Precision Time Protocol Application Note

White Paper
Precision Time Protocol Application Note

Alcatel·Lucent Enterprise

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About this document

Purpose

The purpose of this document is to provide a comprehensive reference guide to the Alcatel-Lucent Enterprise solutions for mission-critical network customers using Precision Time Protocol (PTP). This solution is based on IEEE 1588v2 Standard for a Precision Clock Synchronisation Protocol for Networked Measurement and Control Systems. The standard defines the requirements for a precision clock synchronisation protocol for network elements in the network communications solutions offered by ALE.

Audience

This guide is intended for Alcatel-Lucent Enterprise Business Partner sales and pre-sales staff as well as customers.

Scope

This document focuses on PTP v2 protocol, describing time synchronisation processes within network elements in telecommunication networks in order to maintain consistent and accurate time. It also provides information about AOS capabilities with respect to PTP protocol and related configuration commands.

Acronyms

Frequency	292 incidents, 101 with confirmed data disclosure
AOS	Alcatel Operating System
APTS	Assisted Partial Timing Support
BMCA	Best Master Clock Algorithm
DECT	Digital Enhanced Cordless Telecommunications
DHL	Dual-Home Link
E2E	End-to-End
ERP	Etherent Ring Protection
FTS	Full Timing Support
GLONASS	GLObalnaya NAvigatsionnaya Sputnikovaya Sistema
GMC	Grandmaster Clock
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPSOD	GPS Disciplined Oscilator
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IT	Information Technology
ITU-T	International Telecommunication Union - Telecommunication Standardisation Sector
LACP	Link Aggregation Control Protocol
LAG	Link-Aggregation
MPLS	Multiprotocol Label Switching
P2P	Peer-to-Peer
PRC	Primary Reference Clock
PTP	Precision Time Protocol

Frequency	292 incidents, 101 with confirmed data disclosure
PTS	Partial Timing Support
SFP	Small Form-factor Plugable
TAI	International Atomic Time
T-BC	Telecom Boundary Clocks
T-GM	Telecom Grandmasters
T-TSC	Telecom Time Slave Clocks
TC	Transparent Clock
TDM	Time-division Multiplexing
UTC	Coordinated Universal Time

Abstract

The Precision Time Protocol (PTP) is a protocol used for precise synchronisation of clocks in measurement and control systems that rely on network communications. This protocol enables heterogeneous systems, ones with network elements that include clocks of diverse precision capabilities, to synchronise to a grandmaster clock allowing for system-wide synchronisation accuracy in the sub-microsecond range.

PTP uses a master-slave architecture that allows for a master-slave synchronisation hierarchy, where one device acts as a Grandmaster Clock (GMC) that provides the reference time for the system, and the other devices act as slave clocks that adjust their times to the GMC. The master clock sends out synchronisation messages which the slave clocks use to adjust their own clocks to the master clock.

On select Alcatel-Lucent OmniSwitch® products, ALE provides support for PTP transparent clocks, which measure the propagation delay between the master and slave clocks and provide corrections to the slave clocks for more accurate synchronisation across the network.

PTP clock types

In a network, each device has its own clock, and it is important that these clocks are synchronised to a common time reference to ensure that time-sensitive applications such as real-time video or financial transactions are accurately time stamped.

PTP clocks use the principle of time stamping, where packets are sent and received with a time stamp indicating the time of transmission or reception. By comparing these time stamps, PTP clocks can synchronise their clocks to a common time reference.

PTP domain

A PTP domain is defined as a group of clocks that are synchronised using the PTP protocols. In this document we will always refer to clock synchronisation within a single domain on the network. An example of a PTP domain with different types of clocks is shown in Figure 1.

Grandmaster clock

Within a PTP domain there is a single grandmaster clock which is used by the PTP protocol as the primary source of time synchronisation for the network. This grandmaster clock is responsible for multicasting (unicast communication is also possible) synchronisation messages to all other clocks in the domain. In some mission-critical networks it may be desirable to deploy the grandmaster clock in an active/passive redundant configuration. The active grandmaster clock is responsible for multicasting the synchronisation messages, while the passive grandmaster clock is kept in standby mode, ready to take over if the active grandmaster clock fails.

Boundary clock

A boundary clock is a node in the network that sits between the master clock and the slave clocks as seen in Figure 1. Its main function is to re-distribute the precise time information by performing dual roles. It acts as a slave clock and synchronises to a master clock and, at the same time, but on other port(s), serves as a time source. By doing so, the boundary clock helps to reduce the number of hops between the master clock and the slave clock, which can improve the accuracy and stability of the time synchronisation. Boundary clocks are therefore particularly useful in large, complex networks.

