Synchronous Ethernet (SyncE) Usage for DAA and Mobile X-haul over DOCSIS

A Technical Paper prepared for SCTE by

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1. Introduction

Synchronous Ethernet (SyncE) is used mainly in telecom networks to provide physical layer clock delivery for frequency synchronization (a.k.a syntonization). The cable industry has not yet adopted SyncE as a common supported functionality as IEEE1588 is more commonly used for time synchronization (mainly for DAA use cases).

Adopting SyncE in conjunction or in addition to IEEE1588 may add advantages both from a performance perspective, and from a simplicity and cost perspectives as well.

This paper will describe different use cases for both DAA RPHY/RMACPHY and mobile backhaul (LTE and 5G) where SyncE can add a true value. Analysis of performance compared to traditional IEEE1588 usage will be shown and the benefits in simplicity will be discussed.

2. The Need for Synchronization

Traditional network synchronization has been based on the accurate distribution of frequency. Wireless networks have evolved to require the distribution of accurate time and phase information. In order to deliver this information, network operators have to distribute a reference timing signal of suitable quality to the network elements processing the application.

There are two basic approaches for distributing synchronization information. The first is to follow a distributed primary reference time clock (PRTC) approach, implementing a global navigation satellite system (GNSS) receiver in the end application, and the second is based on a master-slave hierarchical strategy.

Master-slave synchronization uses a hierarchy of clocks in which each level of the hierarchy is synchronized with reference to a higher level, the highest level being the Primary Reference Clock (PRC). Clock reference signals are distributed between levels of the hierarchy via a distribution network which may use the facilities of the network. The hierarchical strategy can be used for physical layer frequency distribution as well as higher layer packet-based frequency, phase, and time distribution.

Packet-based methods for distribution of frequency, phase, and time have been developed using precision timing protocol (PTP) and network time protocol (NTP). PTP is typically used instead of NTP in applications with stricter phase and time synchronization requirements. The improved accuracy for PTP is a result of its hardware-based timestamping.

2.1. Synchronous Ethernet (SyncE) Overview

The ITU has defined mechanisms to use the Ethernet physical layer to distribute frequency information across a network that are similar to the physical layer methods used with synchronous digital hierarchy (SDH)-based network synchronization. ITU-T G.8261 provides the network limits for transferring timing across a packet network. G.8262 defines the timing characteristics of an Ethernet Equipment Clock, while G.8262.1. defines improvements for the Enhanced Ethernet Equipment Clock.

Synchronous Ethernet (SyncE) uses the edges in the Ethernet data signal to define the timing content of the signal and distribute a physical layer clock across a packet network. Each system recovers and forwards the network timing through the distribution path. A reference timing signal traceable to a PRC provides a reference timing signal to an external timing port (e.g., BITS, GPS) on the first Ethernet switch in the path. The system clock function of the switch synchronizes its Ethernet transmit bit stream to the

reference timing signal. Each subsequent Ethernet switch in the path recovers the timing from the incoming Ethernet bit stream on a designated port, and synchronizes its Ethernet transmit bit stream to the recovered timing signal via its system clock function. Like all physical layer frequency synchronization techniques, all network elements between network segments need to be capable of recovering and passing the frequency downstream.

A system clock function that supports SyncE timing contains an Ethernet Equipment Clock (EEC) or a physical layer clock. The EEC provides filtering of noise on the external reference or recovered timing signals. A holdover function is also provided to allow continued operation in the event of a failure in the distribution path.

ITU-T G.8264 adds support for an Ethernet Synchronization Message Channel (ESMC) based on the IEEE 802.3, Organization Specific Slow Protocol (OSSP). This message is used to communicate the clock quality levels (via a Synchronization Status Message, SSM) of the PRC to all EECs in the network. The EEC may use this received information to determine the appropriate actions to take, such as failover to a different SyncE port or enter holdover mode, when network failures occur. As an example, if an EEC loses its connection to the PRC and transitions to a holdover state, it will replace the Quality Level (QL) of the PRC in its outgoing SSMs with the QL of its internal oscillator.

The higher information rate and lower noise of SyncE enables a higher clock bandwidth than for a packet-based clock. The bandwidth of the clock PLL in an EEC as defined in G.8262 is in the range of 1 - 10 Hz. The clock bandwidth for an enhanced EEC as defined in G.8262.1 is in the range of 1 - 3 Hz. The higher bandwidth generally allows for a faster convergence.

The filtering associated with an EEC defined in G.8262 is sufficient for the cable network use cases identified and do not require the tighter filtering associated with enhanced EEC in G.8262.1.

2.2. Precision Timing Protocol (PTP) Overview

IEEE 1588, Precision Timing Protocol (PTP) is a standard for enabling precise synchronization of real-time clocks for devices in communications networks with system-wide synchronization accuracy in the sub-microsecond to micro-second range.

PTP relies on the transmission of dedicated packets that form the significant instants of a packet timing signal. The timing of these significant instants is precisely measured relative to a master time source, encoded in the form of a time stamp, and distributed to a packet slave clock.

PTP timing synchronization starts with a Grandmaster Clock which typically derives its time from a Primary Reference Clock (PRC) such as a GPS Receiver. Timing synchronization then propagates across the network through the exchange of PTP messages between each Master and Slave, allowing each Slave node to synchronize to the PTP timing reference provided by its Master.

There are three 1588 profiles defined by the ITU-T. G.8265.1 supports frequency synchronization, while G.8275.1 and G.8275.2 both support both frequency and phase synchronization.

G.8275.1 profile is defined with full timing support from the network, so all network elements are PTP aware and participating in the protocol. The message rate for this profile is fixed at 16 messages per second. Only two-way communication is supported in this profile. The current version of the specification requires the use of a physical layer clock, like SyncE. A version of the profile that does not include SyncE is considered for further study. R-DTI mentions this as an alternate PTP network profile based on full

timing support in the network. G.8273.2 defines the performance parameters for boundary clocks supporting this profile. The PTP clock in a T-BC defined in G.8273.2 has a bandwidth of 0.05 - 0.1 Hz.

G.8275.2 is defined with only partial timing support from the network, so not all network elements need to be aware and participating in the PTP protocol. PTP messages that transit a non-participating network element are subject to the additional delay variation associated with queuing of traffic before transmission. This can degrade performance. The profile provides flexibility in PTP message rates, from 1 message per second to 128 messages per second. The higher message rates allow support for applications that require higher accuracy and lower rates can be used for less demanding applications. Slower message rates also reduce the load on the processor on the master clock. Only two-way communication is supported in this profile. Because [R-DTI] adopted G.8275.2 as the profile to be used for R-PHY, it may be used for the RMD as well, assuming only frequency information is used. G.8273.4 defines the performance parameters for boundary clocks supporting this profile.

