Using Wide-Area Precise Time Distribution to Increase Dependability and Security of Substation Time Synchronization

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Presented at the
2022 PAC World Americas Conference
Raleigh, NC
August 23–25, 2022

Originally presented at the
75th Annual Conference for Protective Relay Engineers, March 2022

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Abstract—**Reliable and precise timing is a key requirement for critical applications (e.g., synchrophasors, digital secondary solutions, and traveling-wave fault location and protection) that monitor and control the electrical power system and other applications that require a common and precise time reference. The traditional approach is to install a GPS clock inside each substation, which often requires dozens or hundreds of substation clocks network-wide. Each GPS-based timing source operates independently, presenting many potential failure points.**

This paper focuses on a new, resilient approach to time synchronization using time distribution over the wide-area network (WAN) using Precision Time Protocol (PTP). PTP is defined by the IEEE 1588 standard and can be leveraged to mitigate the impact of GPS timing source loss at a substation site. The International Telecommunication Union (ITU) G.8275.1 telecom profile of PTP can be delivered over Multiprotocol Label Switching (MPLS) or Carrier Ethernet-based telecom networks. This solution uses the concept of a time distribution gateway that is able to receive network time either via PTP telecom profile, via GPS directly, or through IRIG-B from a local GPS time source to then provide a submicrosecond timing reference for critical substation applications. The use of multiple time sources, combined with the ability to compare each against a weighted average, provides a resilient and secure time distribution system that can ensure dependable time in the event of localized GPS outages due to antenna failures, jamming, or spoofing attacks. Time distribution to the substation devices is delivered via IRIG-B or PTP power profile from the time distribution gateway.

This paper includes test results of the solution timing scheme operating through laboratory networks from different manufacturers' telecommunications equipment without the threats posed to GPS.

I. Introduction

Global Navigation Satellite Systems (GNSSs) are relied upon to provide positioning, navigation, and timing (PNT) services for a wide range of applications across the globe. Many critical infrastructure systems and assets depend on PNT services, including the electrical power grid, communications infrastructure and mobile devices, transportation, agriculture, weather forecasting, and emergency response.

In North America, GPS receivers are designed to recover low-amplitude radio frequency (RF) signals from the GNSS. But the GNSS has vulnerabilities that make GPS receivers susceptible to both unintentional and intentional interference and jamming. There is growing concern about cybersecurity threats from spoofed signals that have the potential to fool a GPS receiver into reporting a false position or time reference. And, although rare, a solar flare can cause interruptions to GNSSs.

Because of the widespread adoption of PNT services, the disruption or manipulation of these services has the potential to adversely affect the national and economic security of a country. In a direct response to this risk, the United States published Executive Order 13905 on February 18, 2020, with the goal of strengthening national resilience by fostering responsible use of PNT services by critical infrastructure owners and operators [1]. The executive order sets a timeline for a series of initiatives to implement non-GNSS-based secure PNT services, including a GNSS-independent source of Coordinated Universal Time (UTC).

The National Institute of Standards and Technology (NIST) recently published a technical note discussing resilient architectures for time distribution for critical infrastructure applications [2]. One approach being evaluated is using fiber optics to distribute time using Precision Time Protocol (PTP) as a resource for critical infrastructure industries. NIST has cesium fountain-based clocks that operate independently from the GNSS network. Thus, a utility-owned network providing connectivity to critical applications that require PNT information as part of their functions could, in theory, leverage PTP from NIST as a time reference for network operations.

This paper evaluates a hybrid solution that uses PTP time distribution over a wide-area packet-switched network (PSN), in addition to traditional time references, to implement a time distribution gateway (TDG) that mitigates the vulnerabilities of using only GNSS-based time references. The paper provides performance data across PSN transport where the TDG obtains GPS, IRIG-B, and PTP time across a Multiprotocol Label Switching (MPLS) network and uses the time inputs to provide a local time reference for critical substation applications.

II. Precise Time Usage in Power System Applications

Precise time is used across a wide range of applications involved with real-time control and monitoring of the electric power system. GPS clocks are typically used to provide an accurate time reference. In the past, these clocks only provided time signals used to synchronize the real-time clocks of local intelligent electronic devices (IEDs). Device time synchronization allows event data, such as Sequential Event Recorder (SER) and oscillography reports from various IEDs, to be analyzed against a common time reference.

