The Impact of Wireless Communication Networks on Wide Area Monitoring and Protection Applications

Markos Asprou, Antonis Akrytov, Lenos Hadjidemetriou, Charalambos Charalambous, Irina Ciornei, Georgios Ellinas, and Christos Panayiotou
KIOS Research and Innovation Center of Excellence and Department of Electrical and Computer Engineering
University of Cyprus
Nicosia, Cyprus
{asprou.markos, akrytov.antonis, hadjidemetriou.lenos, charalampous.g.charalampos.1, ciornei.irina, gellinas, christosp}@ucy.ac.cy

Abstract—**The fast deployment of the Phasor Measurement Units (PMUs), especially in the transmission level of the power systems, enables the development of wide area monitoring, protection and control (WAMPC) applications that enhance the situational awareness of the power system operator as well as the stability of the power system. Such applications are dependent on the communication network that supports the transfer of the PMU measurements to a central monitoring application or to a local protection application (situated in a substation). It is therefore of paramount importance to ensure the transfer of measurements with the least delay, while at the same time to ensure the integrity of the PMU measurements. In this work, the impact of using a wireless communication network for transferring the PMU measurements to the WAMPC applications is examined and the advantage of the 5G communication network over 4G and 3G in such real-time monitoring and control applications is demonstrated.**

Keywords—PMUs, System stability, wide area monitoring and protection system, Wireless communication network

I. INTRODUCTION

Power system operators today experience unprecedented challenges in maintaining the power system within admissible limits. The decarbonization of the energy sector with the massive penetration of renewable energy sources results in a decrease of power system inertia [1]. Low-inertia power systems are prone to faults that compromise the stability, efficiency, and reliability of the system. On the other hand, the challenges brought by the penetration of renewable energy sources has forced the electric utilities to perform a number of structural changes in order to transform the bulk power system as well as the distribution grid according to the smart grid concept. These changes include the digitalization of the power system substations, the introduction of smart schemes for taking advantage of the distributed resources that can provide ancillary services to the grid, and the monitoring and control of the power grid in quasi real time [2].

Regarding the latter, the advent of synchronized measurement technology in the early 1990s has certainly brought an evolution to the monitoring and control of power systems. The key element of the synchronized measurement technology is the Phasor Measurement Unit (PMU), which is considered the most advanced measurement device that is currently installed in the power system substations. The PMU is a GPS synchronized equipment, which can provide with a great accuracy synchronized voltage and current phasor measurements, frequency, and rate of change of frequency. In addition, the latest models of the PMUs can provide a phasor measurement every 5 ms that corresponds to a reporting rate of 200 phasors per second (in a 50 Hz power system) [3]. Considering that the conventional measurement devices (power meters) provide measurements to the Supervisory Control and Data Acquisition (SCADA) system every 2-5 seconds in an asynchronous way, the key features of the PMUs enable the implementation of wide area monitoring, protection and control (WAMPC) solutions that offer capabilities to the power system operators to monitor and control power systems in near real time [4].

More specifically, the real-time PMU measurements that are received to the control center are processed by a PMU-based state estimator that can provide in milliseconds range the wide area picture of the entire power system (considering a power system fully observable by PMUs). The PMU-based state estimator can increase the situational awareness of the operators by tracking the power system transients in case of faults or disturbance in the system. In addition, PMUs can be used in tie-lines between two areas in order to monitor in real time the power exchange between the areas, as well as the loading of the transmission line. Such information is critical for the operators of the two areas to realize in quasi real time the actual available power margin in the tie-line in case of a power loss in one of the two areas [6]. Regarding the wide area control applications, the PMU measurements provided by the generation substation can be used in a wide area controller for damping inter-area frequency and voltage oscillations in the power system. It should be noted that the damping of inter-area oscillations is not possible by the local controllers of the generators [7]. PMU measurement can also be used in wide area protection systems, such as in differential protection schemes of transmission lines. Such schemes protect the transmission lines in case of a fault that occurs within the transmission line and requires the presence of two PMUs at the ends of the transmission line [8].

A crucial aspect for the designated performance of the aforementioned WAMPC applications is the transfer of the PMU measurements to the application in near real time. Thus, the communication network in a WAMPC system plays a crucial role in its performance and reliability. Data loss due to communication network congestion compromises the integrity of the PMU measurements and essentially affects the accuracy of the WAMPC applications. In addition, large delays that may be imposed to the transfer of PMU measurements (depending on the communication network) affect the real-time responsiveness of the applications [4]. For

---

This work was partially supported by the European Union's Horizon 2020 research and innovation programme, Project Smart5Grid, under grant agreement No 101016912, and by the European Union's Horizon 2020 research and innovation programme under grant agreement N0 739551 (KIOS CoE – TEAMING) and from the Republic of Cyprus through the Deputy Ministry of Research, Innovation and Digital Policy.

instance, data loss or large measurement delays will affect the accurate tracking of transients by a PMU-based estimator in case of a fault, while they can also affect the timely detection of a loading increase in a tie-line. A large measurement delay can also compromise the operation of a wide area differential protection scheme that should trip immediately in case of a fault that may occur within the range of the transmission line. Therefore, the communication network should not be a preventive factor for the actual implementation of wide area monitoring, protection, and control applications.