A PTP clock hierarchy consists of multiple devices that are synchronized within the same Time Domain. PTP timing synchronization starts with a Grandmaster Clock (GMC) which derives its time from a Primary Reference Clock (PRC) such as a GPS Receiver. Timing synchronization then propagates across the network through the exchange of PTP messages between each Master and Slave, allowing each Slave node to synchronize to the PTP timing reference provided by its Master.

PTP defines classifications for clock functionality, including Ordinary Clocks and Boundary Clocks. An Ordinary Clock (OC) is a PTP clock with a single PTP port. An OC may be either a Master Clock or a Slave Clock. An Ordinary Master clock cannot be slaved to another PTP clock. A Boundary Clock (BC) refers to a PTP clock with multiple PTP ports. A BC can synchronize to a Master clock via its Slave PTP port and serve as a Master via its Master PTP port to one or more Slave clocks.

2.3. Hybrid Mode

A node that uses SyncE with an EEC in combination with a timing protocol such as PTP or NTP with a Packet Equipment Clock (PEC) may be referred to as a hybrid EEC/PEC clock. The source of SyncE within a network should be generated from same source as the PTP domain (e.g., GPS or PRTC) to avoid frequency drift.

When SyncE, with its higher level of frequency accuracy and lower level of noise, is used with a timing protocol such as IEEE 1588, a higher level of timing accuracy is achievable across a packet network. Since SyncE is a physical layer clock, it is not subject to packet delay variation as the signal transits the network.

G.8273.2 provides the functional requirements for a telecom boundary clock or telecom time slave clock when used with full timing support from the network. The following figure from G.8273.2 provides an illustration of the clock function in a hybrid EEC/PEC clock.
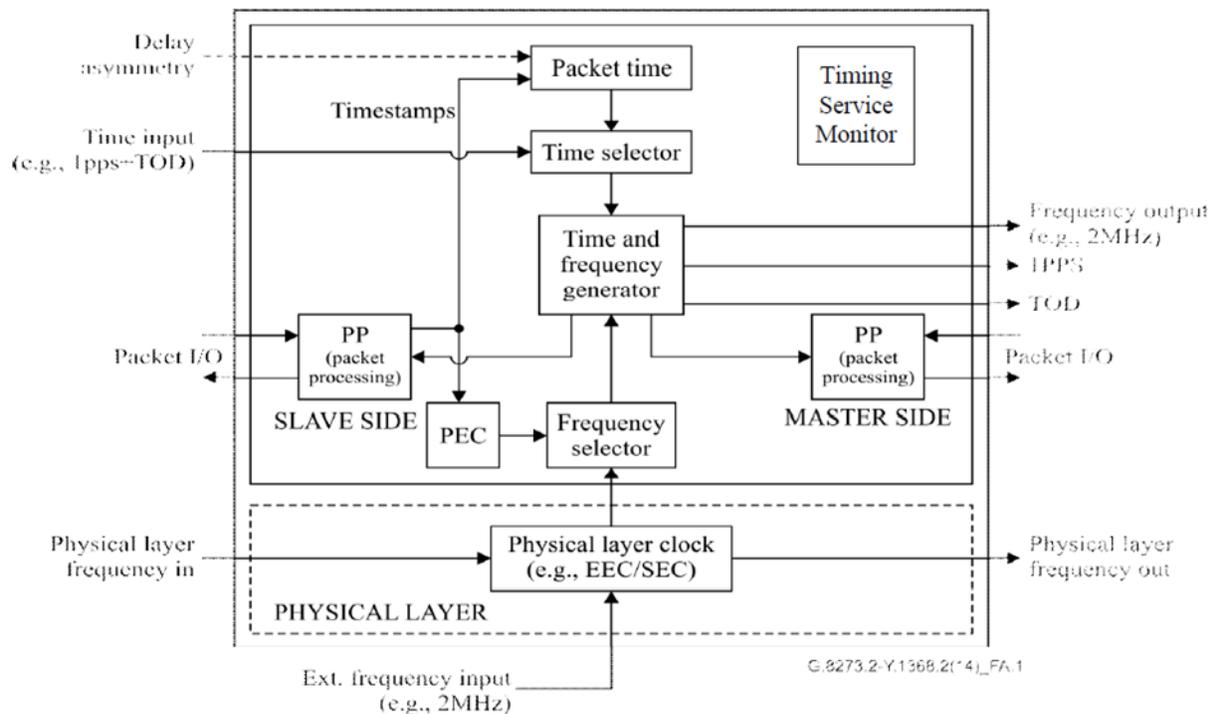
Figure 1 – Telecom Boundary Clock Model [G.8273.2]

The time information carried in the timestamps is used to establish the local time scales. The frequency information carried in the timestamps is used in the PEC to generate the local frequency.

The frequency selector block may select either the frequency information recovered from the timestamps, or the frequency recovered from a physical layer clock (e.g., Synchronous Ethernet).

3. Cable Network Timing

Timing and synchronization requirements for cable networks come from areas including existing DOCSIS specification requirements, Modular Headend Architecture v2 system requirements, and support of precision timing services, like Mobile Backhaul and other Mobile X-haul use cases.

In the MHAv2 architecture, the CMTS Core and the R-PHY are two entities located in separate locations. The DS PHY and US PHY are located in the R-PHY Device, and the DOCSIS MAC is located at the CMTS Core. Frequency and phase synchronization are required between the CMTS Core and the R-PHY Device so that they have a common knowledge of the DOCSIS time and to allow correct burst reception and to align the MAC scheduler with the PHY timestamping at the R-PHY. DOCSIS services require both frequency and phase synchronization while other services only require frequency synchronization, including Video (Sync mode), OOB (55-2 Sync mode), NDF/NDR, or Leakage Detection Signal Generation.

Certain MAC-NE (RMD) services do not require any external timing synchronization. These services can include DOCSIS services, Video (Async mode), or OOB (55-1 and/or 55-2 Async mode). Other services require frequency synchronization of the MAC-NE (RMD to an external frequency source. These services can include Video (Sync mode), OOB (55-2 Sync mode), NDF/NDR, or Leakage Detection Signal Generation.

The Mobile Backhaul application connects the mobile switching core (i.e., evolved packet core, EPC, for LTE or next-generation core, NGC, for 5G) and the radio access network (RAN) node. Long-Term Evolution (LTE) Frequency-Division Duplex (FDD) requires frequency synchronization between neighboring cells. Long-Term Evolution (LTE) Time-Division Duplex (TDD) requires additional phase synchronization between neighboring cells.

3.1. RPD Use Case

Remote PHY Device (RPD) is one type of a Distributed Access Architecture (DAA) that separates the Integrated CCAP into a CCAP Core that remains in the operator's headend and an RPD that resides in a remote fiber node or remote shelf. The RPD provides all PHY-related circuitry needed for HFC high-speed data and video services, including DOCSIS packet timestamping. The CCAP Core contains the DOCSIS MAC and the upper layer DOCSIS protocols, including all signaling functions, downstream and upstream bandwidth scheduling, and DOCSIS framing. It also contains all the video processing functions that an EQAM provides.

