

# Implementing Robust Time Solutions for Modern Power Systems

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# Implementing Robust Time Solutions for Modern Power Systems

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**Abstract**—Modern power systems rely on accurate time for protection, monitoring, and control. Some of these applications include synchrophasors, supervisory control and data acquisition (SCADA), sampled values, user logs, and sequence of events. Precise time has become a critical component of these systems. Further, there has been discussion of the vulnerability of these systems if time sources are lost or disrupted, either through natural events or malicious intent, such as Global Positioning System (GPS) jamming, equipment failure, and geomagnetic storms.

This paper examines various time sources available for use in power system applications, including GPS, Network Time Protocol/Simple Network Time Protocol (NTP/SNTP), IEEE 1588, National Institute of Standards and Technology (NIST) radio station WWVB, and rubidium standards. Each time source is analyzed and evaluated in the following areas: accuracy, distribution methods, applications, costs, benefits, and weaknesses. Time-distribution systems are described that address reliability, scalability, cost, and security.

This paper includes an analysis of the applicability of each time source for use in various control and automation schemes. As examples, synchrophasors, SCADA, and logging time precision are evaluated, and recommendations are provided for each application.

## I. INTRODUCTION

The importance of time was recognized very early in human civilization. Our ancestors measured the passage of time by the motion of the sun, moon, planets, and stars. As our civilization continues to make advances in technology, the need for accurate time becomes more and more important for various applications. High-accuracy time keeping is critical to a number of systems, including electrical power systems, telecommunications systems, and networking systems.

As this paper is being read, networks of computers and servers with their own time sources are logging time stamps on email, files, and other transactions. The accuracy requirement of the time depends on the application. For the network time-synchronization example, an accuracy of a few milliseconds is adequate. But for critical applications like power system monitoring, control, and protection, the accuracy requirements for timing are more stringent and can be on the order of 1 microsecond or less.

## II. APPLICATIONS FOR TIME SYNCHRONIZATION

With the evolution of new technologies for both time sources and time distribution, most modern intelligent electronic devices (IEDs) have at least one form of time synchronization. IEDs with time synchronization have several

applications [1]. Some of these applications are discussed in the following subsections.

### A. Power System Fault and Disturbance Recording

AC power systems are sinusoidal and, in most cases, operate at 50 or 60 Hz nominally around the world. A single cycle for a 60 Hz ac power system lasts for about 16 milliseconds, with zero crossings at about 8 milliseconds. Using quarter-cycle power system measurements, IEDs can easily calculate magnitude and angles via quadrature pairs. In order to compare these magnitudes and angles from different IEDs, it is desirable to have time synchronization to the millisecond.

### B. 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 [2]. 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 time-synchronization accuracy at the 1-millisecond level.

### C. Precise Synchrophasor Measurements (IEEE C37.118)

Synchrophasors are primarily used to collect time-aligned power system state information from a wide geographic area. Synchrophasors make it possible to perform precise post-event analysis and real-time power system state monitoring. They are also used for wide-area control, including fast-acting remedial action schemes, which are critical for system survival during emergencies. IEDs that are capable of performing these functions using synchrophasor data are called phasor measurement units (PMUs). These PMUs take real-time measurements of power system currents and voltages across a wide geographic area and time-align the data. The required time accuracy is in the order of 1 microsecond. For a system implementing synchrophasors, the time-synchronization accuracy for the time source to the PMUs should be  $\pm 500$  nanoseconds. This accuracy can be easily achieved with time sources like GPS and distribution methods like IRIG-B or Precision Time Protocol (PTP).

### D. Process Bus (IEC 61850-9-2)

Process bus involves the exchange of high-speed, real-time 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, such as IEC 61869-9 and IEC 61869-13. 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 (e.g., bus differential protection).

Because the 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 standards recognize these facts and define the synchronization performance classes, as listed in Table I.

TABLE I  
SYNCHRONIZATION PERFORMANCE CLASSES PER IEC 61850-5

Performance Class	Accuracy	Application
TS5	$\pm 1 \mu\text{s}$	Critical process bus and synchrophasors
TS4	$\pm 4 \mu\text{s}$	Process bus and synchrophasors
TS3	$\pm 25 \mu\text{s}$	Miscellaneous
TS2	$\pm 100 \mu\text{s}$	Point-on-wave switching, zero crossing, and synchronism check
TS1	$\pm 1 \text{ms}$	Event time tags (1 ms)
TS0	$\pm 10 \text{ms}$	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  $\pm 10$  milliseconds (Class TS0) and PTP for the remaining accuracy classes.

There are several devices that provide multiple ways to perform time synchronization. Section III discusses various time and frequency standards, and Section IV discusses distribution methods.

### III. TIME AND FREQUENCY STANDARDS

Stratum levels were originally developed by the telecommunications industry and are intended to convey information about the clock distance from the primary reference standard (PRS). The actual meaning of the term stratum depends on the context in most popular sources, including those described in the ANSI T1.101 standard and network time protocol (NTP), defined in the RFC 1305 and IEEE 1588 PTP standards.

ANSI T1.101-1987 defines stratum levels and minimum performance requirements for network synchronization. Stratum 1 is defined as completely autonomous timing with no other input than a periodic calibration. The minimum adjustable range and maximum drift are defined as a fractional

frequency offset  $\Delta f/f$  of  $1 \cdot 10^{-11}$  or less. A Stratum 1 clock is an example of a primary reference standard, as defined in the ANSI T1.101 standard. The usual source of Stratum 1 timing is from an atomic standard (cesium beam, hydrogen maser, and so on).

