DOCSIS Time Protocol Proof of Concept

A Technical Paper prepared for SCTE by

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1. Introduction

Demand for broadband services continues to grow. While wireline access technologies have supported traditional broadband services, a significant amount of broadband traffic is supported by wireless access technologies. Multiple System Operators (MSOs) have deployed Data-Over-Cable Service Interface Specification (DOCSIS) networks for many years to provide wireline broadband access for their customers. Because of the increasing demand for wireless broadband access, MSO interest has grown in deploying and backhauling their own 5G wireless access networks using their existing DOCSIS infrastructure.

Radio access technologies such as the fifth generation (5G) New Radio (NR) require accurate alignment in frequency, phase, and time of day to minimize interference and improve efficiency. Several MSOs have recently acquired Citizen Broadband Radio Service (CBRS) spectrum licenses to deploy time division duplex (TDD) 5G base stations (BSs). 3rd Generation Partnership Project (3GPP) standards specify a time difference of no more than 3 µs between cells which requires timing accuracy to be within 1.5 µs of a Primary Reference Time Clock (PRTC) [1].

Outdoor base station antennas can be oriented to be line-of-sight with Global Positioning System (GPS) satellites for the reception of timing signals. If line-of-sight cannot be achieved, as in the case of indoor base stations (e.g., Femtocells), an alternative timing source with 1.5 µs accuracy is required. IEEE 1588 Precision Time Protocol (PTP) [2] can provide this level of accuracy.

PTP was developed and specified frequency and phase synchronization across Ethernet transmission links using timestamps to address latency and jitter issues. PTP enables Ethernet-based networks to be used as backhaul links for 3GPP Long-Term Evolution (LTE) and 5G systems. However, PTP was not designed for DOCSIS networks.

When DOCSIS is lightly loaded, it is possible to support PTP "over-the-top" of DOCSIS [3]. However, DOCSIS was not designed to support highly accurate PTP "over-the-top". Therefore, a highly loaded DOCSIS system will not be able to support PTP to the accuracy levels required by TDD 5G base stations without the use of DOCSIS Time Protocol (DTP). DTP was introduced in DOCSIS 3.1 to reliably support PTP on DOCSIS networks.

DTP, invented by Cisco [4] and included in CableLabs DOCSIS specifications [5] and [6], enables DOCSIS networks to deliver PTP to wireless base stations. DTP establishes PTP-to-DOCSIS interfaces at the Cable Modem Termination System (CMTS) and at the Cable Modem (CM). DTP allows the timing and frequency system of the CMTS, the Hybrid Fiber Coax (HFC) plant and the CM to be a timing bridge. DTP accurately takes the PTP timing source at the input of the CMTS, and replicates it at the output of the CM with the correct timing offsets to take into account all the delays through the DOCSIS system. Figure 1 shows PTP and DTP operating on a DOCSIS system. Components of a generalized DOCSIS system are shown in green.

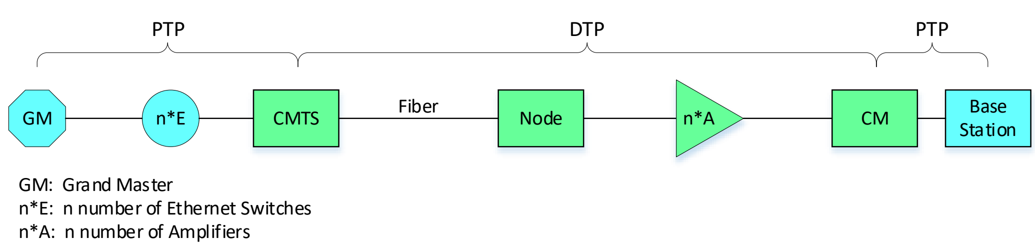

Figure 1 - PTP and DTP on an Integrated CMTS Architecture

The DTP protocol runs between the CMTS and the CM. The CMTS receives a PTP timestamp on a PTP slave port and synchronizes its internal clock to that timestamp. The CMTS synchronizes all DOCSIS timestamps to this internal clock, making the DOCSIS timestamp traceable to a PTP timestamp. The CMTS uses the ranging capabilities of DOCSIS, and delays through the CMTS and CM, to calculate timing offsets for an accurate PTP timestamp at the CM. The CM then regenerates PTP and sends it to the BS.

