A resilient IEEE 1588v2 timing network blueprint for power grid automation

Application note

Contents

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Timing is critical to power grid automation

As power utilities modernize their grids, many are transitioning to digital substations and implementing substation automation powered by digital monitoring and protection and control (PAC) applications, leveraging IEC 61850 standards. This transformation requires precise coordination of intelligent electronic device (IED) activities, data measurement and resource scheduling, orchestrated between IEDs in substations and control software in substations, control centers and data centers. At the same time, utilities are evolving the power grid from generally traditional, centralized steady-state generation to a dynamic mesh of variable distributed energy resources (DERs). To succeed with these changes, utilities need a common time reference to coordinate the temporal behavior of assets and integrate time-sensitive applications across the grid.

Applications that rely on accurate timing include digital fault recorders (DFRs), which monitor power flow with high sampling rates. DFRs require time accuracy on the order of 1 ms so that utilities can time-align substation events across the grid. This level of accuracy enables them to correlate with lightning strike data to determine the origin of the fault.

Differential protection is another critical application that requires accurate timing. Differential relays measure the current at both ends of the protected zone. Each relay sends current samples to the remote end and receives current samples in return. It compares the data sent and received and sends a trip signal to the circuit breaker if it detects a fault. Utilities must ensure that they can accurately time-align current samples from different relays to the order of 10–20 μs.

Synchrophasor, a key application for situational awareness and state estimation, and traveling wave fault detection, require even higher accuracy than DFRs and differential protection—better than 1 μs.

To support these timing needs, utilities have been depending on Global Navigation Satellite Systems (GNSS) such as US GPS or European Galileo as the timing source at substations. However, utilities cannot feasibly equip every substation with a GNSS/GPS receiver or connect every IED to the GNSS receiver with an Inter-range Instrumentation Group (IRIG) interface over copper cable.

Embracing IEEE 1588v2

Recognizing that time synchronization has become essential for power grids and other critical infrastructure, the National Institute of Standards and Technology (NIST) in the US has published NISTIR 8323, a report that identifies the need for resilient, highly available time synchronization distribution.

However, attaining the goal set by NIST is an immense challenge for utilities. First, it is not practical to furnish every substation with a satellite antenna to receive GNSS or GPS signals. Second, GNSS and GPS signals are susceptible to natural, accidental and intentional interference. Degradation in timing caused by interference will impact grid performance, reliability and operations. This means it is imperative for utilities to develop alternative timing sources to GNSS and GPS.

Because a wide area network (WAN) is foundational to utility automation, a sound time synchronization strategy is to utilize the WAN as a backup timing distribution source for substations with GNSS or GPS receivers, and as the primary timing distribution source for substations without these receivers. Consequently, IEEE 1588v2 Precision Time Protocol (PTP), a timing over network technology, has received immense attention from utilities because of its ability to distribute accurate timing across the WAN to each connected substation.

In response to specific utility timing requirements, the International Electrotechnical Commission (IEC) defined a PTP profile for power utility automation in IEC 61850-9-3:2016. The Power Utility profile specified in this standard complies with the most stringent synchronization classes defined in IEC 61850-5. IEEE also published IEEE C37.238:2011, subsequently updated in 2017, which extends PTP capabilities with continuous monitoring of time inaccuracy and optionally local time based on Coordinated Universal Time (UTC). Together, these standards specify a common subset of PTP parameters and options to provide time, device availability and failure management for mission-critical power system protection, control, automation and data communication applications.

A brief overview of IEEE 1588v2

While IEEE 1588v2 was originally designed for mission-critical industrial automation, mobile network operators were early adopters, using it in their mobile backhaul networks to distribute timing to LTE and 5G radio base stations. The International Telecommunication Union – Telecommunication Standardization Sector (ITU-T) developed Telecom profiles to meet these requirements, as specified in G.8275.1 and G.8275.2. Telecom profiles are commonly supported by communication equipment.