Transparent clock

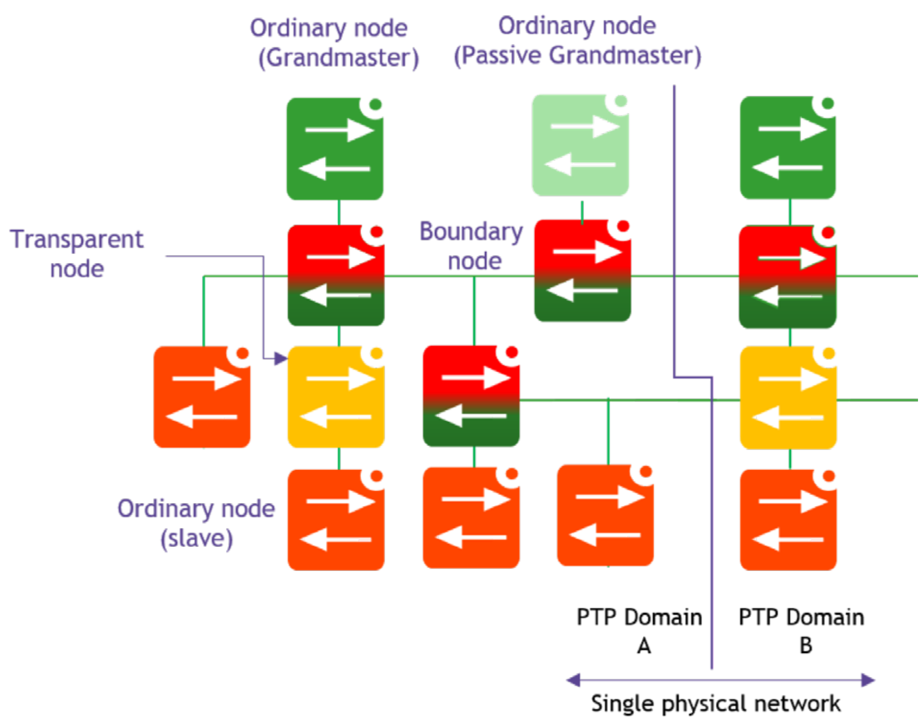
A transparent clock is a type of clock used to improve time synchronisation accuracy and reduce network latency. When a PTP synchronisation message is sent over a network, it may experience varying degrees of latency and delay as it passes through network devices. This can result in timing errors and inaccuracies that can affect the overall accuracy of the time synchronisation system. A transparent clock measures the time needed for PTP messages to transit the network node and forwards this information to clocks receiving this message. In addition to the operation of End-to-End (E2E) transparent clocks, a Peer-to-Peer (P2P) transparent clock also takes into account the propagation delay on the link connected to the ingress port of PTP event messages. Event messages are timed messages in which an accurate time stamp is generated at both transmission and receipt.

Slave clock

In simple terms, a slave clock is a clock on a network node that synchronises to the grandmaster clock. When a slave clock receives time information from a master clock it uses this information to adjust its own clock to match the master clock as closely as possible.

The previously mentioned master clock and slave clock are commonly called ordinary clocks as they have a single PTP port within PTP domain. Ordinary clock is a common name for clocks in the network with a single PTP port, for example, master and slave clocks.

Figure 1: PTP domains and clock types



PTP synchronisation

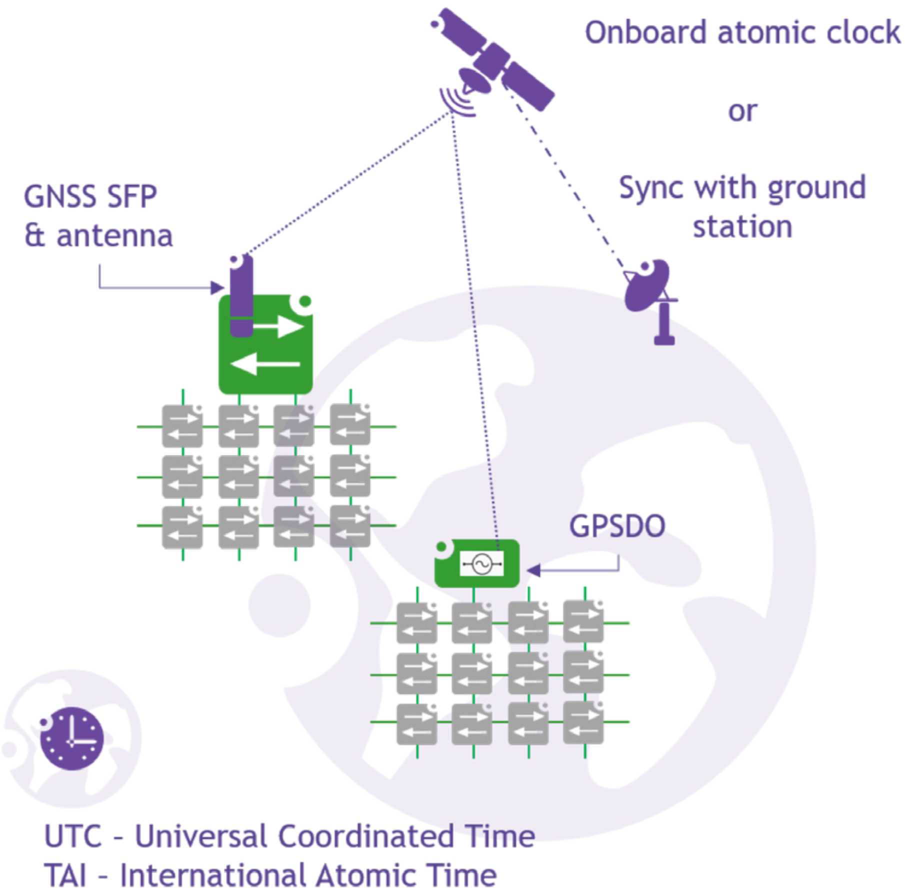
Primary reference clock

So far we have learned that PTP-enabled nodes on the network are synchronised to a master clock. The Grandmaster Clock, or Primary Reference Clock (PRC) in PTP networks is a device that serves as the ultimate time source for the network. The PRC is responsible for generating a highly accurate and stable time signal that is used as the basis for synchronising all other devices on the network. Figure 2 shows how the PRS is used in networks.