Many vendor companies have developed or are developing solutions that support DTP. Support for DTP is planned for the Cisco CMTS (cBR-8), and remote PHY device (RPD) products in a future software release (targeted for 2022). In January 2021, Hitron launched the ODIN-1112, the world's first DOCSIS 3.1 modem to support DTP. The ODIN-1112 supports operating as either a DTP master or a DTP slave. By pairing the ODIN-1112 with a small cell gateway, cable operators can leverage their existing DOCSIS networks to offer 4G/5G services. Hitron is dedicated to helping cable operators capture new opportunities in 5G and will continue expanding its product portfolio to enable not only outdoor but also indoor small cell deployments.

CableLabs, Charter Communications, Cisco and Hitron initiated proof-of-concept (PoC) testing for DTP in Q2 2020. This paper presents the DTP PoC test plan, methodology and up-to-date status.

2. DTP PoC Test Plan

DTP PoC testing started in September 2020 at both CableLabs and Charter. Cisco also conducted tests in their lab. The DTP PoC testing has three phases. Phase 1 evaluates the DTP time error in a lab environment with minimum fiber and coaxial cable length, without amplifiers, without traffic load, etc. The CM synced with DTP is plugged into an LTE base station to test the wireless signal time accuracy over the air (OTA). We also verified three manual calibration methods that allow changing the true ranging offset (TRO) or DTP time adjustment in the CMTS and the CM. The time error (TE) for all test scenarios and cases is compared with the DTP time error budget as defined in [5]-[9]. Phase 1 testing concluded in July 2021. The phase 1 methodology, setup, and results are reported in [9].

Phase 2 is designed to evaluate DTP performance in sophisticated configurations that are representative of anticipated field deployments. Different downstream (DS) and upstream (US) loads will be added to the

Table 1 - Phase 2 Test Plan

Parameter		Baseline test value	Comparative test values	Extreme value (optional test)
DS load		0	25%, 50%	75%
US load		0	25%, 50%	75%
Coax length (R-PHY to CM)		a few meters	1/4 and 1 mile	
Fiber length (Router to R-PHY)		tens of meters	25 km	
Number of amplifiers		0	1, 2	
CMTS config change (DS)	Interleaver	2	1	16
	Modulation	4096-QAM	1024-QAM, 256-QAM	
	Cyclic prefix	1 (1.25 μs, 256 samples)	2 (2.5 μs, 512 samples)	3 (3.75 μs, 768 samples)
CM config change (US)	Frame size	K = 6	K = 9, BW ≥ 72 MHz K = 18, BW < 48 MHz	
	OFDMA modulation	256-QAM	64-QAM	1024-QAM
	Cyclic prefix	6: 256 samples	4: 192 samples	

HFC plant to assess DTP and PTP performance. The coaxial cable and fiber length and number of amplifiers will be adjusted to determine DTP performance. The impact of HFC network configurations will be evaluated. These configurations include: DS interleaver, modulation and cyclic prefix, US frame size, modulation, and cyclic prefix. The phase 2 test plan is summarized in Table 1. For each parameter, a set of baseline, comparative, and extreme test values is defined. The extreme values are optional for phase 2 testing. Only one parameter will be changed for each test case to reduce the number of network configuration combinations. Phase 2 testing is planned for Q3 and Q4 2021.

The DOCSIS 3.1 timestamp transmitted from the CMTS to the CM is delayed while propagating downstream through the HFC network. DTP is designed to calibrate the DOCSIS 3.1 timestamp by using the TRO. DTP automatically compensates for the symmetrical (identical in DS and US) time error in the HFC network. However, the CMTS, RPD, and CM could introduce asymmetrical time errors that reduce the time accuracy of DTP. If pre-calibrated asymmetry values are known, DTP also compensates for asymmetrical time errors. Such asymmetrical time errors need to be measured in the lab before deployment for each combination of CMTS, RPD, and CM hardware and software versions. CableLabs/Kyrio established a Network Timing Lab to conduct these kinds of tests and collect data to calibrate the asymmetrical time error. This calibration data will be distributed by an Amazon Web Service (AWS) cloud server to enable the CMTS to calibrate the asymmetrical time error in the field automatically. The AWS cloud server design is presented in [10]. Once the AWS cloud server is developed and the corresponding automatic calibration feature is added to the CMTS, phase 3 tests will be started to validate the concept of this feature.

