

A time-sensitive networking-enabled synchronized three-phase and phasor measurement-based monitoring system for microgrids

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Abstract

This paper presents the design and implementation of a Time-Sensitive Networking (TSN) protocol-enabled synchronized measurement-based monitoring system for microgrids. The proposed approach synchronizes and prioritizes the communication nodes, allowing it to transfer ultra-high three-phase sampled data and phasors. TSN is achieved by Quality of Service (QoS) profile software library. This allows control, monitoring, traffic scheduling, and prioritization. Some buses in a microgrid may have priority over others; and this can be prioritized at the data level too, where a part of the information is more critical than the others. The advantages of utilizing the TSN protocol on a microgrid with the approach proposed are: it is an alternative to GPS technology, three-phase data can be exchanged at much faster rate and data traffic in the network can be shaped with low packet loss, and low latency, in addition to providing interoperability through Data Distribution Services (DDS). These enhancements improve the communication reliability and enable distributed control, resulting in avoidance of any bottlenecks in the communications network. This proposed approach is implemented and demonstrated in a laboratory-scale microgrid. The results obtained, verify low latency and high throughput of the entire system while meeting the TSN and QoS requirements.

1 | INTRODUCTION

1.1 | Motivation

Historically, power grids were mainly comprised of large power plants based on conventional energy sources, with transmission and distribution networks distributing power to consumers [1]. Even though this power delivery paradigm has proven to be dependable and achieves economies of scale, concerns regarding resilience, robustness, and the push for use of renewable energy sources have called for alternatives to this approach. Microgrids break this customary paradigm. Based on the Department of Energy's definition, the microgrid is 'a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can

connect to and disconnect from the grid to enable it to operate in both grid-connected and island-mode'. Microgrid, for the most part, is comprised of Distributed Energy Resources (DERs), particularly renewable energy sources such as solar-photovoltaic systems and wind turbines, usually accompanied by some forms of energy storage devices, including batteries or supercapacitors [2–4].

Although microgrids offer numerous advantages, they come with engineering challenges. Solar and wind DER are, by nature, more variable and less predictable than power from conventional nuclear or fossil fuel plants. These renewable generation sources are integrated to the power grid and rely on power electronic circuitry for their operation. They also require more sensors, protection devices, control schemes, and communication technologies for their integrated operation. Most DERs are installed on the distribution network, where

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there is an absence of effective communication, monitoring, and control infrastructure in its existing state. Thus, this underlines the need for a monitoring and communication system to enable microgrid operation that meets stringent communication network requirements, including security, reliability, latency, bandwidth, and most importantly, interoperability (specifically in terms of adding more devices from any vendor). Such a monitoring system would improve grid performance and efficiency significantly, but also brings complexity to the integrated system design and analysis [5–9].

To address these complexities, develop functionalities, and analyse their performances, a hardware/software smart grid testbed infrastructure can be used. This testbed needs to support the necessary hardware and software environments to perform different experimental scenarios in real time [10].

1.2 | Literature review

Several microgrids that include hardware and software testbeds have been developed. The hardware structure consists of generators, transmission lines, storage devices, power electronic converters, and loads. The software includes communication and information technologies. However, there is a need to provide the tools and interfaces to integrate several platforms into a scalable system that is expandable and open to new services, components, and operation scenarios. This often leads to a high cost hardware, ad hoc software customization, and highly trained staff requirements. To address some of these problems, middleware can be used [11].

In this context, a middleware can offer common services and ease of software application development by integrating heterogeneous computing and communication devices and supporting interoperability within the diverse applications and services running on heterogeneous devices. These could even reside on the physical devices themselves and provide the necessary functionalities to enable service deployment [12].

The communication middleware is a crucial part of the microgrid testbed. It provides an abstraction layer that simplifies communication amongst the nodes irrespective of the underlying hardware architecture [13,14]. A good middleware also provides a standard Application Programming Interface (API) that helps in multiple and diverse use cases. The communication middleware can be classified into two sub-categories: message centric and data centric. The data-centric middleware technique is used more often because it has more advantages over the message-centric technique. For example, it is more flexible, more reliable, and less prone to errors. It also utilizes the network bandwidth more efficiently [15–17].

1.3 | Contributions

The research presented exploits a data-centric approach to address some of the challenges described above. It is implemented on the Data Distribution Services (DDS) technology from Real-Time Innovation (RTI). DDS is an open

communication protocol that is used to implement Machine-to-Machine (M2M) communication and information exchange. This framework allows to deploy real-time communication and information exchange system that is based on the publisher-subscriber concept and supports peer-to-peer communication. Applying Quality of Service (QoS) profiles using DDS distinguishes the proposed approach from other communication methods. Different QoSs can be applied for different data types making the framework agile and convergent, and thus it can be leveraged to deploy different communication and information exchange mechanisms that have a sense of time, prioritization, and synchronization. These capabilities allow to meet Time-Sensitive Networking (TSN) requirements. The contributions of the proposed microgrid monitoring and communication platform can be summarized are:

- To provide synchronization by offering a common time reference to all the nodes in the network, as an alternate to or in conjunction with Global Positioning System (GPS) technology.
- To provide prioritization of three-phase data and phasor data at the nodes from which data is collected.
- To provide a sense of time, making it time-critical in real time, by meeting TSN requirements, through QoS profiles.
- To enable interoperability, that is devices from any vendor and manufacturers integrated into the proposed framework can be used when adopting the DDS standard
- To provide means for network traffic shaping so to avoid bottlenecks through QoS profiles.
- To provide low latency and high throughput required for microgrid functions through QoS profiles.
- To provide experimental evidence on the implementation of the proposed approach in a laboratory-scale microgrid testbed.

