is a pressing need to develop co-simulation platforms with the ability to simulate both the cyber and physical elements of power systems. The development of co-simulation platforms are imperative as they provide a safer and more cost-effective alternative to prototypes or real systems to conduct experiments.

The cyber and phyiscal elements of power systems are traditionally simulated separately using event-based and continuous time simulators, respectively. Various offline and real-time simulators such as PSCAD, EMTP-RV, PowerFactory, OpenDSS, Typhoon, OPAL-RT and RTDS, to name a few, can be used to simulate power systems. Moreover, various communication network simulators such as Riverbed Modeler, NS3 and OMNet++ can be used to simulate communication networks in power systems.

Numerous co-simulation platforms have been developed over the past decade to simultaneously simulate the cyber and physical elements of various parts of power systems including transmission and distribution networks. The electric power and communication synchronizing simulator (EPOCHS) is one of the first co-simulators developed to simulate both cyber and physical elements of power systems. The PSCAD/EMTDC electromagnetic transient simulator, the PSLF electromechanical transient simulator, and the Network Simulator 2 (NS2) communication simulator are linked together to build the EPOCHS co-simulator for studying protection and voltage collapse [10]. PSLF and NS2 simulators are integrated together in the global event-driven co-simulator (GECO) to model and simulate the wide area power system monitoring, protection and control schemes [11].

A co-simulator is developed in [12] to perform an integrated co-simulation of power and ICT systems for real-time evaluation (INSPIRE). In [13], a co-simulator is developed using OMNeT++ for supervisory control and data acquisition (SCADA) systems. A hierarchical engine for large-scale infrastructure co-simulation (HELICS) is presented in [14]. A co-simulation platform based on OPAL-RT and Riverbed modeler is presented in [15], [16] for investigating the vulnerability of communication assisted protection to cyber-physical attacks and benefits of software-defined networking. Yet, no prior co-simulation platform is provided in the literature with the ability to simultaneously simulate the wireless LTE networks and distribution systems.

In the next section, we present a co-simulation platform which can be used to investigate the performance and security of wireless LTE networks for distribution systems.

III. Proposed Co-Simulation Platform

The proposed co-simulation platform consists of two components including a real-time power system simulator and a real-time communication network simulator. The HIL 604 real time simulator from Typhoon HIL is used to simulate the distribution system as illustrated in Fig. 1 . Various communication protocols such as IEC 61850, DNP3 and IEC 104 are commonly used in power systems. The IEC 61850 communication protocol is used for the smart distribution system here. In this paper, we focused on GOOSE messages.

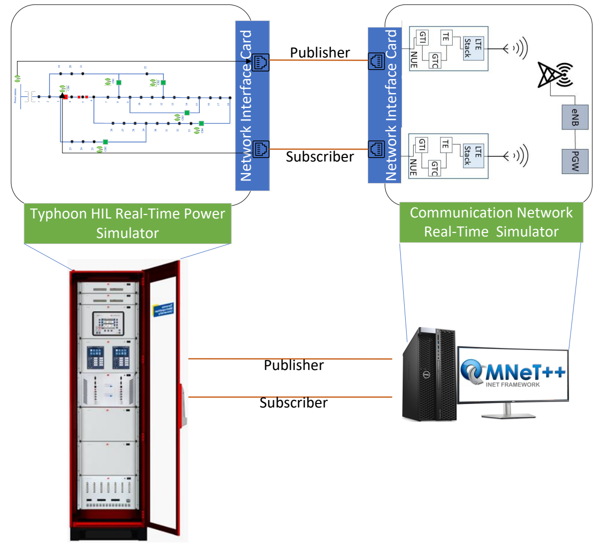

Fig. 1. Co-simulator architecture for simulating LTE networks in smart distribution systems

Two HIL 604 real time simulator are simultaneously used in the proposed platform to separate the subscriber and publisher traffic.

