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Fault simulation in Phasor Measurement Units: A study on system reaction time in a 5G network environment

A R T I C L E I N F O

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A B S T R A C T

In the era of electrical substation digitalization, the reliability of Phasor Measurement Units (PMUs) is crucial. This paper addresses the impact of fault conditions in PMUs on system reaction time, particularly when PMUs are transmitting data over a 5G network. Two types of faults are considered. Step faults affect PMUs for 100–150 ms. Synchronization loss can take up to 10 minutes to return to normal in the case of GPS. The first one considers the PMU losing its sync, although the communication subsystem remains stable. The second instead considers a fault also on the communication. In both cases, the Phasor Data Concentrator (PDC) should be able to detect these anomalies. Nevertheless, the overhead given by 5G latencies should not mask anomalies in the packets sent by healthy and affected PMUs. This study provides valuable insights into improving the robustness and reliability of real-time PMU systems in a 5G network environment.

1. INTRODUCTION

The growing use of distributed generation and renewable energy sources is causing a quick and significant paradigm shift in modern power networks [1,2]. Specifically, electrical substations are transitioning to a completely digital architecture, which includes the infrastructure for measurement and communication [3,4]. Within this framework, the IEC 61850 standard [5] presents the performance criteria and communication protocols for the various equipment and functions found in a digital substation [6–8]. It provides a number of communication types, such as protocols for Generic Object Oriented Substation Events (GOOSE) and Sampled Value (SV). To facilitate a more seamless transition and increased interoperability, it can also utilize existing data formats, such as those used by measuring instruments today. Phasor Measurement Units (PMUs), which generate time-stamped measurement data packets that are usually transferred via Ethernet in accordance with TCP or UDP protocol, serve as a pertinent example in this regard [9]. Different and conflicting requirements in this circumstance must be appropriately matched. A capillary and quick monitoring system that can handle several devices and report at tens of frames per second is required due to the unstable nature of renewable energy sources [10,11]. However, it is not always feasible or financially sustainable to realize a completely connected system [12,13]. In order to solve this, recent research has examined the viability and potential benefits of applying 5G mobile communication technologies in power systems, particularly in distribution grids with short substation-to-substation distances where a single or small number of antennas can adequately cover the whole region of interest [14,15].

In this context, it is important to understand the traffic profile in normal and faulty operating conditions. For this analysis, we consider the measurement packets are produced by Phasor Measurement Units (PMUs), since this class of instruments is widely employed for many monitoring and control routines [1,2,16,17]. In such applications, though, latency plays a crucial role and it is important to characterize each contribution that may affect the overall control system responsiveness [18,19].

To this end, the contribution of the communication infrastructure cannot be neglected, especially when affected by technical faults and resources' limitations [20–22]. In this paper, we address this problem by means of a numerical analysis. We consider a real-world distribution network with 18 buses, already used as a test-bench for similar analysis. We characterize the statistical distributions of packet losses and transmission latencies in the presence of several PMUs synchronized to the same time reference.

In order to evaluate the robustness of such configuration, two kinds of faults are simulated. On one side, the loss of the synchronization source (e.g., the loss of GPS signal) at PMU level. On the other side, an error in the transmission protocol that produces additive random delays in the PMU measurement stream. The analysis of the results provides useful indications for the definition of suitable criteria for the prompt detection of similar events in the control room.

The paper is structured as follows. Section 2 presents the simulation setup. Section 3 describes the results in terms of packet losses and transmission latencies. Section 4 provides some closing remarks and outlines the future steps of the research activity.

2. Simulation setup

In this section we describe the simulation model and parameters to reproduce the 5G communication infrastructure to serve the power grid.

2.1. Power grid and 5G network

In our analysis, we focus on a 10-kV three-phase distribution network

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situated in the Netherlands and operated by DSO Alliander.

The topology of the network is shown in Fig. 1. As can be seen, the system comprises 18 nodes, each equipped with a PMU. In our simulation, we assumed that the Phasor Data Concentrator is situated at Node 1, and all PMUs operate at a uniform reporting rate of 50 frames per second (fps). However, in the simulation we incorporated potential drift in the internal clocks of the PMUs, causing each PMU to generate a frame approximately every 20 milliseconds with a variance of ±100 nanoseconds. This assumption allows for a more precise and realistic estimation of the actual latencies and packet loss involved. While clock drift may introduce challenges in the measurement process, potentially compromising accuracy, it may potentially offer advantages in the communication process. Indeed, slightly shifted and unsynchronized transmissions could reduce the likelihood of collisions when accessing the transmission medium and reducing the instantaneous peak bandwidth utilization of the network. This, in turn, could yield improvements in terms of latency and packet loss, ultimately enhancing the overall efficiency of the system.