The remainder of this paper is organized as follows: Section 2 describes different microgrid monitoring systems, their shortcomings, and how the proposed TSN-enabled approach can be a viable alternative. Section 3 is the proposed system, that is a TSN-enabled synchronized three-phase and phasor measurement-based monitoring system for microgrids. Section 4 presents the experimental validation, detailing each part of the testbed and hardware used. Section 5 depicts the results obtained using the experimental setup. Finally, Section 6 concludes the major findings of this work.

2 | MICROGRID MONITORING SYSTEMS

Microgrids are smaller in size and possess a number of assets when compared with the existing power grids, and communication networks are becoming a vital part for their operation [18] as they may need to operate in two different modes: power-grid connected or standalone. Extensive research has been conducted and several methods are used for monitoring microgrids. Conventionally microgrid monitoring is static and

in non-real time, resulting in additional time for acquiring the microgrid's response when operating in dynamic conditions [19]. These are well-known challenges in systems where Supervisory Control and Data Acquisition (SCADA) is widely used.

2.1 | SCADA

A SCADA system supervises, controls, and regulates the microgrid. It acquires data at regular intervals by polling field devices asynchronously. The polling rates are 1~3 s, resulting in time-skewed measurements with limited information. Other shortcomings of this monitoring system include the type of data collected is scalar and depend on power network models to derive additional information like the phase angle via a state estimator. A major drawback arises from the way data is collected that is non-coherent and a missing common time reference. This power grid monitoring system, that is SCADA, although sufficient for the operation of most of the power transmission grid infrastructures, is generally considered insufficient to meet the monitoring requirements while operating on the status of the newly emerging distributed power systems and microgrids.

2.2 | PMU

Phasor Measurement Units (PMUs) have emerged as a solution to the above stated problems associated with SCADA systems [20]. While some use cases are arising for distribution networks [21,22], they are mainly used in real-world applications only in transmission grids [23] and so far, they are not common for microgrids, but they may enable critical microgrid functions [24,25]. PMUs measure the phasor voltage and current of the field devices deployed. They all have a common time reference provided by the GPS technology, and they are also known as Synchrophasors due to this reason. Synchrophasors provide high-speed coherent data. PMU reporting rates vary from 30 to 120 samples/s by providing an alternative to SCADA. Figure 1 shows a conceptual PMU-based microgrid monitoring system contrasted with a conventional power grid PMU-based monitoring system.

Analysing Figure 1, significant challenges arise when considering the use of PMUs for a microgrid monitoring system, which have been revealed in the experience with transmission grid applications [26]:

- *Poor data quality*: due to poor synchronization of timing measurements [27].
- *Communication*: latency, network congestion, and failure of communication nodes [28].
- *Aggregator*: Data transformation may result in errors, delayed arrival of packets dropped due to exceeding time limits, and unwanted duplication or corruption of data during computations, while increasing the overall latency [1].

- *GPS issues*: Although GPS signal that is widely used in current Synchrophasors can provide a sub-microsecond timing accuracy, there exist geographical constraints and signal limitations, and GPS can be subject to spoofing attacks [29].

A direct implementation of PMU technology in microgrid is therefore not advisable, as the conventional approach to deploy the communication infrastructure is not scalable; however, it is expensive and inflexible. This article proposes an alternative approach to leverage the advantages of PMUs, while mitigating the limitations outlined above.

To leverage situation awareness and support timeliness, adequate quality checking methods must be in place. This article proposes an approach that meets these requirements by enabling TSN capabilities, that can be used for microgrid monitoring using PMUs or even ultra-high sampling rate three-phase measurements.

2.3 | TSN

TSN is the advancement of the standard Ethernet, particularly the IEEE 802.1AS standard that suggests time synchronization of devices utilizing packet transfer over Ethernet. This helps in traffic scheduling and system configuration thus enabling deterministic communication over the Ethernet by allowing users to schedule time-critical data across a network [30,31]. IEEE 802.1AS is an IEEE 1588 profile that provides a common time reference to all the nodes within the IEEE 802.1AS subnet, hence providing an alternative to the GPS-based synchronization while simultaneously being part of the data connectivity (network) of the system. It synchronizes multiple devices using packet-based communication and makes it possible over long distances without any signal propagation delay impact. I/O synchronization on devices using this profile is less than 1 μ s [32,33].

Because it is based on open standards, TSN can be implemented in different ways for different applications. TSN facilitates:

- *Time synchronization*: All devices share a common time reference and can synchronize with each other by synchronizing internal time signals with respect to that reference.
- *Traffic scheduling*: Adding mechanisms to ensure that information is delivered with a certain level of determinism for real-time communication without disrupting the currently existing prioritization mechanisms of non-TSN Ethernet.
- *System configuration*: Standardizing the parameters for configuration such as reservation of communication paths, time slots, and bandwidth to handle fault-tolerance and mission-critical information transfer.
- *Priority scheduling*: To schedule priority traffic among different end devices and switches with a shared notion of time.

