INTRODUCTION

Within the telecom industry there is considerable interest in using packet-based timing mechanisms such as the IEEE 1588 Precision Time Protocol (PTP) to distribute frequency, phase, and time. Packet-based timing solutions such as PTP provide an evolutionary step in the development of next-generation synchronization architectures. One of the first applications for the use of PTP in telecom is in mobile backhaul. Reference [1], published in this issue, provides an overview of mobile backhaul technologies and the radio interface synchronization requirements. It discusses some of the differences with respect to synchronization between frequency-division duplex and time-division duplex mobile systems. It also provides an overview of synchronous Ethernet (SyncE) [2–6] and IEEE 1588 [7] as technologies to be used for the distribution of frequency.

ABSTRACT

This article describes the work performed by ITU-T SG15Q13 for defining the first telecom profile based on the use of IEEE Std 1588-2008. The first profile is specifically developed for the distribution of frequency using unicast IPv4 transmission, and required adaptation of the IEEE1588 protocol to make it suitable for the telecom environment. The objectives, reasons, and results of this adaptation are explained in this article. Since the distribution of phase/time is also gaining importance in telecom, the article briefly discusses the objectives, reasons, and upcoming work for the definition of another profile that will leverage other functions and clocks defined in IEEE1588.

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PACKET-BASED SOLUTIONS TO SUPPORT MOBILE BACKHAUL SYNCHRONIZATION NEEDS

In the initial transition phase from time-division multiplexing (TDM) to a packet network, and when the distribution of timing over the physical layer is not available (e.g., equipment not supporting synchronous Ethernet or physical limitations across administrative domains), the distribution of timing via packets-based solutions (e.g., PTP) is seen as an alternative option.

Although the initial PTP profile covers only end-to-end frequency synchronization, some of the basic principles presented in this section provide background material covering both frequency and time synchronization. Future profiles will address the need to distribute time synchronization.

PACKET-BASED TIMING METHODS

The term packet-based method identifies a generic class of methods that rely on the exchange of timing information carried within packets.

The two main network elements in a packet-based method are the packet master (master) and packet slave (slave). As described later in this article, additional functions may be implemented in the network to enhance performance, especially when distributing phase/time. As shown in Fig. 1, the master generates timing packets based on a timing reference signal (frequency reference). The slave recovers the timing reference signal from the packet timing flow. Between the master and slave, the packet-switched network will generate various types of impairments (packet loss, packet delay variation, route change, etc.).

The general principle behind packet-based methods is to compare the time of arrival of a packet (as measured by the local clock in the slave) with the expected time of arrival of the packet generated by the master (i.e., time of departure of the packet from the master plus an offset related to the transfer delay across the network).

One method to transmit the times of departure and arrival is based on the use of timestamps, and protocols such as Internet Engineering Task Force (IETF) Network Time Protocol (NTP)/Simple NTP (SNTP) and IEEE 1588 PTP adopt this approach between a master and slave for synchronizing clocks in the network. The protocols can be used to distribute frequency and/or time. In addition, the protocols can be used in one-way or two-way mode as shown in Fig. 1.

The comparison of local time of arrival with the content of the timestamp as generated by the master corresponds to a measurement of a time offset in a one-way packet transfer that is analogous to the phase error measurements obtained with current physical layer one-way synchronization. As such it is capable of supporting frequency transfer but not precise time transfer.

In contrast to one-way operation, two-way timestamp operation implies packet timing flows in both directions. The use of two-way is necessary to estimate the network transfer delay between master and slave, thus allowing the distribution of time. The use of two-way operation has also been proposed in case of frequency distribution as it would enable the distribution of additional information that can be used in the frequency recovery process.

From an ITU-T perspective, the clock supporting packet-based methods in a packet slave is called a packet-based equipment clock (PEC), and its characteristics are under study.

Figure 1. General principle of packet-based timing methods.
When phase/time synchronization is required, the estimation of the network transfer delay between Master and Slave is also impacted by any asymmetry in the network. In fact, the basic assumption in any two-way time transfer method is that the delays are symmetric in the forward and reverse direction.

Packet-based timing methods distributing frequency are essentially based on adaptive clock recovery methods [3], and the performance of the recovered timing signal is generally impacted by the PDV in the network.

