VIAVI Solutions

White Paper

Timing and Synchronization Standards for Wireless Networks

Synchronization networks have been critical components of wireless networks for many years. Introduction of advanced LTE services and 5G services poses new requirements for synchronization networks. This white paper describes synchronization requirements, technologies, as well as, synchronization standards and test and measurement applications. The paper closes with a description of ITU G.826x/G.827x standards for synchronization in wireless networks and highlights some of the main metrics and network limits relevant for deployment in field applications.

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Introduction

Synchronization networks have been deployed in telecom networks for many years. Synchronous Digital Hierarchy (SDH)/Synchronous Optical Network (SONET) represented and still constitute a key component in large number of metro core networks. Access networks deployed PDH/DS1/DS3 and SONET/SDH services to synchronize end applications at customer premise. With the introduction of Carrier Ethernet, new standards for packet-based timing and synchronization have been introduced over the past decade.

The need for synchronization goes back decades when digital switching and transmission were introduced in telecom networks. They required the need to synchronize the transmitters and receivers; more specifically the need for receiver clocks to track the transmitter signals. Proper tracking enables to retrieve the transmitted signal correctly; poor synchronization — on the other hand — leads to degraded transmission and consequently the quality of transmitted service such as voice or data.

In an ideal transmission system, the pulses are transmitted in precise intervals and arrive at the receiver with exactly the same time spacing. In real systems, various factors contribute to an imperfect signal that can result in poor frequency or phase synchronization. Also known as syntonization, frequency synchronization is alignment of clocks to the same frequency (Figure 1). Similarly, phase/time synchronization is about aligning two devices to the same phase (Figure 2), and time of the day (Figure 3), respectively.

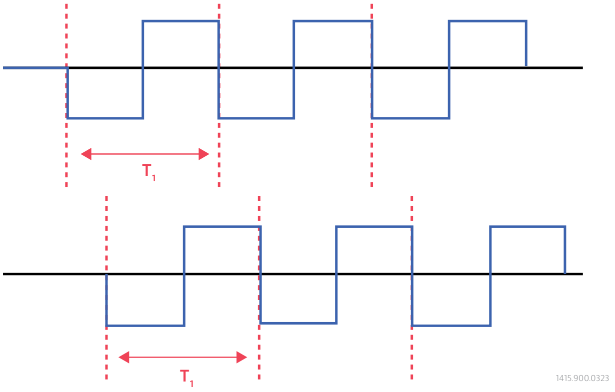

Figure 1: Frequency Synchronization (Syntonation)

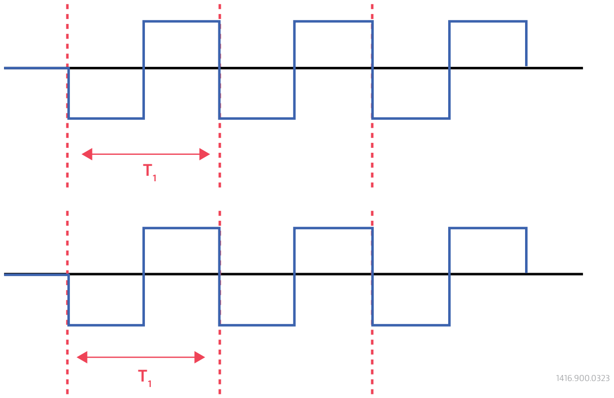

Figure 2: Phase Synchronization

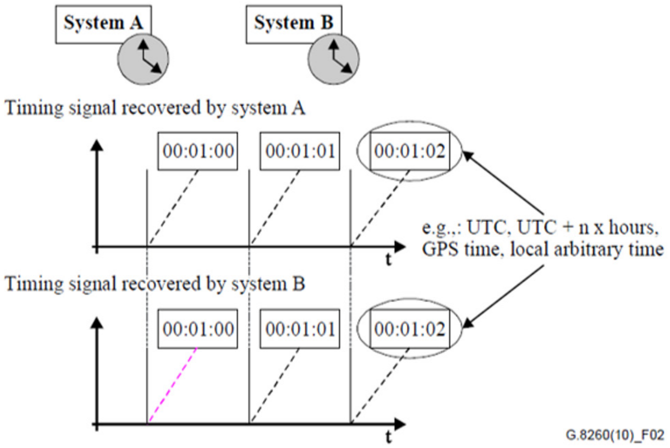

Figure 3: Time Synchronization

Imperfect synchronization can result in jitter or wander. Jitter and wander characterize the deviation of the phase of the transmitted signal. Wander is typically caused by phenomenon that lead to slow phase variation such as temperature variations. Jitter can be a result of clock circuit operation.

Clock performance is specified in ANSI T1.101 with five categories from Stratum 1 through 4 (Table 1). The highest performance is Stratum 1. It is also known as Primary Reference Source (PRS) or Primary Reference Clock (PRC), although there is a difference between them. Unlike a stratum 1 clock a PRS does not need to be autonomous. A PRS must be traceable to a stratum 1. For example, it can be based on GPS which meets the stratum 1 traceability requirement, yet it is not autonomous. Cesium beam clocks are the only autonomous clocks used in telecommunication.

Stratum	Accuracy
1	1×10^{-11}
2	1.6×10^{-8}
3/3E	4.6×10^{-6}
4	32×10^{-6}

Table 1: Stratum classes

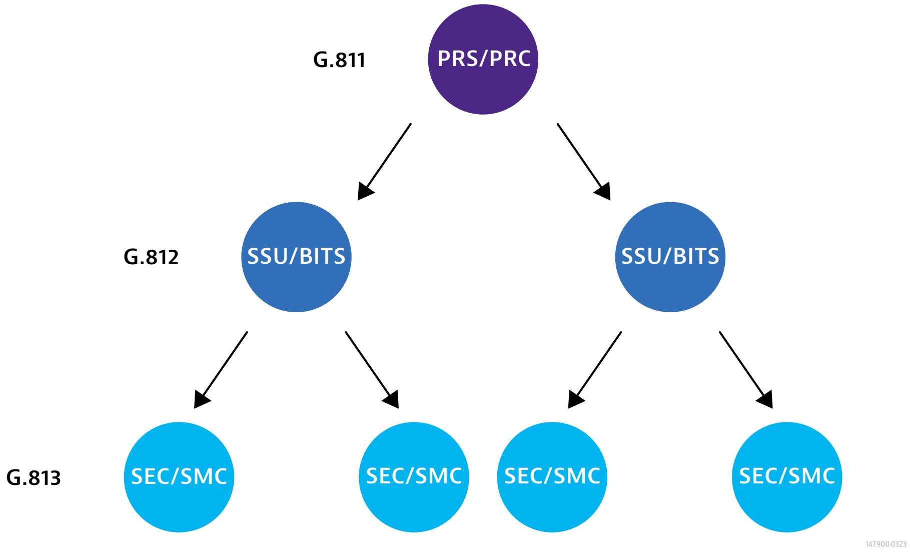

Figure 4: Synchronization Hierarchy

Typical telecom networks deploy one or multiple PRS timing references for the respective nodes. Since it is not economical to deploy PRS at every node, a synchronization method is needed to deliver the minimum synchronization performance for the respective application; such as a stratum 3E at a cell site. The mainstream method is master-slave method (Figure 4) in which a PRS synchronizes a chain of nodes downstream. To deliver redundancy, a second master is needed. SONET/SDH networks deploy Synchronization Supply Units (SSU) or Building Integrated Timing Source (BITS) to accept alternative synchronization sources and select the best available. Between the PRS and SSU, SONET/SDH networks use SONET/SDH Equipment Clock (SEC) to distribute clocks from an upstream node to downstream nodes.

