How DOCSIS Time Protocol makes the SYNC Specification Tick

Automating the DTP Algorithm

A Technical Paper prepared for SCTE•ISBE by

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1. Introduction

CableLabs® released the I01 SYNC specification on April 20, 2020. The SYNC specification describes how to build and deploy an IEEE 1588/PTP participant DOCSIS network. The SYNC specification is targeted at the new and evolving mobile backhaul market.

The core technology that makes timing work is the DOCSIS Time Protocol (DTP). DTP was introduced in DOCSIS 3.1 and described in [1] but has not been deployed as of yet. The operation of DTP is not well understood and there are many new considerations in order to bring it from a specification to a deployed product. As a result of this strong interest by operators, there is a need to re-explore in detail several aspects of DTP, including:

- what DTP does,
- how it works,
- how it is calibrated,
- how it is used in a live system,
- how it interplays with other DOCSIS procedures,
- limitations, and tradeoffs.

The goal of this paper is to provide this detailed exploration of DTP and enable the Cable community to have a common understanding of DTP so they can confidently develop it and use it.

2. Market Opportunity

As highlighted in [2], mobile network operators (MNOs) are relying on densifying their radio access network (RAN) to improve the coverage, capacity, and throughput for both their 4G and, more importantly, 5G systems. As depicted in Figure 1, MNOs achieve this densification by installing low-powered base stations (called small cells) underneath their existing high-powered base stations (called macrocells), creating a heterogeneous network (HetNet).

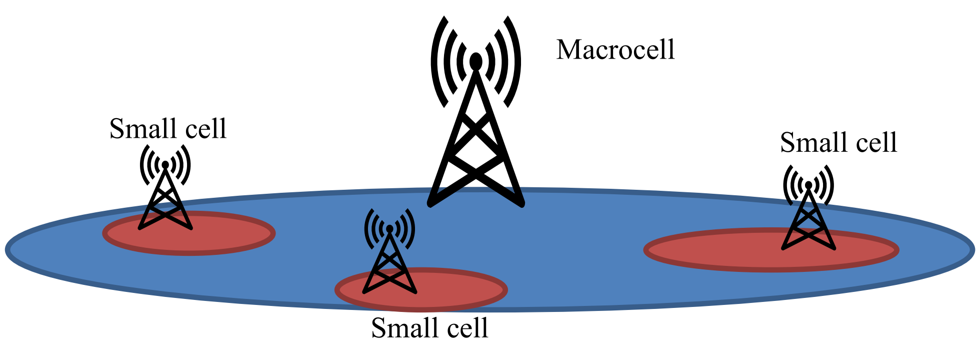

Figure 1 – Heterogeneous Netwok

For small cells to work effectively, three key elements are required:

1. Location
2. Power
3. Backhaul

Cable operators are in an advantageous position to offering a solution for these three requirements, as discussed in detail in [2]. As such, the authors strongly believe that cable operators of today are the mobile network operators of tomorrow.

In terms of backhaul, these are the requirements:

1. high throughput to sustain the traffic of the small cells,
2. low latency and jitter, and
3. network timing.

In [2], the authors focused on how to achieve low latency backhaul over DOCSIS. In this paper, we focus on how to provide network timing by using the DOCSIS Time Protocol.

3. Why is time synchronization needed?

In this section we explore in detail the need for time and frequency synchronization among the elements of the RAN in a mobile network.

First, we will clarify the concepts of frequency, phase, and time synchronization. In Figure 2, we depict the difference among the three. Frequency synchronization refers to two elements that are beating at the same pace, but are not necessarily aligned at the instant when they beat. Phase synchronization refers to two elements that are beating at the same pace, and are aligned at the instant when they beat; however, the time they report at each beat is not necessarily the same. Time synchronization refers to two elements that are beating at the same pace, are aligned at the instant when they beat, and the time they report at each beat is the same. Throughout this paper we will use the term "timing synchronization" to refer to frequency, phase, and time synchronization all together unless explicitly stated.

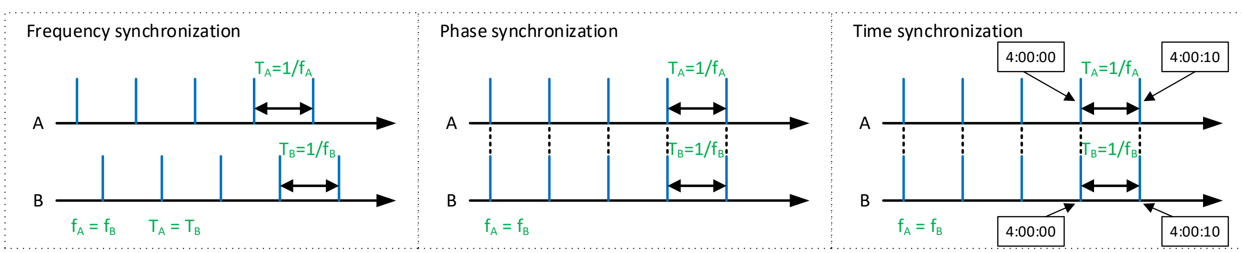

Figure 2 – Frequency vs Phase vs Time synchronization

Many mobile networks previously required only frequency synchronization. However, 4G and 5G networks require also phase and time synchronization for several reasons, including:

a) Use of Time Division Duplexing (TDD): In TDD mode, the base stations (also called eNBs) utilize a same frequency for both upstream and downstream transmission. A single base station will switch in time between transmitting and receiving data. Since base stations have overlapping coverage, particularly in a HetNet, those base stations need to be aligned in terms of when to be in transmission mode, or in reception mode; otherwise, they will cause interference to each other, as depicted in Figure 3. In Figure 3, the base stations are completely misaligned, causing interference between user equipment (UE) at the cell-edge, and also at the base stations themselves.

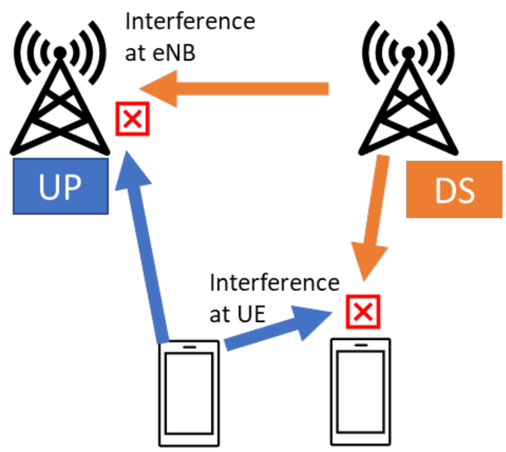

Figure 3 – Interference at UE and eNB

b) Use of advanced base station coordination techniques: In both 4G and 5G systems, new techniques were introduced to either mitigate potential interference among base stations operating in the same frequency band (e.g., enhanced intercell interference cancellation, or eICIC), or improve the throughput achievable by UEs under the coverage of multiple base stations (e.g., Coordinated Multi Point operation, or CoMP). For these techniques to work effectively, the base stations need to be tightly synchronized.

