A Distributed PMU for Electrical Substations with Wireless Redundant Process Bus

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***Abstract*—Protection and measurement systems in electrical substations are required to have high availability. In an all-digital substation protection system, all the components (instrument transformers, processing units, merging units, intelligent electronic devices, communication network, and synchronization source) may affect the overall availability level. In this paper, a solution to enhance distributed PMU availability, during wired network failures, is presented. In the proposed scheme, the process bus has two parallel networks: the classic wired Ethernet link, plus a wireless link (implemented with industrial grade IEEE 802.11 devices), for sampled values packets, which carry measurement information. The time synchronization is carried out only through the wired Ethernet link, but the proposed solution is still able to compensate temporary failures of one of the communication links. Experimental tests have been performed to verify the performance of additional IEEE 802.11 link using different protocols and configurations. Communication parameters which can affect the PMU performance, like propagation latency, are characterized. It is shown that, if the measurement algorithm is opportunely designed, depending on the wireless link quality, it is possible to comply, with a single output, with M and P classes of the synchrophasor standard also during network restoration or, at least, to safeguard protection applications if higher latency occurs.**

Keywords—Phasor Measurement Unit; process bus; wireless LAN; availability; hybrid network; synchrophasor; communication latency measure; IEEE 802.11; Substation Automation System

I. INTRODUCTION

The IEC 61850 [1] standard provides a network-centric design concepts for Substation Automation System (SAS), where Intelligent Electronics Devices (IEDs), Merging Units (MUs), and other devices equipping the Primary Substation (PS) exchange information over a communication infrastructure. In this scenario, the availability of protections and distributed measurement systems strongly relies not only on the availability of instrument transformers or processing unit but also on that of the overall system (which includes both the communication network and the synchronization system). In particular, a distributed Phasor Measurement Unit (PMU), like the one proposed in [2], where the required functionalities (voltage and current sampling, filtering, estimation, time synchronization and communication) are distributed in different nodes in the electrical substation, has more points of failures compared to a centralized PMU, whose analysis has been presented in [3]. In detail, the typical failures of the distributed PMU involve: i) the hardware platform of the nodes (IED, MUs, sensors, ..); ii) the synchronization system; iii) the communication infrastructure (switches, routers, etc.). This work is limited to investigate only the last cause of failure. A detailed analysis of the other two causes is presented, for instance, in [3] and [4].

The network infrastructure is used in the considered PMU architecture to transfer, on the process bus, the data from MUs to the IED; typically, the process bus is used to transfer the Sampled Values (SVs) and to distribute an accurate time reference, by means of IEEE 1588 protocol [5], also known as Precision Time Protocol (PTP). As underlined in [6], the Ethernet switches in the communication infrastructure of the process bus can become the bottleneck of the system reliability and Ethernet network with redundancy may have a great impact on the mean time between failures (MTBF).

A possible solution could be the duplication of all the devices (sensors, MUs, IEDs, switches...) but this solution is, generally, not feasible from the economic point of view. A cost-effective solution to enhance distributed PMU availability could be increasing the redundancy in the communication infrastructure by means of an additional IEEE 802.11 wireless link in the MU, an approach already proposed for industrial applications [7],[8],[9] and recently investigated in power industry [10]. Thus, the process bus could have its wireless counterpart that serves as a parallel path. In addition, it should be highlighted that the wireless redundant path can be applied to improve the availability also of already existing and working substations because it does not involve the cabling of new infrastructure.

The proposed communication redundancy can be applied at several levels: either all the traffic generated by any service in the MU or only the traffic generated by specific service can be duplicated on the two interfaces. The former approach guarantees the higher level of availability but requires a larger bandwidth. On the contrary, the latter guarantees the required level of availability to essential services, preserving at the same time the bandwidth, which (in wireless networks) is usually lower than in wired networks.

In the design of the new architecture for the MU with redundant communication, the main constraint to take into account is that the proposed system should be immediately usable inside real substations: hence, only industrial grade components must be used, since current IEEE 802.11 technology adopted in industrial environment [11] has requirements, in term of robustness and noise immunity, similar to power automation applications.

First of all, the limitations of currently available industrial grade components for IEEE 802.11, have been investigated in the paper, focusing on the synchronization capabilities of these devices; the literature [12] [13] suggests possible solutions, but the experimental results show that time synchronization over IEEE 802.11 link can be obtained with the accuracy needed for PMU applications only if dedicated hardware and software are used [10], whereas the use of industrial grade components required to operate in substation environment could cause the excessive decrease of the time synchronization performance of the MUs.

Given such results, in this paper, only the SVs are sent over the IEEE 802.11 link for increasing the availability. Even if the time synchronization is carried out only through the wired Ethernet link, the solution proposed in this paper is still able to compensate temporary failures of one of the communication links. Clearly, the deployment of a distributed PMU has specific requirements (like low communication latency of SVs packets) which are also addressed in this paper with specific characterization.

