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# IEEE 1588 Time Synchronization in Power Distribution System Applications: Timestamping and Accuracy Requirements

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***Abstract*—The monitoring and control of power distribution systems requires an accurate and stable time synchronization infrastructure. The major requirement for a time synchronization system is sharing a global time throughout the network. This article provides an overview of the synchronization techniques implemented in power distribution systems. The implementation of different techniques for time synchronization due to heterogeneous communication infrastructure creates various challenges in the system. Therefore, this article aims to propose a homogeneous, uniform approach for a network-based synchronization mechanism in or to implement multiple distribution system applications. For this purpose, the precision time protocol (PTP), IEEE 1588, is tested experimentally for various time criticality with an Ethernet-based communication network. The testbed uses single board computers to explore different criticality of the timestampings for IEEE 1588 (PTP) to determine how various applications need different type of timestamping depending upon the performance, cost, and accuracy requirements. These different levels of timestamping requirements for synchronization affect the performance of a range of next-generation distribution system applications. The proposed solution provides monitoring for each application using only a single time synchronization technique with an Ethernet-based network.**

***Index Terms*—Distribution systems, precision time protocol (PTP), single board computers (SBCs), time synchronization, timestamping.**

## I. INTRODUCTION

INFAMOUS blackouts like the Northeastern blackout in 2003 has brought attention to the need for time-synchronized measurement outputs to prevent cascading failure of the whole system [1]. Unreliable and erroneous timestamps have resulted in significant delays in diagnosing the cause of blackouts. The impact of the measurement device's time error is that they are often miscalculated as the power system disturbances [2]. The role of communication and computing technologies in distribution systems has gained momentum with the integration of distributed energy resources(s) in the grid [3]. The challenges faced by the distribution network are different from transmission networks as the size of the distribution network can be hundreds to thousands of times larger than the transmission network, and the distribution network consists of small branches with low impedance and high R/X ratio. It is highly unobservable because of the limited number of real-time measurements. The topology of the distribution network is usually considered to be radial, whereas the transmission network is normally a mesh network which causes the network to be highly unreliable, the radial nature of the distribution network causes the voltage to be affected the most at the far end of the feeder. To overcome these challenges, the distribution network is converting into an active distribution network, with more real-time monitoring and control required in order to integrate high penetrations of distributed energy resources (DERs).

Applications in power distribution network, such as fault detection, fault recording, protection, and substation monitoring require network-wide time synchronization [4]. The automation function of an active distribution system requires uninterrupted monitoring of parameters like voltage and current measurement [5]. Due to this reason, time-related information has become crucial in distribution systems. However, there is no study with a uniform time synchronization technique available to date, which satisfies the requirement of all the different layers of the distribution system. The most crucial challenge for the distribution system operators (DSOs) is to provide the synchronization accuracy of microseconds over a vast geographical area. [6].

Different communication mediums are currently being installed in the network synchronization purpose like Ethernet, power line communication, and Long Term Evolution [7]. However, these different mediums make the DSOs use different synchronization techniques, requiring complex optimization procedures [8]. The demerit of using different communication mediums or synchronization techniques is that they cannot be easily scaled at the different system levels. This creates a demand for a uniform time synchronization technique and communication medium for monitoring and control in various distribution system applications.

Therefore, there is a need to propose a uniform time synchronization technique for different distribution system applications that provide safe, accurate, and independent timestamping over large networks. This should utilize a uniform communication

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medium and mitigate the risks of cyberattacks to distribution systems. This article explores precision time protocol (PTP), IEEE 1588 technique for time synchronization of the measurement devices [9]. It presents experimental results on how this technique provides nanosecond time synchronization results for various power system applications focusing on distribution system synchronization challenges. The protocol accuracy must be in nanoseconds if the applications require the microsecond accuracy. This is due to the fact that the hardware support on the PTP has accuracy limitations. Therefore, to acquire microsecond accuracy the protocol should be capable of synchronizing the clocks in nanoseconds. The time source should be accurate enough to provide microsecond accuracy even after considering the environment delay caused by the hardware limitations [10], [11].

To the best of the authors' knowledge, no comprehensive study looks into different timestamping requirements for various distribution system applications. Therefore, the major contributions of this article are as follows.

1) Outlines the limitations of existing work using time synchronization techniques like inter-range instrumentation group timecode B (IRIG-B), 1-pulse per second (1-PPS), network time protocol (NTP), and GPS, which do not allow them to be used uniformly throughout the network in power distribution applications [12], [13].
2) The limitations of existing time synchronization techniques result in a need to propose a unified time synchronization technique for power distribution network applications which overcomes the challenges due to heterogeneous infrastructure of time synchronization.
3) It describes experimental results related to different timestamping techniques using single board computers (SBCs) and proposes its implementation on the power distribution network;
4) It categorizes the distribution system applications based on the time synchronization performance.

The rest of this article is organized as follows. Section II describes why data timestamping accuracy is essential for distribution system applications and introduces the types of synchronization techniques. Section III presents the design of PTP synchronization architecture, the proposed time criticality, and the algorithm used to test these timestamping techniques. Section IV introduces the experimental setup. Section V provides results for different time criticalities and their implementation examples in distribution system applications. Finally, Section VI concludes this article.

