Wireless Infrastructure M2M Network For Distributed Power Grid Monitoring

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Abstract—With the massive integration of distributed renewable energy sources (RESs) into the power system, the demand for timely and reliable network quality monitoring, control, and fault analysis is rapidly growing. Following the successful deployment of Phasor Measurement Units (PMUs) in transmission systems for power monitoring, a new opportunity to utilize PMU measurement data for power quality assessment in distribution grid systems is emerging. The main problem however, is that a distribution grid system does not normally have the support of an infrastructure network. Therefore, the main objective in this paper is to develop a Machine-to-Machine (M2M) communication network that can support wide ranging sensory data, including high rate synchrophasor data for real-time communication. In particular, we evaluate the suitability of the emerging IEEE 802.11ah standard by exploiting its important features, such as classifying the power grid sensory data into different categories according to their traffic characteristics. For performance evaluation we use our hardware in the loop grid communication network testbed to access the performance of the network.

I. INTRODUCTION

As distribution moves quickly towards an active grid, ensuring balance and stability of grid monitoring in a timely manner requires a robust communication network that can monitor the measured data from different parts of the electrical grid together with an advanced management capability to detect any operational problem. For the Wide Area Measurement System (WAMS) of a transmission grid, for instance, online data and information from the entire system have been very effective in securing operations and control of interconnected systems. In general, system data and information provided by sensors and measurement devices are widely different in terms of their importance, format, and volume and can be classified as Operational and Non-Operational data. The former is mainly concerned with instantaneous measurement of voltages, currents, phasors, and breaker statuses that are measured by intelligent devices (IEDs) or PMUs, and transmitted in real-time. Supervisory Control and Data Acquisition (SCADA) and synchronized Phasor Measurement System are two operational data resources in this category. Traditionally, remote terminal units (RTUs) represent the data acquisition part of a SCADA, while PMUs provide real-time visibility to the dynamics of the power system that can complement traditional SCADA measurements [1, 2]. PMUs are currently being installed in the transmission grid. Their future deployment in the distribution grid is expected to play an important role in improving grid system robustness. In particular, future distribution grids may consist of a large volume of renewables, which need to be managed by a control system that would require the support of a reliable communication network.

In a conventional transmission system, wired sensor technologies are largely used in power plants and substations to control and monitor critical parameters. The distribution system does not normally have the support of any infrastructure network. Despite the fact that wired technologies offer a good level of reliability and security, they are very costly. Therefore, wireless communication networks would be the most cost effective solution. Such networks must be able to carry large data, measured by sensors and actuators. While some are very short and sporadic in nature with a very low duty cycle, the main traffic consists of PMU data which is in real-time and has low latency requirements. It is important that a wireless network should be capable of handling heterogeneous traffic patterns with various Quality of Service (QoS) requirements, such as bandwidth and delay. In particular, as the deployment of PMUs and the use of smart sensors throughout the grid continue to grow, it is important to design a wireless network architecture that can deal with the large quantity of data generated by these devices. Under these conditions, the quest to integrate all sensory data into a single communication network that can cope with the anticipated high traffic data under limited radio frequency (RF) spectrum resources, is becoming a challenging task.

Recently there has been tremendous effort in promoting the wireless based 'Internet of Things' (IoT), or simply 'Machine to Machine' (M2M) communications for wide ranging sensory devices [3-6]. For synchrophasor applications, however, M2M-driven IoT will differ fundamentally from those considered for large scale sensor networks. In particular, the realization of grid monitoring will require low delay and real-time communications. For instance, the bandwidth of a synchrophasor data, while depending on its reporting rate, may take up to a few hundreds Kb/s per PMU node. Since there are always many types of sensors and actuators which together can generate a large amount of data, a careful assessment of the overall bandwidth and delay requirements is essential for future design and planning. Bear in mind that, for most sensor applications, a low power wireless access network has been the main requirement of IoT applications. In a distributed grid system, while the power supply is readily available, these networks should also be able to function during the outage period, which could last for hours or days. In other words, the wireless network should be able to operate in power saving modes.