Table 1 [3] summarizes the synchronization requirements for 4G LTE Frequency-Division Duplex (FDD), 4G LTE TDD, and 5G TDD.

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

Table Heading	Frequency	Phase	
4G LTE FDD	± 50 ppb	None	3GPP TS 36.104 §6.5.1
4G LTE TDD	± 50 ppb (wide area) ± 100 ppb (local area) ± 250 ppb (home)	10 µs (wide: cell radius >3 km) 3 µs (local: cell radius <3 km) 1.33 µs + Tprop (home eNB radius >500 m) 3 µs (home eNB radius <500 m)	Phase: 3GPP TS 36.133 §7.4.2 Frequency: 3GPP TS 36.922 §6.4.1.2
5G TDD	± 50 ppb (wide area) ± 100 ppb (local area)	≤ 3 µs	3GPP TS 38.104 Table 6.5.1.2.1

The SYNC specification was designed with the goal of achieving the 3 µs phase requirement. The key concept to note is that the ±3 µs requirement refers to the allowed time error between the RAN network elements. In a deployed system, this 3 µs requirement is typically achieved by setting a ±1.5 µs phase requirement between the RAN network elements and a common time source, as depicted in Figure 4.

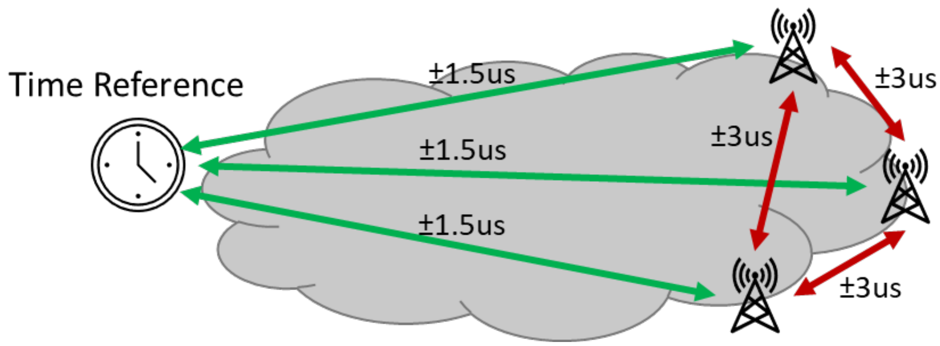

Figure 4 – Phase Synchronization in a Mobile Network

One way to achieve the timing synchronization is to use a Global Navigation Satellite System (GNSS) as time source, and equip every base station with a GNSS receiver. This works well for macrocells. Macrocells are typically deployed in outdoor environments, and the cost of the GNSS receiver is very small compared to the cost of the macrocell itself. For small cells, using GNSS may not work well for two reasons: GNSS signal availability and cost of GNSS receiver.

Small cells are meant to be low-cost devices deployed in large quantities and may be deployed in indoor environments where the signal from a GNSS could be unreliable. Even where the GNSS signal is reliable, the cost of the GNSS receiver might significantly increase the cost of the small cell. Because of these two reasons, network-based timing protocols, which do not depend on GNSS signal availability and have lower cost impact on small cells are preferable.

What Figure 4 shows with a single arrow from the base stations to the time source is actually comprised of the DOCSIS backhaul and other network elements, as depicted in Figure 5.

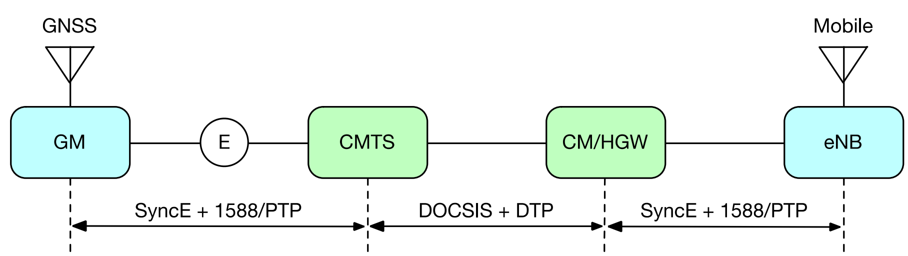

Figure 5 – Timing Delivery over DOCSIS Backhaul

Figure 5 shows a grandmaster (GM) synchronized to a GNSS. Through a series of network elements (marked as E), the timing information is delivered to the CMTS through the use of 1588/PTP and, optionally, SyncE. The CMTS utilizes existing DOCSIS timing properties and the DOCSIS Time Protocol (DTP) to convey the information that the CM needs to be properly synchronized. The CM then delivers the timing information to the base station, called eNB, using 1588/PTP and, optionally, SyncE. The end application resides within the eNB.

Comparing Figure 4 and Figure 5, we see that the DOCSIS backhaul, i.e.,. the CMTS and CM, is only one of the elements between the time source, i.e., GNSS, and the end application. Thus, the 1.5 µs budget is actually distributed among the DOCSIS elements and the rest of the elements sitting between the GNSS and the end application.

In the next section, we discuss the details of how DTP works.

4. DOCSIS Time Protocol (DTP)

4.1. How timing protocols work

Before diving into the specifics of DTP, we will provide a high-level view of how timing protocols work.

All timing protocols use a variant of a Two-Way Time Transfer (TWTT), as depicted in Figure 6.

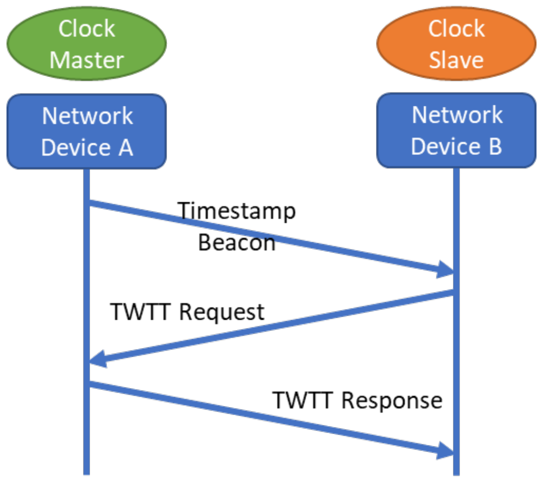

Figure 6 – Two-way Time Transfer

There are two devices, one containing the master clock (Network Device A), and one containing the slave clock (Network Device B). Network Device A sends a timestamp to Network Device B. This timestamp will arrive at Network Device B at some time after it was created by Network Device A. In other words, the timestamp is delayed. Network Device A and B exchange messages to determine the network delay and asymmetry. Once these two factors are identified, Network Device B corrects its timestamp to match the one of Network Device A. Even though this procedure was used to synchronize the time, the same mechanism can be used to synchronize the frequency.