A PRS source can be a clock system employing direct control from Coordinated Universal Time (UTC) frequency and time services, such as the Global Positioning System (GPS). GPS may be used to provide high-accuracy, low-cost timing of Stratum 1 quality. There are several low-cost GPS receivers that are commercially available for this purpose.

A Stratum 2 clock system tracks an input under normal operating conditions and holds the best estimate of the input reference time during the absence of the input signal. The drift requirement for a Stratum 2 clock in the absence of an input reference is less than  $1.6 \cdot 10^{-8}$  in one year. Short-term drift for these clocks is in the order of  $1 \cdot 10^{-10}$  in 24 hours. Examples of Stratum 2 clocks are rubidium standards and double oven controlled oscillators (OCXOs).

A Stratum 3 clock system tracks inputs like Stratum 2 clock systems but is less accurate. A Stratum 3 clock system requires a minimum adjustment (tracking) range of  $4.6 \cdot 10^{-6}$ . The short-term drift of the system is less than  $3.7 \cdot 10^{-7}$  in 24 hours.

Fig. 1 shows the hierarchy of stratum levels.

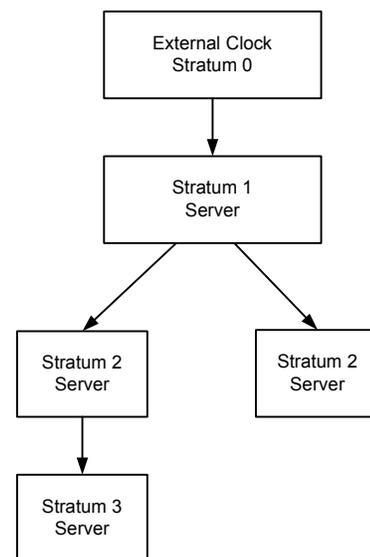


Fig. 1. Stratum levels.

From Fig. 1, we see that an external clock source like the atomic clock (often referred as Stratum 0) runs a Stratum 1 time server, which sends its signals to the Stratum 2 servers, which, in turn, send timing signals to Stratum 3 servers, and so on. Each successive stratum time server is less accurate than the stratum server before it. Because they are all clocked from a Stratum 1 source, their timing is precise with a very tiny amount of jitter that can occur on any instantaneous timing pulse.

#### A. Cesium Standard

The cesium atom natural frequency was formally recognized as the new international unit of time in 1967. The

cesium beam was selected as the primary frequency standard for its accuracy and long-term stability. A second is now defined as exactly 9,192,631,770 oscillations or cycles of the cesium atom resonant frequency, replacing the old second that was defined in terms of the earth's motions. In fact, this new standard is so precise that scientists quickly determined that the earth's motions are not as constant and repeatable as once thought. Therefore, adjustments are now made to the time we associate with the earth's motion, such as the length of a year [3]. The cesium standard is also referred to as the atomic standard. Most of the commercially available cesium beam standards can produce a frequency output with long-term accuracy (Allan variation) exceeding  $1 \cdot 10^{-12}$  over a one-day observation interval. These standards can run continuously (without any external calibration) and maintain accuracy. The frequency stability of the cesium beam standard measured with a measurement interval as long as one year does not vary more than a few parts in  $1 \cdot 10^{-13}$  of its nominal value. A cesium frequency standard can be an expensive solution and is used in applications that need an autonomous frequency standard with no external reference for long intervals. For example, a cesium standard capable of achieving  $1 \cdot 10^{-13}$  stability for observation periods longer than one day will be able to stay within 1 microsecond of absolute time (e.g., UTC) for holdover periods approaching  $10^{-6}$  seconds/ $10^{-13} = 10^7$  seconds, which is equal to 3.8 months ( $10^7$  seconds/3,600 seconds per hour/24 hours per day/30 days per month = 3.858 months).

### B. Rubidium Standard

The rubidium frequency standard is used in many applications that need precise time and frequency. This standard is built in a smaller package and has a much smaller footprint compared with the cesium standard. It is used in applications that need long-term stability that cannot be achieved by the use of quartz oscillators. This atomic standard is not selected as a primary standard due to its inherent frequency drift of about one part in  $10^{-11}$  per month for commercially available devices.

### C. Quartz Oscillators

Quartz crystal oscillators are used in most electronic equipment today. When certain crystals are subjected to mechanical stress, they produce electric signals across opposite sides of the crystal, and conversely, when an electric potential is applied, these crystals produce mechanical vibration. This is known as the piezoelectric effect. Quartz has excellent mechanical stability and decent immunity to external environmental conditions. When a quartz crystal is connected in a closed-loop electronic circuit, it can be used as a reliable source for frequency and time in electronics. Quartz crystals are not as accurate as cesium or rubidium standards when it comes to long-term stability, aging, and temperature stability. Aging is the inherent frequency change due to small physical changes in the crystal structure. Drift or aging for these crystals is the frequency change over a given period of time. Initially, when a crystal oscillator is turned on, the crystal ages (drifts) rapidly but its stability improves with time.

Temperature stability for an oscillator is the measure of drift with respect to temperature. Fig. 2 shows a typical temperature performance of a crystal oscillator.