An IEEE 1588v2 synchronization topology is a hierarchical topology that consists of several different clock types (Figure 1):

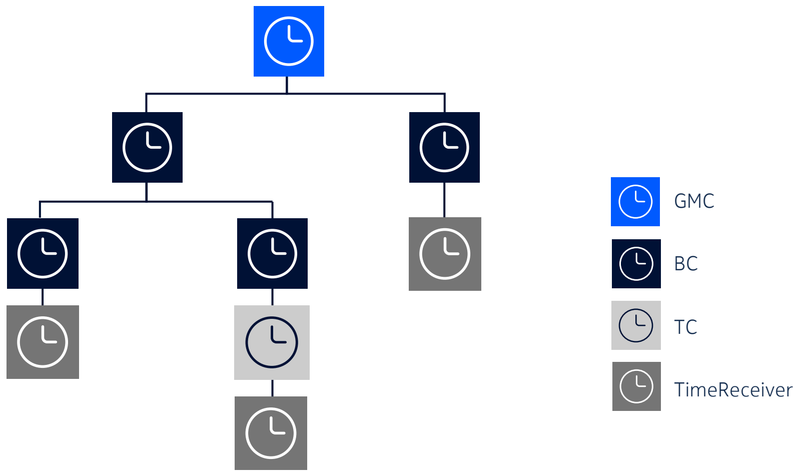
- Grand master clock (GMC): The GMC is connected with a primary reference time clock (PRTC), typically a GNSS satellite or an atomic clock. It acts as the timeTransmitter[1] and sends Sync messages with timestamp information to downstream clocks in the hierarchy.
- Boundary clock (BC): A BC acts as a timeReceiver to the upstream GMC or BC and recovers time information from received Sync messages. It then uses this information to act as a timeTransmitter, sending its own Sync messages to BCs or timeReceiver clocks[2] downstream. In this way, the BC bridges timing information between upstream and downstream clocks, allowing precise timing propagation through the network.
- Transparent clock (TC): A TC forwards all received messages downstream. It uses specialized hardware to precisely measure the residence time of PTP messages, and then updates a field in the Sync messages to account for the delay incurred. Unlike a BC, it does not recover time information or actively participate in the timeTransmitter–timeReceiver hierarchy.
- TimeReceiver clock: A timeReceiver clock receives PTP messages from an upstream GMC or BC. It uses the timing information in these messages to recover and synchronize its local time for local applications. Substation IEDs such as protection relays and merging units have a timeReceiver clock to provide precise timing.

In the case of the Power Utility profile, every clock also exchanges PTP peer delay messages with the neighbor clock to measure the delay across the physical links. These link delays are included in the time recovery process.

1 TimeTransmitter clock has replaced the term “master clock” as per IEEE 1588g-2022.

2 TimeReceiver clock has replaced the term “slave clock” as per IEEE 1588g – 2022.

Figure 1. A hierarchical IEEE 1588v2 topology



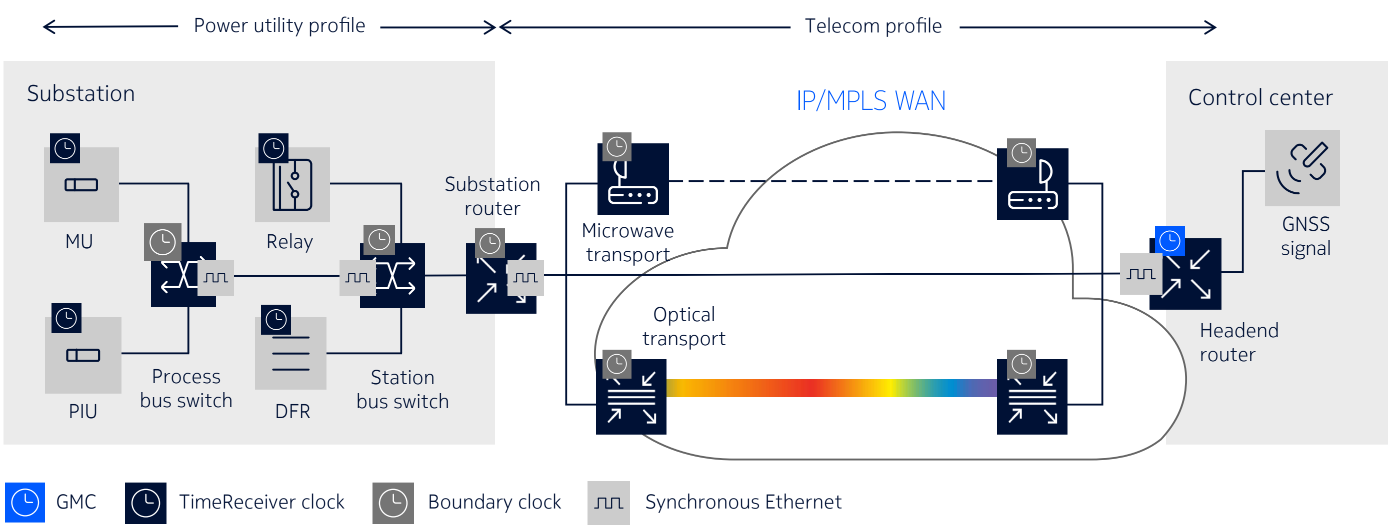
An IEEE 1588v2 network blueprint

The communication infrastructure plays a central role in accurate and reliable timing distribution from the GMC down to each timeReceiver clock in substation IEDs. Figure 2 shows a network blueprint that comprises:

- A multilayer WAN where the IP/MPLS layer rides on top of a transport layer made up of optical DWDM and packet microwave nodes, and connects control centers and data centers to substations
- A substation ethernet LAN that supports IEC 61850-based station bus and process bus communications.

In this blueprint, all network nodes in the IP/MPLS and transport layers actively participate in the IEEE 1588v2 clock topology.

Figure 2. Network blueprint for IEEE 1588v2 timing distribution



BC as the fundamental building block

While TCs can be deployed in the synchronization topology, BCs are the preferred choice because they:

- Recover and clean up timing before sending it downstream to mitigate the impact of accumulated network jitter. This also reduces the impact of delay asymmetry over multiple network hops.
- Strengthen the resilience of the synchronization topology (which will be described in a later section)
- Enable the monitoring of clock performance at each hop in the network for easy troubleshooting and performance monitoring
- Allow the network domain to synchronize with the electrical domain to establish a common timing reference across the grid infrastructure
- Enable the topology to scale by reducing the number of peers with which the GMC needs to connect.

With a BC at every network node, the blueprint can deliver precise time synchronization from the GMC to substation IEDs. This ensures that the time error incurred meets the stringent requirements of critical grid applications that mandate sub-microsecond-level accuracy.

Synchronous Ethernet for highly stable frequency references

In the WAN, utilities can adopt the standard telecom architecture described in ITU-T G.8262, which harnesses Synchronous Ethernet (SyncE) in addition to IEEE 1588v2 with the Telecom profile to further improve timing distribution accuracy. Contrary to IEEE 1588v2, which is a timing over packet technology, SyncE is a line timing technology that provides a highly stable and traceable frequency reference over the physical layer. It utilizes the Ethernet layer to transmit and recover frequency. Frequency synchronization accuracy is not impacted by Ethernet link utilization.

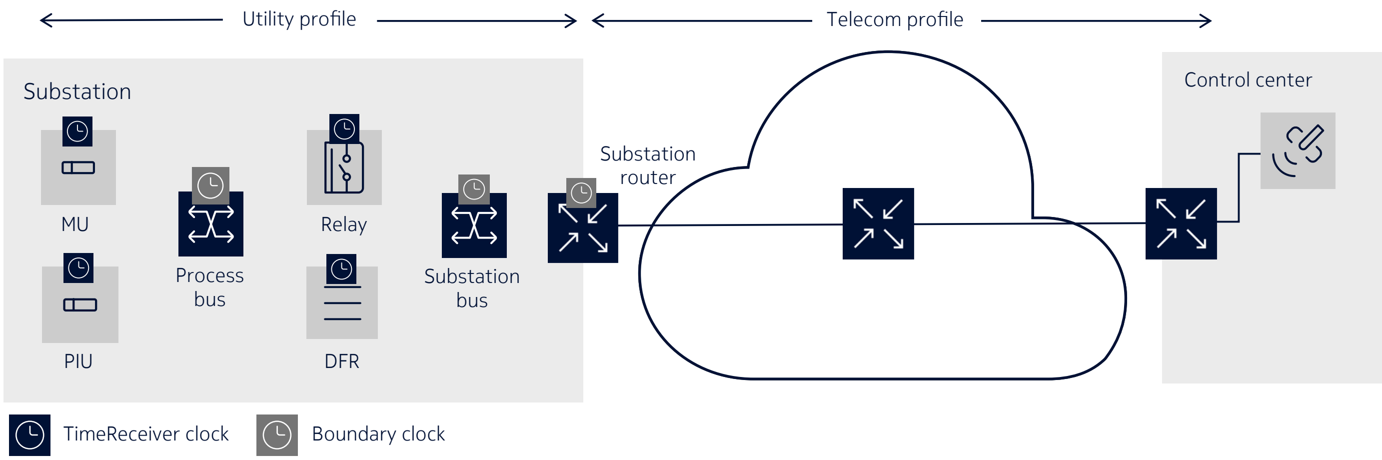
Each IP/MPLS router recovers the frequency from the ingress ports and regenerates it on egress ports, allowing the frequency to be transported across the blueprint. With SyncE minimizing frequency variations, the BC can recover timing with greater accuracy. SyncE can be thought of as providing very high stability oscillators in each of the nodes. This helps to count time forward accurately while PTP messages are processed. It can also help maintain accurate time during PTP outages.