If the delay through the packet network is constant, there is no variable delay added by the network on the time of arrival of packets at the packet slave (PEC clock). If the delay varies, it may be perceived by a clock recovery process as a change in phase or frequency of the timing reference signal at the packet master. Specific algorithms need to be implemented at the slave side to compensate for PDV. The characteristics of the oscillator implemented at the slave clock also need to be considered.

When phase/time synchronization is required, the estimation of the network transfer delay between master and slave is also impacted by any asymmetry in the network. In fact, the basic assumption in any two-way time transfer method is that the delays are symmetric in the forward and reverse direction. As described later in this article, additional requirements on the intermediate network nodes (e.g., IEEE 1588 boundary clock and/or transparent clocks) between the packet master and packet slave can also be considered to enhance the performance of these two-way time transfer methods, and their use in telecom networks is being studied.

The timing target performance of some applications is described in [3].

**PACKAGE TIMING FLOW CHARACTERISTICS**

A timing flow represents the timing information (e.g., via timestamps) that may be carried across a packet network.

Packet equipment is designed for optimizing bandwidth use based on statistical multiplexing. The statistical nature of transmission implies that all flows (either data or timing) interfere with each other to some degree, regardless of the priorities (high or low) assigned to the flows.

The forwarding/routing and priority treatment of packets is typically done using various packet processing techniques, which are implemented in either hardware (e.g., network processing unit [NPU], application-specific integrated circuit [ASIC]) or software (e.g., CPU). These techniques have generally been designed to support a variable set of (sometimes complex) network services, but not necessarily the requirements of timing flows. Depending on the vendor implementation, each equipment will generate unique delay variation characteristics, and it can be quite challenging for an operator to characterize the PDV of the network, especially in a multivendor network. This complex scenario is a difficult challenge since timing flows are extremely sensitive to PDV.

It is recommended that network and timing distribution be engineered closely. For instance, assigning the highest priority to a timing flow and/or engineering a specific path to minimize the packet network impairments can be part of such a process. What constitutes a well-engineered network to transport timing is currently under study. In particular, some packet metrics are being considered to help characterize packet delay and packet delay variation.

**EVOLVING THE SYNCHRONIZATION ARCHITECTURE**

The distribution of frequency using packet-based methods is changing the architecture of the synchronization network to migrate from a link-based approach (e.g., synchronous digital hierarchy [SDH], SyncE) to a path-based distribution mechanism. However, as mentioned above, the use of a well-engineered network is essential to prevent network impairments and allow the proper operation of timing methods such as PTP. Such an engineering approach to the transport of synchronization may not be easy, but the advantage provided is that timing can be distributed through the network without having to use node-by-node support (link-based).

Given the drivers to deploy PTP within mobile networks, the relationship between fixed and mobile networks and their respective operators may well influence the development of the network architecture. For example, the entire backhaul network may be owned by the mobile network operator (MNO), the MNO can purchase Ethernet leased lines from another carrier service that includes the provision of synchronization. All these scenarios and the commercial relationship will thus influence development of the network architecture. This needs to be factored into the limitations of offering PTP technology and the characteristics of the network over which it is transported.

In the case of a fully MNO-owned network, the PTP master may be deployed at the MNO’s central office (or anywhere within the backhaul network) since the MNO has control over the end-to-end architecture. This may also be the case when purchasing some form of backhaul capacity from a fixed (carrier) provider. An example is depicted in Fig. 2a. Note that in such a model the MNO slave may be integrated in the network, or the MNO may buy some form of managed service that includes the provision of synchronization. All these scenarios and the commercial relationship will thus influence development of the network architecture. This needs to be factored into the limitations of offering PTP technology and the characteristics of the network over which it is transported.

In the case of a managed service, synchronization might be provided. In this case timing can be provided to the base station via physical layer synchronization delivered from the service delivery platform (e.g., dedicated 2048 KHz signal). In the situation where it is not possible to provide timing to the service delivery platform via physical layer (e.g., via SyncE), a PTP slave might be integrated in this node, and timing could be delivered via PTP from a PTP master that is owned by the carrier, as shown in Fig. 2b.

