DOCSIS® Time Protocol Proof of Concept Phase II Results

A Technical Paper prepared for SCTE by

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1. Introduction

1.1 What Is DTP?

Mobile networks require high accuracy time and frequency synchronization. 3GPP mandates 1.5 µs of timing accuracy from the base stations (BSs) to a common time reference [1]. Meeting this 1.5 µs target avoids inter-base station interference in time-division duplex (TDD) networks. In addition, inter-network synchronization is required by the FCC for Citizens Broadband Radio Service (CBRS) and is recommended for other bands. In outdoor environments, Global Positioning System (GPS) signals are reliable and can be used to derive an accurate timing signal. However, when BSs are deployed indoors where GPS signals are unreliable, BSs need an accurate timing signal delivered over the backhaul link. DOCSIS Time Protocol (DTP) is designed to provide such a high-accuracy synchronization signal on the Hybrid Fiber Coaxial (HFC) network, serving as the Xhaul (Xhaul refers to backhaul, mid-haul, or fronthaul) for mobile networks.
Figure 1 shows a DOCSIS network as mobile backhaul and DTP as the timing source for a 5G New Radio (NR) or 4G Long-Term Evolution (LTE) base station. The CMTS gets timing signals from the Primary Reference Time Clock (PRTC) using the Precision Time Protocol (PTP), also known as the IEEE 1588 Standard. PTP cannot be directly used on an HFC network (see the reason in Section 3.2). The HFC network (CMTS, remote-PHY device (RPD)/remote-MAC-PHY device (RMD), amplifiers (A) and cable modem (CM)) uses DTP instead. The CM delivers PTP timestamps to BSs using PTP, which BSs widely support. Note that the terminology of PTP/DTP master/slave was used in the IEEE 1588 standards and the DOCSIS specifications. The IEEE 1588 working group is considering using more inclusive language: PTP timeTx and PTP timeRx to replace master and slave, respectively, and we use this new terminology in this paper.

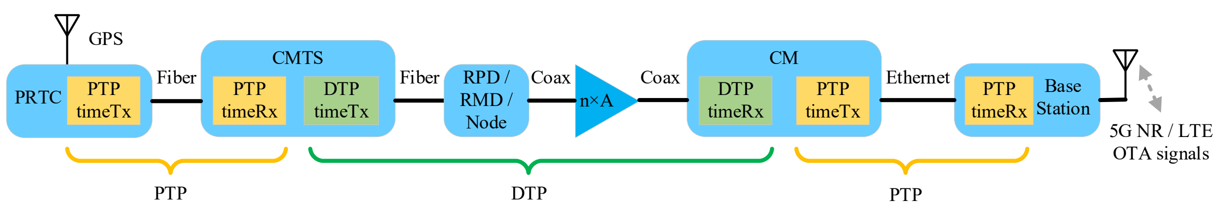

Figure 1 – DTP supports 5G NR/LTE in the field.

1.2 Where Is DTP Needed?

Table 1. Mobile Network Timing Sources.

Timing sources	Accuracy	Applications
NTP	tens of ms	Not usable for BS
PTP	< 1.5 µs	Widely supported by LTE/NR BS, PTP OTT on the HFC network performs poorly
GPS	a few ns	For outdoor BS
DTP	< 1.5 µs	***Fills the gap!***

Table 1 lists potential timing sources for mobile networks. The Network Time Protocol (NTP) accuracy is in the order of tens of milliseconds, which does not meet the 3GPP requirements.

PTP over-the-top (OTT) on the HFC network performs poorly. GPS signal is unreliable in indoor or urban canyon environments. Multi-Service Operators (MSOs) are interested in deploying indoor small-cell networks using HFC as backhaul, for which DTP is the only option, as summarized in Figure 2.

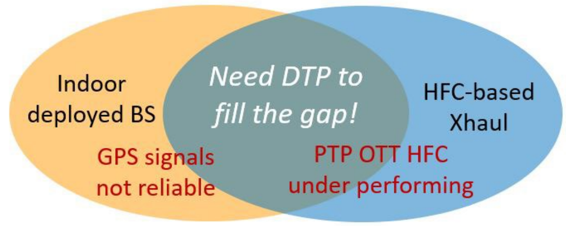

Figure 2 – Where Is DTP Needed?

