Maintaining Precise Time for Power System Applications in the Event of Wide Area Loss of GPS

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Abstract—**Reliable and precise time is a crucial requirement for critical power system applications, including synchrophasors, traveling-wave fault locating, line current differential protection, and digital substations based on Sampled Values. The traditional approach is to install a Global Positioning System (GPS) clock inside each substation site, often requiring tens or hundreds of substation clocks distributed across a utility network footprint. Since Global Navigation Satellite Systems (GNSSs) rely on the recovery of low-amplitude signals transmitted by orbiting satellites, GPS receivers are susceptible to unintentional and intentional interference and jamming, creating multiple points of vulnerability to applications that depend on accurate time.**

Modern positioning, navigation, and timing (PNT) technologies are capable of mitigating disruptions to the GNSS. This paper evaluates a complete PNT system solution. This solution consists of precise time provided by enhanced primary reference time clocks (ePRTCs) via packet-switched, telecommunication networking equipment and a network of innovative time distribution gateways (TDGs) that provide antispoofing and antijamming capabilities. This solution's components work together to maintain submicrosecond time accuracy after a localized or wide-area loss of GPS for significant periods.

We jointly developed and validated a complete system architecture at a laboratory in Kansas City, Missouri. We equipped the laboratory with an ePRTC system that receives GPS signals and connects to a cesium atomic frequency source. The packet-switched network (PSN) supports Precision Time Protocol Telecom Profile G.8275.1 (PTP TP). We included TDGs at PSN sites to perform PTP TP to IEEE/IEC 61850-9-3 PTP power profile (PTP PP) conversion through coordination. For each 2-week test, a PTP test set measured and captured time error data.

This paper provides time accuracy test results to demonstrate that technology is commercially available to address Executive Order 13905 entitled "Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Timing Services" regarding precise time maintenance in the event of a complete loss of GPS.

I. INTRODUCTION

Critical infrastructure, including electrical utility networks, requires frequency syntonization and accurate time of day (ToD) information. Synchrophasor applications require time accuracy to within 1 microsecond to Coordinated Universal Time (UTC). Based on interactions with electrical utilities, we are seeing a need to strengthen and diversify Global Positioning System (GPS) solutions for this level of time accuracy, and the industry is replacing or upgrading clock and network infrastructures with alternative solutions that encompass highly accurate terrestrial time distribution.

Why the shift in approach? Executive Order 13905 [1], which was issued by the President of the United States in February 2020 and aims to strengthen national resilience through responsible use of positioning, navigation, and timing (PNT) systems, motivates the shift. The President wants all critical infrastructures, including the power grid, transportation, emergency response, and commerce, to build resilient systems that responsibly use GPS. One method of responsible use is to build systems that can mitigate GPS outages. Disruption to PNT services for these critical infrastructures could cost the U.S. over one billion dollars daily in financial losses [2].

In North America, the power grid is a critical infrastructure that relies on distributed GPS-based clocks for precise time acquisition. Precise time is a requirement for protection, monitoring, and control functions. Intelligent electronic devices (IEDs) that require precise and consistent access to time references receive it from discrete clock devices. This traditional approach of installing one or more GPS clocks inside each substation requires tens or hundreds of clocks.

There are steps to get closer to the ultimate objective of complete GPS independence for critical infrastructures. Network designs can facilitate a transition from GPS acquisition at every site to terrestrial-assisted time distribution. A hybrid system design can leverage GPS and IEEE 1588, *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*, Precision Time Protocol (PTP). This solution could be viewed as a step in a systematic approach toward solely leveraging terrestrial-based PTP time sources for critical networks. There will be challenges and adoption may be slow, but for critical infrastructure that depends on ToD synchronization, Executive Order 13905 mandates the change.

This paper explores how to get closer to GPS independence using enhanced primary reference time clock (ePRTC)-grade PTP grandmaster (GM) clocks. These clocks connect to multiple autonomous primary reference clocks (PRCs), which are typically a combination of Global Navigation Satellite System (GNSS) and cesium atomic frequency sources. ePRTCs may leverage a packet-switched network (PSN) to distribute time. This approach would either eliminate the need for the discrete substation clock or provide a backup time source in case of localized or system-wide GPS loss if the discrete clock is maintained. The use of ePRTC-capable PTP GM clocks is to maintain synchronization of the routers and switches in the PSN and time distribution gateways (TDGs) and to the edge-connected applications. This paper includes observations taken from various laboratory validations and test results that prove the concept's viability.

