Experiment Results for Supporting LTE-FDD, LTE-TDD, and 5G Timing Synchronization Over DOCSIS CAA and DAA

A Technical Paper prepared for SCTE•ISBE by

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Introduction

The ability to support the transport of accurate timing information over DOCSIS networks has become an important and urgent need for both cable and telco operators as mobile backhaul becomes a key service offering of the future.

The DOCSIS network (without any modifications) is not an appropriate access infrastructure for delivering accurate timing information for both frequency and phase. The latency asymmetry between the DOCSIS upstream (US) and downstream (DS) and the large packet delay variation (PDV) in upstream grant cycles cannot guarantee the timing requirements of LTE; 16 ppb of frequency accuracy for LTE-FDD and 1.5 microsecond of phase accuracy for LTE-TDD and 5G.

There is active research on-going within the cable industry to define the requirements needed for the DOCSIS network to support these stringent mobile backhaul requirements. Much of this work is based on the DOCSIS Timing Protocol (DTP), which was previously defined within DOCSIS 3.1 and the CableLabs MBH (Mobile Backhaul) Synchronization Techniques specification.

This paper will describe modeling and experimental results for accurate phase and frequency delivery over DOCSIS, covering multiple different use cases as LTE-FDD, LTE-TDD, and 5G. Some approaches require minimal changes to the current DOCSIS implementations, while others require incorporating the DOCSIS 3.1 DOCSIS Timing Protocol (DTP). This paper will show how the experiments results prove that DOCSIS Distributed Access Architecture (DAA) and Centralized Access Architecture (CAA) could support the MBH requirements for the various use cases.

In this paper we will focus on two use cases, one for frequency delivery and one for phase delivery. We will describe the mobile sync accuracy requirements in general from 3GPP and ITU-T and the proposed solutions for those use cases over DOCSIS.

Following that, we will describe in detail the MBH over DOCSIS setups we used to explore the performance and show the results for each use case.

Content

1. MBH over DOCSIS Use Cases and Timing Requirements

1.1. LTE-FDD and APTS Support with an IEEE 1588-Unaware DOCSIS Network

1.1.1. Synchronization Requirements

Frequency synchronization is needed in two main use cases. One is for LTE-FDD support and the other is aimed to provide frequency assistance for Assisted Partial Timing Support (APTS) clocks.

LTE-FDD mobile cells use two frequencies for transmitting and receiving data simultaneously, so it requires the frequency to be very accurate so there will not be any interference between the transmissions.

Frequency synchronization over the network can be achieved mainly in one of two methods:

A. Physical layer frequency synchronization, for example Synchronous Ethernet (SyncE). This method requires each network element in the path to support this physical layer synchronization.
B. Using Precision Timing Protocol (PTP) to achieve frequency synchronization with or without phase synchronization. ITU-T G.8261.1 defines the packet delay variation network limits applicable to packet-based methods for frequency synchronization. ITU-T G.8265.1 is the precision time protocol telecom profile used for frequency synchronization.

This paper will focus on the PTP method for achieving frequency synchronization for LTE-FDD.

The LTE-FDD frequency accuracy defined by 3GPP at the air interface is ±50 ppb. The frequency accuracy requirement between the frequency source and the end application is ±16 ppb.

As mentioned above, ITU-T G.8261.1 defines the packet delay variation network limits applicable to packet-based methods for frequency synchronization to achieve the 3GPP required frequency accuracy. The reference model for the network limits is shown in Figure 1.

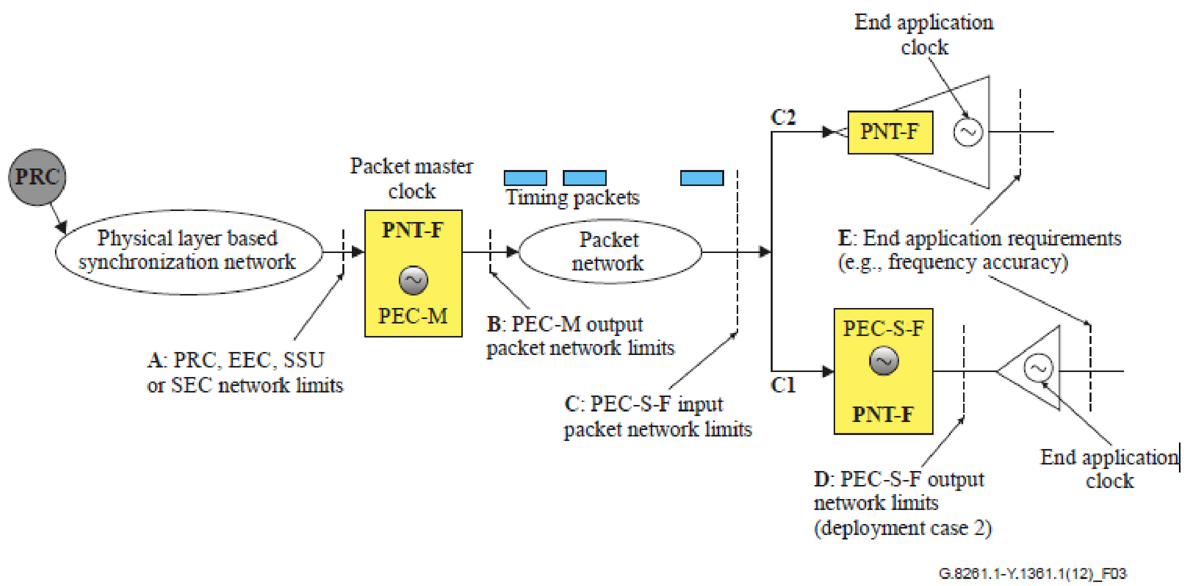


Figure 1 – ITU-T G.8261.1 Reference Model for LTE-FDD

Reference point C is the point where the LTE-FDD cell is connected (and where the DOCSIS network ends). The packet delay variation network limit given in the ITU-T G.8261.1 is defined as follows:

With window interval $W = 200$ seconds and fixed cluster range $\delta = 150$ µs starting at the floor delay, the network transfer characteristic should satisfy a Floor Packet Percentage (FPP) $(n, W, \delta) \geq 1\%$. This means that for any window interval of 200 seconds, at least 1% of transmitted timing packets will be received within a fixed cluster, starting at the observed floor delay, and having a range of 150 µs.

The Maximum Time Interval Error (MTIE) mask is shown in Figure 2:

Observation interval τ (s)	MTIE requirement (μs)
$0.05 < \tau \leq 0.2$	$46\ \tau$
$0.2 < \tau \leq 32$	9
$32 < \tau \leq 64$	$0.28\ \tau$
$64 < \tau \leq 1\ 125$	18
$\tau > 1\ 125$	$0.016\ \tau$

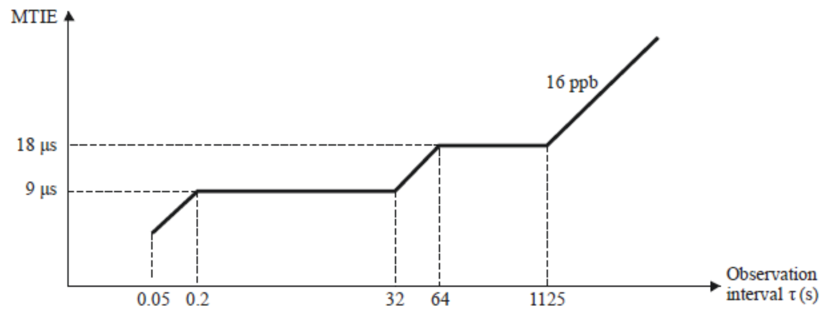


Figure 2 – ITU-T G.8261.1 Network Limits for LTE-FDD

In the APTS configuration, PTP is used as a backup timing source to a local time reference (e.g., Primary Reference Time Clock (PRTC) based on the Global Navigation Satellite System (GNSS)) for durations up to 72 hours. It is not intended to use PTP as the primary timing source. In this case, the PTP source is used to assist with holding an accurate frequency at the APTS clock when its primary phase source fails, avoiding it from drifting.

ITU-T G.8271.2 defines the network limits the network limits to achieve a reliable APTS secondary source. The reference model for the network limits is shown in Figure 3.

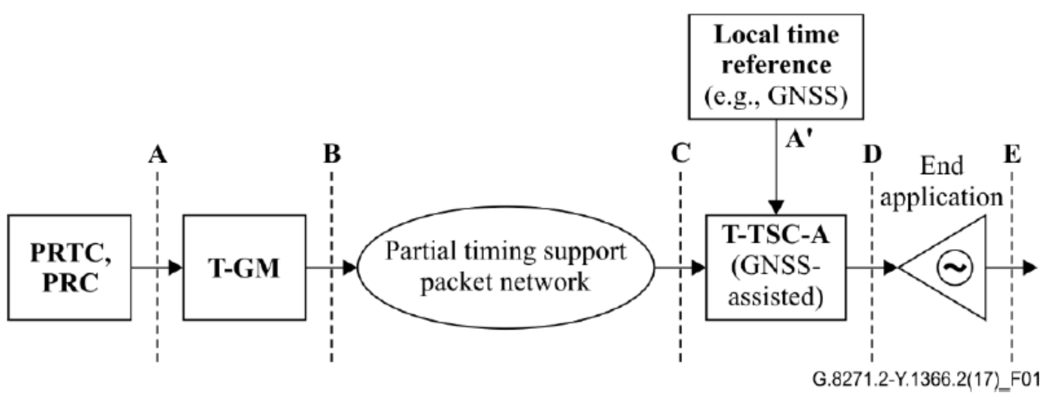


Figure 3 – ITU-T G.8271.2 Reference Model for APTS

Reference point C is the point where the APTS cell is connected (and where the DOCSIS network ends). The packet delay variation network limit given in ITU-T G.8271.2 is defined as below.

The network limit value and the metric processing parameters for assisted partial timing support use the metric pktSelected2wayTE (described in ITU-T G.8260) as follows:

- Peak-to-peak pktSelected2wayTE <1,100 ns
- Selection window = 200 seconds
- Selection percentage = 0.25%

This limit makes sure that when the GNSS source is lost, the absolute Time Error (TE) will remain within expected limits of **100 ns** while PTP is the selected fallback source.

