Infinera

E-BOOK

Synchronization Distribution in 5G Transport Networks

The world is moving to 5G, which offers a wide range of new services beyond the voice and data combination that was the primary service offering in the first four generations of mobile technology. This latest generation of mobile networks will expand service offerings into highly reliable and low-latency services that will potentially revolutionize many areas of industrialization and our day-to-day lives. In order to deliver the higher performance that these new services will require, all aspects of the mobile network will require modernization. This includes the DWDM-based mobile transport network that underpins the end-to-end mobile network.

5G is driving discussion around advances in optical network architecture, such as the move to front/mid/backhaul-based xHaul networks, network slicing, and multi-access edge compute architectures. It is also driving a need to improve performance in many areas of basic transport network performance, such as low latency and synchronization performance. 5G synchronization is a complex topic with many moving parts that all need to come together harmoniously across all aspects of the transport network to provide the right quality synchronization to the cell tower without overengineering the network and driving up cost. This e-book explains the challenges involved in delivering 5G-quality synchronization and the toolbox required to create end-to-end synchronization strategies to meet 5G performance demands now and in the future.

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The Importance of Synchronization in 5G Networks

Network synchronization is a very specialized topic that has seen its relevance to network operators come and go over time as technology trends have changed. In the era of synchronous TDM (SDH and SONET) networks, synchronization was critical, but in recent times the availability of “good enough” synchronization for Ethernet-based transport has pushed the topic to more of a niche in many network operators’ networks. The need for a step change in synchronization performance in 5G networks is reversing this trend, bringing synchronization back into the top group of challenges that need to be addressed within transport networks.

The new Phase 2 5G services, especially ultra-reliable low-latency communications (uRLLC) services, will drive significant changes into overall mobile network architecture, as well as into the mobile transport network that connects the cell tower to core processing resources. These architectural changes include lower latency through multi-access edge compute (MEC), new network slicing capabilities, and better synchronization performance to support new 5G RAN functionality like carrier aggregation (CA) and previous 4G/LTE-A functionality that is now being rolled out in 4G/5G networks, such as coordinated multipoint (CoMP).

This e-book intends to give an overview of synchronization distribution and of Infinera’s approach to this challenging environment. It is split into two major sections to enable readers to quickly navigate to the most relevant sections, or the complete e-book can be read sequentially if preferred. The first section covers the background to network synchronization in mobile networks, why synchronization is needed, and how it works. The second section outlines Infinera’s end-to-end Sync Distribution Solution and the benefits that the breadth and enhanced performance capabilities of this synchronization distribution solution are bringing to mobile operators across the globe as they build out 5G networks.

SECTION 1

Understanding Synchronization and Synchronization Distribution

Synchronization Basics

There are many reasons that a network might require some form of synchronization within its capabilities, either to support its underlying transport mechanisms or because the end service or end devices require some form of timestamping or tight coordination with other locations within the network. From an underlying transport mechanism perspective, Synchronous Digital Hierarchy (SDH) and Synchronous Optical Networking (SONET) are excellent examples of networking protocols that rely on all the nodes in the network being synchronized so that specific timeslots in the data stream can be accessed without the need to completely demultiplex the data stream at each node. Examples of applications/devices that require synchronization include financial trading applications that require accurate timestamping of financial transactions, electrical power distribution management where synchronization is needed for some power line failure management systems, TDM circuit emulation applications, and of course mobile networks.

In the simplest form, mobile networks require good synchronization in the radio access network (RAN) to ensure that devices can connect seamlessly to the cell tower and to enable smooth handover from one cell to another without the user or connected device noticing any drop or interference in the connection performance. All cell sites require good synchronization back to a centralized primary reference time clock (PRTC) so that essentially all the RAN portions of the network are in synchronization with each other, as shown in Figure 1.

Depending on the synchronization capabilities that are required, there are three main components to network synchronization that can be implemented in the network:

- **Frequency synchronization** – ensuring the frequency of the local clock in the cell site is the same as that of the PRTC, so that the time interval between timing pulses is exactly the same but the timing signals do not necessarily occur at exactly the same time
- **Phase synchronization** – ensuring that the timing pulses occur at exactly the same time
- **Time of day** – synchronization messages that have the ability to contain information and include the exact time of the clock signal

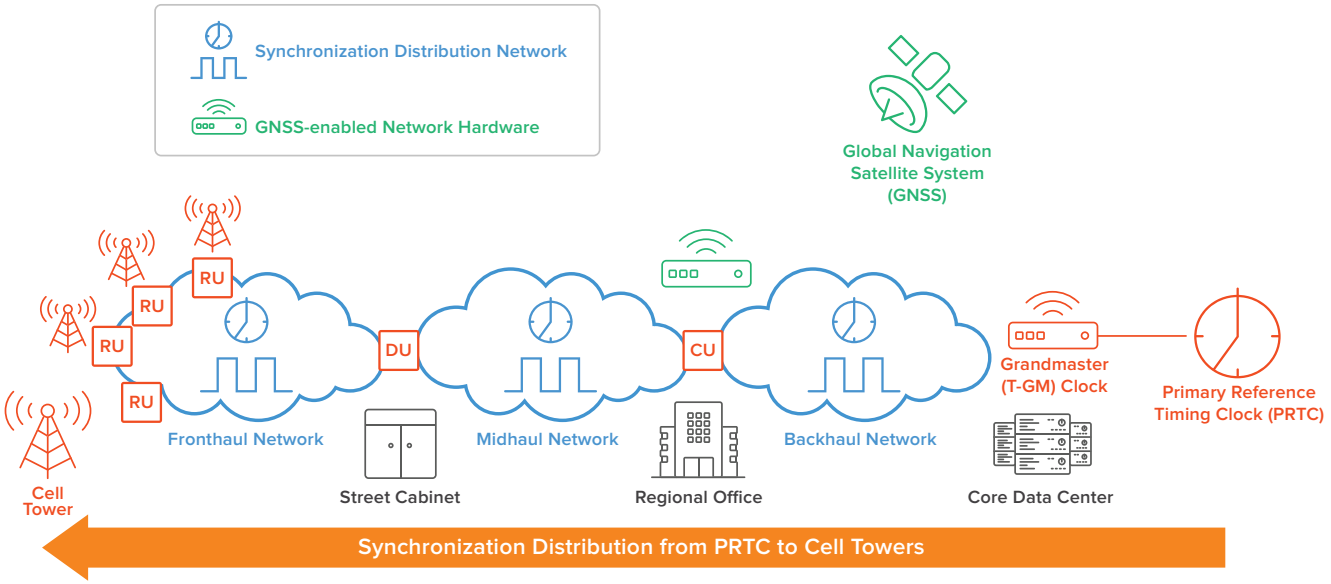


Figure 1: Simplified synchronization network

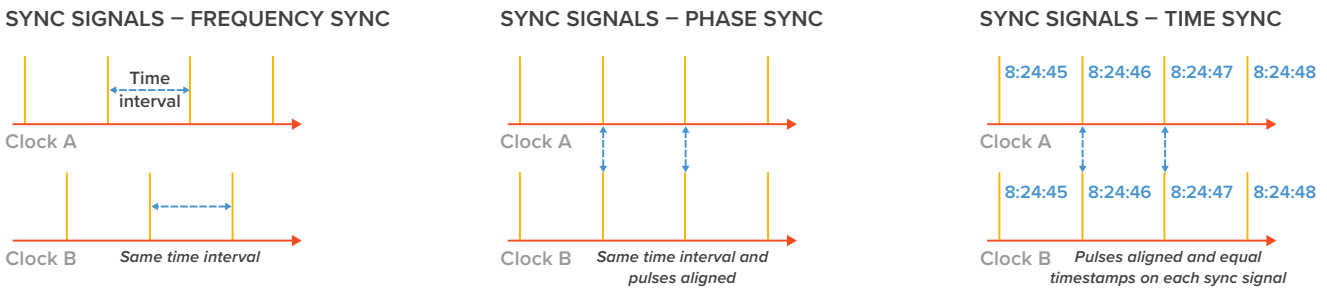


Figure 2: The three basic components of network synchronization

Evolution of Synchronization Requirements

2G, 3G, and initial releases of 4G all use frequency-division duplex (FDD) as the underlying transmission within the RAN. FDD uses two separate frequencies for upstream and downstream communication, and these networks require tight frequency synchronization to ensure the correct frequencies are used and that these frequencies can be tightly packed to achieve efficient use of the available spectrum. Tight alignment to the planned frequencies for a cell also ensures that regulatory commitments are met in terms of spectrum licenses and enables smooth handover of calls to adjacent cells.

Frequency synchronization quality is represented by a measurement of the difference in frequency between the actual and desired frequencies and is represented as a figure showing the difference in parts per billion (ppb). Mobile networks are specified to require 50 ppb at the air interface of the RAN, and to ensure this requirement is met, the backhaul interface from the 4G baseband unit (BBU) back to the transport network is 16 ppb.

As networks move to more advanced 4G Long-Term Evolution (LTE) and 5G mobile networks with more complex functionality in the RAN, such as CoMP, multiple-input multiple-output (MIMO) antennas, and higher frequencies above 2 GHz, the underlying RAN mechanism has to migrate from FDD to time-division duplex (TDD). TDD uses the same frequency for both upstream and downstream communications with specific timeslots allocated to each, as shown in Figure 3. To enable the cell site (4G BBU or 5G distributed unit [DU]) and the devices connected to the RAN to correctly transmit and receive at the right time, networks need to maintain the same frequency synchronization performance that was required in the FDD domain and add phase and time synchronization, as outlined earlier in Figure 2.

Phase synchronization quality is measured by the time difference between the timing signals and is typically represented in microseconds (µs) or even nanoseconds (ns). Initial use of TDD in 4G LTE networks drove a requirement for phase synchronization accuracy of 1.5 µs. As will be discussed in the following sections, 5G has tightened this requirement, especially for the relative difference between adjacent cell sites, where it can be as low as just 60 ns.

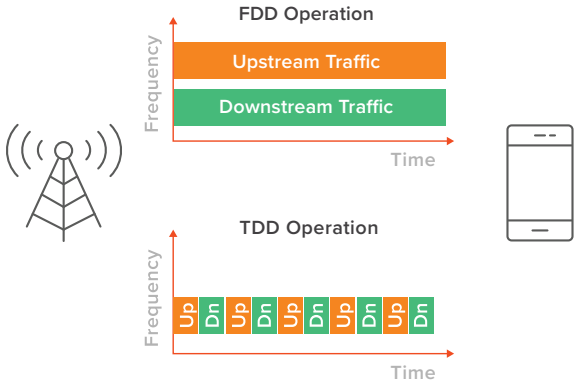


Figure 3: FDD and TDD operation

TDD operation should not be confused with dynamic spectrum sharing (DSS), where a frequency band within the spectrum is simultaneously shared between 4G and 5G radios. DSS operates with differing timeslots that are allocated in increments of 1 millisecond (ms). During a timeslot, the appropriate 4G or 5G RAN technology is used for the defined period of time before stopping to allow the alternative RAN technology to take over for its timeslot.