As long as the equipment clocks have connections to their respective clocks, their synchronization performance will be defined by the reference clock such as a PRC. However, if they lose their synchronization source, their stability will be dependent on the behavior of the internal clock. For some limited time after the loss of reference event, the equipment can rely on its holdover function to limit the extent of drift from its reference. The holdover uses history data before the holdover to control its internal oscillator. Beyond the holdover algorithm and data, the choice of internal oscillator is critical for maintaining a good stability. Ovenized crystal oscillators are broadly used in synchronization applications supporting a range of stability requirements for SEC and other stratum 3/3E use cases. Rubidium oscillators deliver better stability and are typically used in SSU/BITS equipment, and yes, they are more expensive. PRC/PRS and SSU/BITS are typically produced as stand-along equipment; SEC/SMC are more commonly integrated as part of a network element such as a SONET/SDH or Synchronous Ethernet node.

Several factors are considered for distinguishing and selecting the proper synchronization solution for an application. The long-term accuracy and short-term stability are among those factors. The former is guaranteed by use of GPS receiver that is ultimately traced to Universal Traceable Time (UTC). The GPS receivers, however, may not meet the short-term stability requirements. Therefore, a synchronization solution typically relies on some type of precision quartz oscillator with various cost/performance parameters.

Time Error, Jitter and Wander Measurements

G.810 (Definitions and terminology for synchronization network) provides the definitions and abbreviations used in timing and synchronization recommendations.

Standard	Title
G.810	Definitions and terminology for synchronization networks
G.811	Timing characteristics of Primary Reference Clocks (PRC)
G.812	Timing requirements of slave clocks suitable for use as node clocks in synchronization networks
G.813	Timing characteristics of SDH equipment slave clocks (SEC)
G.823	The control of jitter and wander within digital networks which are based on the 2048 kbit/s hierarchy
G.824	The control of jitter and wander within digital networks which are based on the 1544 kbit/s hierarchy
G.825	The control of jitter and wander within digital networks which are based on the synchronous digital hierarchy (SDH)

Table 2: ITU-T Synchronization Standards for timing/synchronization

Time error (TE) function: The time error of a clock, with respect to a frequency standard, is the difference between the time of that clock and the frequency standard one. Time error is the basic function whereby many different stability parameters (such as MTIE, TIErms, Allan variance, etc.) can be calculated.

Time interval error (TIE) function: The difference between the measure of a time interval as provided by a clock and the measure of that same time interval as provided by a reference clock.

Jitter and wander are defined as the short-term and the long-term variations of the significant instants of a digital signal from their ideal positions in time, respectively. Short/long term implies that these variations are of frequency greater/less than 10 Hz (Figure 5).

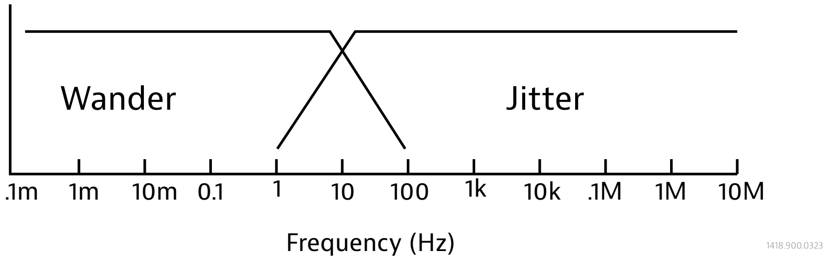

Figure 5: Frequency range for jitter and wander (G.810)

Jitter: Network node interface jitter requirements given in Recommendations G.823, G.824 and G.825 fall into two basic categories:

- specification of the maximum permissible jitter at the output of hierarchical interfaces;
- sinusoidal jitter stress test specifications to ensure the input ports can accommodate expected levels of network jitter.

Jitter is normally specified and measured as a maximum phase amplitude within one or more measurement bandwidths. Jitter amplitude is specified in Unit Intervals (UI), such that one UI of jitter is equal to one data bit-width.

Wander: wander requirements fall into the following categories and are defined in recommendations G.811, G.812, and G.813 for PDH/SDH networks. The requirements for synchronous Ethernet and packet-based networks are defined in G.826x/G.827x standards further described below, and often refer to G.81x standards.

- maximum permissible wander at the output of synchronization network nodes;
- stress tests to ensure that synchronous equipment input ports can accommodate expected
- levels of network wander;
- wander specifications for primary reference and slave clocks may include:
  - intrinsic output wander under locked conditions;
  - intrinsic output wander under free-running conditions;
  - output wander under stress test conditions;
  - wander transfer characteristic.

Wander measurements are typically derived from time interval error (TIE) functions, and characterized by several metrics including maximum time interval error (MTIE), and time deviation (TDEV) in nanoseconds:

- MTIE: the maximum peak-to-peak delay variation of a given timing signal with respect to an ideal timing signal within an observation time (t=nt0) for all observation times of that length within the measurement period (T)
- TDEV: measure of the expected time variation of a signal as a function of integration time.

Wireless Synchronization Requirements

Wireless services relied on synchronization from the very beginning. GSM/EDGE services (Table 3) depended on frequency synchronization for proper network operation. 3gpp standards mandate 50 ppb for the frequency stability of a macro BTS. 3G (UMTS/WDCMA-FDD), 4G (LTE-FDD) and 5G NR (FDD) applied the same requirements. CDMA-2000, WCDMA-TDD, LTE-TDD and 5G NR-TDD networks drove the need for timing and phase synchronization in microsecond range. Implementing these requirements led to the deployment of GPS (GNSS) and PDH/T1/T3/BITS and SONET/SDH timing at cell sites and wireless switch/aggregation sites.

Radio technology	Frequency sync	Time/Phase Sync
GSM	50-100 ppb	
CDMA 2000		3-10 us
UMTS/WCDMA-FDD	50-100 ppb	
WCDMA-TDD		3 us
LTE-FDD	50-100 ppb	
LTE-TDD	50-100 ppb	3-10 us
5G NR - FDD	50-100 ppb	
5G NR - TDD	50-100 ppb	3-10 us

Table 3: Wireless Synchronization requirements (2G/3G/4G/5G)

While Global Positioning System (GPS) technology still represents the primary synchronization method for cell sites; in many countries including the US, network based synchronization has been increasingly deployed in new networks around the world as a back-up or primary synchronization source. Packet-based network synchronization technologies have increasingly been replacing PDH/T1/T3 or SONET/SDH based systems in new networks.

Packet-Based Synchronization Standards

Key component of Carrier Ethernet standard developments was necessary enhancements for a packet-based synchronization standard that can meet critical end user applications such as wireless services. Prior to these activities, various packet-based technologies had been deployed in smaller private networks such as enterprises or industrial automation applications. Network Timing Protocol (NTP) had been used for many years; primarily for obtaining a reference time from a NTP server and synchronize various geographically dispersed end points. NTP was also selected as a technology for radio access networks, although its penetration slowed down with the introduction of IEEE 1588v2 standard (Table 4).

Also known as Precision Timing Protocol (PTP), IEEE 1588v2 was proposed based on IEEE 1588 standard that initially aimed to address the needs of synchronization in instrumentation applications in smaller networks such as production or laboratory test stands. To make it telecom grade for larger geographic distribution and meeting stricter timing requirements, various capabilities were added. Beyond these enhancements, ITU created a powerful set of standards that take advantage of IEEE 1588v2, and define network requirements, clock aspects, methods and profiles for deployment in telecom networks.