## II. TECHNOLOGICAL OVERVIEW

### A. Role of Time Synchronization in Distribution System Applications

In power distribution systems, the distribution of common time reference is essential for smart grid applications like merging users' information and correlating the power quality [14]. The distribution system infrastructure has become digitally more advanced with the introduction of advanced metering iFnfrastructure. It has become more accessible for the DSOs to ensure the reliable flow of information [13]. However, there is a crucial requirement of protecting the distribution network operations with advanced technologies and timing tools to enhance the resilience and robustness of the distribution system. In distribution system networks, synchronization measurements have been essential for resolving different applications such as power quality measurement, stability assessment, fault location, state estimation, system topology detection, and event detection [15], [16]. Depending on the purpose of the applications, the required accuracy of the timestamps differs [17]. Table I lists some of the power distribution applications and their timing requirements. Distribution management systems rely on these timing requirements to analyze various system events and outline other requirements like timestamping for various power distribution applications. These applications are discussed further in detail with their time criticality categorization based on their accuracy and latency requirements in Section V of this article.

TABLE I
DISTRIBUTION NETWORK APPLICATION'S TIMING REQUIREMENT

| **Application** | **Time accuracy requirement (μs)** |
|---|---|
| Islanding in microgrid | 0.5–1 |
| Islanding detection and fast DG disconnection from the grid | 1–2 |
| State estimation | 1–3 |
| Awareness of real-time load | 10–15 |
| Phasor-based control | 10–50 |
| Disturbance analysis | 50–100 |
| Topology detection | 100–150 |
| Thermal overloading | 100–150 |
| Voltage stability monitoring | 150–200 |
| Digital fault recording | 50–1000 |
| Sequence of event recorder | 50–2000 |

Some other power distribution network applications like power quality metering also improves with the implementation of time synchronized measurement.

Likewise, the location of the fault can be calculated by measuring the difference in the measured disturbance times at different synchronized devices [18].

Therefore, there is continuous speculation for a high level of synchronization measurement in the distribution system for various applications at different levels.

Furthermore, with the evolution of distributed computing technologies, where the communication infrastructure properties like data processing speed and latencies can directly influence the capacity to take the control action in real-time [19]. The distribution system's application need to be more sensitive to the timestamping of the incoming measurement. The DSOs should be more responsible to focus on the data gaps and losses. They should have the capability to recognize if the bad timestamps of the output are compromising the quality and credibility of the applications [20].

### B. Significance of Time Accuracy in Distribution Systems

The topology and the state of the system are the primary requirements for analyzing the operation and control properties of the distribution system in real-time. Another vital issue for distribution grid timing applications is what level of accuracy the particular distribution network application needs. Therefore, the accuracy source should be addressed effectively [21]. In a distribution system, a lot of data are collected and recorded by different measurement and control devices. To enable the analysis, diagnostics, and operational decisions, the measurement data should be timestamped to be sorted chronologically as the accuracy of the timestamped data with respect to the single time reference is needed for various monitoring and control applications of the distribution system. For example, the aim of the decentralized distribution system is to attain stable voltage and frequency levels of the distribution network with the help of synchronized distributed generation (DGs) parameters [22], [23], [24]. Likewise, DSOs are responsible for the grid monitoring device testing. The requirement for the time synchronization accuracy for these applications is in the range of 100 milliseconds. On the other hand, the protection system in the distribution system also requires time synchronization from a few milliseconds down to less than 100 microseconds [25]. Therefore, there is an acute need to deploy synchronization measurement devices in the medium voltage (MV) and low voltage (LV) levels of the power distribution network for numerous monitoring and control applications.

### C. Types of Synchronization Techniques for Distribution Systems

Table II showcases the time synchronization alternative techniques for synchronization. According to the time accuracy requirements of the power distribution system, the techniques in the literature have some limitations as shown in the table, because of which they cannot be applied uniformly throughout the network.

Apart from the most popular synchronization technique, there are other low-cost techniques, like Modbus-based (ION-based) over Ethernet or serial communications network. However, they are not accurate enough to be used for various power distribution applications. The best form of synchronization protocol that can be used for many precise distribution system applications is PTP technique, also known as IEEE 1588 protocol, as explained in Section I [36]. It is a viable alternative for high-cost hardwired-based synchronization techniques. Therefore, PTP has been adopted in this article for the synchronization purpose for various distribution system applications, which helps in the uniform time synchronization throughout the network. This reduces the challenges caused by the alternative solution of heterogeneous techniques given in Table I for time synchronization purposes. Table III showcases the primary reason for proposing the unified algorithm utilizing the PTP technique.

TABLE II
AVAILABLE TIME SYNCHRONIZATION TECHNIQUES

| **Available technique** | **Accuracy** | **Transport media** | **Limitations** |
|---|---|---|---|
| IRIG-B | 1–10 ms | Copper or fibre optics cable | It has electromagnetic interference between the devices. Limitation with geographical distance. |
| 1-PPS | 1–10 ms | Copper or fibre optics cable | It is a unidirectional technique and has one micro-sec delay for every 200m cable length. Thus not suitable for distribution system applications. |
| NTP | 1–5 ms | Ethernet cable | It's accuracy lies in milliseconds. Thus can only work for few power distribution applications. |
| SNTP | 5–10 ms | Ethernet cable | It's less accurate than NTP and does not cover multiple Local Area Network which is essential in power distribution applications |
| GPS-only solution | 10–100 ns | GPS antenna via satellites | Vulnerable to interference, jamming, loss of signal, and spoofing, and so cannot be used as the sole source of timing for power distribution system applications. |

