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International Society of Broadband Experts

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From the Editors

Thank you for downloading SCTE·ISBE *Journal of Network Operations* V3 N2, a publication of collected papers by the Society of Cable Telecommunications Engineers (SCTE) and its global arm, the International Society of Broadband Experts (ISBE). In this issue, we continue our focus on DOCSIS 3.1 deployment and optimization for both typical hybrid fiber-coax (HFC) and radio frequency over glass (RFoG) networks. Plus, you'll find two papers on increasing intelligence and adaptability in the access network via next generation proactive network maintenance (PNM) and new dynamic operations support systems (OSS) that leverage software defined networking (SDN) and network functions virtualization (NFV). Finally, as we focus increasingly on business services over fiber, you'll get a review of the five most common mistakes in Ethernet installation for business customers and prevention strategies.

One way to optimize DOCSIS 3.1 deployments is to optimize the cyclic prefix (CP). In "OFDM Cyclic Prefix Elimination," you'll see how an FIR filter and an overlapped Fourier transform can produce the same frequency domain equalization result in DOCSIS 3.1 without the need for a CP and the concomitant overhead and reduced data capacity. But if you're planning to run DOCSIS 3.1 on an RFoG upstream using DOCSIS 3.1's orthogonal frequency division multiple access (OFDMA), then your CP length requirements may be driven more by RFoG laser settling requirements than by micro-reflections in the channel. If you have older RFoG equipment that is not SCTE-174 compliant, the CP may need to be even longer.

DOCSIS 3.1 also provides significant improvements in network measurement and visibility, which is especially important as we add more business customers using DOCSIS 3.1, and we're also adding many new business customers via fiber-to-the-premises (FTTP). We thus need tools that help us fix issues in both the RF and the IP components of the access network. In "Understanding the Limitations of Cable Modem-Based Upstream Interference Measurement," you'll hear how embedding the advanced measurement capabilities of DOCSIS 3.1 strategically in the access network itself will help to solve several key issues in network visibility, especially that of locating the source of upstream transient impairments. In "Common Ethernet Installation Mistakes and How to Avoid Them," you'll see how eliminating the RF altogether via FTTP doesn't make installation mistakes go away, they just morph into different issues that can be detected or prevented with a new generation of test sets.

Finally, service adaptation and reconfiguration is happening as the rule, not the exception in modern networks, so we need more automated and dynamic tools to allow us to configure and reconfigure services quickly and efficiently. New OSS tools are available that leverage the capabilities of SDN/NFV and automate procedures that used to require humans. In "Transforming Operations in a Dynamic SDN/NFV World," you'll get a preview of how this can be done architecturally and automatically using a data model-driven approach. Such an approach, especially when used uniformly across the network, will set the stage for even faster adaptation and evolution of the OSS and unlock the value that still exists within legacy deployments.

We would like to thank the individuals who contributed to this issue of the *Journal of Network Operations*, including the authors, reviewers, and the SCTE·ISBE publications and marketing staff. We hope you enjoy this issue and that the selected papers stimulate new ideas and innovations in cable network operation. If you have feedback on this issue, have a new idea, or would like to share a success story please reach out to us at journals@scte.org for consideration in an upcoming issue.

SCTE/ISBE *Journal of Network Operations* Senior Editors,

Ron Hranac

Technical Leader – Cable Access Business Unit, Cisco Systems, Inc.

SCTE Fellow

Daniel Howard

Director – Hitachi Energy and Environmental Efficiency, Hitachi Consulting Corp.

SCTE Senior Member

Choosing a DOCSIS® 3.1 Upstream Cyclic Prefix

Hybrid Fiber/Coax and RFoG Networks

A Technical Paper prepared for SCTE•ISBE by

Doug Jones, Principal Architect
CableLabs
SCTE/ISBE Member
858 Coal Creek Circle
Louisville, CO 80027
d.jones@cablelabs.com
+1 303.661.3326

Curtis Knittle, VP Wired
CableLabs
SCTE/ISBE Member
858 Coal Creek Circle
Louisville, CO 80027
c.knittle@cablelabs.com
+1 303.661.3851

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1. Introduction

Operators have already deployed the DOCSIS 3.1 downstream and soon will begin deploying the DOCSIS 3.1 upstream. Additionally, operators are building fiber-to-the-home (FTTH) networks for future use of passive optical networking (PON) though in the near term are planning to use radio frequency over glass (RFoG) technology on that FTTH network.

In an RFoG architecture, it is the DOCSIS 3.1 upstream that is impacted because RFoG technology operates in “burst-mode” in the upstream, using a separate piece of customer premises equipment (CPE) called an RFoG optical networking unit (R-ONU) with an upstream laser to transmit DOCSIS signals onto the FTTH network. Burst-mode means every time the DOCSIS modem transmits, the upstream R-ONU laser needs to turn on which takes a measurable amount of time. It is the turn-on time of the upstream R-ONU laser that impacts the configuration of the DOCSIS 3.1 upstream on an RFoG network. The DOCSIS 3.1 downstream operates with no modifications because RFoG technology is “always-on” in the downstream direction.

A key consideration in configuring the DOCSIS 3.1 upstream to work over either a hybrid fiber/coax (HFC) network or an RFoG network is the cyclic prefix (CP) which is introduced with DOCSIS 3.1 specifications. The CP can be thought of as a guard time to separate upstream burst transmissions from inter-symbol interference. With an HFC network, the duration of the CP is chosen to guard against the longest micro-reflection on the coax. With an RFoG network, the duration of the CP is chosen to activate and stabilize the R-ONU upstream laser.

It is this difference in use of the CP between HFC and RFoG networks that can lead to different DOCSIS 3.1 configurations depending on the type of network being used.

2. DOCSIS 3.1 Upstream and the Cyclic Prefix

DOCSIS PHYv3.1 specification [1] introduces orthogonal frequency division multiplexing (OFDM) for downstream signals and orthogonal frequency division multiple access (OFDMA) for upstream signals. OFDM and OFDMA are complimentary. OFDM is used in the downstream where there is one transmitter, the cable modem termination system (CMTS), sending information to multiple receivers, the cable modems (CMs). OFDMA is used in the upstream where there are multiple transmitters (cable modems) sending to one receiver (CMTS).

The CP is common to both OFDM and OFDMA. As shown in Figure 1, the CP can be thought of as a “guard time” that separates data bursts and allows any micro-reflection from one burst to die out before the next burst is transmitted, thereby eliminating interference from one transmission to the next. This is especially true on an HFC network where micro-reflections can exist.

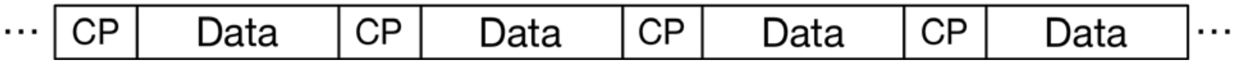

Figure 1 – Cyclic Prefix and Data

As shown in Figure 2, the CP is created by copying part of the data, specifically the end of the OFDMA inverse fast Fourier transform (IFFT) output, and then prepending that information to the beginning of the same IFFT output. The OFDMA symbol is the combination of CP and the corresponding IFFT output.