II. WHAT IS PTP?

PTP is a protocol that distributes time through a PSN. The International Telecommunication Union (ITU) defines various PTP profiles and offers guidance for manufacturer interoperability. Wide-area network (WAN) PTP profiles vary from PTP profiles defined for use in the local-area network (LAN). PTP relies on one or more GM clocks that source UTC via satellite sources, and network administrators install GM clocks in fortified and secured sites with wide geographical footprints to reduce risks of GPS jamming and spoofing. PSNs distribute and treat PTP as a terrestrial source of time.

PTP frames include useful clock attributes. Two attributes to expand upon are clock class and accuracy. Clock class helps identify the current GNSS lock status. Fundamental clock class values to make note of are "6" and "7." A clock class of 6 means the clock synchronizes to a primary reference time source (PRTC) like GPS and not another clock in the domain. A clock class of 7 means the clock was previously synchronized to a PRTC but is now in holdover mode.

Clock accuracy is an attribute that indicates how closely the time produced by the network aligns relative to UTC at the present time. While GNSS signals are attainable, the clock produces time with the highest possible clock accuracy. If GNSS signals are lost and the clock enters a holdover state, clock accuracy begins to degrade until GNSS connectivity is restored. Clock degradation depends on the quality of the clock oscillator.

Together, clock class and accuracy attributes are a way to characterize the GNSS availability and quantify the accuracy of time distributed using PTP. See the G.8275.1 recommendation in [3] for more details.

III. WHAT IS A TDG?

A TDG, which is a gateway device available in the marketplace for getting the most accurate time from all the time sources external to a substation, helps critical infrastructures transition from satellite-only to a hybrid of satellite and PSN-based time sources. A previous paper [4] describes how one might deploy a TDG device that supports both satellite and terrestrial time sources in critical networks.

A TDG can mitigate localized GPS loss. It receives precise time from GPS at sites where direct GPS signals are available. If a discrete substation clock is already in place, the TDG can receive accurate time from the discrete clock using IRIG-B. The IEEE 1588 telecom profile (PTP TP) is a time input option if TDGs interconnect over a PSN. A single TDG can obtain time from one or more references (GPS, IRIG-B, and/or PTP TP) depending on what time sources are available at the installation site.

Multiple TDGs interconnect to form a network. The TDG network can output precise time in a format that is consumable by most substation IEDs. The TDG provides time output to critical applications using IRIG-B or the IEEE 1588 power profile (PTP PP). This set of capabilities facilitates the transition of infrastructure reliance from satellite time to terrestrial time distribution sources, thus preparing networks for possible PNT-disruption scenarios. Hence, we characterize the TDG network design as a hybrid timing model.

What makes the TDG solution defined in [4] unique is that the TDG performs PTP TP to PTP PP time conversion through coordination with all TDGs in the network, making it more accurate than a time format conversion with a single gateway clock. The time provided by the conversion is time-coordinated by a TDG network comprising gateways at various sites. After communicating what each device receives as the current time via all input sources, there is an agreement on the current ToD at a system level. "System time" is an aggregated, weighted average across all time inputs at all TDG sites. A comparison algorithm constantly checks local-node time inputs (GPS, IRIG-B, and PTP) against the system time. The TDG declares any single time source that differs by more than the preset limit (in microseconds) from system time out of tolerance and disqualifies it from participation in the weighted average. If a rejected time source returns to tolerable limits, the TDG allows the time input to resume contributing to the weighted average. TDGs output the weighted average system time to connected IEDs.

If an attacker were to spoof this system, they would have to simultaneously spoof GPS signals at all sites. The attack would have to target sites with PTP GM clock(s) and everywhere that the system leverages direct GPS input, all without triggering the antispoofing mechanisms.

IV. WHAT IS AN EPRTC?

Since the power grid is a critical infrastructure that relies on GPS-based clocks for precise time, time distribution network architects may consider taking advantage of technologies that allow the system to continue functioning during extended GPS outages. High-accuracy time distribution during lengthy GPS outages may require a supplemental atomic frequency source to syntonize the PRTC oscillator, depending on the outage length to be mitigated and the accuracy requirements of the connected applications. The provision of PTP TP to the network with support from GPS and an external atomic frequency input is the function of ePRTCs in this solution. ePRTC technology based on well-defined standards is available now in the marketplace.