The communication network is simulated using OMNeT++ on a PC as illustrated in Fig. 1. OMNeT++ is a discrete event simulator for simulating a distributed system. HIL 604 simulators are connected to the PC used for communication network simulation using separate Ethernet cables for publisher and subscriber traffic. The inet package in OMNeT++ provides simulation framework and protocol modules to implement a communication network. The published GOOSE messages from the Ethernet interface, TP-Eth in Fig. 2, traverses through the simulated communication network in OMNeT++, and delivers back to the Typhoon subscriber Ethernet interface, TS-Eth. We implemented a network edge device (NED) to transfer the real GOOSE packets received at the network interface card (NIC) to the simulated environment in OMNeT++ and vice versa. The network edge device comprises of the following components:

1) GOOSE Traffic Interceptor (GTI): GTI captures all Ethernet packets from the network interface card running on ubiquitous mode. GTI installs filters to allow only GOOSE messages to go through the GOOSE traffic controller before encapsulating in a UDP tunnel.
2) GOOSE Traffic Controller (GTC): GTC implements control and configuration algorithms to control the flow of GOOSE traffic within the network simulator. GTC can be extended to perform monitoring and security screening functions.
3) Tunnel Edge (TE): TE implements the tunnel end point to transport the GOOSE traffic from TP-Eth to TS-Eth. We have implemented a simple UDP tunnel for our implementation in LTE. More secure tunnel such as IPSec tunnel can be implemented to provide end to end secure channel.

IV. Simulation Results

The IEEE 33-bus distribution test system is employed in this paper to test and verify the performance of LTE networks using

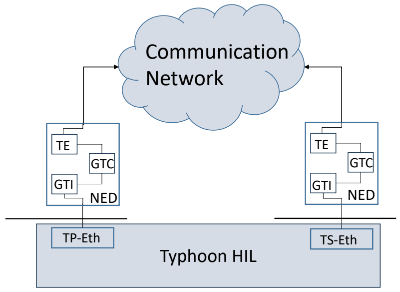

Fig. 2. The communication network architecture

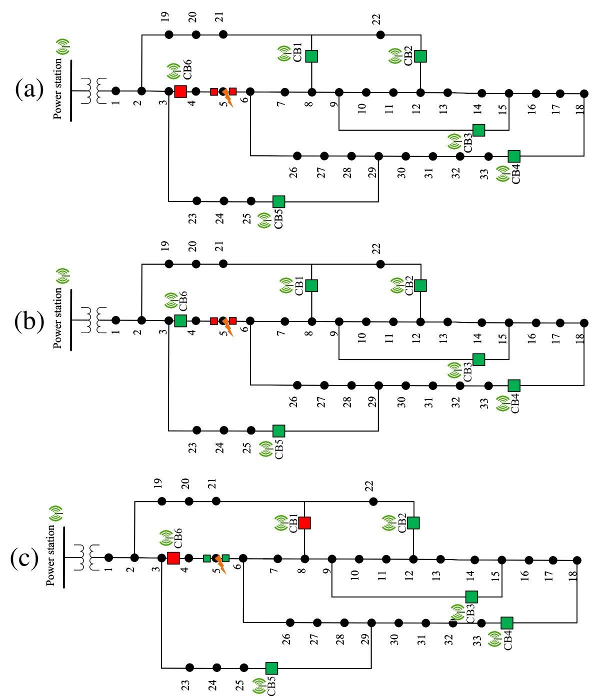

Fig. 3. IEEE 33-bus distribution test system: (a) A fault occurs at node 5, (b) Circuit breaker CB6 opens and clears the fault, (c) Operators in the control centre open the sectionalizing switches at both sides of node 5 and close the circuit breakers CB1 and CB6 to restore power to unfaulty parts of the distribution system.

the proposed co-simulation platform. Moreover, we focus on the fault location, isolation, and service restoration (FLISR) application in distribution systems. It is assumed that a fault occurs at node 5 as illustrated in Fig. 3. The overcurrent protection detects the fault and opens the circuit breaker CB6. Afterwards, the operators at the control centre open the sectionalizing switches at both sides of node 5 to isolate the fault. After isolating the fault, GOOSE commands are sent from the control centre to the circuit breakers CB1 and CB6 to restore the loads at unfaulty parts of the distribution network. The FLISR process is assumed to take around 5 minutes. The current between nodes 6 and 7 is provided in Fig. 4. We investigate the performance of the LTE network for sending the GOOSE command from the control centre to close the circuit breaker CB1.

