The Future of Time: Evolving Requirements for Precise Time Synchronization in the Electric Power Industry

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***Abstract*—Advancements in power system control and analysis methods continue to drive requirements for increasingly precise synchronization of time clocks in control devices and computers. Increasing varieties of sources for precise time are online or are planned for deployment in the near future. Activities in IEEE and IEC standards reflect these time-synchronization requirements, with specifications and recommendations for time-distribution mechanisms within a substation or plant. The availability of precise time sources, distribution methods, and devices that can accurately synchronize time has opened the door to applications that use precise time to coordinate operations between sites for improved voltage control and reduced wear on equipment. Synchronized phasor measurement and control applications also drive the need for precise time coordination and holdover.**

This paper summarizes present and future sources of precise time, including ground-based radio stations (e.g., WWVB, CHU, and GBZ), enhanced Long Range Navigation (LORAN), Global Navigation Satellite Systems (GNSS), and hybrid land-based and satellite systems.

Time-synchronization requirements are matched to time-distribution methods, including IRIG-B, Ethernet Network Time Protocol (NTP), Simple Network Time Protocol (SNTP), IEEE 1588 Precision Time Protocol (PTP), and communications network-based systems, such as a synchronous optical network (SONET).

I. Introduction

The need for precise measurement and distribution of time is an important part of our society, from early civilizations needing to know when to plant crops, to navigating ships or coordinating the first train networks. In the power industry, the need to have globally synchronized time was recognized very early, with many devices capable of time-tagging events and collecting vast amounts of power system data. The quality of time synchronization, however, was very sporadic, and the United States Northeast Blackout of 2003 exposed many weaknesses of time synchronization. Following the blackout, it took several months to parse through and piece together numerous event records, where time-stamp quality ranged from "not synchronized" to "utterly wrong." A small number of systems had access to Global Positioning System-synchronized (GPS-synchronized) clocks, which simplified the overall data analysis.

The Northeast Blackout also exposed the value of precision time-based wide-area data collection technologies, such as synchronized phasor measurements (also called synchrophasors), which, at the time, were mostly deployed in the western part of the North American electrical grid. It can be argued that, if present, an independent synchrophasor-based situational awareness network, by itself, may have been sufficient to prevent this blackout.

In the aftermath of the Northeast Blackout, we have seen a large increase of interest in precise globally coordinated time synchronization, with some of the applications and performance limits becoming specified by international standards and government regulatory agencies.

Overall, the availability and reliable dissemination of precise Coordinated Universal Time (UTC) are becoming critical parts of power grid operation.

II. Time-Synchronization Accuracy Needs

The needs and accuracy of time synchronization have evolved. With new technologies and better distribution methods, most modern intelligent electronic devices (IEDs) include at least one form of time synchronization [1]. Many devices offer multiple ways to synchronize device time, providing different or higher-accuracy synchronization. This section discusses some of these time-synchronization needs.

A. IED Time-Stamp Resolution

It is important to understand the difference between accuracy and resolution when considering devices with time-stamped data. "Accuracy is the degree of absolute correctness of a measurement device; resolution is the smallest number that the device can display or record" [2]. Thus, accuracy is a measure of how close the device time stamp is to an absolute reference (or how close the device relative time is to the true or absolute time). Resolution refers to the smallest increment of time allowed by the time stamp.

IED time-stamp resolution varies from manufacturer to manufacturer and from device to device. Time-stamp resolution is typically available to the millisecond. This means that as events occur through inputs, outputs, and logic, they are time-stamped to the millisecond of when the events were detected. Another important factor to note is the accuracy of the given time stamp, which is based upon the processing interval of the product. Depending on if it is a relay, programmable automation controller (PAC), or supervisory control and data acquisition (SCADA) device, the accuracy of the 1-millisecond resolution time stamp can vary by ±1 millisecond to ±4 milliseconds. When viewing time-tagged data from multiple sources, great care should be taken to use the accuracy of the device and not the resolution. North

American Electric Reliability Corporation (NERC) PRC-018-1 currently requires that all internal clocks in disturbance and monitoring equipment used by transmission and generator system owners be synchronized to within ±2 milliseconds of UTC [3].