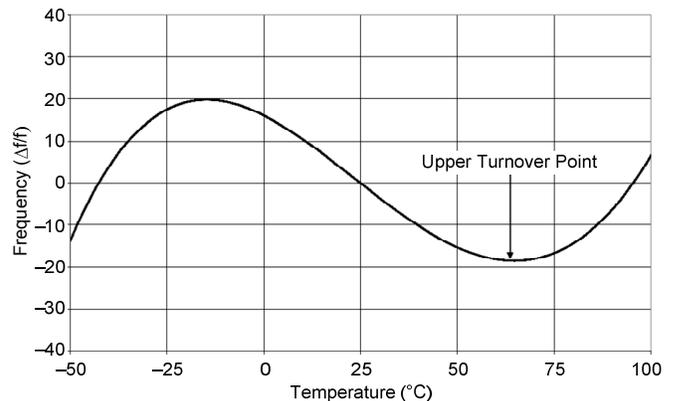


Fig. 2. Temperature performance of a quartz oscillator.

When external time sources are available to calibrate systems, quartz oscillators make an excellent economical choice when better precision is needed.

Table II shows a comparison of the time and frequency standards discussed.

TABLE II  
COMPARISON OF VARIOUS TIME AND FREQUENCY STANDARDS

Time and Frequency Standard	Cost (USD)	Accuracy
Cesium standard	\$20,000	$10^{-13}$
Rubidium standard	\$900	$10^{-11}$
OCXO	\$200	$2 \cdot 10^{-8}$
Temperature compensated crystal oscillator (TCXO)	\$20	$2 \cdot 10^{-6}$
Crystal oscillator (XO)	\$2	$50 \cdot 10^{-6}$

## IV. TIME-DISTRIBUTION METHODS

### A. Wide-Area Wireless Distribution Methods

#### 1) Global Navigation Satellite System (GNSS)

The United States GPS is the best-known component of the GNSS. Some other GNSSs include the Russian GLONASS, Chinese COMPASS, and European Galileo systems. All of these systems broadcast timing signals with carrier frequencies in the range of 1,200 to 1,800 MHz. GPS (shown in Fig. 3) provides a high-accuracy timing signal.

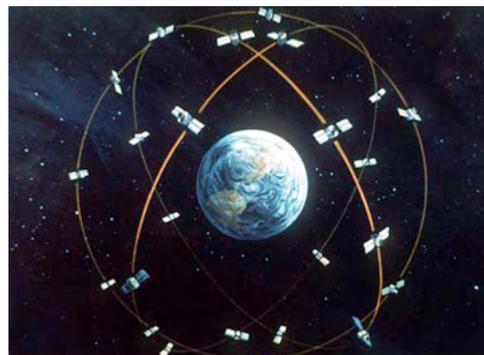


Fig. 3. The Global Positioning System. This image is provided courtesy of the U.S. Department of Defense.

GPS operations depend on a very accurate time reference provided by atomic clocks at the U.S. Naval Observatory. Each GPS satellite has four onboard atomic clocks. All of these clocks are accurate to within a few nanoseconds of each other.

All GPS satellites synchronize operations so that their periodic signals are transmitted at the same instant. The signals, moving at the speed of light, arrive at a GPS receiver at slightly different times because some satellites are farther away than others. The distance to the GPS satellites can be determined by estimating the amount of time it takes for their signals to reach the receiver. When the receiver estimates the distance to at least four GPS satellites, it can calculate its position in three dimensions. Based on its three-dimensional position relative to the GPS satellites, the receiver is able to accurately calculate the propagation delay from each satellite. GPS receiver clocks use this method to synchronize their clocks very closely with the satellite clocks. However, there are several sources of inaccuracies [3], as follows:

- Time adjustments are made assuming that the radio signal propagation delays, based on the speed of light, are constant. In fact, the earth's atmosphere slows the radio signals down slightly. The delay varies depending on the angle at which the received signal passes through the atmosphere.
- The propagation speed in the receiver antenna and antenna lead is different than in free space and the atmosphere. The propagation delay through the antenna lead will therefore vary with length. Some receivers compensate for this delay by assuming an average antenna lead length; others allow the user to input a delay setting. For long distances between the antenna and receiver, some manufacturers provide repeating amplifiers that create an inherent incremental signal delay.
- Problems can occur when radio signals bounce off of large objects, such as adjacent buildings, giving a receiver the impression that a satellite is farther away than it actually is.
- Satellites occasionally send out bad almanac data, therefore misreporting their own position.
- Time jitter may occur when the satellite clock receiver loses lock with one satellite and achieves lock with another.

Today, commercially available GPS receivers claim average timing accuracies as low as 50 nanoseconds to UTC. Commercially available GPS receivers cost between \$20 and \$80 USD, depending on the performance characteristics.

## 2) Ground-Based Radio Stations

Ground-based radio stations that provide UTC time were popular before GNSSs, 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 III provides the description of various signals for different countries that broadcast time using radio waves [4].

TABLE III  
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 since its inception.

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 UTC(NIST). The deviation between the WWVB signal and UTC(NIST) is shown in Fig. 4 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.