4.1. What DTP does

In its simplest form, DTP allows the existing timing and frequency system of DOCSIS to be interfaced to external timing protocols with high accuracy, as shown in Figure 7. Once the CMTS has a frequency and time source synchronized to an external source, DTP allows the source to be replicated at the egress port of the CM.

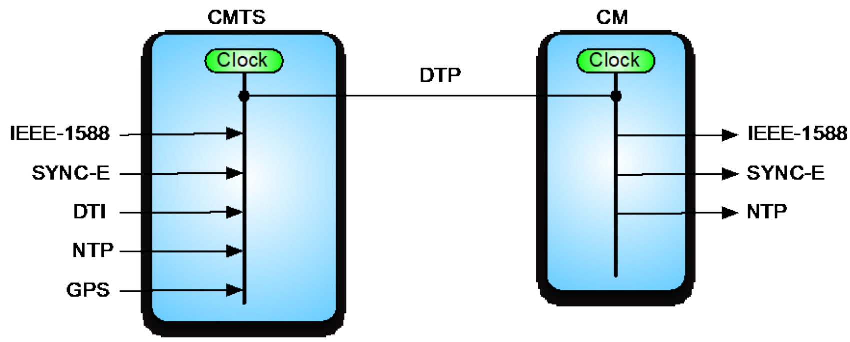

Figure 7 – DOCSIS Time Protocol – System Overview

As highlighted in [4], for the DOCSIS DTP frequency path, the CMTS PLL (Phase-Locked Loop) locks onto the frequency component of the external timing protocol, e.g., SyncE or IEEE-1588. The output of the CMTS PLL drives the DOCSIS downstream baud rate. The CM receives the baud rate frequency and locks to it with its PLL. The CM PLL then drives the frequency output on the CMCI port with SyncE and/or IEEE-1588.

As highlighted in [4], for the DOCSIS DTP timestamp path, the CMTS synchronizes its DOCSIS 3.1 Extended Timestamp to the timestamp of the external protocol, e.g., IEEE-1588. The DOCSIS Extended Timestamp is sent to the CM as part of the DOCSIS protocol where it is converted back to any desired format, e.g., IEEE-1588. The DTP protocol that runs between the CMTS and the CM computes the time delay in the downstream path while taking into account the asymmetry of the DOCSIS system. This delay is then added to the timestamp in the CM so that the timestamp that is sent out from the CM closely matches the timestamp received by the CMTS.

The main takeaways from the above two paragraphs are:

- The CMTS and CM are already synchronized in frequency. The CMTS frequency will need to be synchronized to an external frequency source. The CM will need to pass its local frequency to its CMCI port.
- The CMTS and CM are already phase aligned, but not time synchronized. DTP provides the means to achieving the time synchronization.

4.2. DTP Messaging

Similarly to how other time protocols operate (see Section 4.1), DTP operates under a master/slave approach. The DTP master is in charge of:

a) Initiating DTP message exchange, and
b) Computing the time adjustment for the CM.

The MULPI spec [4] allows for either the CMTS or the CM to be the DTP master. Figure 8 depicts the message flow between the DTP master and DTP slave for the case of the CMTS being the DTP master. The DTP request (DTP-REQ) provides configuration information to the CM regarding the CMTS and HFC timing values. The CM does not need these values to compute the ones that it sends back in the DTP response (DTP-RSP).

The key value reported back by the CM is the true ranging offset (TRO) and the CM timing values. The CMTS uses this data, the CMTS timing values, and HFC timing values to compute the DTP time adjustment, and then sends this time adjustment to the CM in a DTP info (DTP-INFO) message. Once the CM receives the DTP-INFO, the CM replies back with a DTP acknowledgement (DTP-ACK).

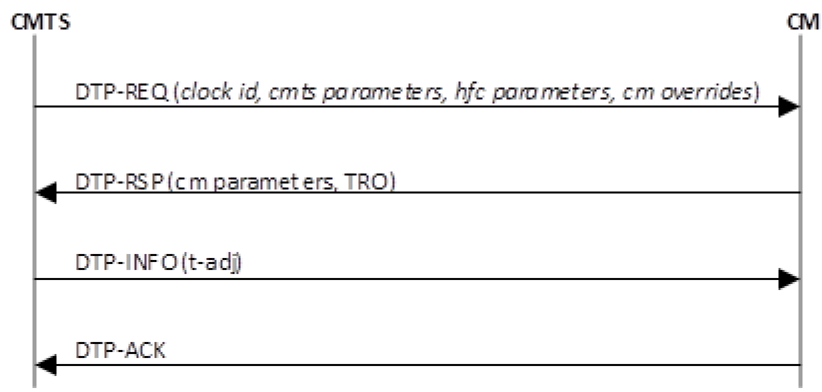

Figure 8 – CMTS is DTP Master

The time interval at which the DTP message exchange is repeated is configurable, with 10 seconds being the minimum value and no maximum value.

4.3. DTP – Determining the path delay

At a high-level, DTP relies on the exchange of messages (see Section 4.2) to determine the forward path delay needed to compensate the time at the CM.