These applications only require a timing accuracy of one millisecond or less. These data are used to perform post-event analysis; timing accuracy has no effect on the performance of the system [3].

GPS clocks today are relatively inexpensive, operate with much greater precision, and can easily provide time signals with one microsecond accuracy. The availability of low-cost, reliable, accurate GPS clocks has helped enable more advanced power system applications, such as those in the following list, which require a time accuracy of one microsecond:

- Synchrophasor measurements
- Sampled measured values
- Line current differential protection
- Traveling-wave fault locating
- Time-domain protective relaying

Except for fault locating, the applications listed can be used to operate the power system directly or indirectly. This elevates the role of the GPS clock in control systems from an accessory to a required service. It is common for critical power system protection equipment to be applied with redundant systems. Typically, a primary control system may require precise time, while the backup system does not. There is a lot of discussion about how vulnerable the power system is to loss-of-time and GNSS-spoof attacks. The practical reality is that critical relay protection schemes are designed to continue to operate after losing their time reference by falling back to secondary protection functions that do not require precise time. The advantage of control systems that use precise time is that they can provide very fast power system fault detection and clearing times. These systems operate in less than half of a 60 Hz cycle to as fast as one millisecond. Losing precise time would result in the protection system falling back to a slower method of fault detection, resulting in longer fault-clearing times. However, the safe operation and integrity of the power system would still be maintained.

As critical infrastructure applications start to rely more on precise time, system operators and engineers need to evaluate how to increase the availability of precise time for these applications. This paper evaluates a method to increase the reliability and availability of precise time for critical power system applications by using the concept of a TDG.

III. Overview of the TDG

The TDG evaluated for this paper is a substation-hardened wide-area network (WAN) edge device. TDGs interconnect to form networks; they receive, consume, and distribute highly accurate time.

As for connectivity models, TDGs can directly connect to form a network using fiber-optic cables. However, since the TDG supports Ethernet as a transport format, a TDG can communicate to neighboring TDGs using "pseudowires," or Ethernet Layer 2 point-to-point services, provided by a transport network. (More on the network implementation models to follow.) Subsequently, the TDG provides connectivity via Ethernet and serial-based interfaces to local devices within the substation that support critical applications. The TDG provides multiplexer functionality to support network connectivity for relay teleprotection, synchrophasor, and supervisory control and data acquisition (SCADA) applications.

As for time, the TDGs need to receive highly accurate time from one or more external UTC references and use it to establish system time. Substation applications typically acquire time from GNSS references using discrete local clocks. There is growing interest in using PTP distributed over a WAN from a centralized grandmaster (GM) clock as an external UTC reference. The TDG evaluated for this paper can acquire time from GNSS directly using an inbuilt receiver and GPS antenna, via an external clock source (a device commonly available in substations) that provides time formatted as IRIG-B, or from IEEE 1588 PTP sources connected via a transport network. Since TDGs connect across WANs, the specific IEEE 1588 PTP profile implemented on the TDG is ITU G.8275.1 telecom profile (hereby referred to as 1588 TP).

The TDG uses accurate time sources providing UTC time references to build a virtual synchronous network (VSN) [4]. A VSN allows critical synchronous applications to communicate and retrieve accurate time. A network of TDGs uses system time for internal purposes, such as generating sequence-of-events (SOE) records with highly precise time stamps. This is extremely useful for historical event analysis and correlation.

The TDG distributes a single time reference across a network of TDG devices that is derived from the weighted average of all TDG-node time-input sources. A comparison algorithm constantly checks local-node time inputs against the system reference time. Any time source that differs by more than the default preset limit (in microseconds) from system time is declared out of tolerance and is removed from participation in the weighted average. If a rejected time source comes back into tolerance, then participation to the weighted average is automatically resumed.

Time is distributed through all TDGs that interconnect and form a synchronous network. Time is also distributed to connected critical applications and is submicrosecond accurate. Time outputs at each TDG node are available in one of two available formats: IEEE C37.118 IRIG-B and IEEE C37.238 Power System Profile (1588 PP). TDG time outputs are derived from the same system time-distributed among the TDG nodes. Fig. 1 shows a diagram of a TDG.