The most accurate stability oscillators are based on the energy levels of the electrons in atoms, with rubidium and cesium being widely used. Rubidium is lower in cost. Cesium is more accurate. When providing time to critical applications while mitigating outage durations that extend to weeks, cesium is better suited as a supplemental, autonomous reference clock for an ePRTC-based PTP solution.

Two benefits of the ePRTC PTP GM clock are:

- Time distributed by the GM ePRTC PTP TP frames are typically accurate to 30 ns while GPS signals are accessible.
- When GPS signals are not accessible, and since an ePRTC can maintain high time accuracy for an extended duration, ePRTCs can produce PTP frames that conceal the state of GPS loss (e.g., with the same clock class of 6 as if a GPS reference is still accessible). The remainder of the network and any connected applications will have no knowledge of the GPS signal loss during this extended time.

Two additional considerations and potential drawbacks to the ePRTC PTP GM clock are:

- Additional costs. Cesium frequency sources can be expensive. ePRTC licenses on these devices are supplemental, and costs increase to operate in ePRTC mode.
- Limited lifespan. Cesium frequency sources typically have a limited shelf and operational lifespan, after which some manufacturers can refurbish or replace the cesium element.

ePRTCs bridge (combine) ToD (from GNSS) with a frequency obtained from an external cesium clock. A standards-based ePRTC follows the performance targets outlined in Recommendation G.8272.1 [5] as defined by the ITU Telecommunication Standardization Sector (ITU-T).

V. LIMITING GPS SOURCES WITH TIME CLOCKS AND ATOMIC REFERENCES

To produce highly accurate time messages and signals in this solution, we leverage time clocks with supplemental atomic references. While actively sourcing GPS signals, Table I represents a subset of compliance recommendations and accuracy targets.

TABLE I
TIME ACCURACY TARGETS OF VARIOUS TIME CLOCKS WITH GPS

Type of Time Clock	**Compliance**	**Accuracy Target**
PRTC A	Meets ITU-T G.8272	100 ns
PRTC B	Meets ITU-T G.8272	40 ns
ePRTC	Meets ITU-T G.8272.1 with cesium	30 ns
ePRTC	Exceeds ITU-T G.8272.1 with hydrogen maser	<1 ns

While GPS signals are no longer available due to intentional or unintentional radio frequency loss or signal corruption, Table II represents a subset of compliance recommendations and accuracy targets.

Notice how all these standards have a more stringent performance profile than the critical application requirements. The performance improvement allows for lingering, uncompensated time error, which naturally accumulates as PTP messages traverse the various electronic devices between the time source and consuming IEDs.

In parallel, networks and network-based time distribution technologies are constantly improving. Critical infrastructure networks are upgrading from synchronous optical network (SONET) to Ethernet technologies using Multiprotocol Label Switching (MPLS) and Carrier Ethernet, and Ethernet networks support time distribution capabilities via protocols like IEEE 1588 PTP.

Between the wide-area transport network and the substation edge, there is a need to bridge and convert time from a WAN profile of PTP that provides the highest levels of accuracy over long distance communications to a LAN profile of PTP that is consumable by substation IEDs. There are devices in the marketplace that can perform a direct, one-to-one profile conversion. However, through coordination, a network of TDGs can provide a more accurate and secure methodology to convert PTP TP to PTP PP.

VI. OUR ePRTC SOLUTION COMPONENTS

The theme of this paper is around important considerations, lessons learned, and pitfalls we encountered as we attempted to validate an ePRTC with cesium assist plus TDG performance in a lab.

Our ePRTC solution with cesium requires the following components:

- Access to good satellite signals
  Having access to strong GPS signals is crucial. Multiple satellites need to be within the line of sight of the clock's GPS antenna. Initial oscillator disciplining requires maintenance of GPS signals during the warm-up period.
- At least one ePRTC clock
  At least one clock that complies with the ePRTC ITU-T G.8272.1 recommendation [5] must be available. This device has the correct hardware, software, and licensing to enable ePRTC functionality, which has a combiner or bridging function that combines frequency from the cesium reference with ToD from the GPS satellites.