B. Power System Characteristics

Because ac power systems are sinusoidal and operate at a more or less fixed frequency (typically 50 or 60 Hz), some timing accuracy needs are fairly concrete. In a 60 Hz system, a single power cycle is approximately 16 milliseconds in length, with zero crossings occurring approximately every 8 milliseconds. Power system events, such as arc extinction, are inherently discretized at the 8-millisecond level.

Thus, time synchronization needs to be accurate to a level less than 8 milliseconds. Most power system IEDs process analog signals every one-quarter of a cycle or faster. This aligns well with the typical 1-millisecond time-stamp resolution.

C. IEEE C37.118 Synchrophasors

Synchrophasors provide a precise absolute time-based measurement technology that enables users to collect power system state information in real time, monitor system stability, implement system-wide control, and perform precise post-event analysis. The IEDs that produce this information are called phasor measurement units (PMUs). These devices take real-time measurements of the power system currents and voltages and time-synchronize these data across a wide geographic area. Required time accuracy is normally in the order of 1 microsecond. In order to maintain this accuracy, a time-synchronization source must provide synchronization to ±500 nanoseconds. The most widely used technology that can provide that level of accuracy is GPS clocks that send out IRIG-B for time distribution.

D. Time-Synchronized Control

Time-synchronized control is an emerging application where multiple control actions are scheduled, synchronized to each other, and executed in a coordinated fashion [4]. Controlled devices include breakers, load tap changers, and capacitor banks. Being able to operate multiple devices at the same time provides better power system stability and minimizes disturbances to the system. This type of control requires a time-synchronization accuracy of 1 millisecond.

E. Process Bus Applications

Process bus is an emerging technology for the high-speed real-time data exchange of instantaneous voltage and current measurements, using an Ethernet network. It is based on IEC 61850-9-2 and related international standards, some of which are still under development. Once fully deployed, process bus technology promises to seamlessly deliver smart instrument transformer measurements to a wide variety of protection and control devices located on the same network. Because process bus inputs are sampled at high rates (typically 4 to 16 kHz) with independent digitizers distributed throughout the substation, time synchronization becomes critical for all applications that require data from multiple locations (for example, bus differential protection).

Because precise time synchronization of process bus measurements is as important as the measurement values themselves, a mechanism must be implemented to deal with system startup, network component failures, maintenance-related shutdown, and other events that may affect data delivery and time synchronization.

IEC 61850-5 recognizes this fact and defines the synchronization performance classes, as listed in Table I.

TABLE I
SYNCHRONIZATION PERFORMANCE CLASSES IN IEC 61850-5

Performance Class	Accuracy	Application
TS5	±1 µs	Critical process bus and synchrophasor applications
TS4	±4 µs	Process bus, synchrophasors
TS3	±25 µs	Miscellaneous
TS2	±100 µs	Point-on-wave switching, zero crossing, synchronism check
TS1	±1 ms	Event time tags (1 ms)
TS0	±10 ms	Event time tags (10 ms)

IEC 61850-5 recommends that time synchronization be implemented over the same communications infrastructure used for data exchange. In practice, this means the preference is given to Ethernet-based synchronization methods, such as Simple Network Time Protocol (SNTP) for ±10 milliseconds (class TS0) and Precision Time Protocol (PTP) for the remaining accuracy classes. Because IEEE C37.238 Standard Profile for Use of IEEE Std. 1588 Precision Time Protocol in Power System Applications is currently going through the final approval process, practically all existing process bus applications currently use alternate time-synchronization methods, such as IRIG-B or one pulse per second (PPS). This results in the need for two physical networks (communication and time distribution), making it more difficult to deploy and maintain. The situation is expected to improve once PTP equipment becomes widely available.

III. TIME-STAMP SYNCHRONIZATION ACCURACY

As time-stamp synchronization accuracy approaches the ±1-microsecond level, it becomes increasingly important to precisely define time-stamp semantics (meaning of the time stamp). Pioneering work in this field was initiated by the IEEE C37.118-2005 synchrophasor standard, which recognizes the importance of measurement delays caused by signal filtering and requires that all such delays be compensated at the source by applying the correct time stamp. This approach, known as source-based group delay compensation, makes it possible to precisely align time-stamped event records regardless of the type of filtering or reporting rate used in the particular application. Fig. 1 illustrates the group delay compensation concept, showing the PMU output for an ideal 10 percent magnitude step occurring at a time equal to zero (shown for a P-class PMU example).