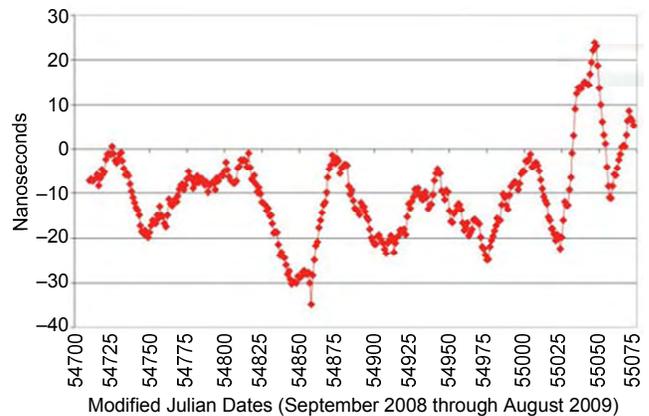


Fig. 4. Deviation between the WWVB signal and UTC(NIST) recorded over a one-year period.

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 that UTC keeps track of leap-second insertion, while TAI does not.

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 GNSSs, like GPS in the United States. The WWVB timing system can still be used as an accurate timing source provided that the timing accuracies due to propagation delays are calibrated out. With proper calibration techniques, this economical WWVB timing source can achieve accuracies of up to 1 millisecond.

### B. Local-Area Distribution Methods

The previous sections discussed various stratum levels for time sources and the different time and frequency standards that are presently available.

Now we will examine several methods and standards used to distribute this time signal to the downstream IEDs. The most popular methods include IRIG-B, NTP, and PTP.

### 1) IRIG-B

IRIG-B is a popular standard for distributing accurate time information over short distances. It is fully described in the IRIG Standard 200 04. It consists of a pulse width modulated 100 Hz signal to represent time information. It provides information about the time quality and indicates the accuracy of the time information. The rising edges of an IRIG-B signal are accurate time stamps that can be designed to be within  $\pm 100$  nanoseconds of UTC (when distributing time from a Stratum 1 clock). IRIG-B signals are normally sent over coaxial cable for short distances (<100 meters) or through fiber-optic cable for greater distances. Fiber-optic transceivers delay the signal by several microseconds, so IRIG-B signals transmitted over fiber cannot normally be used for higher-accuracy timing applications like synchrophasor measurements. However, techniques are available that can compensate for the delay in fiber-optic distribution systems and enable accurate IRIG-B distribution over several kilometers.

IRIG-B has modulated and demodulated time-code formats. The demodulated signal is a pulse train of positive pulses at a rate based on the designated format. The rising edge of the reference pulse coincides with the seconds change in the time source and provides a very precise time reference. The modulated format is an amplitude modulated sine wave with amplitude between 1 Vp-p and 6 Vp-p for the mark (peak), with a mark-to-space amplitude ratio of approximately 3:1.

The demodulated format is shown in Fig. 5, and the modulated format is shown in Fig. 6 [5].

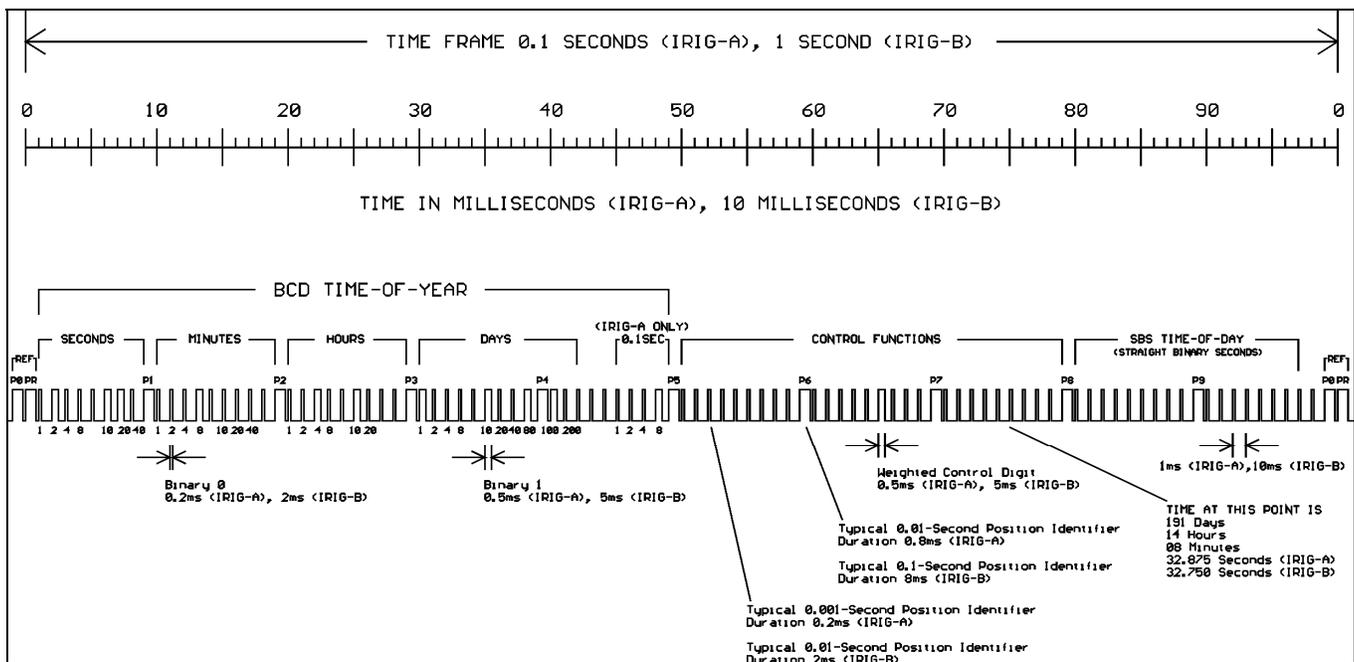


Fig. 5. Demodulated IRIG-A and IRIG-B time-code format [3].

