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Delivering high-quality network-based synchronization

The importance of enhanced telecom boundary clocks in delivering time-sensitive applications

White paper

Synchronization plays a critical role in telecom networks and like power, the mobile network cannot function properly without it. With 5G and the centralized RAN (C-RAN) architectures that it enables, the distribution of highly accurate frequency, phase and time synchronization becomes even more important and challenging. To this end, industry standards bodies such as the 3GPP, ITU-T and the IEEE have defined synchronization requirements to ensure the proper operation of the network and enable interworking. Delivering high-quality synchronization is a must for 5G networks and goes beyond simply meeting minimum standard requirements.

This paper examines the applications, architectures and features that impose strict synchronization accuracy requirements on the distribution of clock timing throughout mobile transport networks. It discusses a hybrid model that uses enhanced synchronous Ethernet equipment clocks to assist IEEE 1588 PTP in generating more accurate timing and enable enhanced telecom boundary clocks, which are required to support time-sensitive applications. The paper also explains how the Nokia IP Anyhaul solution addresses 5G timing requirements with support from enhanced telecom boundary clocks that have full on-path timing support.

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Introduction

Synchronization is critical in telecom networks. Without it, mobile networks cannot operate. Mobile networks rely on accurate synchronization to perform functions such as handovers between cell sites, to minimize interference across sites, and to maximize performance at the cell edge. By enabling tight coordination across sites, time synchronization also provides the ability to detect the movement, location and proximity of devices that depend on the accuracy of the synchronization information to deliver good performance. Time-sensitive applications require highly accurate synchronization to ensure that the frequency, phase and time differences among systems are within tolerable limits for proper network operation.

While synchronization can be achieved by placing GNSS receivers at each cell site, there are cases where this is not viable because of GNSS receiver costs, line-of-sight limitations or a desire to mitigate jamming or spoofing. As such, an alternate backup or primary network-based synchronization source is needed. This white paper focuses on packet network-based synchronization distribution using a combination of the Precision Time Protocol (PTP) and enhanced Ethernet equipment clocks (eEECs). By using this hybrid model, the network can deliver highly accurate synchronization that meets the requirements of all time-sensitive applications.

The need for higher synchronization accuracy

Coordinated RAN

Table 1 summarizes the synchronization requirements for 4G and 5G mobile communications networks. For frequency synchronization, an accuracy of +/-50 ppb is stipulated on the air interface regardless of the application. For phase/time synchronization, the requirements vary depending on the RAN application being used. For example, radios that operate in TDD spectrum have a general requirement to be within +/-1.5 µs of an absolute time reference such as GNSS. However, applications that use coordinated RAN features such as intra-band contiguous carrier aggregation (CA) require much stricter synchronization accuracy, within 130 ns relative time error (between the coordinated cells). Failure to meet these tolerances can result in poor signal quality, lower data speeds, interference and network outages.

Table 1. Frequency, phase and time synchronization requirements in telecom networks

Application	Frequency (network/air interface)	Phase/time	Why it is important	Non-compliance impact
LTE/5G NR (FDD)	+/-16 ppb / +/-50 ppb	—	Call initiation	Call interference, dropped calls
LTE/5G NR (TDD)	+/-16ppb / +/-50 ppb	+/-1500 ns (absolute)	Time slot alignment	Packet loss/collisions, spectral efficiency
Intra-band non-contiguous CA FR2 Intra-band contiguous CA FR1	+/-16 ppb / +/-50 ppb	260 ns (relative)	Coordination of signals to and from eNBs	Poor signal quality at cell edge, lower data speeds
Intra-band contiguous carrier aggregation FR2	+/-16 ppb / +/-50 ppb	130 ns (relative)	Coordination of signals to avoid overlapping of blocks	Network outages, poor performance, high interference

Besides the coordinated RAN features, there are other applications, features and new architectures that require highly accurate synchronization. Each additional nanosecond of time error impacts performance.

E-911 positioning

Wireless devices receive positioning reference signals (PRSs) from multiple sites to help improve horizontal positioning accuracy with the Observed Time Difference of Arrival (OTDOA). To take advantage of the high detection capability of the PRS, the network needs to be synchronized to LTE/NR frame boundaries, and the PRS instances for all eNBs/gNBs on one frequency layer need to be aligned in time.

In the US, roughly two-thirds of all E-911 calls originate from wireless devices. Federal Communications Commission (FCC) guidelines specify that E-911 handset-based positioning methods must be able to identify a wireless device's location with a horizontal accuracy within 50 meters for 80 percent of emergency calls and a vertical accuracy within 3 meters (using barometric sensors within the wireless device) for 80 percent of indoor E-911 calls. Achieving accuracy within 50 meters requires less than 150 ns of total time error since each nanosecond of time error equates to approximately 0.3 meters of error in horizontal position. This means that any eNBs/gNBs that participate in OTDOA should be synchronized to within at least 100 ns of accuracy. For network-based synchronization, this imposes tight accuracy requirements on the nodes that participate in the synchronization distribution.