The 4G LTE cellular wireless network is simulated in OMNeT++ using Simu5G package with LTE option to interconnect the Tyhpoon HIL publisher and subscriber. The

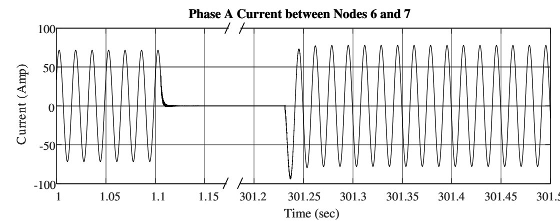

Fig. 4. Phase A current between node 6 and 7 in the IEEE 33-bus distribution test system for the FLISR case under study.

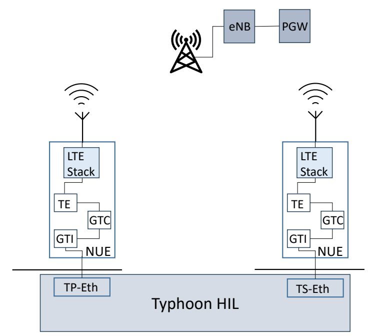

Fig. 5. Co-simulation of LTE network.

LTE UE node is modified to incorporate the co-simulator NED which is called NUE in this paper. It includes all the components of the NED integrated with the LTE stack to communicate the GOOSE traffic through the LTE network, as shown in Fig. 5. We implemented the following three sets of scenarios as illustrated in Fig. 6:

1) D2D scenarios: In these scenarios, publisher and subscriber NUEs are placed 300m from a single eNodeB. The distance between the NUEs vary from 60m to 300m to observe the D2D delays and infrastructure delays after mode switching. The D2D communication link is established when the two NUEs are in close proximity showing higher channel quality indicator (CQI) value. The CQI value drops at higher distance causing mode switching to infrastructure mode when the two NUEs communicate through eNodeB. In order to create a more realistic interference case for infrastructure communication, two small eNodeBs are placed to simulate the adjacent cell interference.

2) Background traffic scenarios: Pairs of user UEs are introduced carrying background voice over IP (VOIP) traffic. The impact of background traffic on the GOOSE traffic delay is monitored in both D2D and infrastructure cases.

3) Multi-cell scenarios: The publisher and subscriber NUEs are placed in different cells. They are placed at a distance of 300m from the eNodeBs in their respective cells. The distance between two eNodeBs (cells) are kept at 1Km.

In a single cell network, a single eNodeB connected with a Packet Gateway (PGW) provides D2D connections among all pairs of UEs. In a multi-cell network, sender and receiver UEs are connected to two different eNodeBs while both eNodeBs are connected through a single PGW. The simulation parameters are shown in Table I. In all the scenarios a single GOOSE flow is carried between a pair of NUEs. In scenario 2, the impact of background traffic on the GOOSE flow delay is studied by varying the background traffic through systematically increasing VOIP sessions by introducing new

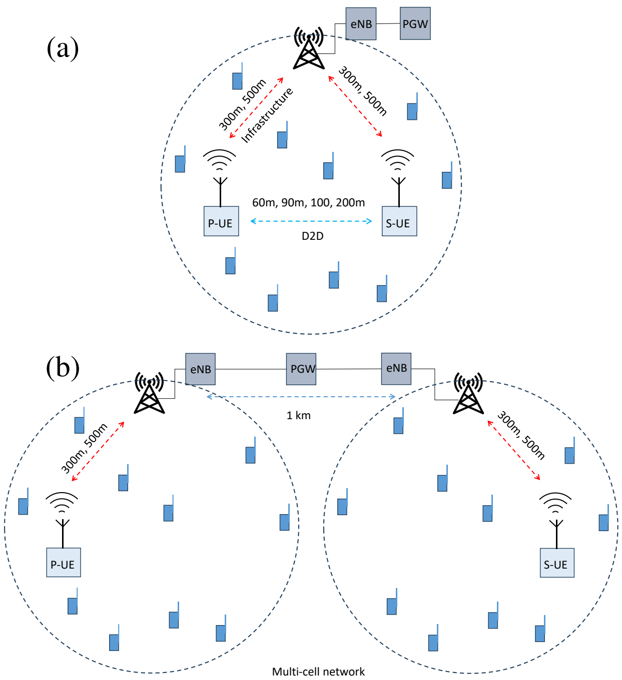

Fig. 6. LTE network configurations: a) Scenarios 1 and 2, b) Scenarios 3.