Lastly, Synchronous Ethernet (SyncE) represents another major enhancement of the Carrier Ethernet project. It merged the best of SONET/SDH synchronization capabilities with Ethernet. Stable oscillators (e.g. Stratum 3E with stability of 4.6ppm) replace conventional oscillators used in asynchronization networks (100pm). Furthermore, SyncE receivers can recover a clock from incoming Ethernet packets and synchronize it to its internal oscillator thereby enabling a node to be synchronized to its upstream node. Finally, Ethernet Synchronization Message Channel (ESMC) delivers a communication protocol for exchange of synchronization quality info between SyncE nodes. Naturally, these capabilities enable SyncE to be a powerful technology for frequency synchronization.

Technology	Frequency	Time/Phase	Network based?
GPS	Y	Y	
PTP/NTP	Y	Y	Packet layer based
SyncE	Y	N	Physical layer based
E1/E3/DS1/DS3, 2/10 MHz BITS/SSU, SONET/SDH	Y	N	Physical layer based

Table 4: Synchronization technologies

IEEE 1588V2

Also known as IEEE 1588v2, the IEEE St. 1588™-2008 defines a protocol enabling precision synchronization of clocks in measurement and control systems using network communication, local computing and distributed objects. The standard allows synchronization accuracies better than 1 nanosecond. It includes a User Datagram Protocol (UDP)/Internet Protocol (IP), and Layer-2 Ethernet implementation and specifies a Precision Time Protocol (PTP) and the nodes, system and communication properties to support PTP. The protocol synchronizes the nodes that are organized in a master-slave hierarchy with the clock at the top determining the reference time for the entire system.

A PTP system is composed of PTP and non-PTP devices. They exchange event and general messages (Table 5). Event messages require accurate timestamping.

Event messages	General messages	Comments
Sync	Follow_up	
Delay_Req	Delay_Resp	
Pdelay_Req	Pdelay_Resp_Follow_Up	Only in PTP networks using Peer-to-Peer Delay mechanism
Pdelay_Resp		
	Management	
	Announce	
	Signaling	

Table 5: PTP Messages

Non-PTP devices can be routers, bridges, computers etc. They don't process PTP messages. PTP devices include:

- Ordinary Clocks (OC) can be a slave clock or a grandmaster clock
- Boundary Clocks (BC) behave as slave devices facing their upstream nodes, and work as a master on the downstream path.
- End-to-End and Peer-to-Peer Transparent Clocks (TC) described below.
- Management nodes serve as a human or programmatic interface to PTP management messages. It can be combined with any of the devices above.

The PTP protocol exchange (Figure 6) starts by establishing a master-slave hierarchy. Using the Best Master Clock Algorithm (BMCA), the announce message contents of incoming clocks are compared to determine the best clock. Once the hierarchy is established, OC and BC's synchronize by exchanging PTP messages (Figure 1) using the Sync, Delay_Req, -if necessary- Follow_Up, and Delay_Resp messages.

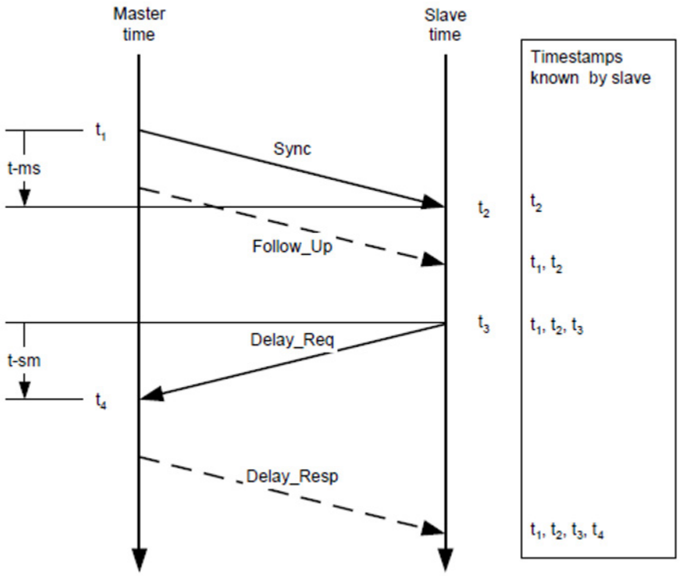

Figure 6: Basic Synchronization message exchange

Beyond OC and BC, Transparent Clocks (TC) can be used in PTP networks. They don't assume the role of a master or slave clock, but -unlike conventional (non PTP) switches- they perform critical operations that allow OC/BC to account for delays occurred by them in the path between a grandmaster and a slave node. There are two mechanisms:

1. End-to-End TC use the Delay_Request and Response mechanism by taking advantage of Sync Delay_Req, Delay_Resp and -if necessary- Follow_Up messages.
2. Peer-to-Peer TC use the alternative Peer Delay mechanisms by exchanging the additional Pdelay_Req, Pdelay_Resp, and -if required- Pdelay_Resp_Follow_Up messages.

End-to-End TC provide transit time information to downstream OC/BC. It is the transit time taken by TC between ingress and egress ports. This information allows the OC/BC to account for the delays, and to calculate the overall delay incurred by TC. Peer-to-Peer TC go beyond providing transit time information. They perform delay measurements using peer to peer delay mechanism allowing them to precisely characterize the delay between the peer ports. They used this information to correct the timing information in Sync and Follow_Up messages.

The last category of PTP messages are management and signaling messages. The former messages are exchanged between management nodes and clocks, and are used to query or update PTP information with individual clock nodes. They are also applied for initialization and fault management nodes. Finally, signaling messages are used for all other necessary functions. For example, they can be used to negotiate the rate of event message exchange between a master and its respective slaves.

IEEE 1588v2 Profiles: since IEEE 1588v2 covers a wide range of applications and attributes, PTP profiles are defined to permit specific selections of attribute values and optional features of PTP that, when using the same transport protocol, inter-work and achieve a performance that meets the requirements of a particular application. Examples for telecom profiles are mentioned farther below.

Telecom Synchronization Standards

IEEE 1588v2 provides a powerful baseline for different synchronization applications. They include telecom/wireless, audio/video, and utility applications. In this section, we are focusing on the applications in telecommunications network. ITU-T has defined a series of standards for synchronization applications (Figure 7).

G.8260 provides the definitions, terminology and abbreviations used in frequency, phase and time synchronization in packet networks. It includes the definitions of various metrics for time error function with reference to the G.810 standard briefly described above.

- Constant time error (cTE) which can be estimated by averaging the first M samples of the time error function
- Maximum absolute time error (Max|TE|) is the maximum absolute value of the time error function

Beyond G.8260, there are two categories of standards for frequency (G.826x) and time/phase (G.827x) synchronization.