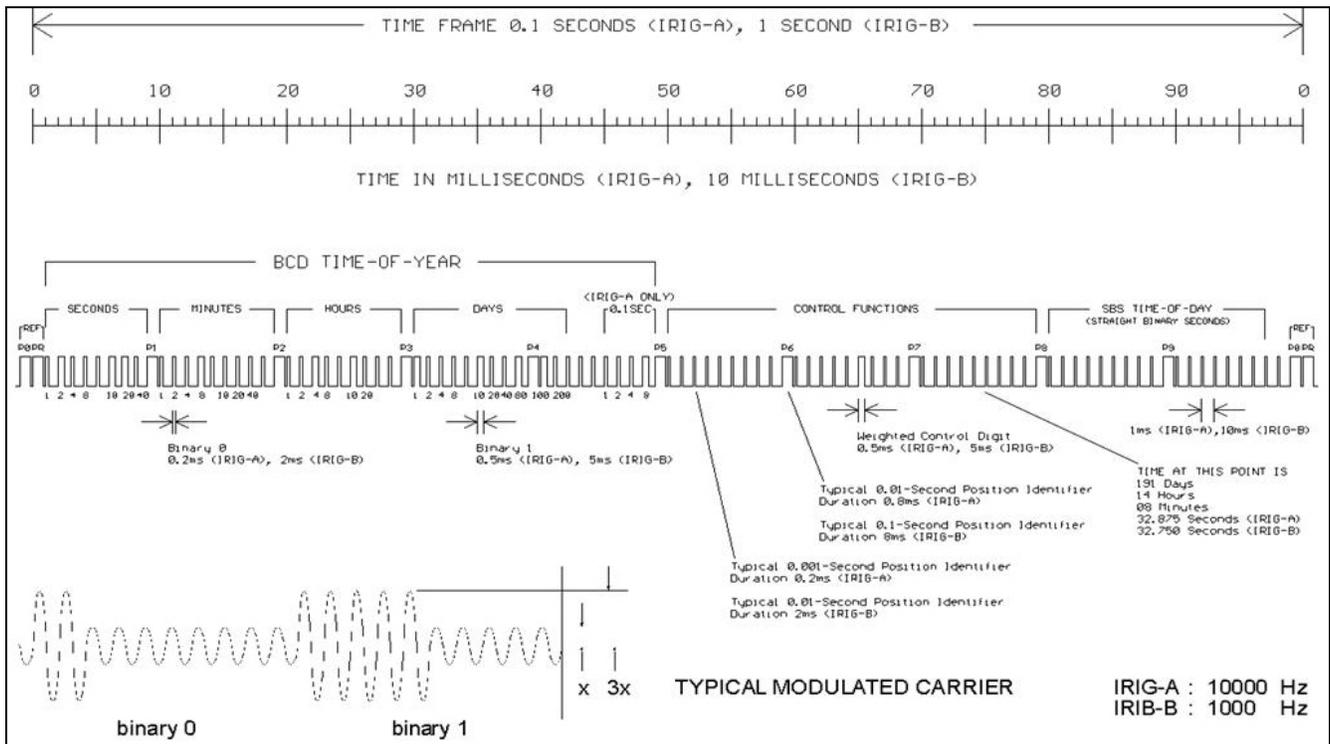


Fig. 6. Modulated IRIG-A and IRIG-B time-code format [3].

## 2) Network Time Protocol

NTP is the most widely used time-synchronization protocol in the world. Almost every computer connected to the Internet is time-synchronized by NTP. All PCs running Windows® or Linux® software 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 subsecond synchronization accuracies are acceptable. NTP is distributed through Ethernet-capable devices [1].

NTP uses a client-server model to communicate time information between devices. The function of a server is to provide accurate time to its clients. The individual clients run a small program as a background task that periodically queries the server for accurate time information. The frequency of these queries is generally about every 15 minutes in order to maintain the synchronization accuracy for the network.

NTP operates using time stamps of messages exchanged between the client and the server. The client stamps the time when it sends an NTP request to the server ( $t_0$ ). The server stamps the time when the message is received from the client ( $t_1$ ). The server stamps the time when it sends the NTP reply message back to the client ( $t_2$ ). The client stamps the time when the NTP reply is received from the server ( $t_3$ ).

By using these four time stamps ( $t_0$ ,  $t_1$ ,  $t_2$ , and  $t_3$ ), the client determines the difference between its internal time and the UTC time reference (assuming that the server has its time source from the UTC) and adjusts its local time with the reference. Any network latency that occurs during these transactions can also be removed to achieve a more precise synchronization, assuming that the paths to and from the server are symmetrical. The accuracy for the NTP system

depends on the choice of the server. The degree of client synchronization also depends on the network latency. Hubs, switches, routers, or any network traffic will reduce the accuracy. Using NTP in a network without too many sources of network delay, the synchronization accuracy is about 1 to 2 milliseconds. The ultimate accuracy of an NTP client depends on the accuracy of the NTP server used, the network latency, and the symmetry of the network paths to and from the time server. A simpler version of NTP is also available called SNTP. The difference between NTP and SNTP is in the time-synchronization program running on the client. NTP uses time from multiple time servers to verify the time and adjust the time accordingly on the client. SNTP uses one time server to calculate the time on the client, and then it jumps to the new calculated time.