Similarly, in substations, the LAN switch in the process bus and station bus can also support SyncE for greater timing accuracy.

IEEE 1588 profile interworking

While the WAN uses the Telecom profile of IEEE 1588 specified in ITU-T G.8275.1, substation IEDs implement the Power Utility profile defined by IEC and IEEE. To enable seamless interworking between these two domains, the substation router in the blueprint, while acting as a BC, plays an additional pivotal role of an interworking gateway, translating between the two profiles (Figure 3).

Figure 3. Enabling seamless interworking between the Telecom and Power Utility profiles



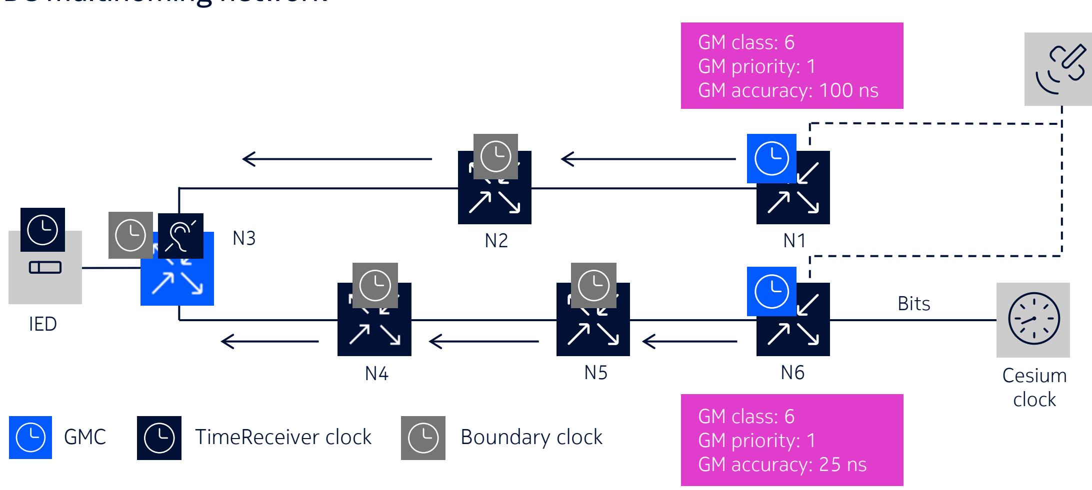
Synchronization network resilience

A resilient time synchronization topology is essential for maintaining safe and efficient grid operations. This requires a network with diverse connectivity for multiple paths to distribute Sync messages. Additionally, a BC is central to synchronization resilience. The resilience engine in the BC is the Best TimeTransmitter Clock Algorithm (BTCA).[3] It allows the BC to connect to multiple BCs or GMCs upstream in the synchronization topology (Figure 4) and enables the BC to continue to provide accurate timing downstream during upstream failures.

The BTCA builds a spanning tree topology to ensure that every clock has a path to the best available GMC. ITU-T G.8275.1 modified the BTCA of the IEEE standard slightly to allow for the closest clock to be selected if there are multiple GMCs of equal quality.

The rest of this section discusses a few failure scenarios to explore how the BTCA in N3 in Figure 4 can select the path to the best available GMC.