The CCAP Core and RPD synchronize their DOCSIS clocks in both frequency and phase so that they have a common view of DOCSIS time. This common view is enabled by Remote DOCSIS Timing Interface (R-DTI), which requires support for IEEE 1588v2 precision timing protocol (PTP). R-DTI further requires G.8275.2 with G.8275.1 and SyncE identified as being optionally supported.

The RPD also provides timing synchronization to subtended cable modems. Frequency synchronization between the RPD and the cable modems is achieved through the DOCSIS symbol rate, and DOCSIS time stamping [via Sync messages in DOCSIS 3.0 or OFDM preamble in DOCSIS 3.1] used to provide relative clock phase synchronization.

[R-DTI] identifies the timing architecture where the Core and the RPD are slaved to an external timing master.
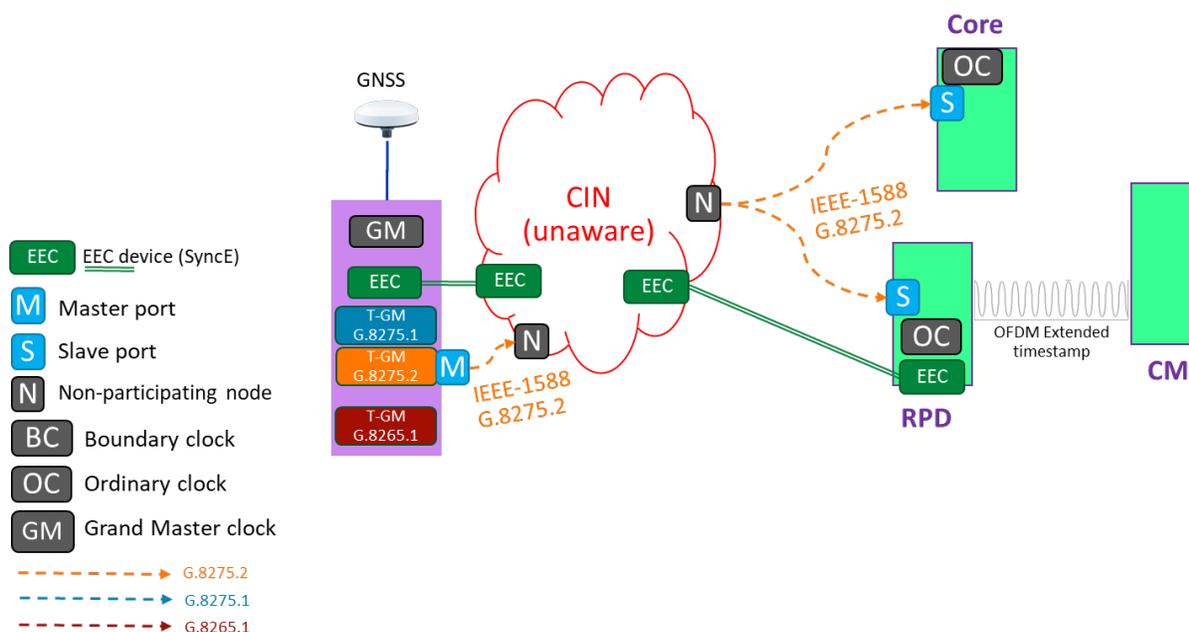

Figure 2 – RPD Use Case

External timing support is needed by the R-PHY application for the following features:

- DOCSIS services (phase and frequency sync)
- Video sync mode (frequency sync)
- Signal leakage detection (frequency sync)
- 55-2 sync mode (frequency sync)
- NDF/NDR (frequency sync)

Frequency synchronization for video sync mode avoids the need to support MPEG PCR restamping.

A summary of timing requirements from [R-DTI] for an RPD in R-PHY mode are listed below.

- The RPD MUST support 1588 OC slave
- The RPD MUST meet time/phase synchronization accuracy of ± 1 ms in reference to the 1588 GM.
- The RPD MUST comply with the T-TSC-P requirements of [G.8275.2].
- The RPD SHOULD syntonize the frequency of the local NDF/NDR clock with the assistance of the frequency recovered from Ethernet.
- The RPD MUST meet the frequency accuracy requirements ($\leq \pm 530$ ppb) specified by [R-OOB] when supporting signal leakage detection.
- The RPD SHOULD support Synchronous Ethernet for Precision Timing Services.
  Note: Precision Timing Services is a term used in [R-DTI] to describe Mobile BackHaul for wireless applications. Synchronous Ethernet is not required and is not even classified as a "truly optional" feature in [R-DTI] for other services, including DOCSIS services.

A summary of timing requirements in [D-RFI] are listed below.

- The 10.24 MHz Master Clock MUST have:
  - Frequency accuracy $\leq \pm 5$ ppm
  - Maximum drift $\leq 10\text{-}8$ per second ($\leq \pm.01$ ppm)
  - An edge jitter of <=10 ns peak-to-peak (± 5 ns)
  - DOCSIS timestamp jitter < 500 ns p-p.

The system clock in an RPD with SyncE support will typically consist of two components, a physical layer clock or EEC that uses SyncE as its timing reference and a packet equipment clock or PEC that uses PTP as its timing reference. The two timing references are normally traceable to a common frequency source since in DOCSIS the frequency and phase are coupled together. The output of the EEC portion may be used to assist and accelerate the PEC portion in achieving lock to the PTP timing reference. A node that uses SyncE with an EEC in combination with a timing protocol such as PTP with a PEC may be referred to as a hybrid EEC/PEC clock.

There are three timing related performance issues that exist in typical RPD implementations that can be improved by the use of a hybrid EEC/PEC clock system. The first is that CIN networks may introduce large PDV that can affect the frequency and phase servo algorithm convergence and accuracy of the RPD. The second is that typical RPD holdover performance is limited while there isn't a holdover specification defined for an RPD in R-DTI. The third is that services can take a while to be restored during initialization of an RPD since they rely on timing lock notification from the RPD which can last a non-negligible amount of time.

Another optional benefit of using SyncE is the ability to use NTP as the time of day (TOD) source instead of PTP for the RPD. Using NTP will eliminate the need to install a pricier PTP GM, since the frequency is already locked via SyncE. This is a subject for more detailed further study.