II. AVAILABILITY IN SUBSTATION NETWORK: SOLUTIONS AND OPEN ISSUES

A. Availability of IEC 61850 process bus

A distributed PMU, inspired by IEC 61850 standard, makes use of the process bus to transfer the information from voltage and current sensors to the IED, where the information is processed and elaborated to estimate the synchrophasor [2]. Typically, the process bus should be a high performance infrastructure, able to satisfy strict requirements: low communication latency, low communication jitter, high bandwidth, high availability and reliability, and accurate time synchronization. The proper configuration of a switched Ethernet network (like the use of message priorities, V-LAN and multicast filtering, as suggested in [14]) allows reducing the communication latency and jittering. The transmission of SVs requires an adequate transmission bandwidth: in fact, each merging unit can generate a stream of data on the order of some megabits per second. The effect of this stream of data over process bus infrastructure is well investigated in [15]. The high availability and reliability of the network is typically obtained adopting physically redundant network topology (e.g. ring structure) managed by redundancy protocols, like RSTP (Rapid Spanning Tree Protocol), which is able to reconfigure a ring network in less than 100 ms. More demanding applications, like protections, which require a zero-recovery time, should adopt solutions like PRP (Parallel Redundancy Protocol) and HSR (High-Availability Seamless Redundancy). In any case, both solutions, if compared to RSTP, imply a relatively high increase of the overall installation costs.

As demonstrated in [16], the failure of the network may cause the loss of packets up to several hundreds of milliseconds - the typical recovery time of an RSTP network. During this interval, the distributed PMU cannot compute synchrophasors. In this case, the availability of the process bus can be increased by means of a parallel communication channel: besides the performing, Ethernet-based, process bus an additional IEEE 802.11 network infrastructure can be installed, as suggested in [17]. In the case a fault affects the wired network, a copy of the information can be transferred to the end user using the parallel IEEE 802.11 connection, achieving a zero-recovery time. The improved architecture of the distributed measurement system over the process bus is shown in Fig. 1. The IED, which collects the SV packets and performs the synchrophasor algorithm, is connected to the distributed MUs by a main wired Ethernet process bus and by a parallel IEEE 802.11 connection. The MUs send simultaneously copies of the SV packet on both the connections: in the case of failure in the wired network, the information is transmitted over the parallel connection. The IED normally receives two copies of the SV message from the two connections; it accepts the first copy and discards the second one. The main advantage of this solution, compared to PRP and HSR solutions, is the lower installation costs: the installation cost of a IEEE 802.11 network is typically lower than the installation cost of a second, additional, cabled infrastructure or the use of specific network hardware interfaces. In addition, as demonstrated in [17], the IEEE 802.11 communication can be advantageously adopted also in electrical substations, despite the high level of electromagnetic noise. However, the ability of the redundant IEEE 802.11 network to transport data with higher reliability does not imply that time synchronization is always possible. In the following subsection the issues of time synchronization in substations will be discussed in details because of the role the time dissemination plays in the implementation of synchrophasor algorithms.

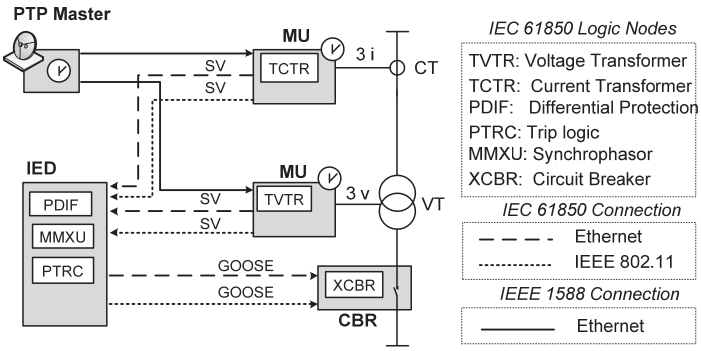

Figure 1. Improving the distributed measurement architecture based on IEC 61850 process bus by means of a parallel IEEE 802.11 link.

B. Time Synchronization over network:general concepts and main problems using IEEE 802.11

The correctness of the results provided by the PMU relies on the time synchronization accuracy, as well as on the algorithm used for synchrophasor, frequency and rate of change of frequency (ROCOF) evaluation. Generally speaking, the time information is recovered by means of an external source of UTC time, like a GPS receivers or an atomic clock, and then distributed to the system using a dedicated hardwired network and the related standards, like IRIG-B. Recently, those dedicated solutions have been replaced by approaches, like

