Calnex Solutions plc
Huawei Technologies Co., Ltd.

Stefano Ruffini, Calnex Solution

Silvana Rodrigues, Huawei

Distribution of Timing: Sync over the Packet Layer of Networks

WSTS Tutorial – May 12-15, 2025

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Note: actions are being taken in various Standardization bodies to revise the Master/Slave terminology («inclusive terminology»).
This slide set is being updated based on the outcome of these initiatives

The use of Inclusive Terminology

- **IEEE Std 1588g-2022** – Amendment to IEEE 1588 for inclusive terminology
  - Scope – “This amendment adds an optional alternative suitable and inclusive terminology to the terms: “master” and “slave”, but it does not replace the terms “master” and “slave”.”
  - timeTransmitter and timeReceiver were selected as an alternative nomenclature for master and slave, and it has been used as a basis for the draft amendment
- **IEEE Std 802.1ASdr-2024** – IEEE 802.1 TSN has published an amendment to IEEE Std 802.1AS to replace non-inclusive terminology in the standard, it is based on IEEE Std 1588g-2022
- IEEE P3400 WG
  - IEEE P3400 Standard for Use of Inclusive Language in Technical Terminology and Communications
  - This standard is going through SA ballot
- ITU-T has almost completed revision of terminology of the active Recommendations
  - Revision of terminology of Physical Layer (SyncPHY) has also been addressed
- Master and Slave may still be used in some figures in this presentation if taken from old documents not revised yet

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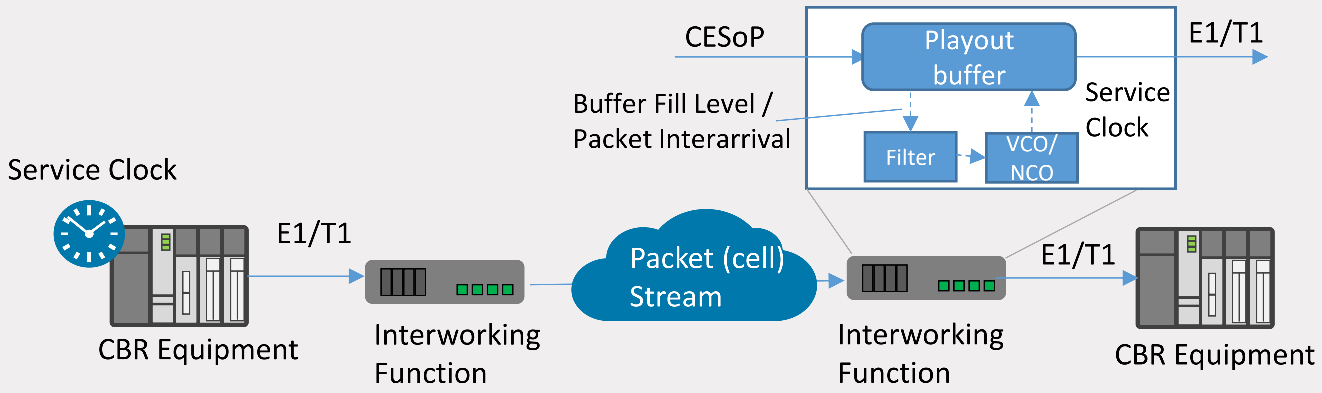
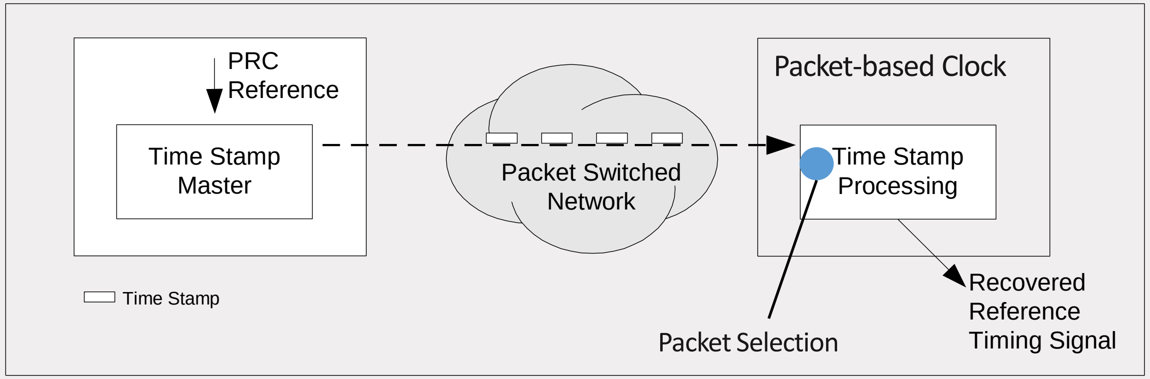
Introduction

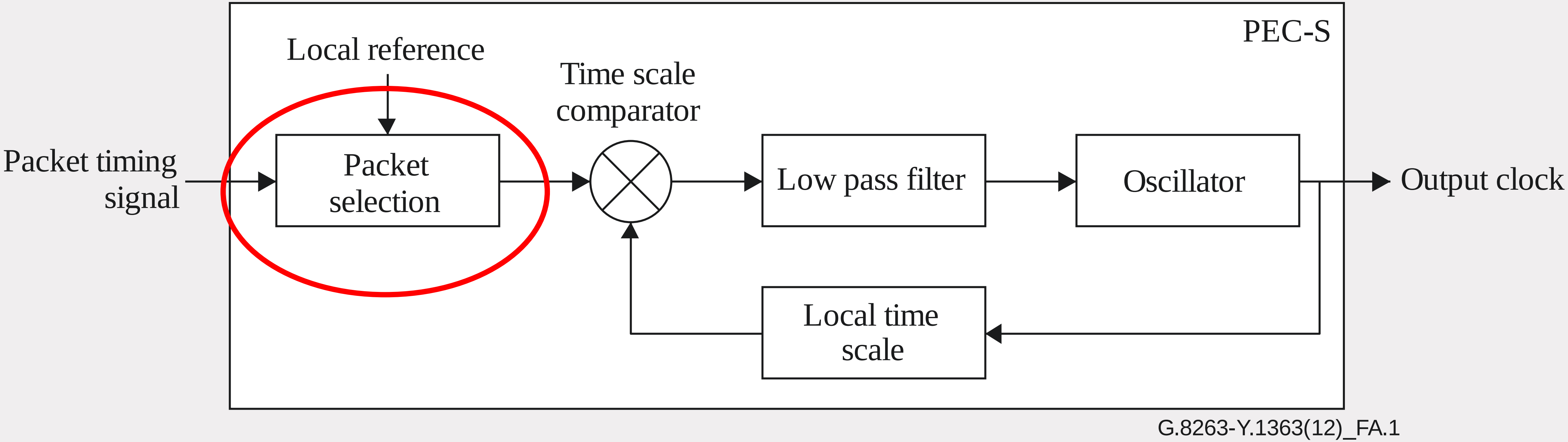
- Timing carried via packets was originally used to recover the service timing (e.g., 2 Mbit/s service carried over packet networks); known as “Circuit Emulation”
  - Service clock adjusts based on buffer fill level / packet arrival rate, **PDV** influences wander at the network output



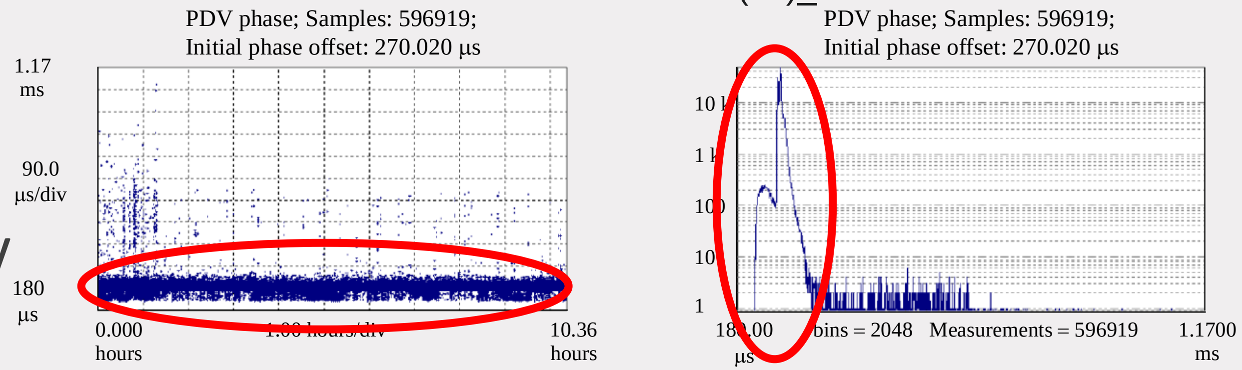
- Similar principle applied replacing traffic data with dedicated timing packets (NTP or PTP)
  - Packets may not arrive regularly, but **timestamps** mean time information can be extracted
  - Timing information contained in the arrival/departure time of the packets
  - **Two-way or one-way** protocols
  - Timing recovery process requires **PDV filtering**



Packet-based Equipment Clock



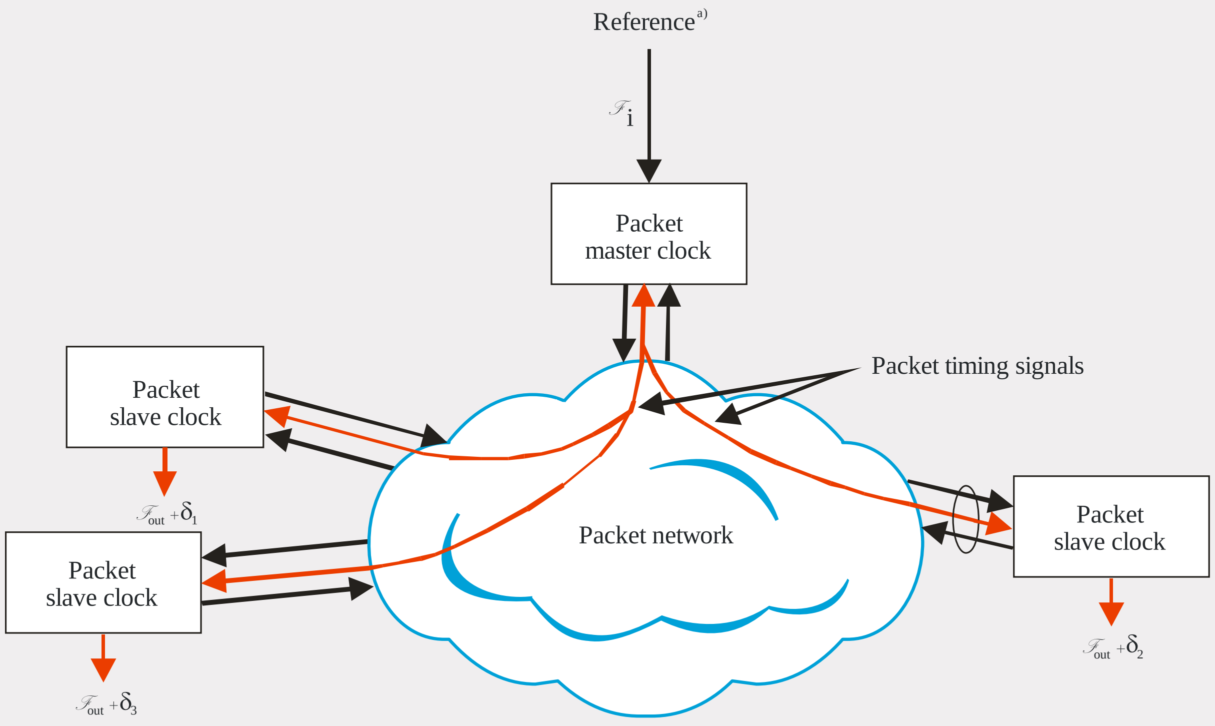
- Concept of «**Packet Selection**»:
  - Pre-processing of packets before use in a traditional clock to handle PDV