The end-to-end architecture models illustrated in Fig. 2 will influence where the masters are located in the network.
to be located, as well as the redundancy aspect of their location. The end-to-end PTP profile is only one part of the synchronization architecture, and this part will be entirely compatible with either an asynchronous or synchronous packet-switched network. Furthermore, the timing signal reference for a PTP master may well be generated from a synchronous network such as SyncE. This can be used to interwork between a synchronous network and an asynchronous network, such as the hybrid Ethernet/packet equipment clock (EEC/PEC) device shown in Fig. 3.

In reference to Fig. 3, it should be noted that, unlike the PECs, the EECs, which are part of the SyncE reference chain, will not be impacted by network traffic. Hence, a high level of performance can more easily be achieved by a SyncE solution, which has an established architecture and performance.

IEEE 1588-2008 AS A SOLUTION
This section provides an introduction to PTP defined in IEEE 1588-2008, and the activities that have been required in order to adapt this protocol to the telecom environment.

IEEE 1588 Protocol Overview
The first version of IEEE-1588, “IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems,” was published on November 2002. It was designed to synchronize real-time clocks in a distributed network and developed to support the timing requirements of industrial automation and test and measurement applications in a local area network (LAN) environment.

However, interest in expanding the application scope of PTP resulted in the development of a second version of IEEE 1588 containing features that enable the protocol to be used over a wide area network. The second version targeted several applications such as military, power generation and distribution, consumer electronics, and telecommunications. To support the different requirements for these applications, the new version introduced the concept of the profile where a set of allowed IEEE 1588-2008 functions may be selected and specified for a particular use.

The ITU-T is currently releasing such a profile for telecom applications. ITU-T Recommendation G.8265.1, “ITU-T PTP Profile for Frequency Distribution without Timing Support from the Network (Unicast Mode)” [8], is intended to be used by telecom applications that need frequency synchronization only, in an environment where the network does not provide any support for PTP, such as boundary clocks or transparent clocks. This first profile is applicable to unicast mode only.

Additional profiles are also expected to be developed later by the ITU to address multicast transmission as well as transport of accurate time and phase. The latter case should involve the use of boundary or transparent clocks, possibly in combination with physical frequency methods such as SyncE. Indeed, while a mode without

Figure 2. Deployment of PTP master and slave in a multi-operator context (MNO/carrier).
Timing assistance from the network may in some cases enable delivering frequency, it is likely that this mode will not be appropriate in general for accurate phase and time delivery.

The basic synchronization principle in PTP is achieved by the transmission of messages between a slave clock and a master clock as illustrated in Fig. 4.

IEEE 1588 defines one-step and two-step clock operations. In a one-step clock the master sends Sync message with the precise timestamp $t_1$ embedded in the message. In a two-step clock, the Sync message contains an approximation of the timestamp $t_1$, and a follow-up message contains the precise timestamp $t_1$ of the corresponding Sync message. Note that in one-way mode, only these messages are used to exchange timing information.

In two-way mode, in addition to the previous depicted messages, the slave sends a Delay_request message to its master and computes timestamp $t_3$. The master sends a Delay_response message with the time of reception $t_4$ of the Delay_request message.

Assuming a symmetric network, the offset and propagation time can be measured as follows:

$$\text{Offset} = \frac{[(t_2 - t_1) - (t_4 - t_3)]}{2}$$

$$\text{Propagation time} = \frac{[(t_2 - t_1) + (t_4 - t_3)]}{2}$$

The offset is the slave time (i.e., the slave clock reading) at an instant of time minus the master time (i.e., the master clock reading) at the same instant of time. It represents the time difference between the two clocks.

**IEEE 1588 Features of the Frequency-Only Telecom Profile**

The profile contained in ITU G.8265.1 adheres to the general rules for profiles outlined in IEEE 1588. Some choices for particular functionality are outlined below and are based on the specific requirements of the telecom environment. It is important to note, however, that while the profile defines the configuration parameters, attribute values, and optional features of PTP necessary to ensure protocol interoperability, specification of the profile itself does not guarantee that the performance requirements of a given application will be met.