The current practice of electric utilities regarding the communication network is to have in some of the substations a dedicated fiber-optic communication network, while some other substations are connected to the control center through the Internet, due to the lack of dedicated communication infrastructure [10]. According to [5], the delay that is imposed by a fiber-optic network is around 100-150 ms, while delays of around 700 ms can be imposed by a satellite link. Although, fiber-optic communication networks seem to be the ideal solution for a WAMPC system, the increased cost associated with the implementation of such a network (mainly the cost for laying the fiber) is sometimes a preventive factor for the electric utilities to have their own dedicated fiber-optic network. On the other hand, one should also consider that only recently PMU deployment in power system substations has started, thus several substations may not be connected through a fiber-optic communication network. Even in the case that there is a fiber optic in the substation control room, there might be not in the rack that the PMU is installed. Therefore, given also the recent advancements in wireless communication technology, a good solution for the actual implementation of a WAMPC system is the consideration of a wireless communication network for the transfer of PMU measurements.

Over the last decade, wireless technology has advanced significantly, with the 5G communication network having significant advantages over its predecessors that can play a crucial role in the transformation of the conventional power system into a smart grid. This is evident by the characteristic of a 5G network in terms of data reliability and latency. Specifically, the 5G network has a packet loss rate on the order of 10^{-5} and theoretical latency in the Radio Access Network (RAN) side of 1-3 ms [6], [13]. Such features can certainly support the safe transfer of PMU measurements in a WAMPC system without compromising the data integrity and the real-time responsiveness of the applications.

In this work, the impact of using wireless communication networks in a wide area monitoring application that observe the line loading of a tie line is examined, comparing the performance of the application in case of 3G, 4G, and 5G wireless networks used as the communication infrastructure. Further to that, the performance of a wide area differential protection system using PMU measurements that are transferred through 3G, 4G, and 5G communication networks is also investigated. The main contribution of this work is the use of wireless communication technology in WAMPC applications, examining the feasibility of such case in terms of the performance of the considered applications. To the best of the authors knowledge this is the first time that the impact of wireless networks on WAMPC applications is examined. The results in this work have been extracted by a realistic laboratory setup, incorporating actual PMUs as well as a communication network emulator in a hardware in the loop framework.

The rest of the paper is organized as follows: A general communication architecture that is used for transferring the PMU measurements in a central WAMPC system is discussed in Section II, while the wide area monitoring application as well as the wide area protection application that are used in this work are described in Section III. Section IV includes the results from the application of a wireless communication network to WAMPC system, while concluding remarks are included in Section V.

II. COMMUNICATION ARCHITECTURE FOR TRANSFERRING PMU MEASUREMENTS

The PMUs are considered the most advanced measurement devices in the power system measuring infrastructure, since they provide synchronized voltage and current phasors, frequency, and rate of change frequency measurements. A general multi-layered architecture that is used for transferring the PMU measurements to the control center is shown in Fig. 1. The first layer mainly consists of PMUs installed in power system substations. The PMU measurements from the first layer are concentrated and time-aligned by regional Phasor Data Concentrators (PDCs) that are situated in the second layer of the architecture. It should be noted that PDCs are valuable components in a WAMPC system, since they are responsible for collecting the PMU measurements. In addition, among other functionalities, the PDC time aligns the PMU measurements according to their timestamp and forwards a time aligned phasor measurement set to the higher layer.

A critical parameter that should be defined in the PDC is the waiting time, which denotes the time that the PDC waits for the phasor measurements to arrive to the PDC before forwarding or storing PMU measurements with the same timestamp. Any PMU measurements that arrive after the waiting time elapses are discarded by the PDC. It should be noted that the PDC starts the countdown for waiting for the PMU measurements with the same timestamp after the arrival of the first PMU measurement with the corresponding timestamp.

The waiting time is a means for compensating delays imposed during the transfer of the PMU measurements by the communication network [8]. By considering the communication network delays in the alignment procedure of the PDC, the integrity of the PMU measurement set is ensured. However, the waiting time is a tradeoff between data integrity and real-time responsiveness. A large waiting time will ensure the completeness of the phasor measurements set for a specific timestamp, but at the same time it will compromise the fast reporting rate of the PMU measurements (since the forwarding of the PMU measurements to the next layer will be considerably delayed).