3.1.1. Benefit #1: Time accuracy can be improved

R-DTI defines the time/phase synchronization accuracy of an RPD to be within ±1 ms when referenced to the 1588 GM for DOCSIS Timing. R-DTI also requires support for the PTP network profile defined in G.8275.2. This profile is defined with partial timing support from the network. Since not all network elements need to be PTP aware, packet delay variation will be imposed on the PTP messages in both directions by each non-participating network element in the timing distribution chain. Long chains of non-participating elements accumulate the packet delay variation and degrade the time accuracy. The more stable and accurate frequency associated with the SyncE timing distribution and the physical layer clock assisting the packet equipment clock can result in lower output frequency and phase noise on the output signals from network element and enable improved time accuracy over using PTP alone.

Assuming SyncE and PTP are traceable to the same PRC, the servo algorithm for PTP could be simplified to lock to phase while frequency is already locked.

3.1.2. Benefit #2: Improved holdover performance

A TCXO is normally be used in RPD applications to meet the timing requirements defined in R-DTI without the increased power and cost associated with other technologies, like OCXOs. When the packet timing reference from the 1588 GM is interrupted, the RPD's clock will transition into holdover and the RPD's clock output will drift according to the characteristics of the TCXO and the quality of the timing reference frequency estimate prior to the holdover event. While R-DTI does not have an explicit holdover specification, an implied specification can be derived from the time/phase synchronization accuracy of ±1 ms and the most restrictive frequency accuracy requirements in [R-DTI] which is ±530 ppb. Currently, the holdover-out-of-specification notification is a vendor-specific implementation which relies on estimates of worst case frequency drift scenarios. The phase drift of a clock x(S) can be calculated using the following equation.

$$|\Delta x(S)| \leq \{(a_1 + a_2)S + 0.5bS^2 + c\}[ns]$$

Where:

a_1 represents an initial frequency offset during the entry into holdover

a_2 accounts for temperature variations after the clock went into holdover

b corresponds to the frequency drift caused by aging

c accounts for any additional phase shift during the entry into holdover

The following table provides some representative values for the phase drift coefficients for the equation above for a clock using TCXO technology and a clock using OCXO technology.

Table 1 – Representative Phase Drift Coefficient Values for a Clock

	Units	TCXO-based	OCXO-based
a_1	ns/s	10	10

	Units	TCXO-based	OCXO-based
a_2	ns/s	200	20
b	ns/s^2	5×10^{-5}	2×10^{-5}
c	ns	10	10

A TCXO meeting the holdover specifications in G.8262 or G.8262.1 will remain within this ±1 ms level for roughly an hour and 20 minutes. Replacing the TCXO with an OCXO extends the time the RPD would remain within the ±1 ms accuracy to roughly 1 day (25 hours), but it does come with additional cost and power associated with the OCXO. By using SyncE and a physical layer clock to enhance the performance of the RPD's packet equipment clock and providing a stable frequency reference that is traceable to the 1588 GM, the time output from the RPD will continue at the correct rate and maintain the correct time for an almost indefinite amount of time. This period of time is primarily limited by failures in the SyncE timing distribution network that interrupt the traceability to the PRC. These values are shown in the following diagram.
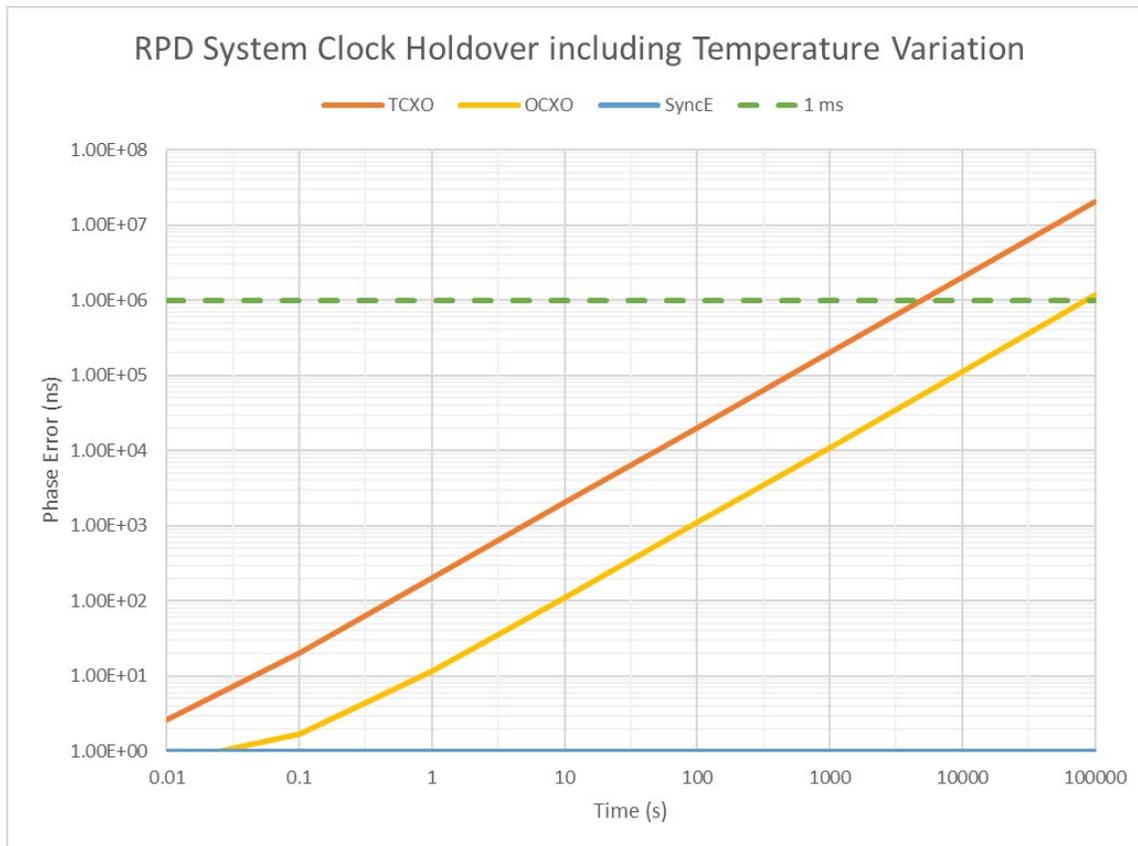
Figure 3 – RPD System Clock Holdover with No Initial Frequency Offset