IEEE 1588-2008 defines several mappings to transport PTP messages, and the default profiles specified in Annex J of IEEE1588 use multicast. However, the standard allows the use of unicast provided the behavior of the protocol is preserved, and defines several optional PTP features.

G.8265.1 contains a general description of unicast and multicast modes. The first version of G.8265.1 defines an Annex for unicast mode where PTP messages are mapped over UDP/IP to facilitate the use of IP addressing. G.8265.1 uses the unicast message negotiation optional PTP feature as this profile is focused on unicast mode. It is planned for G.8265.1 to define another Annex for multicast mode.

PTP is always executed within a PTP domain, representing a logical separation of IEEE 1588 clocks synchronized with each other using PTP. In G.8265.1, for the unicast profile, domains are established by the use of unicast messages, which isolate the different PTP communications. G.8265.1 utilizes the PTP domain number range from 4 to 23.

PTP is a two-way time transfer protocol initially designed to deliver time synchronization, but one-way is also allowed to be used according to IEEE 1588; as for frequency delivery, there is no need to compensate for the propagation delay. Therefore, G.8265.1 allows the use of
both one-way and two-way modes. The mode used depends on the slave implementation.

G.8265.1 only uses ordinary clocks, and allows the use of both one-step and two-step clock behaviors.

**Alternate Best Master Clock Algorithm and Master Selection Process** — IEEE 1588-2008 defines a Best Master Clock Algorithm (BMCA) used to determine the state of each port. The BMCA operates to elect a single PTP clock within a PTP domain as the grandmaster, which is the unique active master in the PTP domain. The standard allows a profile to specify an alternate BMCA that can be used by a profile to determine the state of each PTP clock (e.g., master or slave).

Key telecom-specific requirements include timing protection (slave clocks are visible to multiple master clocks), load balancing (the timing distribution can be shared among multiple active grandmaster clocks in a network), and the need to associate traceability information to the PTP timing flow. Based on examination of these requirements, the ITU-T concluded that clock selection in G.8265.1 would be provided by a master selection process outside of PTP itself, and decided to specify an alternate BMCA.

The alternate BMCA specified in G.8265.1 ensures that masters are always active, and slaves are always slave-only clocks. As IEEE 1588-2008 requires that only one master be active in a PTP domain, each master is isolated in a separate PTP domain by network isolation due to the unicast communication. Moreover, grandmasters do not exchange messages.

G.8265.1 introduces the concept of a telecom slave, consisting of multiple PTP slave-only clock instances. Each instance is configured to communicate with a single grandmaster in a separate PTP domain. This allows the slaves to be connected to several grandmasters, and therefore to participate in different PTP domains.

Figure 5 depicts a logical model of a telecom slave. This model is not intended to imply a specific implementation. In this specific example three different grandmasters are active in the network. As noted above, separate domains are established by unicast communication between the grandmaster and the slave-only clocks. As an example, the telecom slave is locked to the primary grandmaster 1, and grandmasters 2 and 3 will be redundant. If grandmaster 1 fails, the telecom slave will switch to either grandmaster 2 or 3 depending on the master selection process.

The master selection process is based on the quality level (QL)-enabled mode specified in ITU-T Recommendation G.781, “Synchronization Layer Functions” (SDH and SyncE), with some adaptations in order to cover the differences between a physical timing signal and a packet timing signal. The following parameters contribute to the grandmaster selection process:

- **Packet timing signal fail (PTSF):** Failure condition of the PTP packet-timing signal
- **QL:** Traceability information of the grandmaster clocks carried by PTP Announcement messages; interoperable with SDH/SyncE traceability values

### ADDITIONAL CONSIDERATIONS FOR IEEE 1588 DEPLOYMENT

The development of the telecom profile begins to specify the parameters and features specified within IEEE1588 that will allow PTP to be used in carrier networks for distribution of frequency. While much progress has been made in this area, as noted above, it is important to note that other aspects considered to be outside of the scope of the profile itself are, in some cases, critical to the eventual deployment of packet-based timing solutions. At a high level, deployment of packet-based timing requires careful consideration of network design and management in order to meet the end goal of providing traceable timing. The behavior of packet networks under various load conditions will require care in engineering the network to ensure that a packet network does not introduce excessive PDV.