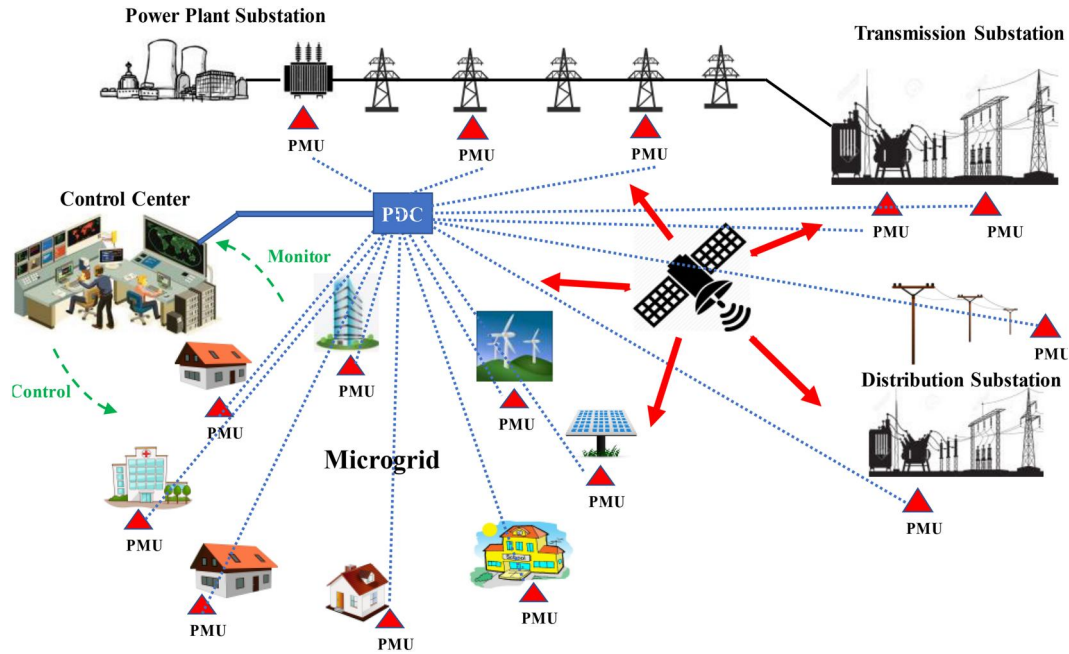


FIGURE 1 A conceptual PMU-based microgrid monitoring system and a traditional power grid PMU-based monitoring system

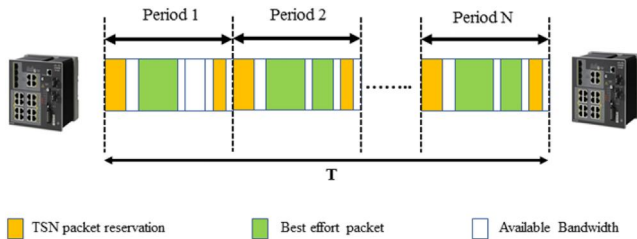


FIGURE 2 A data packet is transmitted between two TSN-enabled devices

In a TSN-enabled network, each transmission link has a schedule that includes flow IDs, Transmission offsets, and expected payloads. Figure 2 shows the data packet being transmitted between two TSN-enabled devices, where T is the total time taken between devices. There are N periods, and within each period there are three slots. Slot 1 that is yellow in colour presents TSN packet reservation containing high priority data, followed by white slot that acts as a transition between slots 1 and 3 and avoids any overlap. Slot 3, in green, is the best effort packet that avoids repetition and data duplicity in the network.

While PMUs have been used at the transmission level, to synchronize voltage and current phasor estimates, the embedded controllers used for power electronics and inverter control are usually not time synchronized. The same applies to other controllers and data acquisition systems that are part of the power grid.

With the augmentation of the TSN capabilities to a microgrid, synchronization can be attained. It ensures that

nodes of a microgrid derive their acquisition or generation timing from the same source. In the absence of proper synchronization, there is no way to know if two measurements happened simultaneously or, in the case of stimulus/response type testing, which stimulus the measurement is a response of. TSN provides the basic infrastructure for synchronization and a common time reference to all devices in the microgrid, while also providing traffic scheduling and system management capabilities [34–36].

All these are important in any smart grid and/or microgrid systems where data exchange between devices must be correctly time-stamped and arrive at its destination within a specific timeframe with minimum jitter. Most advanced control algorithms can take advantage of this capability in distributed systems where a unique time reference and deterministic communication between devices may enable the implementation of such concepts as multi-agent control systems while simultaneously improving the observability of the system.

The authors' previous work [37] presents the design and implementation of a multi-level TSN protocol based on a real-time communication platform utilizing DDS middleware. The performance of the developed protocol was tested and validated using data replay in real-time, that is replaying the voltage and current three-phase waveforms and phasors of a wind farm within different case scenarios. Satisfactory results were obtained for latency and throughput parameters of TSN at high message rates at the sampling rate of 100K samples per second. In this article, previous work is leveraged to enable a complete microgrid monitoring system and to demonstrate its feasibility in a laboratory-scale microgrid environment.

3 | PROPOSED TSN-ENABLED MONITORING SYSTEM FOR MICROGRIDS

To achieve synchronization, traffic shaping, prioritization, and scheduling on a microgrid, a TSN-enabled synchronized three-phase and phasor measurement-based monitoring system for microgrids is proposed and implemented in a laboratory-scale testbed. The proposed system is composed of two layers: a hardware layer for data acquisition and processing, and a virtualization layer for deploying TSN-enabled networking, as shown in Figure 3.

Figure 3 shows the general approach towards the monitoring system for microgrids, where it is bifurcated into the hardware layer and the virtual layer. The implementation of the hardware layer involves not only the hardware components for signal acquisition, but also the electrical components that comprise the microgrid, that is renewable energy sources such as photovoltaic (PV) panel, wind turbine, and microturbine along with a battery-based energy storage system, transmission line emulators, and alternate current (AC) and direct current (DC) loads are considered. All nodes use the virtual layer for sending the data through a common DDS data bus based on a TSN protocol.