1.3 How Does DTP Work?

The CMTS, RPD/RMD, and CM all have their local timestamp. The task for DTP is to synchronize these local timestamps. As illustrated in Figure 3, the CMTS and RPD/RMD have a fiber connection, hence, they use PTP to update their local timestamp. The RPD maps its local timestamp into the DOCSIS 3.1 timestamp that is transferred to the CM via the coaxial plant. The DOCSIS 3.1 timestamp is delayed in the downstream path. The DOCSIS ranging procedure measures the round-trip delay between RPD and CM. This round-trip delay is defined as the true ranging offset (TRO). If the downstream and upstream delays in the cable plant are the same (ideally symmetrical), half of TRO is applied to correct the downstream delay for the CM local timestamp. The CM maps its local timestamp to a PTP timestamp output for mobile networks. The DTP timeTx in the CMTS and the DTP timeRx in the CM exchange messages that include parameters of the HFC plant. The DTP timeRx also reports the real-time TRO to the DTP timeTx. The CMTS uses half of TRO and other parameters to calculate the time adjustment, *t-adj*, that is applied in the CM.

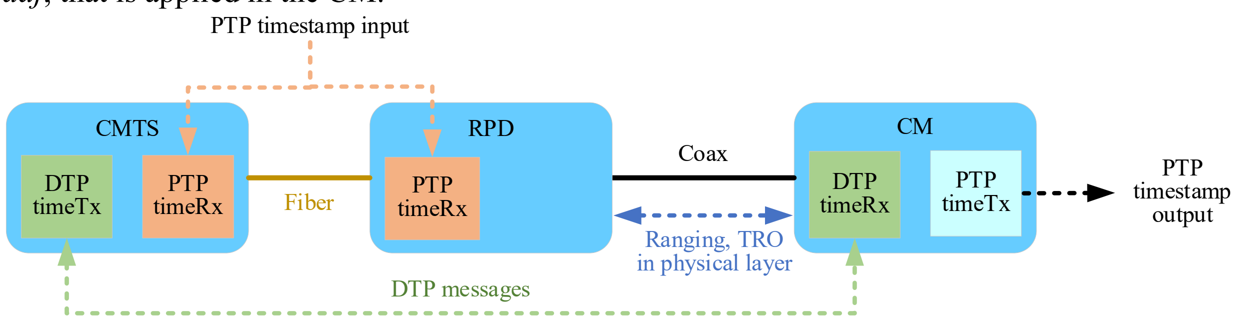

Figure 3 – How Does DTP Work?

DTP has many challenges, such as the asymmetrical delay in the HFC plant (the downstream and upstream delays in the cable plant are different, so half of the TRO cannot perfectly compensate the downstream delay), as well as some non-ideal effects in the CMTS, RPD/RMD and CM devices. A three-step DTP calibration procedure (see Section 7 in [8]) is needed to address these challenges.

1.4 DTP History and Status

DTP was invented in 2011 [2], standardized in the DOCSIS MULPI 3.1 Specification [3], and further incorporated in the DOCSIS SYNC specification [4] in 2020. DTP leverages existing DOCSIS hardware-based timestamp, accounts for path asymmetry, and provides timing performance independent of the traffic load on the DOCSIS network. DTP is being implemented in the industry. From September 2020, CableLabs, Charter Communications, Cisco, and Hitron started DTP proof-of-concept (PoC) tests. A DTP calibration procedure was designed to correct asymmetrical and other non-ideal delays in the HFC network. In December 2021, CableLabs/Kyrio developed a cloud database [5] that distributes the calibration data. The DOCSIS SYNC spec [4] was updated on July 15th, 2022, to describe the DTP calibration procedure and define the interface between the cloud database and CMTS.

1.5 DTP PoC Testing

The PoC testing was split into two phases. Phase I tests were conducted in a basic lab environment, and the results were published in an SCTE 2021 paper [5] and a CableLabs Technical Report [7]. This paper presents the phase II testing results. This second phase evaluates DTP performance in a complex environment similar to a field deployment with different downstream and upstream traffic load levels and fiber and coaxial cable lengths with multiple amplifiers. Phase II testing also considered HFC physical layer configurations such as modulation, interleaver, and cyclic prefix (CP) in the downstream orthogonal frequency-division multiplexing (OFDM) channel. In the upstream orthogonal frequency-division multiple access (OFDMA) channel, Phase II testing considered modulation, frame size, and CP. DTP PoC testing demonstrated that DTP could successfully deliver accurate timing information to end applications. TDD mobile networks successfully met the 3GPP timing accuracy specifications using DTP on the backhaul.