## 3) Precision Time Protocol

PTP is optimized for computer network-based clock synchronization [6]. Although defined for use on Ethernet networks, PTP can be applied to other physical layers and protocols, including DeviceNet™, ControlNet™, and PROFINET. When compared to NTP, PTP provides greatly improved clock accuracy that is typically in the submicrosecond range. This accuracy level enables PTP to meet all of the IEC 61850-5 performance classes shown in Table I.

Although originally developed for local-area networks (LANs), the second revision of the IEEE 1588 (Version 2.2008) standard includes a number of options to enable successful operation in a wide-area network (WAN) environment [6]. Options are further defined to satisfy special requirements present in a wide variety of industries, ranging

from telecommunications, industrial automation, power systems, consumer, and military.

Although necessary to support the wide range of applications, the options can be confusing, making it necessary to define a mechanism to develop industry-specific profiles. The purpose of the profiles, as defined in the IEEE C37.238 standard, is to “allow organizations to specify specific selections of attribute values and optional features of PTP that, when using the same transport protocol, inter-work and achieve a performance that meets the requirements of a particular application” [7]. Most popular profiles include the International Telecommunications Union Telecom (ITU-T) profile, IEEE 802.1AS-2011 audio video bridging profile, LAN eXtensions for Instrumentation (LXI) profile, and the IEEE C37.238-2011 Power System Applications profile [7].

The IEEE C37.238 Power System Applications profile was developed with the joint effort of the IEEE Power System Relaying Committee (PSRC) and the Substations Committee (SUB). It is explicitly optimized for mission-critical power system applications. It was recently added to the NIST Smart Grid Interoperability Panel (SGIP) catalog of standards and is one of the critical elements of the smart grid initiative [7]. Similar to PTP, the Power System Applications profile relies on Ethernet network communications with hardware-layer time stamps used to explicitly measure synchronization message propagation delays through the network. Basic time-stamping hardware is shown in Fig. 7.

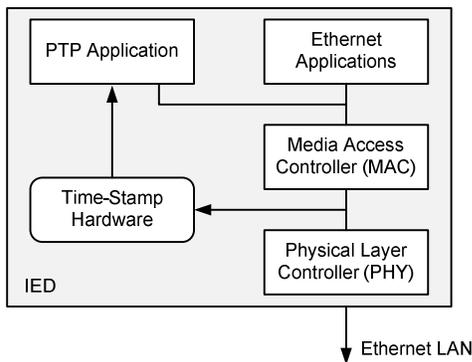


Fig. 7. PTP hardware-based packet time stamps (implementation example).

Time-stamping hardware enables individual devices to precisely measure the time when the first bit of a given PTP message has reached the device input (reception) or has been generated by the device output (transmission). The exact time-stamping point is defined as the physical network interface connector (the end of the fiber or the Cat 5 RJ-45 end connector) but is in practice often implemented at the output of the PHY, as shown in Fig. 7. In this case, the PHY delay must be constant and known or must be below the device accuracy level as specified by the manufacturer.

A precise time stamp is only the enabling mechanism used by PTP and IEEE C37.238 to deliver precise time. A PTP system must at the very minimum consist of a time source, which is called a grandmaster clock, and a single slave clock receiving the time. Most practical systems will also have an Ethernet switch, which, in the case of IEEE C37.238, will

need to support the transparent clock functionality. A simple system example with the three devices is shown in Fig. 8.

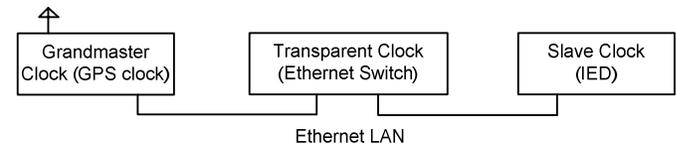


Fig. 8. PTP system example.

Because each of the three devices is equipped with precision time-stamping hardware, it is easy to account for time-synchronization uncertainties, which consist of the following:

- Cable (fiber) propagation delays between the GPS-based grandmaster clock and the Ethernet switch.
- Ethernet switch forwarding delays.
- Cable propagation delays between the Ethernet switch and the IED.

Cable propagation delays are constant and measured using a special link delay measurement message called PDelay, which is exchanged by the two peers. Ethernet switch forwarding delays vary depending on the network loading and message queuing at the switch egress port. Because the delays vary, a PTP-compliant transparent Ethernet switch must perform the additional task of explicitly measuring forwarding delays for individual time-synchronization messages and further inserting that time into a PTP message time correction field. The PTP message time correction field is typically updated in real time in such a way that the final message arriving at the IED contains the total delay contribution accumulated while the message was being transported through an arbitrary number of Ethernet cables or switches along the way. When combined with the original time stamp, the delay correction field enables the IED to calculate the exact moment the message reached it.

As can be seen from the example in Fig. 8, the basic PTP principle is conceptually simple, but achieving high precision requires that all network devices in the chain be PTP-compliant. The ability to satisfy this requirement is determined by the age of the equipment involved. New installations should be simple, with the only requirement being that the installed devices are IEEE C37.238-compliant. Such projects will primarily be affected by limited device availability, which is temporary because the final release of the standard made it possible for equipment manufacturers to start releasing the IEEE C37.238-compliant products.