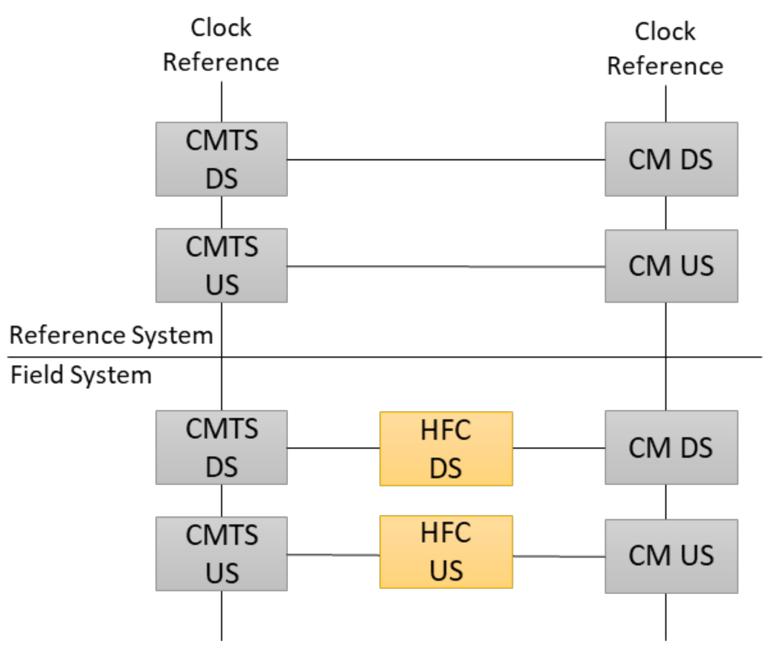

Figure 9 – DTP Operation

In Figure 9, we depict a simplified field system composed of a CMTS (downstream – DS, and upstream – US), and HFC plant (DS and US), and CM (DS and US). In this figure, the forward path delay is composed by the CMTS DS, HFC DS, and CM DS elements. The underlying assumptions used to compute these elements are:

1. The CMTS and CM parameters can be measured offline.
2. The HFC path delay in downstream is equal to the HFC upstream path delay. Note that this assumption is not always true; however, if the error is within the error budget allocated to the HFC, then the error can be ignored.
3. The difference in path delay between a field system and a zero-length plant is attributable to the total HFC path delay (DS & US).

With these assumptions in place, it follows that by computing the difference in path delay between a field system and a zero-length plant, we can obtain the total HFC path delay. We take this value and divide it by two, and we get the one-way HFC path delay. Now, because the CMTS DS and CM DS parameters were calibrated offline, the overall path delay can now be computed as the sum of CMTS DS, HFC DS path delay, and CM DS.

So, for the above to work, we need to have the CMTS and CM parameters calibrated offline, which an entity such as CableLabs® could lead. In the next section, we dive deeper into what exactly the CMTS, CM, and HFC parameters represent.

5. DTP Timing Model

The DTP timing model is depicted in Figure 10.

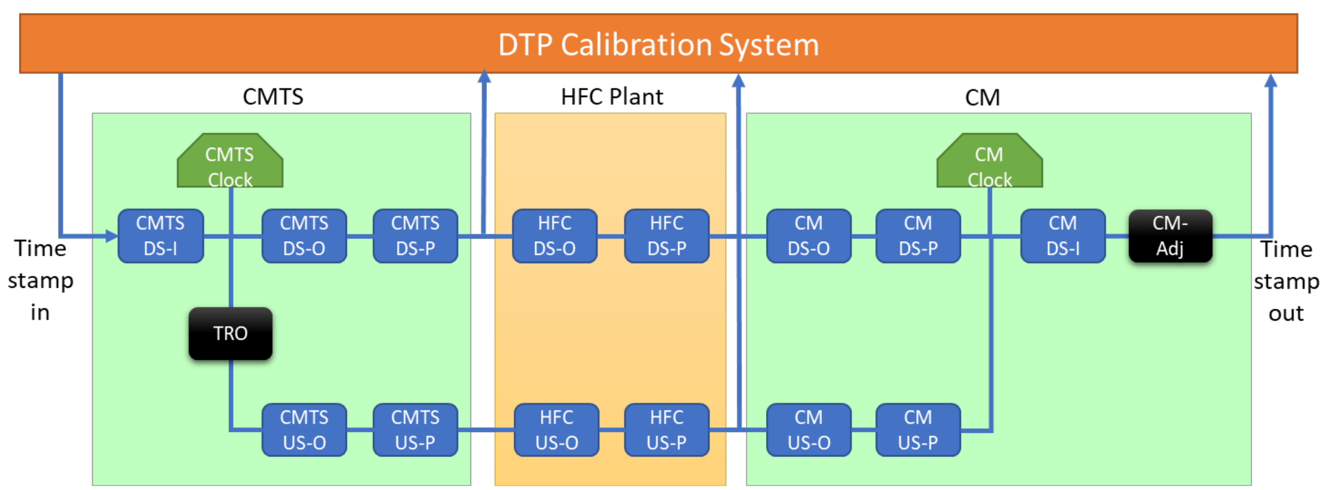

Figure 10 – DTP Timing Model

The timing values have blue background. The ones associated with the CMTS are preceded by the word "CMTS", the ones associated with the HFC are preceded by the word "HFC", and the ones associated with the CM are preceded by the word "CM". The parameters associated with downstream include the word "DS", and the ones associated with upstream include the word "US". There are three types of parameters:

1. Interface Delay: Include the suffix "-I"
2. Path: Include the suffix "-P". This is a vendor specific characterized delay of the physical circuit path. For the CMTS and CM, this may be a measured or calibrated value that is supplied as part of calibration. For the HFC plant, this is the value that is calculated as part of the DTP calculations, as discussed in Section Figure 9.
3. Offset: Include the suffix "-O". This is a known offset due to interleaving or some other configuration.

Table 2 summarizes all the parameters, as defined in [4]. Compared to Figure 10, the spec uses the additional prefix “t-” to refer to the timing parameters.