By prepending a copy of some of the data, the CP provides another function by simplifying the receiver. This explanation delves deep into digital signal processing. A quick way to convey it is that the cyclic extension of the prefix converts the linear convoluted channel to instead simulate a channel performing cyclic convolution, thus ensuring orthogonality and eliminating interference between OFDM/OFDMA subcarriers when the cyclic extension remains longer in duration than the micro-reflection of the channel [2].

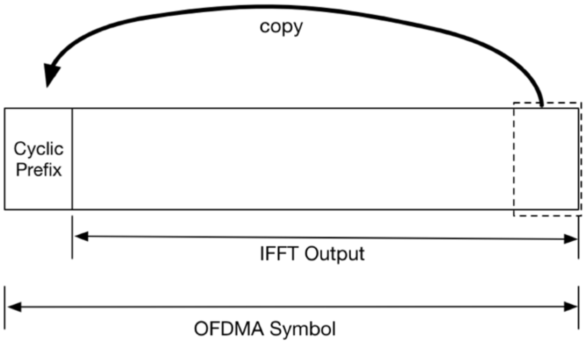

Figure 2 – Cyclic Prefix Construction

The DOCSIS 3.1 PHY specification describes the duration times for the upstream CP. These duration times are shown in Table 1.

Table 1 – DOCSIS 3.1 Upstream Cyclic Prefix Durations

Duration
0.9375 µs
1.2500 µs
1.5625 µs
1.8750 µs
2.1875 µs
2.5000 µs
2.8125 µs
3.1250 µs
3.7500 µs
5.0000 µs
6.2500 µs

3. Configuring DOCSIS 3.1 Upstream Cyclic Prefix on an HFC Network

Micro-reflections are created by impedance mismatches on the HFC network and can be for myriad reasons including manufacturing tolerances of passives, actives and connectors [3]. A micro-reflection falls into a class of impairments known as linear distortions, and can cause amplitude ripple (standing waves), group delay ripple, inter-symbol interference, and degraded modulation error ratio (MER) on digital signals transmitted on the HFC network.

Figure 3 shows a type of commonly experienced micro-reflection which happens when an upstream signal encounters an impedance mismatch somewhere in its upstream path to the CMTS, causing the redirection of a fraction of the signal's energy back towards the CM [4]. For this example, a seizure screw on the 23-tap is not tight enough and causes a slight impedance mismatch on the hardline. When a modem connected to the 17-tap transmits, the main signal (green) heads upstream and passes through the impedance mismatch at the 23-tap and continues toward the CMTS. However, that impedance mismatch causes a fraction of the upstream signal to be reflected (blue) back towards the modem. If this micro-reflection has enough energy, it would interfere with the next symbol from the modem; hence, the CP is used as a guard time to separate symbols to allow the micro-reflection to die out before that next symbol is transmitted.

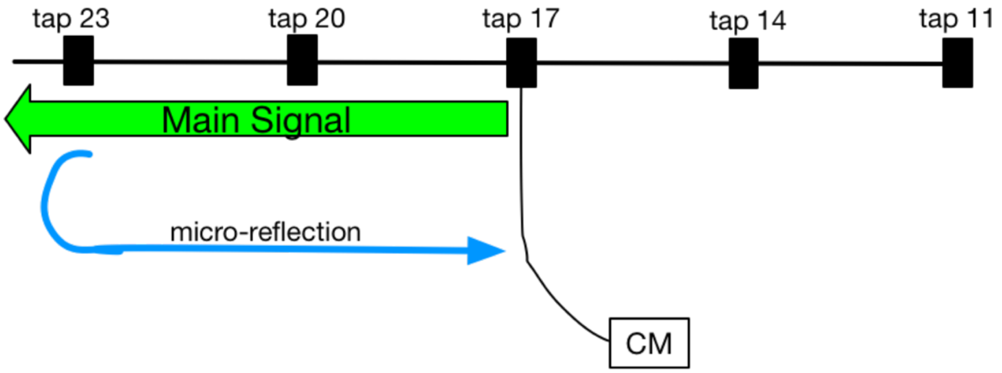

Figure 3 – HFC Micro-reflection

The velocity of propagation of the electrical signal on coax is approximately 87% of the free space value of the speed of light, which corresponds to 1.17 nanoseconds per foot [5]. If the drop is 100 feet long and the taps are spaced 100 feet apart, then the main signal travels 300 feet before hitting the impedance mismatch and then the micro-reflection goes back 300 feet (for a total of 600 feet of propagation) which calculates to about 700 nanoseconds before the micro-reflection gets back to the modem where the transmission originated. In this case, the cyclic prefix would need to be at least 700 nanoseconds in duration to protect against that micro-reflection. Note that a modem on the 11-tap might have an even longer micro-reflection due to that loose seizure screw on the 23 tap. A cable operator can use PNM techniques to analyze the cable modem pre-equalizer coefficients to determine the longest micro-reflection on a coax segment, and use this information to choose the duration of the CP accordingly [4].

As shown in Table 1, various durations of CP are allowed and are intended to accommodate a variety of lengths of HFC network. With the speed of propagation of an electrical signal in hardline coax approximately 1.17 nanoseconds per foot, and assuming a round trip of a micro-reflection, the longest duration CP of 6.25 µs equates to a one-way length of about 2,800 feet of coax. Note that longer networks are intended to still work as a micro-reflection will lose amplitude as it travels through the plant and micro-reflections on longer plants should not have enough energy to impact transmissions.

4. Configuring DOCSIS 3.1 Upstream Cyclic Prefix on an RFoG Network

Key characteristics about an RFoG solution include:

- Micro-reflections normally induced by impedance mismatches on the hardline coax are eliminated because there is no coax.
- The R-ONU detects traditional cable signals from in-home coax (cable modem, set-top boxes, etc.) and converts them to an optical signal for transmission over the FTTH network.
- Because the R-ONU operates in "burst-mode" on the upstream, RFoG has the added benefit of improved noise performance and increased usable RF spectrum in the upstream direction.
- Improved operational expenses; RFoG brings the benefits of a passive fiber topology. Removing active devices in the access network reduces overall power requirements, as well as ongoing maintenance costs that would normally be needed for active elements (such as nodes and amplifiers).
- RFoG operates over FTTH, and building FTTH now allows an operator to future-proof their network.

An example RFoG network is shown in Figure 4, showing how traditional cable television signals are carried over an FTTH network.