3. DTP Performance

3.1. Test Setup

The measurement setup for DTP performance testing is illustrated in Figure 2. Because there is no time measurement equipment available that supports DTP, DTP performance is measured between the input PTP timestamp to the CMTS and the output PTP timestamp of the CM. The Calnex Paragon-X is used to measure the DTP performance. Port 1 (PTP master) on the Paragon-X is connected to the Cisco integrated CMTS (I-CMTS) cBR-8 using PTP. The cBR-8 is connected to a Network Convergence System (NCS) router and a Cisco RPD via fiber. The RPD connects to the Hitron ODIN-1112 CM via a coaxial cable.

DTP is used between the cBR-8 and the CM. The CM is connected to port 2 (PTP slave) on the Paragon-X using PTP. The Paragon-X uses GPS and a Rubidium (Rb) clock to calibrate frequency. The Paragon-X compares the PTP timestamp received on port 2 against the timestamp generated by port 1.

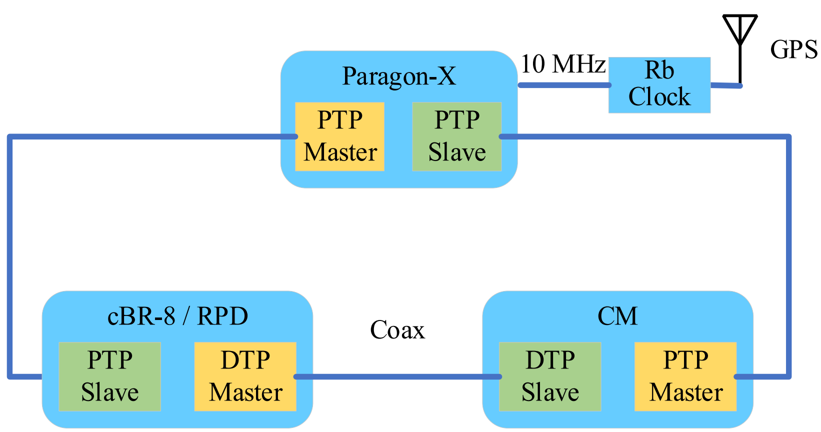

Figure 2 - Block Diagram of DTP Performance Test Setup [9]

The measurement accuracy of the Paragon-X is ±5 ns. CableLabs verified the performance of the Paragon-X before the DTP performance test. The method and results are reported in [9].

3.2. Time Error Budget

3GPP technical specifications 36.133 [1] and 38.133 require LTE and 5G NR base stations to have phase synchronization better than 3 µs between BSs. It indicates that each BS must have synchronization better than 1.5 µs. PTP (IEEE 1588) and ITU-T G. 8271 require a synchronization better than 1.5 µs.

The DTP TE budget for a typical Distributed Access Architecture (DAA) scenario is provided in Table 2, along with the TE budget calculated for the actual DTP test setup with an RPD used in the PoC testing. The clock used in the Paragon-X is compared with a delayed version of itself, so the PRTC does not apply. The test setup only uses one Class B boundary clock (BC) in the NCS. The total “Ethernet and Dynamic Aspects of Ethernet TE Budget” is 470 ns in total. The RPD is Class A. No node or amplifier is used. Hence, the “DOCSIS Network TE Budget” is 510 ns. A base station is not included in this test setup. The total TE budget is 980 ns which is much smaller than the required 1500 ns in PTP and 3GPP specifications. The DTP performance TE test results will be compared with this 980 ns TE budget as a pass/fail criteria.