In most commercial networks today, the PRC is typically a GPS or GNSS receiver capable of receiving timing information from Global Navigation Satellite Systems (GNSS) such as GPS, GLONASS or Galileo. To provide accurate time to networks, satellites can either carry an on-board atomic clock or be synchronised with a ground station to one of two time standards used to measure time. Coordinated Universal Time (UTC) is the primary time standard used for civil timekeeping around the world, while International Atomic Time (TAI) is a more precise time standard used primarily for scientific research and other applications where extreme accuracy is required.

A grandmaster clock on the network could be one of the network nodes that has either an integrated GNSS receiver or support for GNSS SFP. Another type of PRC is the GPS Disciplined Oscillator (GPSDO), which could be used on-site for this purpose. This oscillator uses GPS for long-term stability and an on-board atomic (rubidium) oscillator for short-term stability.

Figure 2: Primary reference source in a network



2-step PTP synchronisation process

Each clock in the network must undergo a 2-step process during PTP synchronisation:

a) Choose the best master using the Best Master Clock Algorithm (BMCA)
b) Synchronise with the master using one of two available methods

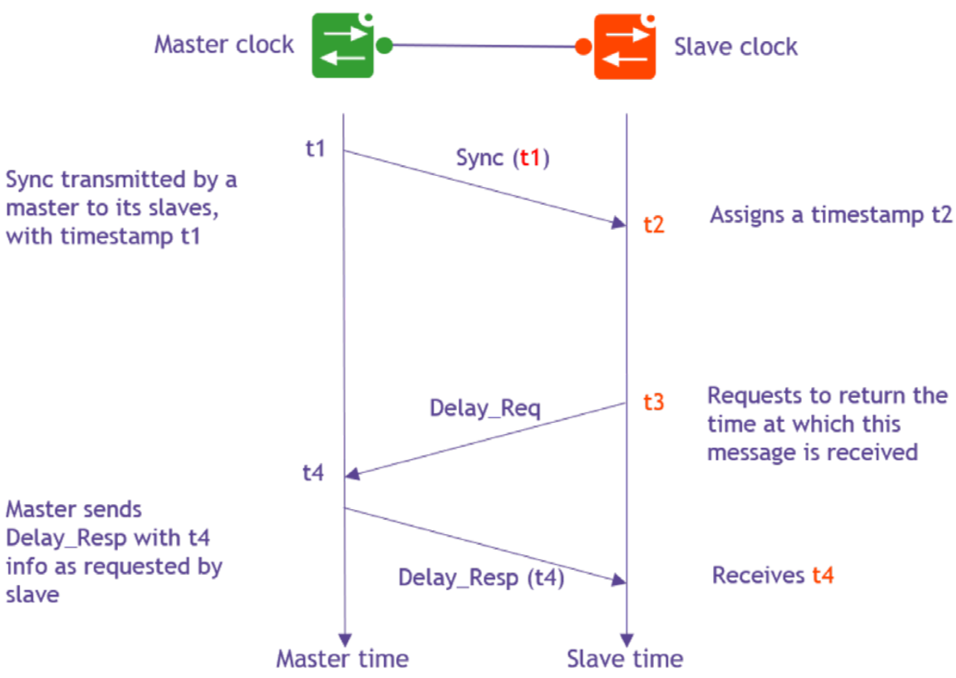
Choose the best master using the Best Master Clock Algorithm (BMCA)

As previously mentioned there might be multiple master clocks in the network. Using the BMCA, each clock will select the best available master clock among all the clocks on a PTP network. To determine the best master clock, the BMCA considers factors such as the user configurable priority, clock accuracy, clock stability and network distance when there are multiple paths available towards a potential master. Once the BMCA has selected the master clock, the local clock starts synchronisation with the selected master.

Synchronisation with the master – Delay request-response mechanism

In delay request-response synchronisation, the delay between the master and slave clocks is calculated as follows. The master sends the Sync message to the slave with the timestep t1, the time when the message egresses the master clock. The slave clock records the t1 received in the message and assigns the timestep t2, the time when the Sync message is received. The slave then initiates a Delay-Req message with the assigned timestep t3 when the message leaves the slave clock. When the master receives this message, it sends the Delay_resp message with the timestep t4, informing the slave clock of the time stamp when the Delay_req message arrives at the master clock. When all 4 time stamps are available at the slave clock, it calculates the "mean path delay" as [(t2-t1)+(t4-t3)]/2 and uses this to calculate the clock offset as t2-t1 - "mean path delay". The slave clock is then adjusted by the value of the calculated clock offset to synchronise with the master clock.