To summarize, the access network must provide a PDV of less than 150 µs and a fractional frequency offset of less than 16 ppb to provide an accurate frequency reference. For APTS support, the MTIE must also be less than 100 ns.

1.1.2. Proposed Solution over DOCSIS

There are mainly two options of supporting frequency delivery over DOCSIS:

A. DOCSIS as a frequency aware network. In this option the DOCSIS Cable Modem Termination System (CMTS) or Remote PHY (R-PHY) locks its internal DOCSIS clock to an external source via SyncE or PTP. The DOCSIS Cable Modem (CM) is natively locked to the CMTS/R-PHY clock through the DOCSIS symbol clock. Lastly, the end slave clock is locked to the CM clock via SyncE or PTP. This option takes advantage of the fact that the DOCSIS system already provides accurate frequency sync between its components. This option is similar to the frequency delivered via physical clocks (SyncE) as described above.

B. DOCSIS as frequency unaware network. In this option, the DOCSIS segment does not contain any of the frequency synchronization elements. Frequency delivery passes "over the top" as regular data packets using PTP messages. The main challenge in delivering timing information over the top of DOCSIS is that there is large latency asymmetry between the DOCSIS upstream and downstream paths. In addition, there is a significant PDV over DOCSIS mainly on the upstream path due to the DOCSIS scheduling. However, for frequency information delivery, asymmetry is not a factor. In addition, taking the fact that G.8265.1 allows the use of 1-way PTP delivery for frequency sync, eliminates the upstream PDV problem and routes the PTP traffic only over the limited PDV downstream path. The PDV can be reduced further by dedicating a DOCSIS service flow for the PTP traffic (UDP port 319).

In this paper, we will focus on the second option. The proposed solution for frequency delivery over the top of DOCSIS is shown in Figure 4.

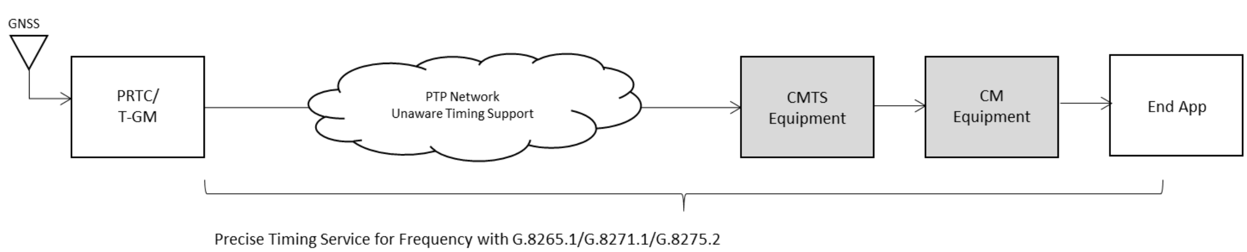


Figure 4 – Proposed Solution for LTE-FDD and APTS Support over DOCSIS

1.2. LTE-TDD and 5G Support with an IEEE 1588-Aware DOCSIS Network

There are two synchronization approaches that allow phase synchronization for mobile backhaul.

- Full Timing Support for Phase Synchronization

- Partial Timing Support for Phase Synchronization

Full Timing Support networks are composed exclusively of network elements that support IEEE 1588 protocol operation. Partial Timing Support networks can include network elements that are not IEEE 1588 aware.

Figure 5 shows an end-to-end view of the synchronization flow for mobile backhaul with full timing support providing phase synchronization service to an end application mobile base station. PTP and SyncE are fully terminated at the PTP-to-DOCSIS Inter Working Function (IWF). DTP is used to transfer the synchronization information between DOCSIS equipment. The DOCSIS-to-PTP IWF regenerates synchronization information in a suitable format for use by the end application mobile base station.

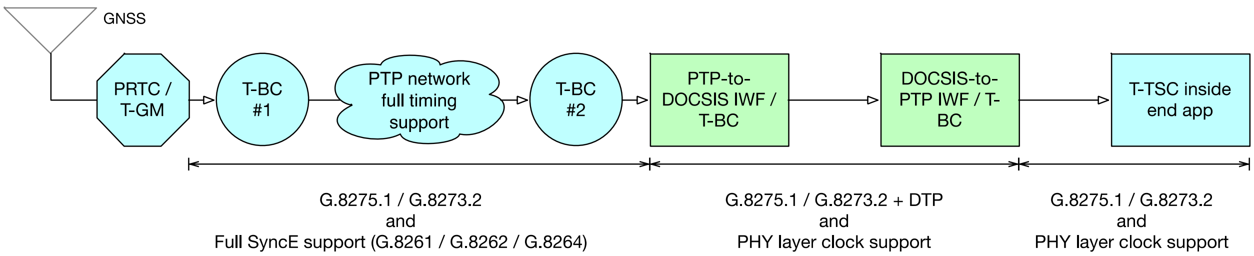


Figure 5 – End-to-End View of Full Timing Support for Phase Sync

Figure 6 shows an end-to-end view of the synchronization flow for mobile backhaul with partial timing support providing phase synchronization service to an end application mobile base station. The DOCSIS interworking functions perform identical functions in a partial timing support network as in a full timing support network.

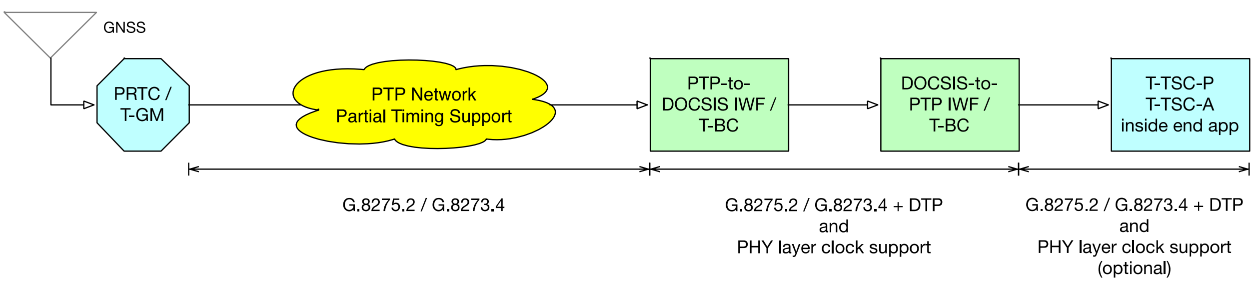


Figure 6 – End-to-End View of Partial Timing Support for Phase Sync

1.2.1. Synchronization Requirements

Phase synchronization is required for LTE-TDD, LTE-Advanced, and 5G.

LTE-TDD mobile cells use the same frequency for transmitting and receiving data, so it requires the time (phase) to be very accurate so there will no interference between different cell's transmissions.

LTE-TDD and 5G frequency and phase accuracy defined by 3GPP as shown in Table 1.

Table 1 – 4G/LTE and 5G Synchronization Requirements

	Frequency	Phase	Notes
4G LTE TDD	±50 ppb (air)	10 µs (wide: cell radius >3	Phase: 3GPP TS 36.133 §7.4.2

	Frequency	Phase	Notes
	±16 ppb (network)	km) 3 µs (local: cell radius <3 km)	Frequency: 3GPP TS 36.922 §6.4.1.2
5G TDD	±50 ppb (air) ±16 ppb (network)	≤ 3 µs	3GPP TS 38.104 Table 6.5.1.2.1

ITU-T G.8271.1 provides examples of the time error budget allocations to meet the LTE-TDD and 5G requirements. Those are shown in Table 2.

*Note that the time error specified in 3GPP is 3 µs while the ITU-T budget is 1.5 µs as the latter splits the overall phase error requirement between each of the Grand Master (GM) to cell paths.

Table 2 – ITU-T G.8271.1 Example of Time Error Allocation

Budget component	**Failure scenario (a)** ***(T-GM rearrangement)***		**Failure scenario (b)** ***(Short GNSS interruption)***	
PRTC (ce_{ref})	100 ns		100 ns	
Holdover and rearrangements in the network (TE_{HO})	NA		400 ns	
Random and error due to synchronous Ethernet rearrangements (dTE)	200 ns		200 ns	
Node constant including intrasite (ce_{ptp_clock}) **(Notes 1 and 2)**	Type A 550 ns	Type B 420 ns	Type A 550 ns	Type B 420 ns
Link asymmetries (ce_{link_asym}) **(Note 3)**	250 ns	380 ns	100 ns	230 ns
Network limit at reference point C (TE_C)	**1 100 ns**		**1 350 ns (Note 4)**	
Rearrangements and short holdover in the end application (TE_{REA})	250 ns		NA	
End application (TE_{EA})	150 ns		150 ns	
Total limit at reference point E (TE_E)	**1 500 ns**		**1 500 ns**	

From Table 2 above, the network is budgeted 1.1 µs of the total 1.5 µs for constant phase error. This includes all the network components between the GM and the end slave. If DOCSIS is part of that network, it will be part of this 1.1 µs budget.

Beside the constant time error budget allocation, G.8271.1 specifies a dynamic low frequency TE network limit in terms of MTIE and shown in Figure 7.