IEEE 1588 protocol, which use the communication infrastructure to distribute also the time reference [18]. IEEE 1588 is able to satisfy the accurate synchronization requirements (on the order of one microsecond), required by synchrophasor estimation. By the way, in a distributed PMU, also MUs need the time synchronization together with the transmission of SVs. In the proposed approach, two parallel infrastructures are considered for the reliable transmission of the MUs data: one using the cabled Ethernet network, the other using IEEE 802.11 link [10]. While the PTP time synchronization over Ethernet is nowadays well investigated in the literature and well accepted in the industrial practice, the PTP time synchronization over IEEE 802.11 link has some open issues and it is not widespread in industrial applications. As demonstrated by the literature [12][13], it is possible to achieve a time synchronization on the order of few microseconds (enough for distributed PMU application) also over IEEE 802.11 link adopting a software-based approach. Despite these results, this approach can be adopted in the implementation of a distributed PMU only if dedicated software and hardware components are used ([19]), with particular regards to network devices, as IEEE 802.11 access point (AP) and bridge, as in [10]. Unfortunately commercial IEEE 802.11 devices, PTP aware, able to provide the required level of robustness for industrial and electrical substation applications, are not available on the market. On this basis, the main goal of the paper is to consider in the design of the system the technical limitations of current commercial industrial devices (see Section IV.A). In particular, the main limit of IEEE 1588 time synchronization over IEEE 802.11 is the network infrastructure (i.e. AP or Bridge) used to transfer the time information from the IEEE 1588 master to the IEEE 1588 slave. In fact, up to now, the IEEE 1588 (and in particular the IEEE C27.238 power profile [20]) does not define the support of IEEE 802.11 links for time distribution, although the IEEE 802.1AS profile [21] defines a first attempt to map IEEE 1588 over IEEE 802.11. This limit of the current normative has limited the development and the commercialization of IEEE 1588 aware IEEE 802.11 network devices. Therefore, the synchronization performance that an IEEE 1588 slave can achieve over an off-the-shelf IEEE 802.11 infrastructure is inevitably limited by the propagation delay introduced by APs and bridges, which is on the order of few milliseconds.

In order to experimentally evaluate the influence introduced by an IEEE 802.11 infrastructure over IEEE 1588 synchronization, two PTP devices (Agilent Trigger box E5818), one configured as PTP master and the other as PTP slave, have been interconnected using industrial grade IEEE 802.11 bridges (Siemens Scalance W784-1RR). The PTP master has been configured to send a PTP sync message every 2 s. In addition, each of the PTP nodes has been configured to generate a hardware 1-PPS (Pulse Per Second) signal, locked with the local time. The time offset between the two PPS signals can be considered as an estimation of the time synchronization accuracy between the PTP master and the slave. The time offset is acquired by means of a performing counter (Agilent 53230A). The time offset measured over an observation interval of 20 minutes (about 1200 samples), is shown in Fig. 2a, while the frequency distribution (1200 samples) is shown in Fig. 2b. The maximum time offset is on the order of 47 µs. As expected, an IEEE 802.11 infrastructure, not IEEE 1588 aware, is not able to distribute the time synchronization information with the accuracy required by synchrophasor application.

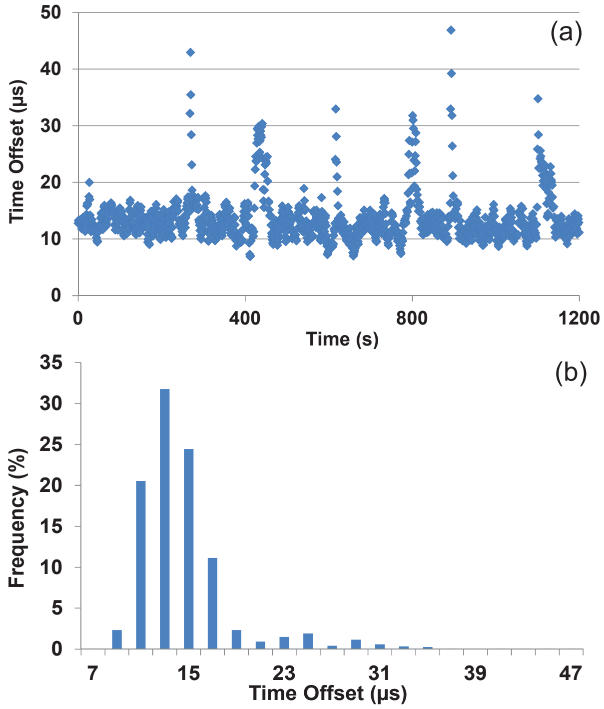

Figure 2. The time offset evaluated over a IEEE 802.11 link (observation interval 1200 s) (a) and the frequency distribution (b).

III. THE PROPOSED ARCHITECTURE OF THE MERGING UNIT

As mentioned in the previous section, the availability of the overall PMU distributed system can be improved by increasing the redundancy of the communication infrastructure. Thus, the structure of the end-nodes (IED and MUs) involved in the distributed PMU has to be modified to support the network redundancy. The architecture of the MU with redundancy (shown in Fig. 3), compared to the architecture introduced in [2], is characterized by the presence of two different network interfaces (net1 and net2), which transmit simultaneously the SVs to the IED. The interface Net1 is connected to the primary connection, typically the Ethernet connection, while net2 is connected to the secondary connection, i.e. the parallel IEEE 802.11 connection. An additional layer, the Link Redundancy Entity (LRE), implemented in layer 2 network stack, is required to duplicate the outgoing SV packets generated by the MU and to discard the duplicated incoming packets. The time synchronization is recovered only from the primary connection, while the secondary one (connected to the IEEE 802.11 link) is used only to transfer the SV packets because of the above discussed issues in transferring IEEE 1588 information over industrial grade IEEE 802.11 network.