While working on the DTP PoC phase 1 and phase 2 testing, the group made many other contributions including designing the DTP cloud database [5], and updating the DOCSIS SYNC Specification [4].

2. DTP PoC Phase II Test Plan and Configuration

The DTP PoC phase 2 testing was conducted in Q3 and Q4 of 2021. This paper summarizes the key observations. More details are presented in [8].

2.1 Test Plan

The DTP PoC phase 2 testing aims to evaluate the DTP performance in a complex field environment. The cases listed in Table 2 cover most of the cases for MSOs' field deployment scenarios. We firstly confirmed that PTP over-the-top of HFC networks performs poorly. Then we tested DTP with different levels of traffic load in both downstream (DS) and upstream (US), fiber and cable lengths, number of amplifiers, and with different HFC network configurations at the CMTS.

The second column in Table 2 contains the baseline values that define the default test case, in which the traffic load, fiber and coax cable length and number of amplifiers are set the minimum value in our lab, and the CM and CMTS configurations capture the most commonly used values

by MSOs. Columns 3 and 4 contain comparative and extreme values that may or may not often be used in field deployments. Each case only changes one value from the default case.
Several factors limit the phase 2 testing: (1) the CMTS serves as the DTP timeTx and the CM serves as timeRx (the SYNC spec also supports the CM serving as the DTP timeTx and the CMTS serving as the DTP timeRx); (2) the test bed uses the distributed access architecture (DAA) with RPD; (3) the primary upstream channel is the OFDMA channel instead of the single carrier quadrature amplitude modulation (SC-QAM) channel (SC-QAM channel has a different TRO, etc.); (4) assumes 4k fast Fourier transform (FFT) size in the US OFDMA channel and 8k FFT size in the DS OFDM channel; (5) assumes the DS OFDM channel has a flat profile; (6) PTP multicast was used between the CM and the Paragon-X and PTP unicast was used between the Paragon-X (or PRTC) and the CMTS & RPD.

Table 2. DTP PoC Phase II Test Plan [8].

Parameters		Baseline test value	Comparative test values	Extreme values (optional test)	Note
DS load impact on PTP over the top		0	25%, 50%	75%, 100%	
US load impact on PTP over the top		0	25%, 50%	75%, 100%	
DS load impact on DTP		0	25%, 50%	75%, 100%	
US load impact on DTP		0	25%, 50%	75%, 100%	
Fiber length (NCS to RPD)		90 m	5 m, 25 km		
Coax length (RPD to CM)		3 m	244 m (800 ft) 591 m (1938 ft) 835 m (2738 ft)		
Number of amplifiers		0	1, 2, 3, 4, 5		
CM configs (US)	Frame size	$K = 6$	$K = 18$, BW < 48 MHz		Assume 4k FFT size. K is number of symbols in a frame
	OFDMA modulation	256-QAM	64-QAM	1024-QAM	1024-QAM only in a clean environment with no noise
	CP	6: 256 samples	4: 192 samples		
CMTS configs (DS)	Interleaver	2	1	16	Assume 8k FFT size
	Modulation	4096-QAM	1024-QAM, 256-QAM		Assume flat profile
	CP	1 (1.25 µs, 256 samples)	2 (2.5 µs, 512 samples)	3.75 µs (768 samples), 5 µs (samples), and 0.94 µs (192 samples)	

In addition to Table 2, we also tested three cases:

- Impact of the Cisco Network Convergence System (NCS) boundary clock (BC), see Section 3.7.
- The upstream OFDMA channel frequency range, which impacts the group delay, see Section 3.8.