TABLE I
SIMULATION PARAMETERS

Parameter	Scenario 1	Scenario 2	Scenario 3
No. of UE pairs	1	1+{1..47}	1
UE TX Power	26dB	26dB	26dB
eNodeB TX Power	46dB	46dB	40dB
No. of Bands	50	50	6
Carrier Frequency	2GHz	2GHz	2GHz
Message Length	100B	100B	100B
Send Interval	1ms	1ms	1ms

pairs of user UEs up to a point where a marked increase in GOOSE traffic delay is observed.

Delay of GOOSE packets is the primary performance measure for our application. In a single cell, LTE provides D2D link between two devices for lower delay over single hop communication. In D2D scenarios with a single eNodeB and two NUEs acting as publisher and subscriber, the minimum average delay of 14.43 ms is observed when the two NUEs are at a distance of 60m, as shown in Fig. 7. As the distance between the two NUEs increases, the delay also increases up to the distance of 250m, at which point the communication is switched to the infrastructure mode. The uplink CQI value 13 is better than the D2D CQI value 6 which shows that the D2D is experiencing a worse channel condition as compared to the uplink. As such, mode switching establishes communication through the eNodeB (infrastructure) instead of D2D. The graph in Fig. 7 shows that D2D communication should be established for the GOOSE publisher-subscriber distances up to 150m. When the distance is greater than 150m, the infrastructure mode can provide similar delay performance to D2D communication. The maximum delay for distances up to 300m is found to be less than 40ms.

We established publisher-subscriber communication through eNodeB (infrastructure mode). The delay is measured by varying the distance between publisher and subscriber NUEs

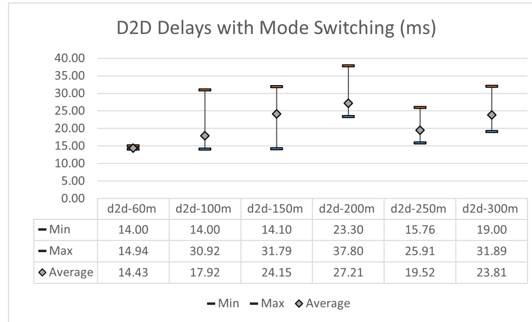

Fig. 7. Average GOOSE flow delay for D2D communication with mode switching in a single-cell network.

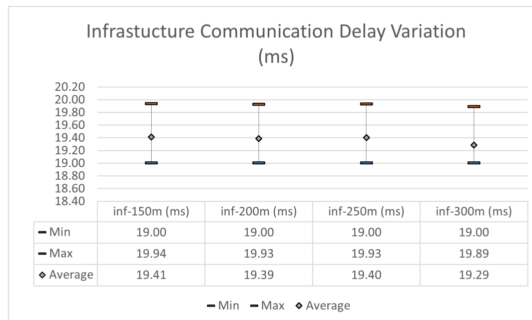

Fig. 8. Average GOOSE flow delay for infrastructure communication in a single-cell network.

from 150m to 300m. The average delay is found to be below 20ms with insignificant variation, as shown in Fig. 8.

We studied the impact of background traffic on GOOSE traffic delay for both D2D and infrastructure links. We systematically increased the VOIP background traffic by adding pairs of user UEs running VOIP application. No significant increase in GOOSE traffic delay is observed for small number of VOIP users. As illustrated in Fig. 9, the background traffic introduces jitter to the GOOSE flows. The delay variation between max and min values illustrated in Fig. 10 confirms this observation. The delay variation is insignificant when GOOSE flow is the only traffic in the network. The background traffic introduces delay variation up to 8ms. It is observed that 40-45 concurrent voice sessions can share the cell bandwidth without significantly increasing the delay of the GOOSE traffic. The number of users in the range of 10 to 20 results in low jitter for the GOOSE traffic.