Synchronization Delivery Mechanisms

The delivery of synchronization information in mobile networks is achievable through several different mechanisms and strategies. The uptake of these various options has varied across the geographic regions of the globe due to technical and geopolitical reasons. The main synchronization delivery options are:

- Synchronization/timing signals from a global navigation satellite system (GNSS), such as the U.S.'s Global Positioning System (GPS), Europe's Galileo, Russia's Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS), or China's BeiDou Navigation Satellite System, directly to every location requiring synchronization in the network
- Synchronization/timing signals delivered from key centralized GNSS-enabled locations in the network through the backhaul/transport network to all other locations requiring synchronization
- Synchronization/timing signals delivered through a totally separate synchronization delivery network

Each approach has its own strengths and weaknesses, and operators across the globe have built synchronization strategies to best suit their own environments. For example, historically GNSS using GPS to every location has been the primary mechanism in North America, whereas Europe predominantly uses synchronization through the backhaul network with GNSS limited to key timing locations.

However, in recent years there has been an increase in the incidence of both deliberate and inadvertent hacking and jamming of GNSS as the use of cheap illegal GNSS jammers has increased and as some countries have even tested GNSS jamming and/or spoofing as part of military strategies. Due to the importance of network synchronization, these factors are leading some countries to introduce legislation to force protection and reliability into synchronization networks. It is possible to protect GNSS receivers from some of this jamming, but this greatly increases the cost per node.

Another consideration that mobile network operators must take into account as they move to 5G is the proliferation of cell sites, especially those in locations that are tough to reach from a GNSS perspective.

5G in dense urban environments will require millimeter-wave small cells that provide high-bandwidth connectivity over a shorter range, and operators are planning deployments of these in those tough-to-reach locations such as deep inside shopping malls, cells per floor in high-rise office buildings, etc.

It should be stressed that while GNSS networks do occasionally suffer from interference and downtime caused by natural effects or deliberate jamming/spoofing, they are still highly reliable and form a key component of most synchronization networks. There are solutions to protect GNSS and deliver GNSS signals into tough locations, but overall, these factors are causing more and more operators that were previously GNSS-focused to plan to utilize network-based synchronization as a backup to GNSS at every node. In some cases, these operators plan to migrate fully to network-based synchronization, with GNSS limited to key centralized locations in the network that use these protection and resiliency methods to harden GNSS against attacks.

Network-based synchronization can take the form of either synchronization delivery through the transport network or through a totally separate dedicated synchronization delivery network. Both approaches provide the operator with the right level of synchronization performance, and backhaul network-based synchronization offers the opportunity for significantly better overall network economics as it avoids a complete overlay network for synchronization. Wherever possible, mobile network operators typically utilize backhaul-based synchronization delivery, but it should be noted that this is not always possible, and therefore, synchronization overlay networks cannot be discounted from the discussion.

Overall, there will always be a mix of strategies deployed across the globe, but the trend is moving more and more toward network-based synchronization delivery, and due to better economics, the option to transport this over the backhaul network is nearly always the primary option.

The rest of this e-book will primarily focus on network-based synchronization delivery approaches and will consider how best to deliver synchronization over mobile transport optical networks.

Frequency Synchronization Standards

When network-based synchronization is used, there is a requirement to deliver the synchronization clock frequency from the centralized PRTC clock to the BBU with less than 16 ppb, as outlined previously. When this is delivered through modern Ethernet-based networks, multiple standards exist to ensure the required level of performance is achieved:

- **Synchronous Ethernet (SyncE)** – A collection of specifications (ITU-T: G.8261, G.8262, and G.8264) together specify the architecture, wander performance, clock performance, and synchronization signaling messages of an Ethernet-based network synchronization method that is comparable to synchronization of SDH and SONET networks.
- **G.8262.1 enhanced Ethernet equipment clock (eEEC)** – Within SyncE, the G.8262 specification covered clock performance, and this has been enhanced to support more demanding 5G specifications in G.8262.1. Often 5G-quality SyncE is referred to by either G.8262.1 or eEEC.

Standard Ethernet does not have any built-in network-level synchronization capability or synchronization signaling mechanism. Ethernet devices include a free-running oscillator for local use with a specified clock accuracy of within ±100 parts per million (ppm). Synchronization is used on each link on a hop-by-hop basis, but it is never passed from one link to the next to create a broader network-level synchronization chain.

The additional SyncE and eEEC frequency synchronization specifications use the physical layer transmission of Ethernet frames to deliver synchronization, add the necessary mechanisms to transfer an input frequency to output ports, and add the necessary synchronization status messages to ensure traceability of the synchronization source. Overall, this creates a network-wide SyncE/eEEC synchronization domain. To ensure that the network can deliver SyncE-compliant frequency synchronization, any device in the optical network path between the clock source and destination must support SyncE/eEEC compliance or be totally transparent to synchronization. In addition to the mechanisms to deliver synchronization, SyncE devices also include an upgraded local oscillator capable of free running at a much tighter specification of 4.6 ppm to improve performance. However, in normal operation, a SyncE device will operate in locked mode, where the distributed synchronization is locked to one of the incoming frequencies. In this mode, accuracy improves again to ±1 ppb, so around 100,000 times better than the original Ethernet clock. Furthermore, if a SyncE device loses incoming synchronization and goes into holdover mode, then the SyncE specifications only allow for the clock to drift by 0.01 ppm per day, meaning this is still 10,000 times better than a standard Ethernet clock after one day. eEEC tightens the clock frequency specification in areas such as jitter and wander performance and ensures the device is never in free running mode with lower clock stability.

Generally speaking, all IP routers and Layer 2 Ethernet switches in the network will need SyncE/eEEC compliance and any Layer 1 DWDM transponders or muxponders must be transparent to synchronization, i.e., they must ensure that any synchronization clocks on a client input are replicated exactly on the corresponding far-end output. Typically, network-level testing is also required to ensure a particular network provides the right level of frequency synchronization performance.

Phase Synchronization Standards

Standardization becomes much more complex as networks move into phase synchronization to support 4G LTE and 5G. As previously mentioned, phase synchronization requires delivery within time budgets for both absolute time error between the PRTC and the cell tower and relative time error between adjacent towers. The main phase synchronization standard is the IEEE's 1588-2008 and 1588-2019, commonly known as 1588v2 and 1588v2.1, specifications for a Precision Time Protocol (PTP) for packet-based networks in a range of applications, including mobile networks within the "Telecoms Profile" definitions of the spec.

1588v2 provides a mechanism for using specific timing packets to deliver frequency information, and by adding very accurate time stamping to the packets, it can also deliver time of day and accurate phase information. 1588v2 is designed to interwork with existing frequency synchronization mechanisms where they exist, such as SyncE or eEEC.

In theory it is possible to build networks with only 1588v2, using the G.8265.1 PTP frequency specification, but the vast majority of modern 1588v2-capable equipment also supports SyncE or eEEC, and most networks today will use a "SyncE assist" mode, which will improve PTP performance to varying levels. IEEE 1588v2 contains a range of standard definitions of differing classes of devices with varying capabilities and performance levels that together can build a synchronization delivery network. The most common of these are:

- Grandmaster (GM), also called a telecom grandmaster (T-GM) in ITU-T specifications – A GM clock is typically located in the core of the mobile network. In the core, the T-GM is typically the PRTC, but in synchronization networks built over different synchronization domains, the T-GM is the master clock at the start of a PTP domain.
- Boundary clock (BC), also called a telecom boundary clock (T-BC) in ITU-T specifications – A device with a built-in PTP clock client and PTP master interconnected with a local clock. This enables a network node (typically a router or Ethernet switch) to synchronize the local clock to the upstream T-GM/T-BC and act as a master to any downstream client clock. Many modern Ethernet switching devices now contain T-BC functionality, whereas earlier implementations often had T-BC capabilities via an external "sync box" that added this capability to the node.
- Transparent clock (TC), also called a telecom transparent clock (T-TC) in ITU-T specifications – A device with the capability to measure any delay created internally within the device by switching or routing functions and correcting the timestamp in outgoing PTP packets to compensate for this internal delay. This gives the effect of reducing the impact of the node on the PTP stream at a lower cost than T-BC capabilities. However, it should be noted that T-TC performance also is significantly lower than that achieved by T-BC devices with a lower level of compensation, issues with longer chains of nodes, and a more restricted range of network architectures than T-BC-enabled networks.
- Time slave clock (TSC), also called a telecom time slave clock (T-TSC) in ITU-T specifications – The end device that receives the clock information, typically a BBU in a 4G LTE network or a DU or RU in a 5G network. Also called a clock client.

To enable 1588v2 to be deployed in telecom networks, the ITU-T has defined a range of specifications that ensure that the mechanism defined in 1588v2 can meet the demanding requirements, especially those of TDD-based mobile networks. These specifications outline the available time error budget, or in other words, the maximum allowed phase error in µs or ns, and how this budget is allocated across the network elements and the performance specifications of specific devices. All these specifications are important, and the most significant of them are as follows:

ITU-T G.8271.1 Network Limits

As previously mentioned, TDD networks, either 4G LTE or 5G, require 1.5 µs maximum time error at the cell site to ensure compliant operation. The maximum absolute time error (MaxITEI) is subdivided into smaller error budgets for differing segments of the network, as shown in Figure 4 for an example 10-hop network.

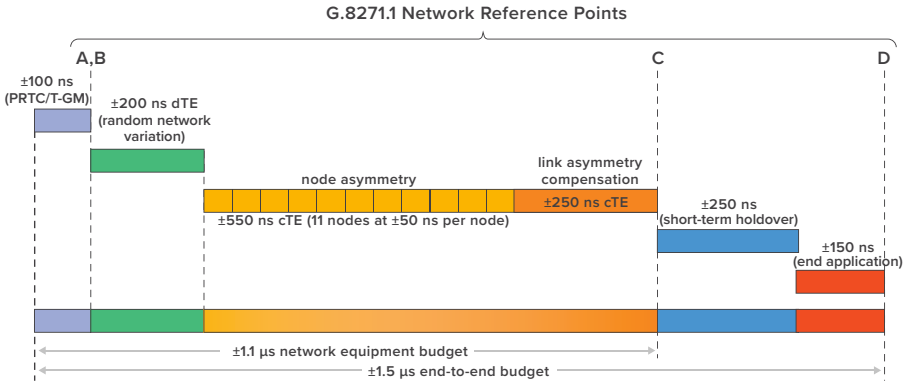


Figure 4: G.8271.1 time error budget and network reference points

This allocation of time error allows for a total of 1,000 ns for the transport network between the T-GM and the T-TSC at the cell site, as shown between reference points B and C in Figure 4. This time error budget is largely taken up by asymmetry in the nodes and the links (fibers). Managing this asymmetry is of paramount importance in building a 5G-quality mobile transport network. The remaining budget includes ±100 ns for the PRTC/T-GM; ±150 ns for the end application, which is essentially the base station in a mobile network; and ±250 ns for short-term holdover in the base station to allow for switching to an alternative PRTC/T-GM in failure scenarios, etc.