For IoT communication, the 3rd Generation Partnership Project (3GPP) has recently introduced a new Radio Access Network (RAN) technology in LTE Release 13 called Narrow Band Internet of Things (NB-IoT) [7]. NB-IoT can provide low-cost and long battery life, which would be suitable for supporting a large number of devices. While NB-IoT could be a viable future candidate for a cellular network solution, there is also an emerging Wireless LAN (WLAN) standard known as IEEE 802.11ah. Compared with other advanced low-power wireless network technologies, such as NB-IoT, which are primarily designed for low date rate applications, the IEEE 802.11ah can support higher bandwidths, therefore is able to handle synchrophasor communication. Moreover, when we look at other technologies in terms of coverage, overhead, power consumption, and network reliability, we believe that the IEEE 802.11ah is currently the best candidate for distribution grid sensing and monitoring applications. Therefore, in this paper we are mainly concerned with evaluating the suitability of the new standard by exploiting some of its important features for synchrophasor communication, as well as other operational and non-operational data. The evaluation is carried out in real-time using our hardware-in-the-loop testbed.

In the following section we first describe the basic concept behind the synchrophasor network, which contains the bulk of traffic data used for monitoring power grid systems. We then present the communication network requirements for handling the synchrophasor data, as well as other periodic and non-periodic data. In Section III, after highlighting IEEE 802.11ah features, we then present our grouping strategy where real-time and non-real-time data are exploited for power quality monitoring. In Section IV, the performance of the IEEE 802.11ah for power grid monitoring is then presented using our hardware-in-the-loop testbed.

II. SYNCHROPHASOR NETWORK

Synchrophasor measurements are envisioned to be a key enabler for real-time power grid situational awareness and control. PMU technology provides phasor information that captures a snapshot of the grid monitoring area in real-time. These devices, which are dispersed in the grid system, measure the phase and voltage variation in buses to evaluate the degree of instability in the system. For example, PMU devices can be installed on buses/feeders throughout a grid system where each PMU representing a communication node that can send its measured data to the local Phasor Data Concentrator (PDC). PMU measurements are obtained by first sampling the voltage and current waveforms using Global Positioning System (GPS) and accurately time stamping each sample in order to provide a meaningful assessment of phase and amplitude variations across the grid. The sampled data are then used to compute the corresponding 60 Hz or 50 Hz phasor component as complex numbers representing the magnitude and phase angle of sinusoidal waveforms. As a result, synchrophasors measured across the power grid will have a common timing reference, hence can be used to assess the power quality and, if necessary, provide an early warning of deteriorating system conditions [8]. The PMU functionally consists of two parts: measurement and data streaming for communications. Both have been defined separately by the IEEE C37.118-1 [9] and IEEE C37.118-2 [10] standard, respectively. Part-1 [9] is mainly concerned with measurements of the synchrophasor parameters, PMU compliance and testing conditions, particularly frequency and rate of change of frequency (ROCOF). Part-2 [10] of the standard deals with the communication and networking aspects of the PMU by focusing on formats and data transfer between a PMU/PDC and a PDC.

As shown in Fig. 1, a synchrophasor network consists of multiple PMU nodes reporting to the local PDC. The PMU nodes are normally placed at sensitive locations and their main functionality is to gather data in real-time which will then be transmitted to the Local PDC (LPDC). The aggregated synchrophasor data collected at each LPDC is then forwarded through a wide area network to the so-called Master PDC (MPDC), which is normally located at the grid regional control center [1].

The synchrophasor data consists of the local measured amplitude and phase angles of voltage and current waveforms sampled at the same instant using 1 Pulse Per Second (PPS) GPS signaling. In addition, based on the measured amplitudes and phase angles, a PMU can then estimate the frequency and rate of change of frequency which will be a part of the PMU data.

Indeed, in power system frequency is a good indicator of the systems' stability in Alternating Current (AC). Under ideal conditions the frequency should remain constant and close to the nominal frequency of 50 or 60 Hz. In reality, however, frequency of voltage and current signals tend to deviate from the nominal frequency due to a mismatch between generators and loads. Therefore, measuring the frequency is crucially important in evaluating the power quality. Indeed, the main objective of monitoring power quality in a distribution or transmission system is to allow grid operators to observe and detect disturbances almost as quickly as they occur. To achieve this, it is essential to develop a suitable wireless access technology that can support communication between PMUs and a PDC.