TABLE II
HOLDOVER ACCURACY TARGETS OF VARIOUS TIME CLOCKS AND WITH PRC ASSIST

Type of Time Clock	**Internal Oscillator**	**External PRC Assist**	**External PRC Compliance**	**Holdover Accuracy Target**
PRTC	Rubidium	None	NA	200 ns for 1 day
ePRTC	Any	Cesium	Meets ITU-T G.811 accurate to $1 \cdot 10^{-11}$	100 ns for > 1 day (as observed in laboratory tests)
ePRTC	Any	Cesium	Meets ITU-T G.811.1 accurate to $1 \cdot 10^{-12}$	100 ns for 14 days
ePRTC	Any	Hydrogen maser	Exceeds ITU-T G.811.1	100 ns for significantly beyond 14 days

Please refer to the standards and recommendations for more details.

- At least one cesium atomic reference that complies with G.811.1 standard

  G.811 cesium atomic clocks have lower accuracy targets than G.811.1-compliant cesium references. A solution requires higher accuracy of G.811.1 or better to guarantee ePRTC performance.
- Accurate antenna cable delay compensation

  One should calculate cable impedance as accurately as possible by referring to cable specifications and include the impact of inline splitters and connectors from the GPS antenna to the ePRTC clock. One should also check that the antenna's gain is sufficient to handle the cable loss.

  One ought to read manufacturer specifications regarding antennas, splitters, cables, surge arresters, transient eliminators, connectors, couplers, electrical to optical (and vice versa) converters, and fiber propagation delays.

  Unless properly compensated, coax cabling can negatively affect the accuracy of time produced by an ePRTC clock by as much as tens of nanoseconds.
- A methodical approach to monitoring system performance

  Ideally, one should use a more accurate time source to validate the time source under test. For example, when testing an ePRTC with G.811.1 cesium reference, a more accurate time source would be an ePRTC with hydrogen maser. If a more accurate source is not available, there will be a range of time errors introduced by the reference that must be considered.

  One should validate ePRTC configuration parameters. One should configure the bridging period or the duration that an ePRTC clock can combine frequency from the cesium atomic reference and ToD from GPS according to the performance ability of the cesium atomic reference.

  Upon initial deployment, an ePRTC system can achieve its most accurate performance only if GPS signals are fully available for the duration of the warm-up period. The warm-up period duration depends on a manufacturer's clock specifications and could vary between 3 to 4 weeks. One must verify ePRTC logs to ensure GPS loss was not experienced during the initial warm-up period.

  Since the G.8272.1 specifications [5] do not dictate a minimum GPS recovery window, one should consult with the clock manufacturer to ensure that GPS signals are available and sufficiently persist for proper ePRTC recovery between GPS outages.
- A network to distribute precise time

  A PSN provides support for PTP TP and distributes time to the various sites. TDGs within a network coordinate to convert PTP TP to PTP PP.

VII. CONCEPT VALIDATIONS

One of our goals was to validate ePRTC clock performance with cesium assist. Our biggest challenges were how to produce, capture and measure, log, and analyze the accuracy of distributed time in the system. Observations from laboratory validation tests are included. Final test results prove the concept's viability.

A. Producing Time

We had most but not all components for a proper ePRTC system. Our time clock did have correct hardware, software, and licensing support for ePRTC functionality. We needed a cesium atomic reference compliant to the enhanced primary reference clock (ePRC) recommendation ITU-T G.811.1 (accurate to $1 \cdot 10^{-12}$). Due to budget and equipment constraints, however, we had access to a cesium PRC compliant to ITU-T G.811 (accurate to $1 \cdot 10^{-11}$).

B. Capturing and Measuring Time Error

The PTP test set evaluated the time quality output of the TDG. See Fig. 1 for a diagram of the PTP test set connectivity. Notice how a second GPS-connected ePRTC provided ToD to the PTP test set.

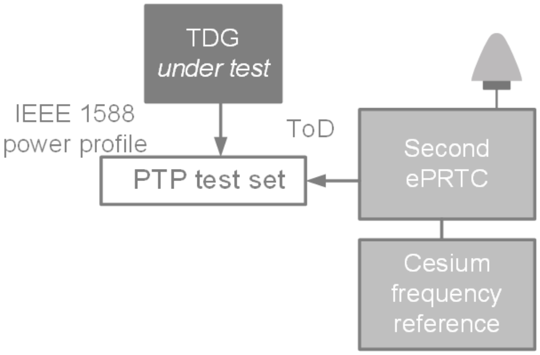

Fig. 1. PTP test set connectivity

One clock was the device under test, which provided time to the network. The second, supplemental clock served as the ToD reference to a PRTC PTP test set. Although the test set included a GPS receiver, using ToD as the source was essential since the ToD provided by the supplemental clock was more accurate than ToD provided by the PRTC A-grade, GPS-connected PTP test.