TABLE III
COMPARISON OF TIME SYNCHRONIZATION TECHNIQUES IN POWER DISTRIBUTION NETWORK

| **Time synchronization** | **Technique** | **Comparison** |
|---|---|---|
| Available literature | Heterogenous time synchronization | Conversion among different time domains (i.e., NTP, IEEE 1588, GPS time) requires the use of dedicated time gateway, which means extra costs. The delay on the propagation of synchronisation packets introduced by each different adopted time synchronisation technology. |
| Proposed algorithm | Unified time synchronization | Do not require a separate gateway. Therefore, no extra cost. No delay for interoperability in propagation of packets through unified time synchronisation technique. |

## III. METHODOLOGY

### A. Design of PTP Synchronization Architecture

PTP is a synchronization technique for the dispersed packet-switched network, which delivers the accuracy of around nanoseconds. The network packets travelling routes change dynamically, thus requiring the correct estimation of network time delay for each packet. This protocol's primary source of delay is the delay caused by the routers and switches. The variability in the network delay is directly related to the transfer of the data packets between routers and switches. Non-PTP switches used in this article do not have the functionality of prioritizing the packets over other packets. Therefore, because of network

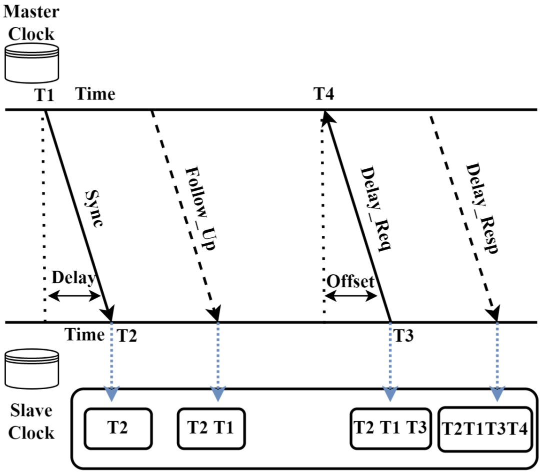

Fig. 1. PTP message exchange.

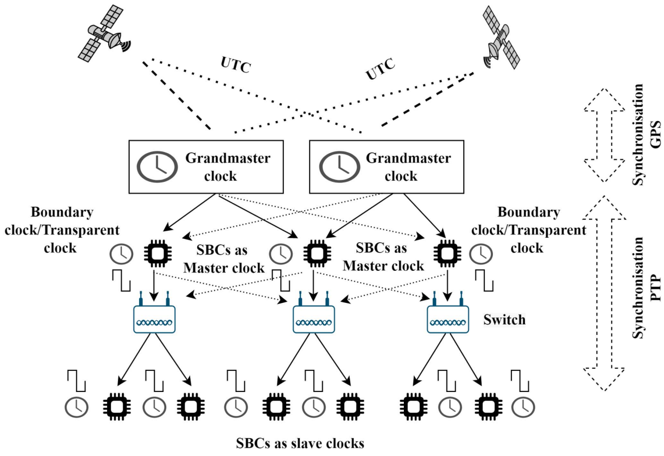

Fig. 2. Clock distribution over PTP protocol.

traffic congestion, the packets suffer high jitters and reduce the accuracy of the PTP synchronization process. Therefore, the non-PTP switch only transfers the $Sync$ and $Delay\_Req$ packets, as illustrated in Fig. 1, which have the lowest network delay. All the other packets with a high variation of delay are ignored. This filtering enables slaves to track the master's time-base precisely when the network delays change over time. This accounts for the variation of the network delay in the master and the slave timestamping [26].[1]

The best master clock algorithm (BMCA) is used in this article for synchronizing the measurement devices [18]. The algorithm of the BMCA developed a hierarchy between the component's clock in the network. Every clock in the network compares its accuracy by generating an announce message. They self-assign the position in the hierarchy after transferring the announce message to the receiver clock. Fig. 2 illustrates the practical implementation of this protocol on a real power distribution network by connecting the active and standby Grandmaster clock to showcase how the PTP algorithm can work on a real power distribution network. The addition of the standby Grandmaster clock and the availability of the boundary clock, which can work as a master clock as well as a slave clock (as it has multiple output ports), during the failure of any clock in the network diminishes the single point failure issue.

After defining the hierarchy of the whole algorithm, the messages are exchanged as shown in Fig. 1, between the master and the slave clock [27]. The algorithm works in the following way.

- Step 1: The algorithm starts with the master clock sending timestamped $Sync$ message at time $t_1$. In the case of one-step operation as shown in [27], the information is transferred to the slave clock at the same time $t_1$ with the help of $Sync$ message, whereas the $Follow\_Up$ message is used in the two-step operation for sync message transfer.
- Step 2: The $Sync$ message are received and timestamped by the slave at $t_2$.
- Step 3: At time $t_3$, the slave transfer the $Delay\_Req$ message with the timestamp to the master clock.
- Step 4: The master clock performs two steps at time $t_4$. It receives the $Delay\_Req$ message and at the same time forwards the $Delay\_Resp$ message to the slave clock.

The slave get synchronized to the master clock after receiving the $t_i$ value by calculating the offset time $\Delta_t$. Furthermore, the path delay $\Psi_{Ma\_Sl}$ is calculated between the master and the slave clock. The sum of path delay is the time interval elapsing between the time sync either between $t_1$ and $t_2$ or $t_3$ and $t_4$.