Teleprotection

The modern power grid has evolved into a smart grid where the power and systems are more dynamic and interconnected than ever before. An event such as a failure in one part of the network can impact the entire grid. Having accurate time information associated with the performance of devices in the grid can help power utilities gain a better understanding of power system operation and predict or prevent faults to improve overall system reliability. Therefore, devices in power utility networks must adapt to support accurate time stamping to maintain the stability of the grid. A highly accurate time reference is useful in fault analysis because the location of faults can be found by analyzing timestamped measurement values such as precise voltage measurements. As specified in the IEEE Std C37.238-2017 power system profile, there are time accuracy needs of less than 1µs for equipment across the network in support of protection relays, phase measurement units and intelligent electronic devices.

Factors that impact synchronization accuracy requirements

In traditional distributed RAN (D-RAN) deployments, CPRI-based radios are connected directly to the baseband unit at the cell site. This local, symmetrical point-to-point fiber link contributes relatively little time alignment error. The CPRI protocol, which carries the synchronization data intrinsically, assumes no asymmetric delay variation. However, in 5G centralized RAN, or C-RAN, architectures, the baseband functionality is located further away at edge/hub locations, which can lead to the introduction of incremental time error. In such architectures, there are several synchronization-related implications, as described in the following sections.

Longer sync chains

The disaggregation of the RAN functions (RU, DU and CU) and the move beyond simple point-to-point connections towards rings and mesh connectivity can increase the number of nodes that time-sensitive traffic must traverse. The location of the grandmaster (GM) clock depends on the time error requirement of the feature or application being implemented and the PTP accuracy of the GM and telecom boundary/slave clocks(T-BC/T-TSC. When using network-based timing, it is important to consider the time alignment error (TAE) limit and factor in the number of nodes traversed between the radio unit (RU) and the distributed unit (DU) in determining where to place the GM or primary reference telecom clock (PRTC).

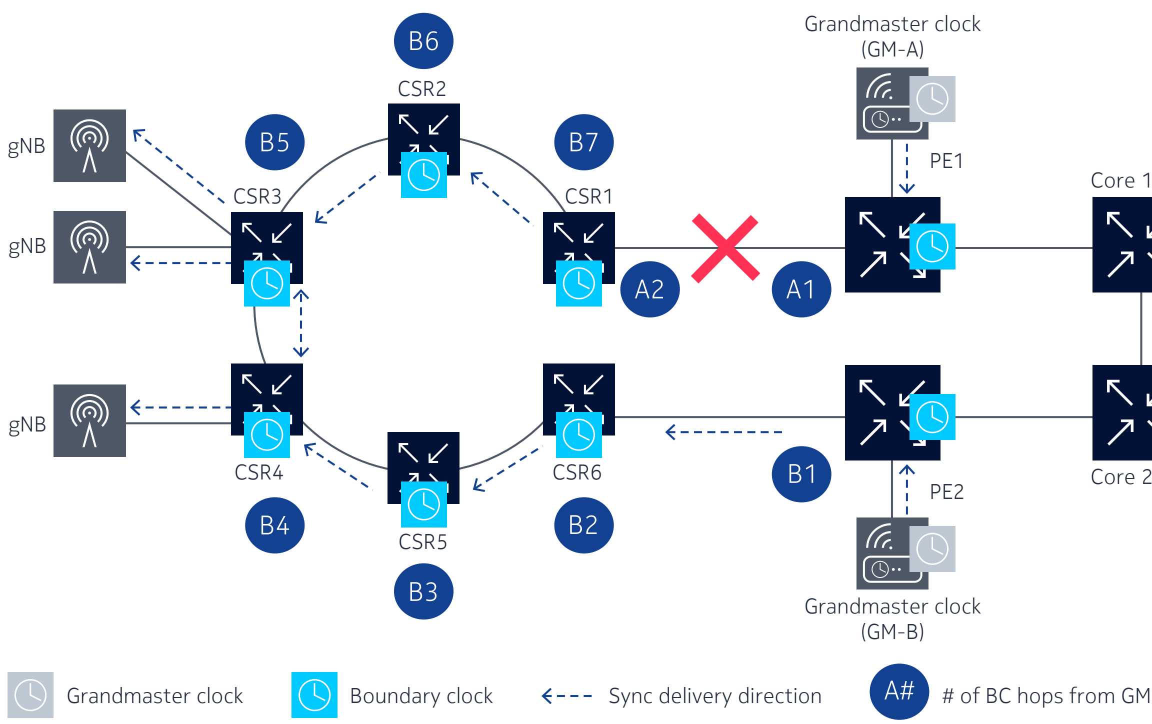
To support all RAN applications, including strictly coordinated RAN features that dictate a 130 ns time error, the IEEE 802.1CM/CMde TSN for fronthaul standard stipulates using Class C T-BCs for all transport nodes that participate in the synchronization chain. Class C T-BCs provide highly accurate synchronization, with each node conforming to a +/-10 ns constant time error (cTE) and 30 ns maximum absolute time error (max|TE|). For very long chains of more than 20 nodes, Class D T-BCs may be required.