Figure 4. A BC multihoming network



3 BTCA was formerly known as Best Master Clock Algorithm (BMCA).

Selecting the best timeTransmitter

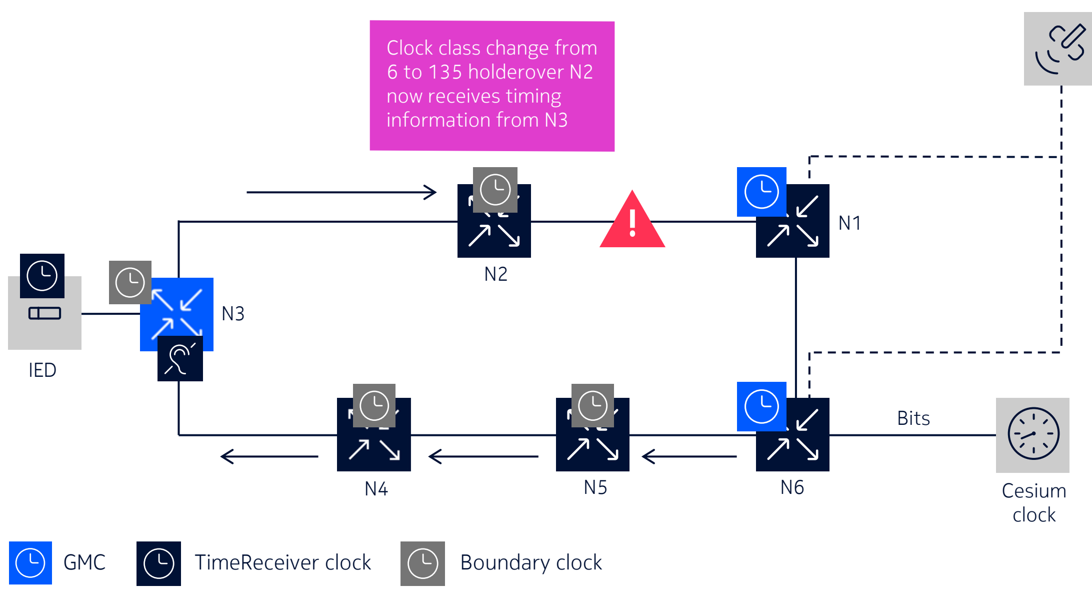
With the BC in substation router N3 dual-homed to two upstream BCs traceable to GMCs N1 and N6, the BTCA on N3 ensures resilient and accurate time synchronization.

In the normal operating scenario, the BTCA running on N3 evaluates the clock properties advertised by N2 and N4 and selects the best clock source based on criteria including clock class, accuracy, priority and the number of BC hops to the GMC.[4] Since the GMC properties of N1 and N6 are the same, N3 will select timing from N2 because it has fewer hops (or steps in IEEE 1588 standard terminology) from the GMC.

Protecting against network link failure

When the N2–N1 link fails, N2 can no longer receive timing from N1. It will then transition into holdover mode with its frequency traced to its internal oscillator and subsequently announce a degraded clock class (135 as specified in ITU-T G.8275.1) to indicate the transition. The BTCA on N3 will compare the two upstream BCs (N2 and N4) based on the new information. It will choose to receive timing information from N4 (Figure 5) because it now is the better clock source traceable to N6. The BTCA on N2 will see that N3 is a better timing source than its local holdover and will adjust to receive timing from N3. (Notice the reversal of the arrow between N2 and N3.)

Figure 5. Protection against network link failure



Protecting against GNSS signal loss

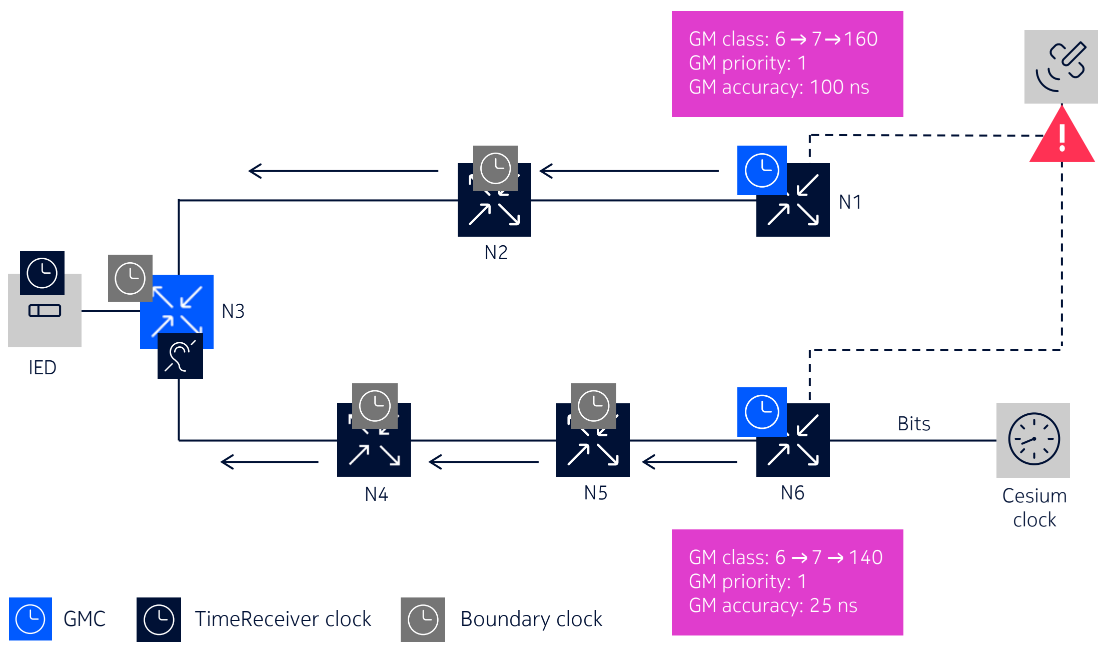
Proper reception of the GNSS signal is fundamental to the synchronization network. GNSS signal loss can occur for various reasons, including ionospheric disturbances caused by increased solar activity, malicious jamming, spoofing attacks or interference from other radio frequency sources. If signal loss occurs over a wide area, timing accuracy will degrade significantly. It is important for utilities to deploy a protection scheme to mitigate the impact of signal loss, particularly long-term signal loss.

