An IEEE 1588 Time Synchronization Testbed for Assessing Power Distribution Requirements

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***Abstract*—Wide-area monitoring (WAM) applications for power distribution rely on accurate global time synchronization. Furthermore, there is interest in replacing current time synchronization methods such as Inter Range Instrumentation Group (IRIG), with distributed time synchronization protocols that utilize the data communication lines eliminating the need for dedicated timing signals within the substation. By understanding the factors impacting synchronization performance, the testbed facilitates the characterization of metrics needed to meet industry requirements. The testbed provides an experimental venue to explore IEEE 1588 Precision Time Protocol (PTP) technologies and determine how new features and requirements for time synchronization can impact the performance of next-generation power distribution applications. Initial results indicate PTP has the capabilities to support an accurate and scalable time synchronization solution given the components are interoperable.**

Keywords: time synchronization, PTP, Smart Grid, PMU

I. INTRODUCTION

The Northeastern blackout of 2003 brought to the attention of the power distribution industry the need for time synchronization requirements for synchronized distributed measurements to preempt cascading failures in the grid. The event also heightened the need for more accurate data recorders on the electrical grid to aid in rapid fault diagnosis. Inaccurate time-stamps caused significant delays in diagnosing the cause of the blackout [1]. Realizing the importance of time synchronization, the power distribution industry adopted several standards dictating minimum synchronization requirements for time synchronization and time-stamping accuracy.

To ensure that the upcoming industry requirements are feasible and sufficient, National Institute of Standards and Technology and University of Michigan (U of M) are jointly developing Institute of Electrical and Electronics Engineers (IEEE) 1588 Precision Time Protocol (PTP) testbed with the objective to develop metrics, measurement methods, and recommended practices based on practical industry scenarios for meeting distributed time synchronization requirements in power distribution applications. The testbed enables the characterization of the factors impacting synchronization precision and the determination of how the synchronization precision in turn affects the reliability and integrity of power distribution monitoring and control. Furthermore, the testbed enables the exploration of how PTP technologies impact the Smart Grid performance requirements.

II. BACKGROUND

A. Smart Grid Wide Area Monitoring

The monitoring, control and protection capabilities of modern grids require wide area distributed measurement systems capable of providing reliable, constant real-time data in order to optimize distributed generation of energy and prevent problems from cascading. Distributed power generation has implications on both power management and protection systems [2]. The quality of the distributed generation system performance relies partly on the quality of the measurement.

Phasor measurement units (PMUs) enable distributed and simultaneous measurement of voltage and current over a dispersed area on the power grid using the UTC time reference to assess and manage the health of the power system. Synchrophasor messages, the data output of PMUs, contain accurately time-stamped current and voltage phasor measurements. PMU performance is dependent upon the accuracy of the timestamps, the reporting rate and the information delivery latency. Data from a network of PMUs dispersed throughout the electrical grid are aggregated at Phasor Data Concentrators (PDCs). A PDC can collect data from a dozen up to 60 PMUs [3]. Depending on the application, PMUs are required to deliver 10 to 60 synchronous reports per second to the PDC, where the data is correlated using accurate time-stamps. PDCs provide the aggregated data to a central control system, Supervisory Control and Data Acquisition (SCADA) or Wide Area Measurement system, in order to present a wide area view of all generators and substations every 2 to 10 s.

B. Time Synchronization Needs

Accuracy, availability, and reliability of time synchronization are required for power systems applications. The accuracy requirements in industry standards range from 1 ms in Disturbance Measuring Equipment (DME) [4] for event reconstruction to accuracy on the order of microseconds or less for PMUs and fault detection.

The IEEE C37.118 *Standard for Synchrophasors for Power Systems* requires the Total Vector Error (TVE) of

PMUs to be 1 percent. For a 60 Hz system, the time synchronization errors can be at a maximum of ±26 μs. However, the TVE is an aggregation of errors based on instrumentation conversion latencies, phasor measurement processing latencies, and time synchronization offsets [5]. To allow tolerances for other sources of errors in the TVE, the testbed is striving to meet 1 μs requirement. Satellite systems provide a wide area global time source with a general accuracy of 1 μs, but there are concerns as to their availability [6].