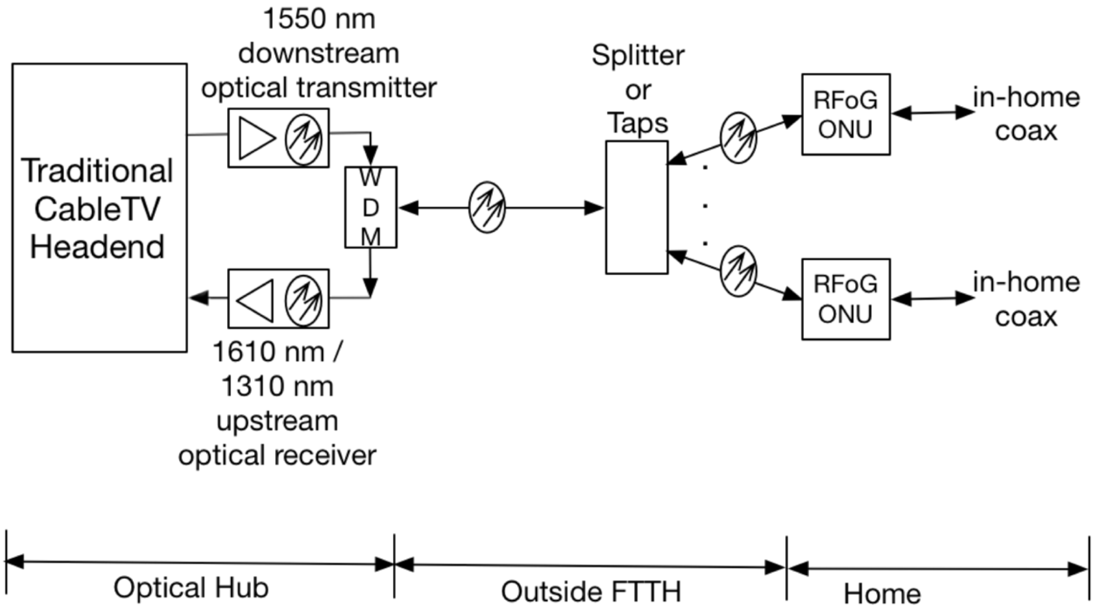

Figure 4 – Example RFoG Network

The R-ONU laser turn-on time is the key characteristic which impacts the DOCSIS 3.1 configuration. In the upstream, SCTE 174 [6] places requirements on these turn on and turn off characteristics as shown in Figure 5. According to this figure, when the R-ONU senses a burst of power on the in-home coax of at least +16 dBmV, the R-ONU must turn on its upstream laser within 1.3 µs and begin transmitting that signal onto the fiber. Correspondingly, the CP for an RFoG network should be on the order of 1.3 µs in duration to ensure the R-ONU laser has time to activate before transmitting customer data.

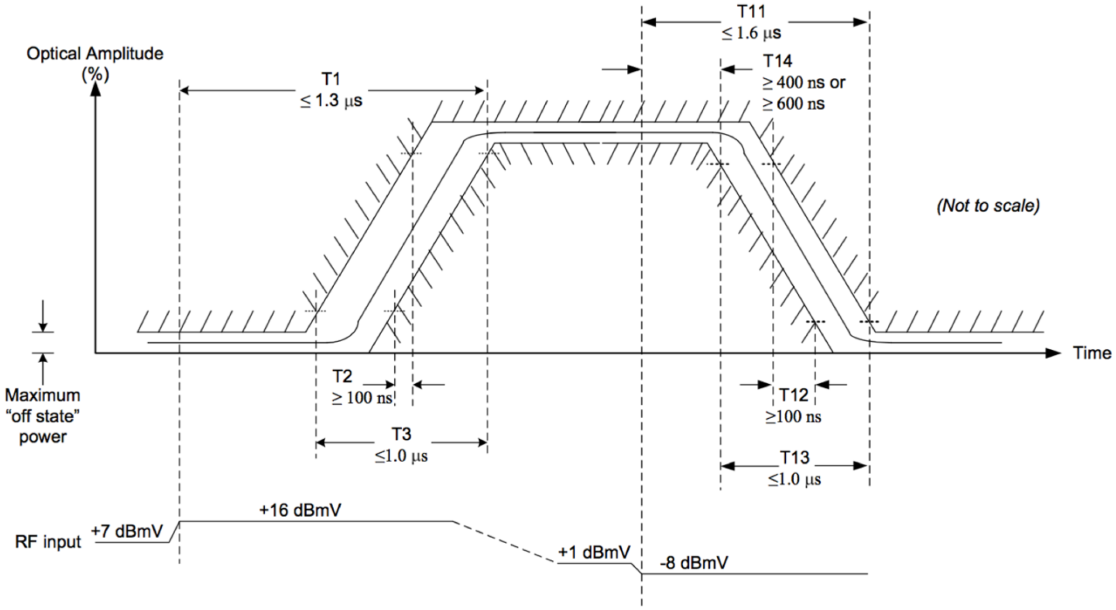

Figure 5 – R-ONU Turn On and Turn Off Characteristics

5. Example RFoG ONU Data

The following figures show oscilloscope traces of actual R-ONU lasers turning on in the presence of an upstream burst from a CM.

In Figure 6, the top trace (yellow) is the upstream OFDMA burst of a DOCSIS 3.1 cable modem. The lower trace (green) is the output of the associated R-ONU. The two markers on the lower trace show the time it takes for the R-ONU laser to first activate (~0.5 µs) and the SCTE 174 requirement of 1.3 µs for the laser to turn on and be settled.