Table 2 - DOCSIS and HFC TE Profile for the DTP Performance Test Setup with RPD [9]

Budget Component	DAA			DTP test setup		
	n	@	TE	n	@	TE
PRTC *(Class A is 100 ns, Class B is 40 ns, ePRTC is 30 ns)*	Class A		100	Class A		0
Network holdover and PTP rearrangements			200			200
Network dynamic TE and SyncE rearrangements			200			200
T-BC *(Class A is 50 ns, Class B is 20 ns)*	4	50	200	0	A@50	0
T-BC *(Class C is 10 ns, Class D is 5 ns)*				1	B@20	20
Link asymmetry			50			50
Ethernet and Dynamic Aspects of Ethernet TE Budget			**750**			**470**
I-CMTS/RPD/RMD *(Class A is 200 ns, Class B is 100 ns)*	Class A		200	Class A		200
DTP			50			50
HFC path			10	DAA		10
HFC node			10	DAA		0
HFC amp/LE	N+3	10	30	N+0	10	0
CM *(Class A is 250 ns, Class B is 100 ns)*	Class A		250	Class A		250
DOCSIS Network TE Budget			**550**			**510**
Rearrangements and short holdover in the end application			0			0
Base station slave or intra-site distribution	Class A		50	Class A		0
Base station RF interface			150			0
Base Station Network TE Budget			**200**			**0**
Total TE Budget			**1500**			**980**

3.3. Phase 1 Test Results

DTP performance tests were conducted in CableLabs, Charter, and Cisco. The testbeds used an upstream Orthogonal Frequency-Division Multiple Access (OFDMA) channel. DTP is manually calibrated by setting the TRO at the CM to compensate the asymmetrical constant TE. Five runs of data were collected at CableLabs, five were collected at Charter, and one was collected at Cisco. Each test is set to either 1076 s, one hour or three hours. The results are summarized in Table 3.

Many TE statistical results were analyzed by the Paragon-X including two-way time error, constant time error (cTE), which is the average two-way TE, maximum and minimum two-way time error, dynamic TE (dTE), maximum time interval error (MTIE) and time Allan deviation (TDEV). Descriptions of these concepts and results were presented in [9]. In this paper, we only focus on the most important parameters, as listed in Table 3.

The results show that the cTE is smaller than 31 ns. The max TE and min TE results are within ±200 ns, which meet the 980 ns TE budget requirement discussed in subsection 3.2. The only exception is run 4 in the Charter testbed. A PTP Delay_Response message in run 4 arrived at the Paragon-X approximately 9 s later than expected. This was not observed in the other four runs in the Charter and CableLabs data and is likely a test anomaly that can be discarded.

Table 3 - Time Error Results with RPD [9]

All TE results unit in ns			Test setup with RPD				
			Two-way Time Error				Peak-to-peak dynamic TE
	Run	Time duration	Mean (cTE)	Max	Min	Max-Min	
CableLabs	1	3600 s	30	46	-47	163	157
	2	3600 s	13	146	-94	240	220
	3	3600 s	31	118	-47	165	144
	4	3600 s	21	138	-67	205	183
	5	3600 s	29	125	-81	206	190
Charter	1	3 hours	-29	97	-151	248	226
	2	3 hours	-30	102	-146	248	225
	3	3 hours	-19	110	-183	293	231
	4	3 hours	13607	9,404,370,078	-147	9,404,370,224	9,449,878,963
	5	3 hours	-26	115	-141	256	222
Cisco	1	1076 s	-20	121	-122	242	225

4. LTE Timing Performance Using DTP in Backhaul

Section 3 verified that DTP provides synchronization much more accurately in a lab environment than the required TE budget of 980 ns. In this section, DTP is used in mobile backhaul to check the LTE OTA signal time accuracy.

4.1. Test Setup

The test setup is illustrated in Figure 3. The grand master (GM) clock connected to a GPS receiver provides the PTP time source for the DOCSIS system. Both I-CMTS and DAA R-PHY architectures use PTP as an input timing source. In the I-CMTS architecture, the CMTS exchanges DTP messages with the CM. In the R-PHY architecture, the CMTS Core exchanges DTP messages with the CM. The CM uses DOCSIS 3.1 timestamps and DTP as its timing source, and provides a synchronization signal for LTE BS1 by PTP. We set up another LTE base station, BS2, that is synchronized to a GPS clock to compare