The selected distribution network also allows interesting considerations regarding the placement of gNBs to serve the PMUs. With relatively short line lengths, none exceeding 2 km and averaging 0.5 km, it’s noteworthy that these distances align well with the optimal inter-gNB and UD-gNB distances in typical 5G scenarios, ranging from 0.1 km to 10 km. Consequently, it’s evident that the inter-PMU distances in this scenario are fully compatible with the general requirements of 5G networks. In principle, it could be feasible to cover all nodes with a single 5G network, utilizing one gNB and a unified 5G RAN and backhaul network. While running the entire infrastructure within a single RAN is entirely viable, leveraging a single gNB to connect all PMUs (i.e., all the UDs) may pose some challenges. Despite the backhaul network’s capacity to support several Gbps of bandwidth, aggregating multiple PMUs to a single gNB could strain the communication infrastructure, particularly in scenarios where a significant number of PMUs transmit simultaneously. Furthermore, deploying a single gNB would result in a greater average UD-gNB distance, potentially reducing the signal-to-noise ratio (SNR) and degrading communication quality, consequently leading to an increase in packet loss. It becomes evident that in scenarios where PMUs and the communication network are utilized within safety-critical contexts, such as the application under consideration where a prompt and timely reaction to faults is imperative, optimizing the network to minimize packet loss and latency becomes of paramount importance. In this sense, this study investigates how different configurations of the communication infrastructure affect the loss of packets and average latency among the different nodes. In Ref. [23], the same network was used to test the stream of ten PMU measurement packets through a set of dedicated 4G routers (R-1300, Garderos Gmbh, Munich, Germany) in turn connected to the Vodafone network without any specific service level implemented (so that the PMU traffic is not prioritized). In that case, the latency showed a bimodal distribution centered around 70 ms. The number of packet losses, instead, is strongly related to the policy implemented within the PDC [24].

The performance of the 5G communication infrastructure has been investigated through an appropriate simulation environment developed using the well-known OMNeT++ simulator, alongside its extension, the Simu5G framework [25,26]. The model for both the protocol stack and transmission channel is based on specifications outlined in 3GPP Release 16 [27].

2.2. Simulation parameters and communication infrastructure model

The distribution network employed as a testbed is depicted in Fig. 1. A Phasor Measurement Unit (PMU) is installed at each black dot to take measurements from the grid at that node. The Simu5G framework was used to simulate the testbed in OMNeT++. User Devices (UDs) collect measurements in this configuration and transmit them via a 5G base station (gNB) network.

For communication to be effective, 5G base stations (gNBs) must be placed in a way that allows them to service as many UDs as feasible while yet providing high-quality communication. The placements of the gNBs were ascertained by the use of an optimization technique, namely the k-means algorithm. The gNBs are located in areas with a greater density of UDs according to this algorithm. The gNBs are located in areas with a greater density of UDs according to this algorithm. Fig. 2 shows an example of clustering for four gNBs. By lowering the mean distance between UDs and the closest gNBs, this strategy allows gNBs to be positioned in close proximity to locations where there is a large concentration of UDs. This promotes communication efficiency and minimizes packet loss. Economic considerations must be taken into account, too, since it would not be feasible or financially feasible to deploy a significant number of gNBs.

We employed UDP as the transport protocol in our simulations. Since UDP is a connection-less protocol, a lost or malformed packet is not retransmitted. The first substation (UD[0]) receives data from the PMUs in a “Edge-to-Edge (E2E)" scenario that we implemented. Included in