Once deployed, the issue of monitoring and maintaining performance exists. Work is ongoing at ITU-T to develop a standardized set of metrics that will allow measurement of basic packet delay metrics in order to estimate the effective performance that may be produced from a slave clock. At present, only proprietary metrics exist, but this is an area of increased interest in standards.

The structure and characteristics of the slave clocks in the network are another critical area
that is outside the scope of G.8265.1, but will have a strong impact on the performance achievable and hence the performance that may be available to support a revenue generating service. For the first version of the profile, the clocks supported are referred to as ordinary clocks. These simply terminate the packet flows containing PTP messages and then generate the appropriate reference. Performance aspects of the clocks are outside of the scope of the profile. Work is currently underway to attempt to define clock performance parameters (holdover, etc.) for use in packet timing distribution. Additionally, future work may look at the applicability to telecom environments of other PTP clocks that have been defined for LAN environments. The impacts on existing network architectures and topologies need to be carefully considered.

**FUTURE PROFILES**

While frequency distribution addresses many current applications, certain technologies require the use of time and phase in addition to frequency. Code-division multiple access (CDMA) and Long Term Evolution time-division duplex (LTE-TDD) are examples of such technologies. The ITU-T is currently planning to develop additional profiles that will utilize IEEE 1588 for the delivery of accurate phase/time and frequency. The accuracy levels for time and phase are application-dependent, and in some cases the frequency stability requirements to attain highly accurate and stable time distribution may involve the use of expensive oscillators. Proposals have been made to the ITU-T to utilize PTP for phase/time distribution in conjunction with synchronous Ethernet to enable the physical layer to provide access to highly stable network clocks, as shown in Fig. 6.

As noted earlier, for phase/time distribution the performance achievable using packet-based methods is affected by network asymmetry. To achieve accurate phase/time synchronization, timing support from the network may be needed as it can significantly reduce the impact of packet network impairments.

In this case the intermediate nodes provide support for PTP, via the implementation of IEEE 1588 boundary or transparent clocks. Each intermediate node is therefore IEEE 1588 aware. Hence, the timing flow containing phase or time information generated by a master is processed in each node. Support of boundary and transparent clocks will require development of additional telecom profiles, and clock or node characteristics and metrics.

In the original LAN environment targeted by IEEE1588, implementing and deploying boundary or transparent clocks is possible, as there is full control over the equipment and topology that may be deployed. However, deploying boundary or transparent clocks in telecom networks may be operationally challenging and need appropriate engineering considerations from the timing and networking standpoints.

**CONCLUSION**

The development of the PTP profile for telecom is a very important step in the ongoing development of the next-generation network synchronization architecture. Considerable development
work has now taken place within the ITU, and the point has been reached where an end-to-end frequency-based profile is nearing completion. This article has highlighted mobile backhaul with its requirements as one of the initial application areas for the profile.

Within the initial profile a number of key decisions have been made in terms of mode of operation (i.e., unicast), aspects of its reach (i.e., specific domains of operation), and master clock selection (i.e., the Alternate Best Master Clock algorithm).

It is critical to understand that to achieve expected application performance, the packet-based timing method requires the network to be well engineered as PDV may impact the achievable synchronization performance.

A number of key areas still require work. These include network design and management, monitoring and metrics, and the implementation of slave clocks, among others. In addition, work to extend its use to transport phase/time information will also be important. Such requirements may well make use of synchronous Ethernet and IEEE 1588 PTP hop-by-hop implementations.

**REFERENCES**


**BIOGRAPHIES**

JEAN-LOUP FERRANT ([jean-loup.ferrant@calnex.com](mailto:jean-loup.ferrant@calnex.com)) graduated from INPG Grenoble, France, joined Alcatel in 1975, and worked on analog systems, PCM, and digital cross-connects. He has been working on SDH synchronization since 1990, and on SDH and OTN standardization for more than 15 years in European Telecommunications Standards Institute (ETSI) TM1 and TM3, and ITU-T SG13 and SG15. He has been rapporteur of SG15 Q13 on network synchronization since 2001. He was an Alcatel-Lucent expert on synchronization in transport networks until he retired in March 2009. He is still rapporteur of SG15 Q13, sponsored by Calnex.