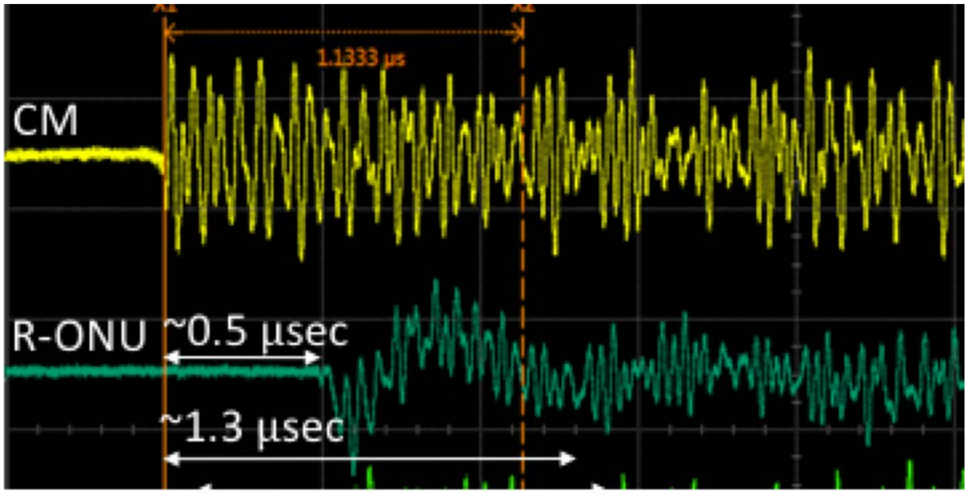

Figure 6 – R-ONU #1 Turn On

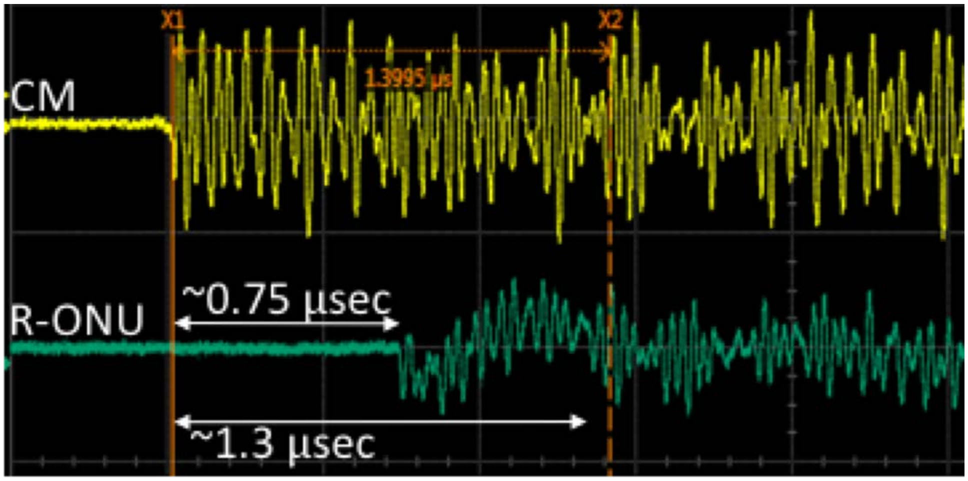

Figure 7 – R-ONU #2 Turn On

In Figure 7, the same cable modem upstream OFDMA burst is applied to a second R-ONU. The time marker on the lower trace shows this R-ONU takes ~0.75 µs to activate and that the output is also turned on by the SCTE 174 requirement of 1.3 µs.

Both R-ONUs comply with SCTE 174 in terms of turning on within 1.3 µs; however, the R-ONUs exhibit different laser turn-on times. Lab testing revealed that while both R-ONUs will work properly with a CP of at least 1.5 µs in duration, R-ONU #1 will work with the shortest CP of 0.9375 µs whereas R-ONU #2 will not work with this shortest CP because of the slightly longer time needed to activate the laser. The significant result of these tests show there could be differences between deployed R-ONUs that will require testing when deploying DOCSIS 3.1 technology over existing RFoG networks.

Note that SCTE 174 was published in 2010 and RFoG technology has been around longer than that. There may be R-ONUs in the network that pre-date 2010 and may not meet the 1.3 µs turn-on time as specified in SCTE 174.

6. Cyclic Prefix and Upstream Efficiency

Since the CP is used as a guard time, it does not carry useful customer information and its duration should be minimized. Said another way, a longer CP causes more inefficiency on the upstream. Table 2 lists the upstream overhead due to the CP duration. Note there are other overheads including protocol headers, pilot subcarriers and unused subcarriers which would add to the values listed in this table.

Table 2 – Upstream Overhead Due to CP Duration

CP Duration	2K Mode	4K Mode
0.9375 µs	4.5%	2.3%
1.2500 µs	5.9%	3.0%
1.5625 µs	7.2%	3.8%
1.8750 µs	8.6%	4.5%
2.1875 µs	9.9%	5.2%
2.5000 µs	11.1%	5.9%
2.8125 µs	12.3%	6.6%
3.1250 µs	13.5%	7.2%
3.7500 µs	15.8%	8.6%
5.0000 µs	20.0%	11.1%
6.2500 µs	23.8%	13.5%

In Table 2, the 2K mode and 4K mode are references to the number of subcarriers used in the IFFT when creating the time domain OFDMA signal, where 2K means 2048 subcarriers and 4K means 4096 subcarriers. In 2K mode, the upstream IFFT duration is 20 µs and in 4K mode the duration is 40 µs. The overhead is calculated by prepending a CP duration to either of these IFFT durations and calculating the overhead.

Longer CPs result in higher overheads, and while a longer CP may be needed on an HFC network to guard against the longest micro-reflection, on an RFoG network, the CP duration is chosen to turn on the R-ONU laser. Different R-ONUs will work with CPs of different durations; however, R-ONUs that meet SCTE 174 should all work with a CP of at least 1.5 µs.

7. Conclusions

The choice of CP directly impacts functionality and efficiency of a DOCSIS 3.1 upstream running over an RFoG network. Too short a CP and the network will not reliably operate because the R-ONU laser is not stabilized before transmitting customer data. Too long a CP and the network will operate inefficiently because a longer duration CP adds unnecessary overhead to the upstream.

8. Abbreviations and Definitions

8.1. Abbreviations

CM	cable modem
CMTS	cable modem termination system
CP	cyclic prefix
CPE	customer premise equipment
dBmV	decibel millivolt
DOCSIS	Data-Over-Cable Service Interface Specifications
FTTH	fiber to the home
HFC	hybrid fiber/coax
IFFT	inverse fast Fourier transform
MER	modulation error ratio
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
PNM	proactive network maintenance
PON	passive optical network
RFoG	radio frequency over glass
R-ONU	RFoG optical networking unit
SCTE	Society of Cable Telecommunications Engineers
µs	microsecond

8.2. Definitions

downstream	1) The direction of RF or optical signal transmission from headend or hub site to subscriber. Also called forward. 2) Information flowing from the headend or hub to the user.
upstream	1) The direction of RF or optical signal transmission from subscriber to headend or hub site. Also called return or reverse. 2) Information flowing from the user to the hub or headend.

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Common Ethernet Installation Mistakes and How to Avoid Them

A Technical Paper prepared for SCTE•ISBE by

Tomas Yanez, Solutions Marketing Manager, Viavi Solutions, SCTE/ISBE Member
Author, 6001 America Center Dr. 6th Floor,
San Jose, CA, 95002
tomas.yanez@viavisolutions.com
267-815-0613

Barry Constantine, Metro Engineer, Viavi Solutions, SCTE/ISBE Member
Author, 6001 America Center Dr. 6th Floor,
San Jose, CA, 95002
barry.constantine@viavisolutions.com
240-404-2227

Michael Bangert, Metro Product Line Manager, Viavi Solutions, SCTE/ISBE Member
Author, 6001 America Center Dr. 6th Floor,
San Jose, CA, 95002
barry.constantine@viavisolutions.com
240-404-1124

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1. Introduction

It’s no secret that telco revenue growth for residential services has been flat for about the last five years. After a big revenue surge in the 2000s driven by broadband Internet connections, the wireline residential business has been vanquished by cloud-based entertainment options, smartphones, and wireless broadband services.

The wireline service providers’ knight in shining armor for revenue growth has been high-margin Ethernet services, sold almost exclusively to business. By offering better security, performance, and scalability than over-the-top connections between locations and data centers, the business demand for Ethernet remains robust.

Of course, the profit potential of the Ethernet market has also enticed competitors to shore up their Ethernet offerings in the hopes of capturing their fair share. Unlike 15 years ago, when business parks lit with fiber were scarce and competition rare, now it is commonplace for an Ethernet shopper to have choices among providers in the ever-growing list of lit buildings.