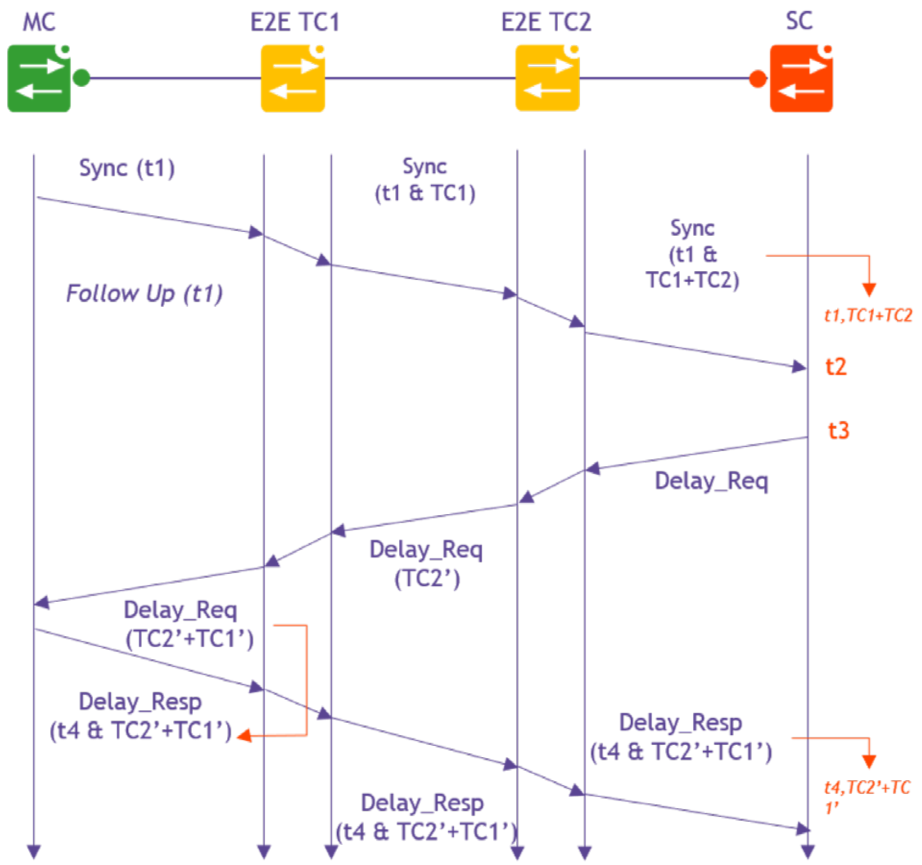
Figure 3: Delay request-response mechanism



In larger networks there may be multiple network nodes between the master and slave devices, and it is recommended that these devices support either a boundary clock or a transparent clock to ensure accurate time synchronisation. A boundary clock typically consists of a single slave port through which it is synchronised to its best master clock, and multiple master clock ports used for time synchronisation of other network nodes in the master-slave synchronisation hierarchy. The boundary clock should support and use the delay request-response mechanism in this environment.

End-to-end transparent clocks can be connected in the topology with ordinary and boundary clocks using the delay request-response mechanism. Transparent clocks measure the residence time of PTP messages, which is the difference between the time stamps on the ingress and egress ports of PTP messages. This residence time is then accumulated in the correction field of PTP event messages sent from the master to the slaves. The slave clock uses this accumulated information to adjust its clock for more accurate time synchronisation.

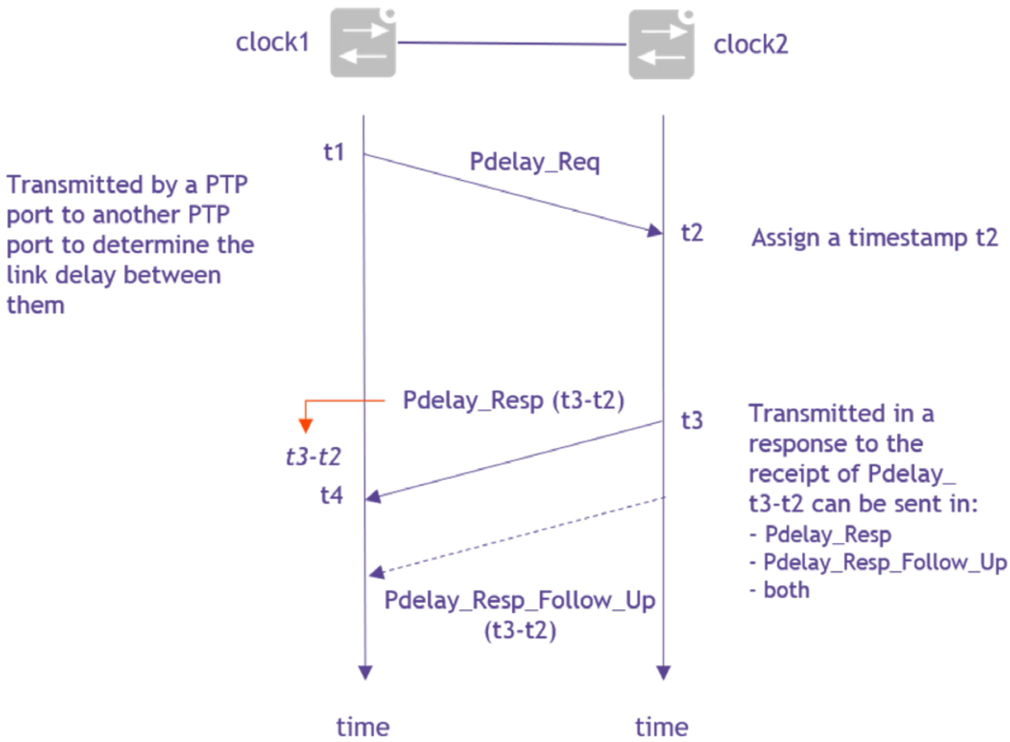
Figure 4: Transparent clock(s) in delay request-response synchronisation mechanism