From Figure I.2 in G.8260 – Measured packet delay and corresponding PDV histogram

ITU-T G.8265.1 Frequency Profile – IEEE-1588 without support from Network

- Profile targeted for applications that need only frequency synchronization
- Packet delay variation (PDV) will impact the performance of the clock (PDV filtering is needed)
- Several ITU-T Recommendations, G.826x series, G.781.1, have been developed to support this profile



[a] The reference may be from a PRC directly, from a GNSS or via a synchronization network

G.8265/Y.1365(10)_F01

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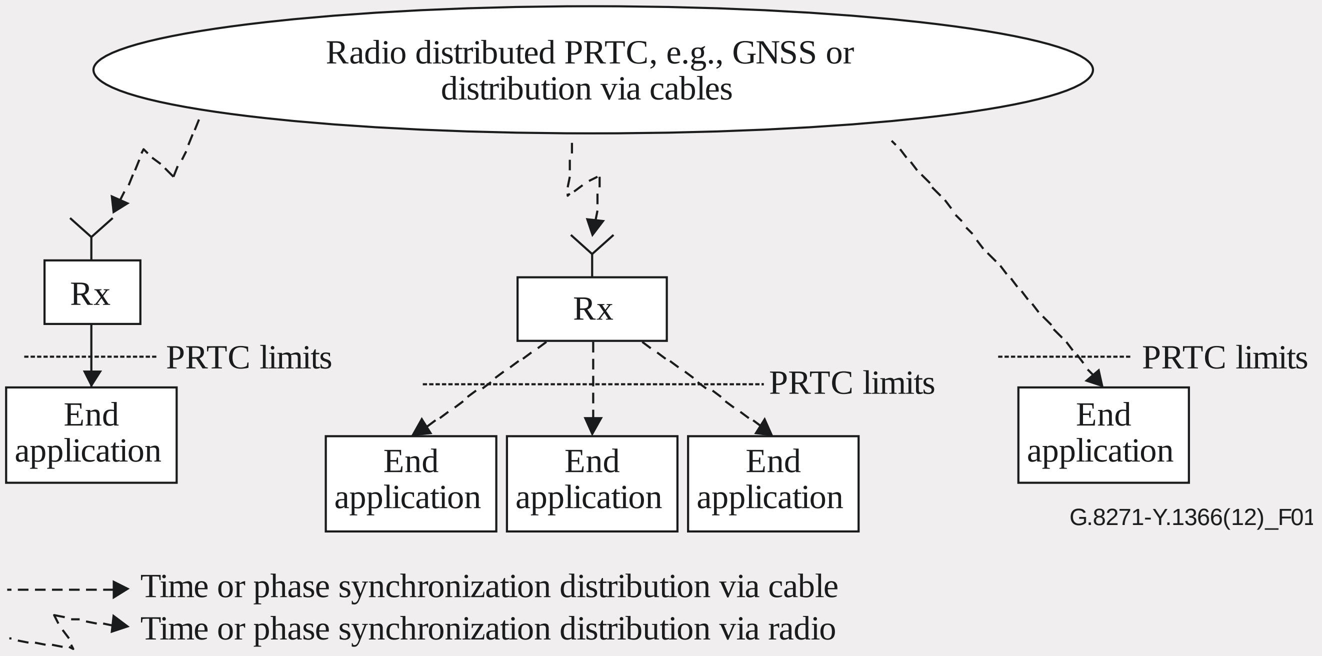
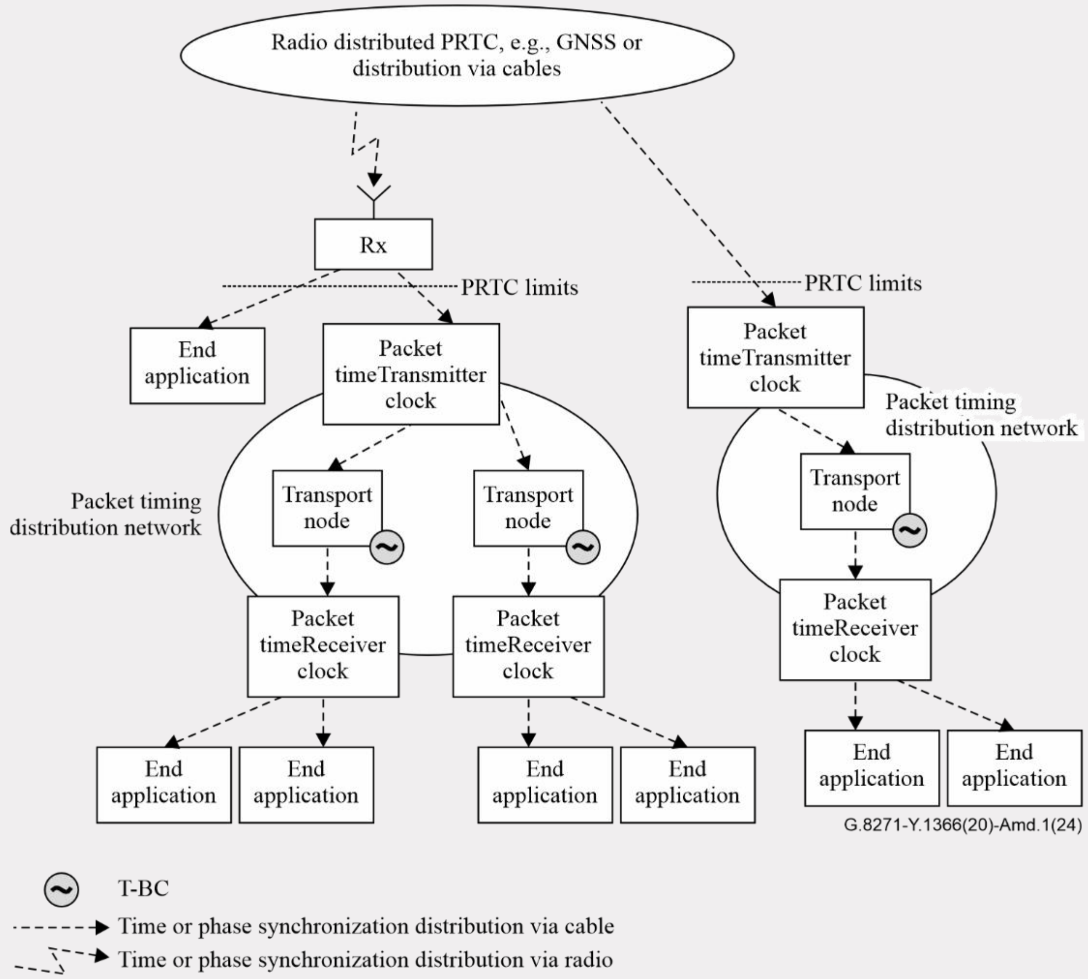
Introduction

- Distributed vs. packet-based

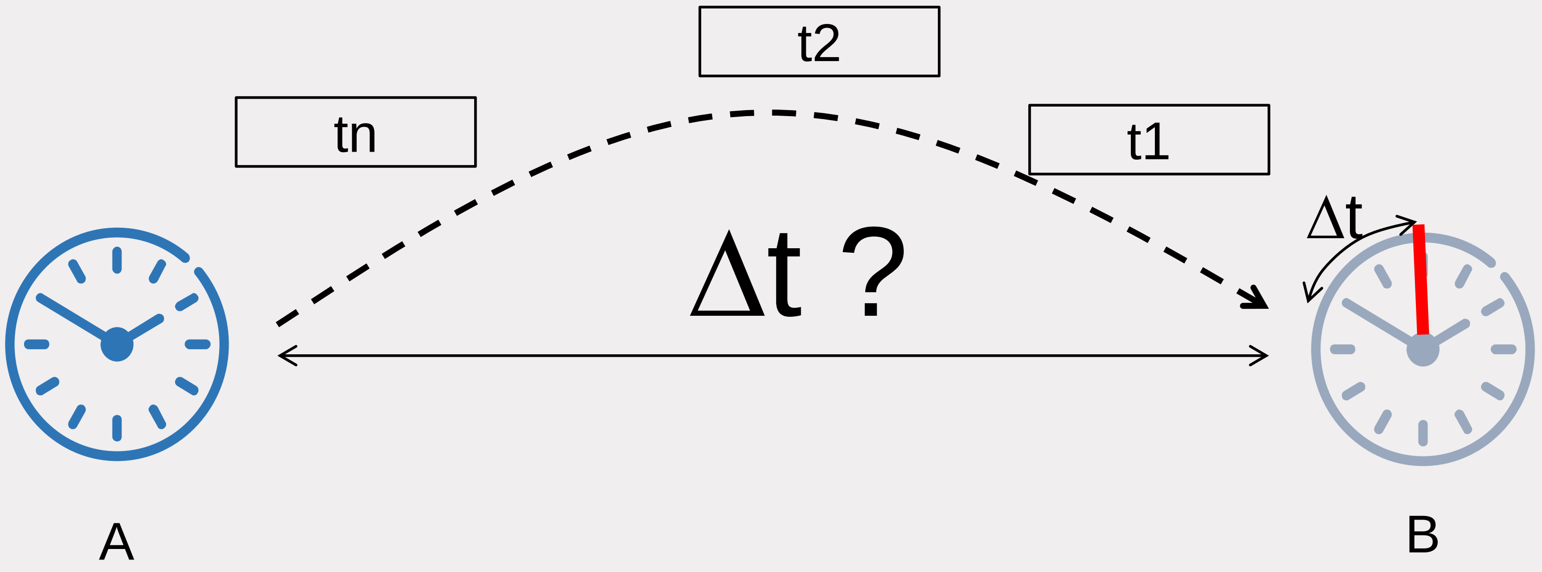




From ITU-T G.8271

Two-ways time transfer

- Delivery of Time synchronization requires also the knowledge of «transit delay» from A to B

