Synchronization in Power Distribution Networks

White paper

Power distribution networks are mission-critical infrastructure. The electric utilities that maintain these networks avoid disruptions that could put people and businesses at risk. To keep their grids running smoothly, utilities need solutions that can support grid monitoring, protection and control applications by reliably distributing synchronized time and phase information across the network.

This white paper describes how synchronization technologies such as the Precision Time Protocol (PTP) can address the demands of power distribution network applications that require synchronization. It also describes the Nokia solution for delivering precise timing across intra-substation and inter-substation communications.

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Introduction

Power distribution networks are mission-critical infrastructure. The electric utilities that maintain them must avoid disruptions that could lead to economic loss or endanger public health and safety. To keep grids running smoothly, utilities need real-time visibility into their operations. The distribution of time/phase synchronization over the network is necessary for monitoring, protection and control of the power grid.

This paper presents key power distribution network applications that require synchronization. It discusses the applicability of synchronization technologies used to distribute timing, with a focus on the Precision Time Protocol (PTP) profiles for the power and telecom industries. It also describes the Nokia solution for delivering precise timing across intra-substation local area network (LAN) and inter-substation wide area network (WAN) communications.

The need for precision synchronization in power distribution networks

Time-critical or time-tagged applications require precise synchronization to play their part in ensuring that the power grid operates properly. These applications include:

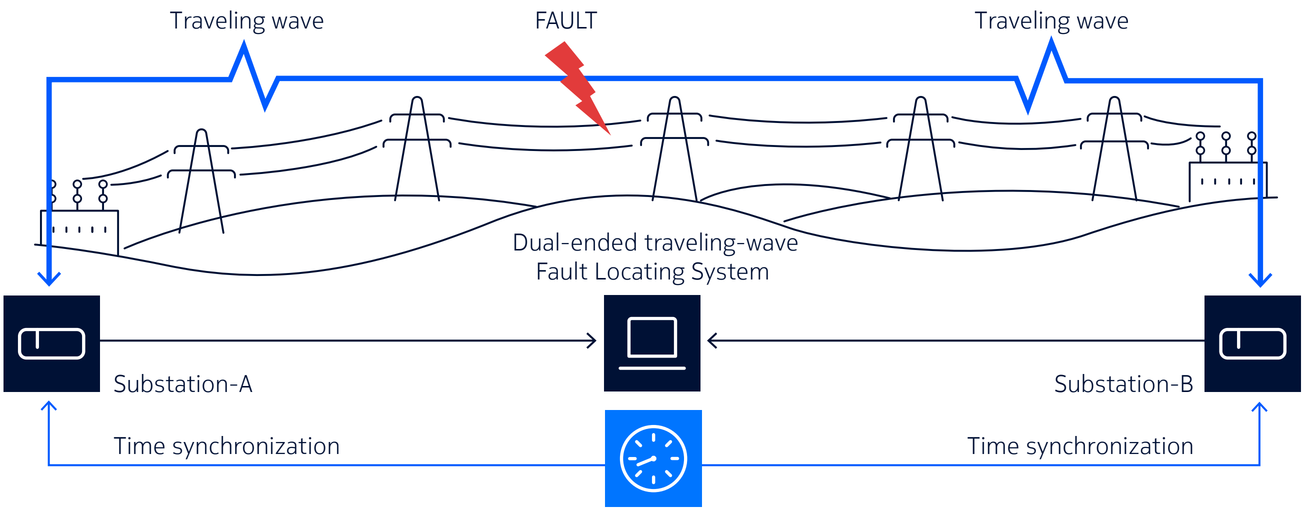
- **Synchrophasors**: Synchrophasors enable utilities to monitor transmission line loadings and recalculate the maximum power flow that transmission lines can carry in real time. They provide time-synchronized phasor measurements across wide areas to support real-time monitoring, protection and control of the power transmission and distribution system.

  Devices called phasor measurement units (PMUs) collect real-time voltage and current phasor measurements from different locations with accuracy and precision time stamping derived from an accurate time source. This data collection requires a time accuracy of 1 μs or better. A utility can use the real-time, time-synchronized data collected by PMUs to dynamically analyze the status of the power grid. It can also use the collected data as control system input to detect anomalies and trigger control actions.