MIKE GILSON ([mike.gilson@bt.com](mailto:mike.gilson@bt.com)) is a technical specialist with BT Innovation & Design at Adastral Park. He joined BT in 1983, and has played a major role in developing and implementing BT’s time and synchronization strategy from 1988 to the present day. He has worked on synchronization standardization in ITU, ETSI, and IETF, but is currently only actively contributing to the ITU and ISF NIST synchronization fora. He is a member of both the ISF and NIST Steering groups. He has a B.A. (Hons) degree in business studies and is a member of the Institute of Engineering and Technology (IET).

SEBASTIEN JOBERT ([sebastien.jobert@orange-ftgroup.com](mailto:sebastien.jobert@orange-ftgroup.com)) is an R&D engineer, Network Synchronization, France Telecom. He received an engineering Master’s degree from Paris University Pierre et Marie Curie in 2005. After two years working on VoIP and data synchronization aspects, he joined France Telecom R&D/Orange Labs in 2006, where his current research domain is focused on time and frequency synchronization in telecom networks, and provides expertise to the France Telecom Group in this domain. He takes an active part in standardization through ITU-T SG15 Q13 dealing with network synchronization and IETF. He is also a member of the ISF steering group.

MICHAEL MAYER ([mmayer@ciena.com](mailto:mmayer@ciena.com)) graduated from Queens University (B.Sc.EE). In 1982 he joined Bell-Northern Research and later Nortel. He is currently with the CTO Department of Ciena Corporation. Since 1995 his area of focus has been systems design and standardization, where he has been actively contributing to standards in the areas of synchronization, OTN, SONET/SDH, and ASON control plane architecture. Within the ITU, he has been a technical editor of several ITU-T Recommendations covering the ASON optical control plane and synchronization related topics.

LAURENT MONTINI ([montini@cisco.com](mailto:montini@cisco.com)) is technical leader in the Office of the CTO at Cisco Systems. Since 2005 he focused his work on frequency and time distribution over

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**Figure 6. Illustration of a packet-based method with timing support from the network combined with frequency distribution delivered at the physical layer.**
packet network, especially in the telecom environment. He participates in standardization efforts including IEEE 1588, ITU-T SG15 Q13, and IETF TICTOC. He joined Cisco in 1997 and for six years has been a consulting engineer for mobile operators promoting network convergence for backbone and radio access networks where the emergence of pseudo-wire techniques raised the timing issue.

MICHEL OUELLETTE (michel.ouellette@huawei.com) is a technical advisor in Huawei’s IP Network Solutions and Clock Laboratory, where he focuses on mobile backhaul networks, and the development and analysis of packet network architectures/protocols for accurate frequency and phase/time distribution. He participates in ITU-T and IEEE 802.3 standardization. Prior to joining Huawei, he spent 12 years at Nortel focusing on ATM/TDM pseudowires, synchronous Ethernet, clock algorithms for base stations, TCP/IP active queue management, and ATM switching. He has been granted 10 patents and has published several international journal papers. He received his B.A.Sc. and M.A.Sc. from the University of Ottawa in 1995 and 1997, and attended l’Ecole Nationale Superieure des Telecommunication.

SILVANA RODRIGUES (silvana.rodrigues@idt.com) is director of system engineering at Integrated Device Technology (IDT). She graduated in electrical engineering from Campinas University, Brazil. She started her career at the Telecommunication Research Center in Brazil; she worked at Zarlink where she held several positions as analog designer, engineering manager, and synchronization system architect. She participates in several standards groups; she is the editor of ITU-T Recommendations G.8263 and G.8262, and secretary for IEEE 1588.

STEFANO RUFFINI (stefano.ruffini@ericsson.com) is Expert R&D at Research & Innovation, Ericsson. He joined Ericsson in 1993 and has been working on synchronization aspects for about 15 years. He has represented Ericsson in various standardization organizations (including ETSI, ITU, 3GPP, and IETF) and is currently actively contributing to ITU-T SG15 Q13 (serving as associate rapporteur and editor) and IETF TICTOC. He is one of the Ericsson experts involved in the definition of equipment and network synchronization solutions.