Since R-DTI contains a frequency accuracy requirement of ±530 ppb, an RPD which is in frequency locked state might go into holdover with an additional initial frequency offset of ±530 ppb. This will cause the RPD to cross the ±1 ms threshold much faster. RPDs with either a TCXO or an OCXO will remain within this threshold for roughly 25-35 minutes. By using SyncE and a physical layer clock, the time output from the RPD will continue at the correct rate and maintain the correct time for an almost indefinite amount of time. These values are shown in the following diagram.
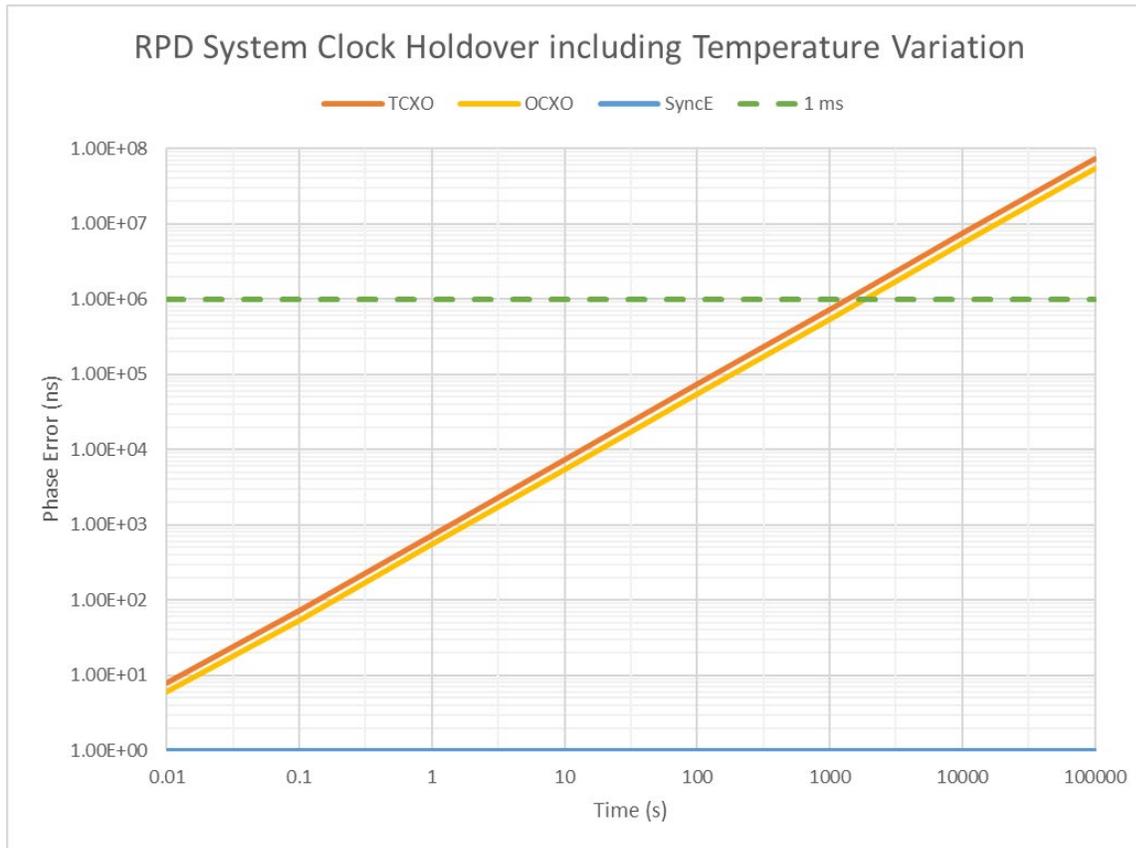
Figure 4 – RPD System Clock Holdover with 530 ppb Frequency Offset

3.1.3. Benefit #3: Reduced time to lock and recover after reset

SyncE as a timing reference to the physical layer clock that assists the packet equipment clock in the RPD's system clock can shorten the time for certain services to be available following an RPD reset.

As required in [D-RFI], an RPD receives its timing reference via PTP. The packet equipment clock is the source for all downstream timing. When exiting reset, the RPD must wait until the packet equipment clock achieves frequency lock and phase lock before it can begin to provide services, even services that only require frequency synchronization, like video and OOB services. Frequency lock can be achieved in a shorter amount of time than the time required to achieve phase and frequency lock. Phase and frequency lock with the ±1 ms specified in R-DTI can take multiple minutes.

Techniques can speed the acquisition of phase and frequency lock for the RPD's packet equipment clock after a reset. A soft reset with warm start relies on frequency information about the operating conditions of the RPD's packet equipment clock prior to the reset. Warm start is most effective if the reset time is brief and network conditions are stable during the reset time. If the conditions are not suitable, then a hard reset will be required. A hard reset is similar to a power-up reset in that it does not rely on information about the packet equipment clock's prior operating and can take longer to achieve lock. [R-PHY] provides an overview of soft reset and warm start functionality.

Reducing the time-to-lock for an RPD system clock using SyncE assistance is partially due to the difference in PLL bandwidths between the two portions of the system clock. The bandwidth of the SyncE physical layer clock PLL is in the range of 1 - 10 Hz for the non-enhanced case defined in G.8262 and in the range of 1 - 3 Hz for the enhanced case defined in G.8262.1. In contrast, the PTP clock in a T-BC defined in G.8273.2 has a bandwidth of 0.05 - 0.1 Hz. While the frequency locking process is non-linear, the difference in bandwidths between the SyncE physical layer clock and PTP clock should result in the SyncE clock obtaining frequency lock at least ten times faster than the PTP clock. Additionally, since the frequency lock is dependent on the SyncE timing reference, a larger amount of PDV can be tolerated on the PTP timing reference without significantly increasing the lock time. Frequency-based services using an RPD clock with SyncE assistance should be available in less than one tenth of the time for the same services to be available for an RPD using only a packet timing clock.

The following table shows some representative time frames for achieving frequency lock after exiting reset. The simplifying assumption is that the time to obtain phase lock after frequency lock is achieved is constant for each of the three cases.

Table 2 – Frequency Lock

	Hard Reset	Soft Reset / Warm Start	Hard Reset with SyncE Assist
Frequency lock achieved	minutes, depends on network PDV	within a minute	within seconds

Because of the faster frequency lock that results from the physical layer clock assistance, the RPD can begin to deliver video services while phase lock is still being acquired by the packet equipment clock portion of the RPD system clock. DOCSIS services may be delayed until phase lock is achieved by the packet equipment clock portion.

3.2. RMD Use Case

The Remote MACPHY Device (RMD) is a Distributed Access Architecture (DAA) device that contains all PHY-related circuitry needed for HFC high-speed data and video services as well as the DOCSIS MAC and the upper layer protocol support. This includes all DOCSIS signaling functions, downstream and upstream bandwidth scheduling, and DOCSIS framing. It also provides the digital interface to an Auxiliary Core for MPEG video and OOB signals as well as the analog interface for transmission over RF or linear optics.