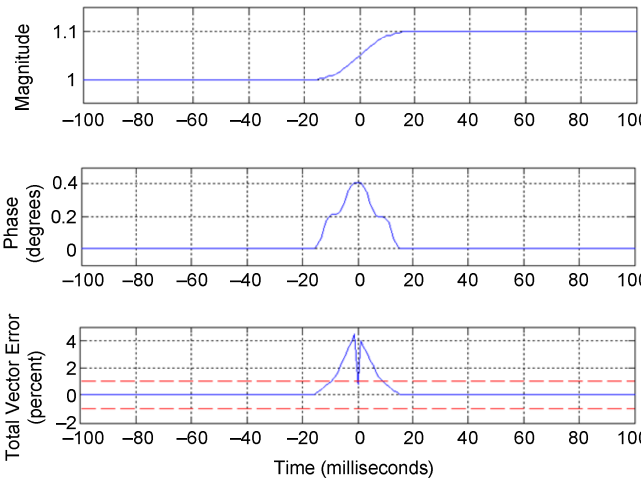

Fig. 1. Typical PMU response to a 10 percent magnitude step

It is interesting to note that the filter output exhibits a noncausal behavior because the measurements start changing before time is zero (before the actual step event). This behavior is caused by the required PMU filter delay compensation.

The group delay compensation concept allows the data time stamp to be precisely associated with events on the power system primary. The concept has been subsequently adopted by IEC 61850-5 Edition 2, which requires that all data be time-tagged in such a way that they can be directly compared without requiring correction at the point of use. A process bus version of the same requirement is being added to the future standard, IEC 61869-9, which will define process bus digitizer apparatus requirements.

Similar time-stamp semantics need to be defined for all other types of power system data, including contact input transitions, contact outputs, and internal IED state changes. The issue is somewhat complicated by the nonlinear operations involved in converting inherently analog signals, such as contact bounce, to a clean digital transition. Standardization work in this area is in progress, with IEC 61850-5 Edition 2 and the Power System Relaying Committee (PSRC) Working Group H3 leading the way.

IV. IED Time-Synchronization Methods

Until the introduction of the first digital relay in 1984, recording capabilities of power system devices were limited or nonexistent. Thus, these devices did not require and were not capable of time synchronization. Early oscillographs, such as the Hospitalier ondograph shown in Fig. 2, provided a means to record system analog signals and disturbances but did not provide time-synchronization capabilities.

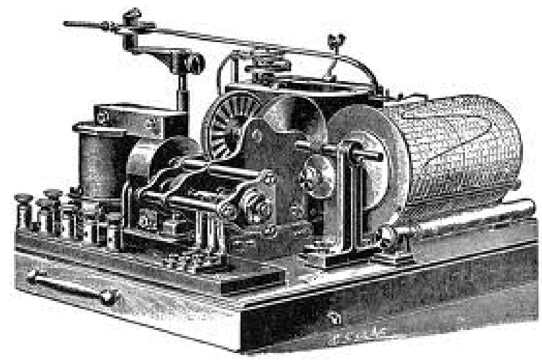

Fig. 2. Hospitalier ondograph

With the advent of digital devices and recording capabilities, time synchronization became important. Over time, many methods of synchronizing device time have been developed. This section describes commonly used time-distribution methods of today and what will be available in the near future.

A. Ground-Based Radio Stations

Ground-based radio stations that provide UTC time were popular before Global Navigation Satellite Systems (GNSS), such as GPS, came into existence. These radio stations embed International Atomic Time (TAI) information onto a radio carrier and transmit the signal to be received at various locations by receivers that require precise time.

These radio stations differ for each country based on the frequency, power, and modulation of the radio signal. Table II lists the description of various signals for different countries that broadcast time using radio waves.