MTIE limit (ns)	Observation interval, τ (s)
$100 + 75\tau$	$1.3 < \tau \leq 2.4$
$277 + 1.1\tau$	$2.4 < \tau \leq 275$
580	$275 < \tau \leq 10\,000$

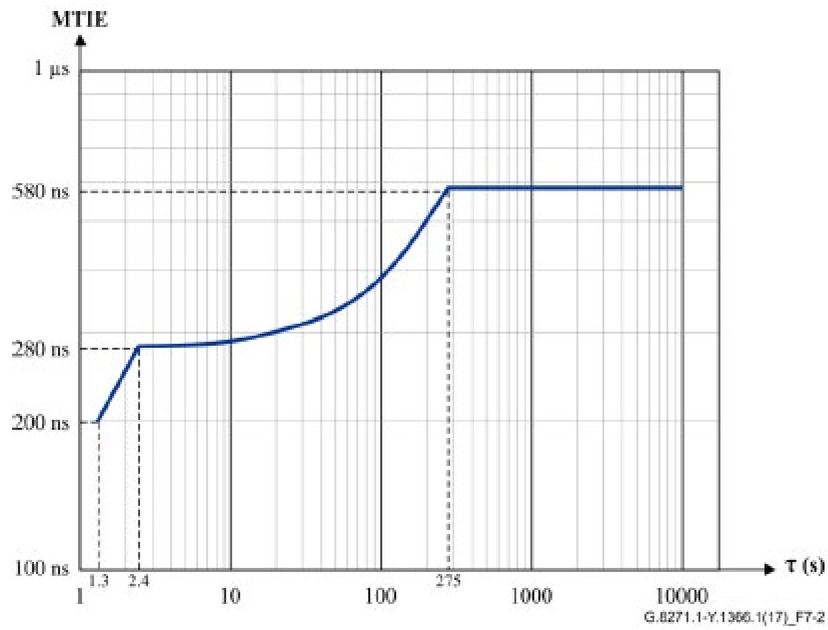


Figure 7 – ITU-T G.8271.1 Dynamic Time Error Network Limit (MTIE)

1.2.2. Proposed Solution over DOCSIS

The DOCSIS Time Protocol (DTP) was introduced in the DOCSIS 3.1 specifications and allows for the passing of the IEEE 1588 protocol operation over the DOCSIS network with no jitter from network buffering. The DTP reference architecture is shown in Figure 8.

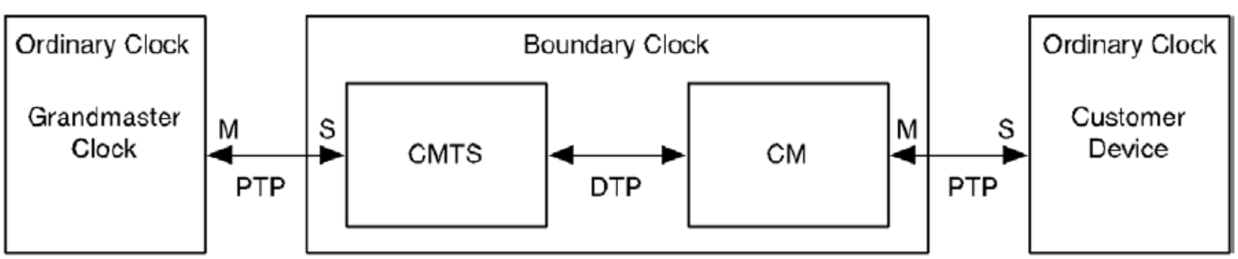


Figure 8 – DTP Reference Architecture

The CMTS and CM in Figure 8 corresponds to the PTP-to-DOCSIS IWF and the DOCSIS-to-PTP IWF respectively in Figure 5 and Figure 6. In R-PHY networks, the R-PHY replaces the CMTS in the timing path to the Customer Device.

The DOCSIS Time Protocol provides mechanisms to distribute frequency and phase information from the CMTS/R-PHY to a DTP-capable cable modem. The CMTS/R-PHY generates the downstream baud rate from its system clock to allow DTP-enabled cable modems to lock to that frequency and obtain frequency synchronization. For phase information, the CMTS/R-PHY synchronizes the DOCSIS Extended Timestamp to the received PTP timestamp. The cable modem recovers this timestamp and aligns its PTP timestamp to it. The DTP protocol computes the downstream delay while accounting for the upstream asymmetry so that the resulting PTP timestamp from the cable modem is closely aligned to the received PTP timestamp at the CMTS/R-PHY. To perform this computation and obtain this close alignment, delay values for components in the CMTS/R-PHY, cable modem, and the DOCSIS network are required.

The DOCSIS CMTS/R-PHY will have a PTP stack, and the CM will have its own PTP stack, so the CMTS/R-PHY will appear as one PTP hop, and the DOCSIS CM will appear as a second PTP hop. As a result, the DOCSIS network will increment the PTP hop count by two, once for the CMTS/R-PHY and once for the CM.

In order to insert IEEE 1588-capable DOCSIS equipment within the network, the total DOCSIS synchronization portion of the chain typically should meet the following performance requirements when measured in isolation between the PTP input on the first IWF (PTP-to-DOCSIS) and the PTP output on the second IWF (DOCSIS-to-PTP). The performance is covered in G.8273.2, Appendix V, “Performance Estimation for Cascaded Media Converters acting as T-BCs” that summarizes noise generation estimation for a pair of media converters based on the Class A and Class B T-BC noise generation specifications and the source for the data in Table 3.

Table 3 – Noise Generation Estimation for a Pair of Media Converters

	Based on Class A T-BC			Based on Class B T-BC		
	Single T-BC	Pair	Pair DOCSIS Class A IWF	Single T-BC	Pair	Pair DOCSIS Class B IWF
cTE (ns)	±50	±100	±500	±20	±40	±250
dTE_L MTIE (ns)	40	60	60	40	60	60
dTE_L TDEV (ns)	4	6	6	4	6	6
dTE_H (peak-to-peak, ns)	70	70	70	70	70	70
max|TE| (ns)	100	160	560	70	100	310

2. Equipment and Lab Setup

The following equipment was used for the different experiments:

- Grandmaster clock with a GPS reference supporting G.8265.1 and G.8275.2 profiles
- IEEE 1588 unaware switch
- CMTS for both Integrated Converged Cable Access Platform (I-CCAP) and CCAP Core functionality with PTP and DTP support
- R-PHY
- DOCSIS 3.0 CMs
- DOCSIS 3.1 CMs with DTP and PTP support
- IEEE 1588 slave probe with a GPS reference
- 4-channel Oscilloscope to measure the 1PPS differences between the GM, CCAP/R-PHY, CM and the slave probe

2.1. LTE-FDD and APTS Support with an IEEE 1588-Unaware DOCSIS Network

ITU-T has defined the G.8265.1 telecom profile to provide frequency-only distribution using PTP. A telecom profile defines the parameters needed to guarantee protocol interoperability between implementations. It also specifies the optional features and default values that must be supported. It does not guarantee a specific level of performance.

In this networking scenario, the network is a single PTP domain, from the PTP master to the clock probe. The intermediate networking equipment is not aware that PTP traffic is being carried between the master clock and the slave clock. It does not terminate or monitor the messages or monitor the timestamps in the messages, thus it is defined as non-participating with the PTP protocol.

Some of the relevant configuration parameters of the G.8265.1 profile are listed below:

- Unicast message transmission
- One-way or two-way messaging
- One-step or two-step timestamping
- Message rates, from 1 per 16 seconds to 128 per second

The networking equipment classifies the PTP traffic as expedited forwarding traffic, which is the highest priority traffic in the network. In these scenarios, a low priority background traffic was not added to compete for queuing and scheduling resources.

As the number of non-participating nodes increases, the accumulation of packet delay and packet delay variation will reduce the ability of the slave clock to recover the master clock’s frequency beyond an acceptable level.

A clock probe is used as the slave clock to measure the clock frequency and phase accuracy. Clock probes measure time error between a source timing signal and a measurement reference timing signal in terms of standard TIE/TE and MTIE measurements.

To reduce the PDV over the DOCSIS downstream path, the PTP packets were put into a dedicated DOCSIS service flow with highest priority. In addition, both DOCSIS 3.1 (192 MHz OFDM) and DOCSIS 3.0 (24 Annex B bonded SC-QAM) where tested.

2.1.1. I-CCAP

The first test configuration is a Centralized Access Architecture scenario. The configuration is shown in Figure 9.

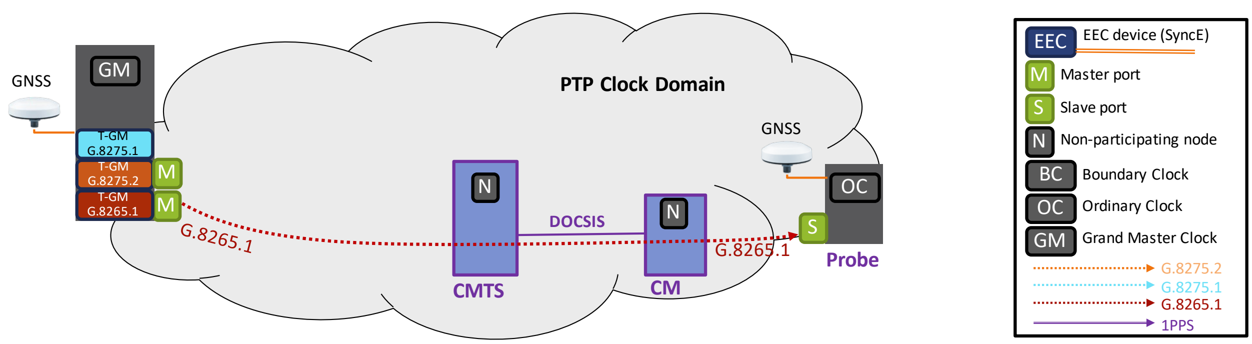


Figure 9 – PTP Frequency Delivery (G.8265.1) with I-CCAP

The network is a single PTP clock domain. The master clock sends PTP messages to the network side interface of the CMTS, which forwards them over DOCSIS to the cable modem. A clock probe is attached to the CMCI of the cable modem and terminates the PTP messages. The master clock and the clock probe are referenced to GPS, providing a common traceable source of frequency and time/phase information. This allows the clock recovery behavior of the slave clock to be measured against the network characteristics.

The PTP timestamped packets are generated at the T-GM and processed by the clock probe. The intermediate networking equipment is unaware that PTP messages are being carried, so they are sent over-the-top, and the CMTS and cable modem are unaware and non-participating in the protocol. The T-GM was connected to the I-CCAP via a 1GbE electrical interface. The cable modem was also connected to the clock probe via a 1GbE electrical interface.