Table 2 – DTP Delays

	Delay Type	Delay Name	Description
CMTS	Interface	t-cmts-ds-i	This is the circuit delay from the CMTS clock input interface (DTI or NSI) to the internal CMTS timestamp reference point. This is a manufacturer's value and is supplied by the CMTS.
	Path	t-cmts-ds-p	This is the intrinsic path delay contribution from the CMTS timestamp reference point to the CMTS downstream PHY output. This is a measured value and supplied by the CMTS.
		t-cmts-us-p	This is the intrinsic path delay contribution from the CMTS PHY upstream input to the CMTS timestamp reference point. This is a measured value and supplied by the CMTS.
	Offset	t-cmts-ds-o	This is the known delay contribution in the downstream CMTS PHY path that is associated with configuration elements such as interleaving. This value is known and is supplied by the CMTS.
		t-cmts-us-o	This is the known delay contribution in the downstream CMTS PHY path that is associated with configuration elements such as interleaving. This value is known and is supplied by the CMTS.
HFC	Path	t-hfc-ds-p	This is the intrinsic path delay of the fiber and coax elements of the HFC plant. The DTP algorithm calculates this value.
		t-hfc-us-p	This is the intrinsic path delay of the fiber and coax elements of the HFC plant exclusive of fixed delay elements. The DTP algorithms calculate this value. The basic DTP algorithm assumes the upstream and downstream path delay are equal by using the offset values to compensate for fixed and asymmetrical delays.
	Offset	t-hfc-ds-o	This delay represents any fixed delay elements in the HFC path that contribute to delay. One example may be a digitization circuit, optical node and amplifier circuit delays. This value may be unique per HFC path due to different path elements. This value is supplied by the CMTS. By specifying appropriate HFC downstream and upstream offset values correctly and by setting the asymmetry appropriately, the HFC downstream and upstream path delays can be assumed to be equal.
		t-hfc-us-o	This delay represents any fixed delay elements in the HFC path that contribute to delay. One example may be a digitization circuit, optical node and amplifier circuit delays. This value may be unique per HFC path due to different path elements. This value is supplied by the CMTS.
CM	Interface	t-cm-ds-i	This is the circuit delay from the internal CM timestamp reference point to the clock output interface (CMCI). This value is manufacturer's value and is supplied by the CM or by a CMTS override.
	Path	t-cm-ds-p	This is the intrinsic path delay contribution from the CM PHY downstream input to the CM timestamp reference point. This is a measured value and supplied by the CM or by a CMTS override.
		t-cm-us-p	This is the intrinsic path delay contribution from the CM timestamp reference point to the CM PHY upstream output. This is a measured value and supplied by the CM or by a CMTS override.
	Offset	t-cm-ds-o	This is the known delay contribution in the downstream CM PHY path that is associated with configuration elements such as interleaving. This value is known and is supplied by the CM or by a CMTS override.

	Delay Type	Delay Name	Description
		t-cm-us-o	This is the known delay contribution in the upstream CM PHY path that is associated with configuration elements such as interleaving. This value is known and is supplied by the CM or by a CMTS override.
	Other	t-cm-adj	This is the value that must be added to the CM unadjusted timestamp to have the CM timestamp be equal to the CMTS timestamp in real time. This value is calculated by the DTP Master.

In the addition to the timing values described above, the other parameter of relevance is the True Ranging Offset (TRO). The TRO is the measured ranging offset of the CM between two defined reference points. TRO is a measured (or derived) value that is different than the actual implemented ranging offset a CM might use in its communication with the CMTS. A key property of the TRO is that the value of TRO is the equivalent to the round-trip delay of the combined downstream and upstream propagation delays of the HFC plant, the CMTS and CM PHY paths. For more details on the TRO, see [4].

With the TRO, CMTS timing values, CM timing values, and HFC offset values, the DTP math described in MULPI [4] provides the formulas to compute the necessary time adjustment for the CM. Those formulas are shown here for reference:

(1) *t-tro = t-cmts-ds-o + t-cmts-ds-p + t-hfc-ds-o + t-hfc-ds-p + t-cm-ds-o + t-cm-ds-p + t-cm-us-o + t-cm-us-p + t-hfc-us-o + t-hfc-us-p + t-cmts-us-o + t-cmts-us-p*
(2) *t-cm-adj = t-cmts-ds-i + t-cmts-ds-o + t-cmts-ds-p + t-hfc-ds-o + t-hfc-ds-p + t-cm-ds-o + t-cm-ds-p + t-cm-ds-i*

The limitation is that there does not exist any measurement equipment that, as of the time of the writing of this paper, can measure separately the CMTS, CM, and HFC timing values. Until the testing limitation is addressed by test equipment vendors, rather than characterizing the CMTS and CM separately, they must be characterized jointly for specific configurations, as discussed in the next section.

6. DTP Calibration

The approach for DTP calibration is based on the following assumptions:

1. The timing values of the CM and CMTS will be characterized jointly due to lack of testing equipment, as of the time of the writing of this paper, that can characterize them separately.
2. The joint characterization of the CM and CMTS needs to be done for every configuration parameter, e.g., interleaving, that affects the upstream or downstream delay.
3. The timing values of an HFC element can be characterized indirectly by comparing timing behavior of a DOCSIS network without such an HFC element and with such an HFC element.

With the above assumptions, the SYNC spec provides the following three steps to perform the DTP calibration and using the measured values on a live system.

1. Measuring the CMTS-CM combined timing parameters: This is done at a reference-length plant. Ideally the plant would be zero-length, but it is sufficient for the plant to be as simple as possible and with a known length.

2. Measuring the HFC timing parameters: This is done indirectly by inserting the HFC element between the CMTS and CM, and computing the difference between this plant and the reference-length plant.
3. Computing the DTP Time Adjustment in a live DOCSIS system. This is done based on the values computed or measured in the previous two steps.

6.1. Measuring the CMTS-CM combined timing parameters

The goal is to jointly characterize the CMTS-CM timing parameters using a reference-length plant, i.e., the HFC path is just a coax connection of reference length from the CMTS to the CM, as depicted in Figure 11.

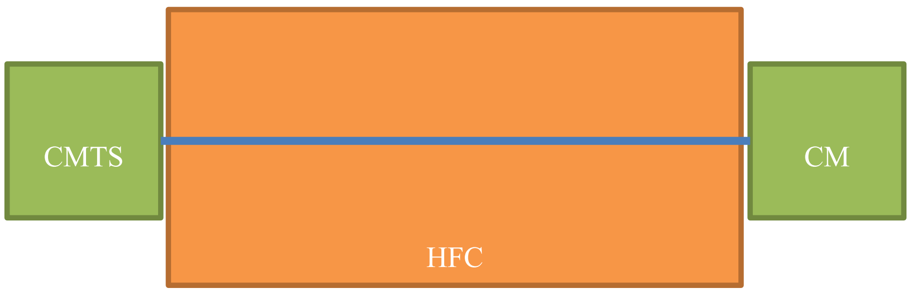

Figure 11 – Measuring CMTS-CM combined timing parameters

In the following formulas, we utilize the suffix "-R" to refer to any values that are specific to the reference-length plant.

For a reference-length plant, formulas (1) and (2) become:

(3) *t-tro-R = t-cmts-ds-o + t-cmts-ds-p + t-hfc-ds-o-R + t-hfc-ds-p-R + t-cm-ds-o + t-cm-ds-p + t-cm-us-o + t-cm-us-p + t-hfc-us-o-R + t-hfc-us-p-R + t-cmts-us-o + t-cmts-us-p*
(4) *t-cm-adj-R = t-cmts-ds-i + t-cmts-ds-o + t-cmts-ds-p + t-hfc-ds-o-R + t-hfc-ds-p-R + t-cm-ds-o + t-cm-ds-p + t-cm-ds-i*

Note that the CMTS and CM parameters do not require a "-R" suffix because their values are independent of the length of the HFC in the reference-length plant.