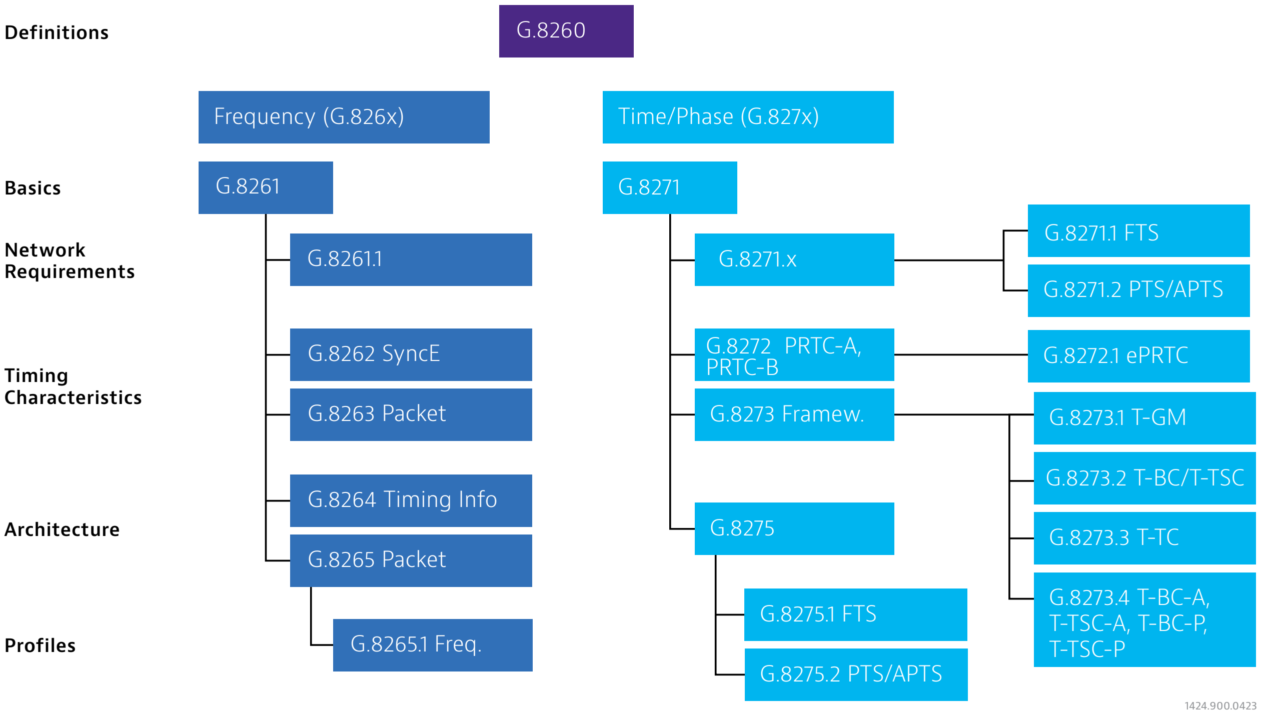

Figure 7: Overview of ITU-T Synchronization standards

Frequency Synchronization Standards

G.8261 (Timing and synchronization aspects in packet networks) and focuses on frequency synchronization applications such as:

- Reference timing distribution over packet networks: PNT (packet networking timing) domain
- Timing recovery for constant bit rate services transported over packet networks: CES (circuit emulation services) domain

The PNT domain can be supported by distributed PRC or master-slave methods. The distributed PRC would have limited scalability and would be relatively expensive. Master-slave methods can include:

- Synchronous Ethernet networks
- Packet-based methods such as PTP or NTP (Network Timing Protocol)

The CES domain is about support for constant bit rate CBR services such as circuit emulated Time domain multiplexed TDM signals. It can be addressed by various methods such as network synchronous operation, differential methods, adaptive methods, or reference clocks available at the TDM end.

Beyond defining the use cases and methods for frequency synchronization, the G.8261 defines the network limits for the applications above. The network limits are characterized by wander and jitter measurements further described below.

G.8261.1 (packet delay variation network limits applicable to packet-based methods) specifies the hypothetical reference models (HRM) and packet delay variation (PDV) network limits when frequency synchronization is carried via packet networks. HRM can be provided by Optical Ethernet based transport technologies or alternative access technologies. The latter can include digital subscriber line (DSL), passive optical networks (PON), or microwave backhaul technologies.

Network limits are defined for various network reference points (Figure 8) such as

- packet-based equipment clock master (PEC-M)
- packet-based equipment clock slave frequency (PEC-S-F)

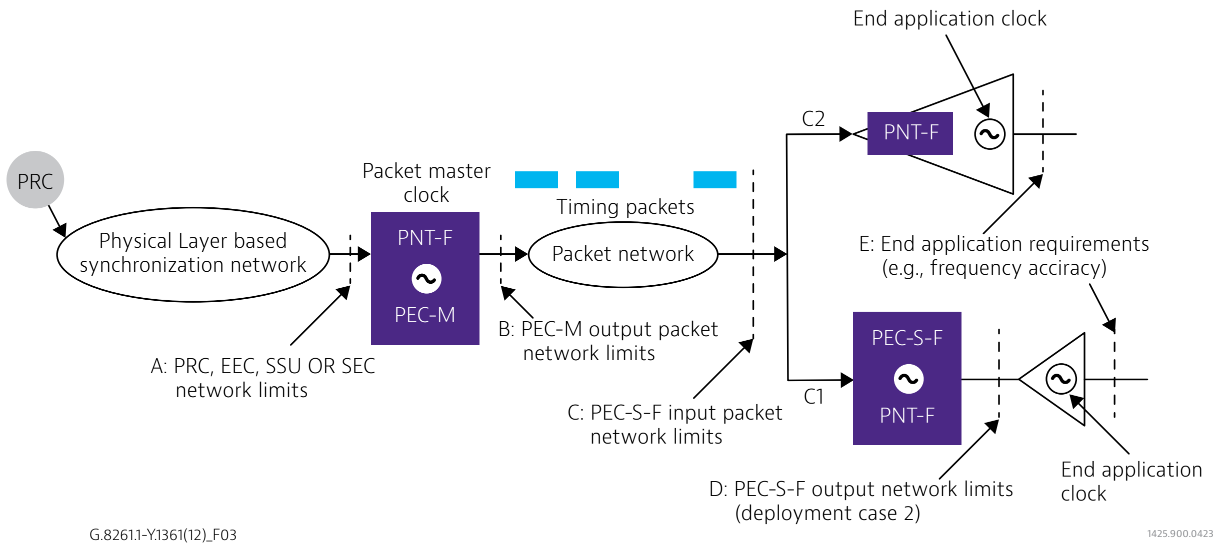

Figure 8: Reference points for network limits

There are three categories for network limits in G.8261.1:

- Network limits at the input of PEC-M
- Network limits at the output of PEC-S-F
- PDV limits

The first two categories deal with clock interfaces and their limits are taken from other standards such as G.8261 or G.823/G.824. The PDV network limit represents the maximum permissible levels of PDV at the interface C (Figure 8 above). A network is qualified to carry frequency synchronization if it can generate a controlled amount of PDV. How do we determine the controlled amount of PDV? G.8261.1 introduced the concept of floor packet percentage (FPP) for HRM-1 (Optical Ethernet networks); PDV for HRM-2 is for further study.

FPP is characterized by a window interval W (200 seconds), and a fixed cluster range δ of 150 μs starting at the floor delay. A network is qualified if for any window interval W of 200 seconds, at least 1% of transmitted packets will be received within a fixed cluster. The cluster δ starts at the observed floor delay for the respective window, and has a range of 150 μs.

$$FPP(n, W, \delta) \geq 1\%$$

G.8262 (Timing characteristics of synchronous Ethernet equipment slave clock) outlines minimum requirements for timing devices used in synchronizing network equipment that supports synchronous Ethernet. The requirements include:

- Frequency accuracy
- Pull-in, hold-in, pull-out ranges
- Noise generation defined in terms of jitter and wander at equipment output (Figure 9)
- Noise tolerance defined in terms of input jitter and wander that the equipment can tolerate
- Noise transfer
- Transient responses

The requirements are applied to a range of interfaces that include PDH/T-carrier, SONET/SDH and Synchronous Ethernet interfaces.