The configured G.8265.1 parameters for this scenario are listed below:

- Unicast message transmission
- One-way messaging
- One-step timestamping
- Message rates: 128 per second (Sync)

2.1.2. Remote PHY

The second test configuration is a distributed access architecture scenario with a CCAP Core and an R-PHY connecting to a cable modem over DOCSIS. The configuration is shown in Figure 10.

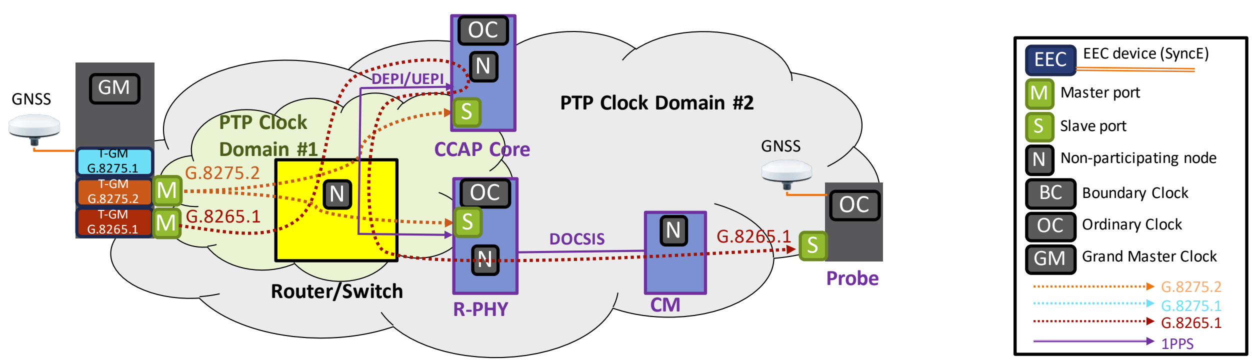


Figure 10 – PTP Frequency Delivery (G.8265.1) with R-PHY

The network consists of two clock domains, one domain provides phase and frequency synchronization for the CCAP Core and the R-PHY for DAA operation and a second for over-the-top frequency synchronization of the clock probe. G.8275.2 was used as the profile for the DAA timing domain while G.8265.1 was used for the LTE-FDD (PTP over the top) timing domain.

The G.8275.2 master clock sends PTP messages through the non-participating switch to the network side interface of the CMTS and to the network side interface of the R-PHY. The CMTS and R-PHY are both slave clocks in the first PTP clock domain.

The G.8265.1 master clock sends PTP messages through the non-participating switch to the CMTS for encapsulation in DEPI pseudowires, back though the switch to the network side interface of the R-PHY, which de-encapsulates them from DEPI and forwards them over DOCSIS to the cable modem. A clock probe is attached to the CMCI of the cable modem and terminates the PTP messages. The G.8265.1

master clock and the clock probe are referenced to GPS, providing a common traceable source of frequency and time/phase information. This allows the clock recovery behavior of the slave clock to be measured against the network characteristics.

The PTP timestamped packets are generated at the T-GM and processed by the clock probe. The intermediate networking equipment is unaware that PTP messages are being carried, so they are sent over-the-top, and the switch, CMTS, R-PHY, and cable modem are unaware and non-participating in the PTP protocol. The T-GM was connected to the switch via a 1GbE electrical interface. The switch connects to the R-PHY through a 10GbE optical interface. The cable modem was also connected to the clock probe via a 1GbE electrical interface.

The configured G.8265.1 parameters for this scenario are listed below:

- Unicast message transmission
- One-way messaging
- One-step timestamping
- Message rates: 128 per second (Sync)

2.2. LTE-TDD and 5G Support with an IEEE 1588-Aware DOCSIS Network

LTE-TDD uses a single frequency for transmitting and receiving data at different times, so it requires the highly accurate distribution and synchronization of frequency information and time or phase information between network elements across the network. ITU-T has defined the G.8275.1 and G.8275.2 telecom profiles to provide time and frequency distribution using PTP. In G.8275.1, timing support is provided by all elements in the network, while in G.8275.2, not all nodes need to provide timing support. For both profiles, physical layer functions like Synchronous Ethernet, may be used to stabilize the frequency operation of the clocks in the nodes and be provided on the CMCI output of the cable modem. Synchronous Ethernet was not used in either of the associated testing scenarios of this section.

The DOCSIS Time Protocol provides mechanisms to distribute frequency and phase information from the CMTS to a DTP-capable cable modem. The CMTS can derive the downstream baud rate from its system clock to allow cable modems to lock to that frequency and obtain frequency synchronization. For phase information, the CMTS synchronizes the DOCSIS Extended Timestamp to the received PTP timestamp. The cable modem recovers the DOCSIS timestamp and aligns its PTP timestamp to it. The DTP protocol computes the downstream delay while accounting for the downstream and upstream asymmetries so that the resulting PTP timestamp from the cable modem is closely aligned to the received PTP timestamp at the CMTS.

A PTP Clock Probe uses the timestamp carried in PTP messages from the CM to measure the TE/TIE between the clock under test and the reference timing signal for PTP clock analysis. The PTP clock probe provides monitor access to the various PTP timestamps.

Due to lack of SyncE support on all DOCSIS components at the time, SyncE was not used for the tests; only PTP was used.

2.2.1. I-CCAP

This test configuration is a Centralized Access Architecture scenario. This configuration is shown in Figure 11.

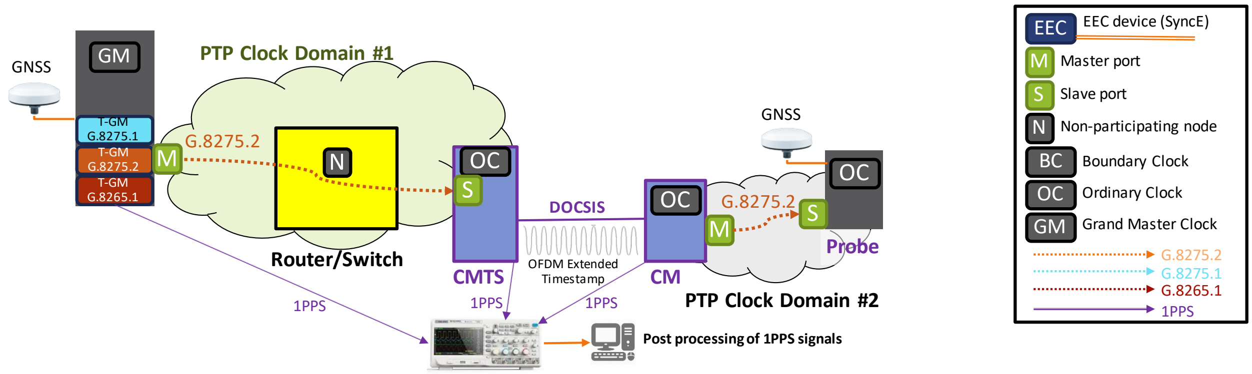


Figure 11 – PTP Time and Frequency Delivery (G.8275.2) with I-CCAP

The network consists of two PTP clock domains, one domain that provides phase and frequency synchronization of the CMTS to the T-GM and a second provides phase and frequency synchronization of the clock probe to the cable modem. G.8275.2 was used for both clock domains.

The T-GM clock sends PTP messages directly to the network side interface of the CMTS. The CMTS is a PTP slave clock in the first domain. It terminates the PTP messages and synchronizes the DOCSIS Extended Timestamp to the received PTP timestamp. The cable modem recovers this timestamp and aligns its PTP timestamp to it. It is the master clock for the second PTP domain and is connected to the slave clock probe using PTP through the CMCI.

The T-GM was connected directly to the CMTS through a 1GbE optical interface. The cable modem was connected directly to the slave clock probe via a 1GbE electrical interface.

The CMTS and the CM exchange DTP messages to calculate the DOCSIS asymmetry. The delay values in the DTP messages was determined manually.

The configured G.8275.2 parameters for the GM to CMTS domain are listed below:

- Unicast message transmission
- Two-way messaging
- One-step timestamping
- Message rates: 64 per second (Sync and Delay)

The configured G.8275.2 parameters for the CM to slave probe domain are listed below:

- Unicast message transmission
- Two-way messaging
- Two-step timestamping
- Message rates: 128 per second (Sync and Delay)

2.2.2. Remote PHY

The second test configuration is a distributed access architecture scenario with a CCAP Core and an R-PHY connecting to a cable modem over DOCSIS. This configuration is shown in Figure 12.

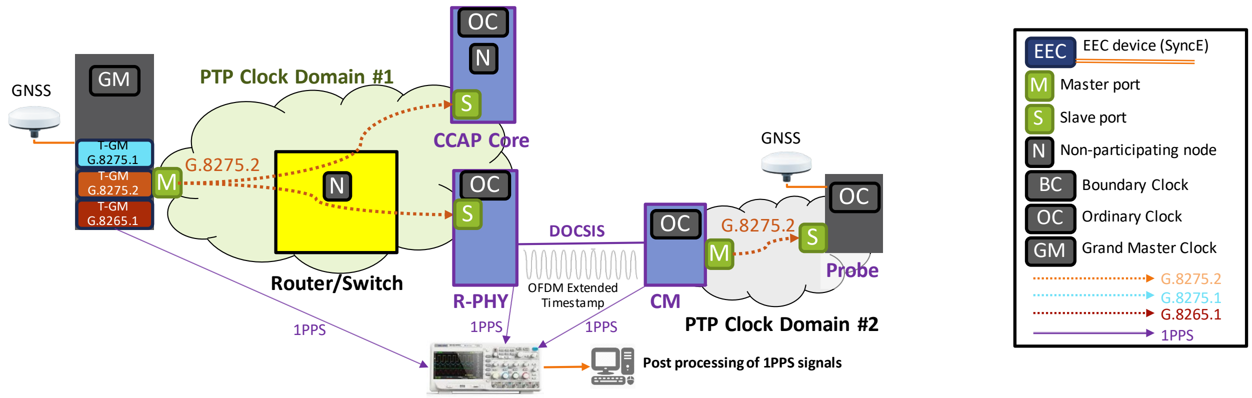


Figure 12 – PTP Time and Frequency Delivery (G.8275.2) with R-PHY

The network consists of two PTP clock domains, one domain that provides phase and frequency synchronization of the CCAP Core and the R-PHY to the T-GM for DAA operation and a second provides phase and frequency synchronization of the clock probe to the cable modem. G.8275.2 is used for both clock domains.