- **Traveling Wave Fault Detection and Location**: Power transmission line failures can wreak havoc on the power grid. These may be caused by lightning strikes, line breaks due to fallen trees, snow, ice or other natural disasters, or, unfortunately, ill-intentioned human actions. It is imperative to locate and repair failures quickly to minimize their impact on the power grid.

  Utilities can use the Traveling Wave method to detect and locate failures. When a failure occurs, a waveform (high-frequency pulse) is generated at its location and travels down both ends of the transmission line (via optical fiber within an optical grounded wire cable) at nearly the speed of light, as shown in Figure 1. The arrival time of the waveform is measured when the high-frequency pulse is detected at each end of the line. The fault location can then be estimated based on the difference between the arrival times at the two ends. More accurate time synchronization distribution produces more accurate fault localization. With a time synchronization accuracy of 0.1 μs or better at both endpoints, the location of the failure can be determined to a scale of hundreds of meters.

Figure 1. Traveling Wave Fault Detection and Location



- **Supervisory Control and Data Acquisition (SCADA)**: SCADA systems are widely deployed in power generation, transmission and distribution systems to provide telemetry data about the status of equipment in the field. The data includes voltage, current, breaker status (open or closed), temperature or other power measurements. SCADA systems collect the data with timestamps and use the information to determine the status of power grid in real time. The typical reporting rate for a SCADA system is about every 4 to 6 seconds with 1 ms time accuracy for time stamping of collected data.
- **IEC 61850 Generic Object Oriented Substation Events (GOOSE) and Sampled Values (SV)**: Communication protocols defined in IEC 61850 are used for connecting substations over Ethernet in LANs: GOOSE for information exchanges between Intelligent Electronic Devices (IEDs) with 100 µs to 1ms time accuracy, and SV for information exchanges between Merging Units and IEDs with 1 µs time accuracy.

Table 1 lists the time accuracy requirements for different grid applications. In general, the required time accuracy ranges from 0.1 µs to 1 ms, with the most stringent application being Traveling Wave Fault Detection and Location. All these applications rely on frequency and time sources and the reliable distribution of both throughout the power grid.

Table 1. Synchronization requirements for power industry applications

Applications	Time accuracy requirement
Traveling Wave Fault Detection and Location	100 to 500 ns
• Synchrometrology (synchrophasors) • Wide Area Protection • Frequency Event Detection • Anti-Islanding • Droop Control • Wide Area Power Oscillation Damping (WAPOD)	Better than 1 µs
Line Differential Relays	10 to 20 µs
Sequence of Events Recording	50 µs to 2 ms
Digital Fault Recorder	1 ms
Communication events	
Substation Local Area Networks (IEC 61850 GOOSE)	100 µs to 1 ms
Substation Local Area Networks (IEC 61850 Sample Values)	1 µs

Source: NIST (National Institute of Standards and Technology) Special Publication 1500-08, “Timing Challenges in the Smart Grid” (January 2017) [12]

New smart grid applications and digitalized substations require greater synchronization accuracy to enable better insights into the power grid and improve grid availability, reliability and operational efficiency.

Synchronization technologies and PTP profiles

Depending on the application requirements, different synchronization technologies can source or transport synchronization in the power distribution network. This spans satellite and network-based timing sources, including Global Navigation Satellite System (GNSS), Network Time Protocol (NTP) and PTP.

GNSS receivers are widely deployed in the power distribution network to provide an accurate synchronization source for NTP or Simple NTP (SNTP) timer servers, PTP grandmaster clocks and other equipment. Receivers can also be integrated into devices such as PMUs or IEDs, which makes it easy to get precise timing at any location. However, this method is expensive and comes with risks such as the potential for GNSS signals to be unavailable or degraded by a jamming or spoofing attack.

Packet network-based timing protocols can also distribute timing to the power distribution network for digital substations and smart grid application scenarios. Historically, NTP was used to provide time synchronization with the time server located in the substation and synchronized by GNSS. In addition, the SNTP, which is a subset of NTP, can provide a precision of about 1 ms within a substation bus. However, these protocols cannot meet the timing accuracy requirements of applications that require sub-1 ms accuracy. In such cases, utilities need another solution based on PTP to support precise time distribution and backup synchronization during events when GNSS signals are unavailable. To help ensure interoperability, PTP works with different profiles that define a set of rules for constraining or optimizing PTP for a specific application or industry.

