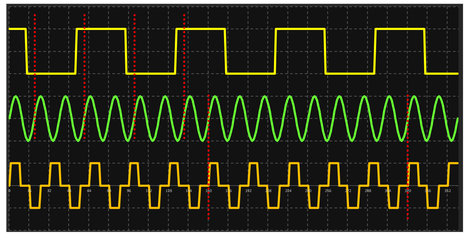
Introduction to Packet Network Synchronization

Practical Reference Guide to 1588v2 PTP & Field Measurements

Physical Layer Clocks, Sync & Timing

Frequency Synchronization

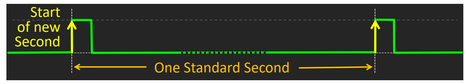
Frequencies are the same, or multiple of each other, but their phase may not necessarily be aligned.



Pulse-per-Second (1PPS) Timing Signal

The 1PPS signal is mainly available in two standard formats defined by ITU-T G.703:

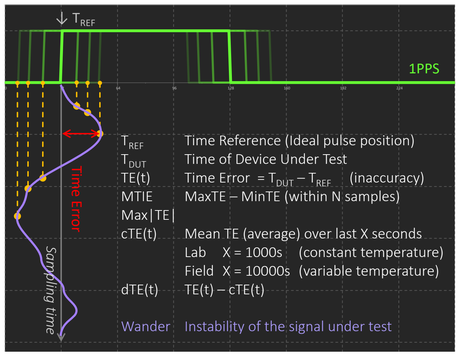
- Unbalanced, using coaxial cables
- Balanced, using V.11 (along with RS422 serial ToD)



Wander (Clock Stability) Measurements

Long-term Time Error or Phase Error measurement helps characterize the clock output quality of a device or link. It provides information about its frequency accuracy, time accuracy or delays, and stability.

TE is normally associated with having a **c**onstant component (e.g., fix delays or inaccurate cable compensations) and a **d**ynamic or variable component (e.g., caused by noise, temperature, PDV), therefore TE ≈ **c**TE + **d**TE.



Time Error Calculation

Delayed pulses are represented by negative TE. Advanced or early pulses have positive TE.

Precision Time Protocol Basics

The Theory

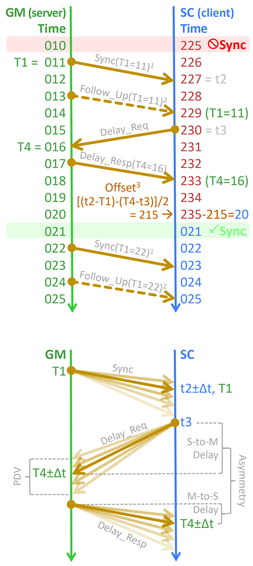
IEEE 1588-2019 PTP defines a hierarchical Server-Client clock distribution architecture, based on a rather simple timestamp-based protocol to correct remote Ordinary Clocks and provide accurate time to remote locations, over packet (Ethernet) networks.

T1 Sync departure timestamp, measured by GM
[1] One Step: Sent inside the Sync message
[2] Two Step: Sent inside a Follow_Up message
t2 Sync arrival timestamp, measured by SC
t3 Delay_Req departure timestamp, measured by SC
T4 Delay_Req arrival timestamp, measured by GM (sent back to SC inside Delay_Resp)

$$\text{Offset} = \frac{[(t2\text{-}T1)\text{-}(T4\text{-}t3)]}{2} \text{ ; SC time correction}$$

[3] It assumes the network delay is symmetric

M-to-S GM to SC direction (Forward)
S-to-M SC-to-GM direction (Reverse)



Real Life

SC manufacturers deal with packet delay variations (PDV), buffering, queuing, delay asymmetry (among others), and rely on statistical process to account for them.

IEEE 1588-2008 introduced the Profile concept, defining PTP operating parameters and options for different environments and applications.