Synchronisation with the master – the peer delay mechanism

The peer delay mechanism measures the link delay between any two ports implementing this mechanism using specific PTP messages. Both ports sharing the link perform this measurement regardless of their PTP role, a master or a slave, and as a result both ports know the link delay for the ingress side of the PTP messages. The path delay for PTP messages that ingress clock 1 is then calculated as [(t4-t1)-(t3-t2)]/2, as shown in Figure 5. This path delay value is used by the slave clock to compensate for the delay introduced by the network link when adjusting its clock.

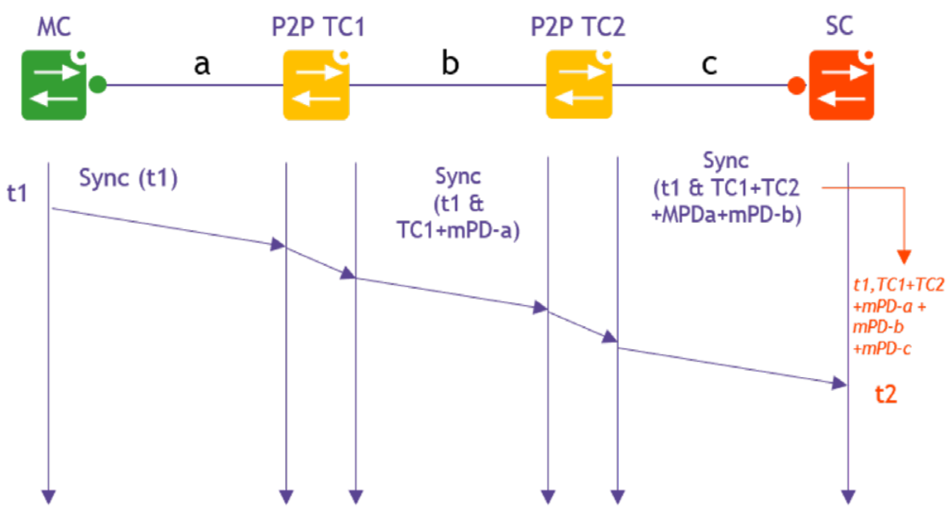
Figure 5: Peer-to-peer propagation time measurement



It is important to note that the peer delay and delay request-response mechanisms do not work together on the same communication path.

Peer-to-peer transparent clocks can be connected in the networks where ordinary and boundary clocks implement the peer delay mechanism. The peer-to-peer transparent clocks have the additional capability, compared to the end-to-end transparent clocks, to calculate a link delay for each port of a transparent clock. The correction field of the Sync message is, in addition to the cumulative update of the residence time only for end-to-end transparent clocks, cumulatively updated with both values; the residence time of the PTP message within the transparent clock and the link delay on the port receiving the PTP message. The slave clock offset is calculated as “t2-t1-Correction field value”, as shown in Figure 6.

Figure 6: Peer delay mechanism offset calculation



PTP profiles

The IEEE 1588 standard defines the purpose of profiles as "...to specify specific selections of attribute values and optional features of PTP ....", therefore they allow, prohibit, or enhance specific features of a rather flexible framework of the standard to achieve performance goals in specific environments such as SDH/SONET or LTE and 5G networks. For example, a profile can enforce the use of boundary clocks only in the architecture hierarchy between master and slave clocks or define whether PTP messages should use unicast or multicast format, or other.

Telecom profiles

While the IEEE standard defines the protocol for time and frequency synchronisation in packet networks, the International Telecommunication Union (ITU) is responsible for information and communication technologies, and ITU-T is the ITU Telecommunication Standardisation Sector that coordinates standards for telecommunications. This agency defines the following telecommunications profiles:

The ITU-T G.8265.1 frequency profile

The ITU-T G.8265.1 PTP profile for frequency synchronisation is designed to facilitate the integration of Precision Time Protocol (PTP) into existing telecommunications networks that rely on TDM technology for synchronisation. The purpose of this profile is not to improve the performance of existing synchronisation protocols or to introduce new functionality, but rather to provide a standardised framework for the use of PTP within telecommunications networks. By adopting this profile, telecom network operators can take advantage of the benefits of PTP, such as improved accuracy and reduced network complexity, without requiring a significant overhaul of their existing infrastructure. This profile doesn't provide support for boundary or transparent clocks in the network, only master and slave clocks are considered to participate in the PTP hierarchy.