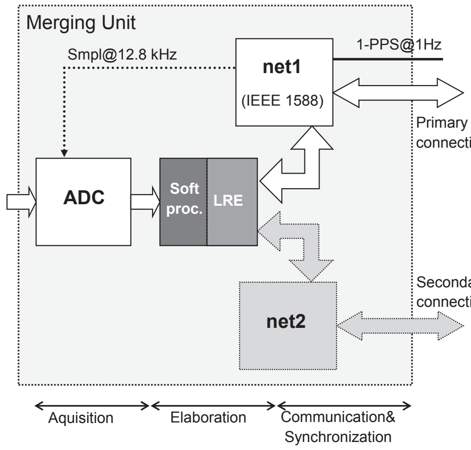

Figure 3. The block diagram of a MU with redundant communication channels.

The MU with redundancy is able to handle the failure of one of its communication links, as shown in Fig. 4. In the case of a failure to the IEEE 802.11 link, the MU still recovers the time information from the Ethernet link and sends the SVs over the wired connection. On the contrary, in case of failure over the Ethernet link, the MU stops to recover the time from the PTP master and the local clock enters in free run mode. In fact, as demonstrated by results reported in Section II.B, the synchronization accuracy when IEEE 1588 protocol is distributed over a IEEE 802.11 network is not enough to satisfy the requirement of PMU. Under these conditions, it is preferable to stop the time synchronization and run temporary in free run mode, until the other communication link will be restored (e.g. temporary Ethernet switch shutdown). As experimentally evaluated in [2], the maximum residual skew (γ_{MAX}) of a clock, implemented using a low cost quartz crystal oscillator and synchronized by IEEE 1588 protocol, is on the order of 0.15 ppm. This means that, considering a linear model of the clock (an approximation of the more complex model of a clock [22],[23] that can be considered valid over the short term) and considering 1 μs as the upper bound of time synchronization requirements for PMU application (S_{MAX}), the maximum time (T_{FR}) that a MU can remain in free-running mode can be expressed as:

$$T_{FR} = \frac{S_{MAX}}{\gamma_{MAX}} = 6.6\ s \tag{1}$$

This limit is compatible with a large part of temporary network failures.

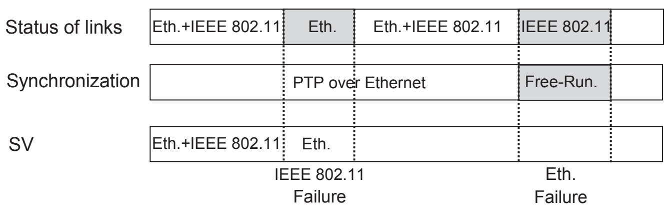

Figure 4. The behavior of MUs in case of failure on communication links.

IV. The Impact of Wireless Communication on Distributed PMU Performance

When the wired Ethernet communication network undergoes temporary outages, as described in previous sections, the IED receives SV packets only from the parallel IEEE 802.11 wireless network. The time tagging of the received packets presents an uncertainty related to the synchronization achievable by the clock of MUs during the free-running conditions, which is until wired network is restored and PTP algorithm can provide again the synchronization.

The synchronization offset, as pointed out in [2], impacts directly particularly on the estimation of the phase angle and thus affects the Total Vector Error (TVE). The TVE is introduced by the IEEE C37.118.1 synchrophasor standard [24] as a synthetic index for the evaluation of PMU synchrophasor estimation errors. In fact, the TVE can be represented in terms of relative amplitude estimation error $\Delta a/a$ and of phase angle error $\Delta\varphi$ as follows:

$$TVE = \left|\frac{\tilde{p} - p}{p}\right| = \frac{\left|\tilde{a}e^{j\Delta\varphi} - a\right|}{a} \approx \sqrt{\left(\frac{\Delta a}{a}\right)^2 + \left(\Delta\varphi\right)^2} \tag{2}$$

where p represents the complex phasor, with amplitude a and phase φ (in radians), the tilde indicates the estimated counterparts, and the approximation is valid for small errors. The phase angle estimation error thus contributes in a quadratic way to the overall TVE and it is linearly related to the time synchronization error when a stationary test signal is considered. On the contrary, when dynamic signals, as the modulation or frequency ramp test signals prescribed by the IEEE C37.118.1 synchrophasor standard [24], are considered, the time-shift caused by synchronization offset has a more complex impact on TVE. For instance, when amplitude and phase modulated signals are considered the timestamping error affects both amplitude and phase estimation.

The maximum frequency estimation errors obtained for tests under off-nominal conditions or in presence of stationary harmonics and interharmonics are, in general, not affected by synchronization errors, since time-shifted analyzed signals present the same time-invariant spectral content. The results of frequency ramp tests are instead prone to the synchronization error, due to the direct impact of the time-shift on the frequency variation However, since the rate of change of frequency used in [24] is equal to 1 Hz/s, even an offset in the order of 10 μs results in an extremely low frequency shift of 10^{-6} Hz.

Wireless communication also introduces higher propagation delays for SV packets with respect to the wired Ethernet process bus. In the next Section an experimental analysis of the propagation performance of IEEE 802.11 for different protocols and configurations is reported. In particular, the overall delay is in the order of milliseconds (ranging from few to tens) and is considered, in the distributed PMU context, the delay affecting SV messages going from MUs to IED. This could be a drawback for latency constraints stated by the synchrophasor standard for P-class PMUs suitable for protection applications. Thus, the distributed PMU algorithm should keep also into account the worst case latency due to IEEE 802.11 communication and, possibly, commute to dedicated procedures for this emergency state.