A more accurate reference time source was not available, and hence, we used two clocks of equal performance for laboratory validations. While connected to GPS, our reference time clock produced time accurate to approximately 30 ns to UTC. Therefore, we expected our results to have an error range of ±30 ns.

C. Logging Time Error

The PTP test set calculated the time error of incoming PTP frames. The PTP test set continually compared incoming PTP time from the network to ToD received from the second, GPS-connected ePRTC. The test set logged the time error and produced a comma-separated value (CSV) file for in-depth data analysis and plotting. The test set logged time error measurements at a rate of 1 measurement per second. We found the PTP test set adequate for logging time errors and saving them for postprocessing.

D. *Analyzing Time Error*

We found a CSV data plotting application that performed calculations and generated graphs used for time error analysis. The x-axis of the graph is time (in seconds) from time 0 (the start of the test), as the PTP test set recorded a single time error sample per second. The y-axis of the graph is the time error (in seconds). Highlighting a portion of the data generates meaningful statistics (minimum, maximum, average, and standard deviation).

VIII. TEST PROCEDURES

Our test procedures were as follows:

1. Connect the clock, GPS, and cesium reference, and enable ePRTC features.
2. Allow the system to discipline (learn) using GPS for 3 weeks.
3. Check the logs of both ePRTCs (the unit under test and the reference unit) for GPS anomalies, intermittent tracking, or erroneous data that the ePRTC under test may have experienced during the learning period. If the ePRTC under test experienced GPS errors, the learning period restarts from the time of the last error.
4. Initiate GPS loss on the ePRTC unit under test.
5. Capture and measure time errors using the PTP test set.
6. Restore GPS connectivity if required by the test.
7. Log the time error for the duration of each test.
8. Analyze results and form conclusions.

See Fig. 2 for a diagram of the laboratory network.

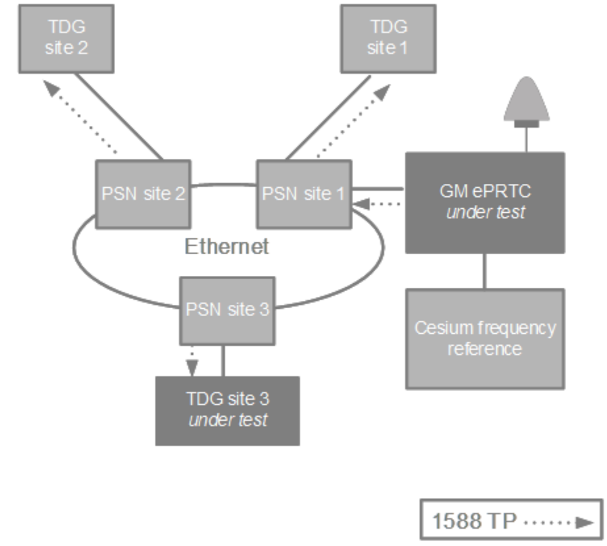

Fig. 2. Laboratory network

IX. ANALYSIS OF EXTENDED DURATION GPS LOSS FOR AN EPRTC WITH CESIUM HOLDOVER

Our extended duration GPS loss test involved GPS loss for 14 days. We expected that the time error from the ePRTC would be below 100 ns to UTC by the end of the test per the ePRTC standard. We expected PTP TP distribution through the PSN and TDG network to contribute additional time error. The PTP test set captured data and calculated the time error using PTP PP output at the TDG under test as per Fig. 1.

See Fig. 3 for a graph of time error data collected by the PTP test set at the TDG during the 14-day loss of GPS for an ePRTC with cesium holdover. To help the reader, a red line at 100 ns is overlayed to help visualize the ePRTC error threshold per specifications in [5].