The G.8275.2 T-GM clock sends PTP messages through the non-participating switch to the network side interface of the CCAP Core and to the network side interface of the R-PHY. The CCAP Core and R-PHY are slave clocks in the first PTP clock domain. The R-PHY terminates the PTP messages and synchronizes the DOCSIS Extended Timestamp to the received PTP timestamp. The cable modem recovers this timestamp and aligns its PTP timestamp to it. It is the master clock for the second PTP domain and is connected to the slave clock probe using PTP through the CMCI.

Two alignment procedures were performed as part of this test. The first compensated for the delay asymmetry present in the first PTP clock domain between the R-PHY and the T-GM, primarily due to the different ethernet speeds used on the R-PHY (10GbE) and GM (1GbE). The second alignment procedure determined the appropriate DOCSIS Time Protocol values used during this test.

The T-GM was connected to the switch via a 1GbE electrical interface. The switch connects to the CMTS through a 10GbE optical interface. The cable modem connects to the slave clock probe via a 1GbE electrical interface.

The CMTS and the CM exchanged DTP messages to calculate the DOCSIS asymmetry. The delay values in the DTP messages was determined manually.

The configured G.8275.2 parameters for the GM to R-PHY domain are listed below:

- Unicast message transmission
- Two-way messaging
- One-step timestamping
- Message rates: 64 per second (Sync and Delay)

The configured G.8275.2 parameters for the CM to slave probe domain are listed below:

- Unicast message transmission
- Two-way messaging
- Two-step timestamping
- Message rates: 128 per second (Sync and Delay)

3. Procedure and Results

3.1. LTE-FDD and APTS Support with an IEEE 1588-Unaware DOCSIS Network

As mentioned in section 2.1, PTP packets were sent over the top of DOCSIS using a 1-way G.8265.1 messaging between the GM and the probe.

Tests were performed on both I-CCAP and R-PHY setups and measurements of MTIE and PDV were taken and compared to ITU-T G.8261.1 and G.8271.2 requirements for LTE-FDD and APTS use cases respectively.

3.1.1. I-CCAP

In the I-CCAP case, two experiments were performed. One using a DOCSIS 3.0 CM with 14 Annex B SC-QAM bonded downstream channels and one using a DOCSIS 3.1 CM with 192 MHz OFDM downstream channel. Results are shown for both.

3.1.1.1. DOCSIS 3.0 I-CCAP

Figure 13 and Figure 14 show the PDV and MTIE results measured at the output of the CM by a probe over SC-QAM channels with DOCSIS 3.0.

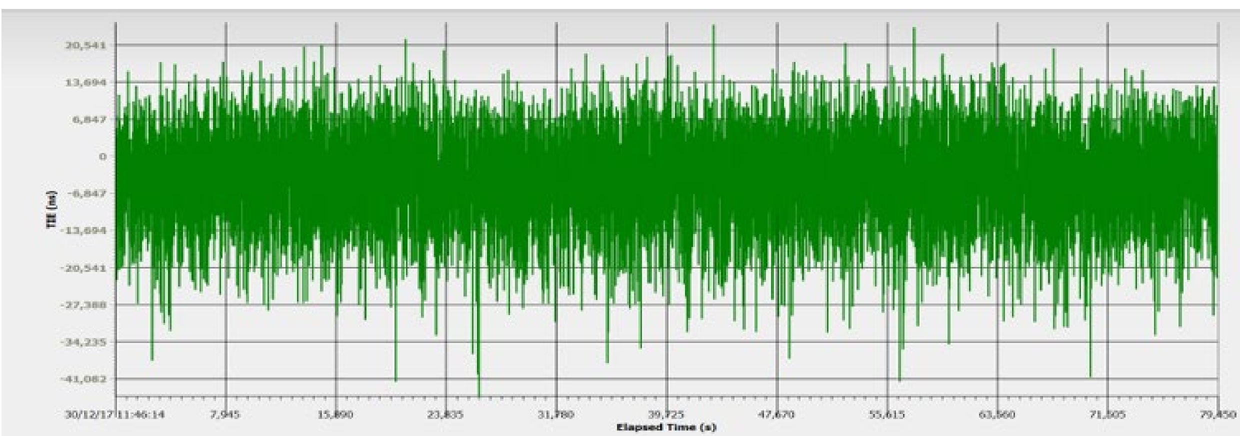
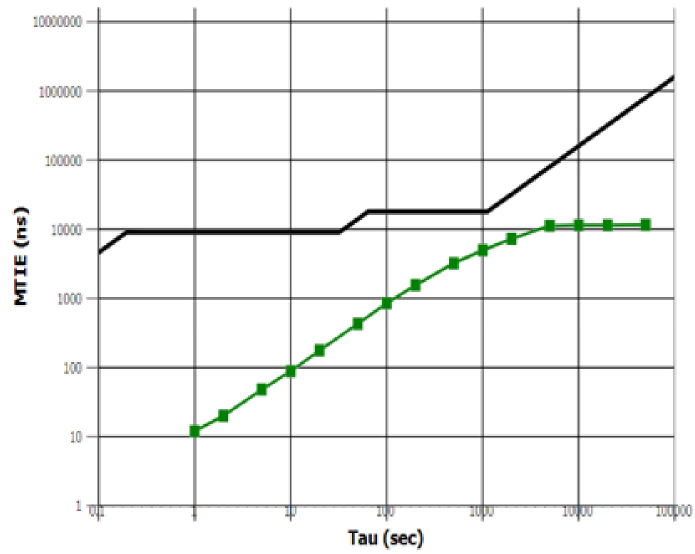


Figure 13 – PDV for DOCSIS 3.0 with I-CCAP



Tests Result

Interval (sec)	Result (ns)	Mask Stat	Margin Stat
0.1	N/A	N/A	N/A
0.2	N/A	N/A	N/A
0.5	N/A	N/A	N/A
1	12	OK	OK
2	20	OK	OK
5	48	OK	OK
10	88	OK	OK
20	176	OK	OK
50	428	OK	OK
100	848	OK	OK
200	1556	OK	OK
500	3216	OK	OK
1000	4968	OK	OK
2000	7244	OK	OK
5000	11272	OK	OK
10000	11412	OK	OK
20000	11412	OK	OK
50000	11588	OK	OK
100000	N/A	N/A	N/A

Figure 14 – G.8261.1 MTIE Results for DOCSIS 3.0 I-CCAP

As can be seen from the above figures, the measured PDV at the output of the CM is roughly 20 µs to 50 µs, and the results meet the MTIE mask of G.8261.1 for LTE-FDD.

However, the MTIE is ~12 µs, which does not meet the 100 ns requirement for APTS.

3.1.1.2. DOCSIS 3.1 I-CCAP

Figure 15 and Figure 16 show the PDV and MTIE results measured at the output of the CM by a probe over OFDM channels with DOCSIS 3.1.

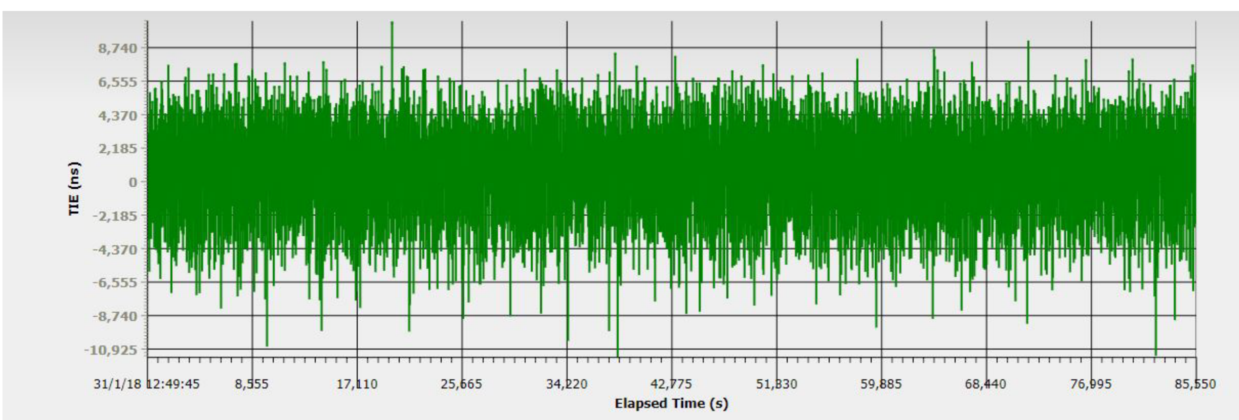
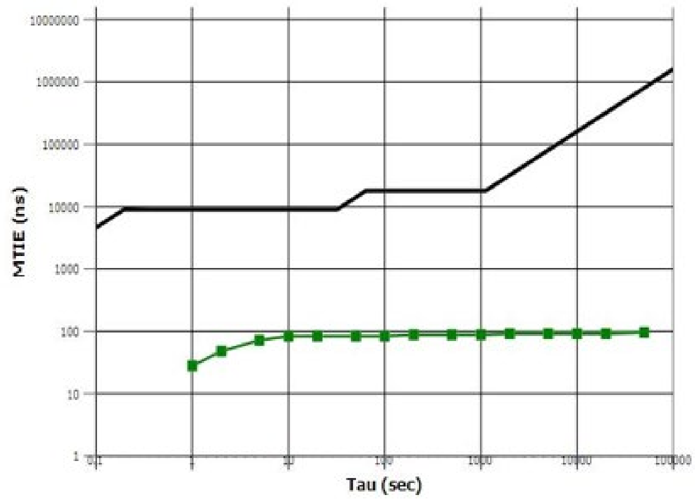


Figure 15 – PDV for DOCSIS 3.1 with I-CCAP



Tests Result

Interval (sec)	Result (ns)	Mask Stat	Margin Stat
0.1	N/A	N/A	N/A
0.2	N/A	N/A	N/A
0.5	N/A	N/A	N/A
1	28	OK	OK
2	48	OK	OK
5	72	OK	OK
10	84	OK	OK
20	84	OK	OK
50	84	OK	OK
100	84	OK	OK
200	88	OK	OK
500	88	OK	OK
1000	88	OK	OK
2000	92	OK	OK
5000	92	OK	OK
10000	92	OK	OK
20000	92	OK	OK
50000	96	OK	OK
100000	N/A	N/A	N/A

Figure 16 – G.8261.1 MTIE Results for DOCSIS 3.1 I-CCAP

As can be seen from the above figures, the measured PDV at the output of the CM is roughly 10 µs to 15 µs, and the results meet the MTIE mask of G.8261.1 for LTE-FDD.