In the sequel, only the hardware components related to communications are described because they are crucial for the proposed design in this article, while the power components are generic; the proposed virtualization layer is also discussed in detail.

3.1 | Hardware layer for data acquisition and processing

This layer can further be divided into data acquisition and communication components.

- *Data acquisition*: The data is acquired from different nodes. This measurement can be a phasor or three phase depending on the type of node and measurement equipment

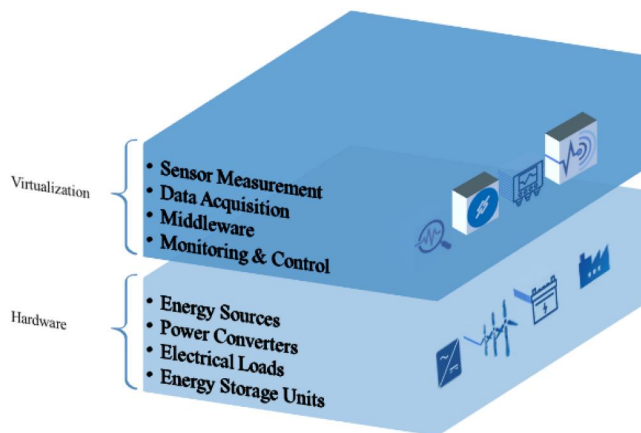


FIGURE 3 Proposed microgrid monitoring system architecture

available. The key to these measurements taken, lie in determinism that is the shared concept of time. To implement, the same TSN system is used.

- *TSN system components*: There are five main components in the TSN system.
- *TSN flow*: This is the time-critical communication between the nodes or devices. It follows a fixed time protocol that every device in the network follows.
- *Nodes*: these are the devices that follow the deterministic communication. They are also referred as subscribers (receivers) and publishers (senders).
- *TSN switch*: They act as a bridge capable of transmitting and receiving data frames of a TSN flow for a pre-determined schedule.
- *Central network controller*: As the name suggests, it controls the TSN switches in the network. It is a software application running on different nodes. It has two main responsibilities. First, determining the route and scheduling the TSN flow through the network and second, configuring the TSN switches for TSN operation.
- *Centralized user configuration*: An application that communicates between Central Network Controller and the nodes. It makes requests for the TSN flow and its prerequisites.

3.2 | Virtualization layer

The communication network requires peer-to-peer communication and the nodes are in direct contact with each other without the third-party intervention. The virtualization layer should abstract complex network details like network topology and nodal information and provides a simpler interface.

- *DDS*: The DDS middleware works on a data-centric approach publisher-subscriber model and focuses mainly on the algorithm and control method. The standard API for the DDS middleware provides the necessary tools to integrate with different simulation and analysis software with the support of several programming languages such as C, C++, and JAVA. Microgrids need low data latency to support fast control actions and maintain stability. TSN offers a wide variety of QoS profiles to meet different needs of controllers and data types.
- *QoS Profiles*: TSN is aware of data types and the priority of each data type. For this purpose, a new library of QoS profile is created to control the data exchange. This feature helps to achieve the TSN capabilities for the network. The QoS policy defines a distinct set of rules that control how the data will be sent and handled by the infrastructure. To attain the TSN features in the network, multiple profiles were developed and assembled in a library.

The QoS profile library developed for this work is the central component for a complete QoS model. The design of the profiles is explained as follows. The time synchronization feature of TSN is fulfilled when all publishers or subscribers

belong to the same domain and, being the domain participants, share the same time reference. For traffic scheduling, prioritization, and system configuration (path reservation, bandwidth, time slots), scheduling policies such as Round Robin (RR), Earliest Deadline First (EDF), and Highest Priority First (HPF) are utilized. The EDF is used for the proposed model and QoS library. In this policy, priority can be decided dynamically based on the latency budget and the deadline. Hence, it is ensured that the data packet is neither lost nor delayed.

There are two separate profiles for defining latency and throughput in the library which help in prioritizing the latency-sensitive data. For the TSN, there is a need for low latency budget. A time period is specified within which the information must be distributed. This time period starts from the moment the data is written by the publisher until it is available in the subscriber's data cache ready for use by the readers. The throughput profile also helps in defining maximum throughput and preventing peak bursts. A library is created by utilizing the listed QoS profiles and it is implemented on the proposed TSN-enabled microgrid.

4 | EXPERIMENTAL IMPLEMENTATION

To implement the proposed TSN-enabled synchronized measurement-based monitoring system for microgrids, the stand-alone laboratory-scale microgrid is shown in Figure 4. It is developed based on the concept of Figure 3.

Figure 4 illustrates the typical scheme of the intended monitoring system including the TSN implementation framework and the data acquisition hardware. Each part of the system is explained individually in the next subsections.

4.1 | Data acquisition

The data which is the three-phase voltage or phasor voltage consisting of frequency, amplitude, and phase, is collected from different nodes of the microgrid that is nodes #1–5 having the same time reference. The data is acquired using the Beagle Bone-Black (BBB) from each node. BBB is a low-cost development board featuring the AM3358 ARM Cortex-A8 processor from Texas Instruments.