Precision Time Protocol

PTP is a network-based time synchronization protocol that enables time and phase distribution from a master clock to slave clocks. The IEEE first defined PTP in 2002 in IEEE Std 1588-2002 (also known as IEEE 1588 v1). It was initially designed for industrial applications to provide microsecond to sub-microsecond accuracy and precision time distribution over Layer 2 Ethernet.

In 2008, IEEE published a major revision, IEEE Std 1588-2008 (also known as IEEE 1588 v2) [1]. This second version introduced features such as new message types, transparent clock, peer-to-peer delay measurement mechanism (versus the Delay Request-Response mechanism) and message extension using Type, Length, Value (TLV) fields as well as many optional features. It also introduced a profile concept that different industries can use to define their own PTP profile. The power industry uses two PTP profiles:

- The power profile, used to support time/phase synchronization for specific applications within power substations and local communication networks
- The telecom profile, used to support time and phase synchronization in wide area communication networks that interconnect power substations or control centers

PTP power profiles

In 2011, the first PTP profile for power network applications was published as IEEE Std C37.238-2011, “Standard Profile for Use of IEEE 1588 Precision Time Protocol in Power System Applications.” This power profile is based on the Annex J.4 Peer-to-Peer default PTP profile of IEEE 1588-2008. It defines specific functionality: IEEE 802.1Q tags, IEEE C37.238 MIB and steady-state performance, and most notably the IEEE C37.238 TLV that is used to distribute the estimated grandmaster time inaccuracy and the accumulation of estimated network time inaccuracy information to the end applications or devices.

The IEC 62439 series specifies relevant principles for high-availability automation networks that meet the requirements for industrial communication networks, and the IEC 62439-3 defines the Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR), which are widely deployed across the power industry in environments such as substations. The 2016 revision, IEC 62439-3:2016 [6], introduced a mechanism for PTP over redundant paths and further PTP profiles (L3E2E, L2P2P). IEC 62439-3:2016 is now withdrawn and replaced by IEC 62439-3:2021. The PTP profile for power utility automation of IEC 62439-3:2016 Annex B provides the same basic services as IEEE C37.238-2011, but the IEEE C37.238 TLV is not specified in this profile. To prevent competition between these two profiles, IEC and IEEE jointly developed standard IEC/IEEE 61850-9-3: 2016 “Power Utility Automation Profile (PUP)” [2] to specify the base PTP profile for power utility automation.

IEC/IEEE 61850-9-3:2016 is the base PTP profile for use in power distribution networks. This profile is also based on the Annex J.4 Peer-to-Peer default PTP profile of IEEE 1588-2008 and includes the following profile-specific features:

- Mandatory support for dual attached clocks (use is optional)
- Extended Best Master Clock Algorithm (BMCA) for dual attached clocks
- The Alternate Time Offset Indicator (ATOI) local time TLV (defined in Clause 16.3 of IEEE 1588-2008), which allows the grandmaster to send time zone-related information and daylight saving indication
- Annex E MIB
- Vendor-specific configuration management options

IEEE C37.238-2011 was then revised to IEEE C37.238-2017 [5] as the extension of IEC/IEEE 61850-9-3:2016, providing additional functionality such as TLV extension for the ATOI TLV and clarification on the use and processing of certain fields (keyField, currentOffset, jumpSeconds, timeOfNextJump).

With these clarifications and extensions, this TLV can provide local time, daylight saving time effect indication features for power utility applications and IRIG-B replacement. The support of the IEEE C37.238-2017 ATOI TLV is mandatory, but its use is optional in this profile.

PTP telecom profile

Recommendation ITU-T G.8275.1 [7] specifies the PTP telecom profile for phase and time information with full timing support from the network. The first edition, ITU-T G.8275.1 (2014), was published in July 2014. Multiple revisions followed, and the latest edition is ITU-T G.8275.1 (11/2022). The PTP telecom profile is based on the Annex J.3 Delay Request-Response Default PTP profile of IEEE 1588-2008 and provides specific features for telecom application and wide area communication:

- The Alternate Best Master Clock Algorithm (ABMCA), defined in clause 6.3, is based on the default BMCA of IEEE 1588-2008 but with modifications to the data set comparison algorithm. The default BMCA of IEEE 1588-2008 allows only one active grandmaster, while the Alternate BMCA allows multiple active grandmasters simultaneously. If there are multiple active grandmasters, every clock that is not a grandmaster is synchronized by a single grandmaster in the PTP domain.
- The local Priority is a newly defined user-configurable attribute for a local clock and a port of a local clock. It provides a powerful and flexible tool for phase and time synchronization network planning. Keeping the default value of localPriority attribute, the PTP topology is established automatically by the ABMCA and is free of timing loops. If the values are configured to differ from the default, it allows manual network planning similar to the way the Synchronous Digital Hierarchy (SDH) network was operated based on the Synchronization Status Message (SSM). However, proper planning is mandatory prior to deployment to avoid timing loops.