Since the DOCSIS MAC and the PHY are collocated within the device, the RMD application does not have the complexity associated with frequency or phase synchronization between two devices for DOCSIS operation that the RPD requires. Non-DOCSIS functions, including some video and OOB functions, require the RMD to be frequency synchronized to the Auxiliary Cores that provide those functions. The Auxiliary Cores could be free running with an internal clock that meets the frequency accuracy specification for the specific application (e.g. ±30 ppm for video) or be synchronized to the PRC using technologies including SyncE, PTP, NTP, GNSS, BITS, etc. This allows the timing synchronization requirements of the RMD to be less strict than the requirements for the RPD.
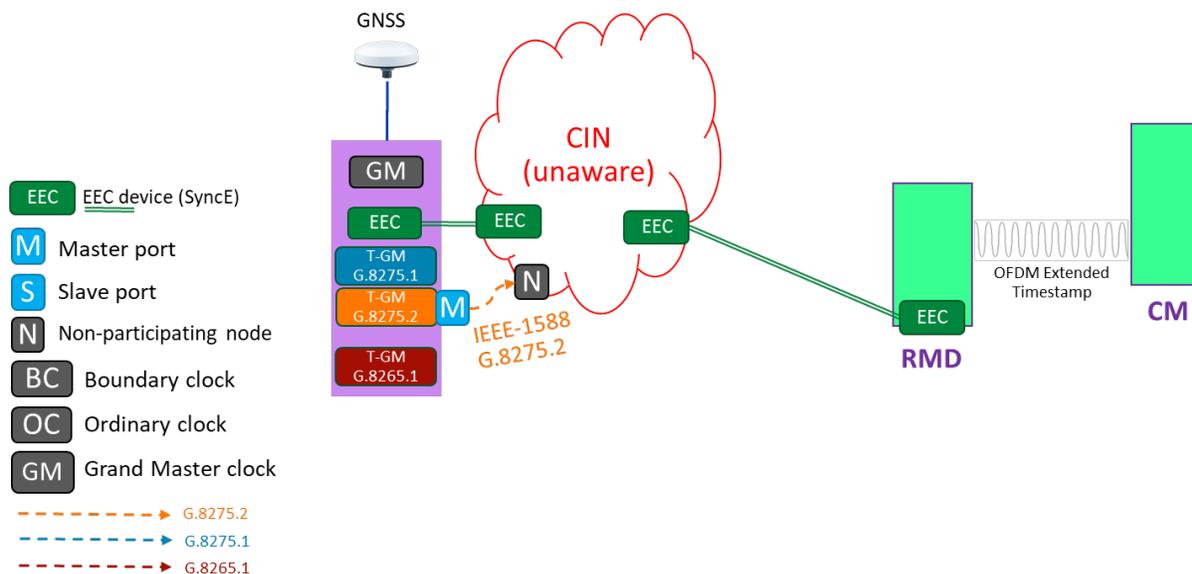
Figure 5 – RMD Use Case

Without a requirement for phase synchronization in the RMD application, there are four options for timing the RMD: free-run, frequency synchronized using the PTP profile defined in G.8265.1, frequency synchronized using SyncE, and frequency and phase synchronized using the PTP profile defined in G.8275.2. Using G.8275.2 is consistent with the requirements for an RPD in [R-DTI].

External timing support is needed by the RMD application for the following features:

- Video sync mode (frequency sync)
- Signal leakage detection (frequency sync)
- 55-2 sync mode (frequency sync)
- NDF/NDR (frequency sync)

For RMD applications that require external timing, frequency synchronization may be provided via SyncE, or by PTP. The timing reference signal in the two PTP options will have a higher amount of noise as a result of the packet delay variation on the PTP messages in the timing distribution network. The higher rate of significant instants in the SyncE timing reference and the lower amount of noise in the SyncE timing distribution network allow for a wider bandwidth of the physical layer clock in the RMD system clock function. This enables a faster lock time and faster restoral of service after a reset for a SyncE-based or SyncE-assisted RMD system clock over a PTP-only timing approach. In contrast to the RPD application, the faster restoral of service when using SyncE for frequency synchronization applies to both DOCSIS and non-DOCSIS services.

An RMD typically provides multiple Ethernet interfaces. The interfaces provide redundant SyncE timing references from the PRC to the RMD and allow the physical layer clock function to monitor the quality of the signal on the interfaces and select the better quality one, if appropriate.

The less complicated filtering and monitoring functions associated with SyncE timing references for the physical layer clock allows functions to be implemented in hardware and reduces the number of functions that need to be implemented in the CPU of the RMD. This reduces the load for timing functions on the

RMD's CPU and allows additional non-timing functions to be implemented in the same class of RMD's CPU.

3.3. MBH Use Case

A mobile backhaul (MBH) network connects the mobile switching core (i.e., evolved packet core, EPC, for LTE or the 5G core) and the radio access network (RAN) node. The SYNC specification [SYNC] describes the architecture and requirements to enable cable operators to use DOCSIS technology to carry precision frequency and phase synchronization signals over the hybrid fiber-coax (HFC) plant. This allows cable operators to take advantage of their rich infrastructural assets to provide backhaul services comparable to fiber for their own mobile traffic.

Although many wireless networks previously required only frequency synchronization, including LTE Frequency-Division Duplex (FDD), other networks require time and phase synchronization. Long-Term Evolution (LTE) Time-Division Duplex (TDD) is an example of a technology that requires frequency and phase synchronization.

3.3.1. Frequency Synchronization

From [SYNC], networks that require only frequency synchronization have a target performance for frequency accuracy of ±16 ppb [G.8261.1]. This is based on the requirement of a ±50 ppb radio frequency accuracy.

3.3.2. Time Error budget

[SYNC] provides a comprehensive view of the end-to-end performance budget of 1.5 μs for maximum time error for networks that require frequency synchronization and phase synchronization. One section covers the DOCSIS portion of the network, and specifically the portion of the budget allocated to CMTS and DAA equipment. The performance target for constant time error of the CMTS, RPD, or RMD is ±200 ns for class A equipment and ±100 ns for class B equipment. The jitter value in the CMTS, RPD, RMD component is been reduced to 5-10 ns (1/204.8 MHz plus phase noise jitter) as a result of using OFDM-based DOCSIS systems.

DOCSIS Time Protocol (DTP) allows IEEE 1588 protocol information to be passed over the DOCSIS network with high frequency and phase accuracy by eliminating the jitter resulting from network buffering in the DOCSIS network. DTP takes advantage of the fact that DOCSIS is a synchronous system and distributes a physical layer clock to distribute frequency information to the cable modems. It also uses the DOCSIS 3.1 timestamp to distribute time information. A signaling path determines the downstream timing offset, which is used as a correction factor for PTP.

3.3.3. Mobile Backhaul Use Cases

Four synchronization use cases for mobile backhaul are identified in [SYNC].

- Physical Layer Timing Support for Frequency Synchronization
- Full Timing Support for Phase Synchronization
- Partial Timing Support for Phase Synchronization
- Partial Timing Support for Frequency Synchronization

The current version of [SYNC] identifies requirements associated with Physical Layer Timing Support for Frequency Synchronization and Full Timing Support for Phase Synchronization. The other two use cases will be addressed in a future version of the document.