In the simulation of a multi-cell network, two LTE eNodeBs are connected through a single PGW. The publisher NUE located in one cell sends GOOSE traffic to a subscriber located in another cell. It shows an average delay of 19.41 ms, as depicted in Fig. 11. This delay is comparable with the 19.29ms delay when the two NUEs are located 300m apart within a single cell communicating through the eNodeB. The impact of background traffic in a multi-cell network is consistent with what is observed in a single-cell network. The background traffic introduces jitter to the GOOSE flow. When the background traffic is created by 40 pairs of UEs as compared to 20 pairs of UEs, the jitter is more pronounced as shown in Fig. 11. This shows that VOIP traffic for small number of UEs can co-exist with the GOOSE traffic without

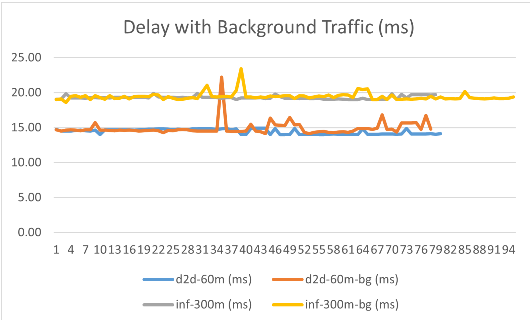

Fig. 9. The impact of background traffic on GOOSE flow delay in a single-cell network with D2D and infrastructure communication

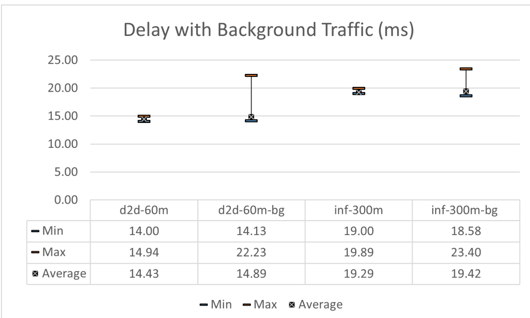

Fig. 10. The impact of background traffic on GOOSE flow delay variation in a single-cell network with D2D and infrastructure communication.

introducing significant delay.

V. Conclusion

A co-simulation platform is presented in this paper to examine the performance of LTE networks for FLISR applications in smart distribution systems. Typhoon HIL real-time simulator and OMNeT++ simulator are integrated together to create a co-simulation platform. The performance of LTE networks are tested for three scenarios including 1) D2D communication within a single-cell for distances between 60m to 100m, 2) infrastructure communication through eNodeB within the range of a single cell (e.g. 150m to 300m), and 3) multi-cell LTE network for distances between 1 to 2 km. It is observed that average delays less than 20 ms can be achieved for GOOSE messages using LTE networks which is appropriate for distribution automation applications. The impact of background traffic on the GOOSE traffic delay is further investigated. It is observed that 20 concurrent VOIP sessions cause no major impact on the GOOSE traffic delay. The proposed co-simulation platform will be used in our future research to examine protection of GOOSE traffic from the background traffic and cybersecurity posture of LTE networks in distribution system applications.

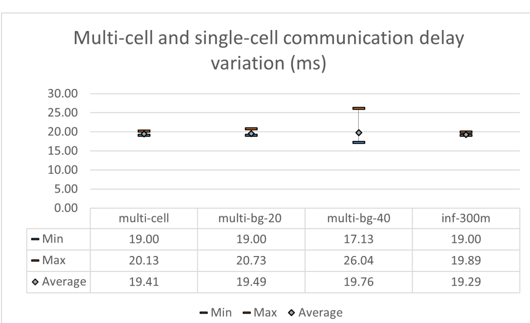

Fig. 11. The GOOSE flow delay in single-cell and multi-cell networks with and without background traffic.

References

[1] W. An, J. J. Ma, H. Y. Zhou, H. S. Chen, X. Jun and X. Jian, “Application of an Integrated Protection and Control System for Smart Distribution Grid Based on PTN and 4G LTE Communication,” *2019 3rd International Conference on Smart Grid and Smart Cities (ICSGSC)*, Berkeley, CA, USA, 2019, pp. 70–75.

[2] A. Derviskadic, P. Romano, M. Pignati and M. Paolone, “Architecture and Experimental Validation of a Low-Latency Phasor Data Concentrator,” in *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 2885–2893, July 2018.