PTP Message Types

Events (time-critical)	General
Accurate departure and arrival timestamping required, as they affect time distribution accuracy.	*No timestamping required*
	Announce
	Follow_Up
Sync	Delay_Resp
Delay_Req	pDelay_Resp_Follow_Up
pDelay_Req	Management
pDelay_Resp	Signaling

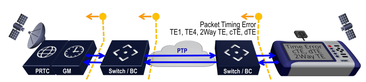
Asymmetry and Time Error Effects

One Way Delay (Direct Asymmetry Measurement)

Using GNSS references and Ethernet test packets, the delay in each direction can be measured independently, including the effects of bare fiber. Before the GM, BCs and/or SC are installed.

PTP assumes symmetrical data links, but longer delay in the M-S (forward) direction causes the T-SC to have negative TE, while longer S-M (reverse) delay causes positive TE.

$TE_1 = T_1 - t_2$ Forward Time Error
$TE_4 = T_4 - t_3$ Reverse Time Error
$TE = (TE_1 + TE_4)/2$ Packet-base Time Transfer Error (2Way TE)

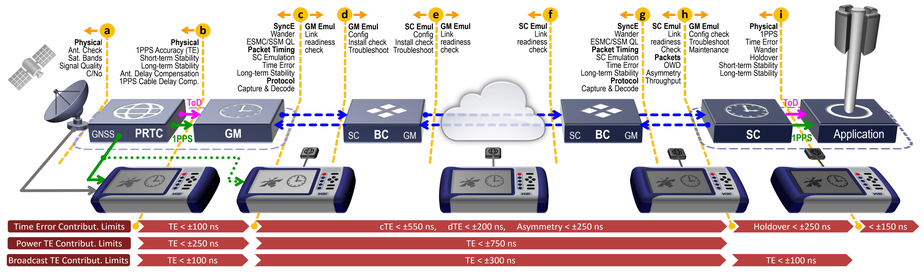


PTP Profiles

IEEE 1588-2008 introduced Profiles, defining PTP operating parameters and options for different environments and applications.

	Frequency	Full Time Support	Partial Time Support	Power Utility	Power Automation
Application	Telecom (legacy)	Telecom	Telecom (GNSS Assisted)	Power Grid	Power Grid Automation
Standard	ITU-T G.8265	ITU-T G.8275.1	ITU-T G.8275.2	IEEE C37.238	IEC 61850-9-3
Profile ID	00-19-A7-00-01-00	00-19-A7-01-01-00	00-19-A7-02-01-00	1C-12-9D-00-00-00	
Transport Layer	Layer 3, UDP, IPv4/6	Layer 2, Ethernet	Layer 3, UDP, IPv4/6	Layer 2, Ethernet	Layer 2, Ethernet
VLAN		Not allowed		Required (ID:0. Priority:4)	Out of scope
Sync & Follow_Up Rate	1/16 ~ 128 pkt/s	16 pkt/s	1 ~ 128 pkt/s	1 pkt/s	1 pkt/s
Delay_Req/Resp Rate	1/16 ~ 128 pkt/s	16 pkt/s	1 ~ 128 pkt/s		
pDelay_Req/Resp Rate				1 pkt/s	1 pkt/s
Announce Interval	1/16 ~ 8 pkt/s	8 pkt/s	1 ~ 8 pkt/s	1 pkt/s	1 pkt/s
Domain Number	4 ~ 43	24 ~ 43 (24)	44 ~ 63	0 ~ 127 (0)	0, 93 (0)
GM Clock Class		6, 7, 140, 150, 160, 248	6, 7, 140, 150, 160, 248	6, 7, 187	6, 7, 52, 187
BC Clock Class		135, 165, 248	135, 165, 248		
SC Clock Class	255	255	255	255	255
Clock Priority 1		128	128		
Clock Priority 2		0 ~ 255 (128)	0 ~ 255		

PTP Network & Test Points



Clock Classes

ITU-T G.8265.1 Frequency

- **G.781 Option 1**: 84 PRC, 90 SSU-A, 96 SSU-B, 104 EEC-1, 110 DNU
- **G.781 Option 2:** 80 PRS, 82 STU, 86 ST2, 90 TNC, 100 ST3E, 102 EEC-2, 106 SMC, 108 PROV, 110 DUS
- **G.781 Option 3:** 82 UNK, 104 SEC