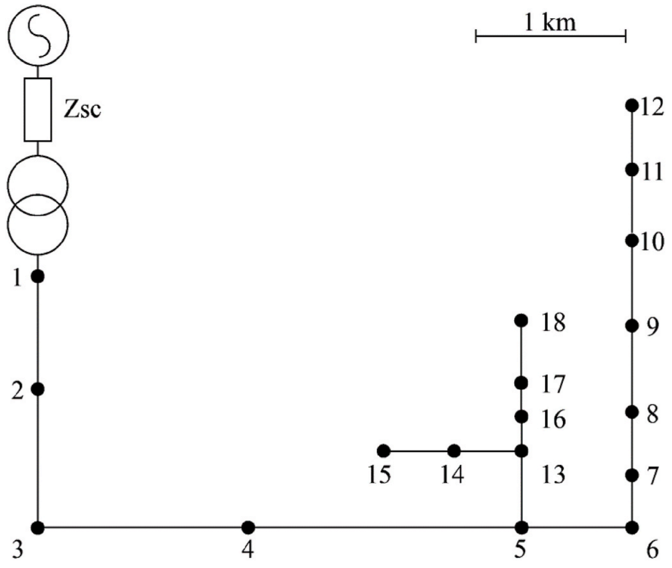

Fig. 1. 18-bus distribution feeder located in the Netherlands and operated by Alliander.

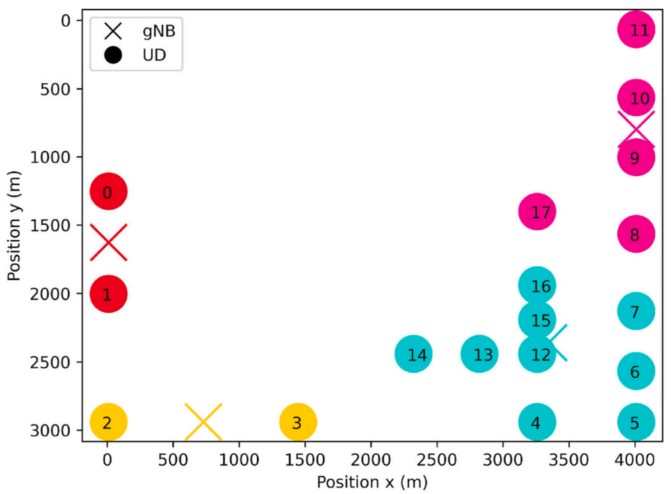

Fig. 2. Position of the devices and gNBs in the simulated network with 4 gNBs. Circles represent the UDs i.e. the PMUs. Stars represent the position gNBs according to the k-means algorithm. The hue represents the number of clusters. Each device is connected to the gNB with the same colour.

this design is the backhaul network, which is regarded as wired yet might, however somewhat, contribute to packet loss overall.

In order to mimic realistically a high density of gNB, we use the 3GPP TR 38.901 channel model for urban microcells, which takes into consideration several variables like as interference, fading, and shadowing. The carrier frequency is set to 2 GHz. We use Adaptive Modulation and Coding (AMC) to minimize latency, improve reliability, and increase spectral efficiency by dynamically adjusting the coding rate and modulation depending on the channel circumstances.

We assume that a private 5G network hosts the Phasor Measurement Units (PMUs) system. The 3GPP Rel. 16 standard, which covers the establishment of Mobile Private Networks (MPNs) with the aim of creating extremely dependable dedicated networks, lends credence to this concept. There are two main methods that private networks can be implemented in this situation. The first one is more dependable but more expensive; it uses a fully private 5G network in which the operator maintains ownership of all systems, hardware, and private clouds. Conversely, a more traditional method uses network slicing capabilities to reserve bandwidth just inside the public 5G network.

We therefore assume the absence of conflicting traffic in our simulation. We note that adding a more practical examination of particular traffic patterns and concentrations of interfering nodes is postponed until later projects.

As mentioned earlier, to address potential challenges arising from drifts in the internal clock of the PMUs, we configured the simulation to introduce a uniform jitter of ±100ns in the transmission rate of packets at each node. Additionally, to consider potential delays in joining the 5G network or variations in startup times among the PMUs, we incorporated a random startup delay ranging from 0 to 20 ms. Consequently, the transmission of the first frame from each PMU is delayed by this amount of time.

In addition to the above considerations, the 5G network is simulated using specific parameters listed in Table 1.

3. Results and discussion

In this section, we analyze the results concerning packet loss and transmission latency. Specifically, we conducted measurements of latency and packet loss for each position of the gNBs obtained using the k-means algorithm. Regarding latency, we focused on End-to-End latency, which encompasses the time elapsed from the transmission of a packet from a PMU to its reception at the PDC, represented by UD[0] in this scenario. It's important to highlight that this represents the worst-case scenario, as the latency involves one or more 5G connections depending on whether the PMU and the PDC are connected to different gNBs. Additionally, it encompasses multiple RAN latencies resulting from transmission across the 5G network, as well as delays introduced by the backhaul network connecting the gNBs to the server.