The equations for $t_2$ and $t_4$ are as follows:

$$t_2 = t_1 + \Delta t + \Psi_{Ma} \rightarrow_{Sl} \tag{1}$$

$$t_4 = t_3 + \Delta t + \Psi_{Sl} \rightarrow_{Ma} . \tag{2}$$

Since, the property of path delay symmetry is very important for the PTP algorithm

$$\Psi_{Ma} \rightarrow_{Sl} = \Psi_{Sl} \rightarrow_{Ma} = \Psi. \tag{3}$$

Therefore, from (1) and (2) and the assumption of symmetry in (3), the value of path delay ($\Psi$) and time offset ($\Delta t$) is calculated as follows:

$$\Psi = \frac{(t_4 - t_3) + (t_2 - t_1)}{2} \tag{4}$$

$$\Delta t = (t_2 - t_1) - \Psi. \tag{5}$$

With regards to the equations mentioned above, in order to reach high synchronization accuracy, two conditions must be met which are: 1) the master and slaves clock's length of sending and receiving link should be equal as the Ethernet cables have symmetric bandwidth because of which the assumption that the latency of sending a message from the master to the slave clock is the same as that of sending a message from the salve to the master clock; 2) the System on Chip (SoC) should be PTP complaint [28].

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[1] Master–Slave can also be called as Primary–Secondary or Leader–Follower.

### *B. Time Criticality*

Data are collected and recorded by various monitoring devices in MV and LV distribution systems. Some of them are recorded at regular intervals, i.e., e.g., every 15 min. In contrast, some of them are recorded when the event occurs, like circuit breaker trip, voltage sag, transient, etc. Therefore, to enable analysis, diagnostics, and operational decisions, these data must be timestamped with a single time reference depending upon the requirement of the particular application. The time accuracy requirement depends on the data usage and, therefore, on the specific distribution system application to be implemented. The concept of time criticality has been defined in this article to understand the selection of various timestamps for different distribution system applications.

The required criticality of the timestamps differs depending on the purpose of various distribution system applications. Based on the applications, the time criticality has been divided into two broad categories: 1) hardware-based; and 2) software-based timestamping. The need to consider a different time criticality type is because if the achieved time accuracy is insufficient due to inappropriate timestamping technique, then the distribution system application may not function accurately. It is imperative to recognize the time accuracy for different applications. Therefore, the applications which do not require a high time accuracy can use the monitoring device, which consists of a software-based timestamping technique. However, the distribution system applications which require high time accuracy, the hardware-based timestamping comes into action [29]. The choice of the time synchronization technique depends upon the requirement, accuracy, and implementation cost.

In order to test the performance of various time criticality, a test setup is assembled where different switch configurations are installed to validate the software and hardware timestamping of the PTP-based time synchronization technique. The detailed proposed algorithm for testing different time criticality is explained in Fig. 3. The various operating conditions have been tested by using non-PTP switches in the network. Non-PTP switches are the ordinary network switches used in the PTP Master–Slave algorithm. These switches' delay greatly depends on the network load. Since the PTP testing performed in this article uses only four hardware; therefore, the non-PTP switches fit perfectly for the lab testing of the algorithm.

*1) Case 1- Software-Based Timestamping:* Timestamps can be generated at different layers of the network. Software timestamps work at the application level by merging with the intended network packet [30]. In this work, the SO_TIMESTAMP option of the inbuilt Linux Kernel is exercised in the open-source implementation of the PTP protocol. Fig. 4 demonstrates the software timestamping process implemented at the network layer. The packets in this type of technique are timestamped using the system time clock. Fundamentally the system time is accessed via memory using regular kernel routines, which results in jitter. This jitter varies from system to system and on the bandwidth of the network. The other limitation of this type of timestamping is that it has to pass from the different network layers to reach the network's physical layer. This causes some amount of delay in the timestamping process.

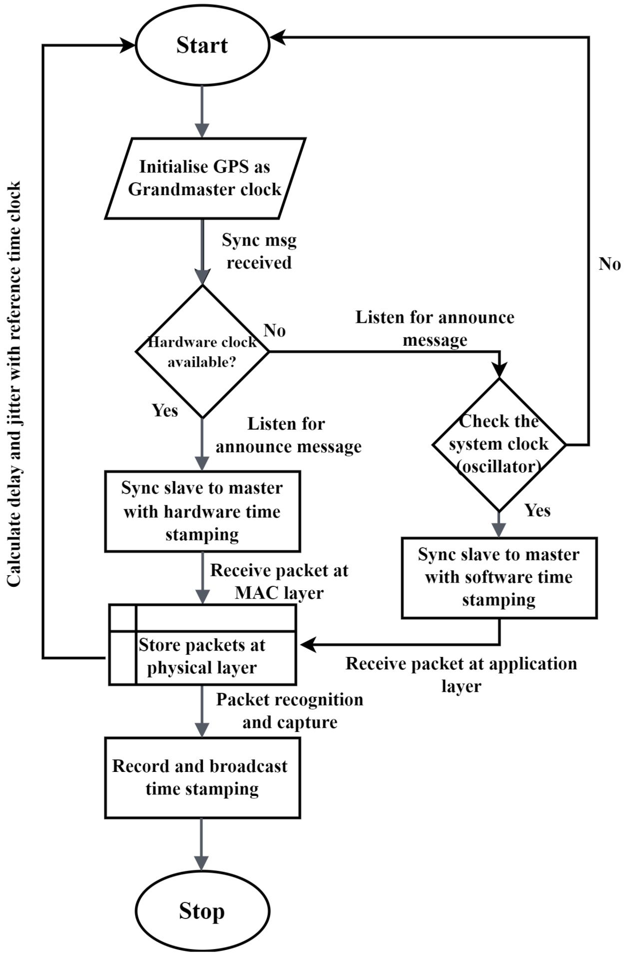

Fig. 3. Proposed time criticality algorithm.