The primary reason that asymmetry management is so important is that 1588v2 fundamentally assumes that the network is symmetrical, with exactly the same delay in both directions. Understanding the transit time from the T-GM to the T-TSC is a critical part of 1588v2 operation, and this is determined by measuring then halving the time for a PTP packet to go from the T-GM to the T-TSC and back again. In a totally symmetrical world, this method would give an accurate calculation, but in reality, as we will discuss at length later in the e-book, there are lots of sources of asymmetry in transmission networks that impact this measurement and need to be managed to enable 1588v2 operation in telecom networks. The situation is further complicated as these time/phase errors are not static over time itself. Therefore, the Max|TE| is calculated from understanding both the constant time error (cTE) of a node, link, or network and the corresponding dynamic time error (dTE), as shown in Figure 5.

Time error (TE) at any given time is the sum of cTE and dTE, as shown in green in Figure 5. Max|TE| is the maximum observed absolute value of TE in the network measured from zero, is represented as a time, usually in ns, and is always a positive figure. cTE, shown in orange, is constant time error, which again is represented as a time figure in ns and can be either a positive or negative figure. For network components with a static error, such as optical fiber, cTE is the same at any instance in time. For network components with a more dynamic nature, such as an IP router, then the standards define that cTE is calculated using an average measurement of time error over a 1,000-second period.

dTE is also represented in ns, although as it varies over time, it is usually specified as maximum time interval error (MTIE) over the observation period, as shown in blue in Figure 5. Max(dTE) is the maximum dTE measured from the cTE, and Min(dTE) is the minimum dTE, again measured from the cTE, giving a negative value.

Looking at the mobile transport network, the main consideration in synchronization-friendly network design is managing both the constant and dynamic time errors throughout all network components, paying particular attention to the asymmetry.

The main contributors to time error in optical transport networks can be summarized as follows:

- Fiber asymmetry within the network. DWDM is typically unidirectional, with each fiber being used for transmission in one direction only and a fiber pair being used for a bidirectional transmission channel. Differences in the lengths of the fibers over the route will create a constant time error. Differences occur in outside plant fiber, patch cable length, repair splicing, etc. Each meter of fiber length asymmetry creates 5 ns of additional latency with a corresponding 2.5 ns of cTE. This asymmetry is predominantly static but will change when fibers are repaired following fiber cuts or when patch cables are changed during network maintenance or reconfiguration.

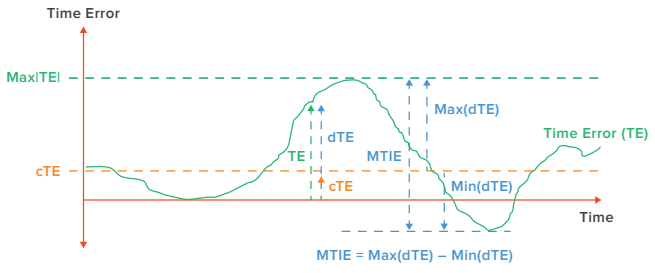


Figure 5: Maximum time error relationship to constant and dynamic time errors

- Dispersion compensation for non-coherent DWDM. Many access networks either are not yet using coherent optics or mix coherent with 10 or 25 Gb/s on/off-keyed optics that require dispersion compensation. Dispersion compensation based on compensating fiber (DCF) is most common and uses lengths of fiber cut to meet a dispersion requirement rather than of constant length. Variable length creates variable cTE issues in synchronization networks. Dispersion compensation modules (DCM) based on fiber Bragg gratings rather than fiber remove this issue, but these are less common in brownfield networks due to the higher cost.
- First-in first-out (FIFO) buffers in coherent optics. DWDM optics operating at 100 Gb/s and above use coherent optics that contain FIFO buffers within the digital signal processor (DSP). These buffers have a random latency/delay upon initial startup, which varies in each optical interface and therefore varies in each direction, creating asymmetry. This creates a random time error that is constant (cTE) over the shorter term but can sometimes be dynamic (dTE) over the longer term if there are restarts on a link due to intentional network maintenance or unintentional network instances such as fiber cuts or power grid failures. These events are not a common occurrence on an individual link in an operational network, but the size of the random cTE that can be created on initial startup and in restarts can be significant.
- DWDM transponders and muxponders based on OTN mapping. OTN mapping chips also utilize FIFO buffers, which have a latency that varies on initial startup and restarts. These deep FIFO buffers are used in OTN mapping to enable the devices to accommodate a wide range of service types and can cause an even larger latency/delay than those in coherent optics. As with the FIFO buffers in coherent optics, the figures here do not vary once the network is up and running, but the size of this error is random across a large range, created on initial startup and every restart, and differs in each direction.
- Time error in IP routers and Ethernet switches. Asymmetry within the router/switch can be created through inaccuracies in timestamping. There are strict T-BC requirements on the specification for these devices for all aspects of time error, which are covered below in the ITU-T G.8273.2 section.

Overall, these elements can be summarized as follows:

Contributor	Fiber	Dispersion Compensation	Coherent Optics	OTN Mapping	IP Routing and Ethernet Switching
Source	Asymmetry in fiber lengths, jumper cables, etc. cTE of 2.5 ns/m.	Random asymmetry in DCF used in each direction.	FIFO buffers in DSP. Varies on restart.	Deep FIFO buffers in OTN mapping. Varies on restart.	Timestamping inaccuracy.
Impact	Large but predominantly static.	Very large but predominantly static.	Varying and random.	Large and random.	Tight requirements to control impact.
Range	Fixed cTE of ±5 to 1,000+ ns.	Fixed cTE of ±5 to 20,000 ns.	Random cTE per device/interface of ±20 to 130 ns on restart.	Random cTE per device/interface of ±20 to 1,000 ns on restart.	Class A/B/C specifications. Max|TE| of 30 to 100 ns. cTE of 10 to 50 ns. dTE (low-pass-filtered) noise generation (MTIE) of 10 to 40 ns.

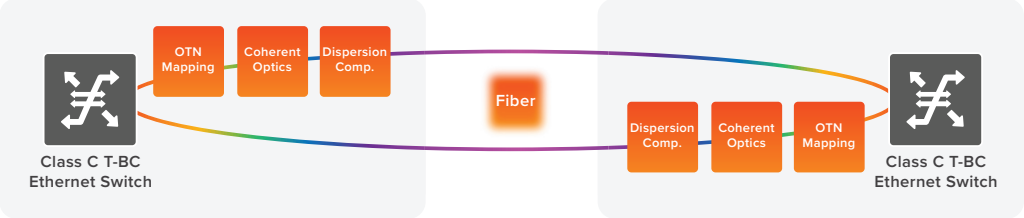


Figure 6: Sources of asymmetry in optical transport networks

Returning to the network limits outlined in G.8271.1 and the allocation within this for node and link asymmetry, it is clear that careful design of the underlying DWDM-based transport network is required. The dTE elements of Max|TE| are largely generated by switching/routing devices that can be managed through the use of G.8273.2-compliant devices. The cTE elements of Max|TE| are either large static figures that can potentially be compensated for within boundary clocks or random elements from coherent optics and OTN mapping. These random cTE elements can be managed through the careful selection of optimized packet optical and DWDM devices with a significantly lower, and more acceptable, level of random cTE, or through optical timing channel techniques that can bypass these elements totally. Without the careful management of dTE and both static and random cTE across the complete end-to-end 5G transport network, these time error limits can be costly and very hard, if not impossible, to achieve.

G.8271.1 defines ±200 ns of dTE for random network variation and ±800 ns of cTE asymmetry error, split between ±550 ns for nodes and ±250 ns for the overall end-to-end link for a Type A network with Class A boundary clocks.

ITU-T G.8273.2 PTP T-BC Classes

G.8273.2 defines the performance of T-BC PTP boundary clocks and defines differing performance classes that devices are required to achieve. Max|TE| and cTE are given in ns as outlined previously. dTE is specified by MTIE figures, as outlined earlier, which are also given in ns. When measuring MTIE, the error is normally low-pass-filtered by the measurement device using the same bandwidth as would be expected to be applied by the next clock in the chain, which is 0.1 hertz (Hz).

The table below compares the G.8273.2 T-BC Classes against various parameters. Due to the more dynamic nature of dTE, multiple parameters are defined in G.8273.2 and multiple measurements are required to classify dTE performance. MTIE, as outlined earlier, is the maximum error measured against the reference clock for the specified time interval. Time deviation (TDEV) is a measurement of the phase stability of a signal over a given period of time. MTIE and TDEV are used together to give a measurement of dTE requirements and performance.

The original G.8273 specification included Class A and B T-BC specifications and G.8273.2 added new Class C and Class D to support tighter 5G requirements, especially to support mobile fronthaul networks. Note that Classes A, B, and C have an unfiltered value for Max|TE|, whereas Class D uses a low-pass-filtered value. Class D also does not contain cTE and dTE specifications as the overall low-pass-filtered Max|TE| of 5 ns is such a tight requirement that any combination of cTE and dTE is permissible as long as the overall Max|TE| specification is met.