In the multi-layered architecture of Fig. 1, when the regional PDCs successfully time align the measurements of a specific region, they forward the measurements to a central PDC situated in the control center of the power system. The central PDC collects all the measurements of the system from the regional PDCs, considering again a certain waiting time according to the communication network delay between the regional PDCs and the control center. It should be noted, that in some WAMPAC communication architectures only a central PDC exists, that is responsible for collecting and time aligning all the measurements from the individual PMUs. This approach, however, reduces the redundancy of the PMU measurements.

Based on the architecture of Fig. 1, the two main sources that introduce delays to the measurement transfer process are the communication infrastructure and the PDCs. The delay due to the communication infrastructure results from the transfer medium, the Wide Area Network (WAN) components (i.e., routers), and the communication protocols. Different medium in case of wired communication networks can result in different delays and different waiting times in the PDC. The same is true for the wireless communication network (e.g., 3G, 4G, and 5G) whose delays should be known in order to set the maximum delay in the PDC. In this work, in order to show the impact of the wireless communication networks in the WAMPC architecture, it is implicitly assumed that the transfer of measurements is supported only by wireless communication networks.

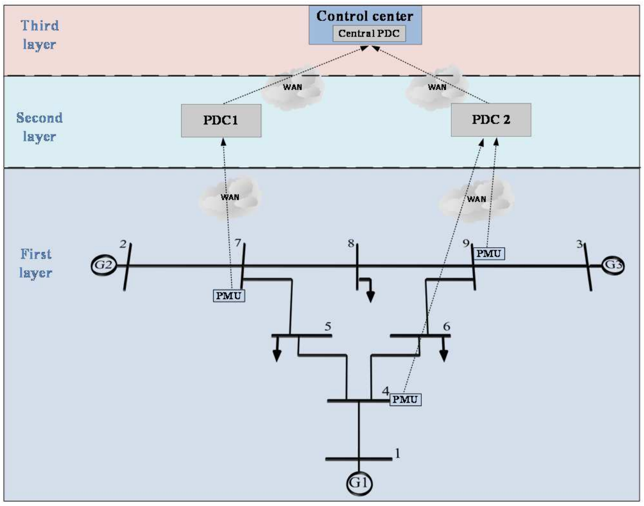


Fig. 1. Communication architecture of a WAMPC system.

III. WIDE AREA MONITORING AND PROTECTION APPLICATIONS

The PMU measurements that arrive to the control center are being processed by dedicated applications that run periodically in the control center for monitoring the operating condition of the entire power system. One of the most conventional applications of the PMU measurements is the state estimation, which provides in quasi real time the state of the power system [9]. Such an application can run every few milliseconds considering the availability of measurements from different substations and given that the power system is fully observable by PMU measurements.

Another important routine that runs in the control center in case of interconnected power systems is a monitoring application for providing the loading condition of tie lines. It should be noted, that tie lines are the lines that connect two individual systems together. Thus, this application runs in real time by receiving measurements from the two PMUs that are installed at the two ends of the tie line. The real-time knowledge of the loading of the tie line enhances the situational awareness of the transmission system operators and ensures the reliability of the power system. Regarding the latter, the knowledge of the available transmission line margin from the tie line facilitates a better planning of the generation resources in case of a contingency, while the real-time information enhances the accuracy of the system stability and contingency analysis that run routinely in the control center.

In the case of wide area control applications, the wide area controller for damping inter-area oscillations is one of the applications that are enabled through the PMU measurements [10], while PMU measurements can also be used in local differential protection schemes for a transmission line. Unlike the monitoring applications, the differential protection scheme can run locally at the substation level, receiving measurements from the two PMUs installed at the two ends of a transmission line. Such schemes are intended to suppress the spread of a fault that occurs at any point of the line by disconnecting the line from the system.

In this work, the monitoring application that deals with the loading condition of a tie transmission line, as well as the differential protection system based on PMU measurements will be considered, with the theory regarding the implementation of such applications described below.

A. *Monitoring of tie line loading conditions*

The tie lines between interconnected power systems can enhance the reliability of each individual power system. Especially in modern power systems, where the penetration of renewable energy sources is high, tie lines can be used efficiently for exporting any excess power from renewable energy sources to neighboring systems and importing power in case of abrupt power deviation for balancing the generation with the demand. Considering that the changes in the generation of renewable energy sources can happen in milliseconds, this necessitates the real-time information of the available power margin of the tie line.