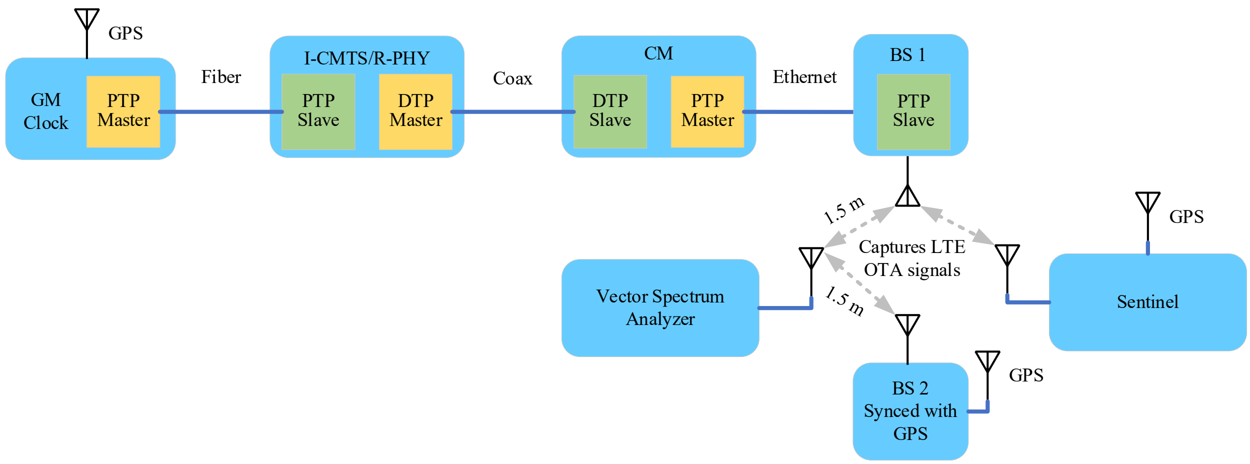

Figure 3 - Block Diagram of LTE OTA Setup

Table 4 - DOCSIS and HFC TE Profile for the LTE OTA Test Setup [9]

Budget Component	**VSA**			**Sentinel**		
	n	**@**	**TE**	**n**	**@**	**TE**
PRTC *(Class A is 100 ns, Class B is 40 ns, ePRTC is 30 ns)*	Class A		100	Class A		100
Network holdover and PTP rearrangements			200			200
Network dynamic TE and SyncE rearrangements			200			200
T-BC *(Class A is 50 ns, Class B is 20 ns)*	0	A@50	0	0	A@50	0
T-BC *(Class C is 10 ns, Class D is 5 ns)*	1	B@20	20	1	B@20	20
Link asymmetry			50			50
Ethernet and Dynamic Aspects of Ethernet TE Budget			570			570
I-CMTS/RPD/RMD *(Class A is 200 ns, Class B is 100 ns)*	Class A		200	Class A		200
DTP			50			50
HFC path	DAA		10	DAA		10
HFC node	DAA		0	DAA		0
HFC amp/LE	N+0	10	0	N+0	10	0
CM *(Class A is 250 ns, Class B is 100 ns)*	Class A		250	Class A		250
DOCSIS Network TE Budget			510			510
Rearrangements and short holdover in the end application			0			0
GPS receiver PRTC clock	1	A@100	100	0	A@100	0
Base station slave or intra-site distribution	2	A@50	100	1	A@50	50
Base station RF interface	2	150	300	1	150	150
Base Station Network TE Budget			500			200
Total TE Budget			1580			1280

with BS1. The two BSs radiate LTE signals over the air. The Calnex Sentinel collects the LTE primary synchronization signal (PSS), the secondary synchronization signal (SSS) and decodes the time of day from the BS1 LTE signal. The Sentinel uses GPS and an internal Rubidium clock as a reference to evaluate the accuracy of LTE timing. The measurement accuracy of the Sentinel is ±100 ns.

A vector spectrum analyzer (VSA) is used as another LTE OTA measurement method. It collects the spectrum of both BS1 and BS2, then converts them to the time domain by an inverse fast Fourier transform (IFFT). Thus, the downlink (DL) time-domain bursts in the TDD LTE signals can be compared. The VSA antenna is equal distance from both BS1 and BS2 antennas. By properly selecting the measurement bandwidth and fast Fourier transform (FFT) size, the VSA measurement accuracy achieved was on the order of tens of ns. The measurement accuracy of the VSA method is constrained by the LTE signal burst uncertainty due to the BS amplifier and local oscillator performance, which can be off by as much as 10 µs. BS1 and BS2 are the same model from the same manufacturer using the same hardware and software, so the relative uncertainty is much smaller than 10 µs. With the VSA method, it is straightforward to check the TDD-LTE signal bursts in the time domain, but it is not a high-accuracy method to judge if the LTE OTA signals meet the 3GPP synchronization requirement.