Four important nodes (nodes #1, #2, #3, and #5) are selected for monitoring purpose with a BBB based data collection unit at each node. The advantage of the BBB for this application is the existence of two ‘Programmable Real-time Units’ (PRUs) which are two separate reduced instruction sets computing CPUs on the same silicon die as the main ARM CPU, with separate data and instruction memories while sharing the same data bus. The PRUs are clocked at 200 MHz and have access to pins, events, and hardware resources on the system-on-chip, so they can be tasked with hard real-time functions. They can be given a function to do that which operates independently of the operating system on the main

CPU; thus the typical causes of delays that would interfere with a real-time process are eliminated, while data can be shared based on the same memory map between ARM Linux and PRUs.

The data is acquired from nodes #1, #2, #3, and #5. This data is transmitted to the master controller through both wired and wireless connections. Nodes #1, #2, and #3 are wired, whereas node #5 sends data wirelessly. For the wireless communication, Xbee-S2 is chosen. To ensure that the acquired data is not distorted during wireless communication, Butterworth low pass filter (LPF) of order 2 is used with an amplifier circuitry as shown in Figure 5.

4.2 | TSN system

After the data is acquired, it is received in the TSN system, Cisco IE-4000. It supports delay-sensitive applications and time-sensitive networks. It has the capability to support up to eight devices and the bandwidth and capacity of 20-Gbps non-blocking switching capacity with up to 20-GB Ethernet ports per switch. It consists of a 1GB DRAM, a 128-MB onboard flash memory, a 1-GB removable SD flash memory card, a mini-USB connector, and RJ-45 connector. Figure 6 depicts the PV, battery bank, bidirectional DC-AC converter, and the TSN system and PXIe connection. The Cisco IE-4000 system benefits from a robust design and user-friendly GUI which allows easy configuration and monitoring.

4.3 | Aggregator

The network of TSN-enabled nodes is monitored by one master controller NI PXIe system which can acquire data and running models in real time (deterministically) and in parallel. The software required to do so is a combination of NI-LabVIEW and MATLAB/Simulink. The model selected is NI PXIe-1073 chassis with the NI PXIe-6356 card.

Because voltage amplitude, phase angle, and frequency, which are all AC parameters, are considered as the main input data of the TSN-based condition monitoring system, the five AC nodes of this microgrid are considered as the data subscribers, while the main microgrid monitoring and control centre, located at a separate location, is the publisher. The DC voltage level and battery's State of Charge (SOC) at node #0 can be also collected and transmitted to the monitoring centre as additional inputs that might be helpful for microgrid operation and in decision-making during adverse incidents or peak hours.

4.4 | Electrical network setup

The experimental setup of the lab-scale microgrid of Figure 4, is designed and implemented in the Lamar Renewable Energy