One of the key elements that drove rapid, global Ethernet adoption was common Ethernet standards. Predictably, those standards also contrived to make carrier Ethernet services hard to distinguish from provider to another, causing price pressure. So that begs the question; although market demand for Ethernet services remains high, how can a carrier compete?

There are basically two ways a carrier can sustain its competitiveness. One is to continually build out new fiber to reach Ethernet-starved business locations before the competition does. “Footprint wins” is the adage in the business. While that can be a winning formula, it requires a lot of capital expenditures (CAPEX) and a high tolerance for risk in the finance department. The other path is to be operationally excellent; to make customers happy by delivering Ethernet services quickly and efficiently the first time. No field team wants to be called back to the scene of a failed install, and no customer wants to see their install techs so often they’re on a first name basis. Businesses will still pay for quality, and to avoid a drama-filled install nightmare.

2. Service Activation Excellence – The Physical Layer

The first thing a tech must do is to make sure the physical layer of the network is intact and functioning properly, because if it's not, there's no point in checking the transmission layer.

The Underlying Fiber

Usually the group that pulls the fiber out to a business park or multi-tenant building will test the integrity of that fiber span to ensure it can transmit a certain bit rate or service type. They may even do a full "characterization" of that span which consists of five tests: optical return loss (ORL), optical time domain reflectometry (OTDR), power meter and light source (LTS), polarization mode dispersion (PMD), and chromatic dispersion (CD). If the network provider uses a contractor company, the contractor won't get paid for their work until they present a report that the fiber pulled met the predefined parameters.

It's important to note that even if the install team did a perfect job of laying that fiber, by the time it comes to activate an Ethernet service on top of it, something bad might have happened to impair that fiber: a kink, a bend, squirrel teeth, or worse the blade of a backhoe. Therefore, at a minimum it's advisable for Ethernet install teams to do a quick OTDR test on that fiber to find faults or splice loss.

Fiber Connection Inspection

If the underlying fiber looks good, the tech is then advised to check the fiber connections. Believe it or not, bad or contaminated fiber connections are the #1 cause of troubleshooting and optical network downtime. Contaminants are everywhere in telco rooms and data centers, whether it's dirt, dust, or oil. These contaminants interfere with light transmission along the fiber, causing back reflection and insertion loss— none of which are good.

The most critical element to safeguarding quality fiber connections is ensuring a proper end-face condition. Circuit uptime and signal performance depend highly on perfectly aligned and thoroughly clean end faces. When working with fibers only a few microns wide, any contaminant can cause poor transmission performance, which leads to a customer trouble ticket. Although a dirty connection is the number one cause of optical network downtime, it's an easy problem to avoid with a good fiber microscope.

3. The Transmission Layer

It's customary for some service providers stop testing there, at the physical layer. While the Ethernet services themselves will likely adhere to a Metro Ethernet Forum (MEF) standard, there are pronounced differences among Ethernet service providers regarding the delivery of that service. The carriers who've earned a good reputation for service activation excellence not only test the physical layer, but the transmission layers as well, before handing off the service to a customer.

Ethernet is remarkably stable if it's installed correctly. That stability tends to lull some field teams into a sense of complacency, so they don't test the network transmission to cut corners (or if they do test, it's a simple ping to check connectivity). Perhaps that reluctance to test is based on the outdated impression that Ethernet is overly complicated, and that testing takes hours, time that can be spent working on the next job. That impression is no longer accurate. Today's test sets come pre-loaded with automated work flows optimized for efficiency, saving technicians valuable time compared to years past.

Here are some common errors that occur when turning up Ethernet circuits at the customer premises. With a high-quality portable network tester that can run standards-based tests, here are some simple ways to avoid the stress and wasted time that these errors may cause.

Misconfigured VLAN

Traditionally, when turning up an Ethernet circuit a technician must enter the correct virtual local area network (VLAN) on the local, portable test set. Many times, this VLAN is incorrect or the technician is not even aware that the network is using VLAN tags. An example would be when the network is configured to use VLAN 202 between the local and remote test device. If the technician does not enter a VLAN or enters the incorrect VLAN, the remote device will never see the loopback commands. This can waste significant amounts of time since the technician must contact advanced engineering or the network operations center (NOC). The situation can be even more problematic if the network is not well documented, which is not uncommon in the case of an acquired/purchased network.

To avoid this frustration, the technician should run a test via a portable network tester that automatically sends test packets to all 4096 VLANs and provides a list of remote devices which reply on a VLAN. It’s a 10-second scan but the time savings are significant because VLAN misconfiguration is one of the most common test configuration errors.

Auto-negotiation Issues

When a local test unit is connected to the network, the test unit and network equipment (e.g. Ethernet switch), should negotiate to the proper full-duplex link speed or the interface will default to half-duplex. If the interface cannot negotiate properly and enters half-duplex state, then a bit error rate test will falsely report a very low throughput for a given committed information rate (CIR). As an example, a CIR of 100 Mbps may only achieve 10 Mbps (or less) if the link is set for half-duplex.

All a tech must do to head this problem off is to run a “quick check” or a pre-test from a hand-held before the longer bit error rate tests, to automatically configure the auto-negotiation settings to match the network. It’s a small step to ensure that the bit-error rate is accurate and doesn’t have to be re-done. It can also potentially expose incorrect duplex settings on the provider's network element (router, switch, etc.).

Sniffing Out Poor Transmission Quality

High-performance data transmission is the goal for all parties. It’s what a business cares about and what they pay for. That said, data transmission can be impaired by a number of things including disconnected patch cables, a misconfigured network switch, rate-shaping issues, or incorrect buffer settings. Non-network elements may also negatively impact performance, for example a slow responding domain name server (DNS) or authentication server. Therefore, a key step on the day of the install is to establish whether the network is delivering the agreed upon, or the CIR of the customer’s circuit. Before the tech leaves the customer premises, he/she should confirm that the customer is getting what they’re paying for and service level agreements (SLAs) are met.

RFC 2544

An effective way to baseline key performance indicators (KPIs), and to identify any transmission problems from the start, is via a specialized network tester running an Ethernet/IP throughput test. Two standard tests dominate Ethernet/IP throughput testing for Ethernet service activation; Y.1564 and RFC 2544. Probably the most common test is RFC 2544, which is a recommendation from the IETF. It is the industry-standard service activation test for single-service Ethernet and IP connection. The test measures KPIs and bandwidth profile such as: throughput, latency, packet jitter, frame loss, and committed burst size (CBS).

Time savers: Although RFC 2544 is the most common test used, it's not without room for improvement. For example, the standard RFC 2544 test specifies that throughput, delay, and jitter tests are to be run sequentially (one test at a time and three different frame sizes). That means a normal test might take 30 minutes. Some test vendors have improved upon the standard RFC 2544 by running the three tests concurrently, reducing that 30 minutes down to a more manageable 10 minutes. The fourth test, the frame lost test, is another area where ops teams can save time. Some test vendors' RFC 2544 tests default settings are optimized for Metro Ethernet services - which is recommended. Specifically, the test defaults to 1 x 30 second trial per frame size for most KPIs. The RFC 2544 specification and many vendors' implementations have extremely long defaults for the frame loss test (example: 20 x 2-minute trials per frame size). This wastes an inordinate amount of the technician's test time, and should be avoided.