V. The Adopted PMU Design

The architecture of a PMU, proposed in [2], and equipped with the enhanced synchrophasor estimation algorithm presented in [25] for the specific reporting rate of 50 frame/s, is considered. In this work, the same concept is kept, but the design is tailored to the new limits of the amendment of the synchrophasor standard IEEE C37.118.1a [26].

The design aims at being 'P+M', that is to give always a single output, for each measured quantity (synchrophasor, frequency and ROCOF), that complies with all the tests of the classes P and M of the standard. It is important to highlight that such estimate is unique, exploiting a selection of the operative conditions, and allowing, for instance, to respect all M-class limits with low latency and to present P-class compliant responses when the dynamic tests of the standard are considered. In fact, the PMU is composed by two parallel virtual channels (both based on the TFT concept [27]), S and D, designed for accurate measurement in quasi-static conditions and fast response to dynamic conditions, respectively. A detector of fast changes allows choosing the best output for each operative condition.

Since the amendment of the synchrophasor standard presents different limits and compliance tests with respect to [24], a modified D-channel is used with respect to [25]. The D-channel has been modified to show very low latency (20 ms) and better dynamic performance. A Kaiser window of two nominal cycles with $\beta = 5$ and a first-order Taylor model is used. As it will be shown in the results section, this choice allows to reduce the over/undershoot in the step response. ROCOF of the D-channel, because of the reduced order, is obtained by derivative from subsequent frequency values.

When failures occur, the increased latency of wireless communication could make the P+M compliance unfeasible. The PMU can also be configured to automatically switch to a "contingency mode", using only the D-channel. The D-channel then works with its own frequency feedback (see [25] for a detailed description of the technique) and its measurements (synchrophasor, frequency and ROCOF) become the main outputs. In this case, an additional one cycle boxcar filter is used to obtain a better rejection of harmonics in frequency estimation. The additional filter would give a further half-cycle delay to frequency and ROCOF computation. However, to keep the latency limited to 20 ms (half the duration of the synchrophasor filter), frequency and ROCOF are given by the current estimations corresponding to the synchrophasor time tag. Frequency value is thus corrected using ROCOF estimation to compensate the lack of alignment, as in [28], and full P-class compliance is reached. This configuration, becomes particularly useful for high latency IEEE 802.11 networks.

VI. Test Results

In this section the results on the performance of a distributed PMU relying on a wireless communication are reported. First of all, the performance of a IEEE 802.11 link is characterized to obtain an estimation of communication parameters, like propagation latency, which can affect the PMU performance. Then, these parameters are used to validate the PMU algorithm. The aim is to verify the performance of the distributed PMU that is compliant with the standard when only the wireless network is working and the MUs are operating in free-running mode, due to the temporary loss of synchronization during network restoration. This approach will allow defining the limits of the given design under failure conditions.

A. Evaluation of IEEE 802.11 link performance

The Quality of Service (QoS) provided by a IEEE 802.11 connection is typically lower than the one of a wired connection: the communication latency is higher and the synchronization performance is lower, a situation that may affect the overall performance of the distributed PMU. In addition, the performance provided by a wireless communication link may be affected by the configuration of the network devices and by the environment itself (e.g. interference with other communication links, multipath noise, obstacles). For these reasons, a careful evaluation of the performance of a IEEE 802.11 link is required. A typical solution adopted for providing IEEE 802.11 connectivity to an existing infrastructure is shown in Fig. 5 IEEE 802.11 bridges (Wi-Fi1 and Wi-Fi2) are connected, by means of an Ethernet connection, to end-nodes, like MUs and IEDs, or to Ethernet switches. Considering the SAS environment, only IEEE 802.11 devices with a sufficient robustness to mechanical and electrical stresses can be used: during the experiments, in this paper, Siemens Scalance W784-1RR, industrial grade IEEE 802.11 devices, have been adopted. These devices can be easily configured to work adopting different IEEE 802.11 protocols (IEEE 802.11a/b/g), different data rates and different frequency bands (2.4 GHz and 5 GHz). In addition, two possible operative modes of IEEE 802.11 network can be used: peer to peer communication (ad hoc mode) or communication via Access Point station (infrastructured or AP mode). The complete list of devices adopted during the experimental evaluation is reported in TABLE I.

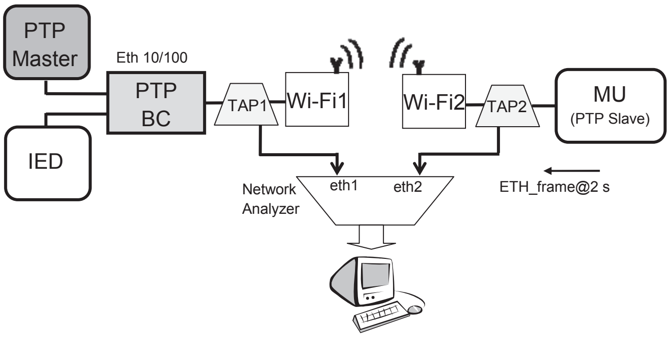

Figure 5. Block diagram of the experimental set-up adopted to evaluate the communication latency of the backup IEEE 802.11 process bus.