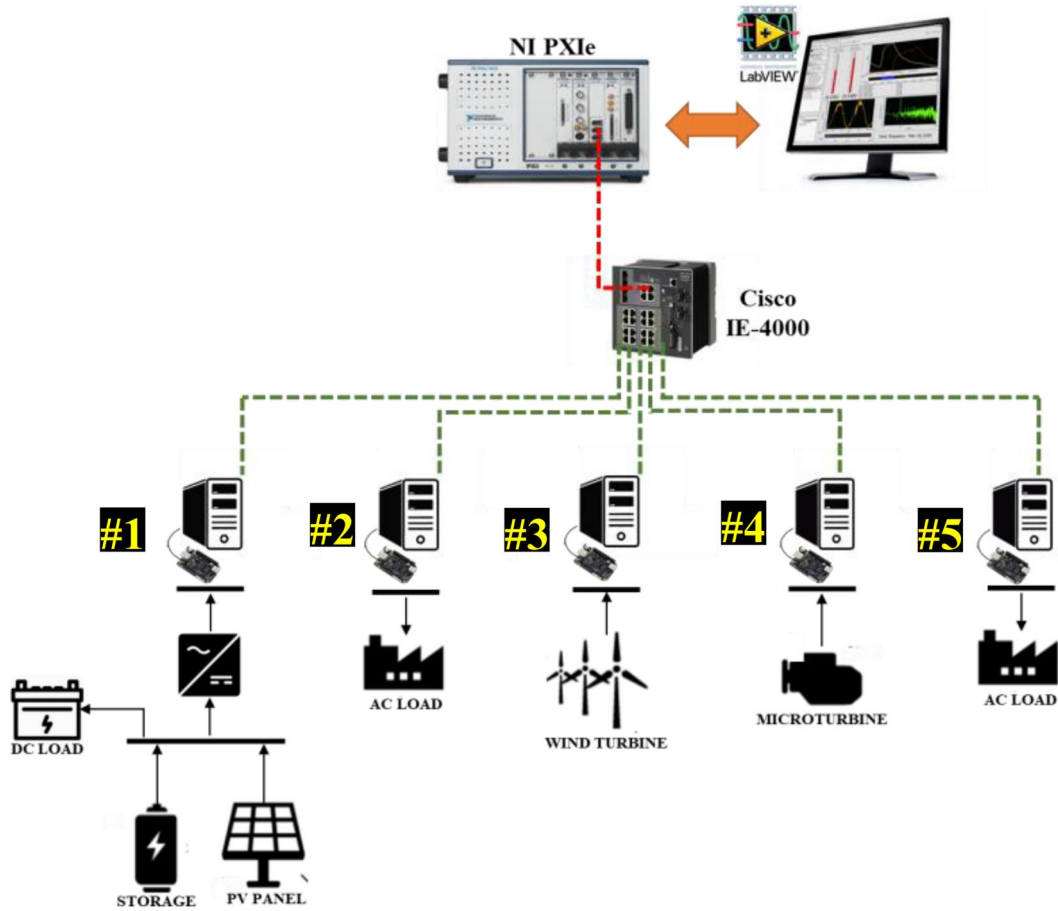


FIGURE 4 Prototype implementation of the microgrid monitoring system

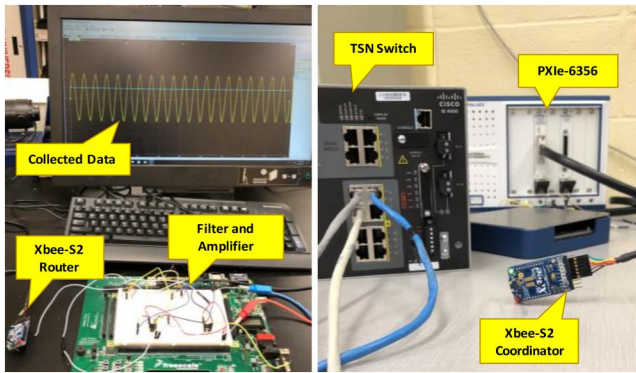


FIGURE 5 Wireless connection between node #5 and the master controller

and Microgrid Laboratory at Lamar University. The wind energy system is emulated by using a three-phase MJB160XA4 208 V 11.8 kW 60 Hz synchronous generator driven by WEG 15HP 208 V 60 Hz three-phase induction motor controlled by ESV752N06TX Lenz variable frequency drive to apply real wind speed and emulate the wind turbine. The same motor-generator configuration with a fixed supply voltage of 208 V 60 Hz is used to emulate the microturbine. Figure 6 shows this emulator.

As shown in Figure 7, an Intertek 4002316 PV panel including a 4×9 array of PV modules with open circuit voltage and short circuit current of 21.06 V and 8.62 A is utilised as a PV source. The energy storage system includes five 12 V 8 A batteries in parallel connected to the DC node. A bidirectional buck-boost converter consisting of 600 V 23 A IRG4PC30UDPBF IGBTs, 600 V 15 A ISL9R1560G2 diodes, WE-SD 20A 15 μ H inductor, and a 250 V 100 μ F capacitor is designed and built to connect the DC node #0 to the AC node #1. To control the converter, the output voltage is sensed with the LEM LV25-P voltage transducer and sent to the LabVIEW controller through NI PXIe-6356 data acquisition device and the 10 kHz PWM pulses are created for the Microchip Technology MCP1406 IC to drive the IGBT as shown in Figure 7.

AC and DC loads are implemented through resistive-inductive 50–400 W units. The loads are connected to the nodes through solid state relays to be able to turn them ON or OFF through the monitoring panel.

5 | EXPERIMENT RESULTS

The TSN protocol is tested by considering a scenario where nodes #1, #2, #3, and #5 are active. The data from these nodes is either three-phase voltage or phasor voltage, which

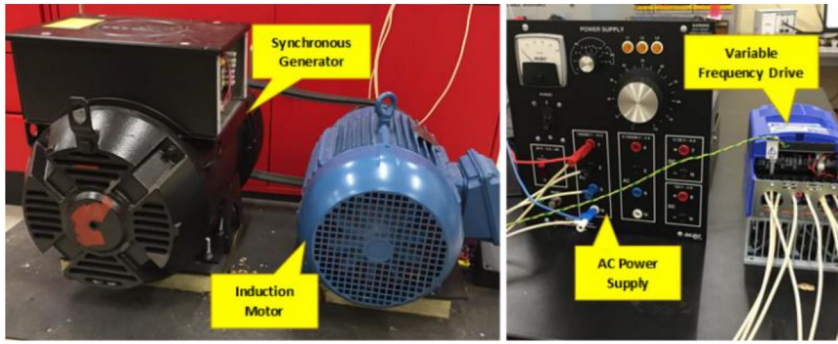


FIGURE 6 The configuration used to emulate wind turbine and microturbine

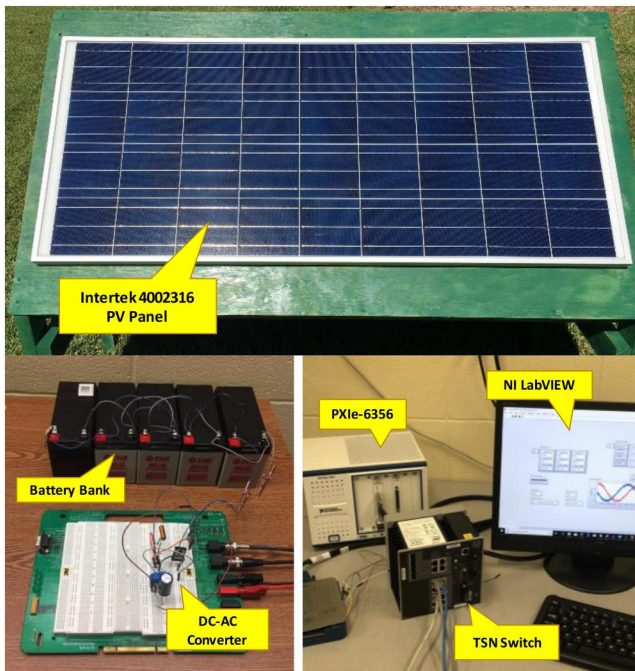


FIGURE 7 PV panel, battery bank, DC-AC converter [38], and TSN switch and PXIe connection

consists of voltage amplitude, phase angle, and frequency. There are four possible cases. First, in the Only Publisher Only Subscriber (OPOS) case there is only one sender and one receiver, it is atypical when using unicast. The second case is the Only Publisher Manifold Subscriber (OPMS), where there is only one publisher or sender that has the information or data to share with multiple subscribers. It introduces the need of the TSN protocol at levels II (subscribers) and level III (data) in the case of multiple data packets. Since two levels of TSN are implemented, it is more complex and hierarchical than OPOS. The third case is the Manifold Publisher Only Subscriber (MPOS) where there are multiple senders, but the receiving node is only one. This limits the protocol as a receiver can select only one publisher/sender at a time that is it cannot read the data of every publisher in the domain simultaneously though it can prioritise the data freely for every publisher separately. The fourth and last case is Manifold Publisher