Concerning packet loss, we computed the packet delivery ratio as the ratio of correctly delivered packets to the total number of sent packets, multiplied by 100. This metric offers insight into the network ability to consistently deliver packets and meet the criteria for transmitting safety-critical data, such as information pertaining to faults on the distribution network.

Table 1

Parameters used for the simulations.

Parameter	Value
Packet size	44 (bytes) according to IEEE C37.118.2
Simulation time	900s
Packet generation frequency	50 pkt/s
Transmission typology	5G ULL
Channel model	3GPP TR 38.901 Channel Model for urban micro cell
Carrier frequency	2 GHz
UD Tx power	26 dBm
gNB Tx power	46 dBm
Inter-packet jitter	Uniform [-100,100]ns
Transmission start delay	Uniform [0,20]ms

Starting from the Packet Delivery Ratio (PDR) presented in Table 2, it's evident that increasing the number of gNBs yields clear benefits by enhancing the overall PDR. Notably, the only scenarios where the maximum PDR is not achieved are those with one or two gNBs serving the entire infrastructure. Despite resulting in the same outcome, the reasons for packet loss in these two cases differ fundamentally. Specifically, in the scenario with a single gNB, the majority of lost packets stem from the absence of connection between the UD and the gNB. We observed that in densely populated areas, particularly during the initial phases of communication, such as joining the network and establishing a connection with the nearest gNB, certain UDs may encounter difficulties due to the high node density attempting to join the network within a limited time frame. Some nodes may fail to join the network altogether, while others may experience delays in doing so. Consequently, this leads to significant packet loss, as the application level expects the successful delivery of all packets, and the lack of connectivity results in the classification of those packets as lost.

The scenario with two gNBs presents a different situation. In this simulation scenario, connectivity is established for all UDs. However, due to the high volume of data exchange, some frames are lost. In all other simulations, i.e., those with more than two gNBs, packet loss is negligible. These findings underscore the critical role of the number of gNBs serving the network, emphasizing the need for careful design to ensure adequate coverage for the nodes. Furthermore, it suggests that the number of UDs per gNB should be carefully considered, as it plays a key role in maintaining stable connectivity. This aspect is particularly important if there are plans to extend or increase the number of UDs for future expansions of the distribution network.

Regarding latency, the results are depicted in Fig. 3, while detailed statistics are provided in Table 2. Analysis of the mean values reveals a slight improvement in latency and its standard deviation with an increase in the number of gNBs. However, employing more than five gNBs does not lead to any significant improvement in latency. This finding suggests the existence of an optimal range for the number of gNBs that offers desired performance enhancements in latency and reliability. Beyond this range, additional gNBs may not yield substantial benefits and could incur unnecessary infrastructure costs. Therefore, careful consideration should be given to determining the appropriate number of gNBs for the PMU-based distributed measurement system to achieve the desired performance targets while balancing the economic aspects associated with deploying and maintaining the 5G infrastructure.

The behavior of the maximum latency values exhibits some interesting patterns. As shown in Fig. 3 and detailed in Table 2, the maximum value tends to increase with one, two, and three gNBs, contrasting with the trend of the mean value. While seemingly counterintuitive, this

Table 2

Statistics of the communication delay and packet loss varying the number of gNBs while maintaining fixed the number of UDs.

# gBNs	mean (ms)	std (ms)	min (ms)	max (ms)	PDR %
1	17,69	2,79	13,07	20,23	53,07
2	17,35	2,75	13,21	20,69	94,12
3	16,43	3,00	13,00	22,19	100,00
4	15,50	2,43	13,14	19,85	100,00
5	14,49	1,73	13,03	19,40	100,00
6	14,12	0,99	13,04	18,20	100,00
7	13,59	0,49	13,03	14,85	100,00
8	14,33	0,95	13,05	16,87	100,00
9	14,26	1,17	13,08	17,87	100,00
10	13,78	0,60	13,05	14,95	100,00
11	14,05	0,97	13,04	16,57	100,00
12	13,84	0,61	13,03	14,96	100,00
13	14,32	1,16	13,03	17,28	100,00
14	13,87	0,60	13,03	14,94	100,00
15	13,56	0,48	13,04	14,87	100,00