In this framework, considering that the tie transmission line that is shown in Fig. 2 is monitored by two PMUs, the voltage and current phasor measurements from the two ends of the line are available to the control center after being concentrated and time aligned by the PDC. It should be noted that in this case a two-layer architecture is considered, which means that only a central PDC exists in the WAMPC architecture. Denoting the two ends of the line as *i* and *j*, the voltage and current phasor measurements from the two ends (buses) $\overline{V}_i, \overline{V}_j, \overline{I}_{ij}, \overline{I}_{ji}$ can be used for calculating the real and reactive power that flows from the two ends of the line as,

$$P_{ij} = \Re\left\{\overline{V}_i\left(\overline{I}_{ij}\right)^*\right\} \tag{1}$$

$$Q_{ij} = \Im\left\{\overline{V}_i\left(\overline{I}_{ij}\right)^*\right\} \tag{2}$$

where, P_{ij} and Q_{ij} is the real and reactive power that flow from bus *i* of the transmission line, respectively, $\Re$ and $\Im$ denote the real and imaginary part of the complex number, respectively, and $(*)$ denotes the conjugate of the phasor. Similarly, the real and reactive power that flow from bus *j* can be calculated as,

$$P_{ji} = \Re\left\{\overline{V}_j\left(\overline{I}_{ji}\right)^*\right\} \tag{3}$$

$$Q_{ji} = \Im\left\{\overline{V}_j\left(\overline{I}_{ji}\right)^*\right\} \tag{4}$$

where, P_{ji} and Q_{ji} is the real and reactive power that flow from bus *j*, respectively.

Regarding the concentration and time alignment of the measurements, the PDC waits one of the two PMU measurements to arrive to the PDC and then the countdown for the waiting time starts in order to wait the measurement from the second PMU. If the measurement from the second

PMU arrives before the waiting time elapses, the PDC forwards a complete phasor dataset to the monitoring application. On the other hand, if the waiting time elapses before the arrival of the measurement, the PDC discards the delayed measurement and forwards to the monitoring application only the measurement from the one (first) PMU.

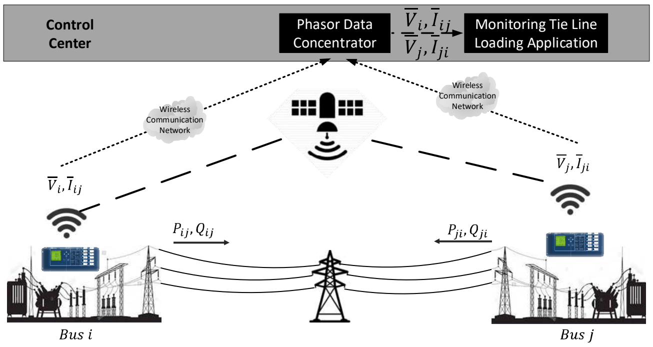


Fig. 2. Tie transmission line monitored by PMUs.

The algorithm of the monitoring application for the tie lines in this work is shown in Fig. 3 and it is based on the integrity of the PMU data set. The concept in this algorithm is to provide in real time the loading condition of the tie line, while in case that there are some data losses due to discarded PMU measurements to replace these measurements with the most recent available measurement.

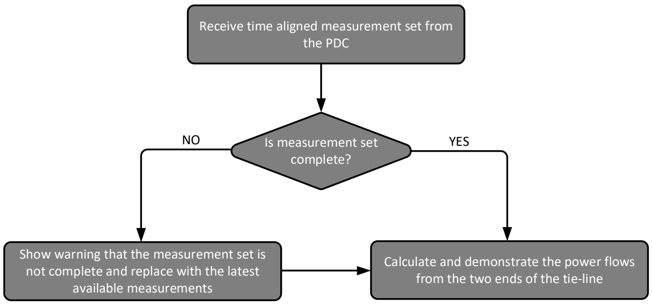


Fig. 3. Monitoring algorithm flowchart.

B. *Differential Wide Area Protection application*

The second application in this paper deals with the wide area protection concept. In this case, again the PMU measurements from both ends of the transmission line are used; however, the protection application processes the PMU measurements in the substation level using a local controller. Therefore, unlike the monitoring application outlined above, in the PMU-based differential protection application no PDC is involved.

The concept of the PMU-based differential application is to detect any faults that occur within the range of the transmission line and trip the breakers of the line in order to isolate the fault in the system. In order to achieve this, the magnitudes of the line currents from the two ends of the line are compared. As it is shown in Fig. 4, without loss of generality it is assumed that the PMU-based differential protection application is installed at bus *i* and it receives local measurements from the PMU at bus *i*, while the remote measurements from the PMU at bus *j* are transferred through a wireless communication network.

The PMU-based differential application compares the current magnitudes (from the PMU current phasors) with the same timestamp and if their difference is larger than a certain threshold (in this work 20 A) then a trip signal is sent to the breakers of the two substations (*i* and *j*). In principal, if there is no fault within the line that connects bus *i* and bus *j*, the current magnitudes from the two ends of the line will be almost equal, with some losses at the shunt admittances of the transmission line (assuming a π model). However, in case of a fault within the line, the difference between the two currents will be more than 100 A, due to the fault current that flows from the two ends of the line.