TABLE I. THE COMPONENTS OF THE EXPERIMENTAL SET-UP

Description	Component
PTP master	Agilent LXI Class-B E5818A
PTP BC	Hirschmann MICE MS20
Industrial IEEE 802.11	Siemens Scalance W784-1RR
MU and IED prototypes [2]	Altera NIOS II development kit
Ethernet TAP	NetOptics 10/100 Ethernet In-line optical tap
Network Analyzer	Endace Ninjabox

This experimental set-up can be used to evaluate the communication latency, i.e. the time required by a packet to reach the destination. The communication latency (T_L) can be expressed as:

$$T_L = T_{BD} + T_W + T_C \quad (3)$$

where T_{BD} is the bridge delay due to network devices, like access points or bridges, T_W is the wireless propagation delay and T_C is the propagation delay over the Ethernet cable. Typically, T_{BD} is the dominant and variable contribution, while T_W and T_C can be considered constant and negligible contributions. The experimental set-up shown in Fig. 5 provides an estimation of the communication latency (T'_L) introduced by the wireless link. The packets sent by the MU (L2 Multicast Ethernet packet, 170 bytes) are logged by an Ethernet Tap (TAP2), which duplicates the traffic on Ethernet link, without introducing any delay on the propagation of the packets. The packets are then transmitted by Wi-Fi2 to Wi-Fi1. On the other side, TAP1 is used to log the traffic received by Wi-Fi1. The packets logged by the Ethernet Taps are collected by the network analyzer. The network analyzer is equipped with two network interfaces (Gigabit Ethernet) and is able to timestamp in hardware (timestamp resolution of 8 ns) two parallel streams. As shown in Fig. 6, the experimental set-up allows to estimate $T'_L = T'_{RX} - T'_{TX}$, which can be considered an accurate estimation of T_L, considering that the contribution of Ethernet cables ($T_{C,1}$ and $T_{C,4}$) is constant and negligible (on the order of 2 ns for a 0.5m long Ethernet cable).

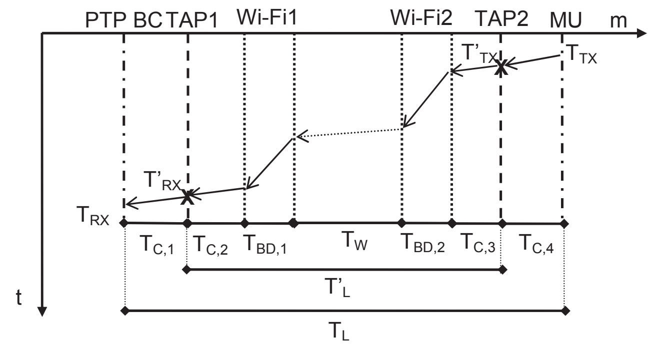

Figure 6. The contributions to communication latency and their estimation.

The communication latency evaluated configuring the IEEE 802.11 devices to work in AP mode, using protocol IEEE 802.11b in 2.4 GHz band, is shown in Fig. 7. The mean value of the latency evaluated over an observation interval of 20 minutes (about 600 samples) is 0.7 ms, while the standard deviation is 0.06 ms. The maximum latency remains, during all the observation interval, below 1.5 ms. It should be noted as, sporadically, the communication latency is affected by additional noises, which is due to collision with other packets on the wireless channel. The IEEE 802.11 devices used during the experiments support an additional working mode, the so called industrial Point Coordination Function (iPCF), which improves the real-time behavior of the communication over IEEE 802.11 links. The communication latency, estimated over 1200 s configuring the devices in iPCF mode (IEEE 802.11a in 5 GHz frequency band), is shown in Fig. 8.

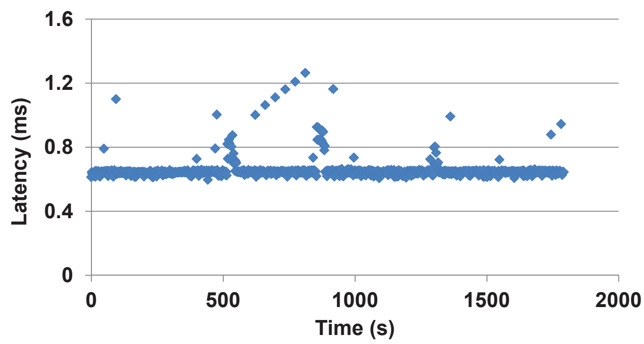

Figure 7. The communication latency evaluated using IEEE 802.11 infrastructure configured in Access Point mode (IEEE 802.11b 2.4 GHz).