2.2 Test Configuration

The lab test configuration is shown in Figure 4. Because there is no solution that can measure DTP performance directly, we used the Paragon-X to measure the PTP time error (TE) between the input of the CMTS/RPD and the output of the CM. The PTP timeTx in the Paragon-X is connected to the Cisco NCS 55A1-24Q6H-SS that serves as a PTP BC, which provide the PTP timing source for both the integrated CMTS (I-CMTS) and RPD. The I-CMTS is the Cisco cBR-8 with software version 16.12.z1. The RPD is the Cisco SmartPHY 120 with software version v7.8.2. The CM is the Hitron ODIN1112 with software version ODIN-724GA-7.2.4.0.152 that uses MaxLinear's Puma 7 solution.

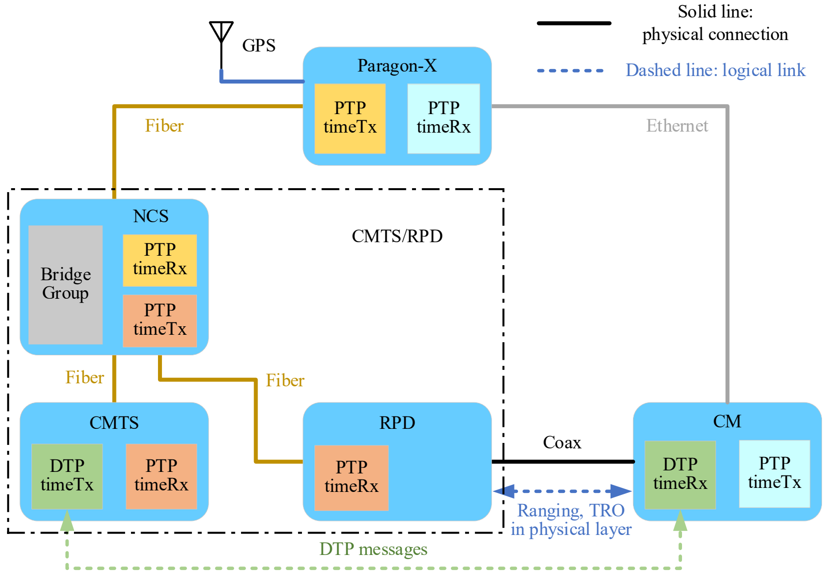

Figure 4 – DTP PoC Testing Lab Configuration.

3. DTP PoC Phase II Results and Observations

3.1 Default Case

The default case uses the baseline values listed in Table 2. Calibration was done before doing the PoC testing, as reported in Section 5.2 in [8]. Each of the phase 2 cases were run five times. Each run was one hour long. The TRO was captured on the CM before and after the run. The Paragon-X generated many statisics of the time error. In this paper we only focus on the constant TE and dynamic TE. The Paragon-X compares the PTP timestamp sent from its timeTx to the HFC network and the PTP timestamp received by its timeRx from the HFC network. The constant TE is the difference (time error) averaged over one hour and five runs. The dynamic TE is the maximum variation of the TE over a 1000 second moving window in each run, then averaged over five runs.

The default case results are provided in Table 3. The time error budget for this DAA scenario is 980 ns, see Table 4 in [7]. The time error has an average value of -35 ns and variation of up to 214 ns, which meet the 980 ns requirement.

Table 3. Default Case Results.

Case Index	Case	Average TRO (ns)	Constant TE (ns)	Dynamic TE (ns)
1	Default Setting	5,315,965	-35	214

Observation 1: DTP will work. The default test case with baseline configurations met the DTP time error budget.

3.2 PTP Over-The-Top

In this case, DTP is not running in the HFC network. PTP messages are over-the-top traffic in the HFC network. Thus, PTP messages are impacted by HFC queueing. Upstream PTP messages go through a DOCSIS upstream service flow configured with a best-effort scheduling service. Case 2 in Table 4 does not have any traffic load. The constant TE is over 3 ms. The TE varies over 4 ms. Both the constant TE and dynamic TE are multiple orders larger than the 3GPP requirement of 1.5 µs.

Two other CMs and a tap were added after the RPD, see Figure 5 in [8]. The two CMs are controlled by a load tester (ByteBlower) to create a certain amount of traffic load either downstream or upstream. Cases 3 to 6 are with DS load from 25% to 100%, and cases 7-10 are with US load from 25%-100%. The constant TE and dynamic TE for all these cases do not meet the 3GPP requirement.

Table 4. PTP Over-The-Top Results.