- The Path Trace function, defined in clause 16.2 of IEEE Std 1588-2008, tracks the actual path of the PTP synchronization reference in the network. The Path Trace TLV is appended at the end of the PTP Announce messages, and each PTP clock in the synchronization path adds its clockIdentity to the field. This allows utilities to determine the actual route taken by the PTP frames anywhere in the network. It is perhaps the most important capability from the new version of the PTP telecom profile, and provides full traceability information at any time, not just during troubleshooting of failures in the network.
- The Packet Timing Signal Fail (PTSF) indicates a failure of the PTP packet timing signal received by a PTP port. It is one of the fault management and monitoring tools for timing signal failure detection (loss of PTP timing message, unusable PTP packet time signal and uncertain timing signal).
- Further PTP monitoring options are defined to support monitoring of alternate master time information provided by a peer PTP port, and dynamic monitoring of a neighbor PTP port by a PTP port experiencing a local PTSF.

Additional features for fault detection, alarm processing and performance monitoring for frequency and time synchronization are defined in ITU-T G Suppl. 68 [11] to provide enhanced synchronization operation, administration and maintenance (Sync OAM) for synchronous Ethernet, PTP and 1PPS. ITU-T Sync OAM greatly improves monitoring and simplifies the operation and maintenance of synchronization layer networks by making it easier to monitor and resolve any issues with the synchronization services.

Performance requirements of the PTP profiles

IEC/IEEE 61850-9-3:2016 specifies the performance requirements for the PTP power profile for networks, grandmasters, transparent clocks, boundary clocks and media converters. The standard indicates that network time inaccuracy shall be better than ±1 μs after crossing 15 transparent clocks (TCs) or 3 boundary clocks (BCs), and that time inaccuracy shall be smaller than 250 ns for grandmaster, 50 ns for TCs and 200 ns for BCs. The media converters should have less than 50 ns jitter and better than 25 ns maximum asymmetry.

For telecom boundary clocks (T-BCs), telecom slave clocks (T-TSCs) and telecom transparent clocks (T-TCs) with full timing support from the network, i.e., the clock types supported in recommendation ITU-T G.8275.1 PTP telecom profile, the clock performance requirements are specified in ITU-T G.8273.2 [8] for T-BC and T-TSC and ITU-T G.8273.3 [9] for T-TC. These two standards categorize performance requirements into Class A, B, C and D and assume frequency distribution underneath PTP. The network limits for time synchronization in packet networks with full timing support from the network are specified in recommendation ITU-T G.8271.1 [10].