Substation Intelligent Electronic Devices (IEDs) use a variety of methods to obtain synchronized time including Global Positioning System (GPS), Pulse Per Second (PPS), and IRIG signals. With the increased use of IEDs, there are benefits associated with using distributed time synchronization protocols such as PTP which leverage data networks. One such benefit is to eliminate the need for a separate time synchronization input for each IED. In order to justify the use of distributed network time synchronization methods, a few questions must first be addressed. Can distributed time synchronization methods offer the required reliability and accuracy? Are the network characteristics of substations amenable to ensuring the time synchronization performance capabilities needed? The testbed has been designed to answer these questions by exploring the feasibility of synchronizing substation components utilizing PTP and their ability to maintain time synchronization in the event satellite systems become unavailable.

III. Testbed Design

A. *IEEE 1588 Profile for Power System Applications*

The testbed is designed based on the *Draft Profile for Use of IEEE 1588 Precision Time Protocol in Power System Applications* to develop the requirements and metrics [7]. The profile is prepared by the IEEE Power System Relay Committee (PSRC) and provides industry specifications for using PTP. The results and conclusions from the testbed can be used as input to ensure the profile provides feasible and sufficient requirements with currently available implementations. The series of test scenarios will focus on the ability of PTP to maintain 1 μs synchronization over one to four hops, where the number of hops is comprised of the number of switches between the Grandmaster (GM) and the slave.

B. *Testbed Network*

The testbed network (Figure 1) consists of two traffic paths, one for configuration of the nodes and switches using the Ethernet port of the host computer (the configuration path), while the other is dedicated to PTP and substation traffic using the Ethernet port on the PTP devices (the 1588 path). The PTP network is comprised of two GPS-synchronized GM clocks which serve as the reference time. The GMs have High Quality Oven Compensated Crystal Oscillators (OCXO HQ). The available PTP Ordinary Clocks, OC1, OC2, OC3, OC4, etc., provide an initial examination on the scaling capabilities. The devices are not identified to maintain neutrality of the testbed. The nodes include slave devices A and B, which have High Quality Temperature Compensated Crystal Oscillators (TCXO HQ) clocks, and C, which has an OCXO Low Quality (LQ) clock. Three of the devices from B were used to ensure the results are independent of vendor implementation. Each GM and PTP slave is attached to the PPS measurement board. The network allows testing of up to sixty slaves to evaluate the impact of scaling the network on performance degradation in terms of synchronization accuracy and reliability. Each hop consists of a switch capable of forward, boundary clock (BC) or transparent clock (TC) mode.

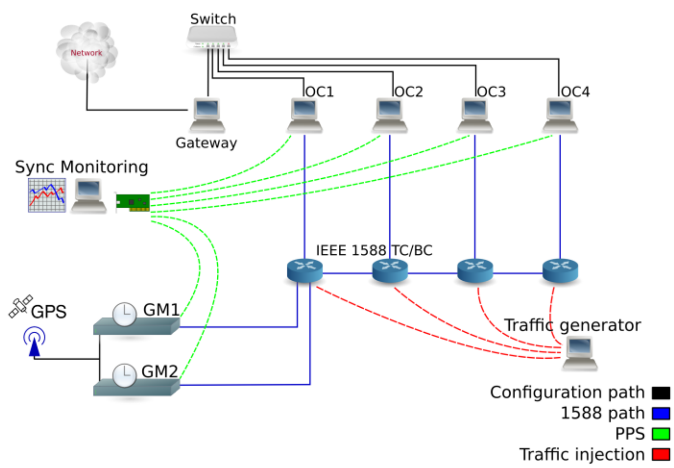

Figure 1. PTP testbed for power distribution applications.

C. *Network Simulation*

A simulation of the PMU nodes will be developed to generate synchrophasor packets. A network traffic generator to examine network load scenarios is also planned to be part of the testbed. Additional PTP switches and slave nodes can be simulated to estimate the capabilities of scaling the network in a large-scale substation local area network (LAN). The simulation can also be extended for experimentation with PTP in wide-area monitoring applications using PMUs throughout the grid. The simulation would enable analysis on the impact of time synchronization performance on wide-area monitoring and control applications.