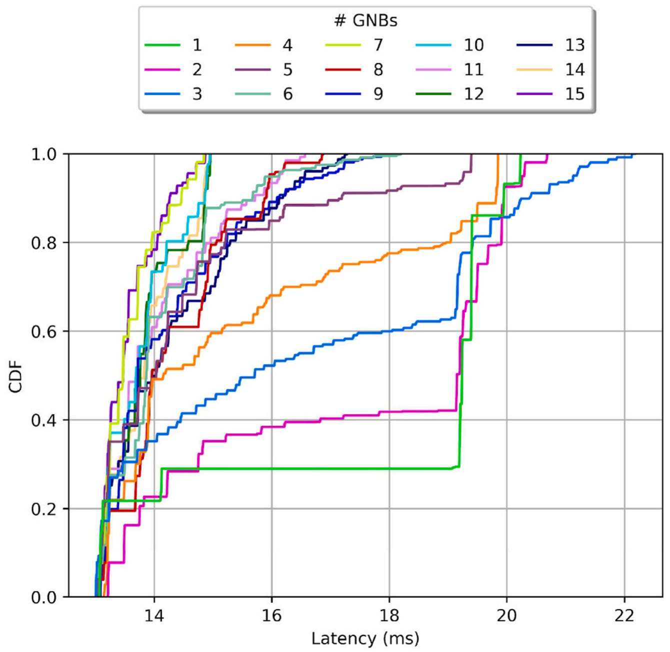

Fig. 3. Cumulative Distribution Function of the communication delay, changing the number of gNBs.

effect is correlated with the packet loss discussed earlier. With an increase in connected gNBs (i.e., with more traffic), there is an escalation in maximum latency, as there may be instances where the instantaneous required bandwidth is high, leading to packet delays. The maximum latency values show a positive trend similar to the Packet Delivery Ratio (PDR). However, starting from the scenario with four gNBs, the trend reverses, and the maximum latency begins to decrease. In this scenario, the network bandwidth capacity can sustain higher bursts of packets as traffic is distributed across multiple gNBs, resulting in a reduction in maximum latency. This outcome supports the earlier observations regarding the optimal number of gNBs, emphasizing the importance of designing the network to also accommodate high bursts of traffic.

We conducted further investigations into the relationship between latency, the number of gNBs, and the distance between UDs and gNBs. The results of this analysis are presented in Figs. 4 and 5, which respectively illustrate the relationship between latency and the distance from the nearest gNB, and the relationship between latency and the total number of deployed gNBs.

Fig. 4 suggests that there is no direct correlation between latency and the distance from the gNB. This indicates that the degradation or improvement of latency is not attributable to transmission medium conditions, such as Signal-to-Noise Ratio (SNR). Regardless of the UD under consideration and its distance from the gNB, the trends do not exhibit a clearly defined pattern.

On the other hand, Fig. 5 reveals a quasi-linear relationship between mean latency and the number of employed gNBs. This implies that the primary contributor to latency is likely traffic congestion resulting from a high number of connected UDs, rather than channel conditions. This observation reinforces the notion that latency is predominantly influenced by congestion within the communication infrastructure. By introducing more gNBs, traffic is distributed across multiple distinct paths, reducing the likelihood of congestion.

Consideration of the suitability of 5G communication and its fault resilience in PMU-based measurement systems reveals significant advantages. As shown, utilizing the 5G Ultra Low Latency (ULL) profile ensures deterministic and loss-free communication across various operational conditions. Particularly, in the event of a fault reported to the Phasor Data Concentrator (PDC) from the PMU, leveraging a 5G connection enables a notably quicker response compared to a 4G connection, which typically incurs latencies of hundreds of milliseconds.