To establish an end-to-end communication link between PMU and PDC, the first step is to set up real-time message communications at the application layer based on the IEEE C37.118-2 standard, which specifies commands and data exchange between a PMU and PDC for real-time communication [9]. The C37.118-2 has also specified a PDC-to-PDC communications protocol for a local PDC to send the aggregated data to the next level PDC (e.g., MPDC). The PMU data frame includes current and voltage amplitudes, their synchronized phasor angles, frequency, as well as a ROCOF. Both PMU-to-PDC and PDC-to-PDC frames also include SYNC, frame size, identification code (i.e., ID Code), a time stamp, which is specified as a Second-Of-Century (SOC) and fraction of second (FRACSEC) of the received data frame, bit-mapped flags (STAT), analog data (ANALOG), digital data (DIGITAL), and CTC check bits (CHK). A PDC after it receives data from its associated PMUs within a predefined time period, will first align the frame according to the time stamps. In a two-level structure as shown in Fig. 2, each local PDC will then send the time aligned aggregated data to the MPDC at the utility control center. The PDC-to-PDC frame size will grow depending on the number of PMUs that report to each local PDC. A method that can reduce the PDC-to-PDC frame size has been investigated in [11]. In addition, [11] also describes a software based implementation architecture for real-time data streaming between PMU-to-PDC and PDC-to-PDC.

The PMU data streaming is built on top of the user datagram protocol over internet protocol (UDP/IP). UDP/IP Compared with TCP/IP is much simpler and more suitable for real-time transmission. For the network layer we use Emulab [12] consisting of 80 switches where each can be either assigned to a PDC or a PMU.

III. M2M NETWORK FOR GRID MONITORING

A major component of a distribution grid monitoring system is the communication aspect in order to support a wide range of data information generated by different types of devices throughout the grid. Indeed, designing a high-performance communication network has been the main driving force in research for the future generation of smart grid to manage energy use and grid monitoring.

The need for rigorous power monitoring and protection is becoming more pressing particularly with the increasing amount of distributed energy resources (DERs) on customer premises [13, 14]. These DERs, which include technologies such as photovoltaic (PV), wind generators, and storage, need operational management and control in the utility distribution system. Bear in mind that traditional distribution grids, which are based on passing power from bulk generators to consumers, face new challenges to manage and control the increasing penetration of DERs. In the absence of any infrastructure network, the main challenge, however, is developing a unified wireless-based IoT that can accommodate all types of traffic that exist throughout the distribution grid system.

Fig. 2 shows a possible coverage of M2M communication for a grid system that consists of various entities including transmission, substation facilities, and distribution. These entities are comprised of many devices such as smart meters, smart sensor nodes, switches, relays, circuit brakes, renewable energy sources, and different types of data collectors, which need to communicate with the control center. As a consequence, it will be necessary to implement communication network architecture to deal with diverse quantity of data generated by those devices.

While the emerging 5G has envisioned a cellular-based network for IoT applications, a new wireless WLAN standard, referred to as IEEE 802.11ah, is being introduced [15-18]. This aims to extend Wi-Fi applications in a sub-1GHz spectrum with carrier frequencies around 900 MHz and an extended coverage up to 1 km in outdoor areas [15]. It can support up to 8191 devices associated with a single Access Point (AP). A 13 bits hierarchical addressing mechanism is used to classify stations (STAs) according to their type of applications, where the AP assigns an Association Identifier (AID) to each STA. In this arrangement, the AID supports four hierarchical levels such as page, block, sub-block, and station’s index in sub-block that are used in the signaling beacons. Its physical layer (PHY) is based on Orthogonal Frequency Division Multiplexing (OFDM) with a 32 or 64 tones/sub-carriers. 802.11ah supports a set of Modulation and Coding Schemes (MCSs), where Binary Shift Keying (BPSK), Quadrature Shift Keying (QPSK) and 16 to 256 Quadrature QAM modulations are employed. It can provide access for 1, 2, 4, 8, and 16 MHz bandwidths, but all stations have to support 1MHz and 2MHz.

Although IEEE 802.11ah has many other attractive features, here we are mainly exploring those that are most suitable for synchrophasor communication. In other words, our goal is to provide communication between a PMU station and a PDC representing an AP. It is important to note that synchrophasor communication is mainly dominated by the uplink data (i.e., PMU-to-PDC). Since PMU measurements are GPS synchronized at 1 PPS, they tend to transmit their data frames as soon as their measurements are complete. This could consequently result in transmitting PMU data packets in about the same time and cause severe contention. Furthermore, the low delay requirement together with real-time nature, as well as relatively high data rates of synchrophasor data, can put a tremendous strain on the network. Overcoming these constraints would require a careful exploitation of the IEEE 802.11ah capabilities. It should be noted that despite PMU's real-time operational requirements and its relatively upstream high data rates, there exists many other low traffic sensory devices within power grid systems (especially distribution).