D. *Metrics*

The metrics tested thus far have been based on the requirements of accuracy and reliability. The characteristics affecting accuracy include offset, convergence, maximum time interval error (MTIE). For reliability, the characteristics to be measured will include holdover, stability, clock drift, and phase change rate. Depending on the test scenarios, the tests are based upon the following relevant metrics:

- *Offset*: the time differences between the reference GM and the slave node. As the power distribution system requirements can range depending on the application, the minimum, maximum, mean and standard deviation of the offset for the system of nodes was observed and analyzed over a period of time.
- *Convergence rate*: the rate at which nodes can be synchronized to the Grandmaster and as a whole

system. Understanding the convergence characteristics enables the power systems relying on synchronized time to have confidence that all nodes are synchronized within 1µs after a period of time, whether from a cold start, after a loss of signal or after reconfiguration of nodes or the reference time. The profile, rate, and peak time to convergence has been assessed.

- *Maximum time interval error (MTIE)*: measures the maximum peak-to-peak phase transient offset over an observed period, τ.
- *Holdover*: measure of the duration of the free-running node or system synchronization based on a required accuracy to Universal Time Coordinated (UTC) without a reference (GM). To meet the most stringent requirements, holdover at various synchronization levels has been identified based on the devices tested.
- *Stability*: a measure of the magnitude of variation in time offsets between the slave node and the reference time after the system has converged. The characteristics of stability including the standard deviation over 24 hr durations have been assessed.

E. Measurement Capabilities

In order to measure the synchronization of the nodes, a scalable and precise measurement system sufficient for monitoring the PTP requirements for power distribution has been developed. To observe the synchronization of the PTP devices over time, the data acquisition card simultaneously and continuously monitors the PPS output of the GM and all slave nodes. The data acquisition card measures the state of the synchronization once every second. The PTP GM and slave nodes are connected to a single Field Programmable Gate Array (FPGA) driven board that samples and timestamps the signals at a frequency of 125 MHz. The uncertainty of measurements from the board is 8 ns. The data acquisition board has 64 inputs to allow the system to simultaneously measure over 60 nodes. To prevent any delays from being introduced due to the propagation of electricity in wires, each wire connecting the PPS output to the acquisition board is the same length. A difference of just 20 cm in a shielded coaxial cable would cause a 1 ns offset.

IV. Test Scenarios and Results

The requirements being discussed for the power grid industry include a 1 µs synchronization capability over 25 hops. The capability to maintain 1 µs synchronization over a significant duration from 1 to 24 hrs was assessed. The duration ensures the devices can reliably maintain synchronization. Failure modes, where the GM is disconnected or switched, were also tested to determine the ability of PTP to maintain integrity of the synchronization.

The testbed runs exclusively on PTP version 2, which includes several features to increase accuracy performance. Among the new features is the TC, which prevents the cascading delay variations at each hop that can be incurred by BC. Switches can also incur significant cumulative, asymmetrical delay variations, compromising PTP synchronization performance. TCs minimize the asymmetrical delays in the network, crucial to achieving more deterministic PTP synchronization accuracy. The initial test scenarios presented, rely on TC switches.

The tests conducted were based on a star topology with 4-hop TC mode where the slave devices are on the first, third and fourth hops (Figure 2). For the remainder of the paper, the devices are denoted as A, B, and C with a number, indicating the hop of the device. B4 would be Device B on the fourth hop. The fourth hop compared three PTP slave devices. Unless otherwise noted, the PTP messages were configured at intervals of 0, 0, and 3 for Sync, Announce, and Delay Request messages, respectively. The test scenarios deployed had no traffic load.

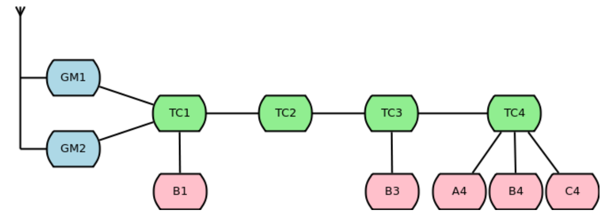

Figure 2. Test scenario topology.

A. Reliability

Figures 3 and 4 provide results of the initial experiment with four hops over a 24 hour period. A software network monitoring tool was used to verify the switch was compliant with the PTP requirements for TC mode. With four TC and two PTP slave nodes, the maximum offset is 120 ns. There is a slight variation in the frequency distribution of the offsets for the devices tested. However, the variation is not significant enough with respect to power distribution requirements. The mean offset ranges from 0.7 to 24.3 ns. Even in TC mode, there is degradation as the distance from the GM increases. The precision of the slaves decreased as the number of hops increased. Under the ideal situation with four hops and negligible traffic loads, PTP devices can reliably maintain synchronization over a 24 hour period.