G.8275.1 Time

- **T-GM:** 6 (PRTC ref, locked mode), 7 (within holdover spec), 140 (out of holdover, Category 1), 150 (out of holdover, Cat. 2), 160 (out of holdover, Cat. 3), 248 (no time ref. since start-up)
- **T-BC:** 135 (within holdover spec), 165 (out of holdover spec), 248 (no time ref. since start-up)
- **T-TSC:** 255 (no Announce message is sent)

Quick Reference to Standards

Standards, requirements and limits continue to evolve, and it is not easy to remember which document defines what. For the latest versions of the applicable standards, refer to the ITU-T website www.itu.int/rec/T-REC-G or scan the QR.

General

G.703	Electrical characteristics of hierarchical digital interfaces, including 1PPS and 10 MHz
G.811	Primary Reference Clock
G.812	Timing requirements of node clocks (SSU)
G.823	Jitter and Wander limits for PDH-based synchronization interfaces
G.824	Jitter and Wander limits for DSn-based synchronization interfaces

SyncE

G.8260	General definitions and metrics
G.8261	Basic introduction and network limits
G.82.61.1	Network limits
G.8262	Timing characteristics of synchronous Ethernet Equipment slave Clock (EEC)
G.8262.1	Timing characteristics of enhanced synchronous Ethernet Equipment slave Clock (eEEC)
G.8263	PEC S-F specifications
G.8264	SyncE requirements
G.8266	PEC M-F specifications

PTP

G.8265	PTP/NTP requirements
G.8265.1	PTP frequency profile
G.8271	General Time and Phase Synchronization aspects for Packet Networks
G.8271.1	Network Limits for Time Synchronization in Packet Networks
G.8271.2	Network time limits for PTS
G.8271.1	ePRTC specifications
G.8272	Primary Reference Time Clock (PRTC) specification
G.8273	Framework
G.8273,1	T-GM specification
G.8273.2	T-BC and T-SC specifications
G.8273.3	T-TC specifications
G.8273.4	APTS specification
G.8275	Architecture for Time/Phase Distribution
G.8275.1	Precision Time Protocol (PTP) Telecom Profile for Time/Phase Synchronization. Full on-path time support (FTS)
G.8275.2	GNSS-Assisted Partial Timing Support (PTS and APTS)