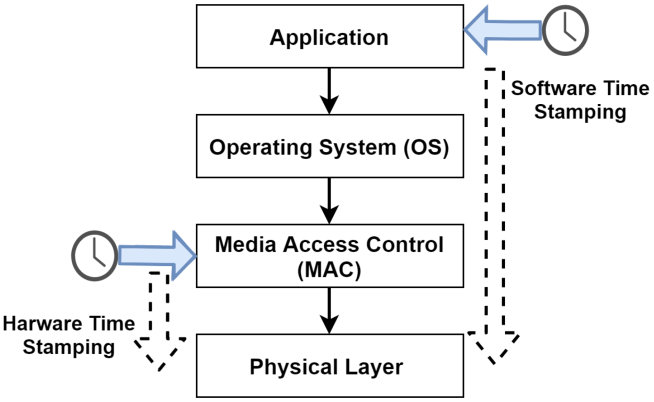

Fig. 4. PTP timestamping stack.

*2) Case 2- Hardware-Based Timestamping:* The hardware-based timestamping reduces the error and jitter caused by the application and OS layers as the packets are timestamped either at MAC or PHY layers depending upon the type of hardware,

TABLE IV
PTP SOCKET OPTIONS

| Sockets | Application |
|---|---|
| SO_TIMESTAMP | Generate timestamps for incoming packets using Linux system time. Its resolution is in microseconds |
| SO_TIMESTAMPNS | Generate timestamps with nanosecond resolution using Linux system time. Information is retrieved via recvmsg() command and sent back via timespec struct command |
| SO_TIMESTAMPING | Generate timestamps using hardware clock with nanoseconds resolution |

as shown in Fig. 4. The main requirement for this type of timestamping is the availability of an internal clock in the hardware used for the synchronization process. Along with that, the kernel version used for timestamping should include the PTP hardware clock driver architecture and the mechanism to control the hardware clock [31].

## C. PTP Software Implementation

There are different types of Linux sockets for generating the timestamping for transferring the data packets at different levels of the network stack, as shown in Fig. 4. The socket options used for timestamping in this article is shown in Table IV.

The first two socket options SO_TIMESTAMP and SO_TIMESTAMPNS, can be used for timestamping packets. However, it mainly provides the licence of timestamps at the software level only. The third socket in Table IV can be used to test both software and hardware timestamping using both system clock and hardware inbuilt clock. The SO_TIMESTAMPING supports multiple types of timestamps requests for incoming and outgoing packets. Table V explains the available parameters used in this article for configuring the SO_TIMESTAMPING option for a different timestamping generation.

An open-source software LinuxPTP is used for testing different timestamping requirements in the PTP protocol [32]. The benefit of choosing LinuxPTP for the testing is because it supports hardware and software-based timestamping using the Linux SO_TIMESTAMPING socket option. This open-source software is based on a two-step synchronization mechanism that yields multiple executable files as shown below.

*ptp4l:* This tool synchronizes PTP hardware clock (PHC) along with the master clock by default in the network. However, when the system does not have an inbuilt PTP hardware clock, the ptp4l tool synchronizes the system clock with the master clock using software timestamping. Software-based timestamping does not require the two-step synchronization mechanism, and the output can be extracted only by running ptp4l in the component. On ptp4l, the slave devices report offset time calculated from the master clock. Thus, offset data information is used to determine whether the systems have been synchronized. The data value reported by ptp4l when the slave clock is locked with the master clock demonstrates the time offset between the PHC and the Grandmaster clock.

TABLE V
CONFIGURATION FOR SO_TIMESTAMPING

| Configuration | Description |
|---|---|
| SOF_TIMESTAMPING_TX/RX | It generates the timestamping |
| SOF_TIMESTAMPING_TX_HARDWARE | Retrieve timestamps for outgoing packets from the hardware clock |
| SOF_TIMESTAMPING_TX_SOFTWARE | Retrieve timestamps for outgoing packets from the software clock |
| SOF_TIMESTAMPING_RX_HARDWARE | Retrieve timestamps for incoming packets from the hardware clock |
| SOF_TIMESTAMPING_RX_SOFTWARE | Retrieve timestamps for incoming packets from the software clock |
| SOF_TIMESTAMPING_RAW_HARDWARE | Command to retrieve original timestamps from the hardware clock. |
| SOF_TIMESTAMPING_SYS_HARDWARE | Command to retrieve hardware timestamps transformed to the system time clock |
| SOF_TIMESTAMPING_SOFTWARE | Command to retrieve timestamps from the system clock |

*Phc2sys:* This tool synchronizes the Linux system clock with the PTP hardware clock. In the entire procedure, the phc2sys is synchronized alongside ptp4l, where the system clock act as a slave and the PTP hardware clock plays the role of the master clock. The phc2sys reports the time offset between PHC and the system clock.