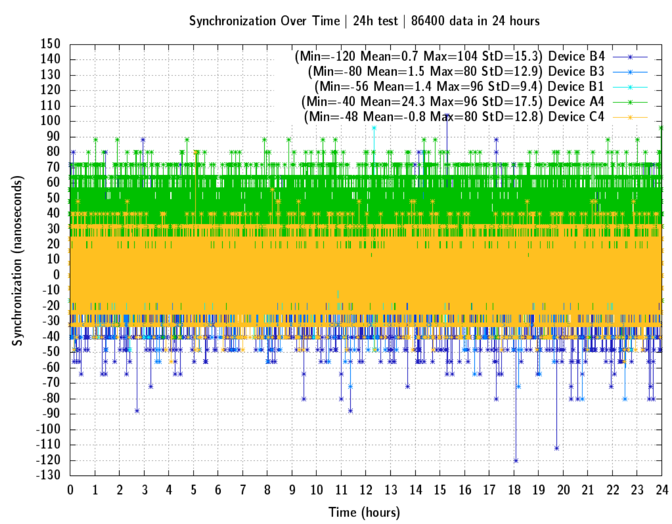

Figure 3. Synchronization offset between PTP slave and Grandmaster.

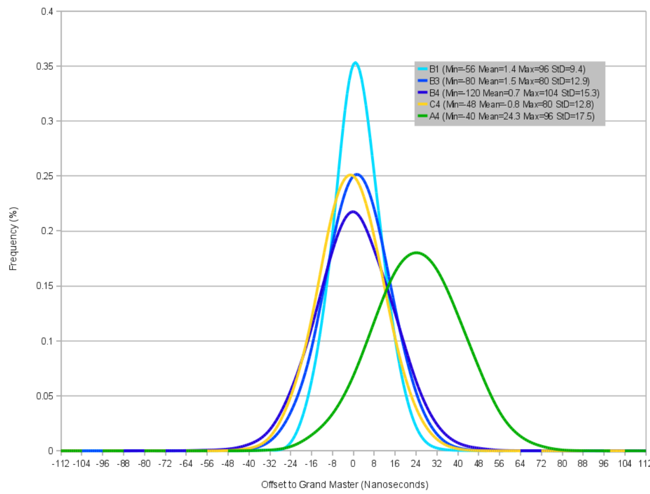

Figure 4. Synchronization offset distribution between PTP slaves and Grandmaster.

B. *Assessment of Holdover Capability*

Holdover focuses on failure modes, where the GM loses the GPS signal, and therefore the LAN must be able to sustain synchronization over a period before the time reference is recovered. The network is intact and the synchronization between the slaves and the GM remains active. However, the GM clock slowly drifts. It is critical that even after a GPS loss, the substation's PTP slaves stay synchronized within the 1 us threshold, until a backup reference can be obtained. The main factor impacting holdover capability is the type and quality of oscillator embedded in the GM. The GM holdover due to GPS loss was not tested for this paper.

Another potential failure mode is a network disruption causing a slave to lose communication with the GM. The free-running slave clock drifts from the GM at a rate dependent on the quality of the oscillator, which is more problematic than the GPS loss because the slave is likely to have a low quality oscillator and can rapidly lose 1 µs synchronization threshold. Figure 5 depicts five PTP nodes losing the synchronization with the GM for 1000 s; the 1 µs synchronization was lost within 100 s in the worst case, where the worst case measured drift rate based on the devices tested was 10 ns/s for the TCXO HQ. The OCXO LQ device had a measured drift rate of 1.5 ns/s.

The subsequent test scenario includes a redundant passive GM2. GM1 is taken offline for 5 minutes. The PTP nodes in the system quickly converge to GM2 within 120 s (Figure 6), where the offset from the drift and convergence of the PTP nodes does not exceed 400 ns. Once GM1 returns, the PTP nodes make their attempt to converge back to GM1, with consistently higher peak-to-peak offset, but all PTP nodes in the network converges within 120 s to GM1. With redundant GM available, the network would be able to maintain 1µs peak-to-peak offset without interruption in the event of a dropout of the primary GM.

Subsequent tests will also explore use of PTP's Best Master Clock Algorithm (BMCA) to improve the holdover of the synchronization network. It is expected that the use of BMCA, the drift rates should be significantly lower, to match the best performing slave.