It is therefore of paramount importance that the fault within the transmission line is detected as quickly as possible, in order to isolate the transmission line and prevent any instability issues in the rest of the power system.

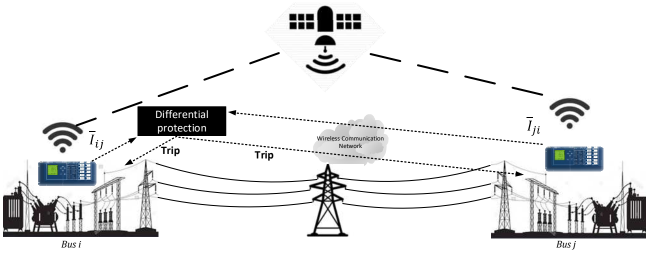


Fig. 4. PMU-based differential protection application.

IV. SIMULATION RESULTS

The aim of this work is to investigate whether the presence of a wireless communication network for transferring the PMU measurements benefits the accuracy and real-time responsiveness of the two applications considered. Thus, in both applications, it is assumed that three wireless communication networks exist for transferring the measurements, namely, 3G, 4G, and 5G network.

In order to create a realistic environment to extract the simulation results, a real-time hardware in the loop setup was developed as shown in Fig. 5, that includes, the dynamic IEEE 9 bus system [11] simulated in the OPAL-RT real-time simulator, two Arbiter Sentinel PMUs [12] that are assumed to be installed in the line that connects bus 4 and bus 6, a SEL 5073 PDC [13], and a network emulator that emulates the delays imposed by the wireless network.

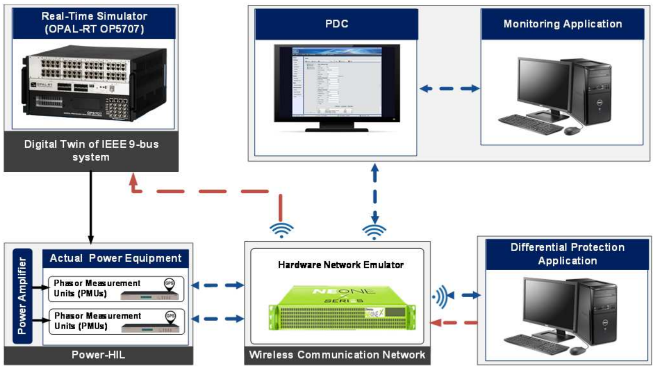


Fig. 5: Real time hardware in the loop framework

As illustrated in Fig. 5, the monitoring application communicates directly with the PDC to receive the measurements, while the differential protection application receives measurements from the two PMUs locally and sends back to the IEEE 9-bus system (OPAL-RT) a signal (red line) for tripping the breakers of the transmission line in case of a fault.

As it was previously mentioned, the investigation of the impact of the wireless communication network to the responsiveness and accuracy of the two wide area applications (monitoring and differential protection) is the main objective of this work. In order to simulate the characteristics of the wireless networks and especially the delay that is imposed to the transfer of the PMU measurements for the two applications, the network emulator is configured accordingly to simulate the 3G, 4G, and 5G latencies. More specifically, the latencies for the three networks are assumed to follow a uniform distribution with limits as shown in Table I [14].

TABLE I.
DELAY MEAN VALUE FOR COMMUNICATION NETWORK

Communication Network	**Uniform distribution limits**	
	Minimum (ms)	Maximun (ms)
5G	3	10
4G	20	60
3G	20	150