## IV. EXPERIMENTAL SETUP

In order to implement the PTP-based architecture, a Linux-based SoC is used with the open-source LinuxPTP software, which is more reliable than the other available software implemented for the testing purpose. The reason for this software to be more reliable is its functionality to test both software as well as hardware timestamping. Whereas other open-source applications software like PTPdaemon (PTPd) are only suitable for software timestamping due to a lack of compatibility for multiple hardware. Linux PTP is run on a testbed consist of 4 SoCs hardware with Sitara processor 1 GHz, 2000 MIPS, 512 MB SDRAM DDR3L 606 MHZ, 4 GB Flash specification as shown in Fig. 5. Data is collected and imported to MATLAB, where the results are plotted as shown in Section V. Also, depending upon the time accuracy and latency required by different distribution system applications, the different timestamping has been categorized in Table VI, which can differentiate whether the specific application needs a dedicated hardware device for time synchronization, or it can use the inbuilt system clock for synchronization purpose.

The LinuxPTP software will run on the SoC to simulate the two-step synchronization mechanism. In this two-step process,

TABLE VI
DISTRIBUTION SYSTEM APPLICATIONS

| References | Application | Time accuracy requirement (µs) | Latency (ms) | Time criticality |
|---|---|---|---|---|
| [34], [35] | Islanding in microgrid | 0.5–1 | 10–50 | Hardware timestamping |
| [36], [37] | Islanding detection and fast DG disconnection from the grid | 1–2 | 5–10 | Hardware timestamping |
| [24], [38] | State estimation | 1–3 | 50–100 | Hardware timestamping |
| [39], [40] | Awareness of real-time load | 10–15 | 100–120 | Hardware timestamping |
| [13], [41] | Phasor-based control | 10–50 | 10–20 | Hardware timestamping |
| [13], [42] | Disturbance analysis | 50–100 | 800–1000 | Software timestamping |
| [43], [44] | Topology detection | 100–150 | 800–1000 | Software timestamping |
| [45], [46] | Thermal overloading | 100–150 | 1000–1500 | Software timestamping |
| [47], [48] | Voltage stability monitoring | 150–200 | 500–800 | Software timestamping |
| [13], [19] | Digital fault recording | 50–1000 | 800–1000 | Software timestamping |
| [5], [19] | Sequence of event recorder | 50–2000 | 500–1000 | Software timestamping |

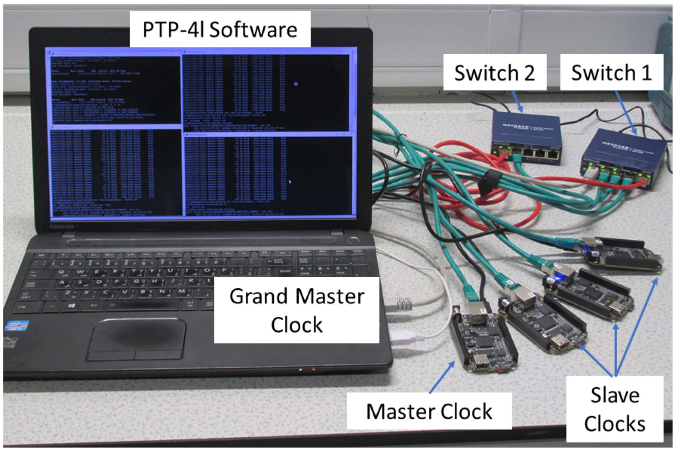

Fig. 5. Experimental setup for LinuxPTP.

the ptp4l tool will synchronize the system clock with the master clock using software timestamping. In hardware timestamping, the phy2sys tool will synchronize the Linux system clock with the inbuilt hardware clock since the network router used in this testbed does not provide PTP support. Therefore, a slight increase in the delay and accuracy is expected. In this article, end-to-end delay mechanism is exercised.

Some specific Linux tools need to be installed in the PTP environment to run software and hardware timestamping for different switch configurations. Timestamping capabilities are tested by using the ETHTOOL_TS_INFO calls. Ethtool is a tool in Linux which gives the ability to inquire about the timestamping capabilities of the hardware. However, in software timestamping, there is no need for kernel configuration. A detailed explanation of how this setup can be implemented in real scenarios is provided in the authors' other work where this PTP-based infrastructure can be used to synchronize a low cost PMU using the experimental setup shown in Fig. 5 of this article [33].

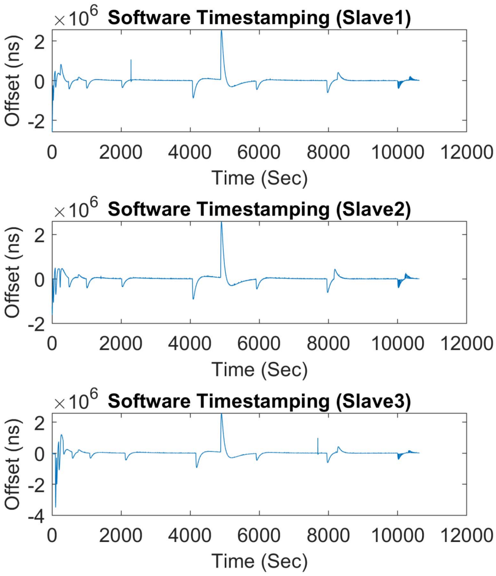

Fig. 6. Software timestamping on two switch network.