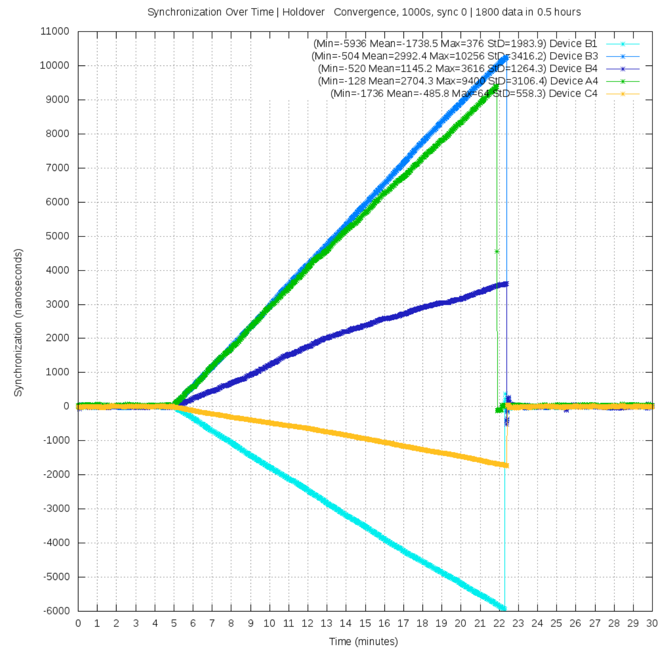

Figure 5. PTP GM1 disconnected from slave nodes without redundancy or use of BMCA.

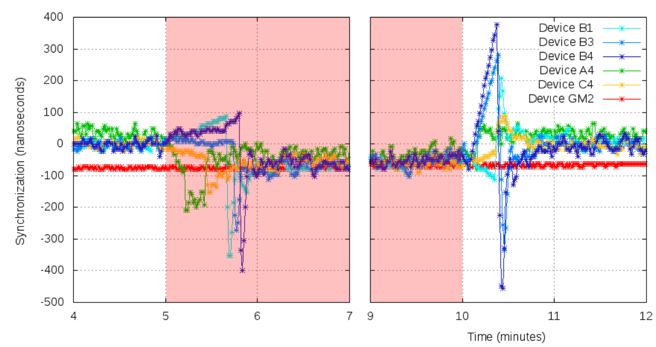

Figure 6. Assessment of PTP switchover to redundant GM. The shaded area depicts the duration when the first GM is unavailable. The red baseline represents the time from the second GM.

C. *Convergence Rate Assessment*

The PTP standard describes how to calculate the synchronization offset between the slaves and the GM, but allows the implementation to handle the synchronization process after the clock has drifted from a reference time. Implementations can slowly converge by slewing, a gradual adjustment in clock frequency, or by stepping, which is a jump immediately to the reference time. The implementation may also take a windowed average of the timestamps received from the first PTP messages after commencing the PTP synchronization or it takes only the last available PTP messages into account during clock adjustment. The methodology varies between manufacturers, and therefore variations in the results are dependent on the implementations tested, as seen in the convergence profiles based on offset measurements in Figure 7.

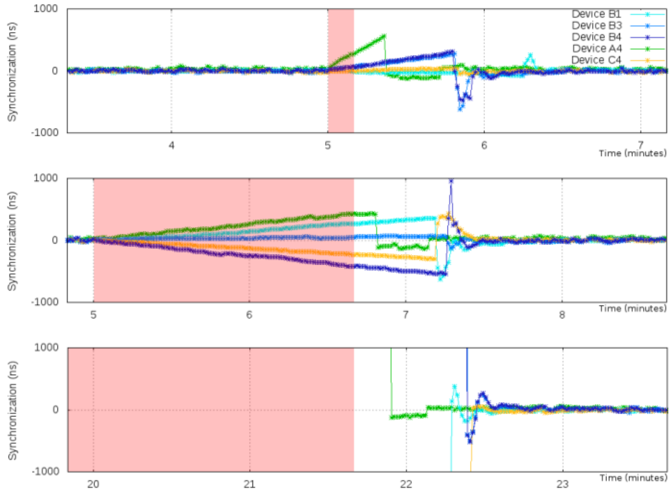

Figure 7. Convergence profiles after a failure mode. GM is disconnected from slave nodes for 10, 100, and 1000 s, respectively. The shaded area indicates the duration of the GM loss.