Case Index	Case	TRO (ns)	Constant TE (ns)	Dynamic TE (ns)
2	No load	5,315,925	3,012,010	4,440,810
3	25% DS load	5,315,925	3,026,168	4,273,112
4	50% DS load	5,315,929	3,017,390	3,656,898
5	75% DS load	5,315,929	3,008,489	3,845,175
6	100% DS load	5,315,929	735,443	6,074,600
7	25% US load	5,315,929	3,173,979	5,383,784
8	50% US load	5,315,929	3,459,314	6,052,003
9	75% US load	5,315,917	3,807,350	5,559,820
10	100% US load	5,315,917	4,672,663	7,603,164

Observation 2: PTP over-the-top does not meet the 3GPP requirement. The dynamic TE is on the order of milliseconds with or without traffic load. The cTE changes with different levels of downstream and upstream load by multiple milliseconds.

3.3 Load Testing

Three CMs share the same channels. Two CMs generate 25% to 100% traffic load in either DS or US. The other CM runs DTP. The results are presented in Table 5. Because DTP messages are designed to be a control message, and the DOCSIS 3.1 timestamp is transferred on the physical layer link channel (PLC), neither the constant TE nor dynamic TE is impacted by HFC network traffic.

Table 5. Load Testing Results.

Case Index	Case	TRO (ns)	Constant TE (ns)	Dynamic TE (ns)
11	25% DS load	5,315,933	-58	216
12	50% DS load	5,315,933	-53	219
13	75% DS load	5,315,925	-64	215
14	100% DS load	5,315,988	-33	222
15	25% US load	5,315,941	-48	212
16	50% US load	5,315,941	-36	208
17	75% US load	5,315,996	-28	225
18	100% US load	5,315,996	-21	189

Observation 3: Neither the DS nor the US traffic load impacts the DTP performance.

3.4 Fiber and Coaxial Cable Length

The fiber length between the NCS and the RPD in the default case is approximately 90 m. Cases 19 and 20 change the fiber length to 25 km and 5 m. The TE is not impacted by the fiber length, see Table 6. Ranging and TRO between the RPD and the CM are also not impacted by the fiber length in such a DAA-RPD architecture.

Table 6. Fiber and Coaxial Cable Length Results.

Case Index	Case	TRO (ns)	Constant TE (ns)	Dynamic TE (ns)
19	25 km fiber	5,315,901	-42	223
20	5 m fiber	5,315,984	-15	215
21	244 m coaxial + 1 Amp	5,318,125	49	223
22	591 m coaxial + 3 Amps	5,320,750	185	237
23	835 m coaxial + 5 Amps	5,323,038	194	224

Observation 4: Fiber length in the DAA-RPD architecture does not impact DTP, nor does it impact TRO.

The coaxial cable length from the RPD to the CM in the default case is approximately 3 m. We replaced it with 244, 591, or 835 m long cables. To compensate high attenuation, multiple amplifiers need to be used. The TE changes slightly from the default case to cases 21-23, which is not due to the asymmetrical TE introduced by amplifiers but instead due to impact from the long cable. The TRO increases with cable length correspondingly to compensate for the additional delay introduced by the long cable.
The delay of the 244 m cable is also measured by a Vector Network Analyzer (VNA); see Table 7. The DS delay at 591 MHz is 1004 ns and the US delay at 32 MHz is 1005 ns, which are almost the same.

Observation 5: Cable length does not impact DTP. VNA measurements indicate that coaxial cable does not introduce any asymmetrical delay. The additional round-trip delay from cable length is symmetrical, and the corresponding TE is well compensated by the TRO, which is verified in the DTP measurements.

3.5 Amplifiers

The constant TE for cases 21-23 in Table 6 are slightly different. We designed cases 24-27 to further check if the additional constant TE is due to the cable length or amplifiers. Cases 24-27 use the same cable length of 3 m, but change the number of amplifiers (from QDAX) from one to four. Each of the amplifiers introduce additional TE from 38 to 83 (case 1 vs. case 24) ns with an average of 54 ns, see Table 8. The VNA measurements for the QDAX amplifiers are listed in Table 7. The QDAX amplifiers have a large asymmetrical delay between DS and US, which introduces an additional TE of 36-40 ns per amplifier. The additional TRO and TE are in the same range with the DTP results. The 591 m cable plant is built with three Arris amplifiers. The Arris amplifiers also have a large asymmetrical TE that introduce additional TE of approximately 27 ns per amplifier.