Indeed, the IEEE 802.11ah has the ability to handle diverse categories of sensor data. In particular, it offers an efficient power saving mechanism, which is based on a new Traffic Indication Map (TIM) classification. For instance, the standard defines three types of stations: TIM station, Non-TIM station, and unscheduled station. TIM stations have to listen to AP beacons to send or receive data within the new channel access method called restricted access window (RAW), whereas Non-TIM stations can get permission from the AP for transmission through a periodic restricted access window (PRAW). The unscheduled stations can request sending data outside RAW by sending a poll frame to the AP at any time, hence they are not required to listen to any beacons to transmit data. A channel access for all the aforementioned stations is shown in Fig. 3. Also, as shown in this figure, there are two types of signaling beacons: TIM and Delivery TIM (DTIM). The TIM beacon, which contains a TIM element, is periodically broadcasted by the AP (every TIM interval). The DTIM aims to inform stations that the AP has a data in its buffer and is ready to be delivered to them [17].

For synchrophasor applications we consider PMUs as a TIM stations using a TIM grouping structure. In each RAW duration, only one group of PMU stations would be able to access the channel. Bear in mind that TIM stations access the channel using the EDCA operation which is based on transmission opportunity (TXOP). A TXOP is a bounded time interval where a PMU station can send a frame in real-time as long as the period of the transmission is less than the specified duration. PMU stations receive the duration and the start time of their RAW contention period via a beacon transmitted by the PDC (e.g., AP). These stations can then access the channel within each RAW period.

In TIM grouping a RAW can be assigned to one or more PMU stations. Since the RAW is also divided into a number of time slots, we considered two approaches for real-time synchrophasor applications. In the first approach (Configuration-A) there is a single RAW in a TIM interval and all the PMUs are allocated to this single RAW, but each is assigned to a different slot (see Fig. 4). In the latter approach (Configuration-B), there are multiple RAWs in a TIM interval and each RAW, using only a single time slot, is assigning to one PMU station. Thanks to the flexibility provided by the new standard the GPS synchronized data which is normally generated around the same time can be taken care of by the new RAW assignment - as long as they do not exceed the maximum selected IEEE 802.11ah capacity. Apart from PMUs we also plan to include other low-traffic volume sensory data in our network as either Non-TIM stations through the PRAW or as unscheduled stations. In these scenarios, multiple PMUs periodically send synchrophasor measurements to a PDC (acting as AP) at specific frame rates, hence dominating uplink traffic (i.e., PMUs-to-PDC).

IV. Performance Evaluation

In this section we evaluate the performance of synchrophasor networks using our hardware-in-loop testbed. The testbed is specifically designed to support CPS-enabled smart grid applications. It is based on an emulation platform that allows a large number of virtual nodes to be created to communicate in a centralized or distributed manner. The network consists of 80 Emulab nodes where each can be configured to represent a PMU, a PDC, or other types of sensors considered in this paper. The testbed also includes necessary modules and services that can support application development for any type of sensory device. For instance, we have developed an interfacing capability for deployment of commercial PMUs, including GPS synchronization of all PMU nodes in the network. The testbed is supported by a software-based grid network modelling using the Electro Magnetic Transients Program (EMTP) software tool, where PMU nodes and other devices can be placed at any desirable location in the grid network. For the wireless medium access control (MAC) layer and PHY layer, we use the IEEE 802.11ah. Scenarios with different RAW configurations are investigated and compared in order to find the best configuration for synchrophasor networks operating in IEEE 802.11ah mode.

Table I displays some of the important PHY and MAC layer parameters employed in our model. Communication amongst PMUs and a local PDC is accomplished through IEEE 802.11ah. The wireless link's bandwidth is set to operate at 2Mb. The noise figure is 3.0 dB and the frequency is 900MHz. The beacon interval and the RAW group duration are set to 0.1 second. The packet payload size is set to 64 bytes, which is the packet size of a C37.118 data frame sent by PMUs to PDCs. PMUs are randomly distributed in a circle around the PDC (AP) within a distance of 500 meters. The retransmission limit is set at 1, based on the consideration that when a packet is lost it may not be necessary to retransmit it since the data packet with next time stamp is expected to arrive via the next data frame [11]. A small buffer space is used to reduce latency. A set of sampling rates, namely 10, 20, 30 and 60 frames per second is used for PMUs to evaluate the network performance in terms of throughput and packet loss. Throughput is the amount of data packets successfully received by an AP per second, and measured in Megabits per second (Mbps). Packet loss rate is the percentage of packets lost with respect to packets sent.