Since the HFC is just a coax connection in the reference-length plant, it is assumed that the HFC upstream and downstream offset timing values are both zero, i.e., *t-hfc-us-o-R = 0 and t-hfc-ds-o-R=0*. Thus, formulas (3) and (4) become:

(5) *t-tro-R = t-cmts-ds-o + t-cmts-ds-p + t-hfc-ds-p-R + t-cm-ds-o + t-cm-ds-p + t-cm-us-o + t-cm-us-p + t-hfc-us-p-R + t-cmts-us-o + t-cmts-us-p*
(6) *t-cm-adj-R = t-cmts-ds-i + t-cmts-ds-o + t-cmts-ds-p + t-hfc-ds-p-R + t-cm-ds-o + t-cm-ds-p + t-cm-ds-i*

Now, we record the following values for the reference-length plant:

- *t-tro-R*: True ranging offset as reported by the CM.

- *t-cm-adj-R*: Value of the DTP time adjustment that brings the average PTP 2-Way Time Error (cTE) to zero.
- *t-hfc-ds-p-R:* Downstream path delay introduced by the coax cable going from the CMTS to the CM. This is computed based on the length of the coax cable and the speed of propagation in the coax cable. Typically, this speed is around 1.5ns/ft.
- *t-hfc-us-p-R:* Downstream path delay introduced by the coax cable going from the CMTS to the CM. This is computed based on the length of the coax cable and the speed of propagation in the coax cable. Typically, this speed is around 1.5ns/ft.

Rearranging the terms in formulas (5) and (6), we get

(7) t-tro-R - t-hfc-ds-p-R - t-hfc-us-p-R = t-cmts-ds-o + t-cmts-ds-p + t-cmts-us-o + t-cmts-us-p + t-cm-ds-o + t-cm-ds-p + t-cm-us-o + t-cm-us-p

(8) t-cm-adj-R - t-hfc-ds-p-R = t-cmts-ds-i + t-cmts-ds-o + t-cmts-ds-p + t-cm-ds-o + t-cm-ds-p + t-cm-ds-i

The most important aspect of the formulas (7) and (8) is that on the left-hand side of each formula we have values that are either measured or calculated based on the reference-length plant, and on the right-hand side we have a combination of CMTS and CM timing parameters. Thus, we achieved the goal of measuring the CMTS-CM combined timing parameters.

Now that we have an expression that summarizes the combination of CMTS and CM parameters (right-hand side of formulas (7) and (8)), we use formulas (7) and (8) and combine those with the generic formulas (1) and (2). Here are the formulas (1) and (2) once more, with the CMTS and CM parameters moved as to group them for simplicity:

*(1) t-tro = t-hfc-ds-o + t-hfc-ds-p + t-hfc-us-o + t-hfc-us-p + (**t-cmts-ds-o + t-cmts-ds-p+ t-cmts-us-o + t-cmts-us-p + t-cm-ds-o + t-cm-ds-p + t-cm-us-o + t-cm-us-p**)*

*(2) t-cm-adj = t-hfc-ds-o + t-hfc-ds-p +(**t-cmts-ds-i + t-cmts-ds-o + t-cmts-ds-p + t-cm-ds-o + t-cm-ds-p + t-cm-ds-i**)*

The terms in bold in formula (1) are the same as the right-hand side of formula (7). The terms in bold in formula (2) are the same as the right-hand side of formula (8). So, plugging formulas (7) and (8) into formulas (1) and formula (2), we get new generic formulas:

(9) t-tro = t-hfc-ds-o + t-hfc-ds-p + t-hfc-us-o + t-hfc-us-p + (t-tro-R – t-hfc-ds-p-R – t-hfc-us-p-R)

(10) t-cm-adj = t-hfc-ds-o + t-hfc-ds-p + (t-cm-adj-R – t-hfc-ds-p-R)

6.2. Measuring the HFC timing parameters

The goal is to characterize the timing parameters of a single HFC element. While it is possible to characterize a set of HFC elements as a single unit, the results would only be usable when that same set is present in a deployment.

First, the HFC element of interest is inserted between the CMTS and the CM, as depicted in Figure 12. For the plant described in Figure 12, we utilize the suffix "-1" to refer to any values that are specific to this plant. This represents the plant under test in an actual deployment. The goal is to generate a formula for CM-adj.

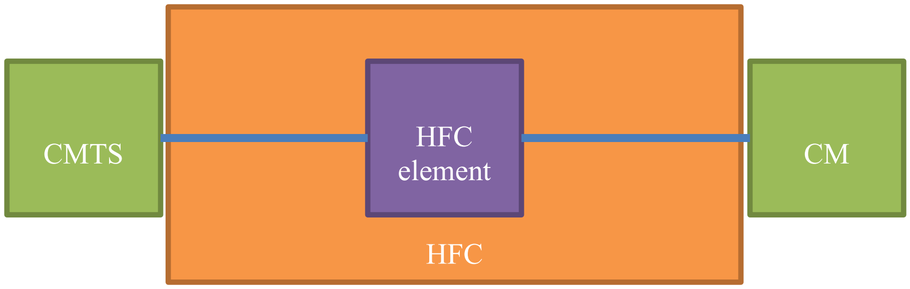

Figure 12 – Measuring HFC timing parameters

In Figure 12, the HFC is composed of three parts. Part 1 is the cable going from the CMTS to the HFC element. Part 2 is the HFC element itself. Part 3 is the cable going from the HFC element to the CM.

Now, we record the following values for the plant in Figure 12:

- *t-tro-1:* True ranging offset as reported by the CM.
- *t-cm-adj-1*: Value of the DTP time adjustment that brings the average PTP 2-Way Time Error (cTE) to zero
- *t-hfc-ds-p-1:* Downstream path delay introduced by the fiber and coax cables going from the CMTS to the CM. This value includes the downstream path delay from the CMTS to the HFC element and from the HFC element to the CM. This value is computed based on the length of the fiber and coax cables and the speed of propagation in each.
- *t-hfc-us-p-1:* Upstream path delay introduced by the fiber and coax cables going from the CMTS to the CM. This value includes the upstream path delay from the CM to the HFC element and from the HFC element to the CMTS. This is computed based on the length of the fiber and coax cables and the speed of propagation in each.

Note that there is no "-1" parameter for the HFC offset because the HFC offset parameter is independent of the coax and fiber lengths between the CMTS and the CM.