In addition, the MTIE is ~96 ns, which does meet the 100 ns requirement for APTS.

3.1.2. Remote PHY

In the R-PHY case, only the DOCSIS 3.1 experiment was performed to see whether the DAA degrades the performance or not.

Figure 17 shows the PDV results measured at the output of the CM by a probe.

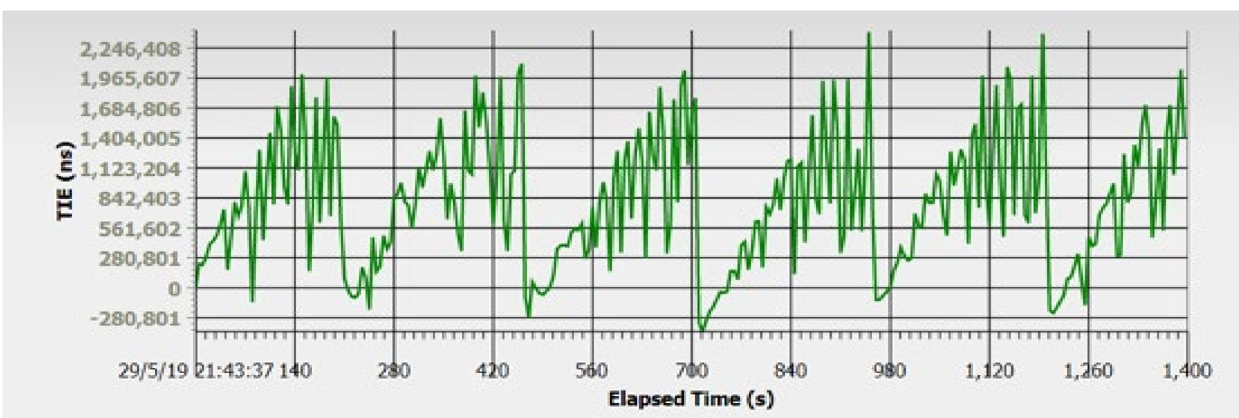


Figure 17 – PDV for D3.1 with R-PHY

As can be seen from the above figures, the measured PDV at the output of the CM was very high with peaks going into the millisecond range. This is at least one order of magnitude higher than the threshold required by G.8261.1.

From the results it seems that the DEPI encapsulation/de-encapsulation in the Core and R-PHY adds a significant amount of PDV to the PTP packets.

When trying to connect a slave clock to this PTP output, the slave clock could not achieve frequency lock.

Therefore, neither LTE-FDD nor APTS can be supported with PTP over the top of a DOCSIS Remote PHY system.

3.2. LTE-TDD and 5G with an IEEE 1588-Aware DOCSIS Network

There were no significant differences in results between the I-CCAP and R-PHY use cases. Therefore, the results shown are from the R-PHY setup only.

3.2.1. Remote PHY

3.2.1.1. Test Calibration

Two alignment procedures were performed as part of this test. The first compensated for the delay asymmetry present in the first PTP clock domain (GM to R-PHY). The second alignment procedure determined the appropriate DTP values to be used during this test.

The delay asymmetry value is configured to compensate for the difference in latency between the ingress and egress path between the R-PHY and its IEEE 1588 GM. When the ingress path is slower than the egress path, a positive asymmetry value is configured, A negative value is configured when ingress path is faster than the egress path. The delay asymmetry value was adjusted until the delay between the 1PPS output from the T-GM to the 1PPS output from the R-PHY was less than ±50 ns.

The DTP algorithm is based on the true ranging offset (TRO) calculated by the CM based on the ranging information. The TRO is effectively a round trip delay measurement.

In the DTP algorithm, both the CMTS and CM are reporting their different US and DS timing path delays. To eliminate any HFC asymmetries, a (nearly) zero-length HFC plant was used.

In the R-PHY setup, the CCAP core is the one communicating DTP with the CM. However, the DS and US delay values were effectively tuned to those of the R-PHY.

Using an oscilloscope, the 1PPS output from the R-PHY and CM were aligned as close as possible limited by the 1PPS accuracy of the CM and the oscilloscope resolution.

The TRO value that was calculated by the CM for the zero-length plant was also read. The DTP math algorithm was performed to determine the required time adjustment value to be used by the CM. Once the appropriate delay values are calculated, the differences between a zero-length plant and a real plant that has the same R-PHY and CM are reflected in the TRO value.

The DTP alignment procedure was performed with a coax cable less than 3 feet long to represent the zero-length plant and those values were also used to initialize the R-PHY and CM pair with a 400-foot cable. The same DTP values were also used to initialize a second DTP-capable CM.

3.2.1.2. Key Measurements

The following measurements were taken throughout the tests:

- 1PPS differences between the R-PHY and CM in long runs to check the phase transfer stability. This was measured using an oscilloscope
- 1PPS differences between the R-PHY and CM after R-PHY/CM reset. This was measured using an oscilloscope
- Overall TE/TIE and MTIE measured by the PTP probe compared to GPS. This gives an estimate of the overall DOCSIS network phase delivery performance

Figure 18 shows the network configuration for PTP Time and Frequency Delivery using R-PHY. This is the same as Figure 12.

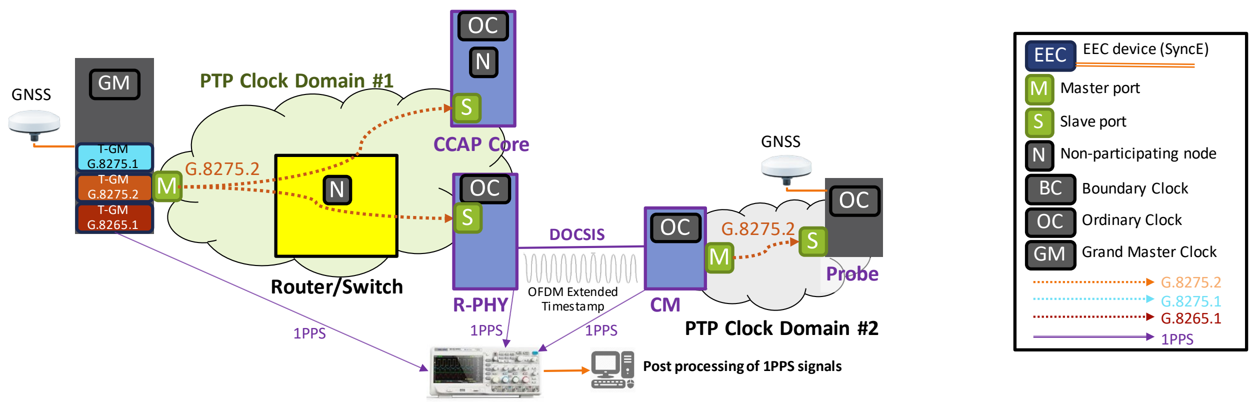


Figure 18 – PTP Time and Frequency Delivery (G.8275.2) with R-PHY

3.2.1.3. Measurement Results

Measurements were made on the difference between the 1PPS signals from the R-PHY and the CM to determine the phase transfer stability. The zero-length plant coax cable was used. Figure 19 shows a set of 20 measurements collected after the DTP messages were exchanged and the CM adjusted its time accordingly. Those measurements spanned 23 ns peak-to-peak, ranging from –17 ns to +6 ns with respect to the average of the group. This was very consistent.

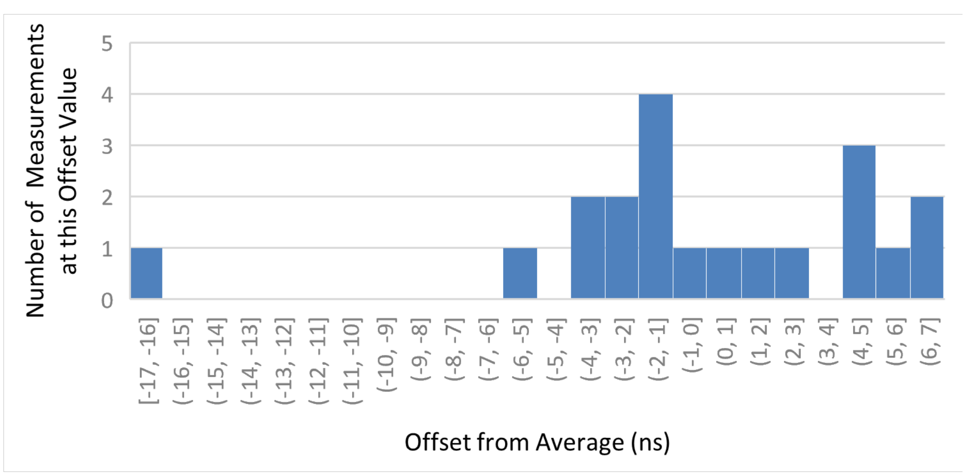


Figure 19 – Phase Transfer Stability Between RPD and CM 1PPS

Figure 20 shows a set of 20 measurements that were taken after only the CM was reset and initialized using the same DTP parameters as in the initial set of measurements. The TRO calculated by the CM increased by 20 ns for this test. The 1PPS phase error spanned 20 ns peak-to-peak, ranging from –12 ns to +8 ns with respect to the average of the group. The average value for this group of measurements was 12 ns more than the average calculated in the first set of 20 measurements. This was also very consistent.