Table II
Ground-Based Radio Stations

Station Call Sign	Frequency (kHz)	Country	Controlling Organization
WWVB	60	United States	National Institute of Standards and Technology (NIST)
BPC	68.5	China	National Time Service Center (NTSC)
DCF77	77.5	Germany	Physikalisch Technische Bundesanstalt (PTB)
JJY	40, 60	Japan	National Institute of Information and Communications Technology (NICT)
MSF	60	United Kingdom	National Physical Laboratory (NPL)

The United States uses WWVB, which synchronizes its local clocks to UTC, an international standard for timekeeping. This station has been active since 1960 and has undergone several changes over the course of time.

NIST keeps a local version of the UTC, called UTC(NIST), that closely agrees with UTC. The timing laboratories that generate UTC are at different locations around the world and are generally at a distance from the radio stations that transmit these signals. The UTC(NIST) timing laboratories are located at a distance from the WWVB radio station that transmits the timing signal. The WWVB radio station has its own clock that is continuously disciplined to match with UTC(NIST). The deviation between the WWVB signal and UTC(NIST) is shown in Fig. 3 for timing samples recorded over a one-year period. This graph also illustrates the typical hardship faced daily by the national laboratories in charge of maintaining the worldwide UTC time, which is synchronized to TAI. TAI is derived by calculating the weighted average of over 200 atomic clocks operated by over 70 national laboratories around the world. Individual TAI clocks are periodically compared to each other using a variety of communications-based techniques. The main difference between UTC and TAI is the fact that UTC keeps track of leap-second insertion, while TAI does not.

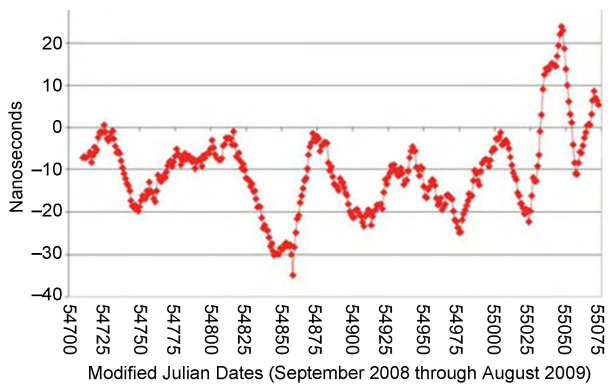

Fig. 3. Deviation between the WWVB signal and UTC(NIST) recorded over a one-year period

Although the WWVB station clock is exceptionally accurate relative to UTC, the propagation delay for the radio signal significantly affects the overall timing accuracy at the receiver. These delays can cause inaccuracies up to 30 milliseconds. The WWVB-based timing solutions for industrial applications were prevalent until the arrival and deployment of GNSS, like GPS in the United States [5].

B. Computer Software

Many modern devices provide computer software tools for use in setting and commissioning the devices. Some of this software allows users to synchronize the device time to the computer time. While this is more accurate than the manual method, it operates on the assumption that the computer time is synchronized to an accurate source. Most software tools do not specify the accuracy of their time-synchronization routine. Also, because many devices are set and commissioned in the field using laptop computers not connected to an external time source, their time synchronization is of dubious accuracy.

C. SCADA Protocols

Many popular SCADA protocols, like DNP3, include provisions for synchronizing device time through existing communications media. While some consider this purely a time-setting mechanism versus a form of synchronization, some provisions are made to account for delays in the communications channel. For example, DNP3 calculates message latency and accounts for this time in its time-synchronization message. Use of the DNP3 protocol to time-synchronize IEDs provides accuracies to within several seconds.

D. Network Time Protocol

Network Time Protocol (NTP) is the most widely used time-synchronization protocol in the world [6]. Almost every computer connected to the Internet is time-synchronized by NTP. All PCs running Windows® or Linux® come with NTP time synchronization. Computers and other communications devices in a substation benefit from the ease of using NTP to set the local time in these devices, where accuracies of subsecond synchronization are acceptable. NTP is distributed through Ethernet-capable devices. Depending on the network topology and the number of devices, NTP accuracies vary from 10 to 250 milliseconds.