Dynamic paths (protection switching)

As new 5G applications drive increases in bandwidth demand, cell site client interfaces are increasing to 10 GbE/25 GbE rates, with network-facing links increasing to 100 GbE to maximize fiber efficiency. These high-speed links must be protected because they carry much more traffic and their failure would greatly impact the network.

Dynamic protection mechanisms such as Ethernet Ring Protection or IP/MPLS Fast Reroute can result in alternate paths for the sync flow, which can impact the number of nodes and asymmetry experienced by the network, and therefore impact sync performance. For example, as shown in Figure 1, the cell site router (CSR1) is only two hops away from the GM clock (GM-A) during normal operation. During failover, the number of hops increases to seven because the sync source now comes from the backup GM clock (GM-B). In such a scenario, a Class B T-BC may not provide enough accuracy to remain within the maximum time error limit.

Figure 1. Dynamic paths from protection switching



The dynamic paths can also be the result of a dynamic path computation element that dictates the route paths or transport slices in accordance with service-level parameters and real-time resources based on network telemetry.

Radio over Ethernet (RoE)

The IEEE 1914.3-2018 RoE standard is used to map CPRI traffic over Ethernet frames for transport over packet fronthaul networks. Ensuring proper RoE operation requires highly accurate synchronization, which means phase/time and frequency synchronization must be tightly controlled. Transport nodes that implement IEEE 1914.3 RoE use a differential timing method, which requires that a common time reference be distributed to both RoE endpoints, and that the endpoints must be in the same time domain with aligned time bases. The common reference time is used to recover the RoE service presentation time on the far-end RoE endpoint. This ensures that the presentation time embedded within the RoE frames is aligned with the time at which the RAN expects the CPRI frames.

The level of accuracy required for RoE will be impacted by the introduction of time error arising from a combination of link delays, radio processing, fiber asymmetries and round-trip delays. When supporting applications such as intra-band contiguous CA with a strict TAE limit of 130 ns, these delays can consume a large portion of the 130 ns budget and potentially leave a mere 30 ns for any additional processing. This means that as RoE nodes are introduced, the incremental time error introduced by the RoE nodes that perform the mapping/demapping functions must be within the 30 ns time budget to meet the TAE limit. Therefore, to leave a margin of error for the RAN elements (RU/DU), it is mandatory that Class C T-BCs or better be employed.

Any-to-any connectivity

5G brings the need for enhanced any-to-any connectivity because it distributes the user plane function further into the network, where connectivity to these functions will be needed. In some cases, local switching or routing may be required to access the internet and other services, or to provide a simultaneous connection to multiple gateways. For example, by distributing layer 3 IP connectivity to these aggregation nodes or to the cell sites, service-aware connectivity can be provided using layer 2 or layer 3 VPNs. This leads to stricter nodal requirements.

High-precision timing with enhanced telecom boundary clocks

The ITU-T has defined new, enhanced clocks to meet the stringent synchronization requirements of disaggregated 5G networks, as shown in Figure 2. T-BCs allow accurate distribution of timing in the network. A T-BC recovers time information from the PTP messages that it receives from an upstream node and uses this information to update its internal time counters. It then generates new PTP messages to provide timing information to downstream nodes. In doing so, the T-BCs minimize the resulting delays that occur in the packet network between the GM and PTP clients, thereby recovering the time information with the highest accuracy. T-BCs incorporated into transport equipment enable timing distribution across the synchronization trail.