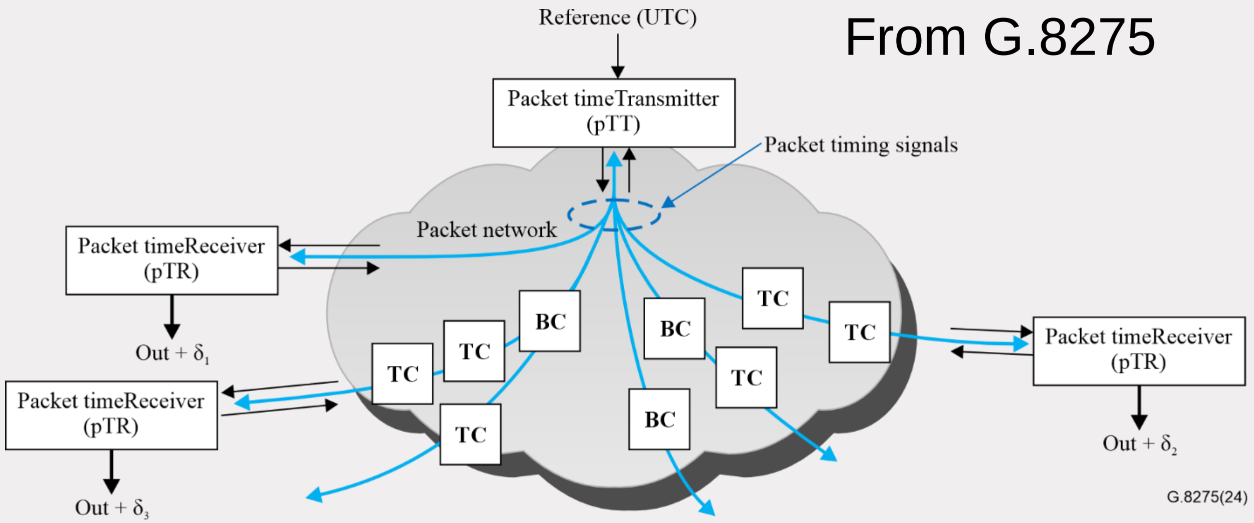


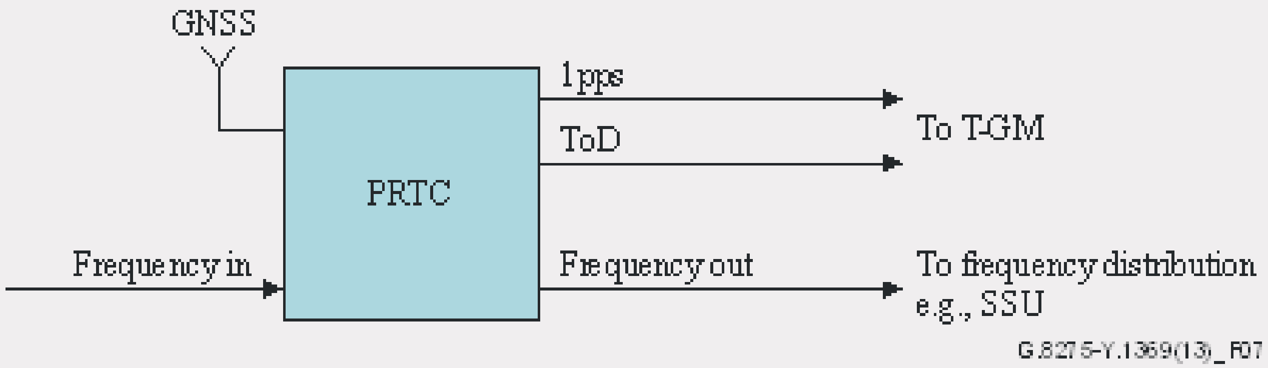
- Two-ways timing protocols (round trip delay)
- Assumption for symmetric channel

Time Synchronization Architecture (Telecom perspective)

- General network topology for time/phase distribution from a Packet timeTransmitter (i.e., Primary Reference Time Clock (PRTC) and Telecom grandmaster (T-GM)) to a Packet timeReceiver (i.e., Telecom Time Synchronous clock (T-TSC))
- The synchronization flow is from the pTT to PTR, although the timing messages will flow in both directions.
- Individual nodes are T-BCs or T-TCs in the case of full timing support from the network

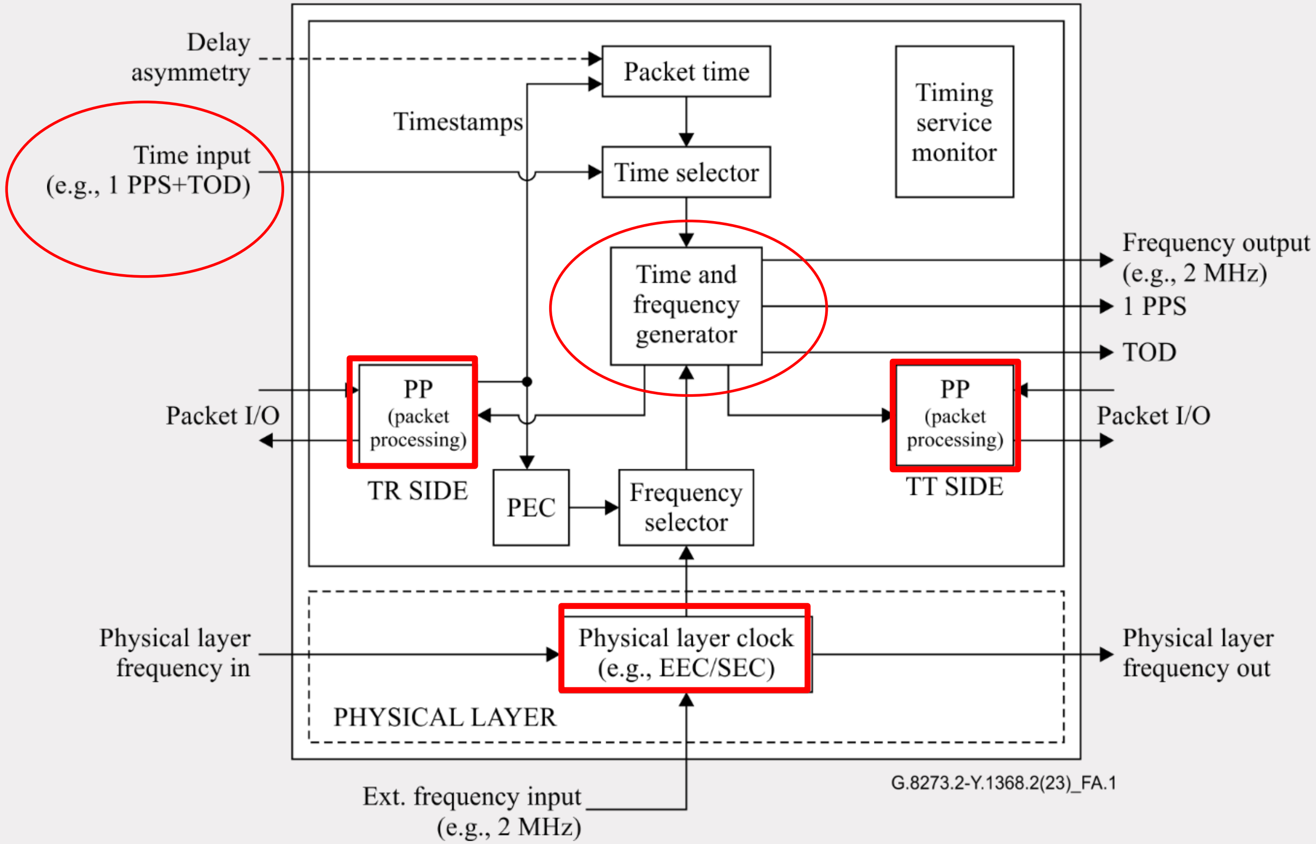
From G.8275

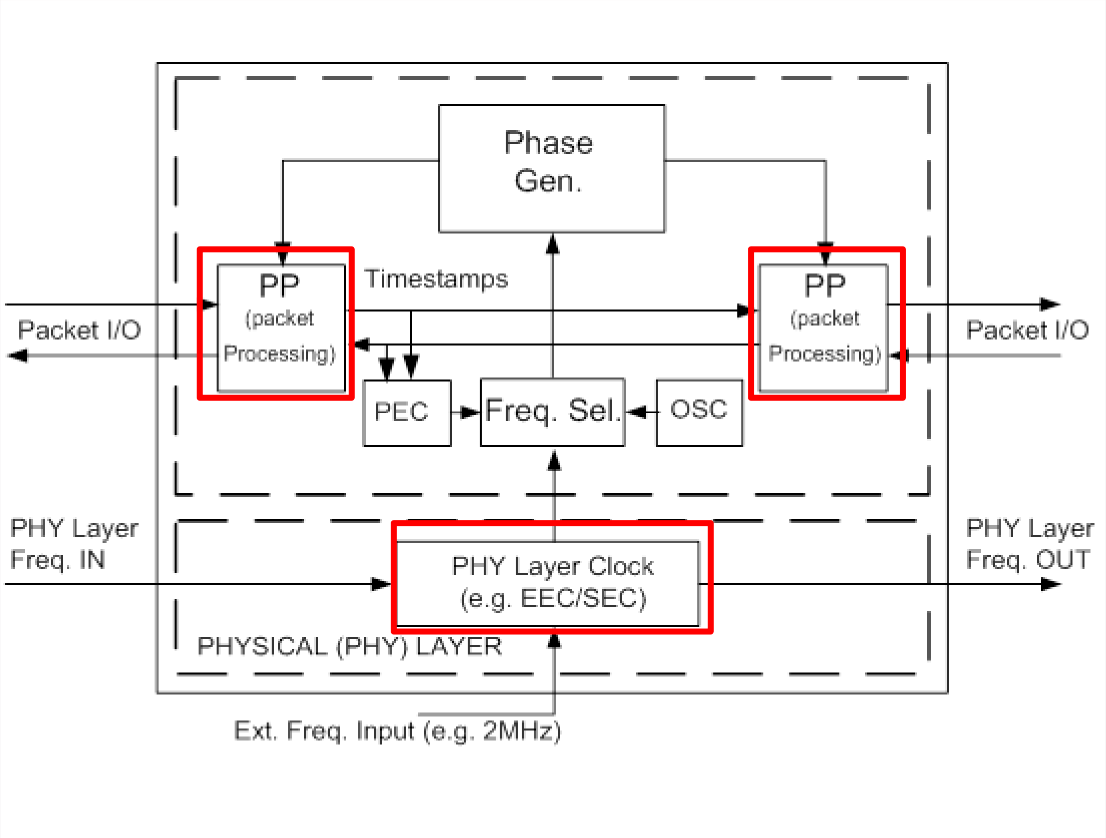




- The PRTC provides the time sync reference for the time synchronization network (G.8272).
- Optional Holdover (as per G.812)
- ePRTC (enhanced PRTC) defined in G.8272.1, with up to 40 days Holdover (100 ns)