Recently built substations with extensive LAN-based infrastructure will be affected the most and will typically require that all Ethernet switches be replaced with IEEE C37.238-capable devices. In these substations, the PTP deployment process is expected to be gradual, because the time synchronization necessary to support the desired functionality has already been implemented using IRIG-B or NTP-based services. PTP service is likely to be deployed in parallel, with a gradual transition toward a full PTP-based system over a long period of time.

Old substations without a LAN-based communications infrastructure will not be affected.

PTP and IEEE C37.238 can easily coexist with IRIG-B and NTP systems. IEEE C37.238 offers improvements to a well-established and understood time-distribution service. Therefore, it is expected that most network-based substation devices will continue to support all three synchronization options, thus offering power system operators the high level of flexibility required to maintain reliable system operations.

Table IV shows a brief comparison between the three local-area time-distribution methods described in the paper.

TABLE IV  
COMPARISON OF SOME TIME-DISTRIBUTION METHODS

Time-Distribution Methods	IRIG-B	NTP	PTP (IEEE 1588 and C37.238)
Physical layer	Coaxial cable	Ethernet	Ethernet
Model	Master-slave	Client-server	Master-slave
Synchronization accuracy	~500 ns to 1 $\mu$ s	~1 to 100 ms	~100 ns to 1 $\mu$ s
Compensation for latency	Yes, using cable length as user input	Yes	Yes
Update interval	Once per second, pulse per second	Minutes	Configurable, typically once per second
Hardware requirements	Special hardware required at master and slave	Master only	Hardware support required for high accuracy
Relative cost	Medium (IRIG-B cabling)	Low (software)	Medium to high (early adoption)

It is interesting to note that some of the hardware time-stamping concepts introduced by PTP are also finding their way into the latest NTP system implementations. In addition, the wide range of applications served by the PTP standard has also created the large device volume required to justify implementing the PTP time-stamping hardware in silicon. The result of this is that a number of mainstream integrated circuit manufacturers are offering a wide range of chips, thus lowering the overall cost of PTP and, consequently, IEEE C37.238-compliant implementations. It may therefore be reasonable to expect that in the near future (<5 years), all network devices will support network-based time synchronization and precise (<10 microseconds) network distributed time will eventually be available virtually everywhere (including homes and the farthest reaches of the Internet).

## V. ROBUST TIME SYSTEM

In previous sections, we discussed time sources and distribution methods.

Some time sources like GPS have been widely used in communications and power systems infrastructures to provide precise time. The wide use of GPS comes with many threats, including jamming, spoofing, and interference from other sources operating in the adjacent band to the GPS band.

GPS jamming is a deliberate attempt to disrupt GPS services. There are several GPS jamming devices readily available on the market today. Most of these devices have very short ranges, in the order of 5 to 10 meters. They are designed for people who do not want rental car, taxi, and delivery companies to use GPS to keep track of their vehicles. Because the GPS signal is very weak, it can be easily jammed using these devices [8].

GPS spoofing is another attack on the system, where a valid GPS signal is transmitted with altered position and time of day content. If the counterfeit signal strength is stronger than the actual valid GPS signal, the receiver could decode the wrong time and location information.

Recently, additional concerns about GPS signal reliability were raised when the U.S. Federal Communications Commission (FCC) approved the use of a satellite L-band spectrum (1,525 to 1,559 MHz and 1,626.5 to 1,660.5 MHz) for terrestrial mobile services. LightSquared is a company that seeks to provide comprehensive mobile satellite communications services. LightSquared was granted the first license to deploy and provide terrestrial service in the L-band by the FCC. Because this L-band is very close to the GPS frequency band, installing a transmitter near the location of a GPS antenna could interfere with the GPS signal reception. The GPS signal power received on earth is  $10^{-16}$  watts. A 3,200-watt transmission from a nearby L-band transmitter in the immediate neighboring frequency would be billions of times more powerful at the GPS receiver antenna. The effect of this is jamming and loss of the GPS signal.

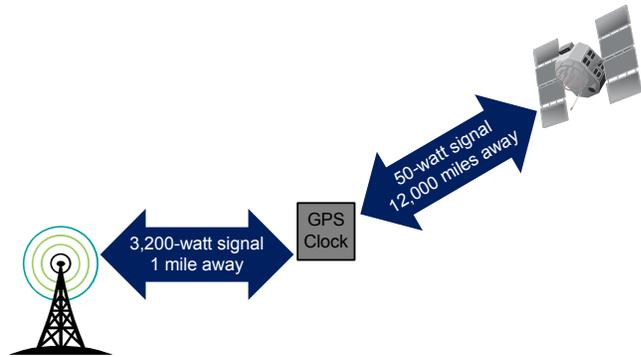


Fig. 9. Illustration of GPS interference from a nearby L-band transmitter.

This problem can be alleviated in the GPS receiver design with the addition of front-end filtering, but real-life effects will remain unclear until this service is widely deployed. At the time of writing this paper, it appears like the LightSquared proposal is finally dead, being rejected by the FCC. However, there appears to be a lot of politics involved, and it may have more than one life. In any case, the LightSquared exercise underscores the vulnerability of GPS and the need for redundancy in distributing precise time over wide areas.

When it comes to the use of precise time for power system applications, it is easy to claim that the current applications have hardly begun to realize their enormous potential [2]. The world is presently in the process of deploying an earth-wide synchrophasor monitoring network, with a select few

applications moving toward wide-area protection and real-time system control.

As the criticality of precise time-based applications increases, so do the requirements for time-distribution system reliability. While a few years ago it may have been acceptable to use a single GPS clock with no backup, new applications are forcing us to look at the time-distribution system reliability, availability, robustness, and security, including cybersecurity and malicious attacks on GPS.