Y.1564

The industry-standard service activation test for multi-service Ethernet and IP is Y.1564. For multi-service, think "Triple Play" or an Ethernet circuit running multiple classes of service. This test measures KPIs and bandwidth profiles such as:

- CIR, EIR (throughput)
- Frame delay (FD), latency
- Frame delay variation (FDV), jitter
- Frame loss rate (FLR)
- Committed burst size (CBS), policing

Time Saver: Y.1564 specifies starting the throughput test at a lower value, for example 10% of the CIR, then ramp up until the CIR is reached. Some vendors have developed a time-saving hack. They start the test at 100% CIR and ramp *down* to find the achievable throughput, which is significantly faster. When running the "ramp down" throughput technique, the time savings can be up to 75% for the Y.1564 configuration.

Automated Work Flows Are a Must

There is some truth to the idea that Ethernet/IP tests like Y.1564 (and RFC 2544 for that matter) can be a bit cumbersome to set up and execute flawlessly, which understandably can intimidate and consequently prevent inexperienced techs from running them, or burn unnecessary labor hours in running them. The key is to select a test set that balances labor time savings via automated workflows vs equipment upfront costs. Test sets that minimize the labor hours required should guide the technician through the test using easy-to-follow steps on a wizard-like GUI. For example, one test set can walk a tech through a Y.1564 test in only three steps. A user-friendly tester takes stress off the technician, speeds work, improves test results, and best of all, reduces trouble tickets.

Don’t Settle for a Constant Bit Rate Test

Traditional Ethernet service-activation test methodologies focus on testing with constant bit rate traffic. While testing with constant bit-rate traffic is certainly better than nothing, it does not validate how well the network will perform when transmitting real-world traffic, which doesn't play as nicely. Real-world traffic is usually a mix of constant bit-rate voice, video, and bursty data traffic. Almost all Internet applications such as Amazon Web Services, Microsoft Azure, YouTube, etc., use TCP as the transport layer and frequently burst traffic at full line rate into the network.

To evaluate bursty traffic, you need to ensure two things: first, that bursty data traffic can pass through the network without frame loss, and second to do so without impacting other services. Consequently, operations teams must ensure that their test methodology incorporates burst testing. Otherwise, they may leave an install thinking all is good, only for the business to experience problems when they start transmitting a live traffic mix over the connection.

Test the Customer Experience: RFC 6349

Activating Ethernet Internet circuits can be problematic for service providers because often their test methodology does not cover the network layer on which the customer’s Internet traffic flows. For example, assume that a conscientious installation tech performs all the above tests to make sure the customer is getting the network service they expect. He/she tests the fiber connections, the physical layer, and even Ethernet Layer 2. Everything checks out so the tech leaves. Then the customer starts using an over-the-top data storage service, or a web-based e-mail service, etc., and the application feels slow. It doesn’t feel like they just bought a 200Mbps dedicated Internet circuit, for example. The problem is that the Internet traffic is via TCP and is transported on Layer 4, where in this case, the tech did not test.

The solution is for the tech to add a RFC 6349 test to their service activation methodology. RFC 6349 is another IETF test, and it allows service providers to accurately test TCP throughput while also diagnosing root causes of inferior performance – something simple Internet-based speed tests cannot. That root cause could be a misconfiguration of an Ethernet access device, for example, something that could possibly be resolved before the tech leaves, preventing future trouble tickets, an expensive truck-roll, and an unsatisfied business customer. RFC 6349 workflows can also be automated, adding only a few minutes to the overall install time. It’s a minor time investment that has been shown to yield significant operational savings down the road by many prominent service providers.

Time saver: Combine Y.1564 and RFC 6349, two essential tests into one! By integrating RFC 6349 testing with Y.1564, some test vendors provide service providers a robust, automated turn-up capability which tests Layer 2/3 services (i.e. voice / video) concurrently with bursty TCP sessions. That combination closes the testing gap and allows the provider to turn-up the customer circuit with confidence knowing that end-user applications will perform as expected.

4. Conclusions

Ethernet services are critical for protecting existing, and creating new revenue streams for wireline service providers. However, in a competitive environment, the name of the game is optimizing the customer experience, which essentially means nailing the install.

To ensure those lucrative customers are happy and buy more, operations teams must quickly sidestep easy-to-avoid mistakes with thorough testing—not just the fiber but also the transmission layers, including Layer 4 TCP. Modern test sets have made testing much easier and faster than before. There’s no excuse not to implement a thorough test plan for every install. After all, the time you invest in activation tests will save time, costs, and reputation in the future.

DOCSIS 3.1 Cable Modem Deployment Strategy

Targeted Deployment Analysis

A Technical Paper prepared for SCTE•ISBE by

Mike Darling, Principal Engineer, Shaw Communications
2728 Hopewell Pl NE
Calgary, AB T1Y 7J7
mike.darling@sjrb.ca
403-536-3977

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1. Introduction

The introduction of DOCSIS 3.1 (Data over Cable System Interface Specification) promises an order of magnitude increase in data rates. However, if not managed carefully, the transition from DOCSIS 3.0 to DOCSIS 3.1 represents a potential discontinuity in the process of upgrading capacity. While DOCSIS 3.1 Converged Cable Access Platform CCAP hardware is currently available, it cannot be leveraged until cable modems are installed in sufficient numbers. The common process for distributing new cable modems is through organic methods of new and churning customers. The major problem with this approach is that the amount of throughput represented by these customers is random and will be weighted towards the average. This means that to transition 50% of traffic to DOCSIS 3.1 50% of subscribers must have DOCSIS 3.1 cable modems. In addition, DOCSIS 3.1 cable modems will be the highest performing modems and there will be a desire to only include them in high-tier Internet packages or with longer-term contracts, thus limiting numbers.

We know from previous studies that a minority of subscribers consume most of the data, and that a more optimal transition may occur if these subscribers could be targeted with DOCSIS 3.1 cable modems. We have undertaken analysis to determine what percentage of subscribers represent 50% of downstream throughput, and whether tier information can be used to target them. The analysis was done on 20,000 subscribers fed from three CCAPs over 11 weeks. We found that in our sample 12% of subscribers represented 50% of traffic, but targeting these subscribers by tier alone increased this number to 25%. A strategy targeting only users subscribed to 30Mbps tiers or above represented a middle ground of 19%. Further analysis was done to determine whether these subscribers demonstrated consistent behavior in their traffic demands and we found that there was a high likelihood that a subscriber in the top 12% of throughput over 10 weeks was in the top 12% each week.