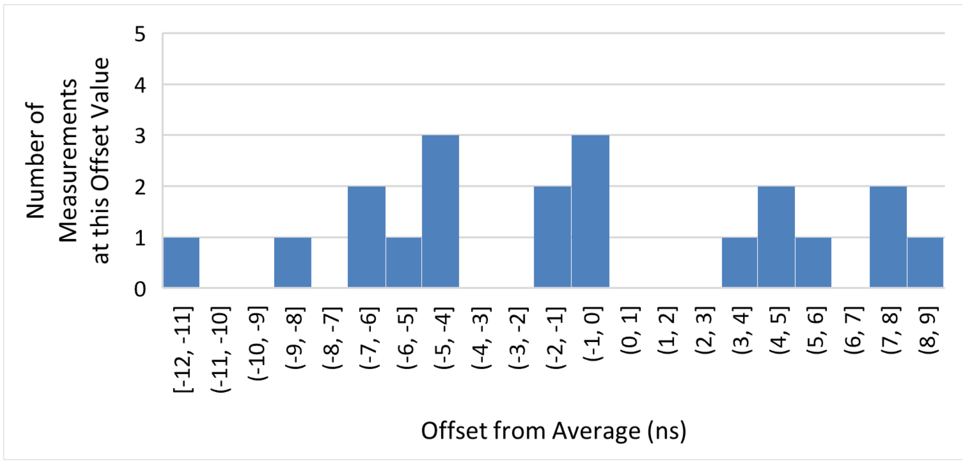


Figure 20 – Phase Transfer Stability Between RPD and CM 1PPS (After CM Reset)

Figure 21 shows the set of 20 measurements that were taken after both the RPD and CM were reset and initialized using the same DTP parameters as in the initial set of measurements. The TRO calculated by the CM increased by 39 ns in this test. The phase error spanned 22 ns peak-to-peak ranging from –10 ns to +12 ns with respect to the average value of the group. The average value for this group of measurements was 47 ns more than the average value calculated in the first set of 20 measurements. This is still very consistent, but it shows that there is some variability in the values after RPD reset. In any case, the difference is less than 50 ns.

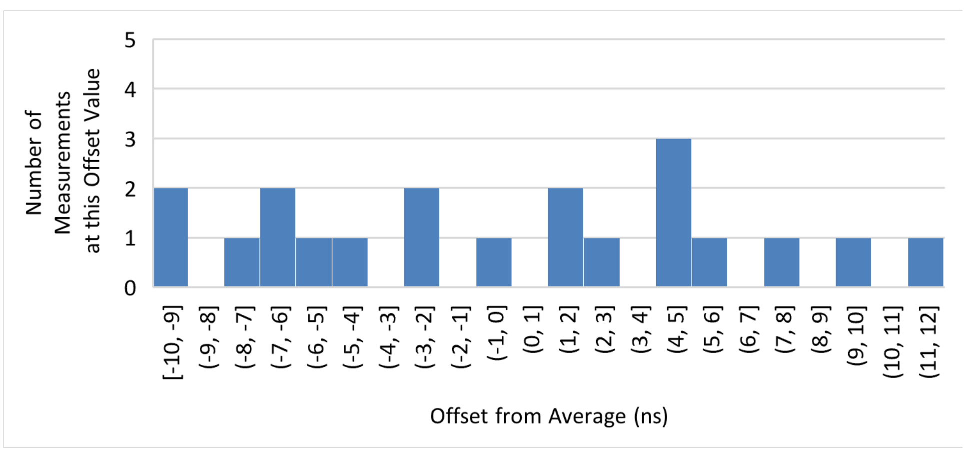


Figure 21 – Phase Transfer Stability Between R-PHY and CM 1PPS (After both CM and RPD Reset)

Table 4 summarizes the phase transfer stability measurements. The average value for the measurements after the CM resets and after both CM and RPD resets is relative to the average for the initial set of measurements. Similarly, the TRO measurements are similarly relative to the TRO from the initial set of measurements. The absolute values are not shown.

As can be seen the phase transfer from the RPD to the CM is stable with variances of less than 50 ns in long run and after CM and RPD resets. The variance in TRO indicated small variances in the DS and/or US paths across reboots. This variance may be reduced in the future after further study.

Table 4 – Summary of Phase Transfer Stability Measurements

	Average Phase Error (ns)	Phase Error Range (ns)	TRO (ns)
Initial set of measurements	0	–17 to +6	–
Measurements after CM reset (relative to initial set of measurements for average and TRO)	+12	–12 to +8	+20
Measurements after both R-PHY and CM reset (relative to initial set of measurements for average and TRO)	+47	–10 to +12	+39

Figure 22 shows the TE of the recovered phase at the slave probe referenced to GPS time. The measurement was taken with a 3-foot coax between the RPD and the CM to approximate the zero-length plant for calibration.

In the graph, it can be seen the recovered phase has a TE of roughly 220 ns with a variation of 100 ns peak-to-peak.

These results are well below the 500 ns TE budget from Section 1.2.2 for a class B DOCSIS system defined in the CableLabs Synchronization Techniques specification.

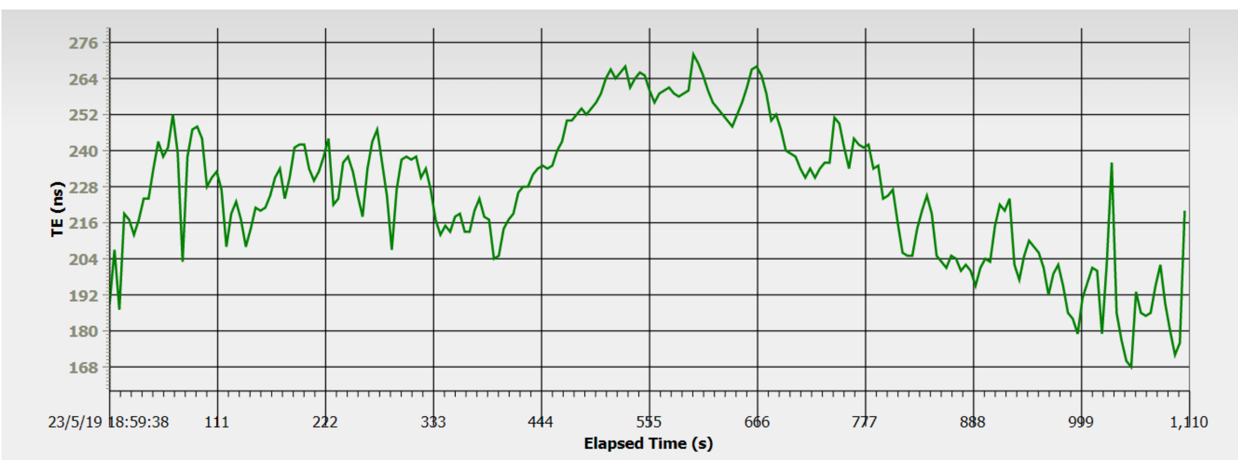


Figure 22 – TE of the Recovered Phase at the Slave Probe with 3' of Coax

In order to reduce the 220 ns cTE artificially, the DTP parameters were adjusted to take into account this 200 ns TE.

Figure 23 shows the TE of the recovered phase at the slave probe compared to GPS time after the DTP parameters were calibrated. The figure shows a compensated TE of roughly 30 ns with a variation of 60 ns peak-to-peak.

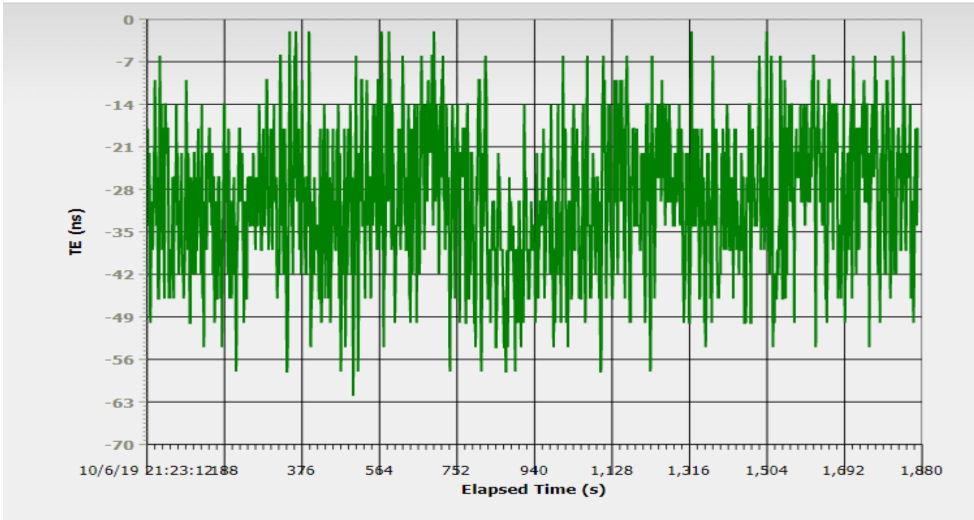


Figure 23 – TE of the Recovered Phase at the Slave Probe with DTP Compensation

In order to check the consistency of the DTP and TRO measurement accuracy, we changed the path between the RPD and the CM to a 400' length of coax. The DTP parameters were unchanged. The TRO increased by approximately 900 ns over the 3-foot plant values.

Figure 24 shows the TE of the recovered phase at the slave probe compared to GPS with a 400-foot coax between the RPD and the CM.

The figure shows a TE of roughly 10 ns with a variation of 50 ns peak-to-peak.

These results are quite consistent with the result of the 3-foot plant and shows that the DTP and TRO calculations are accurate.