With the above values recorded, the following is obtained from formulas (9) and (10):

(11) t-tro-1 = t-hfc-ds-o + t-hfc-ds-p-1 + t-hfc-us-o + t-hfc-us-p-1 + (t-tro-R – t-hfc-ds-p-R – t-hfc-us-p-R)

(12) t-cm-adj-1 = t-hfc-ds-o + t-hfc-ds-p-1 + (t-cm-adj-R – t-hfc-ds-p-R)

Rearranging the terms in formula (11), we get:

(13) t-hfc-ds-o + t-hfc-us-o = t-tro-1 - t-hfc-ds-p-1 - t-hfc-us-p-1 - (t-tro-R - t-hfc-ds-p-R - t-hfc-us-p-R)

Rearranging the terms in formula (12), we get:

(14) t-hfc-ds-o = t-cm-adj-1 - t-hfc-ds-p-1 - (t-cm-adj-R - t-hfc-ds-p-R)

Plugging formula (14) into formula (13), we get

(15) t-cm-adj-1 - t-hfc-ds-p-1 - (t-cm-adj-R – t-hfc-ds-p-R) + t-hfc-us-o = t-tro-1 - t-hfc-ds-p-1 - t-hfc-us-p-1 - (t-tro-R - t-hfc-ds-p-R - t-hfc-us-p-R)

Now, simplifying formula (15), we get:

(16) t-hfc-us-o = (t-tro-1 - t-hfc-us-p-1) - (t-cm-adj-1 - t-cm-adj-R) - (t-tro-R - t-hfc-us-p-R)

The most important aspect of formulas (14) and (16) is that on the left-hand side of each we have the HFC offset parameters, and on the right-hand side we have values that were either obtained from the reference-length plant (the "-R" values), or measured/calculated in the plant with the added HFC elements (the "-1" values). Thus, we get a numeric value for the HFC offset timing values.

The second most important aspect of the above results is that the values obtained for the HFC offset timing values can later be used with any other CMTS-CM pair different from the ones used for the reference-length plant.

Note that if there are multiple HFC elements, then the values of *t-hfc-ds-o* and *t-hfc-us-o* should reflect the addition of the timing parameters of each HFC element.

An operator wanting to use DTP should have all its HFC elements characterized from a DTP point of view. Not doing such characterization would eat away from the overall time error budget allocated to the DOCSIS network. Alternatively, a rough characterization might work as there may be enough margin in the time error budget, or the length of the fiber plant dominates the overall time error and negates small changes on the coax plant. So, the difference in calibration may be the difference between a good result and a great result. Is good, good enough? It depends on the result and the cost.

6.3. Computing the DTP Time Adjustment in a live DOCSIS system

Now that we have the CMTS-CM pair and HFC elements characterized, we can use those values to compute the DTP time adjustment in a live system.

Note: The variables *t-hfc-ds-o* and *t-hfc-us-o* are chosen to model both fixed delays and any path asymmetry between the upstream and downstream HFC transmission paths. This allows the assumption to be made that the remaining path delay from the hfc downstream path and the hfc upstream paths are equal. Hence, *t-hfc-us-p = t-hfc-ds-p*.

Updating formula (9) based on *t-hfc-us-p = t-hfc-ds-p*, we get:

(17) t-tro = t-hfc-ds-o + t-hfc-ds-p + t-hfc-us-o + t-hfc-ds-p + (t-tro-R – t-hfc-ds-p-R – t-hfc-us-p-R)

*(18) t-tro = t-hfc-ds-o + 2*t-hfc-ds-p + t-hfc-us-o + (t-tro-R – t-hfc-ds-p-R – t-hfc-us-p-R)*

Rearranging the terms in formula (18), we get *t-hfc-ds-p*:

(19) t-hfc-ds-p = [t-tro – t-hfc-ds-o – t-hfc-us-o – (t-tro-R – t-hfc-ds-p-R – t-hfc-us-p-R)]/2

Plugging formula (19) into formula (10), we get:

(20) t-cm-adj = t-hfc-ds-o + [t-tro – t-hfc-ds-o – t-hfc-us-o – (t-tro-R – t-hfc-ds-p-R – t-hfc-us-p-R)]/2+ (t-cm-adj-R – t-hfc-ds-p-R)

Distributing the denominator and signs, we get:

(21) *t-cm-adj = t-hfc-ds-o + t-tro/2 – t-hfc-ds-o/2 – t-hfc-us-o/2 – t-tro-R/2 + t-hfc-ds-p-R/2 + t-hfc-us-p-R/2 + t-cm-adj-R – t-hfc-ds-p-R*

Re-arranging and grouping like terms

(22) *t-cm-adj = t-cm-adj-R + t-tro/2 – t-tro-R/2 + t-hfc-ds-o – t-hfc-ds-o/2 – t-hfc-us-o/2 – t-hfc-ds-p-R + t-hfc-ds-p-R/2 + t-hfc-us-p-R/2*

Subtracting like terms

(23) *t-cm-adj = t-cm-adj-R + t-tro/2 – t-tro-R/2 + t-hfc-ds-o/2 – t-hfc-us-o/2 – t-hfc-ds-p-R/2 + t-hfc-us-p-R/2*

Further assuming that *t-hfc-ds-p-R = t-hfc-us-p-R*, we get

(24) *t-cm-adj = t-cm-adj-R + t-tro/2 – t-tro-R/2 + t-hfc-ds-o/2 – t-hfc-us-o/2 – t-hfc-us-p-R/2 + t-hfc-us-p-R/2*
(25) *t-cm-adj = t-cm-adj-R + t-tro/2 – t-tro-R/2 + t-hfc-ds-o/2 – t-hfc-us-o/2*

Now, pulling the denominator back out and group terms for usability, we end up with the final formula for t-cm-adj

(26) *t-cm-adj = t-cm-adj-R +[(t-tro – t-tro-R) + (t-hfc-ds-o – t-hfc-us-o)]/2*

The most important aspect is that the only element on the right-hand side that was not a pre-calibrated numeric value is the TRO (*t-tro*) of the live system. The second important aspect that the formula hints at is that the DTP master, which is the entity computing the DTP time adjustment (*t-cm-adj*) should know what HFC parameters to use. In other words, some entity, e.g., the DTP master, should have an association between the CM and the HFC elements between the such CM and the CMTS. With this association, then the right HFC timing values could be recovered.

7. Requirements, Limitations and other aspects

In this section, we capture requirements, limitations, and tradeoffs related to the use of DTP.

7.1. Requirements

DTP relies on the true ranging offset (TRO), which is itself related to the ranging offset. As such, for the proper operation of DTP, the CM must have properly ranged. Moreover, the DTP message exchange should be repeated at least every time that the ranging offset changes.