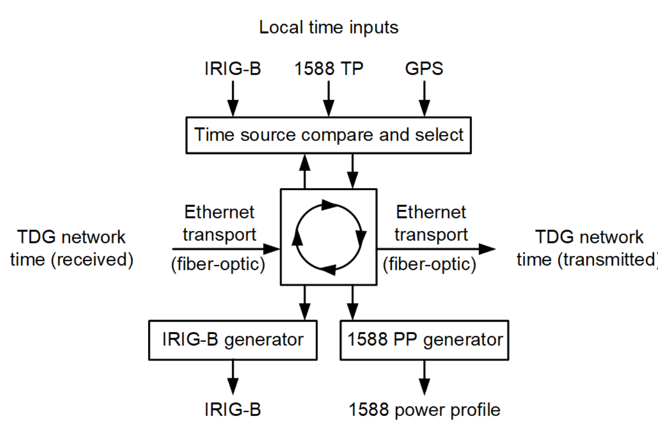

Fig. 1. Example TDG

IV. How the TDG Addresses Time Dependability and Security Concerns

Time alignment is necessary before the VSN can be established. While each TDG has time inputs that are perceived to be valid, a network of TDGs must agree on the system time. Once TDG time is aligned and the VSN is established, the node can perform its duties as a gateway and provide time output to connected critical applications, like relays or synchrophasors.

With time alignment being a primary requirement of TDG (or a TDG network) functions, TDG time-input stability and resiliency is extremely important. Several requirements are defined for the TDG to help maintain time availability and stability throughout the system. The requirements are that the TDG supports several time-input options, including GPS, IRIG-B, and 1588 TP. The TDG allows the network administrator to configure leap seconds for International Atomic Time (TAI) to UTC time conversions required when using IRIG-B and 1588 TP inputs. The TDG alarms if a time input is lost. It provides GPS antispoofing and antijamming technology as well as technology for input time tolerance measurements and comparison. The TDG allows for the network administrator to prioritize time inputs. Finally, the TDG performs weighted averaging of high-priority time inputs.

Once time aligns and a system time is achieved, the TDG network becomes established, and time output becomes possible. At this point, TDG-connected critical applications can receive highly accurate time.

V. Network Implementation Models

A network of TDGs can be implemented in one of two different models.

A. *Network Model A—TDG Nodes Directly Connected Using Fiber-Optic Cabling*

Network Model A (Fig. 2) represents a design option with a network of TDGs directly connected over fiber-optic cabling. No wavelength division multiplexing (WDM) technology is used. The fiber-optic cables are dedicated to the function and the associated synchronous communications required by the TDG. The fiber-optic cabling cannot be shared by non-TDG devices.

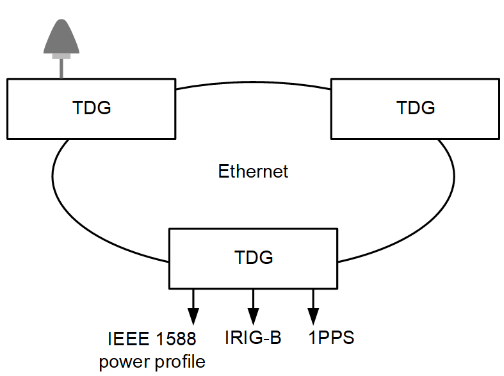

Fig. 2. Network Model A

From a time-gateway-application perspective, the advantage to this implementation model is that time can be distributed reliably between TDG nodes in the network. The direct fiber-optic connections allow the TDGs to "line-time" to one another. This connectivity model offers time resiliency without the need for an external UTC reference at every TDG node.

B. *Network Model B—Transport-Connected TDG Nodes*

Network Model B (Fig. 3) represents a design option with a network of TDGs connected through third-party PSN transport devices. The PSN can be based on MPLS or Carrier Ethernet technologies. The PSN transport provides Ethernet pseudowires, or Layer 2 services, that mimic direct fiber-optic TDG connectivity. Since the fiber-optic connections in Network Model B are *not* dedicated solely for TDG functions, the fiber can be shared by other, less critical applications that require connectivity.