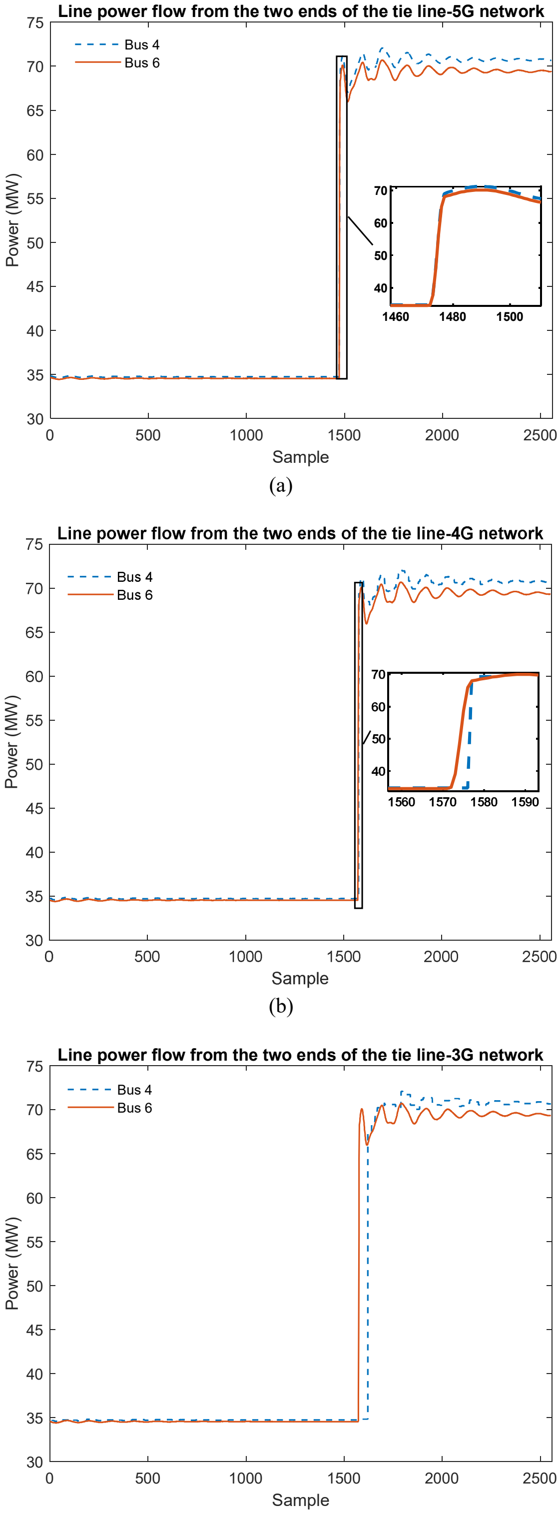
A. Results of the application for monitoring the tie line loading

In this case study the accuracy of the tie line loading application was tested under the delay imposed by the three wireless communication networks. As shown in Fig. 5, the monitoring application receives measurements from the PDC which has a waiting time of 40 ms in order to ensure the fast reporting of the loading condition of the transmission line. It should be noted that the waiting is adjustable and can change according to the WAMPC application. The measurements of the PMUs are transferred with 3G, 4G, and 5G communication networks with the delay characteristics shown in Table I.

Since the tie line connects two independent systems, the measurements received by the two PMUs should be synchronized and time aligned in order to reflect the same operating conditions. Therefore, any change in the power flow of the tie transmission line should be visible to the operators of the two systems in real time. In other words, at each end of the line the same power flow change should be reflected in real time. In this case study, it is assumed that the initial power flow of the line is around 35 MW and suddenly a load increase of 35 MW occurs in the system of bus 6, increasing the line loading of the transmission line by 100%.

The monitoring application that runs in real time in the control center should immediately detect this tie-line loading change and make available (i.e., demonstrate) this change to the two operators of the interconnected system. In Fig. 6, the results of the tie line monitoring application are shown when the PMU measurements from the two systems are transferred with 5G (Fig. 6a), 4G (Fig. 6b), and 3G (Fig. 6c). Based on the simulation results, it is evident that the 5G network ensures the timely arrival of the PMU measurements to the control center before the waiting time of the PDC elapses, and the monitoring application successfully captures the line loading change instantaneously for both systems. On the other hand, 4G communication imposes larger delays to the transfer of PMU measurements (compared to 5G) and therefore, even though the line loading change is detected instantaneously in bus 6, a slide delay is observed for the system that bus 4 belongs to. The impact of the delays is more obvious in the case of 3G, where the line loading change in bus 4 is shown with a considerable delay in comparison to the other two scenarios.

Table II tabulates the PMU measurements that were delayed more than the waiting time of the PDC (40 ms) and therefore were discarded by the PDC. In the case of the 5G network, all the PMU measurements manage to arrive on time and therefore no data loss occurred due to communication delays.



(a)

(b)

(c)

Fig. 6. Line power flow from the two ends of the tie line using a (a) 5G network, (b) 4G network, (c) 3G network.

TABLE II.
DATA LOSS FOR THE TIE LINE LOADING MONITORING APPLICATION

Communication Network	**Data Loss (%)**
5G	0
4G	68.6
3G	87.7

On the contrary, in the other two cases, data loss occurs. In particular, in the case of the 4G network, 68.6% of the PMU measurements were discarded due to their late arrival to the PDC, while in the case of the 3G network, 87.7% of the PMU measurement were discarded. It should be noted, that for the monitoring application considered (as outlined in Fig. 3), in case of measurement data loss the previously available measurement is used (i.e., the measurement that arrived to the PDC with latency less than the PDC waiting time). This is the reason why in the case of 3G and 4G networks at some point the loading change of the tie line is captured (i.e., because at some point a PMU measurement was delayed less than the waiting time of the PDC). It should be noted that in the case that multiple changes occur in the loading of the tie-line in small time intervals, it is possible that some of the changes will be missed by the monitoring application for one of the two interconnected systems if there is a considerable measurement loss (as in the case of the 3G and 4G communication network).