E. IRIG-B

In 1956, the TeleCommunications Working Group (TCWG) of the Inter-Range Instrumentation Group (IRIG) created a standard format for the distribution of synchronized time signals. This resulted in a standardized set of time-code formats, which are documented in IRIG Document 104-60. The standard has been revised several times over the years; the latest publication is IRIG Standard 200-04 [7].

As described in IRIG Standard 200-04, IRIG-B is a popular format for distributing time signals to IEDs. Time is provided once per second, in seconds through the day of the year, in a binary-coded decimal (BCD) format and optional binary seconds of the day count. The standard format allows a number of configurations, designated as B*xyz*, where *x* indicates modulation technique, *y* indicates counts included in the message, and *z* indicates interval. The most commonly used forms for general time synchronization are demodulated IRIG-B000 and IRIG-B002. IRIG-B120 and IRIG-B122 are the counterparts but transmitted as a modulated signal. The last digit of *0* or *2* shows what extra data are encoded. The *0* includes the year information, time quality, leap second, time offset from UTC, and daylight-saving time information. Both the *0* and *2* signals are backwards compatible regarding synchronizing time and obtaining the BCD-formatted time and day of year.

IRIG-B is a time-distribution method (physical layer) used in short- to medium-distance applications, which normally do not require IRIG-B cable delay compensation. The primary source of time is normally from GPS.

Using the IRIG-B000 format along with GPS-based clock synchronization gives accuracy better than ±500 nanoseconds. Using this same method with the modulated format, like IRIG-B120, typically reduces accuracy to the 10-microsecond level. This reduction is due to noise introduced by linear amplification and the zero-crossing detection methods typically used by low-cost receivers. Demodulated IRIG-B uses a digital square waveform that has very sharp zero crossings to give it higher-accuracy capabilities. Demodulated

IRIG-B is normally distributed using coaxial cables or fiber-optic transceivers, giving it excellent shielding and wide bandwidth resources necessary for preserving timing signal integrity.

F. IEEE 1588 PTP

The need for precise time synchronization is directly related to the ability of the distributed systems to communicate with each other. If communication fails, making it impossible to exchange data, it becomes almost irrelevant if the time remains synchronized or not. Systems without outside communication are free to start drifting from each other and can rely on a local reference. The problem reappears once the data from the two systems are brought together (communication is reestablished). The communications method can be as simple as hand-carrying the recorded data to a common location.

It is easy to see that, in an ideal situation, the same channel should be used to provide both communications and time-synchronization services. This approach guarantees all communicating systems have the same notion of time, with well-defined failure and recovery mechanisms. In a local-area network-based (LAN-based) environment, this goal can be accomplished using IEEE 1588 PTP, which is capable of achieving ±100-nanosecond accuracy levels [8]. This accuracy is achieved by using dedicated hardware circuitry for precision time-stamping of the Ethernet frame arrival and departure times, along with methods for precise measurement of communications link delays, as shown in Fig. 4.

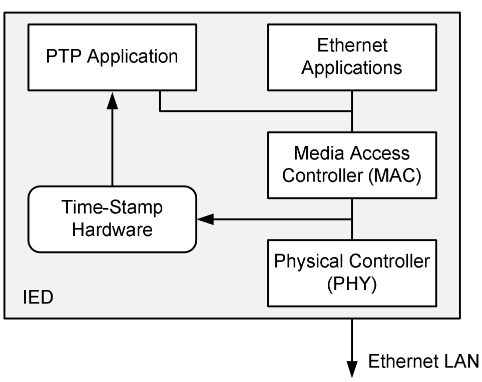

Fig. 4. PTP hardware-based packet time-stamping example

The IEEE 1588 PTP standard also provides a well-defined method for the election of the best-available master clock and a wealth of mechanisms capable of operating in laboratory, consumer, and highly critical industrial and power system networks.

Unfortunately, the wealth of supported mechanisms means that users are left with the responsibility of choosing a subset of mechanisms that are most appropriate for their application. The selection problem is simplified by the development of PTP profiles, notably the IEEE C37.238 standard profile for use of PTP in power system applications. The power system profile establishes default initialization variables, gives preference to the peer delay-based path delay measurement mechanism, limits the number of participants in the best master clock election by requiring that IEDs be configured as simple slaves by default, defines extensive remote management capability using Simple Network Management Protocol (SNMP), and allows for the existence of low-cost IEDs with limited path delay measurement capabilities.