Parameter	Conditions	Class A	Class B	Class C	Class D
Max|TE|	Unfiltered 1,000 second measurement	100 ns	70 ns	30 ns	-
Max|TE_L|	0.1 Hz low-pass filter, 1,000 s	-	-	-	5ns
cTE	Averaged over 1,000 s	±50 ns	±20 ns	±10 ns	-
dTE_L MTIE	0.1 Hz low-pass filter, constant temp, 1,000 s	40 ns	40 ns	10 ns	-
	0.1 Hz low-pass filter, variable temp, 10,000 s	40 ns	40 ns	-	-
dTE_L TDEV	0.1 Hz low-pass filter, constant temp, 1,000 s	4 ns	4ns	2 ns	-
dTE_H peak-to-peak	0.1 Hz high-pass filter, constant temp, 1,000 s	70 ns	70 ns	-	-

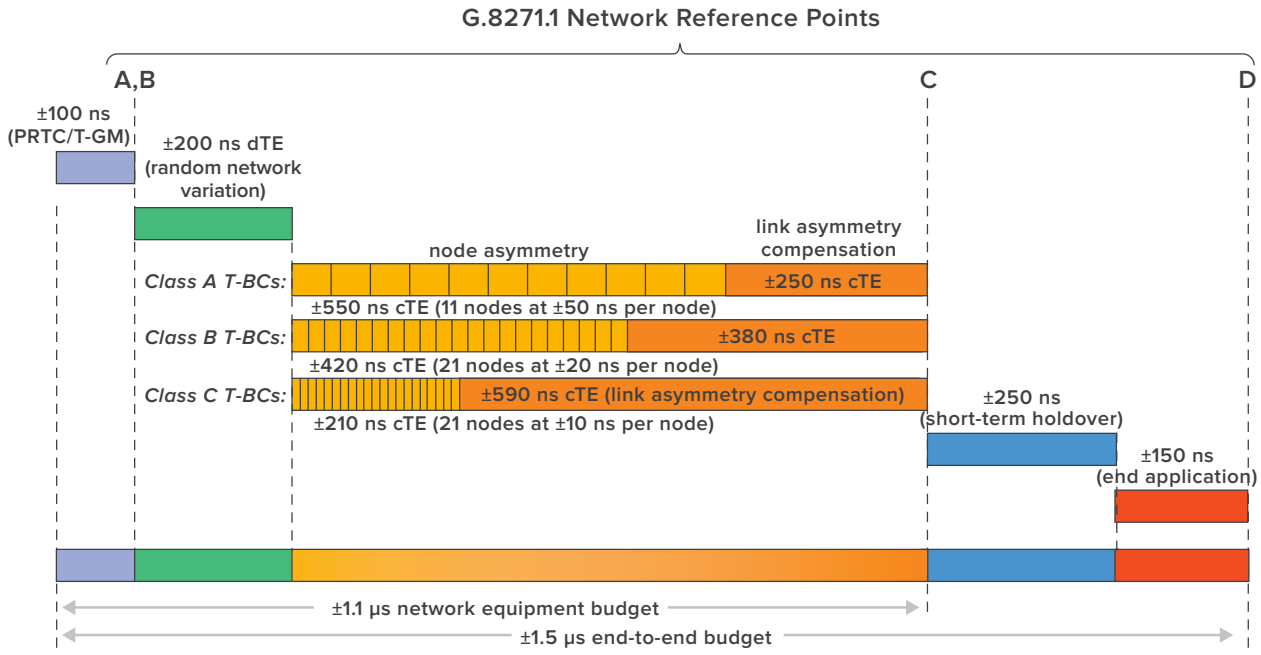


Figure 7: G.8271.1 time error budget including type A, B, and C networks

As discussed in the previous section, G.8271.1 specifies ±550 ns for node asymmetry and ±250 ns for link asymmetry (±800 ns in total) in what it calls Type A networks. Type A networks can contain up to 11 nodes, so 10 links, with ±50 ns cTE per node, hence ±550 ns total node asymmetry. However, the G.8271.1 specification allows network operators to take advantage of T-BC network nodes with better cTE performance with Type B and Type C networks. Type B and Type C networks support 21 nodes, so 20 links, with ±20 ns and ±10 ns node cTE, which reduces the total node asymmetry to ±420 ns and ±210 ns. In turn, this increases the possible link asymmetry to ±380 ns (Type B) and ±590 ns (Type C) while maintaining the overall ±800 ns total node and link cTE. dTE must still be managed within the available ±200 ns random network error budget. Therefore, it is highly desirable to take advantage of T-BC nodes with Class B or ideally Class C performance and lower cTE within a mobile transport network when they are available so as to enable a Type C G.8271.1 network with its higher allocation of cTE to the link elements of the transport network, such as fiber asymmetry and asymmetry within DWDM devices.

ITU-T G.8275.1 Full On-path Support and G.8275.2 Partial On-path Support

The ITU-T has defined two phase profiles for PTP networks. The first is G.8275.1, which provides full on-path support for PTP with boundary clocks at each IP routing or Ethernet switching node in the network. G.8275.1 full on-path support uses Layer 2 multicast Ethernet as the main delivery mechanism and recommends the use of SyncE to assist in locking T-BC nodes to a stable frequency. This profile is intended for all networks where new hardware is being deployed in the network, including both greenfield new deployments and cases where new routing or switching hardware is being added to a network to support higher capacity or performance for 5G. Overall, this approach provides superior PTP performance and is recommended for any new network buildout where mobile traffic is planned.

To allow for the fact that not all upgrades involve complete upgrades to all routing and switching hardware in the network, the ITU-T also developed the G.8275.2 partial on-path support profile. Partial on-path support uses Layer 3 unicast IP as the main delivery mechanism.

This profile uses T-BC functionality at intermediate nodes and, wherever possible, T-TC functionality at other nodes to reduce noise and improve performance over generic Ethernet clock-enabled devices. Some operators are unable to utilize G.8275.1, with its better performance, and therefore need to utilize G.8275.2 partial on-path support when they upgrade older networks. Generally speaking, G.8275.2 is not recommended for 5G synchronization distribution due to its limitations. It is possible to use assisted partial timing support (APTS) mode to help mitigate the impact of issues such as network islands without PTP support, but this is complicated and potentially unreliable. In order to minimize the impact of the poorer synchronization performance, these operators often need to introduce more T-GM clocks into the core network to reduce the distance between the T-GM and the cell tower.

The specifications of both G.8275.1 and G.8275.2 contain a range of features that are required to support the profile across a network domain. The level of support for these features by the products deployed within the network will determine the overall level of support for either of the profiles and the corresponding synchronization delivery performance.

3GPP TS 38.104 Time Alignment Error

The ITU-T specifications that have been described so far in this e-book provide the specifications for frequency and phase synchronization delivery through a transport network to meet the requirements for both 4G LTE and 5G TDD mobile networks, with frequency synchronization of 50 ppb at the air interface of the RAN and 16 ppb from the backhaul network, and phase synchronization of 1.5 µs with a budget of 1 µs allocated to the transport network, as outlined above.

These networks operate with either a distributed RAN (DRAN) architecture with a 4G BBU or 5G DU located at the cell site or a centralized RAN (CRAN) architecture with the BBU/DU a short distance (15-20 km max) from the cell site and a fronthaul network connecting the BBU/DU to the corresponding 4G remote radio head (RRH) or 5G radio unit (RU). Most mobile operators started 5G deployments following their existing 4G LTE DRAN/CRAN architectures, and as they start to migrate to more advanced 5G services and architectures, more will move to CRAN and eCPRI-based fronthaul.

From a synchronization perspective, fronthaul adds another level of complexity, with the need to not only deliver high-quality frequency and phase synchronization but also to manage relative phase synchronization error between adjacent cell towers within the cluster of cells under the DU. The specific level of relative phase error budget is highly dependent on the functionality being utilized within the RAN and within the specifications defined by the 3GPP's technical specification (TS) 38.104. TS 38.104 defines the capabilities of eCPRI-based fronthaul networks and includes the maximum relative phase error that is allowed when specific functions are used within the RAN.

The most demanding functionality, such as inter- and intra-band carrier aggregation and the use of MIMO antennas, have very demanding relative phase error budgets in 5G networks. This is specified as relative |TE| measured at the UNI of the RU of as low as 190 ns to just 60 ns. The corresponding time alignment error (TAE) specification, which is defined as the largest timing difference between any two signals, of 260 ns to just 130 ns as measured at the antenna, is shown in Figure 8. Of course, this should not be confused with the 1.5 µs absolute phase error requirement, which is still required at every cell site – this is an additional requirement to control the relative phase error between all the cell sites within a 4G BBU or 5G DU cluster. These relative |TE| and TAE specifications also apply to cooperating cell site clusters that are subtended from multiple DUs.

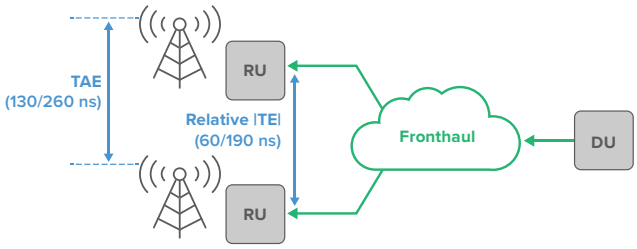


Figure 8: Relative |TE| and TAE in fronthaul networks

Putting It All Together to Provide 5G-Quality Synchronization

Providing 5G-quality synchronization is a complex problem that needs careful consideration early in the network design process. Many factors that impact synchronization quality are fundamentally linked to the operational performance of networking hardware and cannot simply be solved for at a later stage without replacing substandard networking hardware.

Networking hardware needs to meet the strict requirements outlined in the preceding sections of this e-book and summarized below in Figure 9. Every aspect of the transport network needs to be considered from a synchronization point of view. Each domain within the mobile network must be optimized for synchronization performance as follows:

Midhaul and backhaul networks: IP-centric domains where any IP routers must support the necessary synchronization standards and meet T-BC Class B, or ideally Class C, to enable type C networks with a larger allocation of cTE budget to support the links connecting the T-BC clocks. Most of the dTE within the network will come from these IP devices, and any Layer 2 Ethernet devices in the network and dTE must be managed and within budget across the complete network.

cTE must also be managed and within budget for the worst-case links, which are often longer routing paths around networks in protection scenarios where the shortest path has failed. cTE is mainly created within the DWDM layer, and therefore, careful consideration of the cTE performance of these devices is required. For long DWDM links that interconnect T-BC Class B/C routers or switches, it may well be the case that even Class D T-BC devices are needed at intermediate DWDM nodes in order to maintain the required synchronization performance within the underlying DWDM network.

Fronthaul networks: eCPRI/Ethernet-centric domains where Ethernet switches must support the necessary synchronization standards and meet T-BC Class C to support both the absolute and relative phase error budgets. dTE is largely from eCPRI/Ethernet switching devices that will typically also use Time-Sensitive Networking (TSN) capabilities, such as preemption, to prioritize latency-sensitive packets such as eCPRI fronthaul traffic and PTP packets over other traffic within the network. Again, cTE is largely from the underlying DWDM layer, and as cTE must be considered from the PRTC to the cell tower, fronthaul cTE must be managed from end to end along with midhaul and backhaul domains.