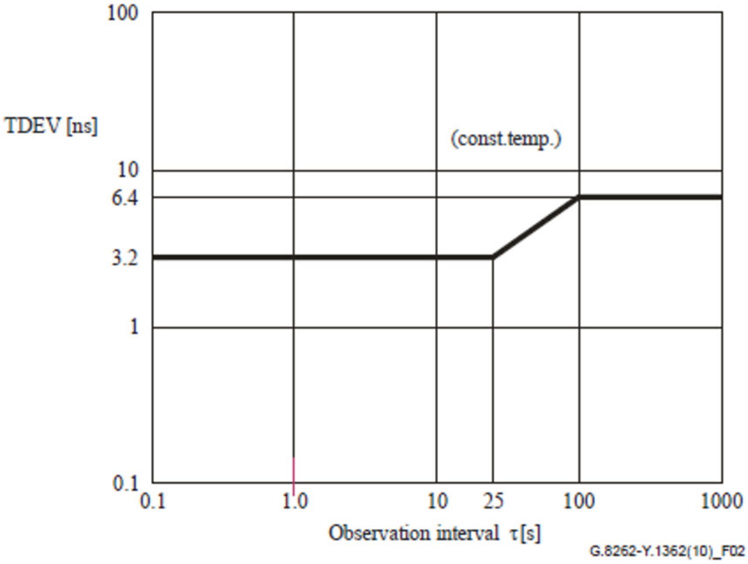

Figure 9: Wander generation (TDEV) for EEC-Option 1 with constant temperature

G.8263 (Timing characteristics of packet-based equipment clocks) outlines minimum requirements for the timing functions of the packet slave clocks (Figure 10). The input interface is Ethernet, the synchronization output may be:

- 1544 kbit/s interfaces according to [ITU-T G.703];
- 2 048 kHz external interfaces according to [ITU-T G.703];
- 2 048 kbit/s interfaces according to [ITU-T G.703];
- synchronous Ethernet interfaces.

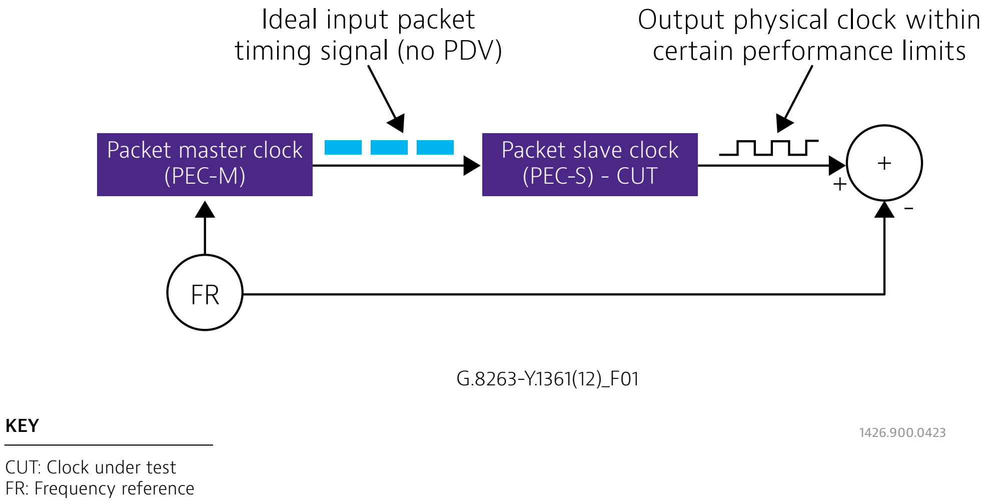

Figure 10: G.8263 Testing procedure for noise generation

The requirements are:

- Output frequency accuracy < 4.6 ppm (free running condition)
- Output noise generation (Figure 11)
- PDV noise tolerance: the noise level that the PEC-S-F should tolerate. It is defined under G.8261.1 PDV limits (above).
- Long term phase transient response (holdover)

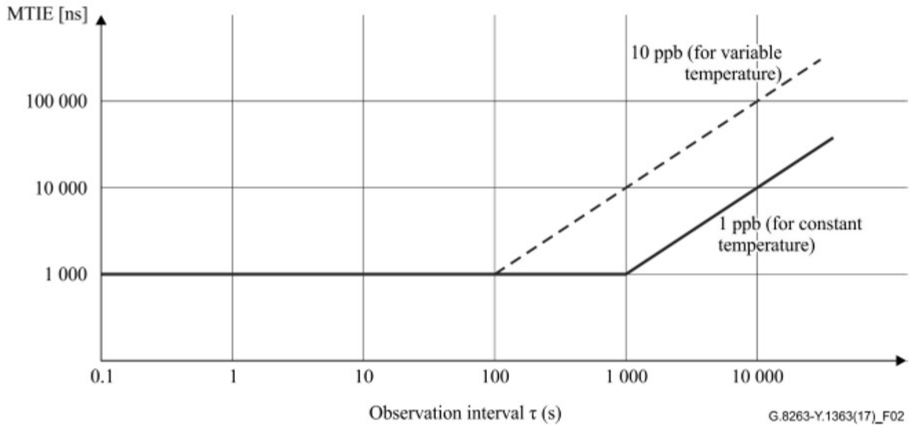

Figure 11: PEC-S-F output noise generation

G.8265 (Architecture and requirements for packet-based frequency delivery) describes the architecture and requirements for packet-based frequency distribution in telecom networks. The recommendation covers:

- Architecture of packet-based frequency distribution (Figure 12)
- Timing protection
- Packet network partitioning
- Packet-based protocols including network timing protocol (NTP) and PTP/IEEE 1588v2. It refers to G.8265.1 as the document describing the profile for PTP profile for telecom applications (next section).
- Security aspects

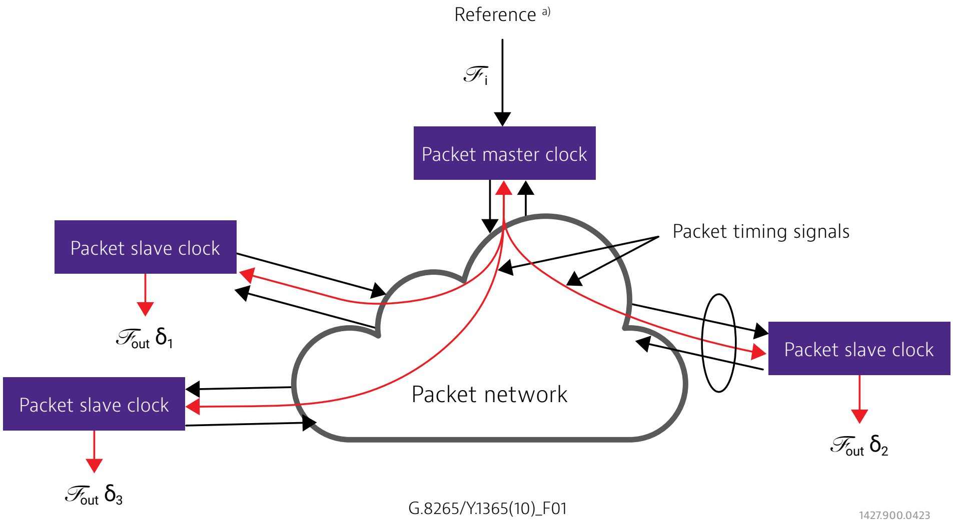

Figure 12: General packet network timing architecture

G.8265.1 (Precision time protocol telecom profile for frequency synchronization) specifies the PTP functions that are necessary to ensure network element interoperability for the delivery of frequency only. Some of the highlights of the profile are:

- No on-path support (no requirement for boundary or transport clock)
- IP/Layer 3 network layer (over Ethernet or other lower-layer protocols) due to its ubiquity across the world
- Announce message carry quality level (QL) that was defined in G.781 and are used in SONET/SDH and SyncE synchronization status messages (SSM)
- Unicast transmission
- Static provisioning (instead of best master clock algorithm BMCA)
- Message rates (Table 6: PTP message rates)

Message Rates	Minimum	Maximum	Default
Announce	1 msg every 16 sec	8 msg/s	1 msg every 2s
Sync	1 msg every 16 sec	128 msg/s	Not defined
Delay_request	1 msg every 16 sec	128 msg/s	Not defined

Table 6: PTP message rates

Time and Phase Synchronization Standards

G.8271 (Time and phase synchronization aspects of packet networks) defines time and phase synchronization aspects in packet networks. There are a number of use cases for time/phase synchronization (Table 7). G.8271 focuses on classes 4, 5, and 6.