Table 7. Amplifiers: VNA Results.

VNA Measurements	QDAX Amplifier					591 m hardline cable + 3 Arris Amps	244 m RG-6 Cable
	#1	#2	#3	#4	#5		
DS delay D_{DS}' (ns)	6.3	6.3	6.3	6.4	6.4	2278	1004
US delay D_{US}' (ns)	81.5	79	80.9	81.3	86	2442	1005

Additional TE (D_{US}' - D_{DS}')/2 (ns)	38	36	37	37	40	82	0.5
Additional TRO D_{US}' + D_{DS}' (ns)	88	85	87	92	92	4720	2009

Table 8. Amplifiers: DTP Results.

Case Index	Case	TRO (ns)	Constant TE (ns)	Dynamic TE (ns)
24	3 m coaxial + 1 Amp	5,316,160	48	218
25	3 m coaxial + 2 Amps	5,316,250	101	215
26	3 m coaxial + 3 Amps	5,316,394	139	229
27	3 m coaxial + 4 Amps	5,316,480	182	217

The additional TE from amplifiers varies in the field. The MSOs need to consider this factor in the field DTP deployment. If a large number of amplifiers is used, the TE from other network elements will need to be reduced in order to meet the entire TE budget. For example, a higher class of CMTS or CM with better quality and smaller TE may be used. An alternative solution is to reduce number of cascading boundary clocks used in the DTP network. These solutions are suggested in Section 8.4.2.5 in the SYNC spec [4].

Observation 6: Amplifiers introduce an asymmetrical delay in the HFC plant and additional TE to DTP. The additional TE varies with amplifier make and model. The QDAX amplifier has an additional TE of 36–40 ns that is accurately characterized by the VNA. Such additional TE from each QDAX amplifier is, on average, 54 ns measured in the DTP testbed.

3.6 HFC Configurations

The baseline value for the US frame size is 6 symbols per frame, the US modulation is 256-QAM and the US CP is 256 samples. The US frame size is changed to 18 symbols per frame in case 28. The US modulation is changed to 64-QAM and 1024-QAM in cases 29 and 30. The US CP is changed to 192 samples in case 31. The results are provided in Table 9. The TE is not impacted by these US configurations.

Observation 7: HFC upstream network configurations of frame size, modulation scheme, and cyclic prefix do not impact DTP performance.

Table 9. HFC Configurations Results.

Case Index	Case	TRO (ns)	Constant TE (ns)	Dynamic TE (ns)
28	US frame size: 18	5,315,965	-32	212
29	US mod: 64-QAM	5,315,925	-50	221
30	US mod: 1024-QAM	5,315,933	-48	227
31	US CP: 192	5,315,941	-48	215
32	DS Interleaver: 1	5,315,968	-33	226
33	DS Interleaver: 16	5,315,992	-30	224
34	DS mod: 1024 for data 256 for control	5,315,965	-44	209
35	DS mod: 256 for data 64 for control	5,315,972	-29	225
36	DS CP: 192	5,276,152	19,898	211
37	DS CP: 512	5,475,554	-79,820	230
38	DS CP: 768	5,635,687	-159,914	228
39	DS CP: 1024	5,795,644	-239,959	221

The default case uses DS interleaver depth of 2 and DS modulation of 4096-QAM for data and 1024-QAM for the control channel. Cases 32 and 33 compare the DS interleaver depth of 1 and 16. Cases 34 and 35 compare DS modulation of 1024-QAM for data and 256-QAM for the control channel, and 256-

QAM for data and 64-QAM for the control channel, respectively. The TE is not impacted by the DS interleaver and modulation.

Observation 8: HFC downstream interleaver depth and modulation scheme do not impact DTP performance.

The baseline value of DS CP is 256 samples. Cases 36-39 compare DS CP values of 192, 512, 768 and 1024 samples. Both the constant TE and TRO are impacted significantly by the DS CP. This is likely due to a frame alignment issue at the CM. MaxLinear and Hitron are working on fixing the frame alignment issue. Before this issue is fixed, an alternative method is to have DTP devices calibrated for each individual DS CP value to compensate the impact.