B. *Results of the PMU-based differential protection application*

In the line protection application, its real-time responsiveness is essential for clearing timely any fault that occurs within the transmission line. As it is outlined in Fig. 5, the PMU-based differential application is executed at the substation level, excluding the involvement of the PDC in the loop. In this case study, it is assumed that the application runs at bus 4 of the IEEE 9-bus system and receives measurements coming from bus 6 of the transmission line. The application compares the current magnitudes of the two ends with the same timestamp. This means that the application waits until two measurements (from the two ends) with the same timestamp are available to be compared.

In this case study, the three wireless networks (5G, 4G, and 3G) are assumed to transfer the measurements from the PMU at bus 6 to the differential monitoring application. The network emulator emulates the three networks, while a uniform delay is assumed with characteristics that are shown in Table I. In order to indicate the impact of the delays on the real-time responsiveness of the PMU-based differential protection, a three-phase fault with 60 Ω fault resistance was applied to the middle of the line that connects buses 4 and 6. Figure 7, indicates the positive sequence voltage of bus 4 before, during, and after the fault when the communication network used for transferring the PMU measurements is 5G, 4G, and 3G.

In the case of the 5G communication network, the voltage is decreased during the fault, while after the clearing of the fault by the PMU-based differential protection application the voltage is restored quickly to the pre-fault values. The 4G communication network inserts larger delays to the transfer of the PMU measurements from bus 6, and as a result, the fault stays longer within the system than in the case of 5G. In the case of the 3G communication network, the differential protection application fails to clear the fault timely and therefore the system is led to instability. This is evident by the high frequency oscillations that occur in the last samples of the voltage (third subfigure of Fig. 7).

In order to better illustrate the responsiveness of the application in case of a three-phase fault in the line (considering the three communication networks), the positive sequence line current (that flows from bus 4 to bus 6) before, during, and after the fault is shown in Fig. 8. It should be noted that the fault current is much larger than the pre-fault current and therefore an increase in the current flowing from bus 4 to bus 6 is observed during the fault. Further to that, in case the differential application detects the fault, a trip signal is sent to the breakers of the line to open and thus the line current is zero after the clearing of the fault.

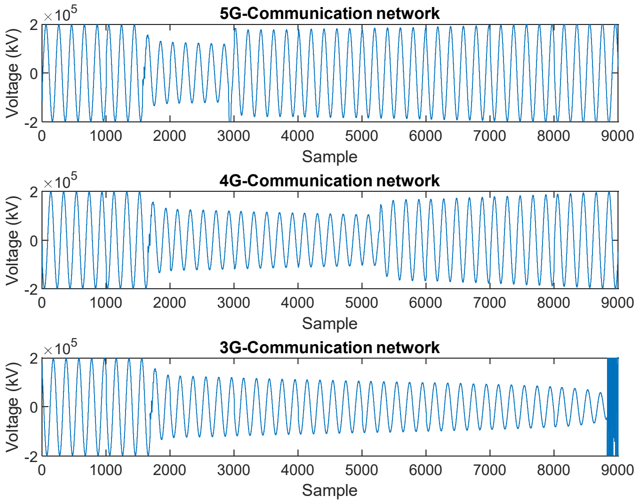


Fig. 7. Pre fault and post-fault positive sequence voltage of bus 4.

From Fig. 8, it is obvious that the fault current stays in the system the least amount of time when the 5G communication network is used for transferring the PMU measurements, while with the 4G network the faults stays longer in the system before the line breakers are opened. In the case of the 3G communication network, the fault stays in the system for such a period of time that leads the system to instability.

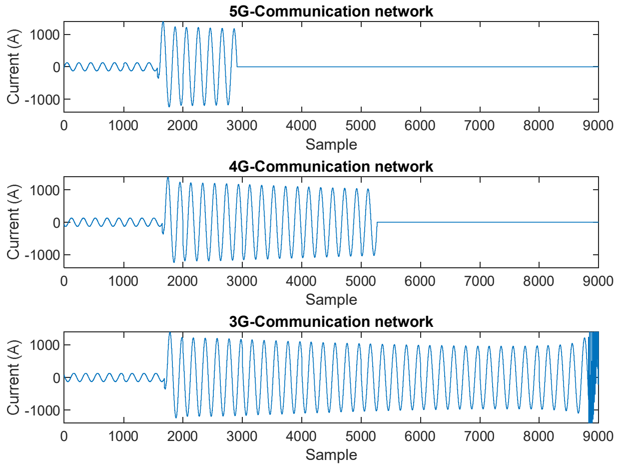


Fig. 8. Pre fault and post-fault positive sequence current flowing from bus 4 to bus 6.