From the user perspective, the most important characteristic of the new PTP-based time-distribution system is the fact that high-precision PTP distribution requires that the network infrastructure (all Ethernet switches) support PTP. Because PTP requires hardware support, this means that existing LAN systems cannot be upgraded without replacing virtually all of their components. On the IED side, this means that most IEDs requiring microsecond-level precision must be equipped with the same hardware (and the associated PTP algorithm support). Fortunately, because IEDs already use precise time, transition to PTP support is somewhat simplified because it can be viewed as an alternate time-delivery mechanism (in addition to IRIG-B), leaving most of the time-synchronization function intact. At this time, PTP support is available in grand master clocks and Ethernet switches, while the availability of relays and other substation IEDs remains relatively limited.

V. Existing Time-Synchronization Infrastructure

Existing infrastructures use various time-synchronization methods that obtain accuracies from hundreds of milliseconds to 1 microsecond. Each product that exists in the substation has different requirements for time accuracy and inherently uses a suitable time-distribution method to meet that accuracy.

A. Communications Devices

In substations, devices such as information processors, SCADA devices, substation computers, and remote terminal units (RTUs) have different synchronization methods and very loose accuracy requirements. Most of these Ethernet-capable devices typically support time synchronization through NTP. NTP on a segregated network can provide reasonable accuracy to a few milliseconds. The problem with NTP is that the accuracy is not consistent. NTP accuracy varies depending on the network topology and use. Moreover, accuracy also depends on how well or what type of NTP the devices support. Devices that support NTP are much more accurate than those that support SNTP. NTP devices use more complicated algorithms to determine variable network delay statistics, whereas SNTP directly sets the time as it is processed.

Most of these products also offer an IRIG-B input—either IRIG-B000/-B002 or IRIG-B120/-B122. The IRIG-B signal supplied to these devices from a GPS source is accurate to the hundreds of nanoseconds using IRIG-B000, but the devices only synchronize to around 1 millisecond. For these devices, 1 millisecond is the highest level of accuracy needed.

B. Digital Fault Recorders and Relays

Microprocessor-based relays in substations almost all have a form of IRIG-B as their time-synchronization source. The time-synchronization requirement for relays is 1 millisecond. This accuracy is used to align sequence of events or oscillographic events from faults on the system. An accuracy of 1 millisecond is adequate to review station-wide events and time-align oscillographic event reports from multiple relays. IRIG-B is the only distribution method available that can provide this level of accuracy. IRIG-B000 can provide 1-microsecond accuracy. IRIG-B120 can provide 10-microsecond accuracy. Either one of these sources provides relays with the accuracy needed and required by NERC.

C. PMUs

Synchrophasor information is a fast developing technology that uses dedicated PMUs or relays and digital fault recorders with PMU capabilities to stream power system values accurate enough to measure power system angles to one degree. In order to obtain that level of accuracy, the time synchronization must be 1 microsecond or better. Currently, the only widespread time-distribution method available to give that accuracy is IRIG-B000. The PMU must be connected directly to a GPS clock source that supports IRIG-B000 to maintain that level of accuracy.

VI. Transition Infrastructures

In the near term (possibly lasting ten years), we expect to see the ever-increasing need for high-precision time-based applications. One of the major drivers is expected to be system-wide deployment of synchrophasor data collection networks, followed by process bus applications. As the data collected become more critical, so does the need to provide reliable system-wide time synchronization. During the transition phase, it is expected that time-distribution methods will remain mixed, with IEDs required to support multiple time-synchronization methods, including SNTP, IRIG-B, and PTP. LAN infrastructure (i.e., Ethernet switches and routers) is likely to start being deployed with PTP support, with the largest penetration seen in new installations. Wide-area time-distribution capability is likely to remain GPS-based, with GPS clocks required to deliver time using all of the enumerated methods. From the user perspective, time distribution should not be a problem, as long as IED manufacturers continue to support multiple time-synchronization methods.

VII. Future Time-Synchronization Infrastructure

Barring the development of unforeseen power system applications with significantly higher time precision or communications requirements, time-synchronization systems within the substation are expected to migrate towards PTP implemented over Ethernet LANs.