Manifold Subscriber (MPMS), this is the complete implementation of the TSN protocols at all three levels that is at publisher level (level I), subscriber level (level II) and the data level (level III). As the name suggests it has manifold publishers, and manifold subscribers may or may not have multiple data packets. Also it is important to note that subscribers are not bound to receive data from every publisher in the network, rather its optional and flexible.

Two profiles are discussed and compared below. The first one is the OPOS and the second one is a typical case scenario of the MPOS configuration. The reason for selecting these two profiles is that there is only one master aggregator in the network (see Figures 4 and 5), which acts as the only subscriber.

5.1 | Case 1: OPOS

In the OPOS profile, only node #2 is active and acts as a publisher, and master controller NI PXIe-1073 acts as the only subscriber. Since there is only one publisher and one subscriber active in the network, prioritization and network shaping are done only at one level that is data level. The data acquired from node #2 (AC loads) which is per-unit three-phase voltage waveform is shown in Figure 8a. The frequency of the entire system is 60 Hz. This part of the system demonstrates the publisher end with just one publisher. In Figure 8b, the interval is zoomed and shown for 0-0.01 s, for a closer look and to demonstrate the deployment of TSN protocol, and Figure 8c depicts the subscriber's end and data prioritization which is done in the order phase A > phase C > phase B.

5.2 | Case 2: MPOS

In the MPOS scenario, each node behaves as a publisher, and the master controller NI PXIe-1073 acts as the only subscriber. Since subscriber can only read data from the publisher at a time, prioritization and network shaping are done at two levels: the publisher level and the data level. Subscriber level cannot be implemented since there is only one subscriber in the setup which is the master controller. To implement it, microgrid nodes are prioritized as nodes #1, #3, and #5 where nodes #1 and #5 are given the highest and the least priority, respectively.

FIGURE 8 Node #2 three-phase measurement: (a) three-phase voltage (b) zoomed 0–0.01 s publisher end (c) subscriber

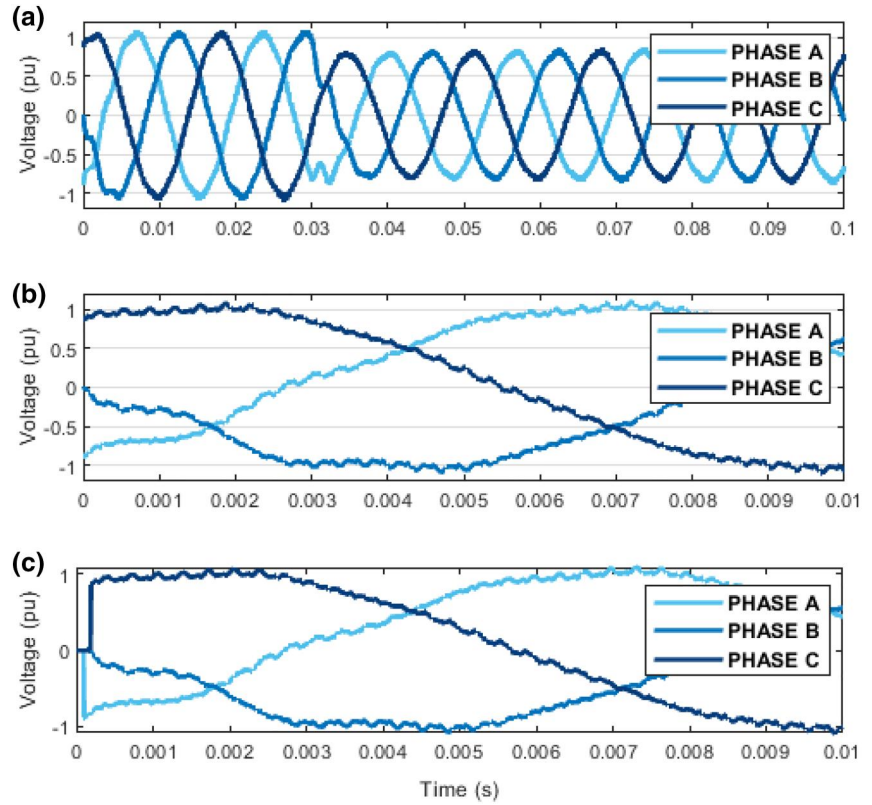
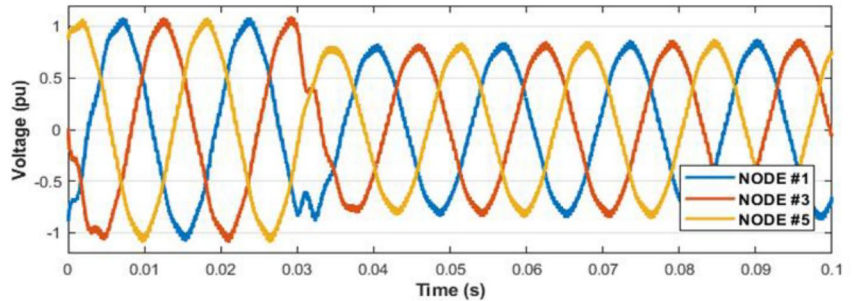


FIGURE 9 Sending end waveforms MPOS



The data waveforms which were acquired from node #1 (PV panel), node #3 (Wind emulator), and node #5 (AC loads) are shown in Figure 9. The voltages are shown in per unit (p.u.) format but the base voltage is 575 V, and they are normalized in the range of 0–1 to keep them comparable and in the same range. The frequency of the entire system is 60 Hz. This part of the system demonstrates the publisher end with three publishers.