In Fig. 5, the throughput and packet loss rate performance is evaluated for a synchrophsor network where 32 PMUs periodically generate and send data packets (synchorphasor measurements) to a local PDC (AP) over a 600 second period. In these figures, MCS0 [15] and 2MHz bandwidth are used for Wi-Fi mode. Five RAW configurations are investigated as follows: configuration-1 with 32 RAW groups and each group consisting of a single slot, configureation-2 with 1 RAW groups and each RAW group consisting of 32 slots, configuration-3 with 8 RAW groups where each consists of a single slot, configuration-4 with 1 RAW groups and each group consisting of 8 slots, and configuration-5 with 1 RAW groups and each group consisting of a single slot. Fig. 5 showed that configuration-1 and configuration-2 achieved the best performance, while configuration-5 obtained the worst performance. This is due to the fact that assigning PMUs into RAW groups reduces contention, hence lowering collision probability. More groups and slots result in a better performance as long as the duration of each slot is large enough for one packet transmission.

In Fig. 6 the impact of the number of PMUs, *N*, associated with a local PDC is accessed by using a configuration consisting of 32 RAW groups where each group contains a single slot. As can be observed, with an increasing number of PMUs, the throughput performance degraded due to more contention and collision.

These preliminary experimental results indicate that the IEEE 802.11ah is capable of handling real-time PMUs' communications, as long as the frame rates and number of PMUs are carefully selected. We should emphasis that one of the main features of the emerging standard is its operation in sub-1 GHz spectrum. This improves the transmission range considerably as compared to other IEEE 802.11 WLANs, which are operating in 2.4 GHz and 5 GHz bands. To a large extent, such an important feature can overcome the need for using multihop transmission, which renders itself susceptible to more delay and packet loss as we previously experienced [11]. In addition, as described above, using a novel RAW channel access mechanism would make this emerging standard very efficient in terms of overhead, power saving, and low latency, which would be crucial for a timely assessment of power quality.

Apart from PMUs we also plan to include other low-traffic volume sensory data in our network as either Non-TIM stations through the PRAW or as unscheduled stations. In Fig. 7, the presence of other devices, namely 50 low-data-rate IoT sensors and 15 unscheduled stations, are investigated and evaluated in the scenario where 30 PMUs periodically generate and send synchrophasor measurements (payload size being 64 bytes) to the same AP over a 600 second period. Two schemes are considered, namely the group scheme and the no-group scheme. In the group scheme, three RAWs each consisting of 10 slots are assigned for 30 PMUs, one PRAW is assigned for 50 IoT sensors with a frame rate of 1 packet/s and payload size being 32 bytes, while 15 unscheduled stations compete for the rest with the frame rate around 2 packet/s and payload size of 32 bytes. Comparatively, in the no group scheme, all 95 devices compete for the channel without a RAW and PRAW mechanism. In this simulation, MCS1 and a 2MHz bandwidth are used for Wi-Fi mode. A set of sampling rates, namely 10, 20, 30 and 60 frames per second is used for PMUs while other devices keep the same frame rate and payload size. Fig. 7 demonstrates the significant advantage of the group scheme over the no group scheme. Thanks to the RAW and PRAW mechanism of the IEEE 802.11 ah, interference is mitigated and minimized in the group scheme.

V. Conclusion

The future Distributed Generation (DG) grid, where renewable energies and MicroGrids play an important role, constitutes a new intelligent management system to handle a wide variety of sensors and actuators with different network characteristics. In particular, the future grid is expected to deploy PMUs which have proven to be very effective in real-time monitoring of the grid. As the communication network is an essential component of grid monitoring, in this paper we investigate the performance of the emerging IEEE 802.11ah WLAN standard. As the use of other types of smart sensors throughout the grid continues to grow, we have classified the data in such a way that can efficiently exploit the wireless access flexibilities envisioned by the IEEE 802.11 standard.