In addition to substation LANs, we also expect an increase in terrestrial-based, wide-area time-distribution systems implemented using long-distance optical fibers. Ownership of the wide-area fiber-optic communications infrastructure (privately owned or leased) is not entirely clear, but it is expected that the precise wide-area time distribution currently needed primarily by power system applications will become ubiquitous and will be extended to the general population.

GPS-based systems are likely to persist for some time, with their role slowly changing to emergency backup and/or holdover-type applications.

VIII. Vulnerabilities of Time Distribution

Given the advantages of global UTC-based power system applications, it is easy to see why precise time distribution is expected to become critical for reliable power system operation. As time distribution becomes more critical, it will need to become very robust with well-defined availability requirements. Those requirements can easily be met by using hardware redundancy. In addition, time-delivery systems need to be hardened against accidental and malicious cybersecurity attacks. Such attacks include GPS signal spoofing, GPS signal denial and/or interference, malicious PTP system hijacking (through misuse of the best master clock election mechanism), PTP packet spoofing, and, in general, denial of the time-distribution service. While any of these attacks can be implemented locally, it is crucial that the time-distribution system be designed in such a way as to eliminate the possibility of a centralized wide-area attack.

Fig. 5 illustrates a novel method for implementing secure wide-area time distribution. This method is based on the well-known frequency-synchronization mechanisms commonly used in synchronous optical network (SONET) communications networks. The main difference is the fact that, while often frequency-locked to a Stratum 1 source ($1 \cdot 10^{-11}$ often achieved with a GPS clock), conventional SONET systems do not have any provisions for transferring absolute time information. Nevertheless, SONET systems provide a great platform that can be designed from the ground up to serve as a secure precision time-delivery system. A SONET system uses a self-healing ring topology, which makes the system more resilient to fiber-optic path failure. By equipping every node with a built-in GPS receiver, the time-distribution system becomes resilient to multiple fiber failures. Under normal operation, multiple GPS receivers make it possible to perform continuous signal quality monitoring, virtually eliminating the threat of localized GPS signal-based attack. Furthermore, the system remains functional even when the GPS system becomes 100 percent unavailable by simply switching to a global (system-wide) holdover mode. Individual devices within the network remain synchronized to each other and, assuming the existence of a terrestrial link to other rings and/or networks, remain synchronized with each other.

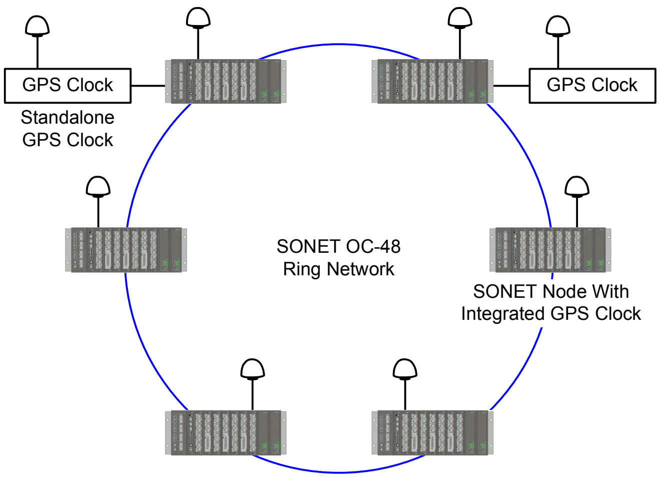

Fig. 5. Wide-area time-distribution and communications system

Holdover time is greatly extended by using the weighted average of all clock oscillators located in individual SONET nodes. Holdover time can be further extended by strategically locating a redundant set of atomic frequency standards, whose cost becomes negligible when compared with the overall communications system cost.

Wide-area time distribution among SONET nodes is performed using a private communications channel, which cannot be accessed from the outside and is not exposed to the general data payload. Locally, each SONET node behaves as a grand master clock with IRIG-B and, in the near future, PTP time output. When in PTP mode, the grand master clock is configured not to participate in the best master clock election process, thus eliminating security concerns normally associated with PTP. Additional details about this system and the methods used to seamlessly transmit Ethernet traffic can be found in [4] and [9].