## V. RESULTS

### A. Two-Switch Setup

Overloading of the communication medium is a common issue in the communication network. This hinders the data packets to transverse the link, which makes the whole network slow. To test this problem on both the timestamping process, two switches have been connected for three slave clocks, as shown in Fig. 5.

*1) Software Timestamping:* This shows that in the software timestamping where the system clock is used for synchronization purposes. The asymmetric link load will cause the asymmetric path delay for the slave clock connected with the second switch.

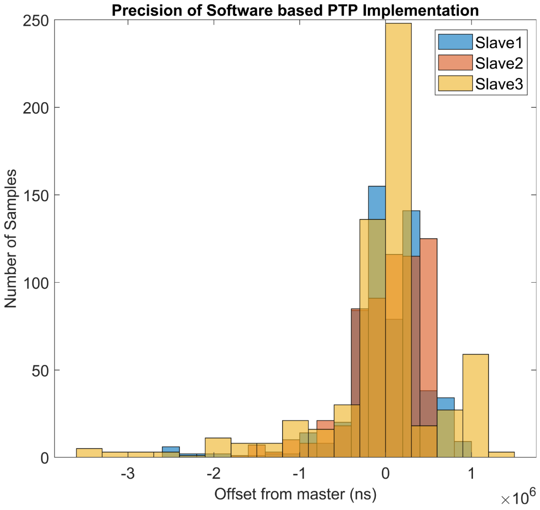

Fig. 7. Precision of software-based PTP implementation.

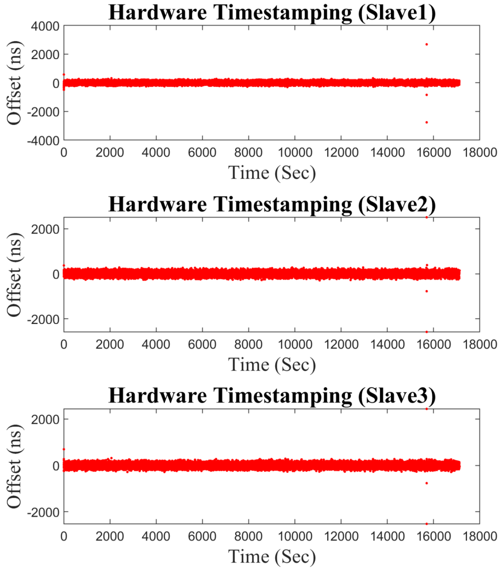

Fig. 8. Hardware timestamping on two-switch network.

Fig. 6 shows the PTP offset for the slave clock over the span of three hours. It can also be seen that the clocks show uncertain behavior. Overall, the offset is between ±0.2 ms for the slave clocks S1 and S2 and ±0.3 ms for the slave clock S3 connected with two switches, as shown in Fig. 5. There is a sudden change in the offset in all the clocks, which may result from varying network traffic.

The precision graph in Fig. 7 is plotted based on the stable synchronization span of Fig. 6. The number of samples is plotted between the range $-3.5 \times 10^6$ ns to $+1.5 \times 10^6$ ns. It can be seen that the third slave S3 has the worst precision as compared to the other two slaves. The reason for this is because the S3 has the delay and offset of two switches.

*2) Hardware Timestamping:* The graph in Fig. 8 shows the slave clocks synchronization over a period of four hours. As can be seen from the Fig. 8, there is no uncertain behavior in all the three slave clocks, as seen in the software timestamping. This proves that the hardware timestamping, which depends upon the inbuilt hardware clock, does not have any fluctuation caused by the network traffic. The offset of the slave clock is between ±200 ns in all three slaves.

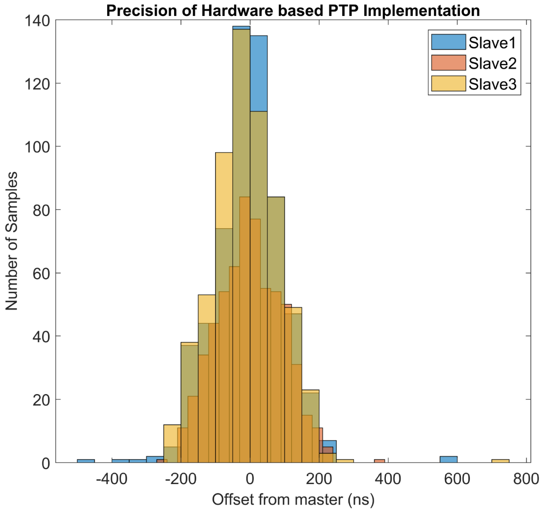

Fig. 9. Precision of hardware-based PTP implementation.

The stability of the hardware timestamping is indicated in the precision bar graph in Fig. 9. The bars are not spread as in the software timestamping, and the number of samples is plotted in the range of −400 ns to +400 ns with three slave clocks with the home router as switches.

### *B. Proposed Technique Implementation on Power Distribution Network*

This experimental setup shown in Fig. 5 is a lab testing for the IEEE 1588 protocol which can be extended in the power distribution network. With the help of PTP-capable switches and the BMCA algorithm, as explained in Section III, the grandmaster clock shown in the lab testing can be implemented at the substation of the distribution network. In addition the master and slave clocks connected at the distribution network's remaining buses uses boundary clock as explained in Fig. 2. Boundary clock is used to segment the timing network as it can be slaved to a master on one port and act as master on all other ports. The implementation of the boundary clock in the BMCA algorithm can help to synchronize the buses; even if one bus loses the connectivity with the other bus, the boundary clock in that particular bus maintain the timing. This holdover option keeps the buses synchronized with minimal delay in the power distribution network.