GLOSSARY

1PPS	One Pulse Per Second time signal. Marks the beginning of standard second (ITU-T G.703 and G.8271)
APTS	(GNSS) Assisted Partial Timing Support (ITU-T G.8275.2)
BC	Boundary Clock (PTP switch)
BDS	BeiDou (Big Dipper) Navigation Satellite System, Chinese GNSS
BMCA	Best Master Clock (selection) Algorithm
C/No	Carrier-to-Noise density in dB-Hz (e.g., satellite signal quality)
Cs133	Cesium (oscillator)
CSAC	Chip-Scale Atomic Clock
cTE	Constant (Mean) Time Error
DOCXO	Double-oven OCXO
DNU	Do Not Use
dTE	Dynamic Time Error
E2E	End-to-End Path Delay Calculation Method
EEC	(Synchronous) Ethernet Equipment Clock
ePRTC	Enhanced Primary Reference Time Clock (ITU-T G.8272.1)
ESMC	Ethernet Synchronization Messaging Channel (ITU-T G.8264)
eSyncE	Enhanced Synchronous Ethernet
FTS	Full Time Support (ITU-T G.8275.1)
Galileo	European GNSS
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema, Russian GNSS
GM	Grandmaster clock (reference)
GNSS	Global Navigation Satellite Systems (generic for GPS, GLONASS, Galileo, Beidou, etc.)
GNSSDO	GNSS-Disciplined Oscillator
GPS	Global Positioning Satellite system, USA GNSS
GPSDO	GPS-Disciplined Oscillator
gPTP	generalized Precision Time Protocol (IEEE 802.1AS)
IED	Intelligent Electronic Device (Power Utilities)
IEEE	Institute of Electrical and Electronics Engineers (Standards body)
IP	Internet Protocol (Layer 3), IP address
IPG	Inter-Packet Gap
ITU-T	International Telecommunication Union, Telecommunication Standardization Sector
Layer 2	MAC sublayer (switches). Provides flow control and multiplexing for the transmission media.
Layer 3	IP Layer (routers). Provides routing capabilities across network boundaries.
MAC	Media Access Control, MAC Address
MAC	Miniature Atomic Clock
Max|TE|	Maximum time difference between DUT and the reference
MTIE	Maximum Time Interval Error
NE	Network Element
NTP	Network Time Protocol
OC	Ordinary Clock (Master/source or Slave/destination device with single network connection)
OCXO	Oven-Controlled Crystal Oscillator
Offset	Error, deviation from the ideal frequency or time
OWD	One-Way Delay (end-to-end latency)
P2P	Peer-to-Peer Delay Calculation Method
PDV	Packet Delay Variation
PEC	Packet-based Equipment Clock
Phase	Relative time difference between two 1PPS signals
ppb	Parts per Billion (1.00E-9), frequency error or uncertainty (offset)
ppm	Parts per Million (1.00E-6), frequency error or uncertainty (offset)
ppt	Parts per trillion (1.00E-12), frequency error or uncertainty (offset)
PRC	Primary (frequency) Reference Clock (ITU-T G.811)
Profile	Set of definitions, settings and functionalities that fit an application.
PRS	Primary Reference Source (see PRC)
PRTC	Primary Reference Time Clock (ITU-T G.8272)
PSN	Packet Switched Network
PTP	Precision Time Protocol (IEEE 1588 2008/2019, ITU-T G.8275.1, G.8275.2)
PTS	Partial Timing Support
QL	(clock) Quality Level (ITU-T G.781, for PTP Clock Class refer to G.8265.1 and G.8275.1)
Rb87	Rubidium (oscillator)
RTD	Round-Trip Delay
SC	Slave Clock (edge client)
SSM	Synchronization Status Message (ITU-T G.707)
SSU	Synchronization Supply Unit (TDM)
SVN	Satellite Vehicle Number
SyncE	Synchronous Ethernet (ITU-T G.8261, G.8262, G.8264)
T1	GM departure timestamp for outgoing Sync messages (one-step: carried in the Sync message, two-step: carried in the Follow_Up message)
t2	Measured timestamp of Sync message arrival to T-SC
t3	Measured timestamp of Delay_Request message departure from T-SC
T4	GM arrival timestamp for incoming Delay_Request messages, sent inside the Delay_Response message
TAI	Atomic Time (Temps Atomique International), PTP time
T-BC	Telecom Boundary Clock (PTP aware switch) ITU-T G.8273.2
T-BC-A	Telecom Boundary Clock for Assisted partial timing support
T-BC-P	Telecom Boundary Clock for Partial timing support
TC	Transparent Clock (PTP aware switch)
TCXO	Temperature-Compensated Crystal Oscillator
TDEV	Time Deviation
TDM	Time Division Multiplexing (networks) such as SDH/SONET, PDH/DSn
TE	Time Error, relative to a standard time reference. (TE = cTE + dTE)
TE1	Forward (Sync) Time Error
TE4	Reverse (Delay_Request) Time Error
T-GM	Telecom Grandmaster Clock (precision time server)
TIE	Time Interval Error
TLV	Type, Length, Value (message fields)
ToD	Time of Day label identifying the last 1PPS pulse (YYYY-MM-DD hh:mm:ss)
T-SC	Telecom Slave Clock (client)
TSN	Time-Sensitive Network/Networking
T-TSC	Telecom Time Slave Clock (time-oriented client)
T-TC-P	Telecom Transparent Clock for Partial timing support
T-TSC-A	Telecom Time Slave Clock for Assisted partial timing support
T-TSC-P	Telecom Time Slave Clock for Partial timing support
UDP	User Datagram Protocol (Layer 4)
UTC	Coordinated Universal Time
VCXO	Voltage-Controlled Crystal Oscillator
XO	Xtal (crystal) Oscillator. (e.g., Quartz)

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