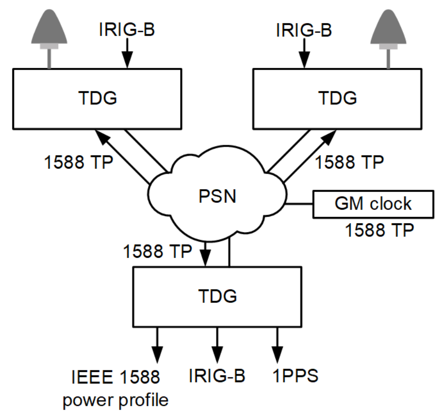

Fig. 3. Network Model B

Network Model B differs from Network Model A in that line-time can no longer be leveraged, and every TDG now requires an external UTC time reference. However, this model is advantageous and a clear choice when fiber-optic cable availability is limited. Fiber-optic cable bandwidth can be extended for use by the transport network for applications deemed less critical than grid operations, and overall network bandwidth is increased beyond the TDG-connected critical applications using high-bandwidth PSN interfaces. From a time-distribution perspective, an advantage to this implementation model is that time can be distributed reliably from the PSN to TDG nodes using 1588 TP. For this reason, Network Model B is considered a hybrid network, as TDGs can retrieve time from GPS satellite and PSN-based sources.

VI. Validation Scenarios

Network Model A baseline tests leverage GPS and IRIG-B as timing sources and exclude 1588 TP. Network Model A tests are used to baseline TDG performance and, therefore, are not included in this paper.

Network Model B differs as follows. Each site consists of a TDG node connecting to a PSN node, and TDG and PSN nodes are named appropriately (e.g., TDG Node A connects to PSN Node A). Then 1588 TP is distributed through a transport PSN to all TDGs as follows. An external PTP GM clock is connected to the transport network at PSN Node A. PTP frames are distributed between PSN nodes, which are configured as boundary clocks (BCs). The PSN provides full, on-path support of 1588 TP. Each PSN node then provides 1588 TP to the locally connected TDG (See Fig. 4).

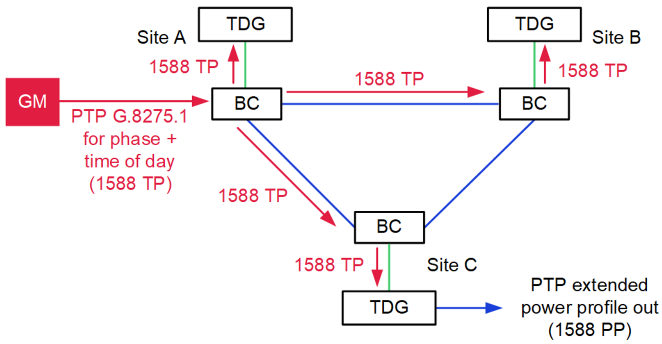

Fig. 4. PTP Flows Through Network Model B

The testing focuses on Network Model B configuration where 1588 TP timing inputs are included (see Fig. 5). The inclusion of PSN-based sources makes it a hybrid timing model. The goal of these validation scenarios is to examine the TDG's ability to provide accurate time output during various disruptive events when some, but not all, external UTC time-input references are lost.

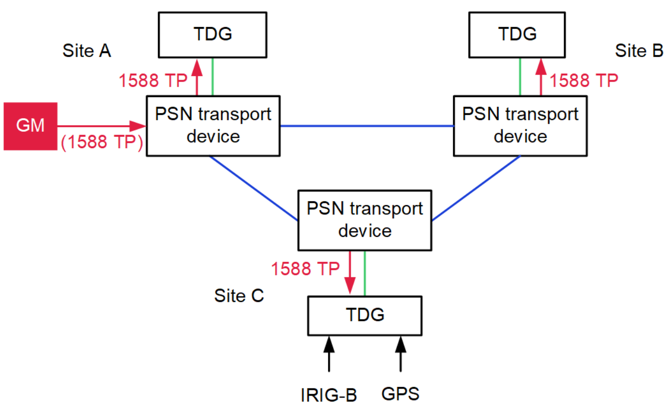

Fig. 5. Validation Configuration for Network Model B.