4 Read ITU-T G.8275.1 for a description of BTCA. It is referred as BMCA in this standard.

After losing timing traceability to the GNSS, the GMC would go into holdover mode while locking to a local frequency source. The quality of the local frequency source is vital to the quality of timing distribution during this holdover period. If the holdover is based on a local frequency source (e.g., a stratum 3 oscillator in the network node), the BC will deviate from the holdover specification very quickly. An effective measure for mitigating long-term GNSS signal loss while maintaining time accuracy is to connect a Stratum 1 cesium frequency reference to the GMC. This can be done in strategic GMC locations across the grid infrastructure.

Figure 6 describes a scenario where a wide-area GNSS signal degradation affects the N1 and N6 GMCs. These GMCs will enter holdover mode and announce a degraded clock class (class = 7) to indicate the transition, as specified in ITU-T G.8275.1. When N1 and N6 come out of holdover mode, N1 will announce a new degraded clock class (class = 160) because it is only traceable to a Stratum 3 clock, the internal oscillator in N1. However, N6 will announce a new degraded clock class (class = 140) because it is traceable to a Stratum 1 cesium clock. Therefore, downstream BCs such as N3 will recover timing from the upstream N4 instead of N2.

Figure 6. Protection against GNSS failure



By continuously evaluating announced clock properties and automatically selecting the best upstream clock source, the BTCA provides resilience against network failures and timing signal degradations of a PRTC such as GNSS. If an upstream clock source has a problem, the BMCA intelligently and seamlessly switches to an alternative path, ensuring uninterrupted and accurate time synchronization throughout the network hierarchy.

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Extending synchronization to private wireless networks

As utilities continue automation at the distribution, they are deploying private wireless networks to connect to IEDs in the distribution systems. LTE or 5G wireless systems require frequency and time synchronization to operate effectively. Routers in the synchronization network blueprint can also connect to LTE base stations (eNB) or 5G base stations (gNB) to distribute the necessary synchronization. This convergence of timing distribution for wired and wireless networks enables a unified synchronization architecture that simplifies network management and reduces operational complexity.

Why choose Nokia for synchronization?

Synchronization is integral to communications networks and foundational to power grid automations. Grid applications, including synchrophasor and differential protection, require their IEDs to have reliable access to accurate time.

With more than 30 years of utility industry experience and a long pedigree in implementing synchronization capabilities across large-scale networks, Nokia has deep expertise in distributing frequency, phase and timing with high reliability and accuracy.

We have a broad communications product portfolio that spans IP/MPLS, LTE, 5G, packet microwave and packet optical transport. This comprehensive portfolio offers the unique capability and flexibility to help utilities transform their networks to deliver the highest reliability and strongest cybersecurity defense. We complement our products and solutions with a full suite of professional services, including network audit, design and engineering practices.

Visit our power utilities web page to learn more about how Nokia solutions can help your organization get empowered for the new energy future.

Abbreviations

BC	boundary clock
BMCA	Best Master Clock Algorithm
BTCA	Best TimeTransmitter Clock
DER	distributed energy resource
DFR	digital fault recorder
GMC	grand master clock
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
IEC	International Electrotechnical Commission
IED	intelligent electronic device
IEEE	Institute of Electrical and Electronics Engineers

IP	Internet Protocol
IRIG	Inter-range Instrumentation Group
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
LTE	Long Term Evolution
MPLS	Multiprotocol Label Switching
NIST	National Institute of Standards and Technology
PAC	protection and control
PRTC	primary time reference clock
PTP	Precision Time Protocol
TC	transparent clock
UTC	Coordinated Universal Time
WAN	wide area network

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