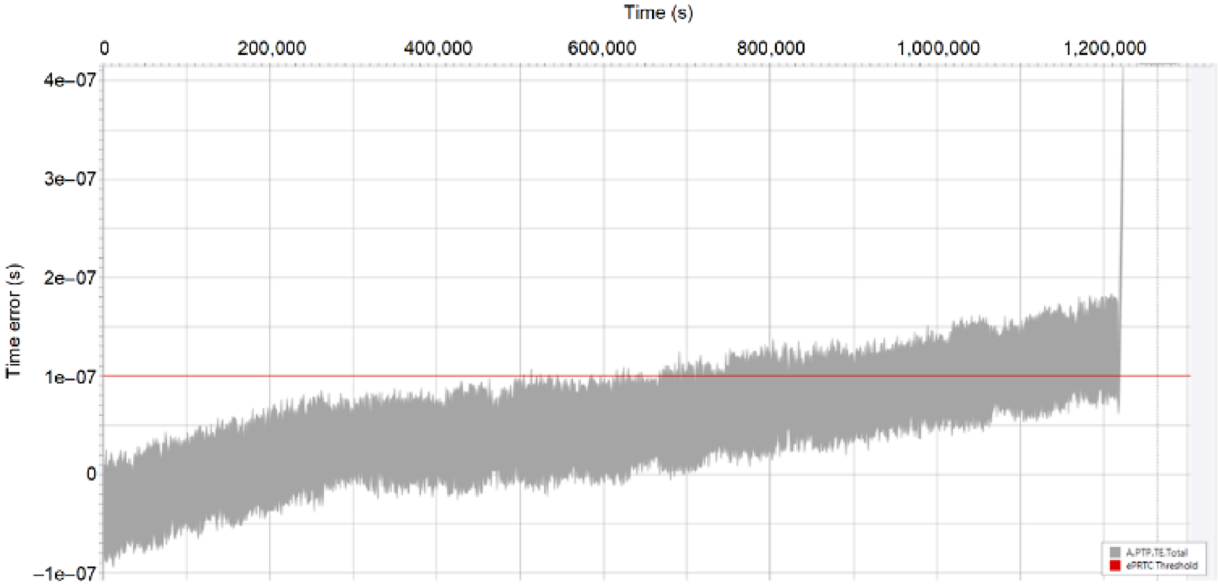

Fig. 3. Holdover Test 1—time error at the TDG during 14-day GPS loss of ePRTC with cesium holdover

The x-axis of the graph is time (in seconds) from the start of the test. The data range from 0 to 1,209,600 seconds (14 days). The y-axis of the graph is the time error (in seconds). The PTP test set recorded 1 time error sample per second.

What we observed was a total (ePRTC + PSN + TDG) average time error of 130 ns at the 14-day (1,209,600 second) test point. The time error observed was about 30 ns beyond the desired limit of 100 ns to UTC. Note that at the very end, there will be a time error spike. This represents the rapid accumulation of time error as the clock stops functioning in ePRTC mode and runs as a deprecated PRTC. The spike represents the holdover performance of the clock's internal rubidium oscillator.

X. ANALYSIS OF SHORTER GPS LOSS AND RECOVERY ANALYSIS FOR AN EPRTC WITH CESIUM HOLDOVER

Our shorter duration GPS loss and recovery test involved GPS loss for 7 days followed by GPS recovery for 7 days. The expected result was that the time error, per the ePRTC standard defined in [5], would not exceed 100 ns to UTC. The main goal of the test was to observe whether the transition of the time error back to initial levels of 30 ns accuracy to UTC would occur gradually or abruptly. If a time error transitions abruptly, there is a possibility that critical applications may experience a momentary service disruption on GPS recovery.

As expected, we observed that the ePRTC advertised a GPS clock class 6 (GNSS reference) and clock accuracy of fewer than 100 ns to UTC throughout the 14-day test. See Fig. 4 for a graph of the time error comparing time output accuracy at the TDG to the ToD input from the second GPS-connected ePRTC reference, as shown in Fig. 1.

The x-axis of the graph is time (in seconds) from the start of the test. The data range from 0 to 1,209,600 seconds (14 days). The y-axis of the graph is the time error (in seconds). The PTP test set recorded 1 time error sample per second.

We noticed a gradual transition of the time error back to initial levels upon GPS signal recovery. The gradual transition behavior is ideal since a gradual transition would not impact critical applications. The tests concluded that if GPS signals recover before the bridging time expires, the ePRTC will produce time with a smooth transition to initial time error levels. The ePRTC-plus-TDG solution gets us closer to a time distribution methodology with minimal reliance on GPS.