Fig. 5 shows how the wide-area communications and time-distribution system can be hardened at the basic architecture level. However, it is important to remember that sound system architecture represents only one of the security factors. A robust system requires the establishment of layered security procedures and policies, known as the defense-in-depth strategy, where continuous performance monitoring and alarming systems may be as important as the overall system architecture.

IX. Conclusion

Precision time synchronization is gaining popularity in the electric power industry, with a number of new applications promising to improve power system operation. As the number and criticality of applications increase, the same happens with the importance of the substation time-synchronization infrastructure. This paper documents some of the most popular synchronization methods and explains some of the trends seen in the industry.

X. References

[1] E. O. Schweitzer, III, D. Whitehead, G. Zweigle, and K. G. Ravikumar, “Synchrophasor-Based Power System Protection and Control Applications,” proceedings of the 36th Annual Western Protective Relay Conference, Spokane, WA, October 2009.

[2] E. O. Schweitzer, III and D. Whitehead, “Real-Time Power System Control Using Synchrophasors,” proceedings of the 34th Annual Western Protective Relay Conference, Spokane, WA, October 2007.

[3] NERC Standard PRC-018-1. Available: http://www.nerc.com.

[4] H. J. Altuve Ferrer and E. O. Schweitzer, III (eds.), *Modern Solutions for Protection, Control, and Monitoring of Electric Power Systems.* Schweitzer Engineering Laboratories, Inc., Pullman, WA, 2010.

[5] M. Lombardi, “How Accurate Is the Radio Controlled Clock?” *Horological Journal*, March 2010.

[6] RFC 1305 Network Time Protocol (Version 3). Available: http://www.faqs.org/rfcs/rfc1305.html.

[7] IRIG Serial Time Code Formats, IRIG Standard 200-04, September 2004.

[8] IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, IEEE Standard 1588-2008, July 2008.

[9] K. Fodero, C. Huntley, and D. Whitehead, “Secure, Wide-Area Time Synchronization,” proceedings of the 12th Annual Western Power Delivery Automation Conference, Spokane, WA, April 2010.

XI. Biographies

Jackie Peer has a BS in electrical engineering from Washington State University (WSU). In 1996, she joined Schweitzer Engineering Laboratories, Inc. (SEL) as an application engineer. She managed distribution engineering in research and development (R&D) and product marketing. She is presently the R&D manager for precise time and communications solutions. Prior to joining SEL, she worked for the U.S. Army Corp of Engineers at a hydroelectric facility. She is a member of the American Marketing Association, IEEE, and IEEE Women in Engineering (WIE) and a senior member of the Society of Women Engineers. She also serves on the WSU Electrical Engineering and Computer Science Industry Advisory Board.

Eric Sagen received his BS in electrical engineering from Washington State University in 1997. He joined General Electric in Pennsylvania as a product engineer. In 1999, Eric was employed by Schweitzer Engineering Laboratories, Inc. as a distribution product engineer. Shortly after, he was promoted to lead distribution product engineer. Eric transferred to the time and communications group in 2006 and is currently a lead product engineer. He is certified in Washington as an Engineer in Training (EIT).

Shankar Achanta received his MS in electrical engineering from Arizona State University in 2002. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2002 as a hardware engineer, developing electronics for communications devices, data acquisition circuits, and switch mode power supplies. Shankar received a patent for a self-calibrating time code generator while working at SEL. He currently holds the position of development manager for the precise time and communications group at SEL.

Veselin Skendzic is a principal research engineer at Schweitzer Engineering Laboratories, Inc. He earned his BS in electrical engineering from FESB, University of Split, Croatia; his Masters of Science from ETF, Zagreb, Croatia; and his PhD from Texas A&M University, College Station, Texas. He has more than 25 years of experience in electronic circuit design and power system protection-related problems. He is a senior member of the IEEE, has written multiple technical papers, and is actively contributing to IEEE and IEC standard development. He is a member of the IEEE Power Engineering Society (PES) and the IEEE Power System Relaying Committee (PSRC) and a chair of the PSRC Relay Communications Subcommittee (H).