Observation 9: The downstream cyclic prefix significantly impacts DTP. Every 1.25-µs CP length reduces cTE by approximately 80 µs. As of August 2022, this issue is being investigated by the CM vendor and chipset vendor.

3.7 NCS Boundary Clock

The PTP timeTx in the Paragon-X is connected to the PTP timeRx in the NCS, and the PTP timeTx in the NCS is connected to the PTP timeRx in the Paragon-X directly to evaluate the performance of the NCS as a boundary clock. The NCS employs a class B boundary clock with a theoretical TE of 20 ns. The measured TE is listed in Table 10. The constant TE ranges from -8 to 1 ns with an average of -3 ns. The dynamic TE is 15 ns.

Observation 10: The NCS class B boundary clock TE is between -8 and 1 ns, which is smaller than the 20-ns TE budget defined in the SYNC spec [4].

Table 10. NCS Boundary Clock Results.

Case Index	Case	Constant TE (ns)	Dynamic TE (ns)
40	NCS	-3	15

3.8 Upstream OFDMA Channel Frequency

Diplexers, amplifiers, and filters have frequency dependent group delay, which may impact DTP performance. A plant with five cascade diplexers is used to verify if the upstream OFDMA channel frequency may impact DTP. The diplexers have an upper cutoff frequency of 42 MHz. The group delay from 5 to 45 MHz for the five-cascade-diplexer plant is measured by a VNA. As shown in Figure 5, the blue curve is the group delay over frequency, which increases gradually from 115 ns at 5 MHz to 375 ns at 42 MHz, then increases dramatically after 42 MHz. Two US OFDMA channels are selected for the comparative analysis that are on the two edges of the diplexer frequency range: (1) 5-17 MHz (green box in Figure 5); and (2) 31-42 MHz (red box in Figure 5). The average group delay in the 5-17 MHz channel is 128 ns, and in the 31-42 MHz channel 241 ns. In comparison between these two channels, the impact on TRO is 113 ns, and the impact on TE is 56.5 ns (half of TRO).

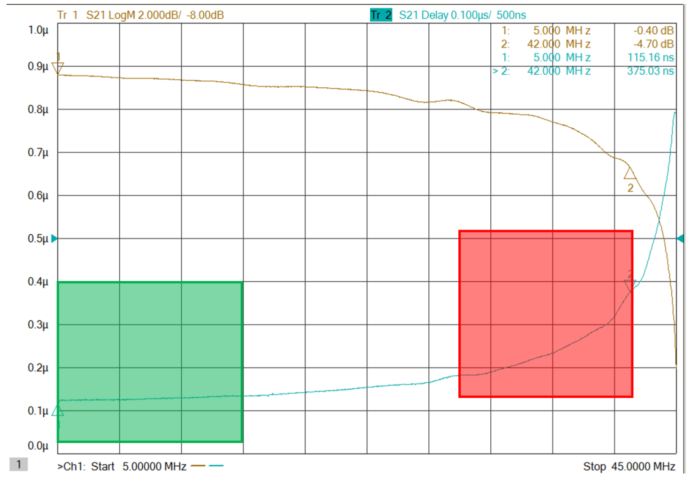

Figure 5 – VNA Measured Group Delay for a Five Diplexers Plant.

This five-diplexer plant is plugged into the DTP test bed to replace the coaxial cable shown in Figure 4. The DTP measurement results are provided in Table 11. The TRO increased by 99 ns between 5-17 MHz and 31-42 MHz channels, and the constant TE increased 49 ns between the two channels. The DTP results confirmed that the group delay and US OFDMA channel frequency does impact DTP.

Observation 11: The US OFDMA channel frequency does impact DTP depending on the group delay variation over frequency.

Table 11. US OFDMA Channel Frequency Results.

	DTP Results		VNA Results	
	TRO (ns)	Constant TE (ns)	Impact on TRO (ns)	Impact on constant TE (ns)
5-17 MHz vs. 31-42 MHz	99	49	113	56.5

4. Conclusion

DTP provides an accurate timing source for mobile networks. DTP is particularly helpful for the scenarios where the GPS signal is unreliable (e.g., indoor) and the HFC network is used for mobile backhaul, where over-the-top PTP performs poorly. The PoC testing proved DTP meets the 3GPP requirement of 1.5 µs. A three-step DTP calibration procedure is required to correct non-ideal effects in the CMTS, RPD/RMD, and CM devices. Here are the observations from the PoC phase 2 testing:

Observation 1: DTP will work. The default test case with baseline configurations met the DTP time error budget.