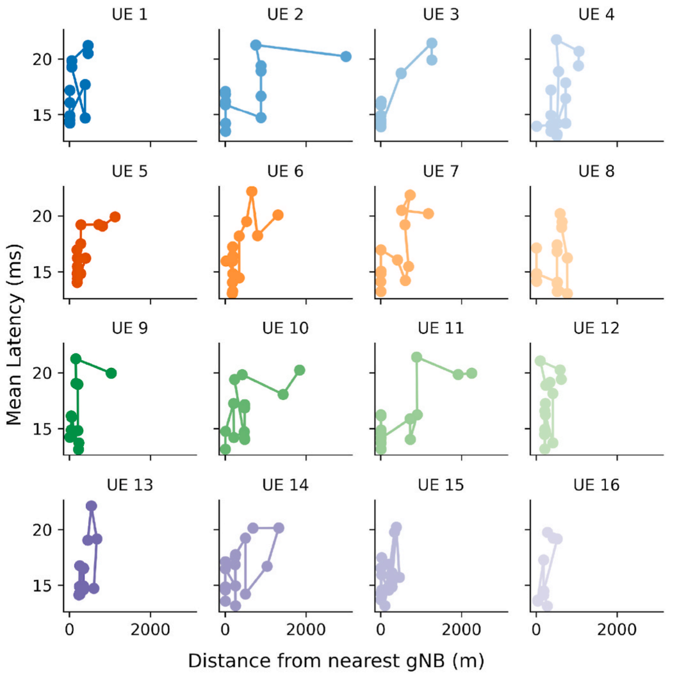

Fig. 4. Mean latency over the distance from the nearest gNB for each UD.

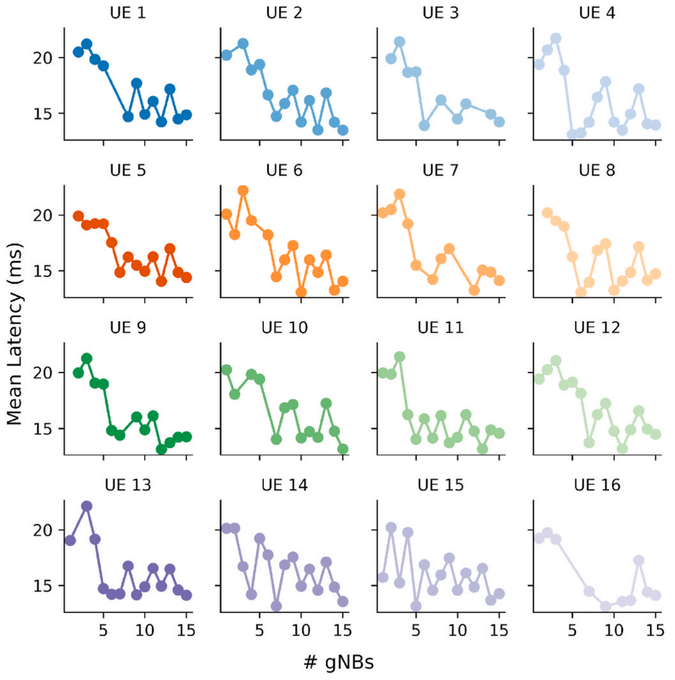

Fig. 5. Mean latency over the total number of gNBs for each UD.

The minimal jitter in latency also facilitates robust and timely fault detection in the PMU, including loss of synchronization. Variations in packet arrival rates at the PDC beyond the characteristic jitter of communication can indicate potential synchronization loss in the PMU. Assuming a stable communication infrastructure, detecting consistent delays or significant deviations from the expected reporting rate becomes feasible, thereby isolating network-induced contributions and identifying potential synchronization issues in the PMU.

Furthermore, considerations regarding latency enable prompt detection of packet loss. As shown, the low latency variability permits the establishment of stringent packet reception deadlines. Upon expiration of these deadlines, packets can be reliably marked as lost. In the analyzed scenario, featuring a reporting rate of 50 fps, all described fault conditions can be detected within the reporting period, given that latency remains below the reporting period in the majority of cases. This capability ensures prompt reaction times and enhances overall system reliability.

4. CONCLUSIONS

In this paper, we conducted an evaluation of a 5G infrastructure's performance for transmitting IEC61850 data, particularly focusing on fault-critical conditions in communication systems. In systems reliant on Phasor Measurement Units (PMUs), ensuring low transmission latencies and minimal packet loss is paramount to maintain timeliness in reporting measurements to the Phasor Data Concentrator (PDC) and guarantee system stability. The simulation results shown that a 5G infrastructure can effectively serve a PMU-based measurement system. We found that performance in terms of latency and packet loss is strongly influenced by the topology of the 5G network, particularly the number and deployment of gNBs (5G base stations) serving PMUs. Deploying gNBs to serve a limited number of PMUs consistently resulted in low latency and zero packet loss. Leveraging the Ultra-Low Latency profile of 5G, stringent deadlines can be set for the PDC to promptly detect synchronization issues, packet loss, and excessive delays. Future work will focus on enhancing the simulation setup by incorporating a more detailed modeling of faults and impairments affecting PMUs and PDCs within the communication network. This will involve simulating various fault scenarios and communication network impairments to better understand their impact on the overall system performance and to mitigation strategies to improve the reliability and resilience of the PMU/PDC system in real-world deployment scenarios.

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