3.3.4. *Physical Layer Timing Support for Frequency Synchronization*

For Physical Layer Timing Support for Frequency Synchronization, the RPD or RMD is synchronized to the PRC using SyncE, and the cable modem provides the frequency reference to the end application using SyncE.

The RPD uses PTP to align its frequency and phase for R-PHY operation and generates the downstream DOCSIS frequency and timestamp traceable to the PTP clock domain. For the downstream clock to be SyncE-traceable, the input SyncE and PTP should be generated from the same source. The RPD operates in Hybrid mode so that SyncE may be used to assist the PTP clock for functions like holdover and fast-lock. The frequency source of SyncE should share a common frequency source with the PTP domain (e.g., GPS or PRTC) since DOCSIS couples the frequency and phase together and to avoid frequency drift between the two domains. Cores usually only support G.8275.2 as defined in [R-PHY]. Supporting different profiles for RPD and Core will require different GMs.
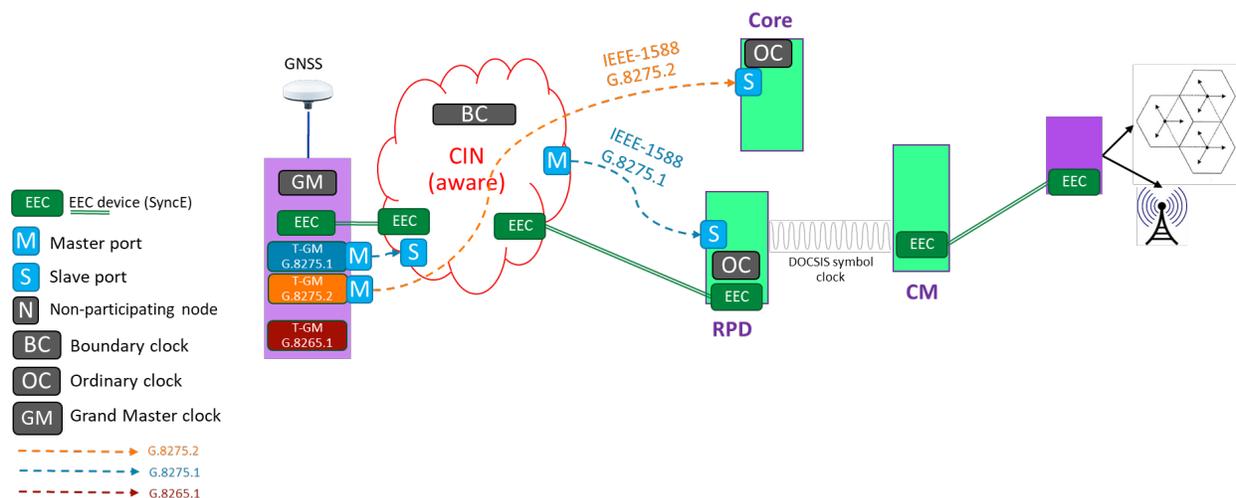
Figure 6 – RPD Physical Layer Timing Support for Frequency Synchronization Use Case

The RMD's system clock is locked in frequency via SyncE. Without a requirement for phase synchronization in this application, the RMD may use an arbitrary time of day or use NTP to establish the system's time of day. The lower amount of noise on the SyncE timing reference allow for a wider bandwidth of the physical layer clock in the RMD system clock function. This enables a faster lock time, faster restoral of service after a reset and more accurate holdover for a SyncE-based RMD system clock over a PTP-only timing approach.
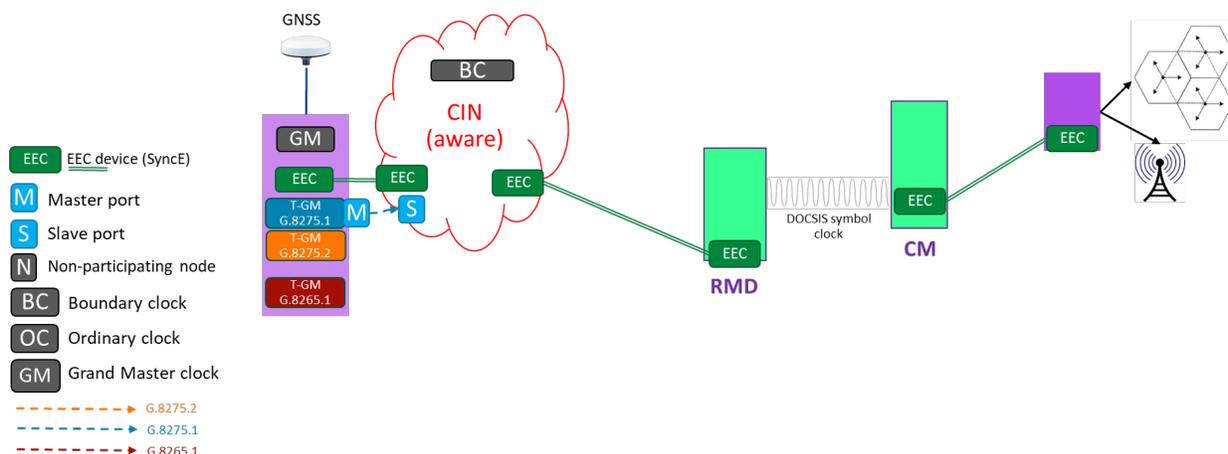
Figure 7 – RMD Physical Layer Timing Support for Frequency Synchronization Use Case

3.3.5. *Full Timing Support for Phase Synchronization*

Full Timing Support for Phase Synchronization in [SYNC] requires the DOCSIS interworking function to support the network profile defined in G.8275.1 with each switch in the network having PTP awareness (such as Ordinary Clock or Boundary Clock). It also requires the use of a physical layer clock, like SyncE, at each element in the network.

R-PHY has timing requirements specified in [R-DTI] that are different from the timing requirements for MBH support, i.e., the timing accuracy requirements (for frequency and phase) and the timing delivery requirements (profile, 1588/SyncE, etc.). The challenge is to have the R-PHY Device (RPD) clock support the requirements for two timing applications when the set of requirements for one application is not a superset of the other.

The following table from [SYNC] contrasts the requirements for an RPD operating in a MBH application and an R-PHY application.