[3] R. S. Simoes and E. L. Pellini, “Evaluation of the GOOSE Protocol in an Energy Distribution Network Through Wireless Private 4G,” *2023 9th International Conference on Control, Decision and Information Technologies (CoDIT)*, Rome, Italy, 2023, pp. 41–46.

[4] J. Sanchez, T. Braconnier, R. Caire, N. Sibileau and L. Chotard, “Test bed: 4G LTE pertinence for power distribution networks,” *2015 IEEE Eindhoven PowerTech*, Eindhoven, Netherlands, 2015, pp. 1–5.

[5] D. M. Saraiva, D. Corujo and R. L. Aguiar, “IEC 61850 Data Transfer Evaluation over Public Networks,” *2019 22nd International Symposium on Wireless Personal Multimedia Communications (WPMC)*, Lisbon, Portugal, 2019, pp. 1–6.

[6] L. Lutze, C. Sorgatz, C. Freudenmann and M. Rademacher, “A Modular Framework for Evaluating Smart Grid Communication Protocols over Mobile Networks,” *2023 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, Glasgow, United Kingdom, 2023, pp. 1–6.

[7] M. Rahmani, A. Mozafari and K. Pedramnia, “Cyber security considerations of 4G mobile networks as a communication service in smart grid,” *2021 11th Smart Grid Conference (SGC)*, Tabriz, Iran, Islamic Republic of, 2021, pp. 1–5.

[8] A. Allam, M. Saied, and I. Aly, “Adapting LTE M-2-M Protocol Standard to Fulfil Latency Requirements for IEC 61850 GOOSE Messages,” *International Journal of Communications, Network and System Sciences*, vol. 8, No. 5, pp. 154–160, May 2015.

[9] G. Bag *et al.*, “Performance Evaluation of IEC 61850–90–5 over a latency optimized 3GPP LTE Network,” *2018 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, Aalborg, Denmark, 2018, pp. 1–7.

[10] K. Hopkinson, Xiaoru Wang, R. Giovanini, J. Thorp, K. Birman and D. Coury, “EPOCHS: a platform for agent-based electric power and communication simulation built from commercial off-the-shelf components,” *IEEE Transactions on Power Systems*, vol. 21, no. 2, pp. 548–558, May 2006.

[11] H. Lin, S. S. Veda, S. S. Shukla, L. Mili and J. Thorp, “GECO: Global Event-Driven Co-Simulation Framework for Interconnected Power System and Communication Network,” *IEEE Transactions on Smart Grid*, vol. 3, no. 3, pp. 1444–1456, Sept. 2012.

[12] H. Georg, S. C. Müller, N. Dorsch, C. Rehtanz and C. Wietfeld, “INSPIRE: Integrated co-simulation of power and ICT systems for real-time evaluation,” *2013 IEEE International Conference on Smart Grid Communications (SmartGridComm)*, Vancouver, BC, Canada, 2013, pp. 576–581.

[13] C. Queiroz, A. Mahmood and Z. Tari, “SCADASim–A Framework for Building SCADA Simulations,” *IEEE Transactions on Smart Grid*, vol. 2, no. 4, pp. 589–597, Dec. 2011.

[14] B. Palmintier, D. Krishnamurthy, P. Top, S. Smith, J. Daily and J. Fuller, “Design of the HELICS high-performance transmission-distribution-communication-market co-simulation framework,” *2017 Workshop on Modeling and Simulation of Cyber–Physical Energy Systems (MSCPES)*, Pittsburgh, PA, USA, 2017, pp. 1–6.

[15] A. A. Jahromi, A. Kemmeugne, D. Kundur and A. Haddadi, “Cyber-Physical Attacks Targeting Communication-Assisted Protection Schemes,” *IEEE Transactions on Power Systems*, vol. 35, no. 1, pp. 440–450, Jan. 2020.

[16] A. Kemmeugne, A. A. Jahromi and D. Kundur, “Resilience Enhancement of Pilot Protection in Power Systems,” *IEEE Transactions on Power Delivery*, vol. 37, no. 6, pp. 5255–5266, Dec. 2022.