T-BC and T-TC clock models for full timing support

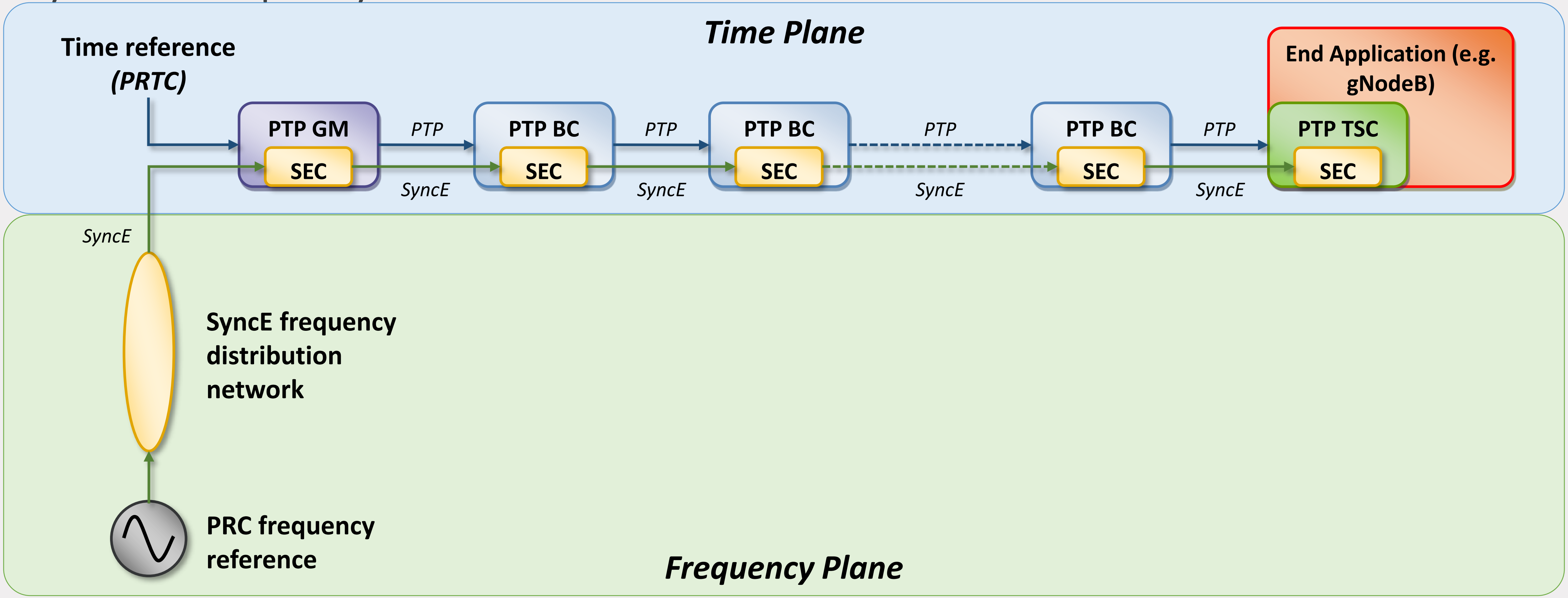




- G.8273.2 and G.8273.3 provide models for the Telecom Boundary and Transparent Clocks
- Frequency sync via physical layer
  - Option without physical layer did not get much traction, but recent studies shows that it may be feasible (Physical layer used only for "time holdover"?)

Combined PTP-SyncE

- SyncE as "frequency assistance" to PTP



- Gives immediate "frequency lock" to the PTP client
- SyncE & PTP functionality may be in the same node/element
- SyncE might be used for "time sync holdover"

SEC Synchronous Equipment Clock

G.8275.1- ITU-T Time/Phase Profile – IEEE-1588 with full timing support (FTS) from Network

- Profile for applications that need accurate phase/time synchronization
- Based on the full timing support (FTS) from the network (i.e., T-BCs and T-TCs are used in every node)

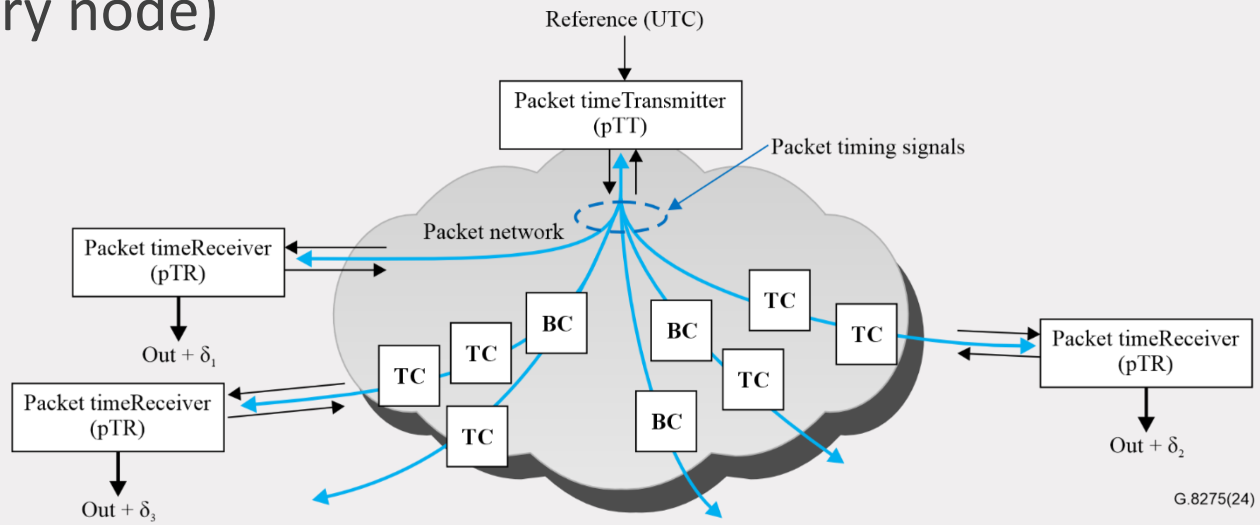
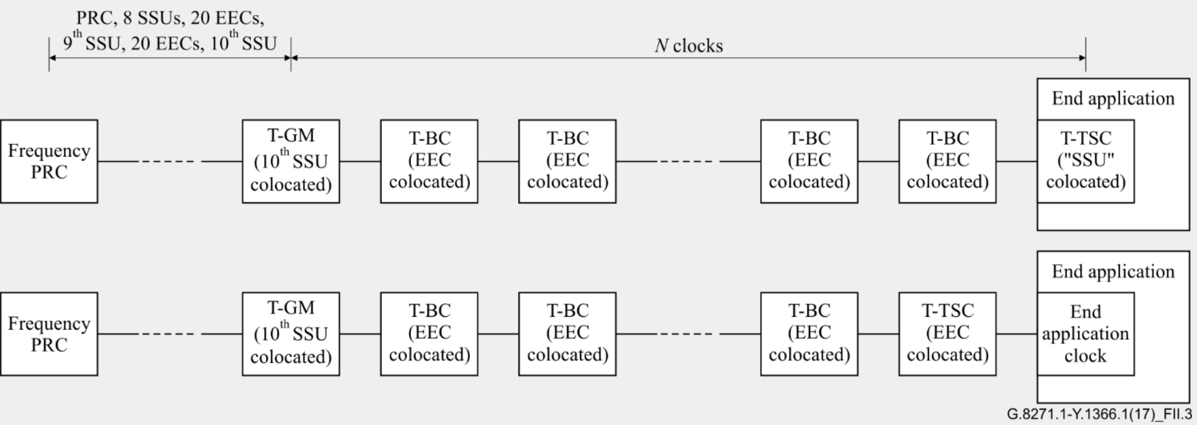


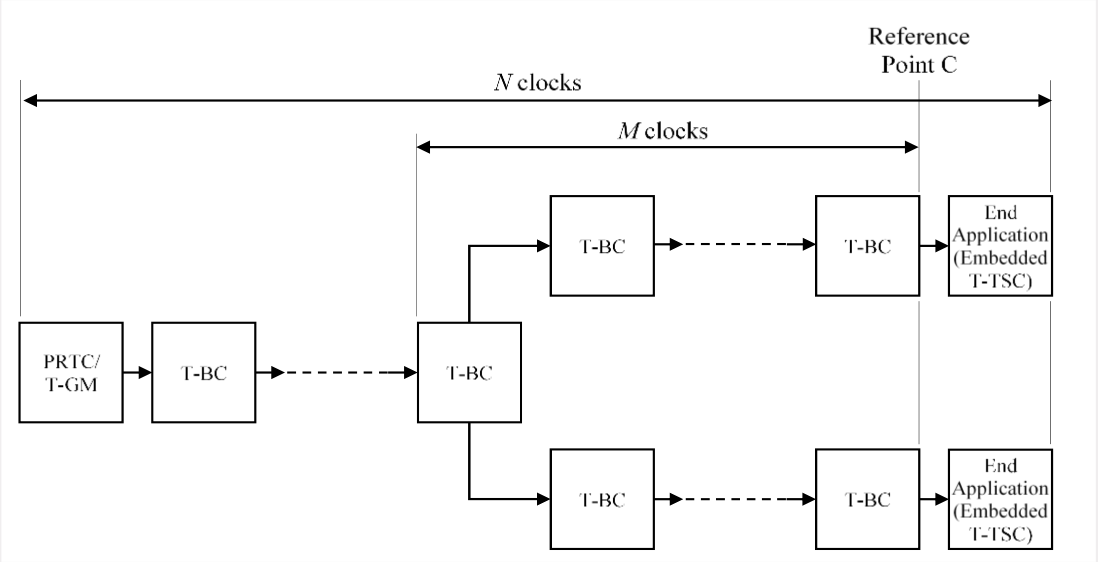
Figure 1 from ITU-T G.8275

BC – Boundary Clock
TC – Transparent Clock
T-BC – Telecom Boundary Clock
T-TC – Telecom Transparent Clock

- Several ITU-T Recommendations (G.827x series, G.781.1) have been developed to support FTS phase/time synchronization

ITU-T G.8271.1 Sync Network Reference Models





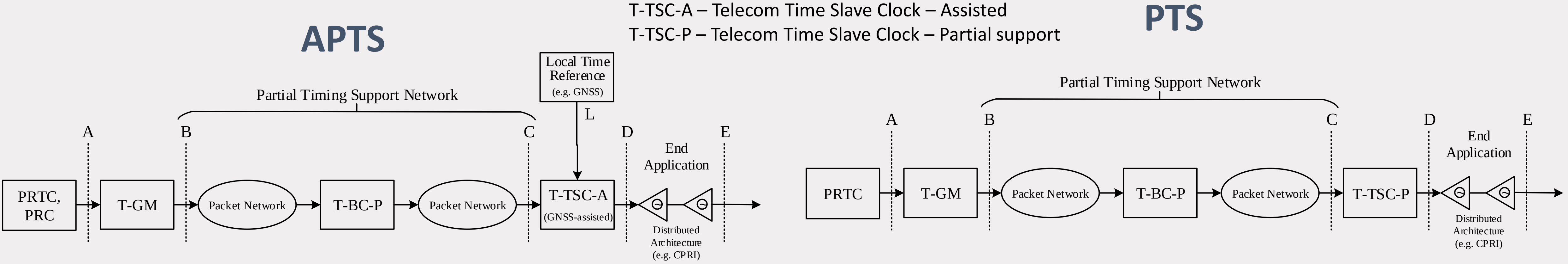
PRC = Primary Reference Clock
PRTC = Primary Reference Time Clock
T-GM = Telecom Grand Master
T-BC = Telecom Boundary Clock
T-TC = Telecom Transparent Clock

- G.8273.2 and G.8273.3 define several classes of T-BCs and T-TCs to be used in G.8271.1 architecture. Reference chains with class A and B have been fully studied for telecom backhaul
  - For a shorter chain N=12 (uses T-BC/T-TC class A)
  - For longer chain N=22 (uses T-BC/T-TC class B or C)
- Guidelines for network dimensioning for fronthaul
- Use of G.8273.2 Clock Class C (enhanced Synchronous Ethernet is required) or T-BC class B
- Short clock chain (M ≤ 4 with class C and M= 1 for class B)

T-BC/T-TSC/T-TC	cTE	dTE (MTIE)	max|TE|	dTE (High-Pass filtered)
Class A (with SyncE)	+/-50ns	40 ns	100 ns	70ns
Class B (with SyncE)	+/-20ns	40ns	70ns	70ns
Class C (with eSyncE)	+/-10ns	10ns	30 ns (T-BC) Under Study for T-TC	30 ns (T-BC) Under Study for T-TC
Class D(with eSyncE) Only T-BC/T-TSC	Under Study	Under Study	5 ns	Under Study