The distribution of the communication latency (estimated over 600 samples) clearly highlights the effect of the iPCF mode, i.e. it provides a deterministic upper bound (6.2 ms in this case) to the communication latency, limiting the effect of traffic congestion. The results obtained using different device and network configurations are summarized in TABLE II. Note as the different working modes affect in different way the communication latency: the AP mode provides the best results compared to bridge mode. In addition, as a general consideration, the devices working in 5 GHz band are less affected, compared to devices working in 2.4 GHz band, by the communication interference with other devices

TABLE II. THE COMMUNICATION LATENCY EVALUATED CONSIDERING DIFFERENT IEEE 802.11 CONFIGURATIONS.

Protocol	Datarate (Mb/s)	Mode	Freq.(GHz)	Channel	Latency(ms)						
					mean	*Std.dev.*	*Mode*	*min*	*jitter*	*95-perc.*	*99-perc.*
IEEE 802.11b	11	Bridge	2.4	1	3.7	6.7	2.2	2.2	63	5.9	37.1
IEEE 802.11g	54	AP	2.4	6	2.9	2	2.2	2.2	17.2	4.5	15.3
IEEE 802.11b	11	AP	2.4	6	0.7	0.1	0.6	0.6	0.7	0.7	1
IEEE 802.11a iPCF	54	AP	5	36	3.3	1.6	1.6	0.8	5.45	5.9	6.2

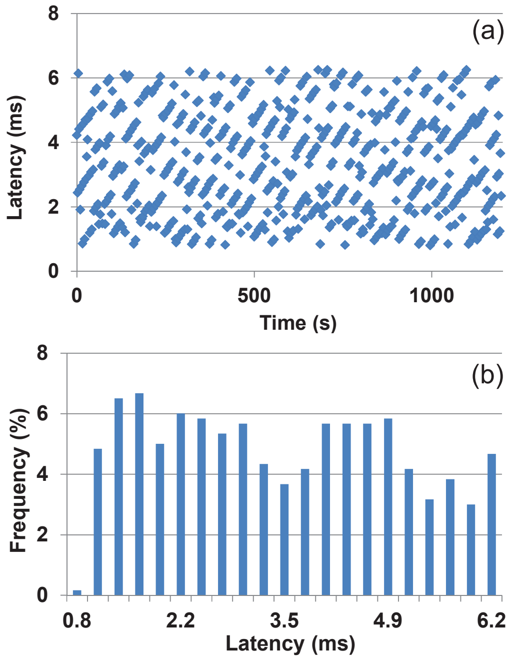

Figure 8. The communication latency (a) and the distribution of the communication latency (b) evaluated using the IEEE 802.11 infrastructure configured in iPCF mode (IEEE 802.11a 5 GHz).

B. *Evaluation of PMU algorithm*

The tests prescribed by the synchrophasor standard have been performed considering the MU free-running mode. A 1 µs worst case maximum synchronization offset is contemplated for each test. As mentioned in Section III, this worst case boundary is obtained considering a maximum free running interval of 6 s. In the case of longer interval, the synchronization error exceeds the time synchronization constraints of the PMU. All the simulated test results are obtained with a sampling frequency F_s=4000 Sample/s (80 Sample/cycle at 50 Hz) as suggested by the standard IEC 61850-9-2 for protection purposes. In the following, the obtained measurement errors are compared with the limits given by the synchrophasor standard [24], along with its amendment [26], for the measurement reporting rate of 50 frame/s. The reported limits, unless otherwise indicated, refer to the stricter limit between P-class and M-class, thus allowing to appreciate the "P+M" compliance.

TABLE III. MAXIMUM TVE % FOR STEADY-STATE TESTS

Test Type		TVE %	
		Limit	***IEEE 802.11***
Signal Frequency (range: $f_0 \pm 5$ Hz)		1	0.22
Harmonic distortion (10 % each Harmonic)		1	0.05
Out-of band interference (10% of signal magnitude with f_0 at 47.5 Hz, 50 Hz, 52.5 Hz)	25 Hz	1.3	0.27
	75 Hz	1.3	0.26

Table III shows results in terms of maximum TVE % for synchrophasor estimations and steady state tests. The system provides a good performance in presence of off-nominal frequencies, harmonic and interharmonic distortion. The results show that compliance with the M-class of the standard is reached in steady state conditions, even in presence of degraded synchronization.

TABLE IV. MAXIMUM TVE % FOR DYNAMIC TESTS

Test Type		**TVE %**	
		Limit	***IEEE 802.11***
M-class Modulation (max f_m = 5 Hz)	AM k_x = 0.1	3	0.211
	PM k_a = 0.1	3	0.696
P-class Modulation (max f_m = 2 Hz)	AM k_x = 0.1	3	0.046
	PM k_a = 0.1	3	0.088
Frequency ramp ($f_0 \pm 5$ Hz, ±1 Hz/s)	1 Hz/s	1	0.046
	-1 Hz/s	1	0.031

The test results in dynamic cases (modulation and frequency ramp) are shown in Table IV. In such cases, compliance with the standard is easily obtained.

Frequency estimation results are shown in Table V and VI. Such results are reported, in terms of frequency error (FE), to highlight that the impact of synchronization offset is very small for frequency estimation. In fact, as aforementioned, the time-shift does not have any impact in frequency estimation under steady-state conditions, while for dynamic signals, its impact is small because of the low rate of change of frequency.