Observation 2: PTP over-the-top does not meet the 3GPP requirement. The dynamic TE is on the order of milliseconds with or without traffic load. The cTE changes with different levels of downstream and upstream load by multiple milliseconds.

Observation 3: Neither the DS nor the US traffic load impacts the DTP performance.

Observation 4: Fiber length in the DAA-RPD architecture does not impact DTP, nor does it impact TRO.

Observation 5: Cable length does not impact DTP. VNA measurements indicate that coaxial cable does not introduce any asymmetrical delay. The additional round-trip delay from cable length is symmetrical, and the corresponding TE is well compensated by the TRO, which is verified in the DTP measurements.

Observation 6: Amplifiers introduce an asymmetrical delay in the HFC plant and additional TE to DTP. The additional TE varies with amplifier make and model. The QDAX amplifier has an additional TE of 36–40 ns that is accurately characterized by the VNA. Such additional TE from each QDAX amplifier is, on average, 54 ns measured in the DTP testbed.

Observation 7: HFC upstream network configurations of frame size, modulation scheme, and cyclic prefix do not impact DTP performance.

Observation 8: HFC downstream interleaver depth and modulation scheme do not impact DTP performance.

Observation 9: The downstream cyclic prefix significantly impacts DTP. Every 1.25-µs CP length reduces cTE by approximately 80 µs. As of August 2022, this issue is being investigated by the CM vendor and chipset vendor.

Observation 10: The NCS class B boundary clock TE is between -8 and 1 ns, which is smaller than the 20-ns TE budget defined in the SYNC spec [4].

Observation 11: The US OFDMA channel frequency does impact DTP depending on the group delay variation over frequency.

4.1 Suggestions for MSOs

A three-step DTP calibration procedure is required to guarantee DTP performance. The calibration test needs to be done for each pair of CMTS/RPD/RMD and CM devices. The calibration test needs to be repeated for each of the key software releases of these devices. The calibration data will be distributed by a cloud database. The CMTS will query the calibration data and apply them in the field.

DTP performance is impacted by amplifiers, diplexers, and filters, as well as the number of boundary clocks in the field plant. Each amplifier may introduce 36-40 ns additional TE to DTP due to the asymmetrical TE. When multiple amplifiers are used for a DTP CM, in order to meet the entire TE budget, a higher class (with smaller time error) of CMTS or CM may be needed, or a smaller number of boundary clocks may need to be considered [4].

The upstream channel frequency may impact DTP depending on the number of diplexers, amplifiers and filters, which change the group delay over frequency. In the case that the group delay in the upstream varies significantly over frequency, consider using the portion of the channel closest to the center of the upstream band in order to stay clear of the expected delay variation/increase at the band edges [4]. For example, the band edge frequency above 42 MHz should be avoided for the specific HFC network discussed in Section 3.8.

Abbreviations

3GPP	3rd Generation Partnership Project
A	Amplifier
BC	Boundary clock
BS	Base station
CBRS	Citizens Broadband Radio Service
CM	Cable modem

CP	Cyclic prefix
cTE	Constant time error
DAA	Distributed access architecture
DS	downstream
DTP	DOCSIS time protocol
FCC	Federal Communications Commission
FFT	Fast Fourier transform
GPS	Global Positioning System
HFC	Hybrid fiber coaxial
I-CMTS	Integrated cable modem termination system
LTE	Long-term evolution
MSO	Multi-Service Operator
NCS	Network Convergence System
NR	New radio
NTP	Network time protocol
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal frequency-division multiple access
PoC	Proof of concept
PTP	Precision time protocol, also known as IEEE 1588
PLC	Physical-layer link channel
PRTC	Primary Reference Time Clock
QAM	Quadrature amplitude modulation
RMD	Remote-MAC-PHY device
RPD	Remote-PHY device
SC-QAM	Single carrier quadrature amplitude modulation
SCTE	Society of Cable Telecommunications Engineers
TDD	Time division duplexing
TE	Time error
TRO	True ranging offset
US	upstream
VNA	Vector Network Analyzer

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