XI. TEST RESULTS AND LESSONS LEARNED

There are two ways to estimate precision as time is distributed through a network:

- Observe the estimated time accuracy reported in PTP messages. PTP fields include clock class, which describes the state of satellite connectivity, and clock accuracy, which describes a worst-case estimated time error relative to UTC. Decoding the time error reported in the PTP clock accuracy field is the simplest form of time error estimation. However, the time error is merely an estimate.
- Measure the accuracy of the timing signal using dedicated equipment. This is the choice we selected when performing laboratory validations since we wanted to precisely determine the time error of the system.

Even though we leveraged a lower specification cesium reference for the ePRTC under test and leveraged a suboptimal reference source for time error measurements, results from multiple laboratory tests showed that the time distribution solution continued to provide UTC to all sites with an accuracy better than 130 ns for a 14-day period after a total loss of all GNSS time sources.

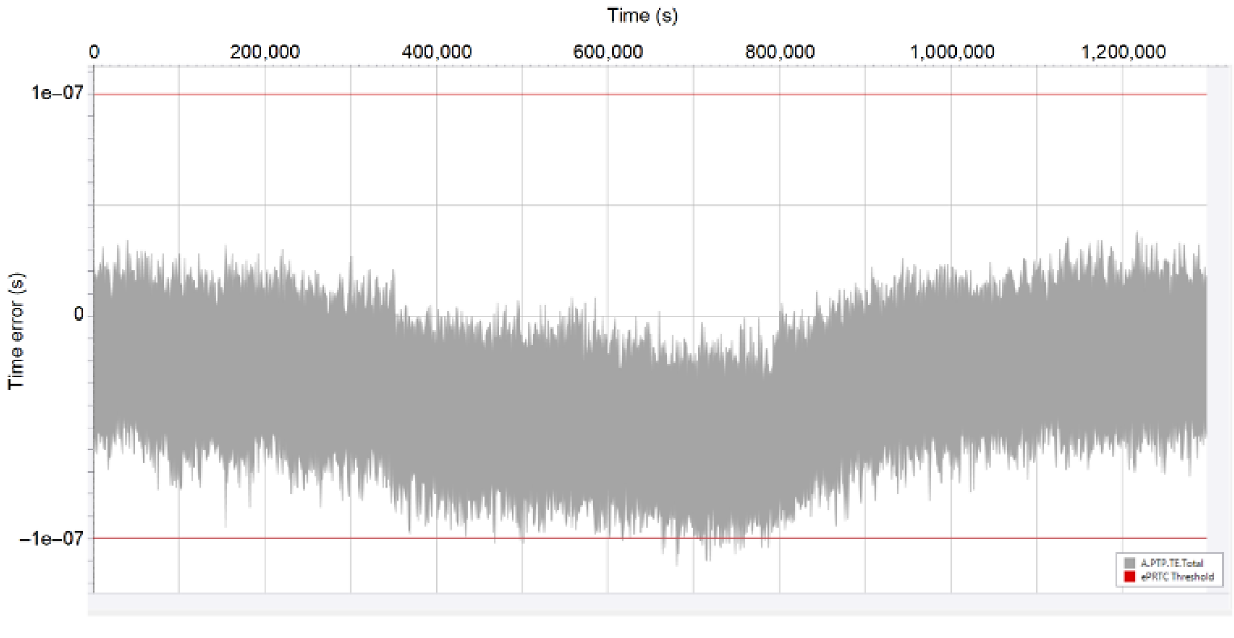

Fig. 4. Holdover Test 2—time error at the TDG with ePRTC experiencing 7-day GPS loss and 7-day GPS recovery

We learned that if you decide to measure the time error, use a better reference time source than the equipment under test. To achieve subnanosecond accuracy measurements, one will require hydrogen maser equipment when validating G.811.1 cesium references. These systems are very costly and run in the hundreds of thousands, if not millions, of dollars to buy. Since we had a G.811 cesium reference, our system was not fully compliant to an ePRTC of 100 ns accuracy up to 14 days after GPS loss. We did not have access to a cable impedance measurement device, and thus, we could not properly compensate for cable delays, and as a result, we suspect that there are errors in our data.

XII. Conclusions

To address Executive Order 13905, we developed a solution for critical infrastructure that delivers precise time in the event of a complete loss of GPS. We used over-the-shelf, commercially available manufactured equipment. The solution is comprised of ePRTCs, a PSN, and TDGs. We described these components and highlighted the advantages of using them together as a combined system.