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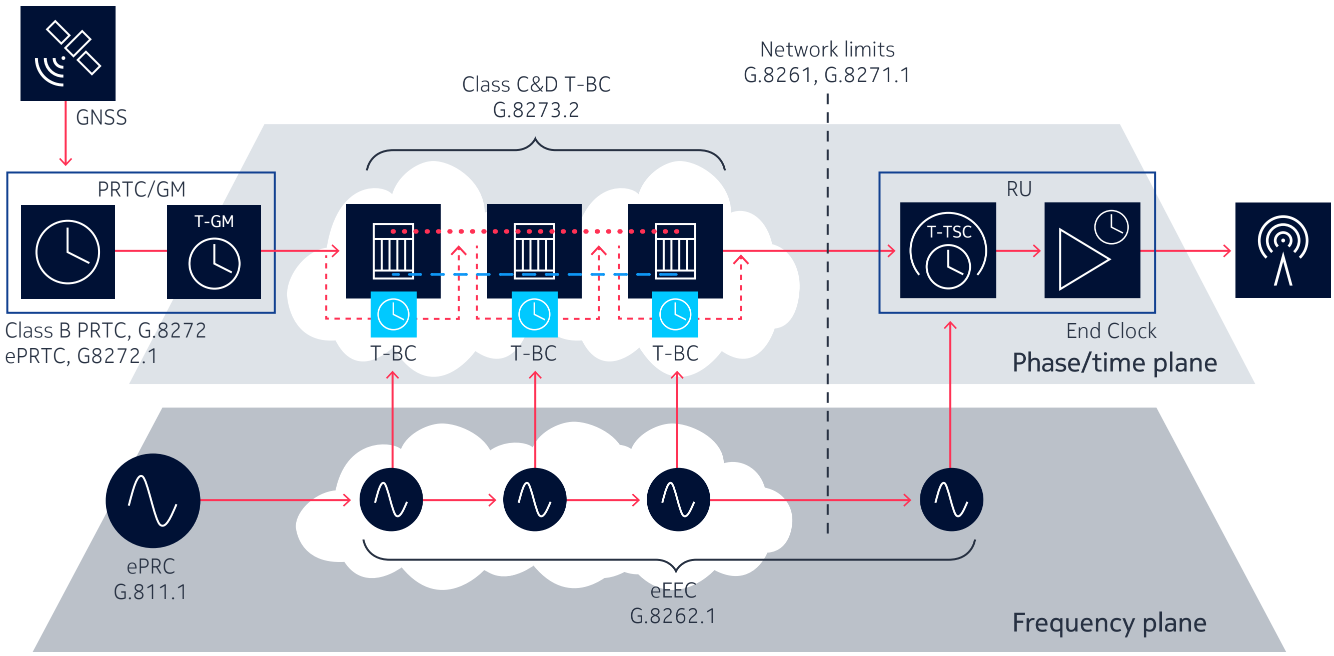
Figure 2. Enhanced clock specifications for the frequency and phase/time planes



The ITU-T released a revision of its recommendation on the timing characteristics of T-BCs and time slave clocks (G.8273.2), which describes the performance standards for boundary clocks in the network. The revision added two new high-accuracy clocks, Classes C and D[1], to the original Classes A and B. These new clocks are intended for use within fronthaul networks, where the synchronization requirements are the most stringent.

New ITU-T eEEC standards (G.8262.1) define performance requirements for new synchronous equipment clocks. The improvement of frequency synchronization is vital because it helps to syntonize the network and leads to more accurate phase/time synchronization. The IEEE 802.1CMde-2020 standard specifies use of T-BCs assisted by eEEC instead of EEC because the fronthaul network needs higher performance in terms of PTP accuracy than that needed by backhaul networks.

The role of eEEC in enhancing phase/time synchronization accuracy

Telecom networks use a hybrid model whereby SyncE assists PTP in generating more accurate timing. SyncE adds physical-layer clock distribution and synchronization to Ethernet. This physical layer frequency (after eEEC frequency filtering) is inputted to the PTP time clock, where it serves as the stable reference frequency. This stable reference frequency is traceable to the primary reference clock (PRC) and is critical for maintaining PTP accuracy. In SyncE networks, the various slave clocks are locked to the frequency of the PRC, where they recover the clock from the incoming physical layer signal. However, there are high-frequency variations (jitter) and low-frequency variations (wander) caused by network device processing, temperature changes and other factors that can impact the timing signal quality. Therefore, jitter and wander should be minimized in network devices that process clock signals to avoid mistiming the transmitted signal and impacting the distribution of the clock reference across the network.

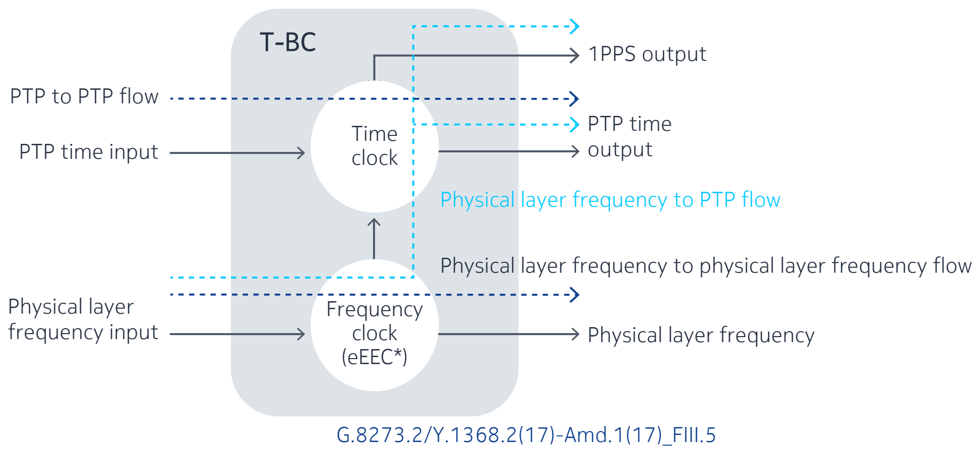
In support of packet-based network synchronization, the boundary clock and transparent clock functions are defined within the IEEE 1588v2 PTP protocol. Use of these clocks avoids the accumulation of packet delay variations (PDVs) that would impact the PTP messages as they transit non-PTP routers and switches.