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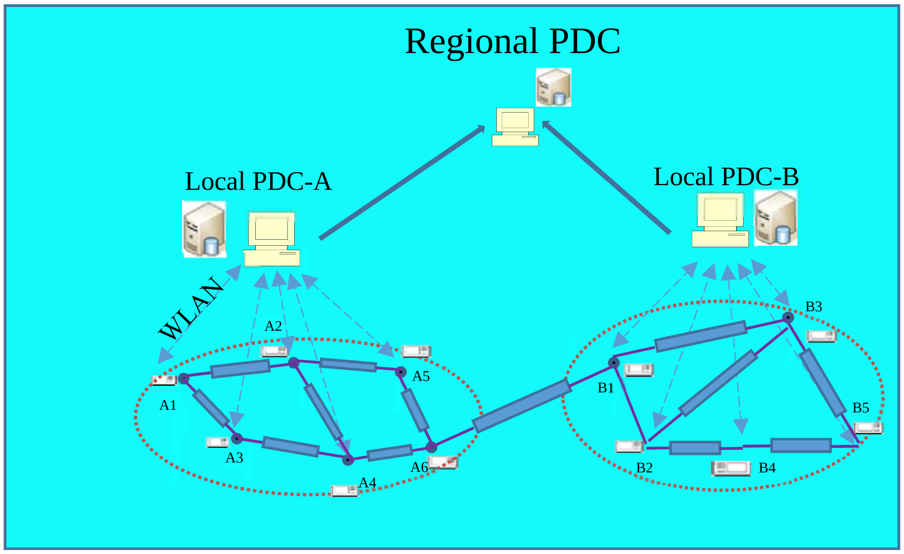

Fig. 1: Hierarchical synchrophasor network with two local PDCs

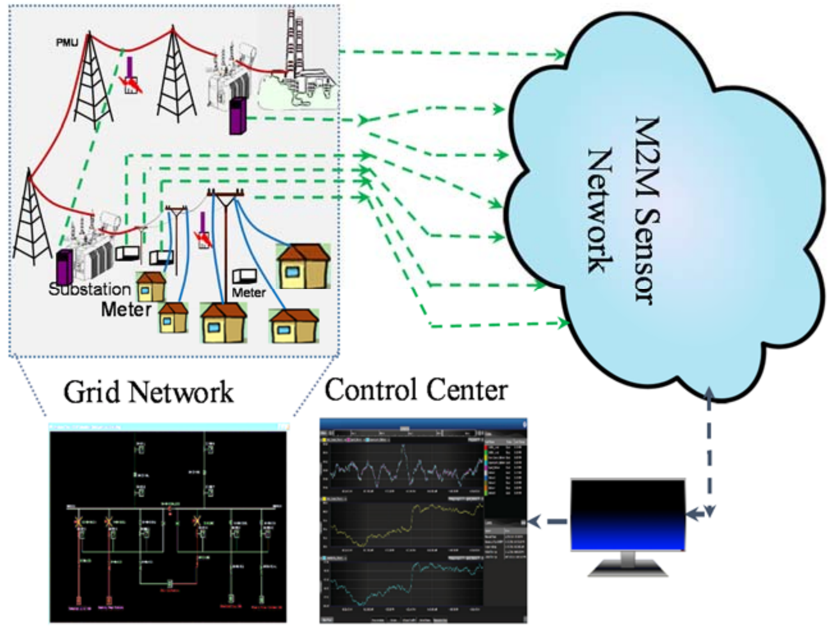

Fig. 2: M2M communication for Transmission and distribution electrical networks.

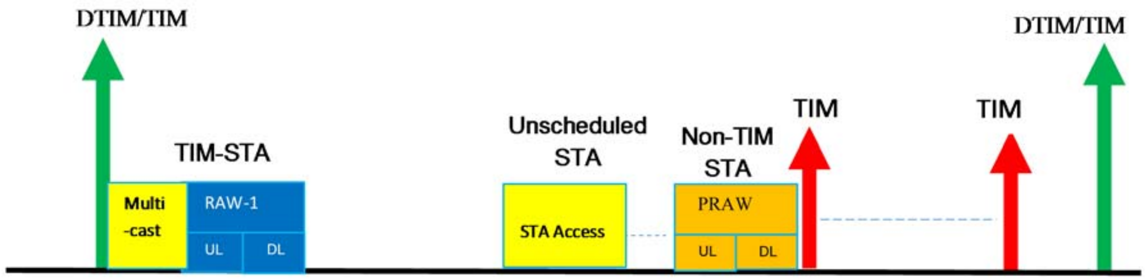

Fig. 3: IEEE 802.11ah channel access for TIM STA, Non-time STA, and Unscheduled STA.