### *C. Timestamping Requirement for Distribution System Applications*

Based on the data timestamping results, the applications that improve the reliability and security depending upon the asset utilisation in the distribution systems are listed in Table VI. The requirement of accuracy and data rates for these applications are defined on a 50 Hz network. The time accuracy requirement

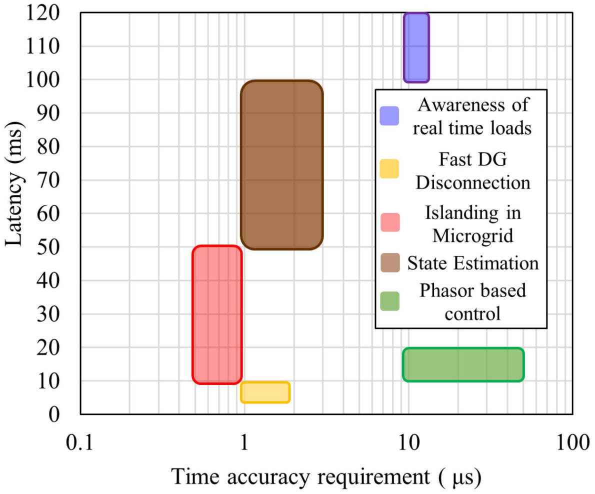

Fig. 10. Applications requiring hardware timestamping.

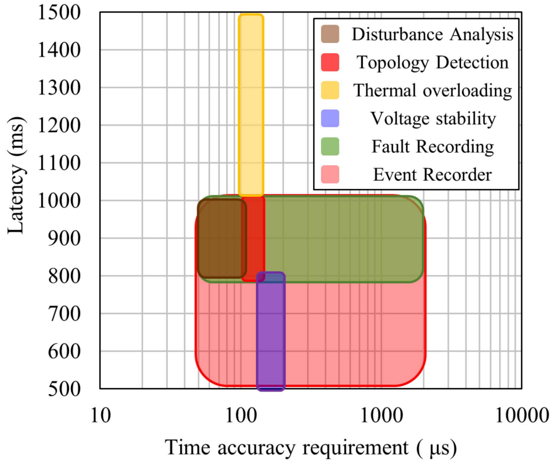

Fig. 11. Applications requiring software timestamping.

in microseconds ($\mu$s) and the latency in milliseconds (ms) for individual applications have been extracted from the given references, as shown in Table VI. This time accuracy requirement is the time required by the communication protocol to run on the ethernet cable. These protocol accuracies provide the different reporting rate accuracy of every application. Depending on the message rate and latency requirement, these applications are classified whether they require a software-based timestamping with no inbuilt clock component or a hardware-based timestamping with a dedicated inbuilt clock component for synchronization.

The distribution system applications requiring low latency and high message rate require very high time synchronization accuracy, such as islanding in the microgrid, state estimation, system oscillation detection, etc. The synchronization between measurement devices is critical with 1 ms or better time resolution. The applications requiring accuracy of 1–10 s of $\mu$s with latency in 100 s are plotted in Fig. 10 for hardware timestamping. In comparison, the application requiring accuracy in 100 s of $\mu$s with latency in 1000 s are plotted in Fig. 11 for software timestamping. As suggested in [33], these results from the lab setup could be implemented in the real-world distribution network by installing the SoCs with the already assigned smart meters. With the help of smart meter sensors like the current transformer and potential transformer, this PTP lab setup can be put into practice on the distribution network.

## VI. CONCLUSION

This article provides an indepth study of the importance of the time synchronization technique for various distribution system applications. It explains why IEEE 1588 is considered preferable for synchronizing measurement devices in this context, given all of the different approaches available.

This article also explores the importance of synchronizing time signals with different timestamping techniques using hardware and software timestamping. Experimental tests have evaluated the performance achievable by the proposed solution on different SBCs. Linux PTP running ptp4l and phy2sys test has been performed on a number of SBCs utilizing the component inbuilt hardware clock and its system clock. The results show that the SBCs achieve accuracy to within nanoseconds when running the hardware clock, and were not impacted by the communication medium bandwidth or traffic fluctuation. On the other hand, the SBCs using an inbuilt system clock had variations with the changes in data bandwidth and traffic load.

The results clearly indicate why the requirement of a dedicated inbuilt hardware clock for distribution system applications requiring high accuracy timestamping is necessary. This is due to the fact that the variation in the accuracy due to network traffic load and bandwidth variation can cause an error in the monitoring and control application. On the other hand, some applications can work with a system clock as they do not require a high precision timestamping in several nanoseconds, which can be achieved by the inbuilt system clock of the measurement instrument.

Table VI of the article outlines the time accuracy requirement and latency of various distribution system applications and differentiates the applications requiring hardware timestamping or software timestamping. This shows that the monitoring and control of these applications can be handled with a uniform time synchronization technique using different time criticality. This resolves the time synchronization challenges caused by the delay in the propagation of the synchronization packets introduced by different technologies adopted in the heterogeneous communication networks. This IEEE 1588 protocol over the ethernet with different timestamping fulfils the requirement for various distribution system applications and mitigates the challenges associated with various other synchronization techniques.

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