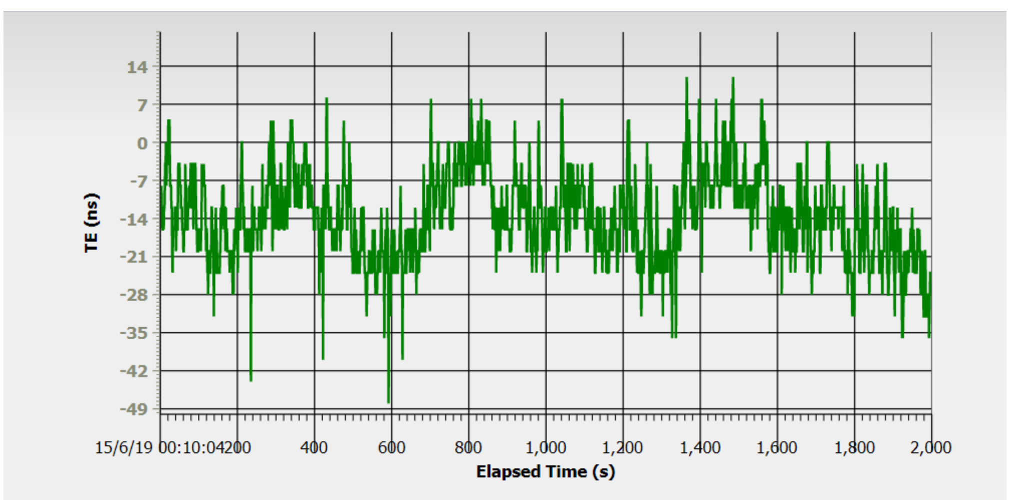
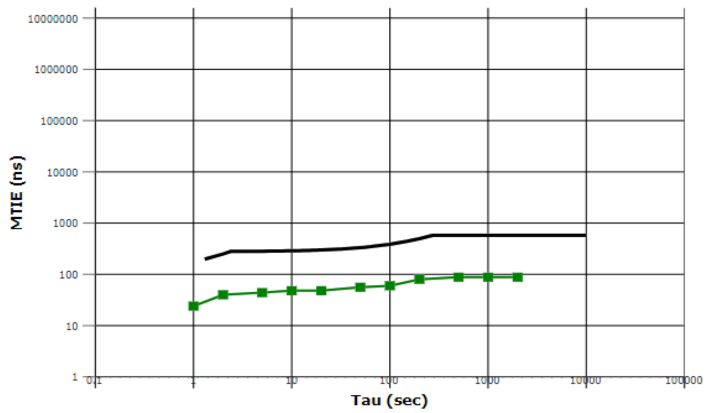


Figure 24 – TE of the Recovered Phase at the Slave Probe with 400' of Coax

Figure 25 shows the MTIE measurement taken by the slave probe.

The MTIE performance of at the output of the CM is below 100 ns and meets the MTIE requirements for phase delivery defined in G.8271.1.



Tests Result

Interval (sec)	Result (ns)	Mask Stat	Margin Stat
0.1	N/A	N/A	N/A
0.2	N/A	N/A	N/A
0.5	N/A	N/A	N/A
1	24	N/A	N/A
2	40	OK	OK
5	44	OK	OK
10	48	OK	OK
20	48	OK	OK
50	56	OK	OK
100	60	OK	OK
200	80	OK	OK
500	88	OK	OK
1000	88	OK	OK
2000	88	OK	OK
5000	N/A	N/A	N/A
10000	N/A	N/A	N/A
20000	N/A	N/A	N/A
50000	N/A	N/A	N/A
100000	N/A	N/A	N/A

Figure 25 – G.8271.1 MTIE Mesurements Calculated by the Slave Probe with 400' of Coax

In order to estimate the PDV and asymmetry of the PTP output from the CM, we used the PTP probe to compare the offset between the T1 and T4 timestamps to GPS time. This mesures the PDV of the PTP packets between the CM and PTP slave probe for the forward and reverse direction. It can also show the delay asymmetry of the path.

Figure 26 and Figure 27 show the PTP probe for Probe-CM (upstream direction) and CM-Probe (downstream direction) paths respectively.

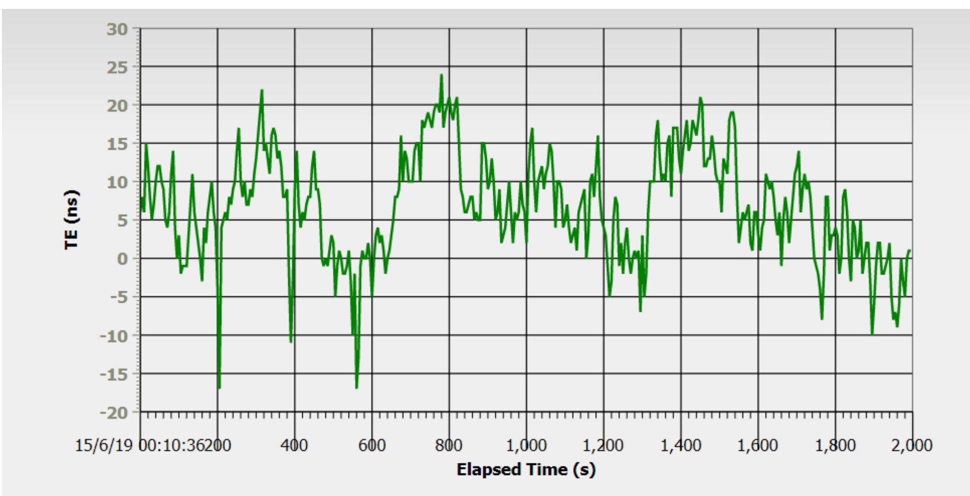


Figure 26 – PTP Probe (Probe to CM)

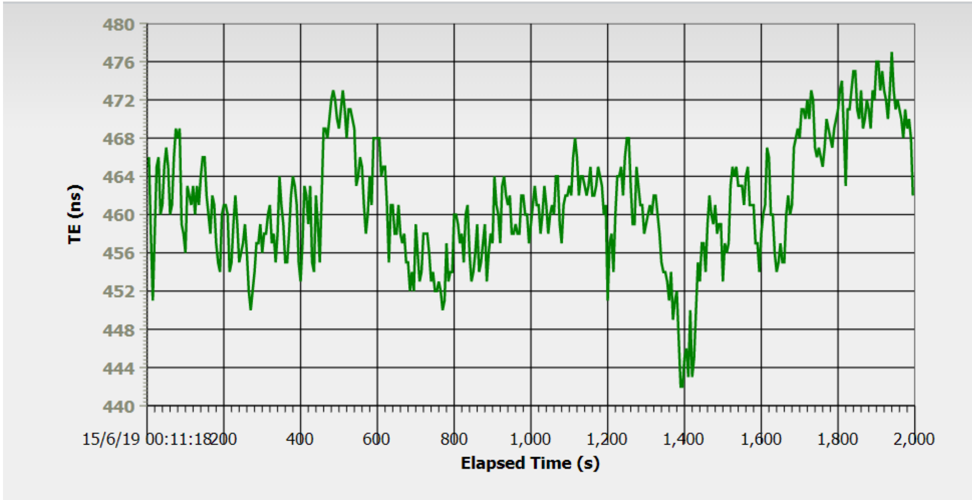


Figure 27 – PTP Probe (CM to Probe)

As can be seen when comparing the two PTP paths, the PDV is quite similar at 25 ns. The difference in delay between the upstream and downstream paths is roughly 400 ns. The asymmetry value is roughly 400 ns with a median value of ~200 ns. This is as expected since the the recovered clock has a n offset of 200 ns. Each path has a 200 ns delay from the rececered clock on opposite directions.

Conclusion

In this paper, we constructed and tested DOCSIS CAA and DAA networks to provide sufficiently accurate synchronization for various LTE-FDD, LTE-TDD, and 5G use cases.

We showed that for LTE-FDD and APTS, a DOCSIS CAA system can carry over the top PTP information and still maintain accurate synchronization. This approach can be deployed today with minimal changes.

The IEEE 1588-unaware over-the-top DOCSIS DAA network did not meet the required performance for LTE-FDD and APTS.

For LTE-TDD and 5G, both DOCSIS CAA and DAA systems can provide accurate sync delivery using DTP and meet the requirements specified for MBH. This solution requires the full support of PTP and DTP on the CMTS/R-PHY and CM as defined in the CableLabs Synchronization Techniques specification.

Network and module improvement such as using SyncE as part of the synchronization chain as well as embedding a switch within the CM with their impact on the overall frequency and phase accuracy for these and other applications are areas for additional studies.

Abbreviations

1GbE 10GbE	1 Gb/s Ethernet 10 Gb/s Ethernet
1PPS	1 Pulse Per Second
3GPP	3rd Generation Partnership Project
APTS	Assisted Partial Timing Support
CAA	Centralized Access Architecture
CCAP	Converged Cable Access Platform
CM	Cable Modem
CMCI	Cable Modem to Customer Premises Equipment Interface
CMTS	Cable Modem Termination System
cTE	Constant Time Error
DAA	Distributed Access Architecture
DEPI	Downstream External PHY Interface
DOCSIS	Data-Over-Cable Service Interface Specifications
DS	Downstream
dTE	Dynamic Time Error
DTP	DOCSIS Time Protocol
FPP	Floor Packet Percentage
GM	Grand Master
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HFC	Hybrid Fiber Coax
I-CCAP	Integrated CCAP
IEEE	Institute of Electrical and Electronic Engineers
IEEE 1588	IEEE Std 1588-2008 (PTP)
ITU-T	Telecommunication Standardization Sector of the International Telecommunication Union
IWF	Inter Working Function
LTE	Long-Term Evolution
LTE-A	Long-Term Evolution Advanced
LTE-FDD	Long-Term Evolution Frequency Division Duplex
LTE-TDD	Long-Term Evolution Time Division Duplex
MBH	Mobile Backhaul
MTIE	Maximum Time Interval Error
OFDM	Orthogonal Frequency Division Multiplexing
OTT	Over The Top
PDV	Packet Delay Variation
PHY	Physical
ppb	parts per billion
PTP	Precision Time Protocol
QAM	Quadrature Amplitude Modulation

R-PHY	Remote PHY
RPD	Remote PHY Device
SC-QAM	Single Carrier QAM
SyncE	Synchronous Ethernet
T-BC	Telecom Boundary Clock
T-GM	Telecom Grand Master
TDEV	Timing Deviation
TE	Time Error
TIE	Time Interval Error
TRO	True Ranging Offset
UEPI	Upstream External PHY Interface
US	Upstream

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