Table 3 – R-PHY Requirements vs. MBH "Full Timing Support for Phase"

Item	R-PHY	MBH	R-PHY requirements when supporting MBH precision timing services
Lock threshold	1 ms	50 ns	See Section C.2.1 of [SYNC]
Phase lock time	Few minutes	Not defined (should be short)	See Section C.2.2 of [SYNC]
Profile	[G.8275.2]	[G.8275.1]	See Section C.2.3 of [SYNC]
SyncE	Recommended	Required	See Section C.2.4 of [SYNC]
Holdover requirements and duration	Not specified	[G.8273.2]	See Section C.2.5 of [SYNC]
Phase steps	Not allowed when locked	Not specified	See Section C.2.6 of [SYNC]

Item	R-PHY	MBH	R-PHY requirements when supporting MBH precision timing services
Frequency change rate	10 ppb/s	Not specified	See Section C.2.6 of [SYNC]
Precision timing frequency and phase budget	Table based on old DTP section	Specified in Section 8 of [SYNC]	See Section C.2.7 of [SYNC]
"soft reset" support	The RPD holds in holdover for <1 min during a soft reset in order to have a quick reset using a warm start. The RPD goes operational even before it re-locks to the GM.	Convergence after soft reset is for further study	See Section C.2.8 of [SYNC]
BC functionality	Allowable	Required on every Ethernet hop	See Section C.2.9 of [SYNC]

The RPD uses PTP to align its frequency and phase and generates the downstream DOCSIS frequency and timestamp traceable to the PTP clock domain. For the downstream clock to be SyncE-traceable, the input SyncE and PTP should be generated from the same source. The RPD operates in Hybrid clock mode so that SyncE may be used to assist the PTP clock for functions like holdover and fast-lock. The frequency source of SyncE should share a common frequency source with the PTP domain (e.g., GPS or PRTC) to avoid frequency drift between the two domains.

DTP functions are distributed between the RPD and the Core. Cores usually only support G.8275.2 as defined in [R-PHY]. Supporting different profiles for RPD and Core will require different GMs. PTP announce message delivery is from the RPD to Core via UEPI to forward to the CMs. Core needs to encapsulate the PTP announce messages on the UEPI PW from the RPD and forward to all CMs on relevant DSIDs.


Figure 8 – RPD Full Timing Support for Phase Synchronization Use Case

The RMD's system clock is locked in frequency and phase via PTP using G.8275.1 with SyncE assistance. The lower amount of noise on the SyncE timing reference allow for a wider bandwidth of the physical layer clock in the RMD system clock function. This enables a faster lock time, faster restoral of service after a reset and more accurate holdover for a SyncE-based RMD system clock over a PTP-only timing approach. The lower noise on the system clock as a result of the SyncE assistance allows for lower noise and better accuracy of the timestamps.

All DTP functions are co-located in the RMD so there isn't the complexity associated with coordinating and synchronizing between two devices.
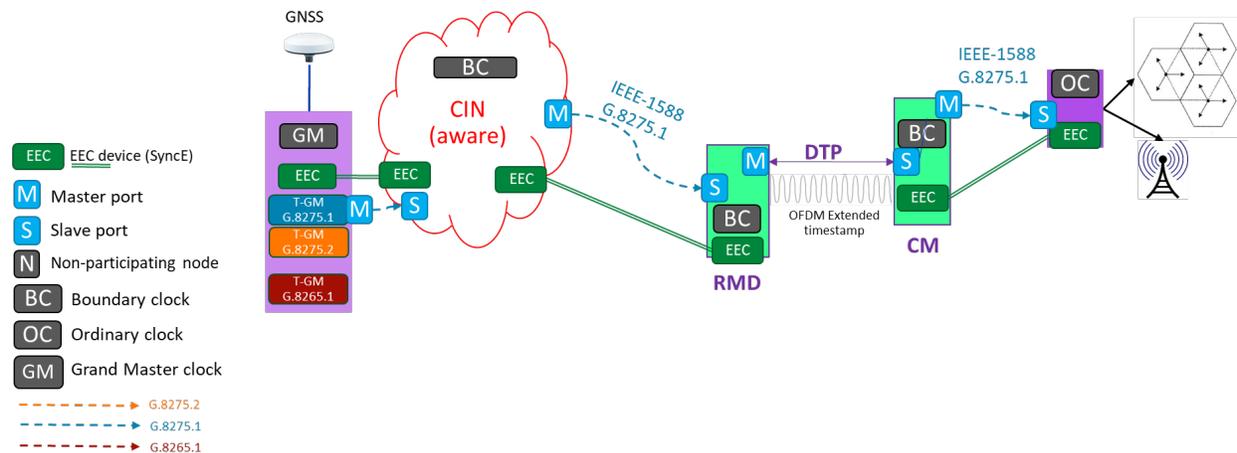

Figure 9 – RMD Full Timing Support for Phase Synchronization Use Case

4. Conclusion

Synchronous Ethernet (SyncE) is used mainly in telecom networks to provide physical layer clock delivery for frequency synchronization (aka syntonization). The cable industry has not yet adopted SyncE as a common supported functionality while IEEE1588 is more commonly used for time synchronization (mainly for DAA use cases).

The paper investigated the impact of providing SyncE support in DAA R-PHY and R-MACPHY applications as well as two use cases for mobile backhaul (LTE and 5G) applications. The RMD implementations provided additional benefits over the RPD implementations for each use case due to the integrated DOCSIS MAC and PHY functions in a single system and simplified timing interface. SyncE provided multiple benefits over the traditional PTP-only based implementations in these applications including:

- Improved timestamp accuracy
- Improved holdover performance
- Reduced time to lock and reduced time to recover services after reset

These improvements are realized without additional complexity. As a result, it is clear that SyncE is a valuable functional addition to the cable network.

Since converged interconnect networks (CINs) are generally new networks, requiring SyncE support for equipment in the CIN is a reasonable requirement. Even in case where a portion of the network does not support SyncE, there are reasonably priced boundary clocks that can be plugged into the CIN equipment to provide SyncE support.

Abbreviations

BC	Boundary Clock
BITS	Building Integrated Timing Supply
CCAP	Converged Cable Access Platform
CIN	Converged Interconnect Network
CMTS	Cable Modem Termination System
DAA	Distributed Access Architecture
D-RFI	Downstream Radio Frequency Interface
DTP	DOCSIS Time Protocol
DS	Downstream
EEC	Ethernet Equipment Clock
E-EEC	Enhanced Ethernet Equipment Clock
FDD	Frequency Division Duplex
GM	Grandmaster
GMC	Grandmaster Clock
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HFC	Hybrid Fiber Coax
LTE	Long Term Evolution
MBH	Mobile Backhaul
MHA	Modular Headend Architecture
MHz	Megahertz
MPEG	Moving Picture Experts Group
NTP	Network Time Protocol
OC	Ordinary Clock
OCXO	Oven Controlled Crystal Oscillator
OOB	Out of Band
PEC	Packet Equipment Clock
PRC	Primary Reference Clock
PRTC	Primary Reference Time Clock
PTP	Precision Time Protocol
RAN	Radio Access Network
R-DTI	Remote DOCSIS Timing Interface
RMD	Remote MACPHY Device
RPD	Remote PHY Device
SyncE	Synchronous Ethernet
TDD	Time Division Duplex
TDD	Time Division Duplex
TOD	Time of Day
T-TSC-P	Telecom Time Slave Clock for Partial timing support
US	Upstream

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