G.8275.2- ITU-T Time/Phase Profile – IEEE-1588 without timing support from Network

GNSS= Global Navigation Satellite System
T-TSC-A – Telecom Time Slave Clock – Assisted
T-TSC-P – Telecom Time Slave Clock – Partial support

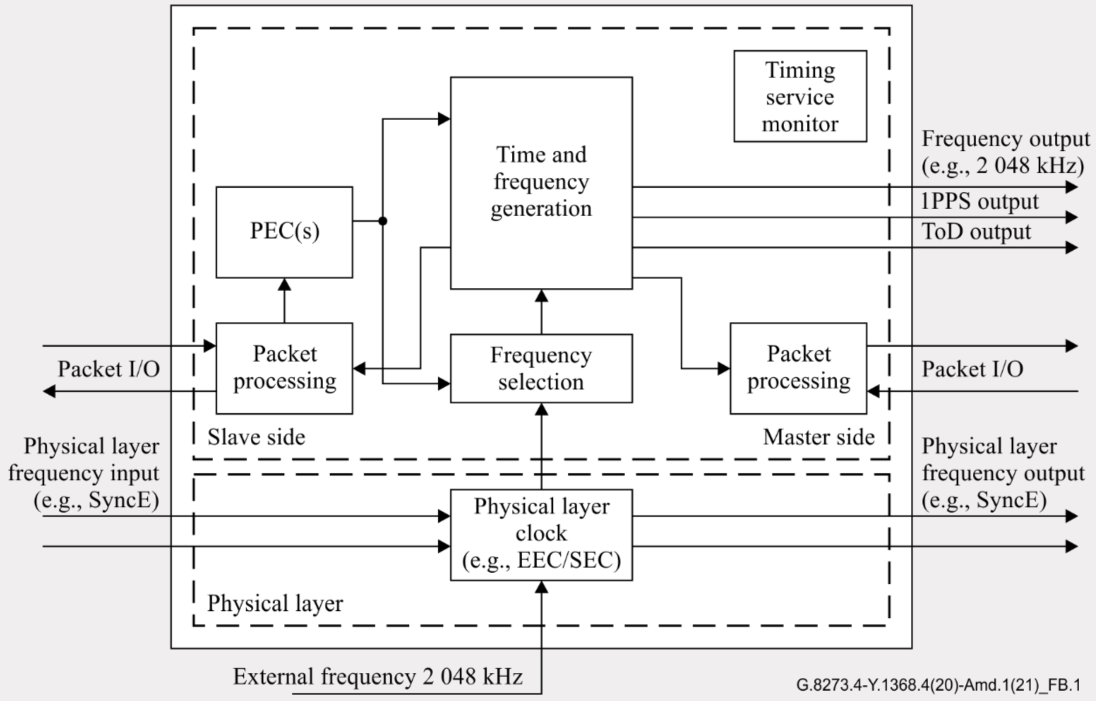


- Assisted Partial Timing Support (APTS) – GNSS is co-located with the T-TSC-A
  - PTP is used as a backup for GNSS failures
- Partial Timing Support (PTS) – without the GNSS co-located with T-TSC-P
  - Only PTP is used for timing

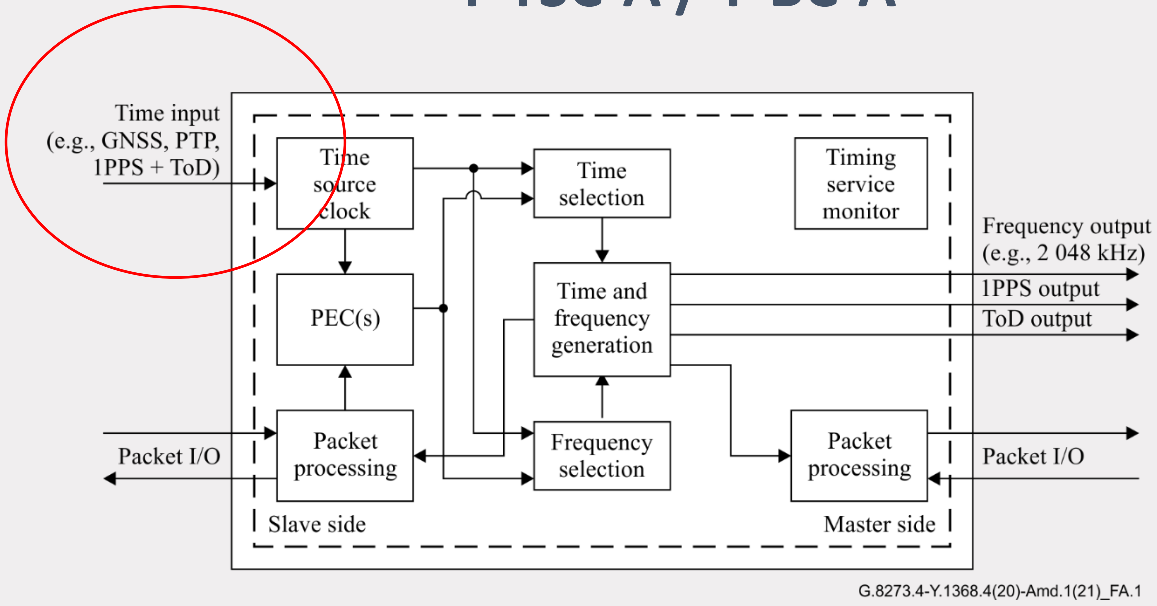
- Several ITU-T Recommendations, G.827x series, G.781.1, have been developed to support PTS phase/time synchronization (PTS)

G.8273.4: Clock functional models for Partial Timing Support

T-TSC-P / T-BC-P



T-TSC-A / T-BC-A



- G.8273.4 provide models for the Telecom Boundary and Telecom Synchronous clocks for PTS and APTS
  - Frequency sync via physical layer is optional for PTS

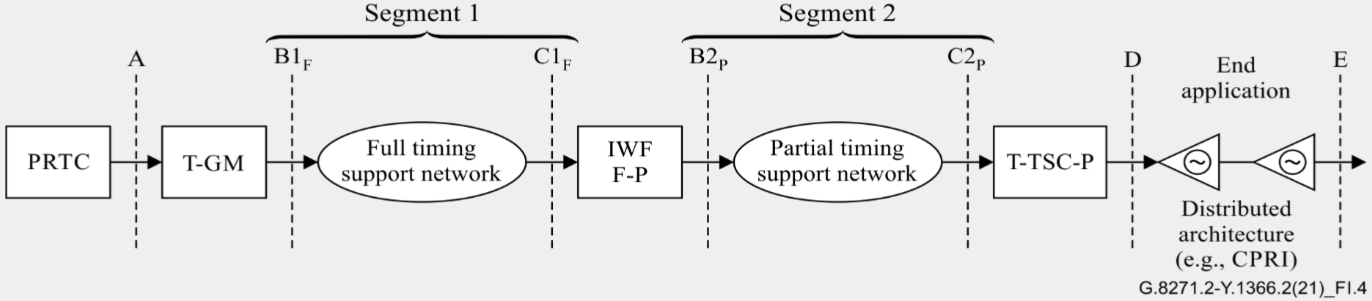
G.8265.1, G.8275.1, G.8275.2 - PTP Options and Configurable Attributes

PTP Options/Attributes	G.8265.1	G.8275.1	G.8275.2
Domain Number	Default: 4, range: (4-23)	Default: 24, range: (24-43)	Default: 44, range: (44-63)
Types of Clocks	-Ordinary Clocks (grandmaster, TimeReceiver-Only)	-Ordinary Clocks (grandmaster, TimeReceiver-Only) -Boundary Clocks -End-to-End Transparent Clocks	-Ordinary Clocks (grandmaster, TimeReceiver-Only) -Boundary Clocks
Time transfer	- One-Way - Two-Way	- One-Way - Two-Way	- One-Way - Two-Way
Type of Clocks	- One-step - Two-Step	- One-step - Two-Step	- One-step - Two-Step
Transport Mode	Unicast (IPv4, IPv6)	Multicast (IPv4, IPv6, OTN, MTN, FlexE)	Unicast (IPv4, IPv6)
Path delay Measurement	Delay request/delay response	Delay request/delay response	Delay request/delay response
PTP message rate (pckt/s)	- Sync & Follow-up/Delay_request/response: min 1/16, max 128 - Announce: : min 1/16, max 128	- Sync & Follow-up/Delay_request/response: 16 - Announce: 8	- Sync & Follow-up/Delay_request/response: min 1 / max 128 - Announce: min 1 / max 128 - Signalling messages: no rate
BTCA	Alternate BTCA	Alternate BTCA (modified default BTCA)	Alternate BTCA (modified default BTCA)

- Note 1: support for IEEE1588-2019 in all the Telecom Profiles
- Note 2: support for IPV6 is mandatory for G.8275.2 and G.8265.1

IWF Between PTP Profiles (G.8275)

- In some deployment scenarios an inter-working function (IWF) may be used to connect synchronization network segments that are running different PTP profiles.



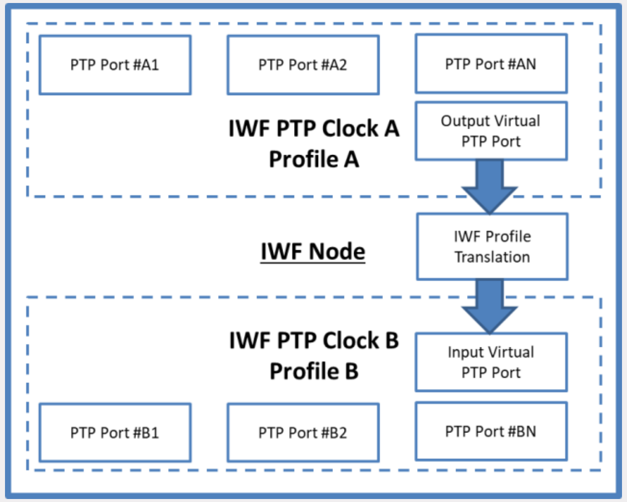
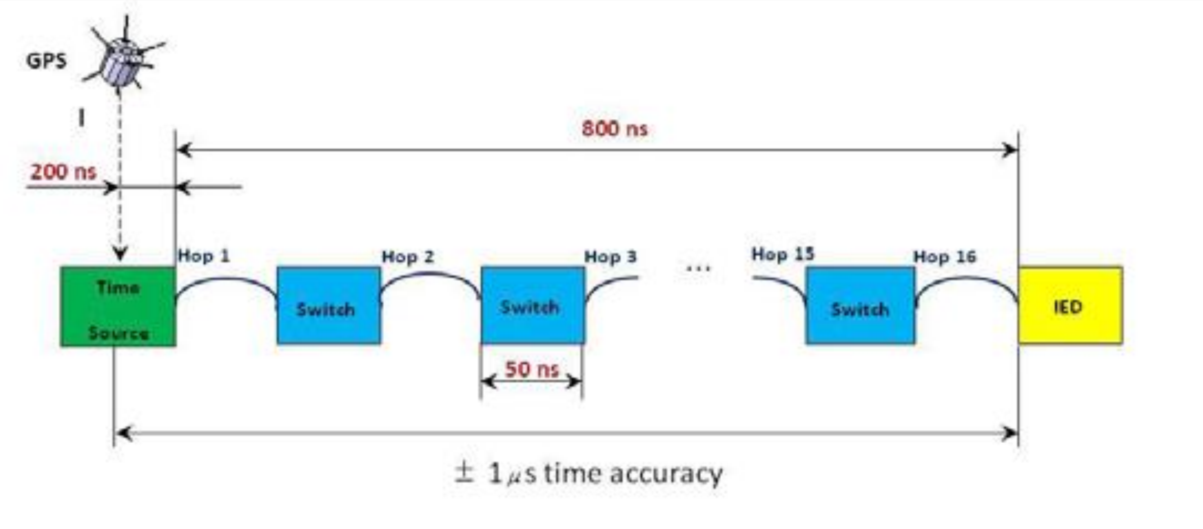