Level of accuracy	Time error requirements (Note 1)	Typical applications (for information)
1	500 ms	Billing, alarms
2	100 μs	IP Delay monitoring
3	5 μs	LTE TDD (Large cell)
4	1.5 μs	UTRA-TDD, LTE-TDD (small cell) WiMAX-TDD (some configurations)
5	1 μs	WiMAX-TDD (some configurations)
6	x ns (Note 3)	Various applications, including Location based services and some LTE-A features (Note 2)

Table 7: Time and phase requirement classes

Just as with frequency synchronization, the time/phase synchronization requirements can be met either with a distributed PRC method, or packet-based methods. The packet-based method can be deployed with protocols such as PTP. The G.8271 currently focuses on cases where the timing reference is carried with support from the network, i.e. the intermediate notes will implement boundary clock or transparent clock functions. Finally, G.8271 defines a measurement interface to allow network operators to measure the quality of the time/phase synchronization along the synchronization chain. The one pulse-per-second (1PPS) interface is specified in Annex A.

G.8271.1 (Network limits for time synchronization in packet networks) specifies the maximum network limits of phase and time error that shall not be exceeded. It specifies the minimum equipment tolerance to phase and time error that shall be provided at the boundary of packet networks at phase and time synchronization interfaces. It also outlines the minimum requirements for the synchronization function of network elements.
This recommendation addresses the use case for full timing support. The limits are defined for two main cases (Figure 13):

- deployment case 1: the telecom time slave clock (T-TSC) is integrated in the end-application
- deployment case 2: the T-TSC is external to the end application

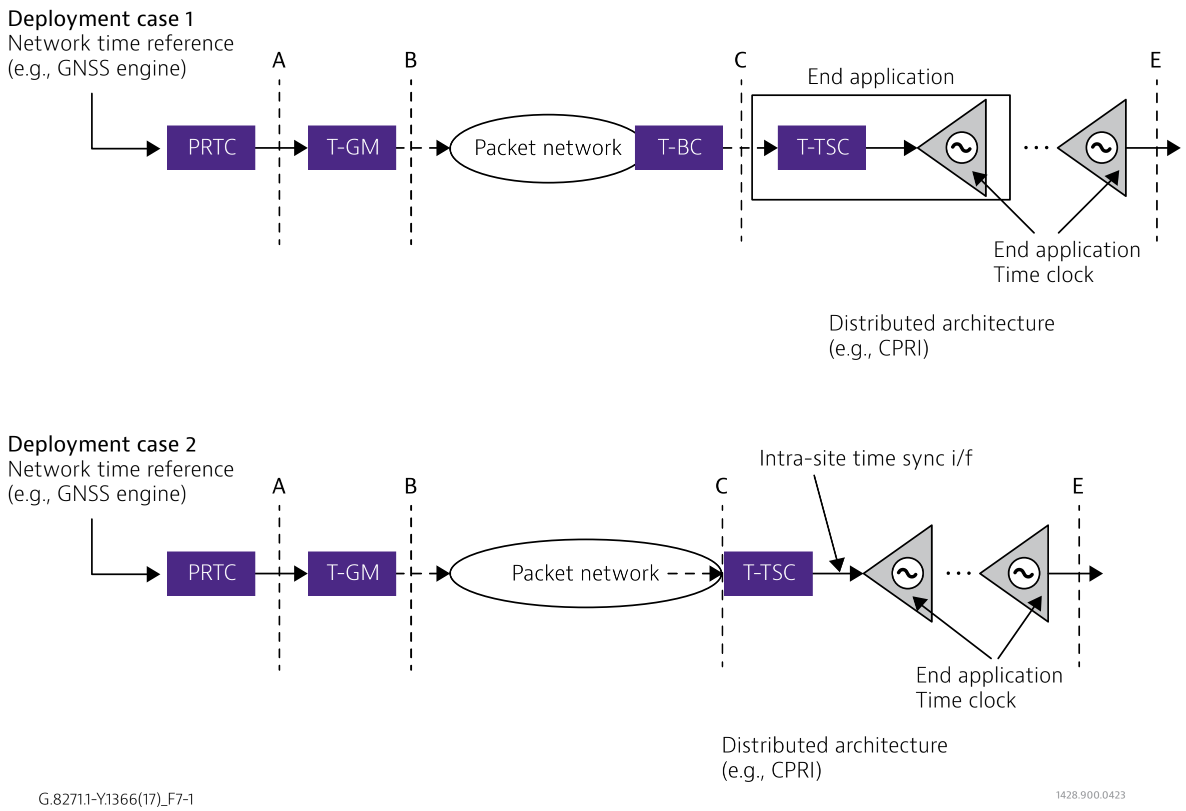

Figure 13: Time synchronization deployment cases

Network limits at reference point A: they are specified in G.8272 (see below)

Network limits at reference point B:

- In case of a telecom grand master (T-GM) integrated into the PRTC, the network limits are the same as the ones at reference point A. In case of T-GM external to the PRTC, the limits are for further study.

Network limits at reference point C: this recommendation provides the limits for class 4 (Table 7). They are defined for deployment case 1. The limits for deployment case 2 are for further study. The noise is characterized by two main aspects:

- Maximum absolute TE, max |TE| < 1,100 ns
- MTIE defined in figure (Figure 14); TDEV is for further study.

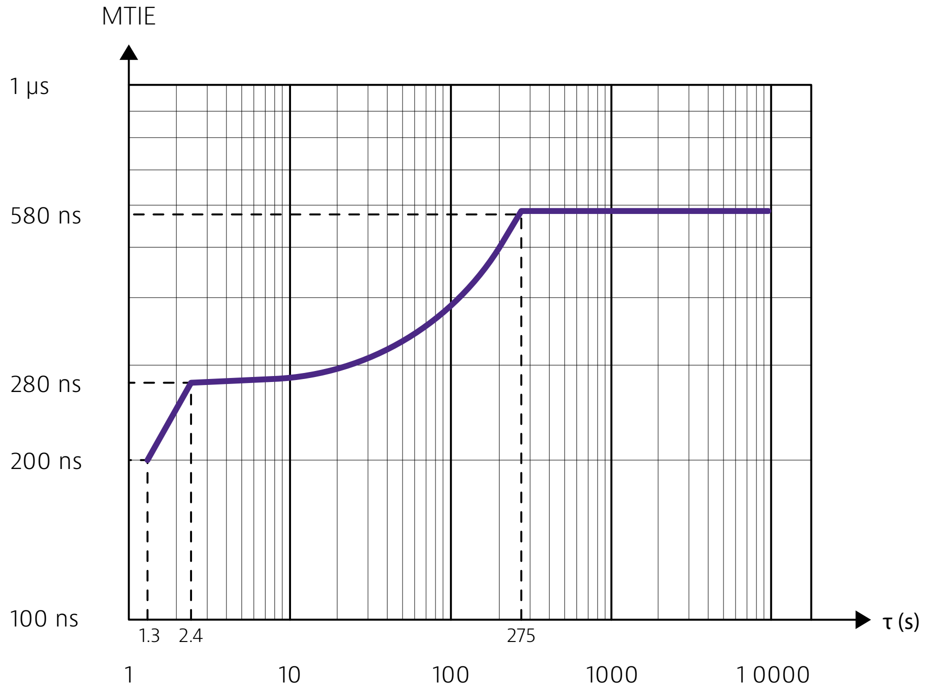

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Figure 14: Dynamic time error network limit (MTIE) at reference point C

Network limits at reference point D: for deployment case 1 are for further study. For deployment case 2, the limits are the same as with reference point C in deployment case 1 (Figure 13).