1 Class D clocks are for further study; only Class C is fully specified.

The PTP protocol is designed to interwork with existing frequency synchronization mechanisms such as EEC or eEEC, where the nodes supporting this functionality operate in a “SyncE assist” mode to improve PTP performance. To meet the stringent timing requirements of fronthaul and other applications, the packet transport networks can use Class C T-BCs, as recommended by the IEEE 802.1CM/CMde TSN for fronthaul specification. These Class C (and Class D) clocks make use of eEEC (instead of EEC) for higher synchronization accuracy. The new eEEC specification of ITU-T G.8262.1 is about five times more stringent than the existing EEC specification of ITU-T G.8262.

Figure 3 shows a simplified model of a T-BC as described in the ITU-T G.8273.2 specification. T-BCs consist of a frequency clock (eEEC in this example) that is locked to the physical layer frequency input and a time clock that is locked to the PTP time input. The T-BC has three primary timing flows for which noise transfer specifications are given: 1) PTP time input to PTP phase/time outputs; 2) physical layer frequency input to physical layer frequency output; and 3) physical layer frequency input to PTP phase/time outputs.

Figure 3. Simplified model showing signal flows through a telecom boundary clock



* Note: EEC for class A/B and eEEC for class C/D

During normal operation, the transport nodes that serve as T-BCs will operate in locked mode, where the distributed synchronization is locked to one of the incoming frequencies. However, during a loss of the incoming frequency signal, the transport nodes will operate in holdover mode using a local oscillator (OCXO) capable of maintaining the frequency with high stability.

Benefits of eEEC

In packet-based networks, eEEC delivers much better performance than EEC. The main points of differentiation are summarized in Figure 4 and include:

- **Better frequency synchronization performance:** eEEC has stricter clock frequency performance requirements for jitter and wander and improves clock stability. The maximum time interval error (MTIE) for wander generation [for τ (s) @ 0.1 s observation interval] is 7 ns for eEEC versus 40 ns for EEC which is a roughly five-fold increase in performance. It improves synchronization accuracy by reducing the time error.
- **Better phase/time synchronization performance for SyncE-assisted PTP:** SyncE aids in minimizing the phase/time error for PTP to reach Class C. It provides a physical layer source that enables frequency alignment. By improving on the noise generation, transient and holdover performance of EEC, it improves the time noise generation, transfer and time holdover of SyncE-assisted T-BCs.