Table 2. Performance requirements for PTP power and telecom profiles

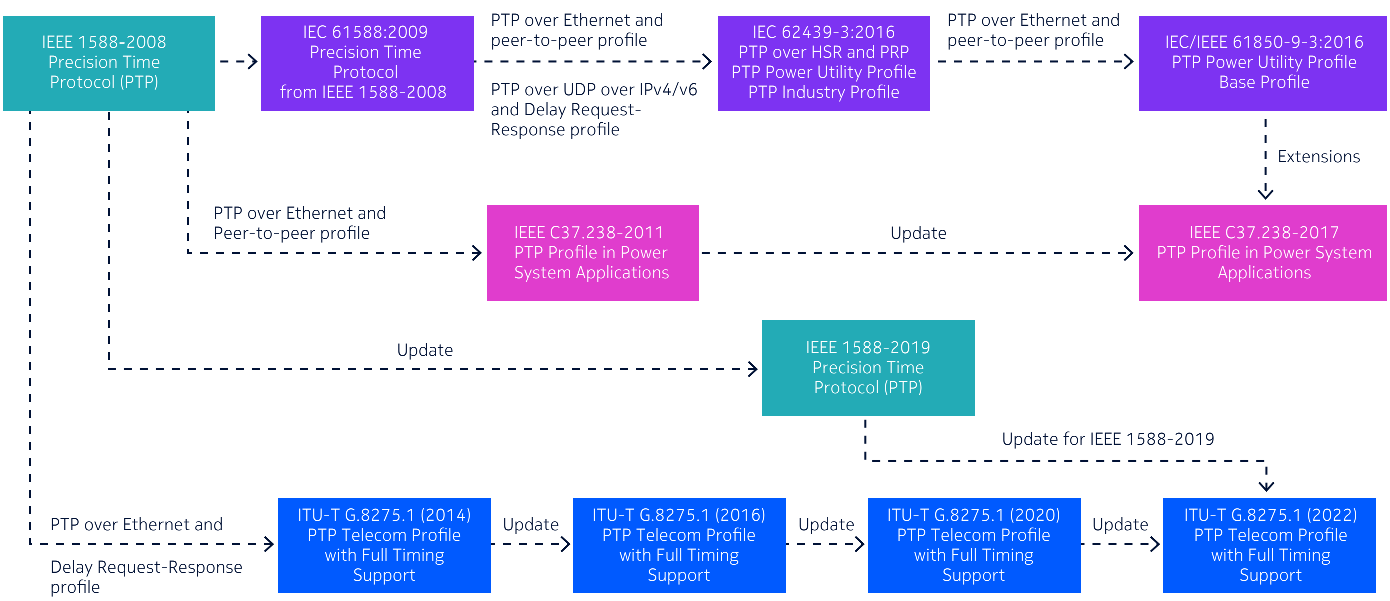
Performance requirements	ITU-T G.8273.2, G.8273.3 & G.8271.1	IEC/IEEE 61850-9-3:2016	IEEE C37.238-2017
Network limits	± 1.1 µs	± 1 µs	Same as IEC/IEEE 61850-9-3
Grandmaster clock accuracy	± 100 ns	± 250 ns	Same as IEC/IEEE 61850-9-3
Boundary clocks accuracy	• Class A max|TE|: 100 ns • Class B max|TE|: 70 ns • Class C max|TE|: 30 ns • Class D max|TE_L|: 5 ns	± 200 ns	Same as IEC/IEEE 61850-9-3
Slave clocks accuracy	• Class A max|TE|: 100 ns • Class B max|TE|: 70 ns • Class C max|TE|: 30 ns • Class D max|TE_L|: 5 ns	Not specified	Same as IEC/IEEE 61850-9-3
Transparent clocks accuracy	• Class A max|TE|: 100 ns • Class B max|TE|: 70 ns	± 50 ns	Same as IEC/IEEE 61850-9-3
Media converters	Each device is equivalent to a single T-BC	± 50 ns	Same as IEC/IEEE 61850-9-3
Maximum number of hops	20 hops	15 x TC or 3 x BC	Same as IEC/IEEE 61850-9-3

PTP power profile and telecom profile evolution and comparison

The PTP power profiles and telecom profiles are both based on the default profile of IEEE 1588-2008 but have been tailored for different applications. The PTP power profile is mature and has not seen any changes since 2017. In comparison, the telecom profile continues to be enhanced by ITU-T SG15 and therefore supports a much more comprehensive, superior feature set. This feature set is clearly necessary for managed transport applications. The PTP power profile would not be suitable for transport, mainly because it lacks the necessary operation, administration and maintenance (OAM) and monitoring capabilities.

The respective evolutions of the PTP power and telecom profiles are illustrated in Figure 2 below.