To validate timing inputs, all TDGs are configured to leverage 1588 TP as a reference timing input. TDG Node C leverages GPS and IRIG-B as additional reference timing inputs. If at least one highly accurate timing reference is applied to each TDG, the TDGs can agree on a system time, construct the synchronous network, and begin to function as timing gateways.

To validate the accuracy of time output, the TDG Node C is configured to output timing using 1588 PP. A test set is then connected to TDG Node C. The test set receives 1588 PP and compares the 1588 PP time to GPS time using an inbuilt GPS receiver and antenna. The test set represents a critical electrical protection or grid event monitoring application. With the use of the test set actively comparing TDG time output to UTC time from a GPS reference, TDG time output is measured and evaluated for accuracy. This is the main criterion used to evaluate overall TDG performance.

Four validation scenarios were conducted as follows:

1. The direct GPS input was disconnected from TDG Node C. The 1588 PP test set collected data for one hour, and measurements were noted. Test 1 concluded with a recovery of GPS as an external timing reference to Node C.
2. The IRIG-B input was disconnected from TDG Node C. The 1588 PP test set collected data for one hour, and measurements were noted. Test 2 concluded with a recovery of IRIG-B as an external timing reference to Node C.
3. The 1588 TP GM clock input was disconnected from PSN Node A. The goal of this test was to evaluate the impact of 1588 TP loss to TDG Node C, which still had GPS and IRIG-B connections. The 1588 PP test set collected data for one hour, and measurements were noted. Test 3 concluded with a recovery of 1588 TP as an external timing reference to PSN Node A.
4. The direct GPS and IRIG-B inputs were disconnected from TDG Node C. The 1588 PP test set collected data for one hour and measurements were noted. Test 4 concluded with a recovery of GPS and IRIG-B as external timing references to Node C.

Test cases are deemed successful only if the TDG is able to exclude disconnected time sources from the weighted average and maintain highly accurate time output to the test set.

VII. Validation Observations

The following time-*input* observations were noted during the validations of the TDG network:

1. A TDG network correctly functioned if at least one external UTC time reference input was provided. The loss of any single time source input when others were available had no observable impact on TDG network operations.
2. Assuming the TDG network administrator configured inputs with the same priority, a TDG correctly functioned using any combination of highly accurate sources of time: GPS, IRIG-B, and 1588 TP. Across all active sources, incoming time was weighted (based on time quality) and averaged.
3. A TDG interpreted the quality of incoming time as follows:
   a. With external UTC reference from GPS, the TDG leveraged the inbuilt GPS receiver to process RF signals from satellites to determine precise location and time.
   b. With time references from an external clock providing IRIG-B, the TDG could discern accuracy from time quality (TQ) and continuous time quality (CTQ) fields embedded within the timing signals.
   c. With time references from a PSN device providing 1588 TP, the TDG could discern accuracy from fields embedded in the 1588 TP frames (namely, clock class and clock accuracy).

4. A TDG interpreted the quality of time input based on internal calculations. Skew measurements were calculated as the difference between an external time source and internally distributed TDG system time. It was observed that the TDG correctly checked timing input sources for accuracy. If a TDG determined that a timing source exhibited error, or skew, when compared to other inputs, the source was disqualified.
5. When GPS was lost from Node C during Tests 1 and 4, it was verified that GPS was disqualified as a timing source and dropped from the list of valid timing inputs.
6. When IRIG-B was lost from Node C during Tests 2 and 4, it was verified that IRIG-B was disqualified as a timing source and dropped from the list of valid timing inputs.
7. When 1588 TP was lost from TDG Node C during Test 3, it was verified that 1588 TP was disqualified as a timing source and dropped from the list of valid timing inputs.

The following time *output* observations were noted during the validations of the TDG network:

1. 1588 PP was the time format evaluated and provided as the accurate timing outputs from the TDG. It was observed that the TDG advertised 1588 PP with a clock class of 6 (meaning GPS source locked and synchronized to a primary reference clock [PRC]) and a clock accuracy of 250 nanoseconds in the 1588 PP frames. The test set reports measured time error and phase offset.
2. The TDG provided accurate time output to a connected test set as long as the TDGs were each synchronized to at least one highly accurate time source.

The baseline measurements collected from the TDG, and test set are in Table I.