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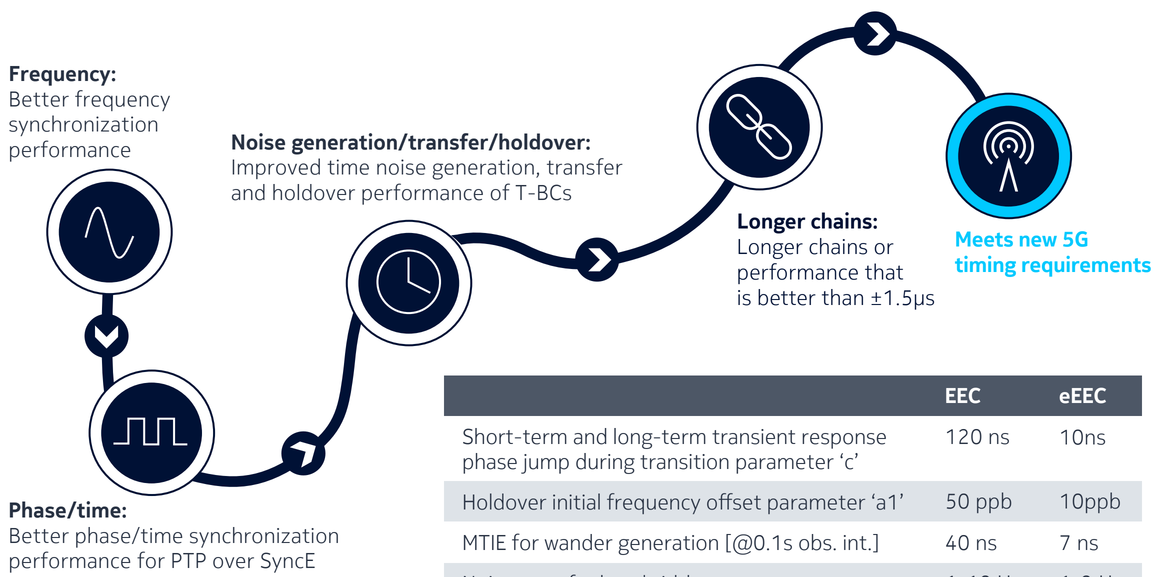
- **Improved time noise generation, transfer and holdover of T-BCs**
  - **Noise generation:** The noise generation of a T-BC is an amount of noise (time error) produced at the output of the T-BC assuming the ideal input reference signal. T-BCs are divided into classes based on maximum absolute time error. Class C T-BCs have a maximum absolute time error of 30 ns.
  - **Noise transfer bandwidth:** Class C and D clocks contain an eEEC instead of an ordinary EEC. eEEC enables a noise transfer bandwidth of 1–3 Hz versus 1–10 Hz for EEC. This affects the noise transfer from SyncE to PTP for the T-BC. SyncE input is low-pass filtered by eEEC, which removes the high-frequency noise before passing the low-frequency input to downstream nodes.
  - **Improved holdover:** The permissible phase error for an enhanced equipment clock under holdover operation at constant temperature is reduced for eEEC. Short-term and long-term transient response phase jump during transition parameter ‘c’ is 10 ns for eEEC versus 120 ns for EEC. In addition, the holdover initial frequency offset parameter ‘a1’ is 10 ppb for eEEC versus 50 ppb for EEC.
- **Longer chain or performance that is better than +/-1.5 µs performance:** Because of the increased synchronization accuracy possible with enhanced SyncE-assisted T-BC clocks, each Class C node conforms to a +/-10 ns cTE and 30 ns max|TE| time error. This enables longer chains and more robust architectures with support for transport path diversity. The improved synchronization performance goes well beyond the +/-1.5 µs needed for TDD applications. It also meets the accuracy demands of coordinated RAN applications that have relative timing error accuracy requirements within 130 ns.

Figure 4. Performance improvements in moving from EEC to eEEC



	EEC	eEEC
Short-term and long-term transient response phase jump during transition parameter ‘c’	120 ns	10ns
Holdover initial frequency offset parameter ‘a1’	50 ppb	10ppb
MTIE for wander generation [@0.1s obs. int.]	40 ns	7 ns
Noise transfer bandwidth	1-10 Hz	1-3 Hz

PTP profiles (full timing support versus partial timing support)

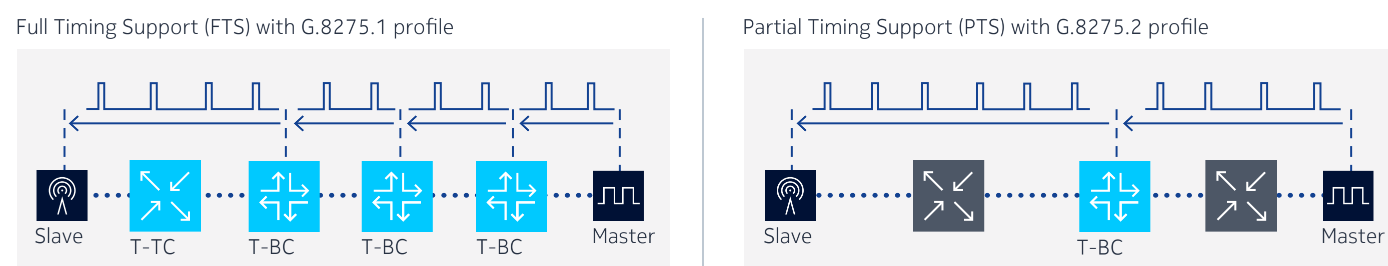
The IEEE 1588v2 PTP protocol allows other standards bodies to define PTP profiles. These profiles can define options and attributes of the PTP protocol to support specific applications, meet the performance demands of the applications and foster interoperability. To this end, the ITU-T has defined a telecom PTP profile with full timing support:

- ITU-T Recommendation G.8275.1: This PTP profile for phase/time synchronization uses full timing support from the network whereby each transport node that participates in the synchronization chain must be PTP aware. This means that each node (router or switch) performs as a T-BC that receives timing from the GM, which it uses to update its local clock. Each T-BC node, in turn, acts as a PTP master for downstream nodes to deliver accurate phase/time synchronization to the end application. This profile also allows for the use of transparent clocks (T-TCs), which update the PTP messages with their transit times across the T-TC to remove uncertainty and allow accurate time recovery. In PTP over Ethernet networks, all PTP messages are exchanged between the PTP master and PTP slave using Ethernet encapsulation and Ethernet multicast addressing. In this profile, the use of SyncE is mandatory to assist in locking T-BC and T-TC nodes to a stable frequency. In the case of Class C or D T-BCs and T-TCs, eEEC is used to meet the need for higher accuracy. This PTP profile is recommended for greenfield deployment scenarios or where new hardware is needed to support capacity upgrades – for example, for new 5G deployments, teleprotection, industrial automation and other time-sensitive applications – because it provides the most accurate timing.