Figure 2. Evolution of PTP power and telecom profiles

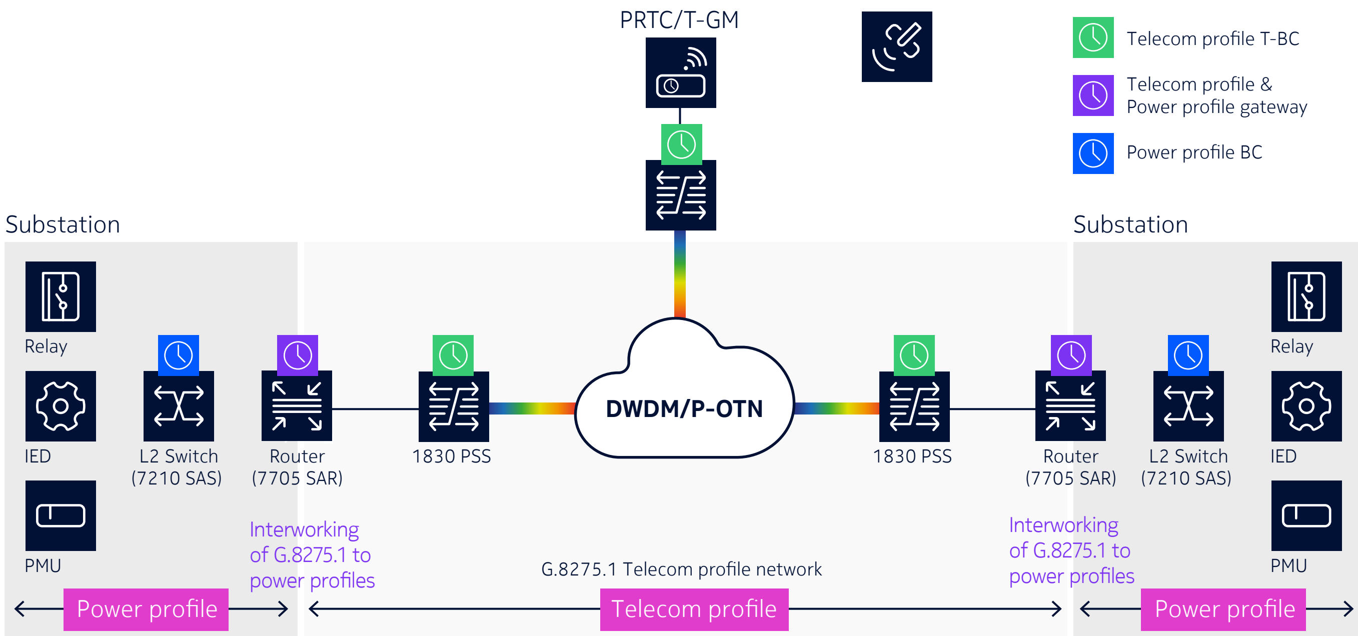


Contact your Nokia technical sales representative for a detailed comparison between ITU-T G.8275.1, IEC/IEEE 61850-9-3:2016 and IEEE C37.238-2017, if needed.

Nokia solution for synchronization distribution

The Nokia synchronization distribution solution employs the right PTP profiles in the right place of the network to enable utilities to distribute accurate timing across their grids through the WAN and down to substation LANs to reach relays, IEDs and PMUs, as shown in Figure 3.

Figure 3. Nokia synchronization distribution solution for power utilities



The IEC/IEEE PTP power profile and ITU-T G.8275.1 PTP telecom profile enable synchronization distribution for intra-substation and inter-substation communication, respectively. Within substations, Nokia IP/MPLS routers support the PTP power profile by providing accurate time synchronization for substations and power industry applications. Across the WAN, Nokia optical transport systems connect the control centers to each substation and distribute precise synchronization via the ITU-T G.8275.1 PTP telecom profile and Class B/C T-BCs.

In addition to improving supervision, performance and reliability, this approach allows for longer synchronization chains in the transport network and avoids side effects of cascading routing and optical network elements (each counting as a T-BC hop), while still meeting 0.1 μs or better performance from end to end. ITU-T Sync OAM with flexible provisioning and strong OAM and monitoring tools for synchronization distribution are available over the optical OTN/DWDM transport network. The IP/MPLS router, implementing both profiles, plays the essential role as the profile gateway between the power and telecom PTP profiles when distributing synchronization from the central site to remote sites.

The Nokia PTP synchronization distribution solution comprises:

- 7705 Service Aggregation Router (SAR), a family of IP/MPLS service platforms purpose-built for the utility WAN. Offering SyncE and PTP capabilities and an integrated GNSS receiver module, these platforms enable utilities to distribute frequency, time/phase synchronization across the WAN.
- 7210 Service Aggregation System (SAS), a family of Ethernet service demarcation platforms that can also be used in substation LANs. These platforms offer PTP capabilities that let utilities distribute frequency, phase and time synchronization over the LAN to IEDs throughout the substation.