4.2. Time Error Budget

The TE budget for the LTE OTA setup is listed in Table 4. In comparison to the TE budget for the DTP performance test listed in Table 2, the LTE OTA setup includes extra TE budget for the PRTC and base station. The TE budget for BS1 is 200 ns, and for BS2 it is 300 ns. Since BS2 uses GPS, that introduces an additional 100 ns into the TE budget. Given that the VSA test compares the relative TE between BS1 and BS2, the total TE budget is 1580 ns which is smaller than the 3 µs (air to air) TE budget required by 3GPP specifications. The Sentinel only uses BS1. The total TE budget is 1280 ns which is smaller than the 1.5 µs (air to GPS) TE budget required by 3GPP specifications.

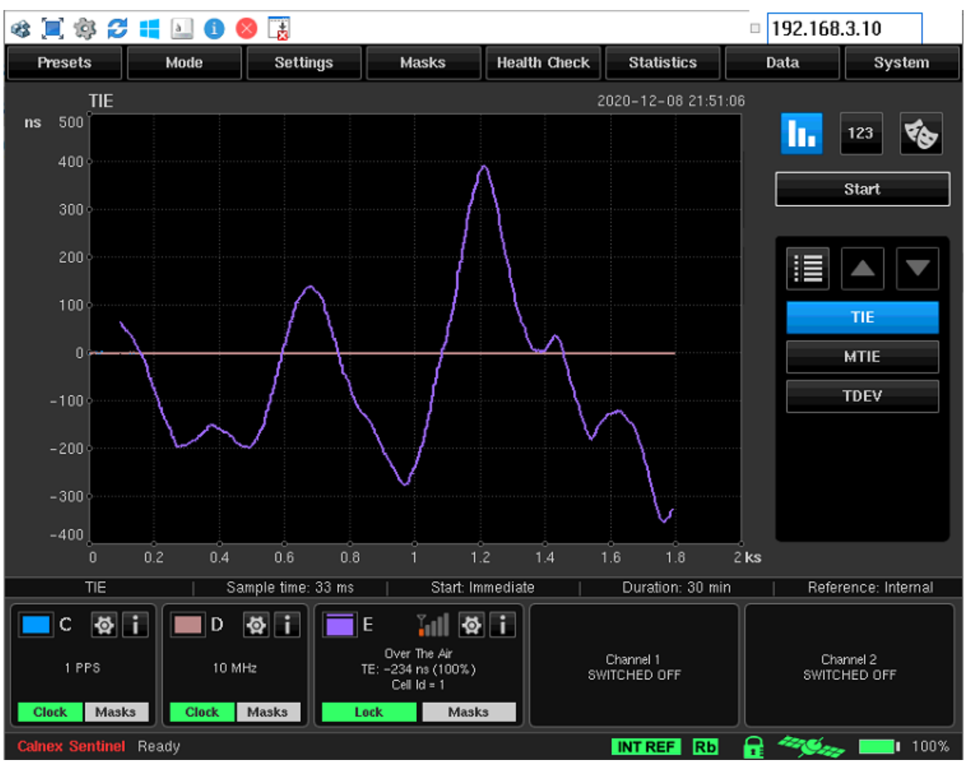

Figure 4 - RPD Sentinel OTA Measurements [9]