The ITU-T G.8275.1 phase/time profile

The purpose of ITU-T G.8275.1 is to enable the deployment of highly accurate time and phase synchronisation in telecommunications networks based on the PTP protocol. This profile requires extensive on-path support, meaning that all network equipment that needs to deal with PTP traffic must be PTP-aware and implement specific functions such as Telecom Boundary Clocks (T-BCs), Telecom Grandmasters (T-GMs) and Telecom Time Slave Clocks (T-TSCs).

The profile defines the permitted node types as ordinary clocks, boundary clocks and end-to-end transparent clocks, while prohibiting the use of peer-to-peer transparent clocks. All messages are sent using multicast addressing and the frame structure is Ethernet based on IEEE 1588-2019 Annex E.

The reason for this level of precision and efficiency is to meet the demands of modern applications, particularly those related to cellular and wireless communications, which require highly accurate time and phase synchronisation in the microsecond range. This level of synchronisation is required for technologies such as 5G and beyond, as well as for applications such as high-speed trading and financial transactions that require precise time alignment.

The ITU-T G.8275.2 phase/time profile

The strong on-path support requirements of the Full Time Support profile make it less applicable to existing networks with complex infrastructures that may not be feasible to modify extensively. To address this issue, ITU-T has published a new PTP profile for phase/time synchronisation, known as ITU-T G.8275.2, which requires only partial timing support.

Both PTS and APTS are time and phase distribution architectures that relax the strict requirements of the FTS architecture, allowing more flexibility in the deployment of PTP. In particular, the PTS architecture does not require all transit nodes between the grandmaster and the slave to be PTP-aware. This means that FTS can be converted to PTS by replacing at least one T-BC with a non-PTP-aware device, making it more suitable for existing networks that cannot support the full on-path requirements of FTS.

Overall, the development of PTS and APTS profiles reflects the need for greater flexibility in the deployment of PTP-based synchronisation solutions, enabling more efficient and cost-effective synchronisation in a wider range of network environments.

The role of OmniSwitch in PTP hierarchy

PTP compatibility matrix

In mission-critical or telecom networks, accurate time synchronisation is essential for various applications. Transparent clocks, supported by select OmniSwitch models, allow intermediate switches to accurately measure and compensate for the delay introduced by the network, resulting in more accurate time synchronisation between master and slave clocks.

OmniSwitches support both types, end-to-end and peer-to-peer transparent clocks, according to the following matrix based on the current OS release at the time of writing, 8.9R2:

Table 1: PTP support matrix

Transparent clock	OS model
End-to-end	OS6465, OS6560 (1&10G ports), OS6860, OS6865, OS6900-X72/Q32
Peer-to-peer	OS6465, OS6560 (1 & 10G ports)

As shown in Table 1, an end-to-end transparent clock is supported across the entire ALE portfolio, including core and access network switches, as well as the hardened portfolio. A peer-to-peer transparent clock is supported on the Alcatel-Lucent OmniSwitch 6560 (OS6560) product line only. Both transparent clock modes support 1-step clock as described in this document, where the time stamp is included in the sync message. OmniSwitch models with PTP support both, unicast and multicast communication of PTP messages on the network.

For all other actual Alcatel-Lucent OmniSwitch 6900 (OS6900) and Alcatel-Lucent OmniSwitch 6860N (OS6860N) models, a PTP end-to-end transparent clock is currently under development and is on the roadmap for the next AOS release.

PTP CLI commands

With the following single command, an administrator can enable (or disable) the PTP transparent clock feature globally, on all interfaces. The default mode is end-to-end transparent clock:

```
-> interfaces ptp admin-state enable
```

In case a peer-to-peer transparent clock is needed, the following command must be placed for the desired interfaces:

```
-> interfaces port 1/1/1 ptp p2p admin-state enable
```

When peer-to-peer is enabled on a port, link delay will be computed dynamically for the corresponding link.

It is possible to change the priority of PTP messages from its default value of 5 with the following command:

```
-> interfaces ptp admin-state enable priority 4
```

PTP design

For many of today's applications, such as critical Internet of Things (IoT) and industrial automation IoT services, time synchronisation is fundamental. In these cases, the delay asymmetries and packet delay variations present in PTP-unaware networks would make it impossible to meet the stringent accuracy and stability requirements. To mitigate such effects, the transport network requires all network elements to be PTP-aware and to support PTP throughout the time distribution chain.

In the following transportation network design example, a grandmaster clock is provided by a GPS Disciplined Oscilator deployed in a redundant configuration for higher resilience and availability. This transport network uses IP/MPLS technology at the core and edge layers, deployed with IP/MPLS supported network elements such as Nokia 7250 IXR and Nokia 7210 SAS. These carrier-grade network elements also support different PTP clock functions, master, boundary and transparent clocks. In this design, Nokia network elements are configured as boundary clocks. They are synchronised to their best master clock, which is an active GPS Disciplined Oscilator, and provide synchronisation to slave clocks along the PTP synchronisation hierarchy.