V. CONCLUSIONS

With the vast deployment of PMUs in the transmission level of the power systems, the use of wireless communication networks for supporting the transfer of PMU measurements to wide area monitoring, protection, and control applications is a flexible and cost-effective solution for the operators. Considering the three available wireless communication networks in the field today, 3G, 4G, and 5G, this work investigates how the use of each one of these networks impacts the accuracy and real-time responsiveness of two wide area applications, namely (i) the monitoring of the tie line loading application and (ii) the PMU-based differential protection application.

As it is evident from experimental results, the type of the wireless communication network used for transferring the measurements significantly affects the performance of the examined applications. More specifically, the 3G network impacts negatively the wide area monitoring and protection applications, making it unsuitable for usage within a WAMPC system. In the case of the 4G wireless network, it is shown that it imposes delays to the transfer of the PMU measurements that affect the performance of the applications; nevertheless, with the 4G wireless network the accuracy and real-time responsiveness of the applications is improved as compared to 3G. The two considered applications achieve their best performance when a 5G communication network is used for transferring the PMU measurements. In the case of the 5G communication network, no data loss occurs, while the applications perform as expected. Considering the many capabilities that are provided by the 5G network, it is evident that such a communications infrastructure can be a reliable solution for future WAMPC systems.

REFERENCES

[1] F. Milano, F. Dörfler, G. Hug, D. J. Hill and G. Verbič, "Foundations and Challenges of Low-Inertia Systems (Invited Paper)," in *2018 Power Systems Computation Conference (PSCC)*, Dublin, Ireland, Aug. 2018.

[2] L. Barroso and H. Rudnick, "The Future Power System: Centralized, Distributed, or Just Integrated?," *IEEE Power and Energy Magazine,* vol. 17, no. 2, pp. 10-14, Apr. 2019.

[3] "IEEE standard for synchrophasors for power systems," 2011.

[4] A. G. Phadke and T. S. Thorp, *Synchronized Phasor Measurements and Their Applications*, New York: Springer, 2008.

[5] M. Kezunovic, S. Meliopoulos, V. Venkatasubramanian and V. Vittal, *Application of Time-Synchronized Measurements in Power System Transmission Networks*, Springer International Publishing, 2014.

[6] A. Phadke and T. BI, " Phasor measurement units, WAMS, and their applications in protection and control of power systems," *Journal of Modern Power Systems and Clean Energy ,* vol. 6, pp. 619-629, Jul. 2018.

[7] L. Zacharia, M. Asprou and E. Kyriakides, "Wide Area Control of Governors and Power System Stabilizers With an Adaptive Tuning of Coordination Signals," *IEEE Open Access Journal of Power and Energy,* vol. 7, no. 1, pp. 70-81, Dec. 2020.

[8] J. O'Brien et al., "Use of synchrophasor measurements in protective relaying applications," *2014 67th Annual Conference for Protective Relay Engineers*, pp. 23-29, Apr. 2014.

[9] M. Asprou and E. Kyriakides, "The effect of time-delayed measurements on a PMU-based state estimator," in *2015 IEEE PowerTech Eindhoven*, Eindhoven, Jun. 2015.

[10] V. K. Sood, D. Fischer, J. M. Eklund and T. Brown, "Developing a communication infrastructure for the Smart Grid," in *2009 IEEE Electrical Power & Energy Conference (EPEC)*, Montreal, Canada, Oct. 2009.

[11] B. Naduvathuparambil, M. C. Valenti and A. Feliachi, "Communication delays in wide area measurement systems," *in Proceedings of the Thirty-Fourth Southeastern Symposium on System Theory, Huntsville*, AL, pp. 118-122, Mar. 2002.

[12] 3G PPP, "Study on Communication for Automation in Vertical domains (CAV)," 2018.

[13] 5G PPP, "The 5G Infrastructure Public Private Partnership," 2014.

[14] "IEEE standard for synchrophasors data transfer for power systems," 2011.

[15] M. Asprou, S. Chakrabarti and E. Kyriakides, "The use of a PMU-based state estimator for tracking power system dynamics," in *2014 IEEE Power and Energy Society General Meeting*, Washington DC, Jul. 2014.

[16] P. Demetriou, M. Asprou, Q.-T. J. and E. Kyriakides, "Dynamic IEEE Test Systems for Transient Analysis," *IEEE Systems Journal,* vol. 11, no. 4, pp. 2108-2117, Dec. 2017.

[17] "Model 1133A GPS-synchronized power quality/revenue standard operation manual,," Arbiter Systems Inc., CA, USA, Sept. 2006.

[18] "SEL-5073 Synchrowave Phasor Data Concentrator Instruction Manual," Schweitzer Engineering Laboratories, Inc. , WA, USA.

[19] M. Agiwal, H. Kwon, S. Park and H. Jin, "A Survey on 4G-5G Dual Connectivity: Road to 5G Implementation," *IEEE Access,* vol. 9, pp. 16193-16210, Jan. 2021.