2. Background

Hybrid Fiber Coax (HFC) networks are upgraded when peak throughput breaches a threshold, such as 70% of total capacity. An upgrade can come in the form of a node split or added DOCSIS carriers. Although the DOCSIS 3.0 standard does not have a limit on the number of downstream channels that can be deployed, MSOs (Multiple System Operators) will cap this number and transition to DOCSIS 3.1 which is more spectrally efficient. Due to the exponential nature of peak throughput growth, once traffic begins to transition from DOCSIS 3.0 to DOCSIS 3.1 the demands on the latter will increase quickly. Given today's traffic growth rates, this will result in 50% of traffic running on DOCSIS 3.1 within two years of launch.

If DOCSIS 3.1 cable modems are deployed organically, this means that 50% of cable modems will have to be DOCSIS 3.1 within two years of the start of the transition. There are many challenges to reaching this level of DOCSIS 3.1 cable modem deployment, including cable modem availability and limits on success-based capital.

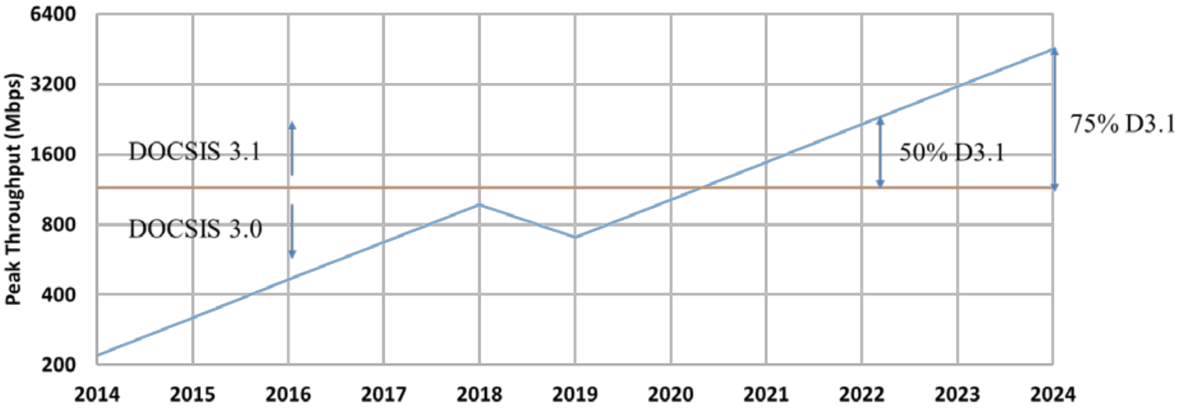

Figure 1 - Transition from DOCSIS 3.0 to DOCSIS 3.1

Figure 1 shows a representative node growing at 45% downstream CAGR (Compound Annual Growth Rate) on a logarithmic scale. A node split is performed in 2018 which will delay the need for DOCSIS 3.1, but very quickly after hitting the maximum DOCSIS 3.0 throughput, most traffic will be carried by DOCSIS 3.1 as indicated by the 50% D3.1 and 75% D3.1 annotations on the right.

We know from previous studies that the majority of data is consumed by a small percentage of subscribers.

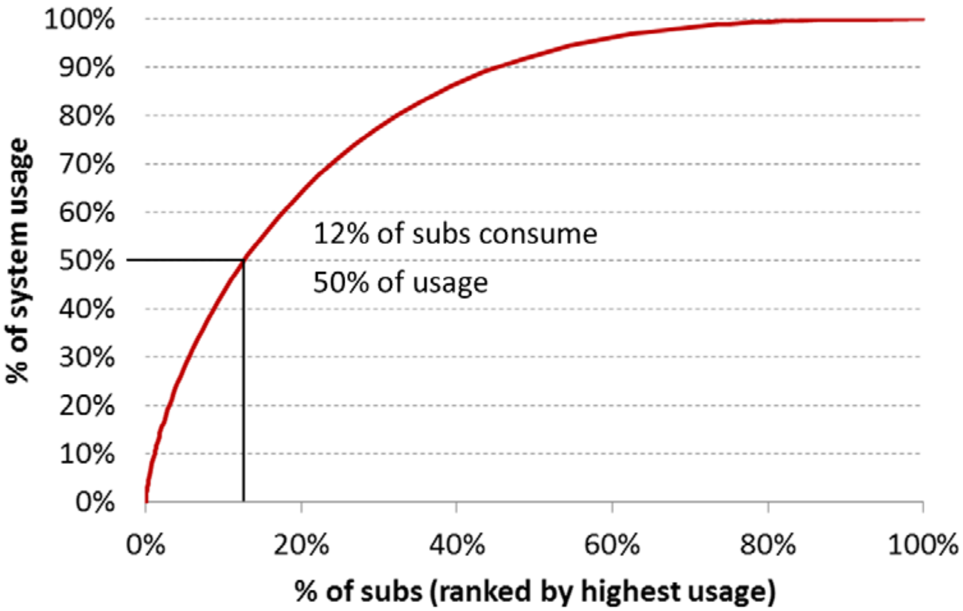

Figure 2 - Downstream Consumption Cumulative Distribution Function

Figure 2 shows the cumulative distribution function for downstream data consumption. 50% of data is consumed by only 12% of subscribers.

If this is true for peak throughput as well, we could potentially target these subscribers for DOCSIS 3.1 modems and move a large amount of traffic to DOCSIS 3.1 spectrum with a relatively small number of cable modems. A question that arises is whether peak throughput is correlated with service tier, and whether subscribers on the highest tiers could be targeted with DOCSIS 3.1 cable modems. This scenario would match the highest paying subscribers with the newest technology.

3. Data Collection and Analysis

Per-subscriber throughput data was collected for 56 nodes over 11 weeks using a deep packet inspection platform. The 95th percentile was recorded and sorted using three criteria:

1. Throughput
2. Service tier then throughput
3. Service tier greater or less than 30Mbps then throughput

As expected, a small percentage of subscribers represent a large percentage of peak throughput. Somewhat surprisingly, however, these subscribers are not necessarily subscribed to the highest tiers.