Studies of the convergence profile for 10, 100 and 1000 s durations of GM loss were conducted. Device A takes from 10 to 20 s to begin the convergence process, and stabilizes after 60 s with no oscillation. Device B begins convergence after 40 to 60 s, but stabilizes more quickly, in less than 20 s. Device B4 has convergence profile with oscillations over 1 us even when the drift remains within the 1 µs window when the device is left to run freely from a GM. Device C has significantly less drift, with a convergence profile that oscillates within a controlled tolerance window based on the data. Regardless of implementation, the devices are able to converge within 120 s despite the extent of drift up to 1000 s. Furthermore, the devices are able to reach 1 µs offsets within 65 s. A sync interval of 0 was used. More frequent sync intervals may further improve the results.

D. *Impact of Syntonization on Synchronization Performance*

Devices do not need to implement the syntonization to be PTP compatible, however it is recommended by the standard. Therefore it is important to know how significant syntonization of the PTP devices impacts the synchronization performance in terms of accuracy, reliability and frequency of PTP synchronization messages. A TC without syntonization measuring a residence time of 100 µs with a 10 ppm oscillator

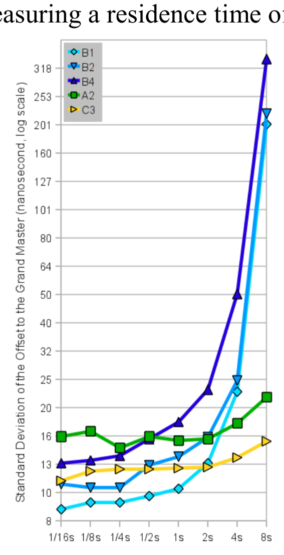

Figure 8. Distribution of standard deviation with respect to offset distribution by sync interval, device type and hop.

can lead to a 1 ns error. The test was deployed for 1 hour with a sync interval of -2. The devices did not show a significant difference in PTP offsets between the devices on hops 1 through 4. However, syntonization is expected to be more significant given varying network traffic loads and scaling to a greater number of hops, which can result in greater jitter and asymmetric delays; therefore, further tests will need to be made once the traffic generation is deployed.

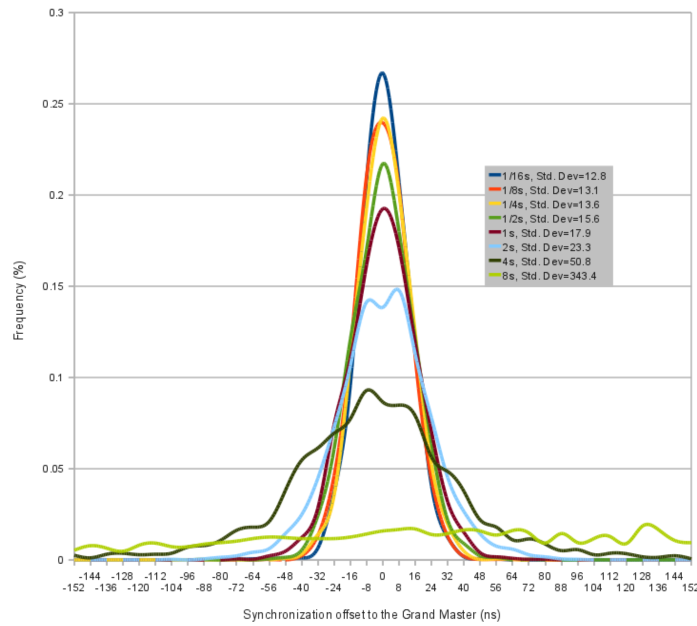

Figure 9. Impact of sync interval on offset distribution for the same device (B4).

E. *Impact of PTP sync interval on synchronization*

Configuration of PTP message exchange frequency directly impacts synchronization accuracy. The initial experiment focused on message intervals ranging from 2^{-4} to 2^{3} s for PTP synchronization (*sync*) messages. Here we observe the tradeoff between the synchronization accuracy and the *sync* message frequency.