Table 1 – Mapping between IWF, ITU-T G.8275.1, ITU-T G.8275.2 and PTP clock types

IWF Node Type	PTP Profile	Clock type from [G.8275.1] & [G.8725.2]	Clock type from [IEEE 1588]
IWF F-P	A (G.8275.1)	T-TSC or T-BC	OC or BC
	B (G.8275.2)	T-GM	OC or BC
IWF P-F	A (G.8275.2)	T-TSC-P or T-TSC-A	OC or BC
	B (G.8275.1)	T-GM	OC or BC

Power Profile Architecture and Profile

- IEC/IEEE 61850-9-3:2016, Communication networks and systems for power utility automation – Part 9-3: Precision time protocol profile for power utility automation
  - to deliver time to clients with an accuracy of one microsecond or better over a network comprising up to 15 TCs or 3 BCs.
  - A TC shall introduce less than 50 ns time inaccuracy; A BC shall introduce less than 200 ns time inaccuracy
  - Layer 2, peer-to-peer profile of based on J.4 of IEEE Std 1588-2008.



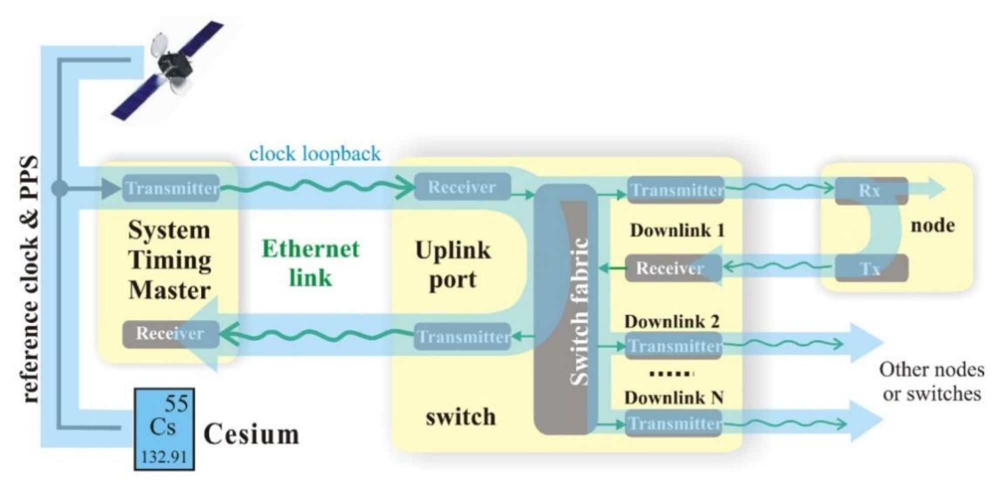
From Standard Profile for Use of IEEE Std 1588-2008 Precision Time Protocol (PTP) in Power System Applications, IEEE PES PSRC Working Group H7/Sub C7 Members and Guests, 2012 IEEE Conference

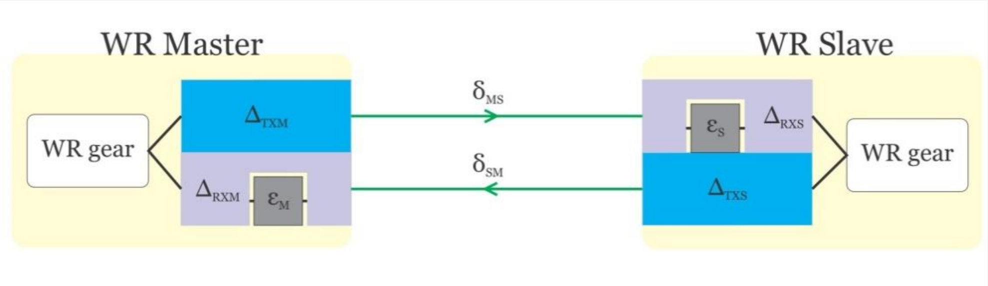
- IEEE C37-238: IEEE Standard Profile for Use of IEEE 1588™ Precision Time Protocol in Power System Applications (2017)
  - extension of IEC/IEEE 61850-9-3:2016 with two TLVs: one mandatory, providing additional information to monitor clock performance in real time, and an optional TLV, providing local time zone information, to ease transition from IRIG-B systems and for local display applications
  - Clocks claiming conformity with this standard can be used without restriction in an IEC/IEEE 61850-9-3 network

High Accuracy/«White Rabbit» Architecture and Profile

Calnex

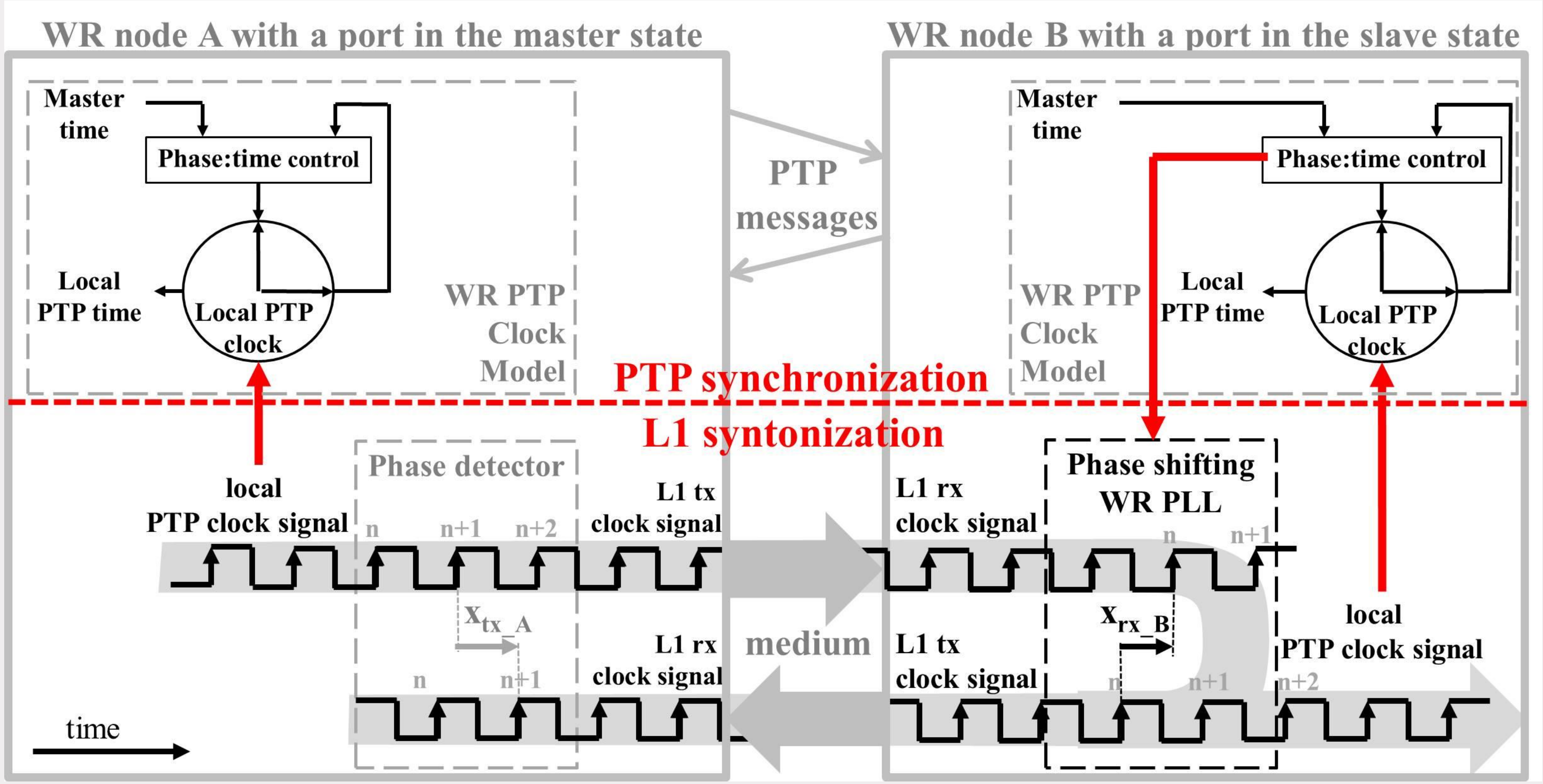
- PTP-based solution originally specified by the CERN targeting sub-ns accuracy, max(|TE|) < 1ns (typically, to support scientific applications); White Rabbit is the name of the project and of the related profile.
- Specified as High Accuracy Default PTP Profile in IEEE 1588-2019 (Annex J.5)
- Performance is enabled by the following building blocks:
  - Clock model in which Layer 1 syntonization cooperates with PTP synchronization
  - Phase detection to enhance timestamping precision using Digital Dual Mixer Time Difference (figure in backup slides)
  - Compensation of hardware & link asymmetries using “link delay model” and calibration





courtesy by Maciej Lipinski

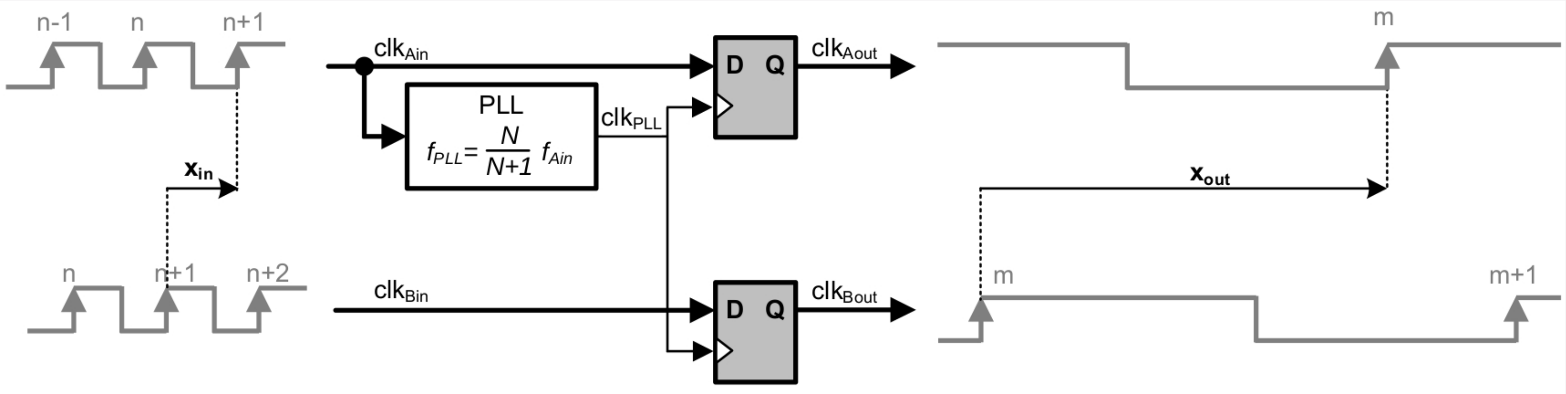
PTP Synchronization and L1 Syntonization in the White Rabbit



courtesy by Maciej Lipinski

Digital Dual Mixer Time Difference (DDMTD)

