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Distribution of Timing: Sync over the Packet Layer of Networks

WSTS Tutorial – May 7-9, 2024
1. Frequency sync via packets
   1.1 Introduction
   1.2 G.8265.1 Profile

2. Time sync distribution
   2.1 Introduction
   2.2 Two-Way Time Transfer
   2.3 Architectures and Clocks
   2.5 Time sync Profiles

Note: actions are being taken in various Standardization bodies to revise the Master/Slave terminology («inclusive terminology»). This slide set is planned to be 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 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 is in the process of revising terminology of active Recommendations
  - Revision of terminology of Physical Layer (SyncPHY) is also being performed

- Master and Slave may still be used in some figures in this presentation
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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

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

- Distributed vs. packet-based

Radio distributed PRTC, e.g., GNSS or distribution via cables

Rx

PRTC limits

End application

End application

End application

Time or phase synchronization distribution via cable

Time or phase synchronization distribution via radio

Packet timing distribution network

(From ITU-T G.8271)
Two-ways time transfer

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

\[ \Delta t \]

- 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 master clock PRTC to a telecom time slave clock (T-TSC)
- The synchronization flow is from the master to slave, although the timing messages will flow in both directions.
- Individual nodes are T-BCs or T-TCs in the case of full support from the network.

From G.8275
- Primary Reference Time Clock (PRTC) is the master of 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) under specification.
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”
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 from the network (i.e., T-BCs and T-TCs are used in every node)

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

- 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) | Under Study | Under Study | 5 ns | Under Study |

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

FRC, 8 SSUs, 20 EECs, 0°SSU, 20 EECs, 10°SSU
**G.8275.2 - ITU-T Time/Phase Profile – IEEE-1588 without timing support from Network**

- **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

- 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
### PTP Options/Attributes

<table>
<thead>
<tr>
<th>PTP Options/Attributes</th>
<th>G.8265.1</th>
<th>G.8275.1</th>
<th>G.8275.2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Domain Number</strong></td>
<td>default : 4, range: {4-23}</td>
<td>default : 24, range: {24-43}</td>
<td>default : 44, range: {44-63}</td>
</tr>
<tr>
<td><strong>Types of Clocks</strong></td>
<td>Ordinary clocks (i.e. Grandmasters, slave-only clocks)</td>
<td>- Ordinary clocks (i.e. Grandmasters, slave-only clocks) - Boundary clocks - End-to-end transparent clocks</td>
<td>- Ordinary clocks (i.e. Grandmasters, slave-only clocks) - Boundary clocks</td>
</tr>
<tr>
<td><strong>Time Transfer</strong></td>
<td>- One-way</td>
<td>- Two-way</td>
<td>- Two-way</td>
</tr>
<tr>
<td><strong>Type of clocks</strong></td>
<td>One-step and two-step</td>
<td>One-step and two-step</td>
<td>One-step and two-step</td>
</tr>
<tr>
<td><strong>Path delay measurement</strong></td>
<td>delay request/delay response mechanism</td>
<td>delay request/delay response mechanism</td>
<td>delay request/delay response mechanism</td>
</tr>
<tr>
<td><strong>BMCA</strong></td>
<td>Alternate BMCA</td>
<td>alternate BMCA based on the IEEE 1588 default BMCA</td>
<td>alternate BMCA based on the IEEE 1588 default BMCA</td>
</tr>
</tbody>
</table>

- **Note 1:** support for IEEE1588-2019 in all the Telecom Profiles
- **Note 2:** support for IPV6 was made mandatory for G.8275.2 and G.8265.1 in 2021
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

<table>
<thead>
<tr>
<th>IWF Node Type</th>
<th>PTP Profile</th>
<th>Clock type from [G.8275.1] &amp; [G.8275.2]</th>
<th>Clock type from [IEEE 1588]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IWF F-P</td>
<td>A (G.8275.1)</td>
<td>T-TSC or T-BC</td>
<td>OC or BC</td>
</tr>
<tr>
<td></td>
<td>B (G.8275.2)</td>
<td>T-GM</td>
<td>OC or BC</td>
</tr>
<tr>
<td>IWF P-F</td>
<td>A (G.8275.2)</td>
<td>T-TSC-P or T-TSC-A</td>
<td>OC or BC</td>
</tr>
<tr>
<td></td>
<td>B (G.8275.1)</td>
<td>T-GM</td>
<td>OC or BC</td>
</tr>
</tbody>
</table>
Power Profile Architecture and Profile

  - 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

  - 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

• PTP-based solution originally specified by the CERN targeting sub-ns accuracy, \( \text{max}(|TE|) < 1\text{ns} \) (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 latest revision was to address other applications besides audio and video.

- A revision of IEEE 802.1AS is planned, the work will start once current amendments are published.

Copy of figure 11-2 from IEEE 802.1AS:
Transport of time-synchronization information
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 being defined: Global Time (synchronized to TAI (International Atomic Time)), and Working Clock (synchronized to an arbitrary time (ARB))
- The 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 are being run to define key parameters that will be specified in the profile (e.g. residence time, Sync and Pdelay message rates)

![Diagram of Data flow in a control loop](image)

Source: IEC/IEEE 60802 D2.1 draft
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)
- Being addressed by ITU-T Q13/15

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)
  - Liaison from 3GPP SA2 to Q13

### Use case | Holdover time (note 3) | Sync target | Sync accuracy | Service area | Mobili ty | Remarks |
--- | --- | --- | --- | --- | --- | --- |
Power grid (5G network) | Up to 24 hour UTC (note 1) | <250 ns to 1000 ns (note 2) | < 20 km² | low | When 5G System provides direct PTP Grandmaster capability to sub-stations |
Power grid (time synchronization device) | >5 s UTC (note 1) | <250 ns to 1000 ns (note 2) | < 20 km² | 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.

### 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 P802.1D / 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» (Published in March 2023)
  - 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'

- 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-v2.2-Final.pdf (mopa-alliance.org)
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Insight and Innovation
• 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
  • 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
• 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: Technical Paper v2.2
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 clock),
- **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)