The accuracy of DTP relies on the accuracy of the DOCSIS extended timestamp, which is obtained by the CM from an OFDM primary downstream channel. Thus, for the proper operation of DTP, the system must have an OFDM primary downstream channel. From the CM side, not only D3.1 support is needed but also DTP support (since its support is optional), and PTP support on its CMCI interface.

7.2. Limitations

The focus of DTP is on providing the CM with the appropriate time adjustment to be synchronized to an external time reference. However, what protocols such as PTP also provide is traceability information of the timing source and the path to the timing source. DTP does not provide this traceability. Rather than making DTP aware of PTP-specifics, the SYNC committee decided to let the PTP traceability information be sent from the CMTS (acting as a boundary clock) to the CM (acting as a boundary clock). DTP does not need to modify the traceability information, but DOCSIS does need to transport it..

As discussed in Section 6, the calibration of the DTP timing values must be done jointly for the CMTS and the CM, and must take into account any configuration values, such as interleaving, that affects those timing values. The output of this calibration will be two-fold: a list of timing values per CMTS-CM pair and per configuration, and a list of timing values per HFC element per configuration. The industry can choose one of these two approaches to carry out the calibration efforts:

a) Let every MSO, CMTS, or CM vendor build its own calibration facilities and perform its own calibration measurements, or
b) Have a central entity, such as CableLabs®, be the one in charge of setting the calibration facilities and performing the calibration measurements.

It is the opinion of the authors that the first approach will be initially used by the CM and CMTS vendors releasing DTP support. However, for scalability and consistency purposes, it is the opinion of the authors that the second approach is better.

The I01 version of the SYNC specification was released on April 20, 2020. It includes a robust description of the overall system and its operation when the external timing sources are using PTP profile G.8275.1. The support for G.8275.2 is work in progress and expected to be added in a future release; this works includes the allocation of time error budget for the network elements and the definition of the transport mechanism for the PTP Announce and Signaling messages.

While the SYNC specification is not completed yet for G.8275.2, there is nothing preventing DTP to be tested in a network using G.8275.2 for the purposes of measuring the overall time error; the caveat is that the traceability information would not be available at the CM. In other words, DTP itself is agnostic to the PTP profile being used by the CMTS or the CM themselves.

7.3. Other aspects

The SYNC specification not only deals with the details of DTP, but also with the suggested allocation of the time error budget for the elements in the network. As discussed in Section 3, the DOCSIS network elements need part of the overall time error budget, but cannot be allocated all of it.

Each MSO needs to characterize the performance of their existing networks (from a time error point of view), including its non-DOCSIS elements, to validate if their existing networks can meet the total timing requirements or not. MSOs may find out that they need to upgrade parts of their networks, DOCSIS or non-DOCSIS elements, to meet the timing requirements.

For DTP to work effectively, the recovery of the DTP values by the DOCSIS system must be automated. As mentioned in Section 6.3, the DOCSIS system not only needs to recover the timing values of the CMTS-CM pair, but identify the HFC elements between the CMTS and CM to then recover the timing values for those HFC elements.

8. What's next?

In this section, we highlight the next steps for the industry to drive the adoption and use of DTP.

Key to the adoption of DTP is the calibration of the CMTS/RPD/RMD-CM pairs and the HFC elements. With these calibration values collected, a repository where this data is store needs to be established. CableLabs® is uniquely positioned to be the lead in this calibration initiative.

Having the calibration data available, DOCSIS systems need to introduce automated mechanisms to recover the DTP calibration data of the CMTS-CM pairs, identify the HFC elements between the CMTS-CM pair, and recover the DTP calibration data of those HFC elements.

In parallel, test equipment vendors need to build calibration tools to allow the calibration of CMTS, CM, and HFC elements separately from each other to simplify adoption of DTP.

9. Conclusions

The I01 version of the SYNC spec, released on April 20, 2020 describes how to build and deploy an IEEE 1588/PTP participant DOCSIS network. The SYNC specification is targeted at the new and evolving mobile backhaul market, if the DOCSIS system has the required throughput, latency, and timing.

The authors in [2] described how to achieve low latency backhaul over DOCSIS. In terms of timing, the DOCSIS system is already based upon highly precise timing. DTP leverages this asset to provide accurate timing to end applications connected through a CM. Rather than run NTP or PTP over-to-the-top, the DOCSIS system can be used as-is to generate or correct these timing protocols with a very high degree of precision.

Abbreviations

CM	Cable modem
CMCI	CM to CPE interface
CMTS	Cable modem termination system
CoMP	Coordinated Multi Point operation
DOCSIS	Data-Over-Cable Service Interface Specification
DTP	DOCSIS Time Protocol
DS	downstream
eICIC	enhanced inter-cell interference coordination
eNB	Evolved Node B
FDD	Frequency-Division Duplex
GM	Grandmaster
GNSS	Global Navigation Satellite System
HetNet	heterogeneous network
HFC	hybrid-fiber/coax
LTE	Long Term Evolution
MNO	mobile network operator
MSO	Multiple Systems Operator
MULPI	MAC and Upper Layer Protocols Interface
NTP	network time protocol
OFDM	Orthogonal Frequency Division Multiplexing
OTT	over-the-top

PHY	physical
PLL	Phase-Locked Loop
PTP	Precision Time Protocol
RAN	radio access network
RMD	Remote MACPHY Device
RPD	Remote PHY Device
TDD	Remote PHY Device
TRO	true ranging offset
TWTT	Two-Way Time Transfer
UE	user equipment
US	upstream

Bibliography & References

[1] J. T. Chapman, "The DOCSIS Timing Protocol (DTP)," in *SCTE Spring Technical Forum*, 2011.

[2] J. T. Chapman and J. Andreoli-Fang, "Mobile Backhaul over DOCSIS," in *SCTE*, Denver, 2017.

[3] Cable Televsion Laboratories, Inc., "Data-Over-Cable Service Interface Specifications; Synchronization Techniques for DOCSIS® Technology," 2020.

[4] Cable Television Laboratories, Inc., "Data-Over-Cable Service Interface Specifications; MAC and Upper Layer Protocols Interface," 2020.

[5] J. Andreoli-Fang, J. T. Chapman, T. Liu and D. Poltz, "Blueprint for Mobile Xhaul over DOCSIS," in *SCTE Fall Technical Forum*, 2019.

[6] J. Andreoli-Fang and J. T. Chapman, "Synchronization for Mobile Backhaul over DOCSIS," in *SCTE Fall Technical Forum*, 2017.