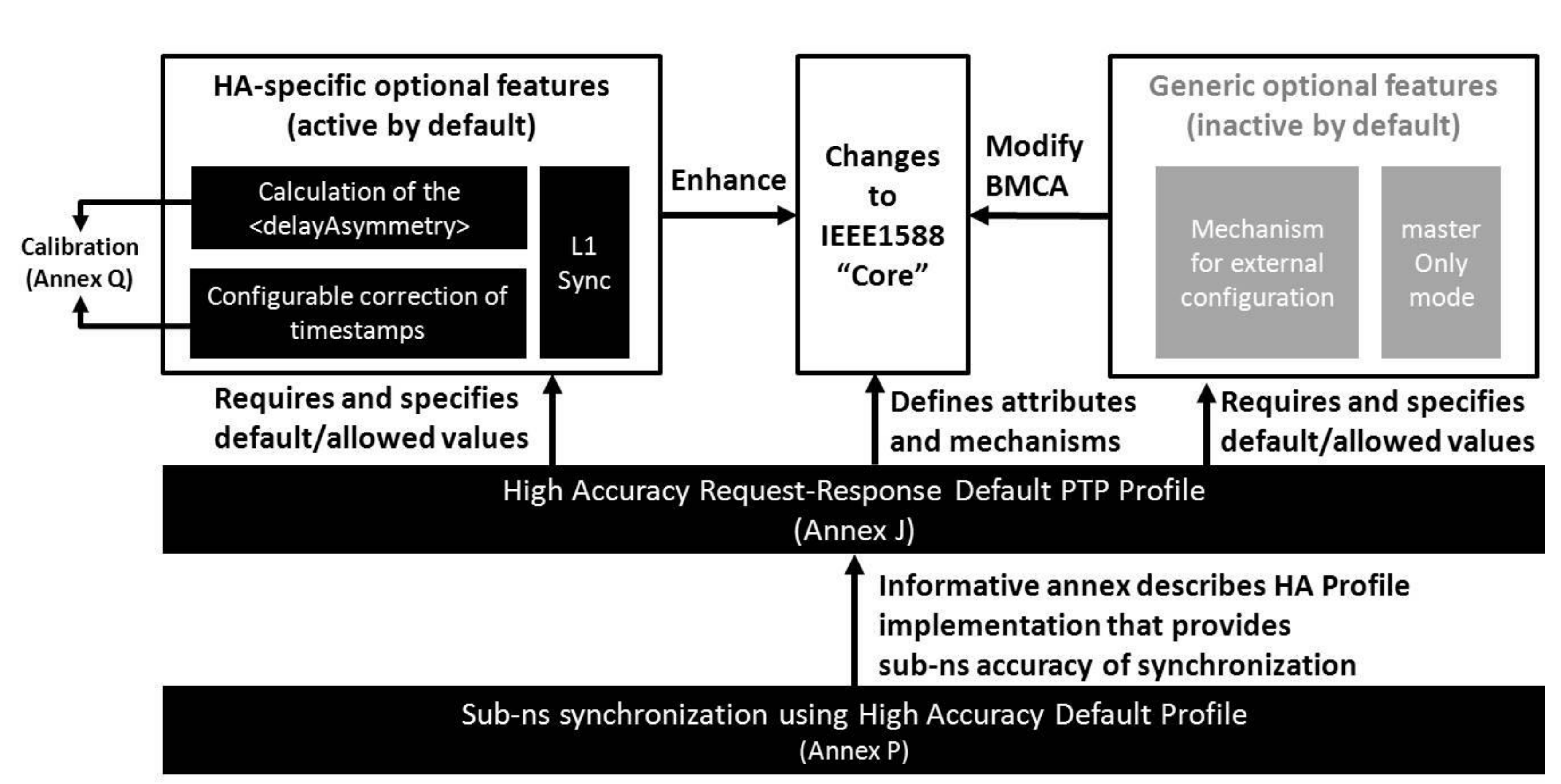
- Clever implementation of a phase detector in an FPGA
- Uses D-flip-flops to zoom-in phase offset
- Allows for phase measurements at picosecond level



- www.cern.ch/white-rabbit/documents/DDMTD_for_Sub-ns_Synchronization.pdf

courtesy by Maciej Lipinski

White Rabbit integrated into IEEE1588-2019 as High Accuracy



courtesy by Maciej Lipinski

Timing and Synchronization for Time-Sensitive Applications : IEEE802.1AS

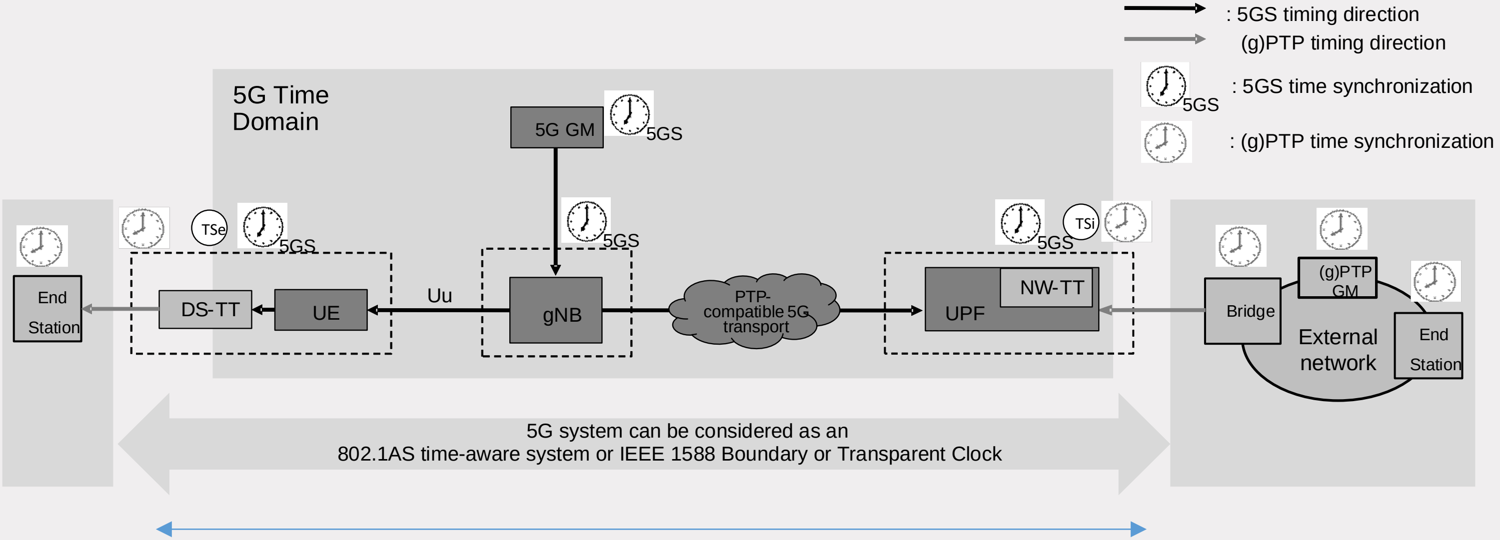
- To support time-sensitive applications, such as audio, video, automotive, and Industrial Automation, across networks
- First released in 2011; Latest revision: 802.1AS Std. 2020 (Timing and Synchronization for Time-Sensitive Applications).
- Target Performance:
  - Any two nodes separated by six or fewer PTP instances (i.e., seven or fewer hops) will be synchronized to within 1 µs peak-to-peak of each other during steady-state operation.
- Make use of a “hybrid TC/BC” (Clocks participate in the Best Master Clock Algorithm, but are not required to recover the GM time).
- Based on peer-delay mechanism. Use of “rateRatio” parameter (to correct for frequency differences between local clock and grandmaster clock).
- One of the main objectives of the 2020 revision was to address other applications besides audio and video.
- The first draft of the revision of IEEE 802.1AS is available and going through Task Group ballot.

Time-Sensitive Networking (TSN) Industrial Automation Profile (IEC/IEEE 60802)

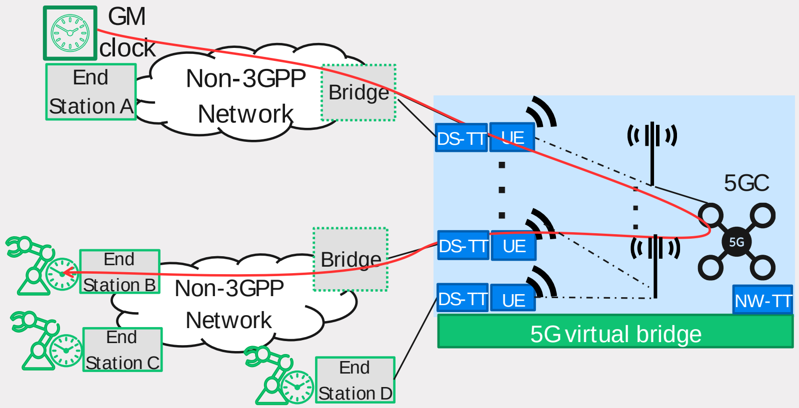
- IEC/IEEE 60802 profile is a joint project between IEC SC65C/WG18 and IEEE 802
- It addresses bridges and end stations for industrial automation
- Time synchronization is based on IEEE 802.1AS
- Typically, Industrial automation contains multiple tasks that are based on time or cycles
- The data flow needs to operate continuously and relies on regular updates based on a local or network time base
- Latency and time delays are critical and needs to be minimized and bounded
- Two types of clocks are defined: Global Time (synchronized to TAI (International Atomic Time)), and Working Clock (synchronized to an arbitrary time (ARB)
- Working Clock: a network must support 100 nodes between the grandmaster and the end application
  - Need to meet a maximum absolute Time Error of 1us
  - Simulations have been implemented to define key parameters that are specified in the profile (e.g. residence time, Sync and Pdelay message rates)

3GPP: Integration of 5G with «TSC»

- From 3GPP TS 23.501: Integration between 5G and TSC (Time Sensitive Communication)
- Replacing wired connection with a 5G link
- Original focus: TSN and IEEE 802.1AS (for Industrial Automation) ;
  - Extended to other profiles (e.g., SMPTE)
- The 5GS transparently carries the client PTP messages (e.g., according to IEEE802.1AS), updating the correction field
- DS-TT and NW-TT at the external interfaces must be synchronized
  - NW-TT via the Telecom Profile
  - DS-TT synchronized by the gNB (over the air)
- Various "Scenarios" are possible, with different budgeting examples for the Time Error allocated to the air interface
  - 145 ns / 275 ns for the most stringent scenarios (to support 700 ns or 900 ns total budget)
- Addressed by ITU-T Q13/15 in latest G.8271.1 draft



700 ns or 900 ns (under discussion; 3GPP TS 22.104)