Figure 10 illustrates the waveforms at the subscriber end. The waveforms are obtained from the master controller PXIe-1073. Figure 10a–c shows the implementation of TSN on amplitude, phase angle, and frequency waveforms, respectively. The same order of priority is assigned to the nodes.

5.3 | Performance quantification

The performance of the above demonstrated communication network is benchmarked by calculating the corresponding

latency and throughput for the testbed discussed earlier. The latency and throughput are measured for both the selected cases at a sampling rate of 100K samples per second. For OPOS the simulated values were recorded as 140 μ s and 145 Mbps, while 215 μ s and 255 Mbps for latency and throughput, respectively, for the experimental tests. Similarly, for MPOS configuration the simulated values of latency and throughput were 290 μ s and 290 Mbps and experimental values as 265 μ s and 310 Mbps, respectively. These values are for one-way latency for publish/subscribe application. The throughput is measured over Gigabit Ethernet and a single domain. It is observed that the proposed framework maintains satisfactory latency, even at high message rates where the latency increases with throughput. Consequently, as these requirements are beyond those set for PMU data transfer, they are more than sufficient for PMU-based monitoring and are attractive even for point-on-wave based monitoring.

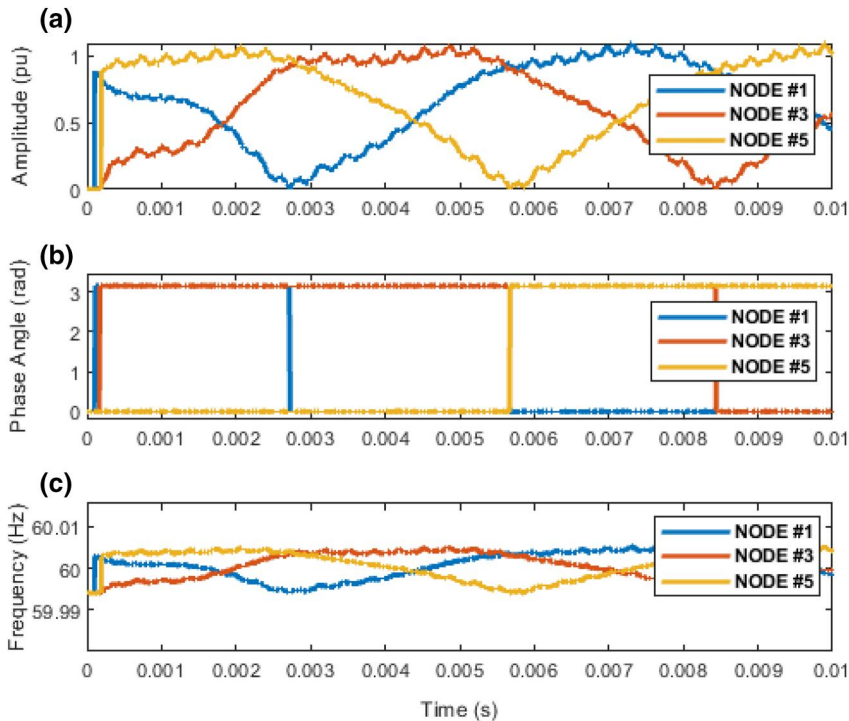


FIGURE 10 Monitored data at the subscriber end: (a) voltage waveforms, (b) amplitudes, (c) phase angles, (d) frequencies

6 | CONCLUSION

In this article, a TSN-enabled monitoring system was proposed, implemented and demonstrated for a laboratory-scale microgrid. TSN provided the capability to shape the network traffic and prioritise the time-critical data. The utilized node communication was reliable and flexible and eliminated network congestion. The QoS profile library defined on the DDS middleware, offered high throughput, low latency, reliable streaming, alarm event, and last value cache. The performance of the entire system was tested and validated on a laboratory-scale microgrid using, the Cisco IE-4000 TSN switch and the NI PXIe data acquisition platform. A security layer and bi-directional communication between nodes and the master controller will be carried out in the future work.

All listed contributions in Section 1 are reflected respectively with their outcomes, as follows:

- The proposed approach for time-synchronization provided a common sub-microsecond time reference to the nodes of network, which can address the current limitations of GPS technology.
- The proposed approach was applied to a 4-node laboratory-scale microgrid, providing time synchronization to simultaneously collect data from frequency, amplitude, and phase of phasor voltages.
- Time-critical communication was designed to meet real-time requirements by using QoS profiles and by following a fixed time protocol.
- The experimental platform successfully demonstrated interoperability by interfacing different devices from different manufacturers through the DDS standard

- The developed QoS profiles in this study provided low latency and high throughput at the sampling rate of 100K samples per seconds, preventing peak bursts.
- Traffic scheduling was formed by QoS profiles in this system configuration to preclude bottlenecks, providing deterministic communication.
- Experimental results indicated the feasibility of the implemented laboratory-scale testbed in providing time-critical data and node prioritization as well as communication network's satisfactory latency and throughput.

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