The best way to avoid such attacks is to use terrestrial-based time distribution. As stated by the smart grid initiative, a large number of improvements in power system efficiency and reliable operation are expected to come from better resource utilization enabled by network-based communications. It is therefore natural that time-distribution services be combined with the wide-area communications.

Both IEEE 1588 V2 and the IEEE C37.238 power system profile make it possible to use PTP for wide-area time synchronization. However, as indicated by the NIST Smart Grid Interoperability Standards Cyber Security Review, neither of the two standards is presently hardened against malicious attacks, so the SGIP is recommending future enhancements in this domain.

The questions at hand are “What does this mean?” and “Can the standards be used in their current form?” This overall situation is no different than most power system communications used to date. Security is and will always remain a multilayer process, which cannot be delegated to a single mechanism or any given encryption standard. When built-in mechanisms are not available, it becomes necessary to use other engineering means, such as private communications networks, security perimeters, firewalls, encryption, virtual private networks (VPNs), virtual LAN (VLAN) segregation, and so on. Most of these measures apply even when the particular protocol (i.e., PTP) has been hardened. There is no substitute for vigilance, expertise, and good engineering work.

Fig. 10 illustrates a novel way to implement secure wide-area time distribution. This method is based on the well-known frequency synchronization capability used by synchronous optical network-based (SONET-based) transport systems, which have been further enhanced to transmit absolute (UTC) time.

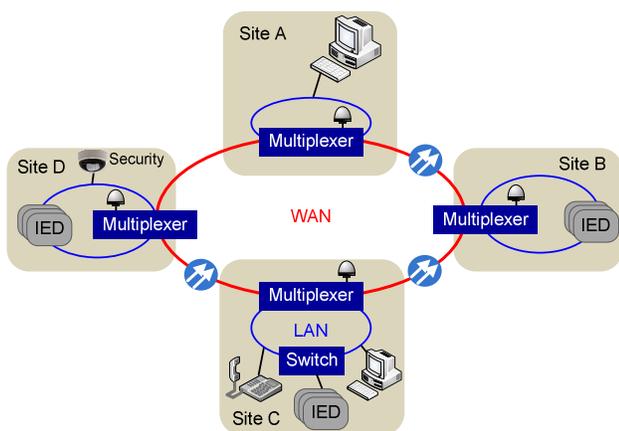


Fig. 10. SONET multiplexer network-based time-distribution system.

Individual SONET nodes are typically distributed over a wide geographic area, enabling built-in GPS receivers to perform measurements from widely distributed locations. In addition, individual SONET nodes are equipped with high-quality oscillators that are capable of keeping the network together in a holdover state even if all GPS receivers were rendered inoperative by a wide-scale attack (or in the unlikely event that the GPS satellites were turned off). System holdover can further be improved by adding a primary standard source, such as a cesium beam atomic clock, which enables better than 1-microsecond time accuracy for holdover lasting several months. A preferred system should be equipped with two atomic clocks that provide exceptional availability, special redundancy, and the ability to ride through multiple fiber link outages.

System security is provided by temporally separating the clock synchronization communications from the data payload, thus preventing all possibility of malicious attacks at the intermultiplexer time and frequency synchronization. When required, the ultimate protection against malicious attacks by a “man in the middle” of the fiber is provided by adding an OC-48 line encryption module. Encryption modules are required at each end of the fiber link and are installed in the standard multiplexer chassis.

## VI. CONCLUSION

Today, information is literally flowing at the speed of light in computers and communications systems. The number of applications and the diversity of the applications using precise timing are increasing. This paper discusses the importance of time for power system applications.

There are several time sources and distribution methods available today to provide accurate time synchronization to various systems. Many of these methods are analyzed for cost, performance, spatial extent, and accuracy tradeoffs. Also, with the evolution of new time-distribution methods like PTP, this paper proposes a robust time system. With IEDs supporting multiple time protocols and time synchronization inputs, this paper discusses several technologies that can provide the right choice for time synchronization in modern power systems.

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## VIII. BIOGRAPHIES

**Dr. Edmund O. Schweitzer, III** is recognized as a pioneer in digital protection and holds the grade of Fellow of the IEEE, a title bestowed on less than one percent of IEEE members. In 2002, he was elected a member of the National Academy of Engineering. He is the recipient of the Graduate Alumni Achievement Award from Washington State University and the Purdue University Outstanding Electrical and Computer Engineer Award. In September 2005, he was awarded an honorary doctorate from Universidad Autónoma de Nuevo León in Monterrey, Mexico, for his contribution to the development of electric power systems worldwide. He has written dozens of technical papers in the areas of digital relay design and reliability and holds more than 30 patents pertaining to electric power system protection, metering, monitoring, and control. Dr. Schweitzer received his Bachelor's and Master's degrees in electrical engineering from Purdue University and his Ph.D. from Washington State University. He served on the electrical engineering faculties of Ohio University and Washington State University, and in 1982, he founded Schweitzer Engineering Laboratories, Inc. (SEL) to develop and manufacture digital protective relays and related products and services. Today, SEL is an employee-owned company that serves the electric power industry worldwide and is certified to the international quality standard ISO-9001. SEL equipment is in service at voltages from 5 kV through 500 kV to protect feeders, motors, transformers, capacitor banks, transmission lines, and other power apparatus.

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