Network limits at reference point E: are defined by the specific application as outlined in table x above.

G.8271.2 (Network limits for time synchronization in packet networks with partial timing support from the network) defines the network limits for the case of a packet method with partial timing support that is characterized by two cases:

- Assisted partial timing support (APTS) in which case PTP is used as a backup to a local time refence based on the global navigation satellite system (GNSS) (Figure 15)
- Partial timing support (PTS) in which case PTP is the primary source of time (Figure 16)

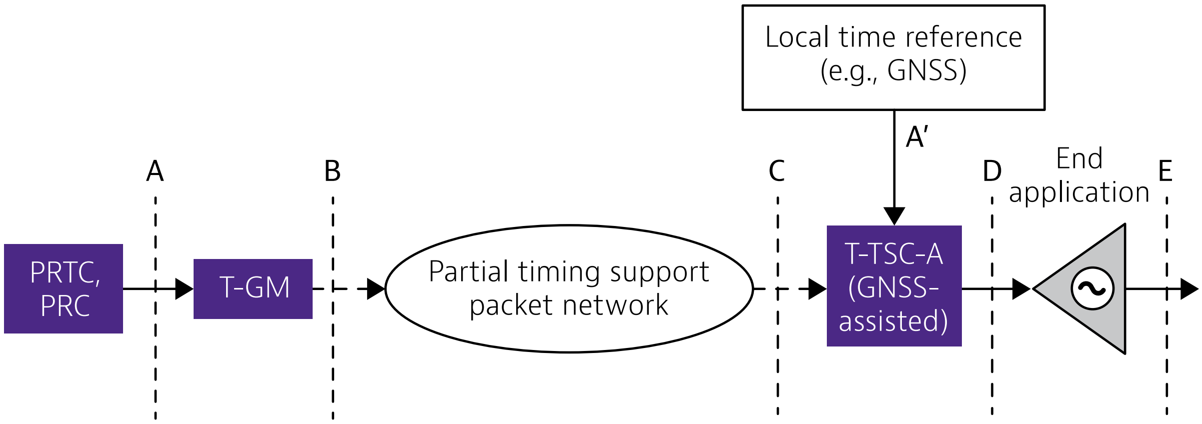

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Figure 15: APTS

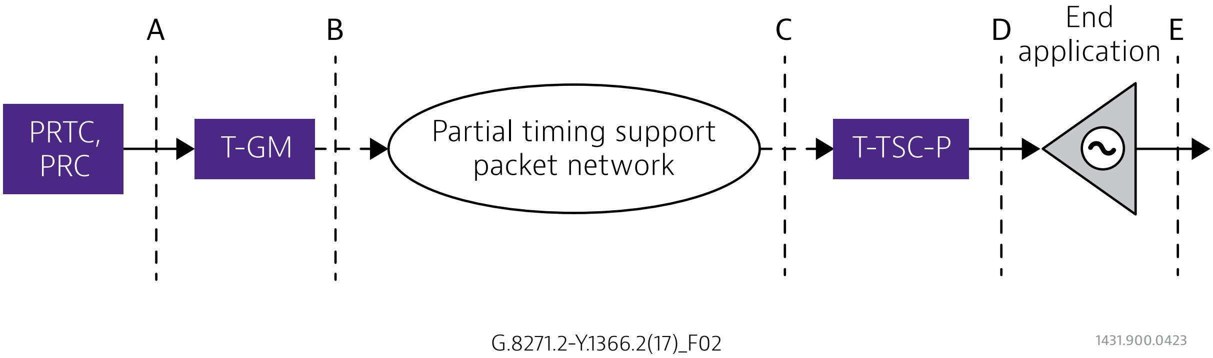

Figure 16: PTS

Network limit at reference points A and A': they are defined in G.8272 (below); in particular,

- Max |TE| < 100 ns

Network limit at reference point B: the limits are the same as for reference points A/A', if the T-GM is integrated in the PRTC. For external T-GM, the limits are for further study.

G.8272 (Timing characteristics of primary reference time clocks) specifies the requirements for primary reference time clocks (PRTC) suitable for time, phase and frequency synchronization in packet networks. There are two types of PRTC: PRTC-A and PRTC-B. The timing output of PRTC-B is more accurate than the one of PRTC. A typical PRTC provides the reference signal for time, phase and frequency synchronization for other clocks within a network or section of a network. This Recommendation defines the PRTC output requirements. The accuracy of the PRTC should be maintained as specified in this Recommendation. This Recommendation also covers the case where a PRTC is integrated with a T-GM clock. In this case it defines the performance at the output of the combined PRTC and T-GM function, i.e., the precision time protocol (PTP) messages.

The recommendation contains the time error, wander and jitter requirements in locked mode, as well as the holdover requirements. In particular, the recommendation defines:

- Time error of 100ns for PRTC-A or 40 ns for PRTC-B against an applicable primary reference such as universal time clock (UTC)
- MTIE (Figure 17) and TDEV

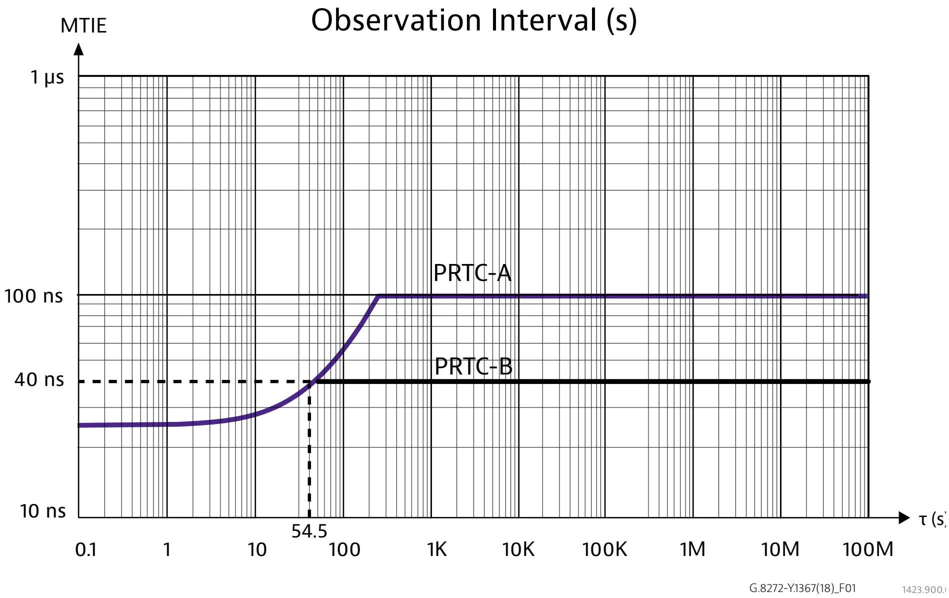

Figure 17: MTIE for PRTC -A and PRTC-B

The limits are defined for the PRTC output, or for T-GM output, if the PRTC is integrated with PRTC. Following test interfaces are possible:

- For time/phase:
  - ITU-T V.11-based time/phase distribution interface, as defined in [ITU-T G.703] and [ITU-T G.8271];
  - 1PPS 50 Ω phase-synchronization measurement interface, as defined in [ITU-T G.703] and [ITU-T G.8271];
  - Ethernet/PTP interface
- Frequency:
  - 2 048 kHz interfaces according to [ITU-T G.703]
  - 1 544 kbit/s interfaces according to [ITU-T G.703]
  - 2 048 kbit/s interfaces according to [ITU-T G.703]
  - Synchronous Ethernet interfaces (including PTP)
  - V.11-based time/phase distribution interface, as defined in [ITU-T G.703] and [ITU-T G.8271];
  - 1PPS 50 Ω phase-synchronization measurement interface, as defined in [ITU-T G.703] and [ITU-T G.8271]

G.8272.1 (Timing characteristics of enhanced primary reference time clocks) specifies the requirements for enhanced primary reference time clocks (ePRTCs) suitable for time and phase synchronization in packet networks. It defines the error allowed at the time output of the ePRTC.:

  - Time error of 30 ns against an applicable primary reference such as universal time clock (UTC)
  - MTIE and TDEV

G.8273 (Framework of phase and time clocks) is a framework Recommendation for phase and time clocks for devices used in synchronizing networks defined in G.827x series of recommendations (above). This recommendation refers to a series of G.8273.x recommendations further described below. While the IEEE 1588v2 defines equipment such as OC, BC, TC, and GM, the ITU-T G.8273.x series define the following type of devices. The following devices include not only the specification of respective IEEE 1588v2 devices, but also contain additional performance characteristics outlined in sections farther below in this paper

- Telecom Grand Master (T-GM) in G.8273.1
- Telecom Boundary Clock (T-BC) and Telecom Time Slave Clock (T-TSC) in G.8273.2
- Telecom Transparent Clock (T-TC) in G.8273.3
- Partial and Assisted partial timing Telecom Boundary Clock and Telecom slave clock (T-BC-P, T-BC-A, T-TSC-P, T-TSC-A) in G.8273.4

G.8273.1 is about requirements for Telecom Grandmaster and is not public at the time of the writing of this paper.

G.8273.2 (Timing characteristics of telecom boundary clocks and telecom time slave clocks) allows for proper network operation for phase/time synchronization distribution when network equipment embedding a telecom boundary clock (T-BC) and telecom time slave clock (T-TSC) is timed from another T-BC or a telecom grandmaster (T-GM). This Recommendation includes noise generation, noise tolerance, noise transfer and transient response for telecom boundary clocks and telecom time slave clocks.

The noise generation of a T-BC is characterized by max|TE| (Table 8), cTE (Table 9), and dynamic TE. Class B devices have more stringent requirements, and therefore allow operators to design networks with larger number of T-BC between the T-GM and T-TSC.

T-BC/T-TSC Class	Maximum Absolute Time Error – max|TE| (ns)
A	100 ns
B	70 ns
C	30 ns
D	For further study

Table 8: Max|TE| limits for T-BC

T-BC/T-TSC Class	Permissible Range of Constant Time Error – cTE(ns)
A	±50
B	±20
C	±10
D	For further study

Table 9: cTE limits for T-BC

The dynamic TE is characterized by two components dTE_L and dTE_H. The former is further verified by measuring MTIE and TDEV (Table 10). These measurements are done through a first-order low-pass filter with a bandwidth of 0.1 Hz. The dTE_H is characterized by measuring the peak-to-peak time error with a first-order high-pass filter with a bandwidth of 0.1 Hz.

T-BC/T-TSC Class	MTIE Limit (ns)	Observation Interval τ (s)
A	40	$m \le \tau \le 10{,}000$ (Notes 1, 2)
B	40	$m \le \tau \le 10{,}000$ (Notes 1, 2)
C	For further study	For further study
D	For further study	For further study

Table 10: MTIE Limits (G.8273.2)

Beyond noise generation, G.8273.2 specifies more requirements which are beyond the scope of this paper. They include noise tolerance, noise transfer, transient response and holdover performance. It also includes requirements on relative time error noise generation (TE_R). Finally, it includes requirements for physical layer frequency performance requirements which are in line with the ones outlined in G.8262 document described above.

G.8273.3 (Timing characteristics of telecom transparent clocks for use with full timing support from the network) provides similar requirements as in G.8273.2, but in regard to T-TC devices (Table 11, Table 12, and Table 13). This document also includes requirements on dynamic TE which is characterized by dTE_L and dTE_H.

T-TC Class	Maximum Absolute Time Error – max|TE| (ns)
A	100 ns
B	70 ns
C	For further study

Table 11: Max|TE| limits for T-TC

T-TC Class	Permissible Range of cTE(nS)
A	±50
B	±20
C	±10

Table 12: cTE limits for T-TC

T-TC Class	MTIE Limit (ns)	Observation Interval τ (s)
A	40	$m < \tau \leq 1000$ (Notes 1, 2)
B	40	$m < \tau \leq 1000$ (Notes 1, 2)
C	10	$m < \tau \leq 1000$ (Notes 1, 2)

Table 13: dTE limits for T-TC

NOTE 1: The minimum τ value *m* is determined by a packet rate of 16 packet per second (m=1/16)

NOTE 2: The values in Table 7-3 are valid for 1GbE, 10GbE, 25GbE, 40GbE, and 100GbE interfaces. Values for other interfaces are for further study.

G.8273.4 (Timing characteristics of assisted partial timing support slave clocks) specifies minimum requirements for time and phase synchronization equipment used in synchronization networks that operates in the assisted partial timing support (APTS) and partial timing support (PTS) architectures. The requirements reflect the same types of categories as in the G.8273.2, but relate to Telecom Boundary Clocks for Partial Timing Support (T-BC-P) and Assisted Partial Timing Support (T-BC-A), as well as, Telecom Slave Clock for Partial Timing Support (T-TSC-A) and Assisted Partial Timing Support (T-TSC-A).

G.8275 (Architecture and requirements for packet-based time and phase distribution) describes the general architecture of time and phase distribution using packet-based methods. This Recommendation forms the base architecture for the development of telecom profiles for time and phase distribution.

G.8275.1 (Precision time protocol telecom profile for phase/time synchronization with full timing support from the network) contains the ITU-T precision time protocol (PTP) profile for phase and time distribution with full timing support from the network. It provides the necessary details to utilize IEEE 1588 in a manner consistent with the architecture described in Recommendation ITU-T G.8275/Y.1369. Some of the highlights of the profile are:

- OC, BC, and TC are used in this profile
- PTP over IEEE 802.3/Ethernet
- Multicast
- Alternate best master clock algorithm (BMCA)
- Message rates

Message Rates	Nominal
Announce	8 msg/s
Sync/Follow_up	16 msg/s
Del_req/Del. Resp.	16 msg/s

Table 14: PTP message rates (G.8275.1)

G.8275.2 (Precision time protocol telecom profile for phase/time synchronization with partial timing support from the network) specifies a profile for telecommunication applications based on IEEE 1588 precision time protocol (PTP). The profile specifies the IEEE 1588 functions that are necessary to ensure network element interoperability for the delivery of accurate phase/time (and frequency) synchronization. The profile is based on the use of partial timing support (PTS) or assisted partial timing support (APTS) from the network architecture as described in ITU-T G.8275 and definitions described in ITU-T G.8260. Similar to G.8275.1 document, this document specifies different aspects of PTP when in PTS/APTS networks. They include PTP modes, mapping, message rates, and unicast message negotiation. Annex A delivers the detailed specifications of the unicast with examples such as profile identification and PTP attribute values.

Outlook

The synchronization community continues to work on new standards for wireless applications. 5G networks present a new range of requirements that represent significant challenges for network synchronization. Ultra-low latency applications, and the use of advanced radio technologies such as carrier aggregation, transmit diversity, and coordinate multipoint are examples of these new challenges.

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