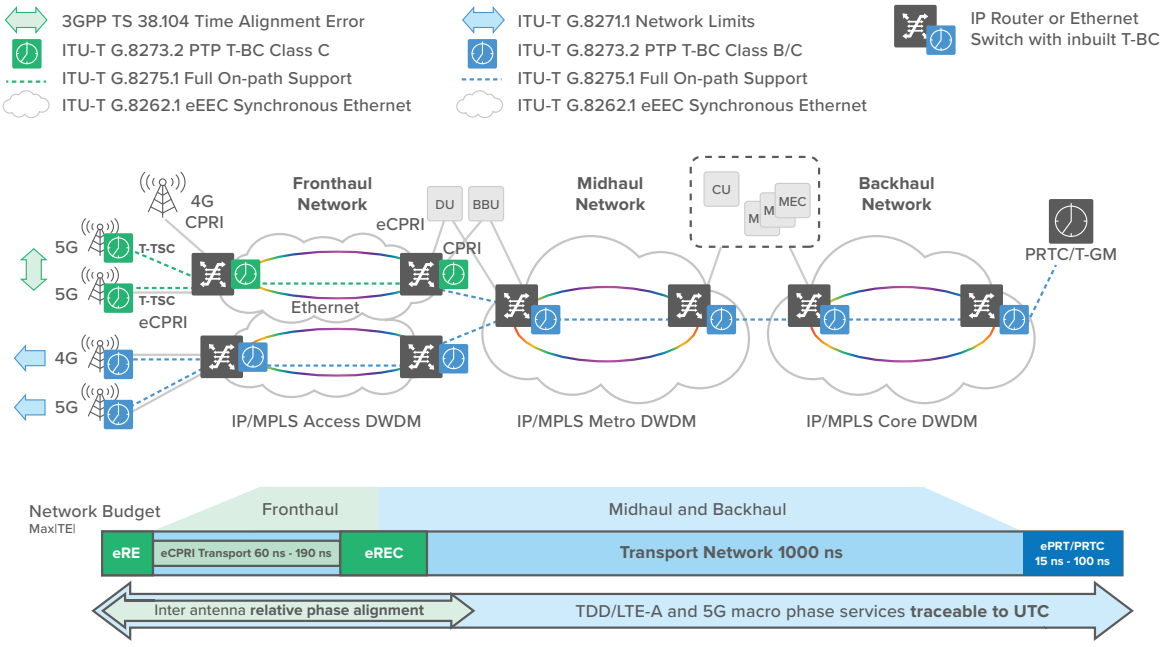


Figure 9: Delivering 5G-quality synchronization across the transport network

Getting Synchronization Right

Hitting the required synchronization performance within a network requires a combination of features/functionality and measurable performance characteristics, such as cTE and dTE of networking devices. The specifications enable the transport network to deliver a suitable clock to the cell towers in the mobile network of the right quality to support the demanding features required in the 5G RAN. Meeting the basic synchronization performance levels enables network operators to fully utilize their most valuable asset, their spectrum. Lower synchronization performance can mean that frequency management within the RAN isn't tight enough and the spectrum can't be fully utilized or that advanced functionality such as carrier aggregation or MIMO antennas cannot be fully utilized or even activated at all. Overall, getting synchronization right is mandatory in mobile networks.

However, synchronization performance is not simply a pass/fail test. It is possible to exceed the synchronization specifications and have a higher-performance network. It is too early to see the impact of higher synchronization performance that exceeds the specifications in full 5G standalone (SA) networks yet, although we can be sure this certainly will not be a negative factor. But we can look back at 4G networks to see how above-standard synchronization helped network operators improve network efficiency and user experience. These performance improvements are hard to quantify in most cases – sometimes it is simply a case of network engineers being able to tell which backhaul network a cell tower is supported by just from looking at the performance metrics for the cell site, for example, one backhaul network with OK synchronization versus one with much better synchronization performance. In other cases, network operators have used before-and-after user experience data such as upload speed, download speed, and latency and seen over 40% improvement in all metrics once the backhaul network was upgraded to one with much better synchronization performance. In this instance, there was no increase in backhaul capacity to the cell site, just better synchronization over the backhaul network and the capacity for growth in the future.

In summary, delivering high-quality synchronization is a must for 5G networks, and it is not simply a case of meeting the minimum possible standard. Superior synchronization performance can bring improved network performance and user experience. It is always a balancing act over the economics of chasing ever-improving synchronization performance, but the goal should always be to get the best performance that meets or exceeds the required level for 5G without breaking the bank.

SECTION 2

Infinera's Sync Distribution Solution for End-to-End Synchronization Delivery

In order to meet the complex transport requirements in 5G mobile networks, Infinera has developed a complete end-to-end mobile transport solution. This includes synchronization delivery for all aspects of the optical network from the mobile core to the cell tower. The following section of this e-book will outline the Infinera synchronization delivery solution by looking at its major building blocks. These building blocks can be deployed in a standalone manner for a particular segment, layered in the 5G transport network, or deployed together as a complete solution.

Infinera has a full portfolio of DWDM, Layer 2/2.5 packet optical, and IP products that are widely deployed across fixed and mobile networks around the globe. The synchronization distribution solution outlined in this section focuses on the products within the portfolio that are most commonly positioned today for mobile networks where synchronization is a critical consideration. Within the DWDM and Layer 2 packet optical layers of the network, this comprises the XTM Series within the access and aggregation packet optical domains at the edge of the network and the OTC2.0 solution deeper in the network across regional and long-haul networks. Other products within Infinera's portfolio, such as the 7090 and 7100 packet optical platforms, are also widely deployed in mobile networks, providing high-quality synchronization delivery.

Synchronization in the IP Layer

Infinera's IP portfolio for mobile applications embraces the open and disaggregated approach as promoted by industry organizations such as the Telecom Infra Project (TIP). This approach takes the traditional closed router architecture, with a complete software and hardware package provided as a single entity from one vendor, and breaks it into network operating system (NOS) software and open white box hardware from potentially different vendors. Synchronization features in this environment rely on both software capabilities within the NOS and hardware features within the specific white box hardware selected for the various network domains by the network operator.

Infinera's Converged NOS (CNOS) builds on 15 years of experience in IP networking, especially in mobile networks with Infinera's 8600 Series of IP routers. With a deployed base of over 200,000 routers supporting over 300,000 cell towers in leading mobile operators' networks across the globe, the 8600 Series was optimized for IP in mobile environments, and CNOS takes that heritage into the open disaggregated age. CNOS includes the broad range of synchronization features that are required in order to provide 5G synchronization, including:

- ITU-T G.8262 and G.8262.1 eEEC
- Station clock input and output ports
- Pulse-per-second (PPS) input and output
- Time-of-day input

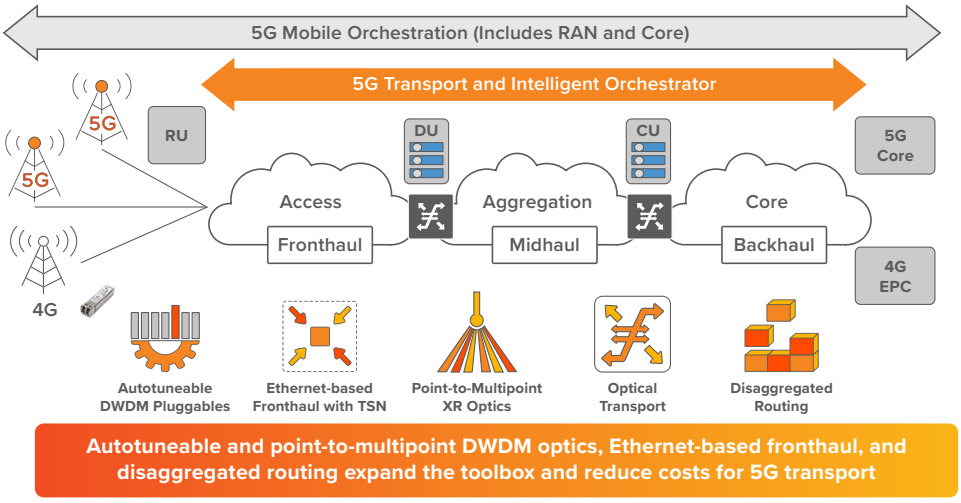


Figure 10: Infinera's end-to-end 5G transport solution

- Synchronous Ethernet
- SSM over Ethernet [G.8264]
- SyncE Master (GNSS input as PRC for SyncE-unaware island)
- IEEE 1588v2 Boundary Clock for phase synchronization (G.8275.1, G.8273.2)
- Fully G.8275.1 profile compliant, including priority 2 and local priority attributes
- G.8275.1 topology control via port configuration
    - Auto (the PTP state is determined by the BMCA rules)
    - Master (the PTP state is determined by the BMCA rules, with the “notSlave” attribute of G.8275.1 enabled)
    - Disabled (all frames with PTP EtherType 0x88F7 are dropped)
- IEEE 1588v2 PTP telecom profile for frequency synchronization (G.8265.1)
- 1588v2 HW base timestamping
- SyncE Assist
- GNSS input (built-in GNSS chip) including the latest technology:
    - Multi-constellation
    - Synchronization by only single satellite visibility
    - Multi-band (solution to mitigate ionosphere delay)
        - Ionosphere is one of the biggest error sources in GNSS timing
- Monitoring and measurement capabilities

In synchronization hardware matters, and key to understanding how this broad range of features can be deployed is the understanding of the synchronization features and relative performance of the underlying hardware. Today’s white box hardware has evolved from its data center origins into carrier-grade hardware where many, but not all, of the options available in the market support the capabilities needed for complex networks such as mobile transport networks.

Infinera’s CNOS is an open NOS designed to run on a variety of commercially available hardware platforms from both Infinera and third-party vendors, with commercial deployments to date running on both Infinera and Edgecore hardware.

Infinera’s disaggregated IP hardware, the DRX Series, brings additional carrier-grade functionality over standard white box hardware and includes a range of devices optimized for mobile networks from the cell site through aggregation nodes to the core. The extended capabilities found in the DRX-30 and DRX-90 include the broad range of synchronization features needed for 5G mobile networks, such as:

- GNSS receiver ports for customers that use GNSS-based synchronization strategies
- Timing port input/output options, including 1PPS/ToD ports and PTP ports
- T-BC Class C performance

Class C performance at every IP node is an important tool in enabling the wider 5G transport network to achieve the G.8271.1 network limits with tight control over dTE budgets. Furthermore, the CNOS software and DRX platforms also support a comprehensive range of features within G.8275.1, beyond standard features such as T-GM/T-BC/T-TC/T-TSC clock options, alternative best master clock algorithm, and manual configuration of various topology preference options.