TABLE V. MAXIMUM FE FOR STEADY-STATE TESTS

Test Type		FE [Hz]	
		Limit	***IEEE 802.11***
Signal Frequency (range: $f_0 \pm 5$ Hz)		0.005	0.0004
Harmonic distortion (10 % each Harmonic)		0.005	0.0011
Out-of band interference (10% of signal magnitude with f_0 at 47.5 Hz, 50 Hz, 52.5 Hz)	25 Hz	0.01	0.0043
	75 Hz	0.01	0.0022

TABLE VI. MAXIMUM FE FOR DYNAMIC TESTS

Test Type		FE [Hz]	
		Limit	***IEEE 802.11***
M-class Modulation (max f_m = 5 Hz)	AM k_x = 0.1	0.3	0.0005
	PM k_a = 0.1	0.3	0.0892
P-class Modulation (max f_m = 2 Hz)	AM k_x = 0.1	0.06	0.0001
	PM k_a = 0.1	0.06	0.0187
Frequency ramp ($f_0 \pm 5$ Hz, ±1 Hz/s)	1 Hz/s	0.01	0.0002
	-1 Hz/s	0.01	0.0002

The results for rate of change of frequency (ROCOF) estimations are shown in the Tables VII and VIII, in terms of maximum ROCOF error (RFE). As happens for frequency estimation, ROCOF evaluation is only slightly affected by synchronization offset in the dynamic cases. As a consequence, the accuracy of the PMU in frequency and ROCOF estimations is almost the same as in the Ethernet-based architecture.

TABLE VII. MAXIMUM RFE FOR STEADY-STATE TESTS

Test Type	RFE [Hz/s]	
	Limit	***IEEE 802.11***
Signal Frequency (range: $f_0 \pm 5$ Hz)	0.1	0.0086
Harmonic distortion (10 % each Harmonic)	0.4	negligible

TABLE VIII. MAXIMUM RFE FOR DYNAMIC TESTS

Test Type		RFE [Hz/s]	
		Limit	***IEEE 802.11***
M-class Modulation (max f_m = 5 Hz)	AM k_x = 0.1	14	0.32
	PM k_a = 0.1	14	1.03
P-class Modulation (max f_m = 2 Hz)	AM k_x = 0.1	2.3	0.06
	PM k_a = 0.1	2.3	0.90
Frequency ramp ($f_0 \pm 5$ Hz, ±1 Hz/s)	1 Hz/s	0.2	0.10
	-1 Hz/s	0.2	0.10

Table IX reports the results in terms of maximum response time of TVE, frequency and ROCOF for the amplitude and phase step tests. The limit of the standard for the under/overshoot is 5% and in the tests it is always lower than 1%, while delay time is far smaller than the required 5 ms. Thus, compliance with P-class and, as a consequence, with M-class is obtained.

TABLE IX. STEP TESTS RESULTS: MAXIMUM RESPONSE TIME AND MAXIMUM UNDER/OVERSHOOT

Test Type	***TVE response time (ms)***		***Frequency response time (ms)***		***ROCOF response time (ms)***	
	Limit	***IEEE 802.11***	***Limit***	***IEEE 802.11***	***Limit***	***IEEE 802.11***
Amplitude Step (±10 %)	40	18	90	34	120	36
Phase Step (±10°)	40	19	90	46	120	46

The results show that, when the wired process bus is unavailable and only the IEEE 802.11 is working during network recovery, the distributed PMU could measure synchrophasors in compliance with the M class, if the IEEE 802.11b AP Mode is used. In fact, in this case, the latency introduced by wireless communication is below 1 ms, thus allowing the P+M PMU to operate correctly. For other IEEE 802.11 configurations, the communication latency is higher and prevents the PMU from respecting also the latency compliance required for P class. In particular, as it can be seen from Table II, IEEE 802.11b Bridge Mode, presents a worst case latency that is almost equal to the maximum PMU latency required by the standard (40 ms) and thus it should not be used in any application. On the contrary, if the other IEEE 802.11 configurations are used (namely those based on IEEE 802.11g and 802.11a), even if "P+M" compliance is not possible, it seems reasonable to safeguard protection functionalities. Thus, as described in Section V, a low latency P-class compliant algorithm could be triggered in contingency conditions. This shows how the chosen IEEE 802.11 communication protocol and configuration have an impact on the possible operative modes of the PMU and why it is not possible to use a generic P-class algorithm.

VII. CONCLUSIONS

Network infrastructure is one of the main weakness points of a distributed PMU system in electrical substations. The availability of the process bus can be improved using a wireless parallel connection in addition to wired infrastructure. In case of fault on the cabled connection, the measurement information can be transferred using the wireless link. Nevertheless, the performance of a wireless infrastructure is lower compared to wired network. In particular, experimental tests on IEEE 802.11 industrial devices have provided that communication latency could range from one to tens of milliseconds. It has been shown that, with the algorithm proposed in [25], a single PMU output compliant with the P and M class of synchrophasor standard can be achieved with the most performing IEEE 802.11 solutions. In other situations, when the wireless communication introduces higher latency, the PMU algorithm can be designed to maintain compliance with P-class, in order to safeguard protection functionality, also during temporary network failures.

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