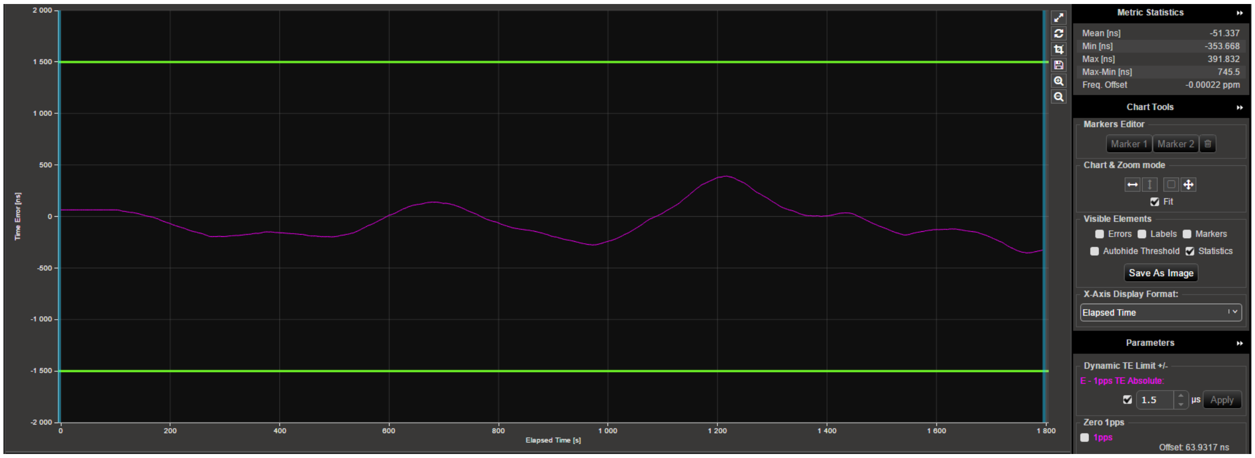

Figure 5 - Sentinel OTA Results [9]

4.1. Sentinel Measurements

The eNodeB (eNB), using DTP in the DOCSIS backhaul, radiates an LTE signal from 3620 to 3630 MHz with a cell ID of 1. Channel E on the Sentinel decodes the time of day on the LTE signal. This time of day is compared with the GPS time of day. Figure 4 shows an example of Sentinel measurement data. The OTA LTE signal TE varies from -354 to 392 ns, with a mean value of -51 ns. Figure 5 shows statistical results that are further processed by the Calnex Analysis Tool (CAT).

Five sets of Sentinel data were collected. Table 4 lists the results. The average LTE signal TE is between -71 and 9 ns. The largest peak-to-peak variation is 746 ns. All the TE results meet the ±1.5 µs 3GPP requirement.

Table 5 - Sentinel OTA Results Summary [9]

Run	Time duration (s)	Two-way Time Error (ns)			
		Mean (cTE)	Max	Min	Max-Min
1	1800	-51	392	-354	746
2	1800	-25	269	-255	524
3	1800	-41	186	-286	472
4	3600	9	159	-107	266
5	3600	-71	131	-332	463

4.2. VSA Measurements

The VSA measures LTE signals in the frequency domain and converts them into the time domain. To avoid mutual interference between the two LTE signals, the two BSs are configured on two separated channels: BS1 uses 3620-3630 MHz and BS2 uses 3690-3700 MHz. The VSA compares LTE signals from BS1 and BS2 in the time domain. As shown in Figure 6, the upper two subfigures (yellow and blue) are the frequency domain magnitude spectrum, and the lower two subfigures (green and red) are the time domain waveforms. The left side two subfigures (yellow and green) are BS1 signals using DTP in the backhaul, and the right side two subfigures (blue and red) are BS2 signals synced to GPS.

Both BS1 and BS2 employ LTE TDD configuration 2 and special subframe configuration 7. The subframe structure of TDD configuration 2 is provided in Figure 7, where D represents downlink, U represents uplink, and S means special subframe. The time duration of each subframe is 1 ms. The special