The station network is implemented with AOS switches, OS6465 for harsh environments such as outdoor stations and OS6560 for indoor stations. Both OmniSwitch models support a transparent clock, either in end-to-end or peer-to-peer mode. The mode must be chosen at the design stage and should be consistent throughout the network as these two modes are not compatible. In this design, their role is to provide accurate and precise synchronisation to slave clocks on the network. Slave clocks would be different IoT elements connected to the access network layer.

Figure 7: Transportation network design

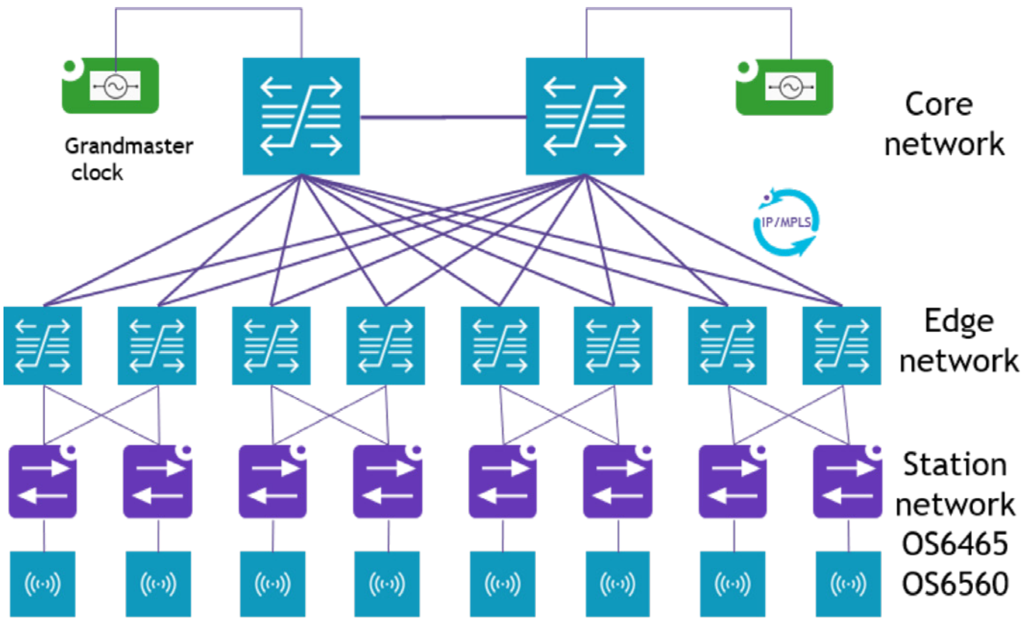
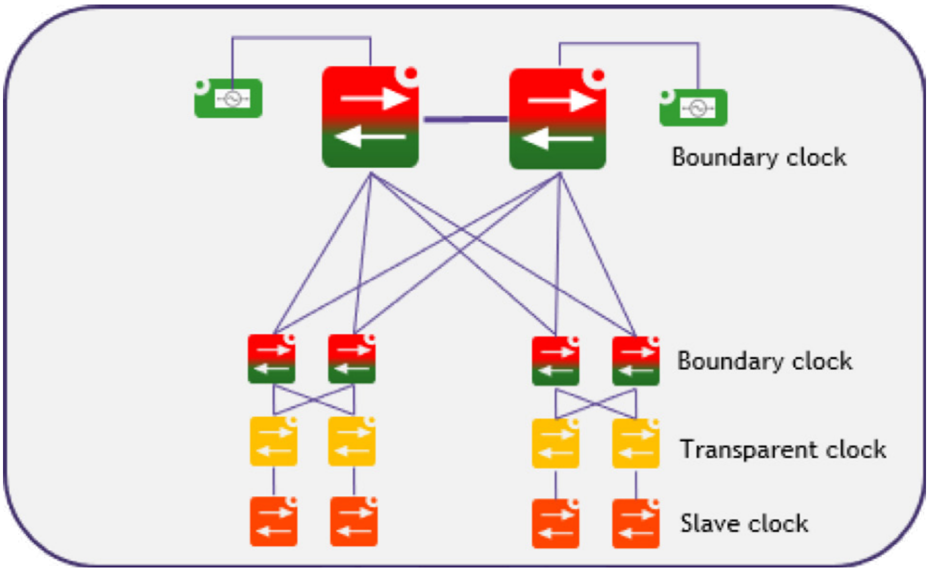