Figure 8 provides the results of the offset standard deviations by device type on hops 1 through 4 for each synchronization interval tested. The results indicate that devices can be improved to require less synchronization frequency, whether through algorithm or clock quality. Figure 9 provides a view of the offset dispersion based on a single device. The dispersion begins to deteriorate at a sync interval of 1, but remains within the 1 µs requirement. It is evident that sync intervals greater than 2 would not be recommended as the maximum peak-to-peak offsets nears 2 µs when accommodating a variety of devices (Figure 10). Furthermore, greater synchronization frequency, an synchronization intervals between 2^{-4} to 2^{-1}, do not appear to have a significant impact from the perspective of power distribution requirements. In fact, a few tests have indicated greater synchronization frequency can degrade performance. One significant factor impacting the need for greater synchronization frequency appears to be the implemenation.

PTP configuration of message intervals can significantly impact the synchronization performance, even without additional traffic loads or hops. Additionally, PTP *delay_req* can each be adjusted, which will be explored in future work.

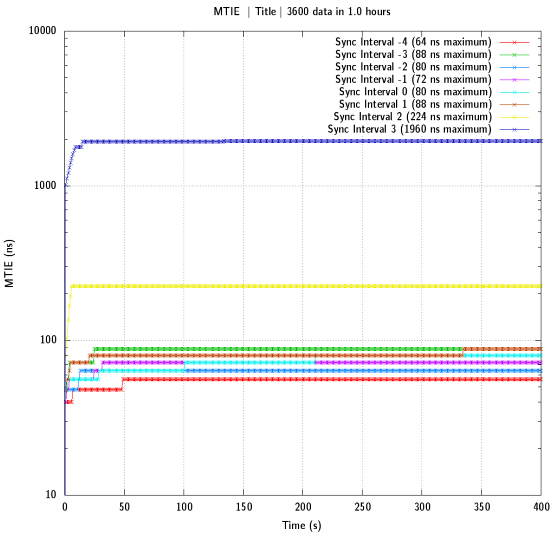

Figure 10. MTIE of sync interval tests ranging from 2^{-4} to 2^{3} s. The maximum peak-to-peak offset for each sync interval scenario is noted in parantheses.

V. Conclusion and Future work

From the initial test results, commercially available IEEE 1588-compatible products are able to achieve the accuracy requirements of 1 µs in a four-hop network. The stability of the synchronization for four hops is also demonstrated by the tests over a 24-hour period, where the time offset maintains well below the 1 µs requirement. Devices are capable of converging within 120 s based on the devices tested. The convergence will require further testing with varying network loads, as greater traffic loads are expected to impact convergence rates. Reliability is of greater concern, as initial results indicate holdover capability is only within a minute with TCXO HQ clocks. The OCXO LQ clock has better short-term stability and holdover on the order of a few minutes. Reliability of PTP can readily be achieved with high quality oscillators; a network with redundant GMs provides an extra buffer to ensure the PTP nodes stay within the 1 µs range when one GM is unreachable. Furthermore, the initial tests have also shown significant variations in behavior among PTP implementations under different test scenarios. The variation can cause reliability issues for a substation planning to architect a PTP network using different implementations with stringent time constraints. Either the PTP profile will need to accommodate for the implementation differences or provide a conformance testing suite to ensure the PTP implementation can meet power distribution requirements.

For future work, more extensive testing with practical scenarios using various network loads and patterns are planned. Topology of the network can also influence the accuracy, scalability and reliability of PTP. The testbed will be used to explore typical topologies in a power substation. An assessment and comparison of the star and ring topologies for PTP will be made to provide insight into how the topologies impact the time synchronization performance metrics. The ring topology adds redundancy by offering two different paths for the packets.

The network traffic scenarios study the impact of the network loads on the synchronization performance with respect to the accuracy and reliability metrics. The network profiles we plan to use are the network traffic models and test cases described in the G.8261/Y.1361 *Timing and Synchronization Aspects in Packet Networks* [8]. While the profiles are typical for telecommunication networks, they provide a framework that can be updated for traffic load patterns within the substation and extending to the Smart Grid. The profiles enable tests based on different parameters, such as load variations of up to 80 percent. An understanding of automated substation network traffic pattern and loads would enable the testbed to produce more relevant results.

Future work will include implementation of the PTP security annex K, focusing on assessing their performance impact with respect to providing a level of assurance in the integrity of the synchronization network. A simulation component will be used to generate PMU traffic and to assess the impact of scalability for a larger number of nodes and network hops as required by the PTP Profile for Power Distribution, as well as synchronization on WAM applications for the Smart Grid will also be implemented. Additionally new topologies such as high-reliablity seamless ring (HSR) protocol will be included in the simulation.

Acknowledgments

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