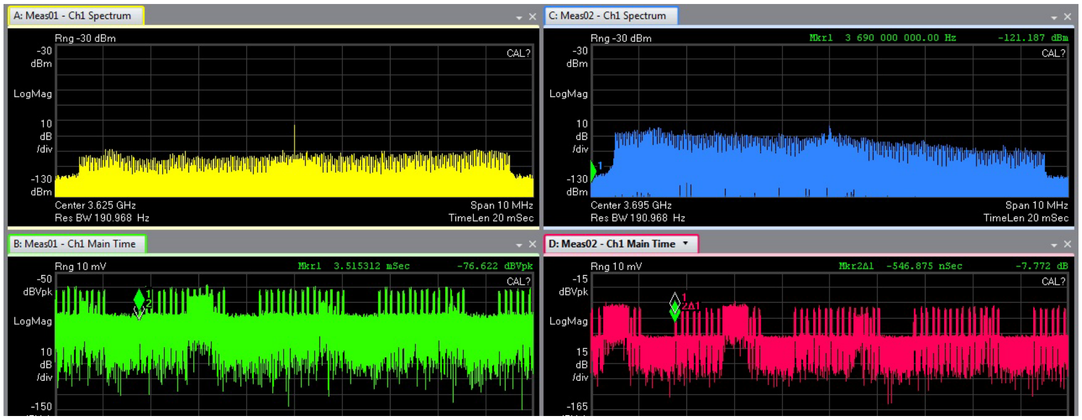

Figure 6 - VSA OTA Results [9]

Subframe number									
0	1	2	3	4	5	6	7	8	9
D	S	U	D	D	D	S	U	D	D

Figure 7 - LTE TDD Configuration 2 Subframe Structure

subframe consists of 14 symbols, where 10 symbols are allocated for the downlink in special subframe configuration 7. So each of the downlink signals should last $3\frac{10}{14}$ ms. There were no UEs in the lab, and no traffic in either the downlink or the uplink during the VSA OTA measurement. BSs only transmit reference signals and control channel information in downlink subframes.

The lower two subfigures in Figure 6 present bursts with a period of 5 ms, each group of bursts lasts for less than 4 ms, which agrees with theoretical TDD LTE downlink signals. Marker 1 is placed on the rising edge of the burst for the BS1 signal (green), and marker 2 is place on the rising edge of the burst for the BS2 signal (red). VSA syncs markers are placed in both channels so that they are comparable. "2Δ1" represents the time difference between markers 1 and 2. 2Δ1 is 529 ns. The relative time error between BS1 and BS2 LTE signals is 529 ns which is much smaller than the required TE budget of 1580 ns as listed in Table 3 and the 3 µs requirement in the 3GPP specifications.

5. Conclusion

DTP is designed to provide accurate synchronization for the backhaul of TDD mobile networks. DTP PoC testing was conducted by CableLabs, Charter, Cisco and Hitron. PoC testing was divided into three phases:

- Phase 1 validates that DTP works in a basic lab environment.
- Phase 2 evaluates DTP performance in sophisticated environments that mimic field deployments.
- Phase 3 verifies automatic DTP calibration in field deployments by using an AWS cloud server to distribute calibration data.

This paper reported up-to-date progress of DTP PoC testing, and key findings in phase 1 testing. The results successfully demonstrated that DTP works in a lab environment. The measured DTP time error results meet the time error budget. Using DTP and PTP in the backhaul, LTE over-the-air signals meet the 3GPP synchronization requirement. DTP is being evaluated in various HFC network configurations. An AWS cloud server is being developed to enable automated DTP calibration.

Abbreviations

3GPP	3rd Generation Partnership Project
5G	fifth generation
AWS	Amazon Web Service
BC	boundary clock
BS	base station
CAT	Calnex Analysis Tool
CBRS	Citizen Broadband Radio Service
CM	cable modem
CMTS	cable modem termination system
cTE	constant time error
DAA	distributed access architecture
DL	downlink
DOCSIS	Data-Over-Cable Service Interface Specification
DS	downstream
dTE	dynamic time error
DTP	DOCSIS Time Protocol
eNB	eNodeB (LTE base station)
FFT	fast Fourier transform
GM	grand master
GPS	Global Positioning System
HFC	hybrid fiber-coaxial
LTE	long-term evolution
I-CMTS	integrated cable modem termination system
IFFT	inverse fast Fourier transform
MSO	multiple-system operator
MTIE	maximum time internal error
NCS	Cisco Network Convergence System
NR	new radio
OFDMA	orthogonal frequency-division multiple access
OTA	over the air
PoC	Proof of concept
PRTC	primary reference time clock
PSS	primary synchronization signal
PTP	precision time protocol
QAM	quadrature amplitude modulation
Rb	Rubidium
RPD	remote physical layer device
R-PHY	remote physical RF layer
SSS	secondary synchronization signal
TDD	time division duplex
TDEV	time Allan deviation
TE	time error
TRO	true ranging offset
UE	user equipment
US	upstream
VSA	vector spectrum analyzer

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