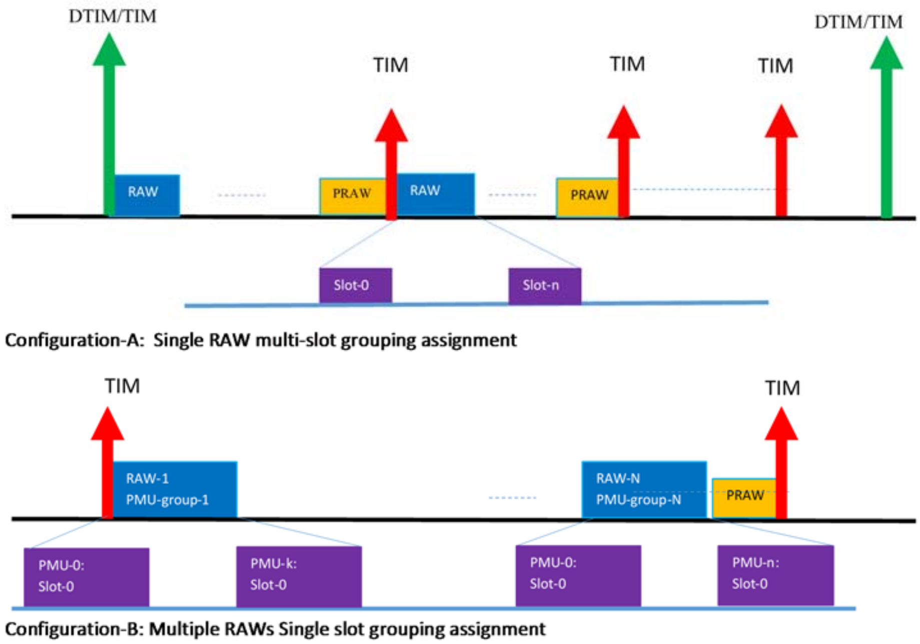

Fig. 4: Two approaches for real-time synchrophasor applications.

TABLE I: DEFAULT PHYSICAL AND MAC LAYER PARAMETERS USED IN OUR EXPERIMENTS

Parameter	Value	Parameter	Value
Frequency (Mhz)	900	MAC header type	legacy header
Channel Coding	Binary Convolutional Coding (BCC)	Beacon Interval (s)	0.1
Noise Figure (dB)	3	AIFSN	3
Propagation loss model	Outdoor, macro	Wi-Fi mode	MCS0/MSC1, 2 Mhz
Error Rate Model	YansErrorRate [19]	Payload size (bytes)	64
CWmin	15	Cross slot boundary	enabled
CWmax	1023	Rate control algorithm	constant

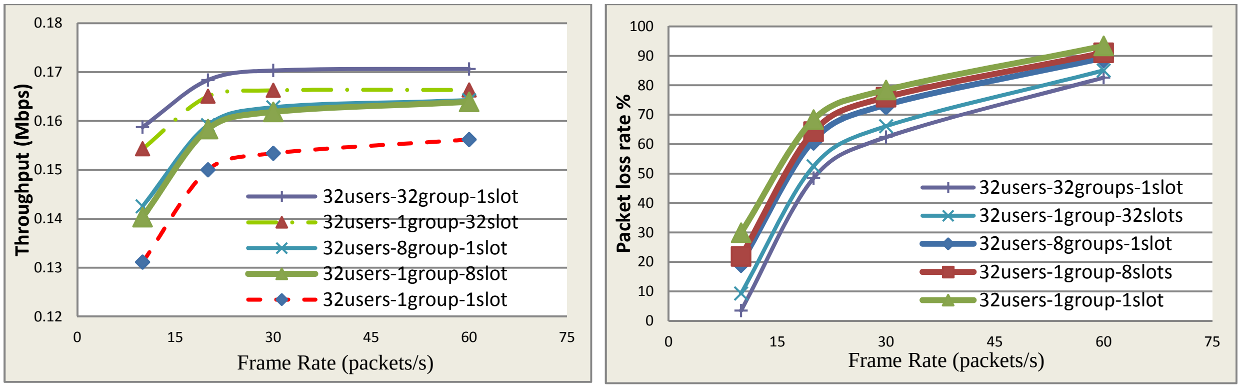

Fig. 5: Throughput and packet loss rate performance of the synchrophasor network operating in 802.11ah mode, where 32 PMUs periodically send synchrophsor data to a local PDC (AP).