TABLE I
SITE C PERFORMANCE DATA COLLECTED

Validation Results	Test 1 GPS Loss	Test 2 IRIG-B Loss	Test 3 1588 TP Loss	Test 4 GPS and IRIG-B Loss
Valid sources	IRIG-B and 1588 TP	GPS and 1588 TP	GPS and IRIG-B	1588 TP only
Observations	1588 PP frames received throughout; VSN stays running			
Advertised clock class	Synchronized to PRC			
Advertised clock accuracy	250 ns	250 ns	250 ns	250 ns
Measured time error	163 ns	166 ns	28 ns	240 ns
Measured phase offset	–157 ns	–171 ns	–69 ns	–221 ns

The TDG successfully distributes time that is accurate within the advertised limit in each test case.

VIII. Building a Resilient Network

TDG Network Model B, the hybrid network, was the design focus during validations, and the validations prove that the hybrid network model is more resilient because it leverages highly accurate time from both satellite- and PSN-based time sources.

The system operates best in this hybrid mode where 1588 TP time is distributed over a WAN and received by the TDGs as a supplement to traditional time reference formats (GPS and IRIG-B). As observed, the addition of 1588 TP inputs increases reliability and security, because the TDG weighs and averages all inputs.

Distribution using 1588 TP mitigates GPS and local satellite clock outages and increases reliability. A hybrid network design removes the need for local substation clocks and improves the precision of the time signals by pulling from highly accurate sources in the transport network. PSN timing designs can be engineered to provide predictable timing flows. A well-designed PSN providing 1588 TP time can reduce costs by reducing the number of substation clocks required throughout the electrical grid, and it can reduce outages due to loss of GPS signals or local satellite clock failures.

IX. Conclusion

The goal of the paper was to investigate and validate a time distribution solution that increases the reliability and availability of precise time for power utility substation applications, compared to current methods of using discrete GNSS-based clocks.

The TDG approach uses a WAN to distribute precise time from a centralized reference and provide the medium for the TDG devices to communicate with each other and form a synchronous network. The ability for each TDG to receive time from multiple sources (1588 TP, GPS, and IRIG-B) adds resiliency to the system by allowing the time distribution system to survive the loss of a time source and still maintain accurate time. By establishing a synchronous network, the TDGs create network time that is based on the weighted average of all time inputs across the network. This capability allows each timing input to be compared against the weighted average (network time) so that the skew can be measured for each timing input, enabling the detection and disqualification of a degraded or compromised source.

The validation tests performed prove that the TDG provides reliable, precise time and effectively mitigates the vulnerabilities of using only GNSS-based time references. If at least one external UTC reference is made available to the TDG system, a connected application receives highly accurate time via reliably produced 1588 PP frames. Accurate time is necessary for local protection and event correlation. From a security standpoint, the ability to disrupt timing at a single substation can be reduced or almost eliminated using a hybrid network design.

X. References

[1] "Executive Order 13905 of February 12, 2020, Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Timing Services," Executive Office of the President. Available: federalregister.gov/d/2020-03337.

[2] NIST Technical Note 2187, "A Resilient Architecture for the Realization and Distribution of Coordinated Universal Time to Critical Infrastructure Systems in the United States," Available: doi.org/10.6028/NIST.TN.2187.

[3] K. Fodero, C. Huntley, and P. Robertson, "Secure and Reliable GPS-Based Time Distribution," in H. J. Altuve Ferrer, E. O. Schweitzer, III, G. Zweigle, S. Manson, S. K. Raghupathula, D. E. Whitehead (eds.), *Wide-Area Protection and Control Systems: A Collection of Technical Papers Representing Modern Solutions*, Schweitzer Engineering Laboratories, Inc., Pullman, WA, 2017, pp. 491–496.

[4] P. Robertson, K. Fodero, and C. Huntley, "Deterministic Communications for Protection Applications Over Packet-Based Wide-Area Networks," proceedings of the 44th Annual Western Protective Relay Conference, Spokane, WA, October 2017.

XI. 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 (WAN), substation local-area networks (LAN), 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.

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.

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.

Christopher Huntley, PE, received his MASc 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 ten patents on communications circuit technologies.

Paul Robertson is a senior product manager for the wireless 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.

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20220309 • TP7052-01