From TD7-3 Liaison from 3GPP to Q13/15

3GPP: Timing Resiliency

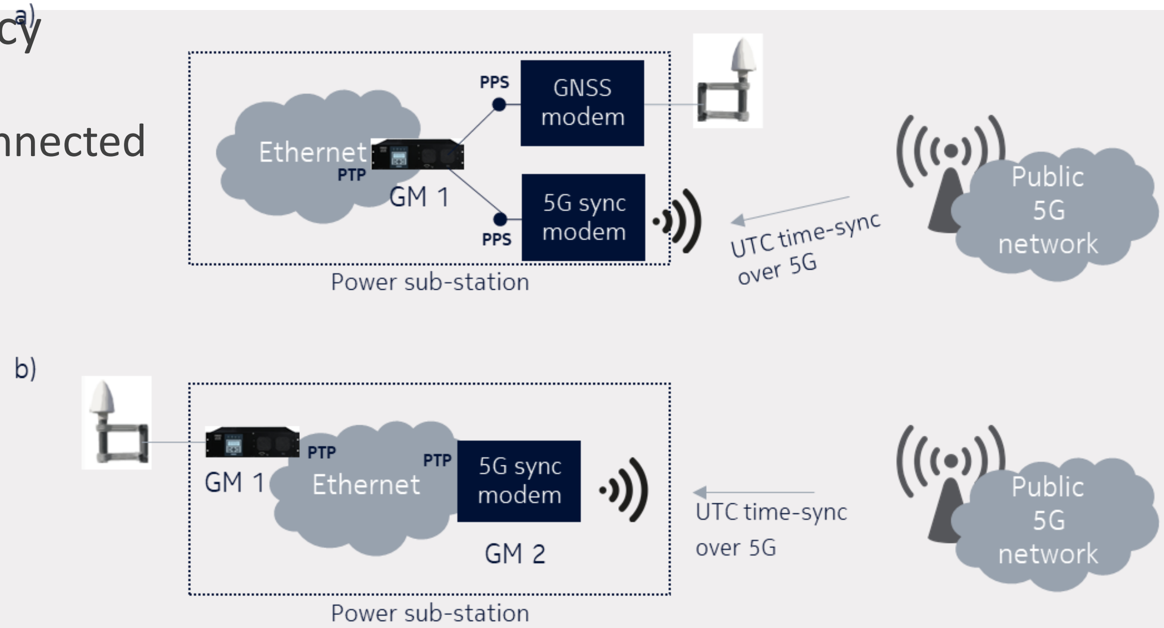
- New requirements from 3GPP related the 5G Timing Resiliency applications (TS 22.261, TR 22878)
  - Timing over 5G used as back –up (or primary reference) for connected devices
  - Example Applications: Power Grid, Trading, etc.
- Ongoing study item on monitoring and reporting for timing synchronization status in the 5G system (TR 23.700-25)
- Addressed by Q13 in G.8271 and G.8271.1

Use case	Holdover time (note 3)	Sync target	Sync accuracy	Service area	Mobility	Remarks
Power grid (5G network)	Up to 24 hour	UTC (note 1)	<250 ns to1000 ns (note2)	< 20 km^2	Low	When 5G System provides direct PTP Grandmaster capability to sub-stations
Power grid (time synchronization device)	>5 s	UTC (note 1)	<250 ns to1000 ns (note2)	< 20 km^2	Low	When 5G sync modem is integrated into PTP grandmaster solution (with 24h holdover capability at sub-stations)

NOTE 1: A different synchronization target is acceptable as long as the offset is preconfigured when an alternatively sourced time differs from GNSS. In this case, a 5G end device will provide PPS output which can be used for measuring the difference.

NOTE 2: Different accuracy measurements are based on different configurations needed to support the underlying requirements from IEC 61850-9-3 [32]. The range is between 250 ns and 1000 ns. The actual requirement depends on the specific deployment.

NOTE 3: This requirement will vary based on deployment options.



From TR 22.878 Figure 4.1.3-2:
5G integration into system – resilience and alternative mode

Type of trading activity	Maximum divergence from UTC	Granularity of the timestamp (note 1)
Activity using high frequency algorithmic trading technique	100 µs	≤1 µs
Activity on voice trading systems	1 s	≤1 s
Activity on request for quote systems where the response requires human intervention or where the system does not allow algorithmic trading	1 s	≤1 s
Activity of concluding negotiated transactions	1 s	≤1 s
Any other trading activity	1 ms	≤1 ms

NOTE 1: Only relevant for the case where the time synchronization assists in configuring the required granularity for the timestamp (for direct use), otherwise it will be configured separately as part of the financial transaction timestamp process.

Time-Sensitive Networking (TSN) Automotive and Aerospace Profiles

- IEEE 802.1 TSN working group is working on a set of profiles to address bridges and end stations for automotive (IEEE P802.1DG) and for aerospace (IEEE P802.1D /SAE AS6675)
- IEEE P802.1DG is referencing AUTOSAR, IEEE 1588, and IEEE 802.1AS for time synchronization
- IEEE P802.1DP /SAE AS6675 is using IEEE 802.1AS for time synchronization
- Targeting Ethernet networks to support in-vehicle and aerospace on-board bridges and end stations

IEEE P802.3cx: Accurate Timestamping; MOPA: Time Error in pluggables

- IEEE 802.3cx-2023 «Improved Precision Time Protocol (PTP) Timestamping Accuracy»
  - Enhancements to Ethernet support for time synchronization protocols to provide improved timestamp accuracy in support of ITU-T Recommendation G.8273.2 'Class C' and 'Class D' clocks

- MOPA (Mobile Optical Pluggable Alliance)
- Classes of pluggables based on achievable accuracy. Examples
  - a “Class C.2” pluggable : 2% of the cTE budget ITU-T G.8273.2 allocated for Class C nodes. (i.e, +/-0.2ns, that translates in both Δtmax and Δrmax = +/-0.2ns). For very simple pluggable implementations, maintaining an analogue signal chain.
  - - A ”Class A.20” pluggable : 20% of the cTE budget ITU-T G.8273.2 allocated for Class A nodes. (i.e., +/-10ns, that translates in both Δtmax and Δrmax = +/-10ns). To enable use of complex digital parts inside the pluggable.

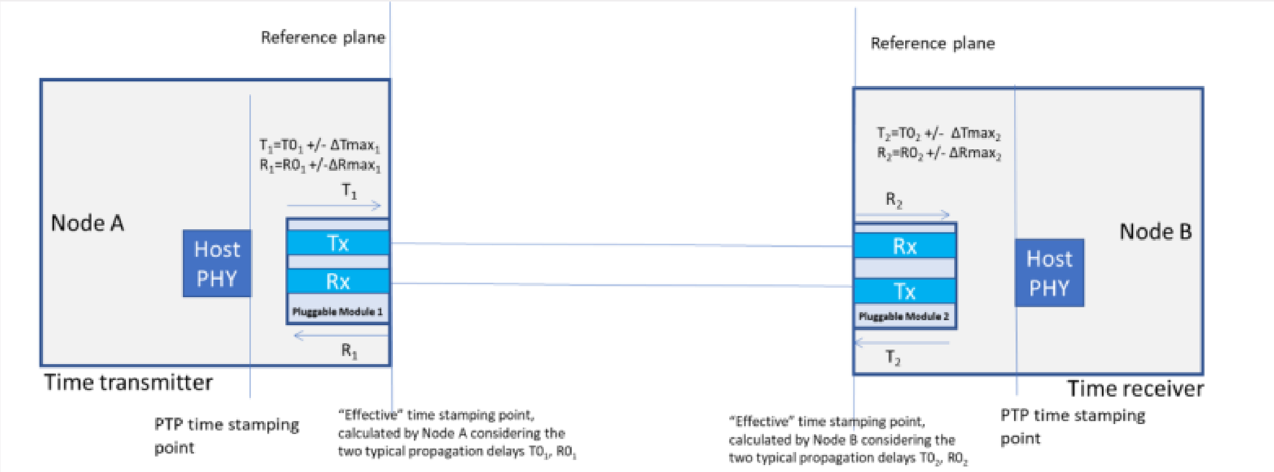


Figure APB.9 from
MOPA Technical paper on Optical pluggable performance for tight synchronization v1.0

Calnex Solutions plc

Stefano Ruffini, Strategic Technology Manager, Calnex Solutions
Stefano.ruffini@calnexsol.com

Silvana Rodrigues, Senior Principal Engineering, Huawei Canada
Silvana Rodrigues@huawei.com

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References

- ITU T Recommendations (**Published Recommendations can be downloaded from: http://www.itu.int/rec/T-REC-G/e**)
  - G.810, Definitions and terminology for synchronization networks.
  - G.811, Timing characteristics of primary reference clocks.
  - G.781, G.781.1
  - time sync: G.827x
  - frequency sync: G.826x
  - G.Sup65, Simulations of transport of time over packet networks
  - G.Sup68, Synchronization OAM requirements
  - G.Sup83, Full Timing Support Options
  - ITU-T GSTR-GNSS - Considerations on the use of GNSS as a primary time reference in telecommunications (https://www.itu.int/dms_pub/itu-t/opb/tut/T-TUT-HOME-2020-PDF-E.pdf
- NTP: IETF RFC 5905/6/7/8
- PTP: IEEE 1588-2008, IEEE1588-2019
- CES: RFC 5087, RFC 5086, RFC4533, ITU-T Y.1413, ITU-T Y.1453, MEF3, MEF 8
- Power Profile: IEC/IEEE 61850-9-3:2016, IEEE C37-238
- High Accuracy/White Rabbit:
  - IEEE1588-2019 (High Accuracy Default PTP Profile in Annex J.5);
  - WR-PTP = White Rabbit Profile defined in WR Spec
- TSN: IEEE 802.1AS-2020
- Over the Air sync: 3GPP TS 22.104, TS 23.501, TS 22.261
- MOPA: MOPA Technical paper on Optical pluggable performance for tight synchronization v1.0

ITU-T G.826x and G.827x series

- **G.8260** (Definitions, Metrics),
- **G.8261** (Timing and synchronization aspects in packet networks) ,
- **G.8261.1** (Packet Delay Variation Network Limits applicable to Packet Based Methods),
- **G.8263** (Timing Characteristics of Packet based Equipment Clocks (PEC)),
- **G.8265** (Architecture and requirements for packet-based frequency delivery),
- **G.8265.1** (Precision time protocol telecom profile for frequency synchronization),
- **G.8271** (Network limits for time synchronization in packet networks with full timing support from the network),
- **G.8271.1** (Network limits for time synchronization in packet networks with full timing support from the network),
- **G.8271.2** (Network limits for time synchronization in packet networks with partial timing support from the network) ,
- **G.8272** (Timing characteristics of Primary reference time clock),
- **G.8272.1** (Timing characteristics of enhanced primary reference time clock),
- **G.8272.2** (Timing characteristics of coherent network primary reference time clocks)
- **G.8273** (Framework of phase and time clocks),
- **G.8273.2** (Timing characteristics of telecom boundary clocks and telecom time slave clocks for use with full timing support from the network),
- **G.8273.3** (Timing characteristics of telecom transparent clocks for use with full timing support from the network),
- **G.8273.4** (Timing characteristics of partial timing support telecom boundary clocks and telecom time slave clocks),
- **G.8275** (Time Sync Architecture),
- **G.8275.1** (PTP telecom profile for phase/time synchronization with full timing support from the network),
- **G.8275.2** ((Precision time Protocol Telecom Profile for time/phase synchronization with partial timing support from the network)