Figure 8: PTP hierarchy in a transportation network



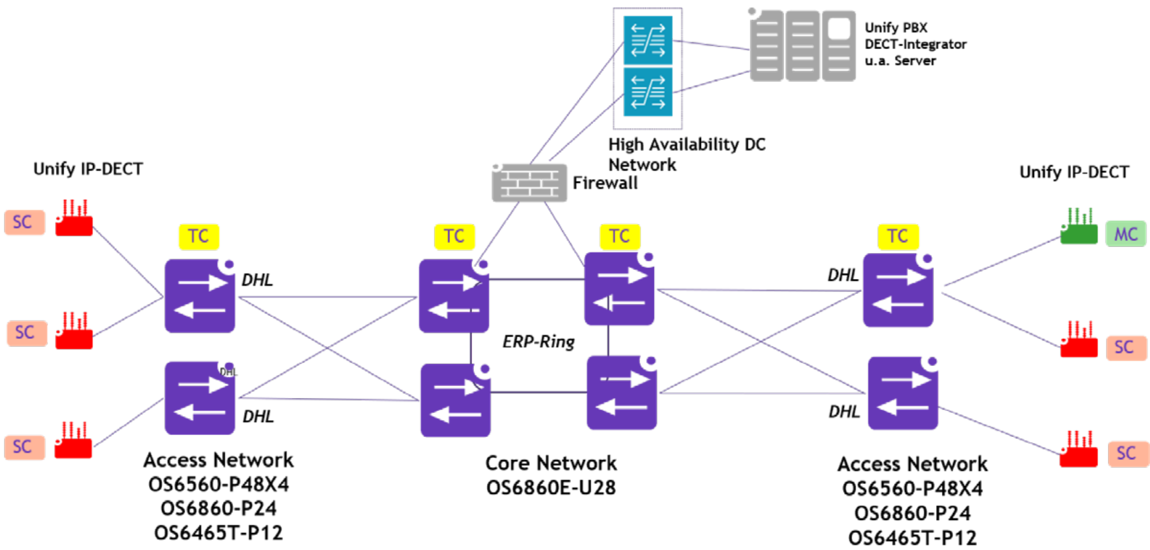
PTP use case

In this use case the customer required a reliable network infrastructure with high levels of redundancy and synchronisation for their DECT over IP solution. The solution is based on DECT IP base stations deployed at the access layer of the network. The DECT IP base stations are assigned with IP network addresses and connected to the access switches using Ethernet interfaces.

Accurate time synchronisation between the DECT IP base stations is essential for seamless call handover, which could take place between all DECT IP base stations within a single cluster. The IEEE 1588 protocol is required to synchronise the DECT IP base stations over the Ethernet LAN. Within the cluster, a maximum of one base station acts as a synchronisation master and all other base stations involved in the synchronisation, act as synchronisation slaves. For the successful implementation of a DECT over IP solution, the network must also meet the following additional requirements:

- The number of L2 Ethernet switches between the Synchronisation Master and a Synchronisation Slave must be as low as possible
- Only enterprise-class switches are supported
- The packet flow in the network must be symmetric and jitter must be minimal
- VLAN based prioritisation of LAN packets could be a fruitful measure to minimise packet delay and its jitter
- Jitter must be below an average value of 500ns
- PTPv2 is defined in the standard IEEE 1588-2008
  - The PTPv2 datagrams are (partially) sent as multicast and transported via UDP on IPv4
  - Multicast destination address: 224.0.1.129 UDP/PTP2 Ports 319/320
  - Multicast destination address: 239.0.0.37 UDP/propritaey Ports 21045/21046
- IGMP snooping is supported by OSCIPv2 and should be supported by the switch, so that the switch can be automatically configured on which ports the multicast packets should be sent to

Figure 9: PTP use case of deploying DECT over IP solution



As shown in Figure 9, the solution was delivered using OmniSwitch products; OS6860E in the core and OS6465/OS6560/OS6860 in the access layer. These products were chosen for their ability to provide high levels of redundancy and resiliency using the Ethernet Ring Protection Switching (ERPS) protocol and Dual-Home Link (DHL) technology, as well as their ability to support transparent clock. Support for TC is a critical element in providing the required end-to-end synchronisation between DECT stations.

Conclusion

In conclusion, the use and importance of the 1588 Precision Time Protocol (PTP) in today's interconnected world cannot be underestimated. This protocol has revolutionised the way time synchronisation is achieved in distributed systems, enabling precise and accurate coordination of devices across different networks.

Use of 1588 PTP has brought significant benefits to industries where precise timing is critical, such as telecommunications, finance, power utilities, industrial automation and transportation. Sub-microsecond synchronisation has improved the reliability and efficiency of critical operations, enabling seamless coordination between devices and systems.

One of the key benefits of the 1588 PTP is its ability to synchronise devices over Ethernet networks, eliminating the need for specialised timing infrastructure and reducing costs. It enables the precise alignment of distributed clocks, ensuring that time-critical applications such as real-time control systems or financial transactions can be executed with the utmost accuracy and consistency.

In addition, the 1588 PTP has played a key role in enabling the development and adoption of new technologies. It has facilitated the implementation of advanced applications such as 5G networks, the Internet of Things (IoT) and the Industrial Internet of Things (IIoT), where accurate time synchronisation is essential for seamless communications and efficient data exchange.

By embracing this precision time protocol, ALE is demonstrating its commitment to providing reliable and accurate time synchronisation solutions to its customers. With support for the IEEE 1588 transparent clock, ALE is enabling its customers to take advantage of the protocol's benefits, such as sub-microsecond synchronisation. In addition, by supporting IEEE 1588, ALE is demonstrating its commitment to interoperability and industry standards. This ensures that ALE solutions can be seamlessly integrated with other devices and systems that also adhere to the protocol, promoting compatibility and enabling smooth communications across networks.

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