Recognizing that many networks do not have PTP-aware nodes and operators do not want to replace all their equipment with PTP-aware equipment, the ITU-T has defined a telecom PTP profile with partial timing support that can operate over existing networks:

- ITU-T Recommendation G.8275.2: This PTP profile for phase/time synchronization uses partial timing support from the network. It permits the use of T-BCs or T-TCs but does not require them. Using this profile, T-BCs can be placed at strategic intermediate locations to reduce noise as the timing signal passes through the network. The profile operates over existing switches and routers using unicast IP. This makes upgrades easier than having to rip and replace all nodes that lack PTP awareness. However, partial on-path timing support is usually found in older networks and only targets the "coarse" accuracy of ±1.5 µs. Due to limitations in synchronization accuracy that arise from this profile, it is not recommended for use with time-sensitive applications, including new 5G wireless applications.

Figure 5. Full on-path timing support versus partial on-path timing support



- All intermediate nodes on PTP path operate as boundary clocks or transparent clocks
- PTP/Ethernet with Ethernet multicast mode
- Only profile agreed for packet fronthaul (IEEE 802.1CM)

- Some or none of the intermediate nodes on PTP traffic path operate as boundary clocks
- PTP/UDP/IP/Eth with IP unicast mode
- Two modes: PTS and assisted partial timing support (APTS)

Nokia IP Anyhaul synchronization blueprint

Nokia IP routers and Ethernet switches support SyncE and the IEEE 1588v2 PTP to distribute highly accurate frequency and phase/time synchronization in support of time-sensitive applications. For mobile transport, they deliver clock distribution with full timing support (Figure 6). This includes supporting multiple classes of T-BCs along the path as defined by ITU-T G.8273.2. For fronthaul-connected sites, they support enhanced Class C T-BCs to keep the relative phase/time error to a minimum. In the backhaul or midhaul segments, where the overall absolute timing error budget is more relaxed, they support Class B T-BCs.

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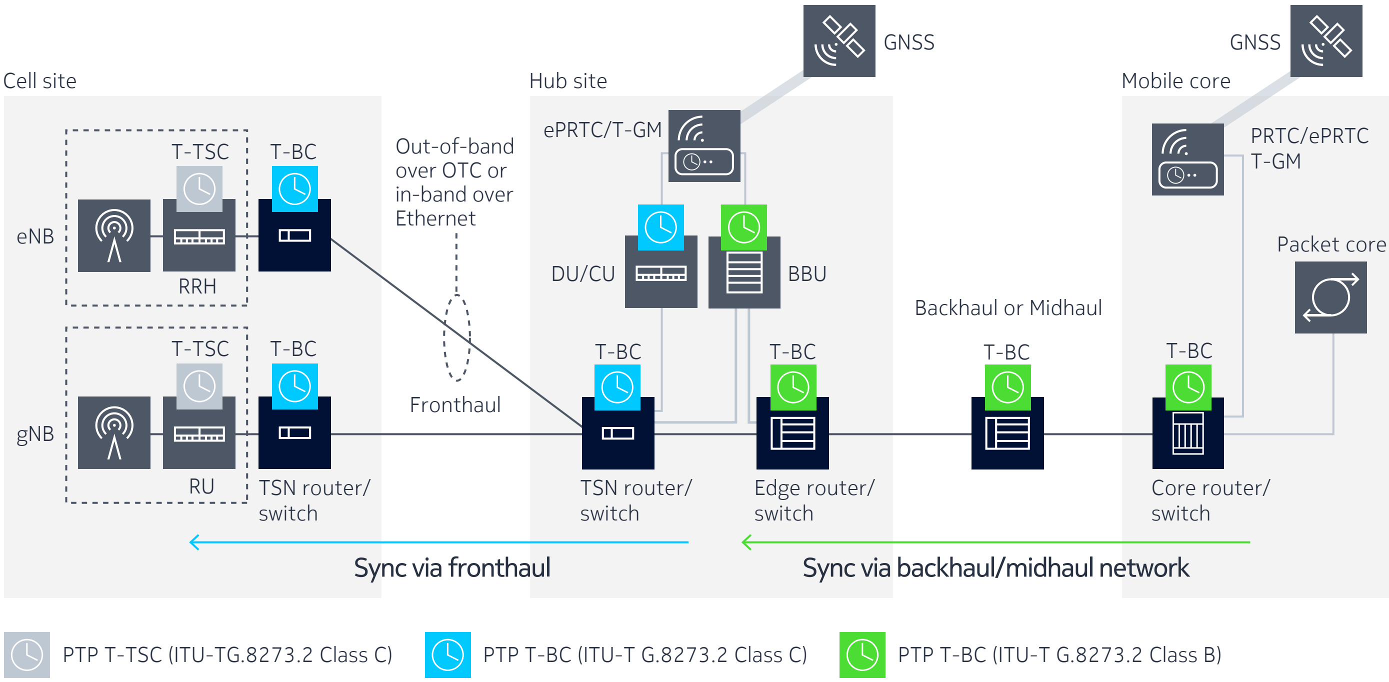
Figure 6. Nokia IP Anyhaul clock distribution with full timing support