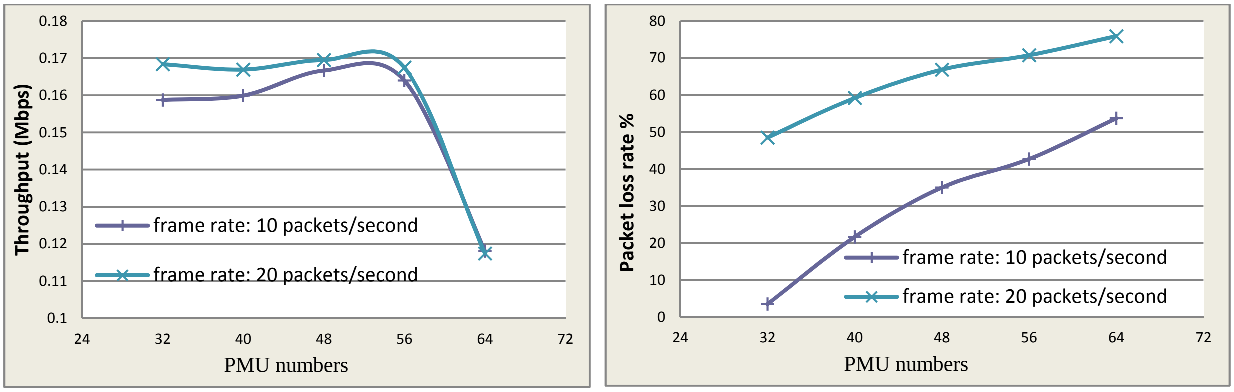

Fig. 6: Throughput and packet loss rate performance of the synchrophasor network operating in 802.11ah mode, where the impact of the number of PMUs (N) associated to a local PDC is accessed.

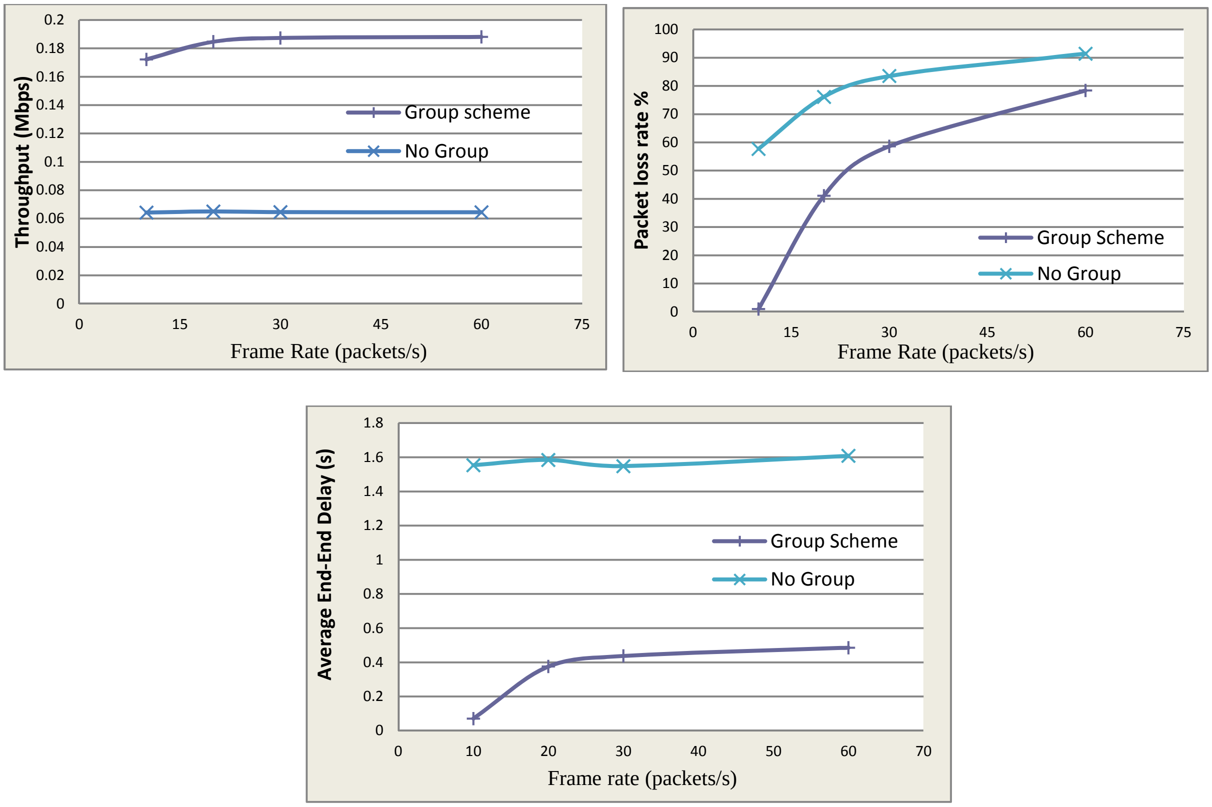

Fig. 7: Throughput, packet loss rate and average end-end delay performance of the considered schemes.