Figure 11: Infinera’s DRX-30 DCSG router with T-BC Class C performance for demanding 5G networks

Of particular interest in the wider 5G sense is the push by TIP for an open approach to their Disaggregated Cell Site Gateway (DCSG) router, which provides a standardized hardware specification for 5G networks, including synchronization features. This open approach has been embraced by many hardware and software vendors and has now started commercial deployment with a range of mobile operators, including some of the world’s largest, such as Telefónica and Vodafone, both of which have deployed Infinera’s CNOS software over either Infinera DRX or Edgecore DCSG hardware. Synchronization capabilities are key selection criteria in 5G networks, and real-world deployments using network-based synchronization delivery are an important validation of the broad synchronization feature set and the high performance in IP networks.

Synchronization in Packet Optical Transport in Metro and Regional Networks

To interconnect the devices within the IP layer, DWDM is typically used for reach and fiber capacity or availability reasons. As outlined in part one of this e-book, the main challenge in delivering synchronization over fiber and DWDM is controlling asymmetry and corresponding cTE, although any elements in the network that extend into Layer 2 Ethernet switching will introduce a dTE factor that also needs management. To understand how cTE and dTE can be managed across the network, the packet optical domain will be subdivided further into the Ethernet switching layer and the optical DWDM layer for access and aggregation networks and legacy/long-haul networks.

Packet Optical Transport with Layer 2 Ethernet/eCPRI Switching

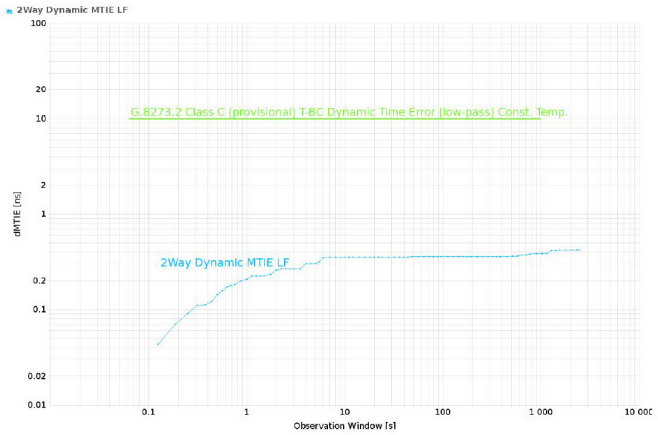
Fronthaul networks and those that support a combination of front/mid/backhaul over an xHaul infrastructure utilize Ethernet switching capabilities that from a synchronization perspective need to be considered in a similar manner to the IP layer due to the predominately dTE implications on synchronization. Due to the extremely tight relative phase error budgets within fronthaul networks, which can be as low as 60-190 ns, synchronization performance is critically important within these networks.

Infinera's XTM Series is widely deployed in packet optical networks with a broad range of EMXP devices. The EMXP range utilizes a switch-on-a-blade architecture that provides significantly better synchronization performance than comparable packet optical transport devices. In wholesale environments, the switch-on-a-blade architecture enables the XTM Series to support multiple synchronization domains within a single chassis, which enables wholesale operators to support multiple mobile operators over the same chassis and network, each with its own independent synchronization domain.

To address the new eCPRI-based transport requirements within fronthaul networks, Infinera has extended the EMXP range with the EMXP-XH800, which is a hardened 800 Gb/s device supporting a broad range of functions required from fronthaul networks and hybrid xHaul networks, which encompass fronthaul, midhaul, and potentially backhaul traffic flows over the same infrastructure, such as TSN.

Figure 12: XTM Series EMXP-XH800 for fronthaul and xHaul networks

From a synchronization perspective, the EMXP-XH800 brings the range of synchronization features needed to support 5G fronthaul and xHaul environments, such as fiber asymmetry compensation, SyncE/eEEC, and nanosecond-level timestamping for very accurate T-TC operation coupled with T-BC Class C performance that significantly exceeds the required performance for Class C certification, as shown in Figure 13. Along with the rest of the EMXP range, the EMXP-XH800 also utilizes a hardware design with a highly accurate SyncE assist mode for 1588v2 PTP operation that is optimized for demanding 5G fronthaul applications.



Min [ns]	0.043
Max [ns]	0.421
Max-Min [ns]	0.378

Figure 13: EMXP-XH800 MTIE performance

Most xHaul networks require tight control of both cTE and dTE in order to meet tough synchronization requirements. In the most demanding networks, the EMXP-XH800 can be coupled with an optical timing channel (OTC) approach that bypasses coherent optics and other optical components that can add further elements of fixed and random cTE. The fixed and random cTE of these elements may be small, but over a complete optical network, they can add up to considerable levels that need management. dTE is kept low through the hardware design of the device and is a key factor in the T-BC performance that significantly exceeds Class C.

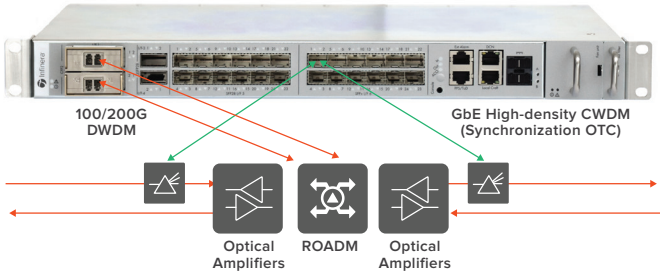


Figure 14: EMXP-XH800 optical timing channel in action

The EMXP-XH800 optical timing channel implementation uses a high-density CWDM (HDCWDM) channel that provides bidirectional single fiber working (SFW) operation over a single CWDM wavelength to remove the majority of the fixed and random cTE elements of the underlying DWDM and fiber components. The use of Gigabit Ethernet CWDM optics enables longer optical reach, which means the configuration can use CWDM filters to bypass the inline optical amplifiers and high-speed 100G/200G coherent optics due to the longer reach of the lower-speed CWDM optics. SFW requires a different wavelength in each direction over the fiber and HDCWDM uses two tightly spaced CWDM channels within a single standard CWDM channel. Using just one of the fibers removes the asymmetry due to differing fiber lengths in DWDM networks and limits overall fiber asymmetry to the very small level of asymmetry from the differing speeds of the two wavelengths.

Overall, the XTM Series EMXP range and the EMXP-XH800 in particular enable network operators to build packet optical networks for mobile xHaul that meet or exceed the tight requirements for 5G transport.

DWDM Transport

In addition to widespread deployments within 4G and 5G Layer 2 packet optical networks, the XTM Series also supports many network operators with Layer 1 DWDM-based mobile transport networks for both 4G and 5G transport.

One of the most challenging aspects of building synchronization distribution networks is controlling fixed and random cTE within the DWDM links that interconnect Ethernet or IP devices. In metro and regional mobile transport networks, Infinera uses the XTM Series as the platform is highly optimized for this application. The optimization includes a wide range of factors such as TSN support for mobile fronthaul and hardened hardware options. Of particular importance from a synchronization perspective are:

- Single platform for packet optical networks – when Layer 2/2.5 capabilities such as those described above are required, the XTM Series provides these in a single platform
- Optical timing channel – HDCWDM single fiber working optical timing channel supports PTP in higher layers either through the XTM Series EMXP-XH800, Infinera's OTC2.0 solution (outlined below), or other third-party timing solutions
- DWDM transport options with very low random cTE

At the DWDM layer, this third item is probably the most critical as without it, 5G-quality synchronization distribution networks can be very difficult to build and can rapidly become very expensive to build and maintain. Mobile operators often design, build, and manage their DWDM transport and IP layers as separate domains, which means that ideally the DWDM layer needs to have very low cTE, including those components that create random cTE, to enable the DWDM layer to support PTP packets within the IP data plane without the need for special management of these IP flows.

The biggest challenge with this underlying DWDM layer is cTE, or random cTE from OTN mapping chips used in transponders and muxponders. These devices use deep FIFO buffers to enable support for a broad range of service types, which of course is an advantage in general networking terms but a serious challenge from a synchronization perspective.

The XTM Series provides a range of DWDM transponders and muxponders that are OTN-based and use the same commercial off-the-shelf (COTS) OTN chips as the rest of the industry. In addition, the XTM Series also contains devices that are optimized for applications such as mobile transport with a very tight focus on optimal performance for a more limited set of services. These devices avoid the COTS OTN mapping chips and focus on providing a low-latency, low-power, and high-density offering with the very positive side effect of a very low cTE on restart.

To put this into perspective, Infinera has tested a wide range of transponders, muxponders, and packet optical switches from the EMXP range for random cTE and dTE performance, and the results are summarized below.

The cTE figures quoted are maximum random cTE figures for cTE on restart of the device, and therefore on each restart there will be a random cTE within ± the quoted figure. Devices with larger random cTE may well initially start up with a lower acceptable level of cTE but in a restart situation this may change to a much larger and unsupportable level of cTE.

By careful network design, it is therefore possible to build a DWDM transport layer that is capable of supporting 1588v2 PTP in higher networking layers with a low enough cTE within DWDM links that the overall G.8271.1 network limits can be achieved.

This challenge is compounded by the fact that optical layer design is built around fiber availability and routing, and while the normal working path may be a relatively direct route between two T-BC-enabled routers or switches, the protection route may be substantially longer and involve a lot more DWDM components that will potentially have a substantial impact.