The Nokia IP Anyhaul solution addresses synchronization through the following elements:

- 7250 Interconnect Router (IXR): This family of IP/MPLS/Ethernet service platforms is purpose-built for access and aggregation in mobile anyhaul, fixed–mobile convergence and mission-critical enterprise applications. The family includes 7250 IXR-e series cell site routers, which support eEEC and Class C T-BCs for noise generation with GNSS variants that can also serve as a GM or slave clock (T-TSC). This enables operators to use both GNSS and network-based timing as a primary and backup source for resiliency. The family also includes edge/aggregation routers such as those in the 7250 IXR-X series, which deliver multi-terabit-scale interconnectivity and support enhanced Class C T-BC functionality for time-sensitive applications.
- 7210 Service Aggregation Switch (SAS): This family of Ethernet service platforms delivers high-throughput, high-density access and aggregation in support of mobile anyhaul. These platforms provide SyncE and IEEE 1588v2, enabling precise frequency, phase and time distribution along with precise timestamping for enhanced service-level agreement (SLA) reporting and management of services.
- 7750 Service Router (SR): The 7750 SR and SR-s platforms feature high densities of high-speed ports and are well suited for use at the edge and core in mobile anyhaul applications. These platforms support SyncE and IEEE 1588v2, enabling frequency, phase and time distribution.
- Network Services Platform (NSP): The NSP provides common operations and management across the 7x50 and 7210 platforms. As the synchronization manager, it oversees all T-BC peering relationships and provides a synchronization layer topology. Operators can monitor clock status and trace the path between a master clock and all downstream T-TSCs and vice versa, providing key information for synchronization planning and troubleshooting.

Conclusion

Delivering high-quality network synchronization is of paramount importance to the proper operation of 5G networks, particularly for time-sensitive applications, architectures and features that impose strict synchronization accuracy requirements. In these cases, there are standards and telecom profiles that define minimum requirements and methods for the proper distribution of synchronization. Distribution of this timing through packet mobile transport networks must meet or exceed these requirements to optimize the performance of the mobile network, increase the flexibility of the network (e.g., by supporting longer chains or better path diversity) and ultimately deliver a better end-user experience.

A hybrid model where SyncE physical layer frequency is used to assist PTP helps minimize the phase/time error for PTP to reach Class C or better. This enables the packet transport network to meet or exceed the synchronization demands of time-sensitive applications such as those in the fronthaul segment, which have the most stringent requirements.

The Nokia IP Anyhaul solution addresses strict 5G timing requirements by supporting enhanced T-BCs with full on-path timing. Nokia has extensive experience and expertise in addressing synchronization and has deployed PTP in IP/MPLS networks that contain more than 30,000 cell sites. This includes supporting synchronization for anyhaul connectivity in D-RAN and C-CRAN architectures as well as enterprise vertical applications.

Abbreviations

APTS	assisted partial timing support
BBU	baseband unit
CPRI	Common Public Radio Interface
C-RAN	centralized RAN
CSR	cell site router
CU	centralized unit
cTE	constant time error
D-RAN	distributed RAN
DU	distributed unit
EEC	Ethernet equipment clock
eEEC	enhanced Ethernet equipment clock
eCPRI	evolved CPRI
FDD	frequency-division duplexing
FR	frequency range
FTS	full timing support
GE	Gigabit Ethernet
GM	grandmaster

GNSS	Global Navigation Satellite System
IP	Internet Protocol
LTE	Long Term Evolution
MPLS	Multiprotocol Label Switching
MTIE	maximum time interval error
NR	New Radio
OCXO	oven-controlled crystal oscillator
OTDOA	Observed Time Difference of Arrival
PTP	Precision Time Protocol
PRC	primary reference clock
PRTC	primary reference time clock
PRS	Positioning Reference Signal
PTS	partial timing support
RAN	radio access network
RoE	Radio over Ethernet
RU	radio unit
SyncE	Synchronous Ethernet
TAE	time alignment error
T-BC	Telecom Boundary Clock
T-TSC	Telecom Slave Clock
TDD	time-division duplexing
TSN	time-sensitive networking
VPN	virtual private network

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