The ePRTCs connect to autonomous PRCs and leverage the PSN to distribute PTP TP, which is used as a backup time source in case of localized or system-wide GPS loss. The use of ePRTC-capable PTP GM clocks is to maintain synchronization of the routers and switches in the PSN and TDGs and to the edge-connected applications.

Laboratory validations prove that solutions exist to maintain precise time for power system applications in the event of a wide-area loss of GPS. Validation results are included. Along the way, we learned many lessons. Our goal was to capture and share some of the important lessons to aid the reader who may decide to implement and validate a solution in their network.

XIII. References

[1] "Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Timing Services," February 18, 2020, federalregister.gov/documents/2020/02/18/2020-03337/strengthening-national-resilience-through-responsible-use-of-positioning-navigation-and-timing.

[2] E. Berger, "Study finds that a GPS outage would cost $1 billion per day," Ars Technica, June 2019. Available: arstechnica.com/science/2019/06/study-finds-that-a-gps-outage-would-cost-1-billion-per-day/.

[3] ITU-T G.8275.1, Precision time protocol telecom profile for phase/time synchronization with full timing support from the network, 2022.

[4] D. Williams, M. Elshafi, K. Fodero, C. Huntley, and P. Robertson, Using Wide-Area Precise Time Distribution to Increase Dependability and Security of Substation Time Synchronization, proceedings of the PAC World Americas Conference, Raleigh, NC, August 2022.

[5] ITU-T G.8272.1/Y.1367.1, Timing characteristics of enhanced primary reference time clocks, 2016.

XIV. Biographies

Dustin Williams, PE, is a senior technical consultant in the Transmission & Distribution Group at Burns & McDonnell. He specializes in telecommunications and network engineering, with experience in Multiprotocol Label Switching wide-area networks (WANs), substation local-area networks (LANs), and synchronous optical network (SONET) design and implementation. Dustin earned a Bachelor of Science in electrical and computer engineering from the University of Missouri–Columbia.

Rob Jodrie joined Syncworks in 2015 and is presently the director of technical support. He began working in the telecommunications industry with the Bell System in 1982. After working for 15 years as a central office technician, he was promoted to a Tier II technical support role with Verizon and was responsible for both transport systems and network synchronization. Rob received a Bachelor of Science in Electronic Engineering from Wentworth Institute of Technology in Boston, Massachusetts. He has been supporting network timing for over 20 years.

Ken Fodero is a senior engineering manager in the wired networks product group at Schweitzer Engineering Laboratories, Inc. (SEL). Before coming to SEL, he was a product manager for four years at Pulsar Technologies in Coral Springs, Florida. Prior to Pulsar Technologies, Ken worked at RFL Electronics for 15 years, and his last position there was director of product planning. He is a member of IEEE and has authored and presented several papers on power system protection communications topics.

Paul Robertson is a senior product manager for the wide-area networking communication product line at Schweitzer Engineering Laboratories, Inc. (SEL). He has over 25 years of experience developing and marketing products for the telecommunication industry, spanning cellular wireless and wireline communication systems. Paul worked in various technical and marketing roles for Motorola, Hewlett-Packard, and Agilent Technologies before joining SEL. He has a BEng in electrical and electronic engineering from the University of Strathclyde, Scotland, and an MBA from Edinburgh Business School, Scotland.

Chris Huntley, PE, received his Master of Applied Science in engineering physics from the University of British Columbia (BC), Canada, in 1960. After a two-year Athlone Fellowship in the United Kingdom and a diploma in electrical engineering from Imperial College, Chris joined the research and development group of GTE Lenkurt Electric in Burnaby, BC. There he designed both analog and digital (frequency-division multiplexing and synchronous optical network [SONET]) multiplexer products, including teleprotection interfaces (direct transfer trip, HCB, IEEE C37.94) under a variety of owners, from GTE and BC Tel through Nortel and GE. In 2007, he started a communications development group for Schweitzer Engineering Laboratories, Inc. (SEL) in Burnaby, BC. He is a senior member of IEEE and is active in many IEC, International Council on Large Electric Systems, and Advanced Encryption Standard professional groups. He also holds 10 patents on communications circuit technologies.

Motaz Elshafi is a senior application engineer in the communications group at Schweitzer Engineering Laboratories, Inc. (SEL). His job is to make electric power safer, more reliable, and more economical. He majored in computer engineering and received both his Bachelor of Science and Master of Science degrees from North Carolina State University. He has held various technical positions in telecommunications since 2000.

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