XTM Series Device	Function	Client	Line	Maximum Random cTE	Maximum dTE_L (Low-pass-filtered) MTIE	5G Phase Sync Support?
FXP400G	Dual 100G/200G flexponders on a single card. 1 or 2 x 100G clients mapped into each of the 100G or 200G lines.	100G	100G or 200G	±20 ns	0 ns	Yes
MXP200G	200G multi-service muxponder. Various lower-speed services (OTN, Ethernet, Fibre Channel, etc.) at rates from 10G to 100G mapped into 100G or 200G line.	10G, 32G FC, 100G, etc.	100G or 200G	±670 ns	0 ns	No
FHAU/1	6 x 10G transponders on a single card or hardened pizza box option for street cabinet deployments. Non-OTN-based mapping.	10G	10G	±10 ns	<1 ns	Yes
TPHEX10GOTN	6 x 10G transponders on a single card. OTN-based mapping.	10G	10G	±372 ns	<5 ns	No
EMXP440	440G packet optical transport switching card.	10G	100G or 200G	±37 ns	2 ns	Yes
EMXP-XH800	800G hardened pizza box packet optical transport switch.	10G or 25G	100G or 200G	±28 ns	2 ns	Yes

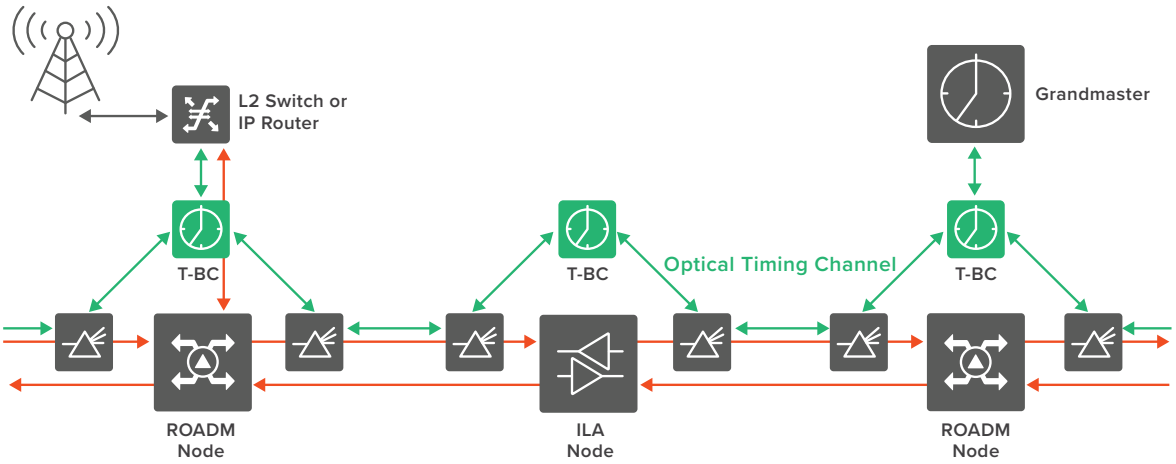


Figure 15: Infinera's OTC2.0 Solution

Synchronization in DWDM Transport over Regional, Long-haul, and Legacy Networks

Outside of the metro access, metro aggregation, and regional footprint that is addressed with the XTM Series, Infinera has developed a very high-performance OTC2.0 solution in conjunction with Microchip, a market leader in network synchronization technology.

The OTC2.0 solution builds on the combined synchronization and optical networking strengths of the two companies to provide network operators with highly optimized and highly reliable synchronization distribution solutions. OTC2.0 provides synchronization distribution over Infinera's full portfolio of DWDM platforms, such as the 7100, 7300, FlexILS, and GX Series platforms, or even over third-party DWDM networks. The solution can also be deployed over the XTM Series when extreme performance and an enhanced synchronization/timing feature set is required. OTC2.0 essentially couples Microchip's industry-leading TimeProvider® 4100 with a broad range of DWDM optical timing channel capabilities and a deep understanding of how the two systems can be optimized to meet the toughest synchronization requirements for mobile networks.

The TimeProvider 4100 supports the very broad range of synchronization features required for 5G synchronization and timing distribution, such as a high-performance boundary clock operational mode, GNSS and network inputs, multiple output options, and the full range of frequency and phase synchronization standards. The device also couples T-BC Class D performance with a range of rubidium and OCXO local oscillator options to provide a very high-quality timing source for downstream networking nodes. A summary of the TimeProvider 4100 features that are utilized in the OTC2.0 solution includes:

- IEEE 1588v2 PTP grandmaster
- Timing distribution over T-BC 1588/SyncE via overlay optical timing channel
- GNSS (GPS, GLONASS, BeiDou, QZSS, and Galileo) and SBAS support
- PRTC Class A and Class B
- Enhanced PRTC (ePRTC) that meets 30 ns performance and uses a combination of Cesium and GNSS time sources
- Oscillator options – SuperOCXO (future support), OCXO, and rubidium (Rb)
- Standard base unit with 8 Ethernet ports, 4 E1/T1 ports, 1 craft port, 2 × 1PPS/ToD ports, 2 × 1PPS/10 MHz ports

Figure 16: Microchip TimeProvider 4100

- Optional internal expansion module with 4 SFP and 4 SFP+ for 10G support, 100M Fast Ethernet, and 1G fanout
- Support for multiple IEEE 1588v2 profiles per unit
- Support for high-performance single domain/multi-domain boundary clock with Class C and D accuracy
- Fully supports ITU-T profiles for phase synchronization: G.8275.1 and G.8275.2
- Fully supports ITU-T profiles for frequency synchronization: G.8265.1, Telecom 2008, and default
- ITU-T G.8273.4 APTS with enhanced automatic asymmetry compensation over multiple network variations
- Supports timing in DWDM networks with up to 6 DWDM degrees, optional extension to 14 DWDM degrees
- PTP timing path protection (bidirectional timing service for resiliency)
- Monitoring and measurement capabilities
- Multiple management options – Microchip TimePictra® synchronization management system support, Microchip Web GUI, CLI, SNMP, and Open API support planned (NETCONF)

Looking at the optical layer, OTC2.0 uses two very tightly spaced WDM channels, often bidirectionally over a single fiber, for transmit and receive channels for PTP messages to minimize network asymmetry and the corresponding impact on PTP operation. OTC2.0 provides a broad range of WDM options such as O-, E-, and L-band timing channel options to optimize these timing channels to the specific characteristics of the DWDM network. Furthermore, the solution utilizes both PTP T-BC and 3R DWDM regeneration options to ensure a high-performance, robust, and economical network.

Critically, Infinera's OTC2.0 also brings a detailed understanding of how DWDM and synchronization interact over complex and varied DWDM networks, such as those involving Raman amplification over very long distances. Furthermore, the capabilities and expertise in Infinera's Synchronization Verification Lab in Munich enables Infinera and Microchip to collaborate to verify and optimize OTC2.0-based synchronization network designs for customers.

From an overall solution perspective, OTC2.0 provides network operators with a high-performance timing solution that is also highly robust and very scalable. The solution is decoupled from the underlying DWDM layer, which enables timing resiliency during network upgrade and reconfiguration activities. The broad range of synchronization and optical timing channel features, coupled with support for any transport network topology, including meshed, ring, tree, and point-to-point architectures, enables network operators to bring 5G-quality synchronization to even the most demanding networks, including those with high levels of asymmetry.

Field deployments of OTC2.0 using TimeProvider 4100 have shown that networks can exceed G.8273.2 Class D cTE performance over long-distance DWDM networks. Figure 17 shows one-week live traffic test data of the OTC2.0 solution in action over a 500-km, 96-channel DWDM network. The network comprises six DWDM spans connecting a combination of ROADM and in-line amplifier (ILA) sites using a mix of EDFA-only and hybrid EDFA/Raman amplification options. With TimeProvider 4100-based T-BC timing at the end nodes and the five intermediate sites, this is therefore seven hops from a synchronization perspective. The results show an impressive end-to-end cTE performance of 11 ns throughout the one-week monitoring period. To put this performance into perspective, Class D performance over seven timing hops would result in a time error of 35 ns at 5 ns per hop.

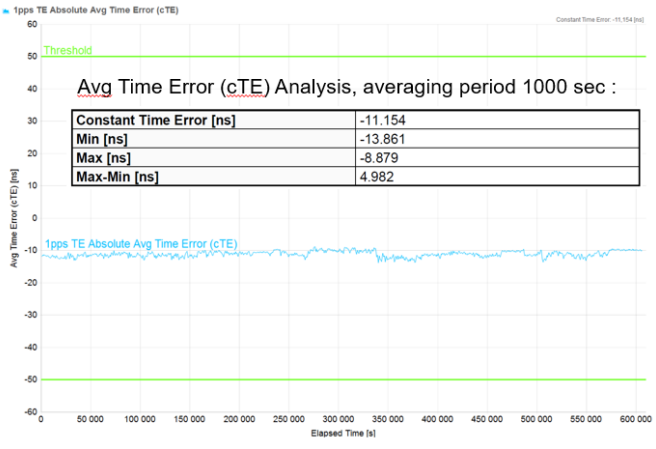


Figure 17: OTC2.0 time error of 11 ns after 500 km over six DWDM spans and seven timing hops

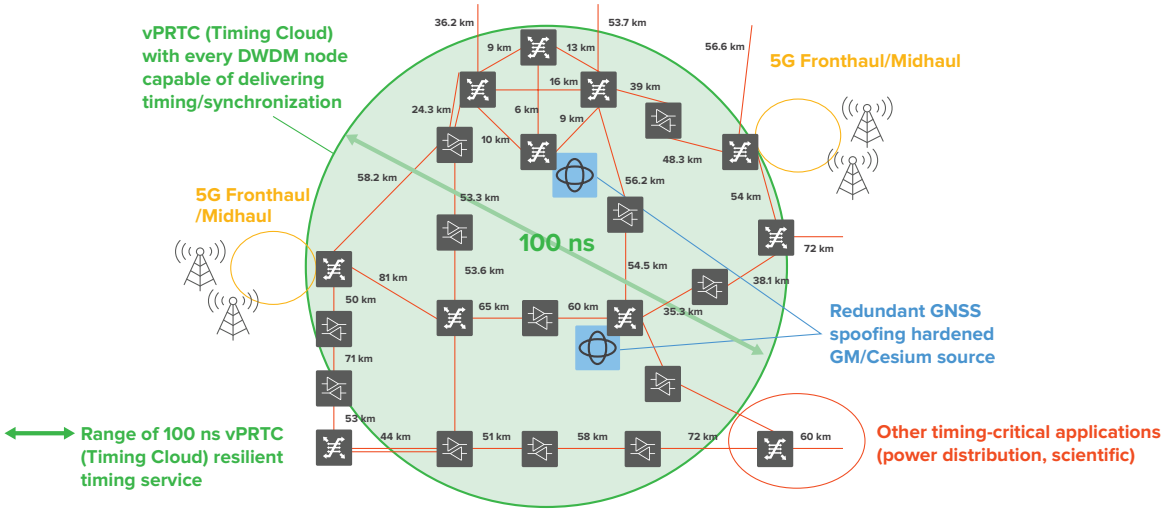


Figure 18: OTC2.0-enabled vPRTC regional/core network preserves G.8271.1 network limits for fronthaul and midhaul packet optical networks and other timing-critical applications

The combination of synchronization and optical networking capabilities within OTC2.0 also enables network operators to create a highly flexible and resilient virtual PRTC (vPRTC) or "Timing Cloud" architecture over long-haul and regional networks. This essentially converts the complete regional/long-haul network into a distributed PRTC within the G.8271.1 PRTC budget of ±100 ns, or even potentially the enhanced ePRTC budget of ±30 ns, with timing source redundancy. This architecture pushes the PRTC from a few core node locations out across the long-haul and regional network, preserving critical G.8271.1 budget for metro access and aggregation DWDM networks and further last mile access for non-fiber-connected cell sites, as shown in Figure 18.

End-to-End Sync Planning and Management Interconnection

Having high-quality synchronization requires more than simply high-performance hardware and software capabilities. Planning and management capabilities are critical in building real-world networks and managing synchronization through the life cycle of a network.