- 1830 Photonic Service Switch (PSS), a family of optical transport systems that carry highly precise synchronization at the photonic layer, with highly accurate (Class B/C) T-BCs to distribute timing from the core of the network all the way to the edge. To eliminate delay variations due to link asymmetry, the 1830 PSS provides out-of-band synchronization over a dedicated wavelength using bidirectional transmission, called the Optical Timing Channel (OTC). Having point-to-point links with bidirectional signaling prevents asymmetry from the photonic layer and OTN mapping and demapping.
- Network Services Platform (NSP), a network and service manager for the IP/MPLS routers used in the utility WAN and substation LAN. The NSP provides information on the synchronization layer topology, clock status and timing paths, as well as other key information for synchronization planning and troubleshooting.
- WaveSuite Synchronizer, an application within the WaveSuite NOC management system that provides a network-wide view of the synchronization layer within the optical network, along with intuitive tools to control the entire network synchronization infrastructure. It enables power distribution network operators to easily distribute synchronization by aiding in the planning, provisioning, operation and maintenance of synchronization distribution networks. These capabilities help simplify network operations and ultimately improve synchronization performance.

In this Nokia blueprint, the 1830 PSS is deployed at a centralized control center and receives the primary timing signal from a telecom grandmaster. It distributes synchronization over the OTN/WDM network with each hop having full timing support and serving as a T-BC to ensure the highest accuracy.

Each optical node is a T-BC and will recover frequency and time/phase information and distribute it towards the edge until it reaches the 7705 SAR or 7210 SAS routers in the substation.

Each IP/MPLS router is a T-BC and will perform an interworking function to comply with the PTP power profile. It will recover synchronization information and distribute it to connected relays, IEDs and downstream routers. The 1830 PSS at the edge will also distribute time to other routers deployed at other downstream substations.

Conclusion

Precise synchronization distribution is paramount for the operation of today's mission-critical power substations and applications. Grid applications, including synchrophasor and GOOSE, require their IEDs to have reliable access to accurate time information. Fault location techniques such as Traveling Wave Fault Detection and Location require precise timing to accurately locate faults in the power grid. While GNSS receivers can serve as a primary source of synchronization at power substations, they are subject to vulnerabilities, including interference and malicious attacks such as jamming and spoofing. Network-based synchronization can serve as a reliable backup to GNSS-based synchronization.

The Nokia synchronization distribution solution provides precise timing using a combination of the IEC/IEEE power profile and the ITU-T G.8275.1 PTP telecom profile to distribute synchronization for intra-substation and inter-substation communications. It delivers outstanding performance and flexible provisioning and monitoring tools for wide area synchronization distribution between power substations interconnected by an OTN/DWDM network. Within the substation LAN, IP/MPLS routers serve as the profile gateway between the PTP power and telecom profiles, providing timing to the substation devices and grid applications.

Nokia has more than 30 years of experience helping utilities tackle the challenge of large-scale WAN synchronization. We have deep expertise in distributing frequency, phase and time information with high reliability and accuracy. To learn more about our solutions for utilities and synchronization, visit our power utilities web page and synchronization web page.

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Abbreviations

1PPS	one pulse per second
ABMCA	Alternate Best Master Clock Algorithm
ATOI	Alternate Time Offset Indicator
BC	boundary clock
BMCA	Best Master Clock Algorithm
DWDM	dense wavelength division multiplexing
GNSS	Global Navigation Satellite System
GOOSE	Generic Object Oriented Substation Events
HSR	High-availability Seamless Redundancy
IED	Intelligent Electronic Device
IRIG-B	Inter-Range Instrumentation Group Serial Time Code B
LAN	local area network
maxTE	maximum Time Error
MIB	management information base
NE	network element
NOC	network operations center
NTP	Network Time Protocol
OAM	operation, administration and maintenance
OTC	Optical Timing Channel
OTN	optical transport network
PMU	phasor measurement unit
P-OTN	packet optical transport network
PRP	Parallel Redundancy Protocol
PTP	Precision Time Protocol
SCADA	Supervisory Control and Data Acquisition
SDH	Synchronization Digital Hierarchy
SNTP	Simple Network Time Protocol
SSM	Synchronization Status Message
SV	Sampled Value
Sync OAM	synchronization operation, administration and maintenance
T-BC	telecom boundary clock

TC	transparent clock
TE	Time Error
T-GM	telecom grandmaster
TLV	Type, Length, Value
T-TSC	telecom time slave clock
T-TC	telecom transparent clock
UDP	User Datagram Protocol
WAN	wide area network
WDM	wavelength division multiplexing

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