During the network planning and design stages, Infinera's planning tools enable network designers to model fixed and random cTE and dTE across Infinera's synchronization portfolio to ensure that optical layer designs support the required cTE and dTE budgets, as well as from an optical design perspective.

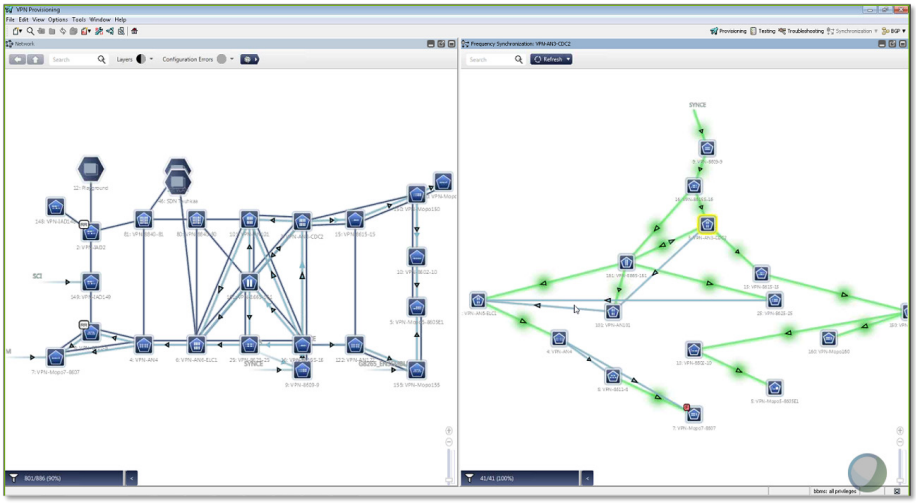


Figure 19: Infinera's Transcend synchronization management in action

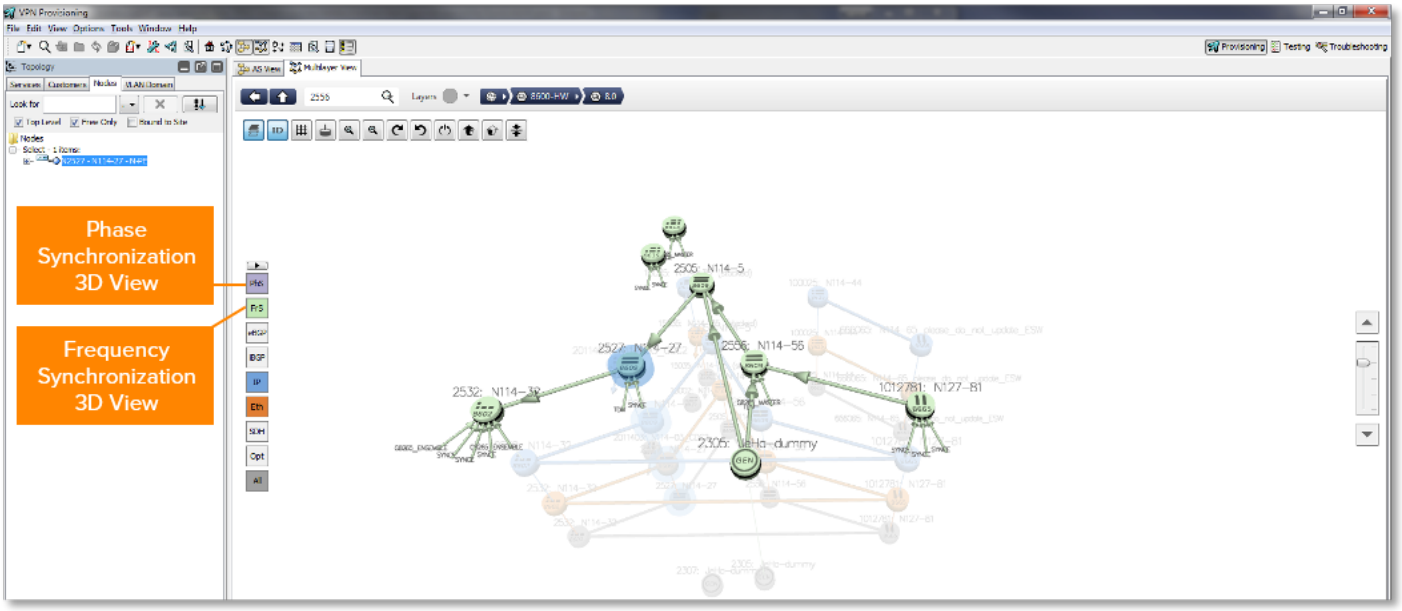


Figure 20: Infinera's Transcend 3D synchronization view with frequency and phase planes

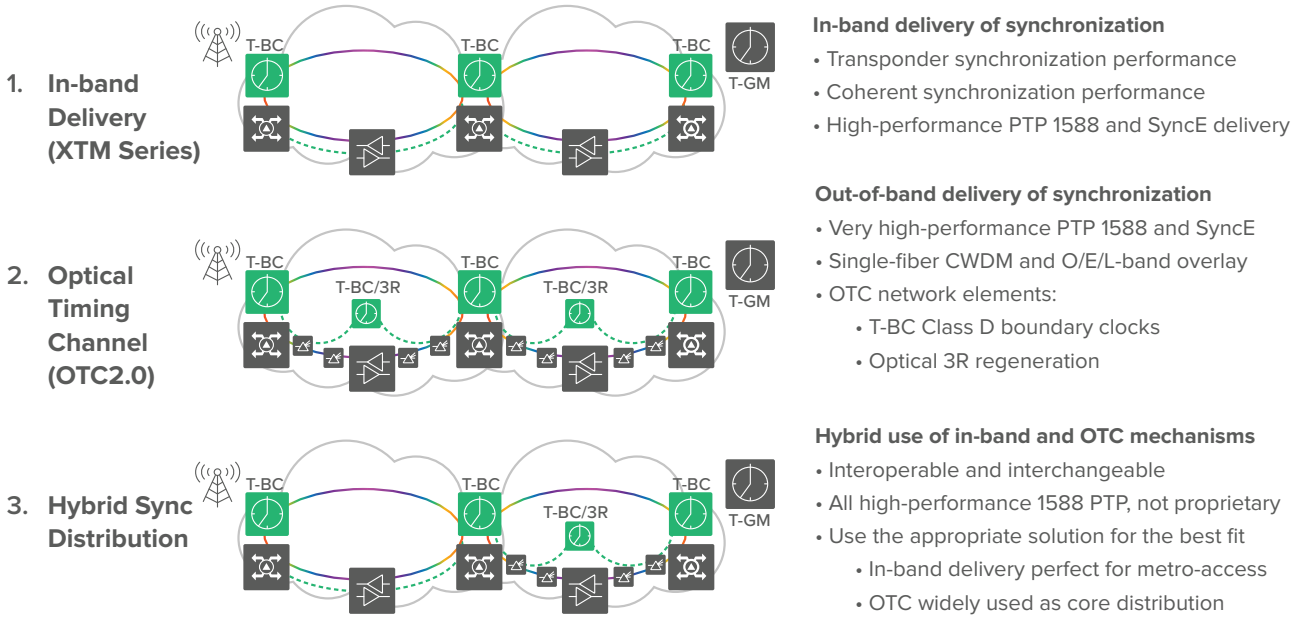
Once installed, Infinera's Transcend NMS (TNMS) provides synchronization management features to provide visibility, management, and traceability of synchronization signals and sources, such as:

- Support for configuring all synchronization-related functionalities in node manager
  - IEEE 1588v2, phase/time and frequency
  - SyncE
  - GNSS synchronization
- IEEE 1588v2 clock monitoring and troubleshooting
- Third-party network element integration in common sync network map
- Synchronization network view
  - Phase/time and frequency
  - 3D network view

Summary

5G synchronization is a complex topic with many moving parts that all need to come together harmoniously across all aspects of the transport network to provide the right quality synchronization to the cell tower without overengineering the network and driving up cost. Infinera's toolbox of high-performance synchronization capabilities is enabling both mobile network operators and wholesale carriers that provide mobile transport services to deliver network-based synchronization with industry-leading performance. In some cases, this Infinera solution simply supports high-quality synchronization within a particular network layer or geographic domain, and in others, operators are able to combine the solutions outlined in this e-book to create end-to-end synchronization strategies to meet their 5G performance demands now and in the future.

GNSS has a critical role to play in synchronization distribution, but operators are moving away from "GNSS everywhere" strategies to those that utilize resilient GNSS at key network locations and network-based synchronization distribution. This approach provides better holdover performance and removes the risk of GNSS jamming and interference at cell sites.



In-band delivery of synchronization
- Transponder synchronization performance
- Coherent synchronization performance
- High-performance PTP 1588 and SyncE delivery

Out-of-band delivery of synchronization
- Very high-performance PTP 1588 and SyncE
- Single-fiber CWDM and O/E/L-band overlay
- OTC network elements:
  - T-BC Class D boundary clocks
  - Optical 3R regeneration

Hybrid use of in-band and OTC mechanisms
- Interoperable and interchangeable
- All high-performance 1588 PTP, not proprietary
- Use the appropriate solution for the best fit
  - In-band delivery perfect for metro-access
  - OTC widely used as core distribution

Figure 21: Infinera's synchronization options in DWDM transport networks

It also removes the challenges of providing GNSS signals into hard-to-reach cell sites planned for 5G, such as those deep inside buildings or in underground metro railway stations.

The benefits that Infinera's solution brings to those operators that are building network-based synchronization strategies over alternative approaches include:

- Better overall synchronization performance leading to potentially better RAN performance and spectrum utilization
- Better overall network economics with optimized solutions for in-band synchronization delivery for metro access and aggregation networks, OTC2.0 for long-haul/core/legacy networks, and the ability to blend the two solutions within the same network
- More resilient synchronization distribution
- More stable synchronization environments requiring less ongoing maintenance and support

This e-book has focused on synchronization in mobile networks as this is a large focus area currently within the telecom industry. But the benefits of high-performance synchronization are not limited to mobile networks. Network operators are also benefiting from Infinera's high-quality synchronization in a broad range of applications such as power utility networks, financial trading networks, TDM circuit emulation, and video/DAB distribution networks.

Further Reading

Infinera has a range of more detailed product-specific synchronization documentation, such as product data sheets and sync performance testing documentation for the solutions outlined in this e-book. Please contact your Infinera sales representative for more details.

All Infinera and Microchip product feature lists and specifications referenced in this e-book are subject to change over time. Please refer to the appropriate product data sheets and detailed documentation for the most up-to-date features lists and specifications.

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