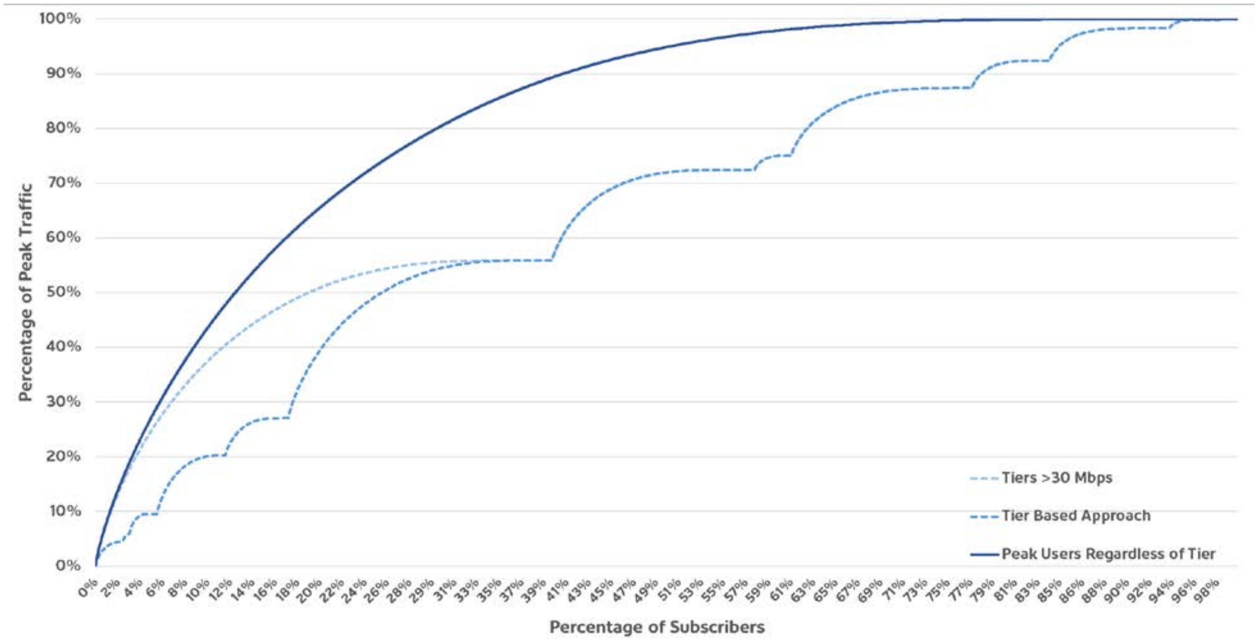

Figure 3 - Peak Traffic Cumulative Distribution Functions

Figure 3 shows the results for all subscribers. We can see that when we rank subscribers in terms of peak throughput we get the solid blue curve, which is similar to the consumption curve in Figure 2, indicating that a low number of subscribers account for a large amount of peak traffic. However, when we sort by speed tier we get the dark-blue dashed line which climbs more gradually than the solid blue line, indicating that peak throughput is not strongly correlated to speed tier. If we only target subscribers on a 30Mbps tier and above we get the light-blue dashed line, which lies in between the other lines.

Taking the average for all 56 nodes we find that 12% of subscribers represent 50% of peak throughput, while upgrading based on tier requires 25% of subscribers to reach the same amount of peak throughput. The compromise of upgrading based on whether a subscriber’s tier is greater than 30Mbps requires 19% of subscribers for 50% of peak throughput.

While transitioning the highest peak throughput subscribers to DOCSIS 3.1 would result in the fewest modems required, there may be reluctance to upgrade the modems of subscribers in lower tiers. Transitioning subscribers by service tier alone, however, will be much less efficient. Using a mixed method where high peak throughput users with a service tier over 30Mbps is a potential compromise.

Subscriber consistency was tested over 10 weeks. Subscribers in the top 12% over the entire period showed a 71% likelihood to be in the top 12% in each week. The average weekly peak throughput for the top 12% of subscribers was 47.3%, demonstrating a high level of consistency.

4. Conclusions

The transition to DOCSIS 3.1 requires a strategy for deploying new cable modems. A strategy based around targeting high peak throughput subscribers can reduce the speed of deployment required and reduce the risk of a discontinuity in upgrade planning. Our data shows that approximately 12% of subscribers account for 50% of peak throughput, but that those 12% of subscribers are not necessarily subscribed to the highest tiers. The data shows that targeting subscribers based on service tier results in a much less efficient deployment, where 25% of subscribers account for 50% of peak throughput. If there is resistance to upgrading low-tier subscribers, a mixed method where subscribers with a 30Mbps tier or greater are targeted provides a compromise between the previous two cases.

5. Abbreviations and Definitions

5.1. Abbreviations

CAGR	Compound Annual Growth Rate
CCAP	Converged Cable Access Platform
CM	Cable Modem
DOCSIS	Data over Cable System Interface Specification
HFC	Hybrid Fiber-Coax
MSO	Multiple System Operator

Transforming Operations in a Dynamic SDN/NFV World

A Technical Paper prepared for SCTE•ISBE by

Guy Meador, Senior Solutions Architect, Cox Communications, Inc., SCTE/ISBE Member
6305 Peachtree Dunwoody Rd.
Atlanta, GA 30328
guy.meador@cox.com
404-269-5625

Patrick Moore, Director, Advisory Services, Itential, LLC, SCTE/ISBE Member
1350 Spring Street NW Suite 200
Atlanta, GA 30309
patrick.moore@itential.com
256-503-1099

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1. Introduction

The rise of software defined networking (SDN) and network functions virtualization (NFV) presents service providers with benefits and opportunities in service design and operation. New service designs are more varied, flexible, and dynamic and have an increased dependence on shared infrastructure as compared to the service designs of the past. The NFV and SDN communities are developing management, network orchestration, and controller capabilities with data model-driven techniques as a core characteristic.

Typical legacy operations support system (OSS) tools and techniques are not well-positioned to handle this new dynamic world and must evolve, both to interface with SDN/NFV-enabled domains, and to integrate continued legacy service operation with the new dynamic OSS approach. The paper outlines opportunities and challenges and suggests a way forward that uses model-based techniques to drive new operations automation and OSS tools for a unified, dynamic OSS approach across disparate domains and service types.

2. Network Transformation

A fundamental and revolutionary transformation is underway in network service design, deployment, and operation. Key driving factors enabling the transformation include software defined networking (SDN), network functions virtualization (NFV), service function chaining (SFC), and multi-layered automation; all of which employ model-based approaches for deployment, configuration, and operational control.

A network service is composed of a mix of interconnected physical and virtualized network functions, and may also include within its composition other network services.

Physical network functions (PNFs) are characterized by a tight integration of specialized (often expensive) hardware and software (or firmware). This tight integration has the effect that deployment of the embodied network function instance is identical with deployment of the PNF hardware. Service design and deployment with PNFs have limitations when it comes to dynamic flexibility and speed-to-deploy that are being overcome with software-based techniques, virtualization, and pervasive automation.

Virtualized network functions (VNFs) implement the network function as software that can be deployed using a virtualization layer on general purpose (commodity) hardware. This breaking of the tight dependency between software and hardware allows the network function instance embodied in the software to be quickly deployed and replicated at scale anywhere an appropriate hardware/virtualization environment exists.

SDN separates the network control plane from the data plane, providing for flexible and dynamic relationships between, and configuration of, underlay and overlay networks. The network functions of a network service can be dynamically interconnected by a service-specific overlay network constructed and configured on demand. SDN techniques are being applied to various network domains, including in the data center and wide area network (e.g., software defined wide area networking or SD-WAN), with multiple SDN regimes being active simultaneously within a provider footprint at any given time.

Network functions virtualization infrastructure (NFVI) is the term defined by the ETSI NFV Industry Specification Group (ISG) for the hardware/virtualization environment on which virtualized network functions are deployed. An NFVI instance provides physical and virtualized compute, network, and storage, and is a common resource on which multiple virtualized network functions for disparate network services can be deployed. SDN is employed within NFVI to provide for flexible network function interconnects as described previously. The NFVI approach brings greater flexibility and choice in contrast with appliance-based physical network functions where the hardware and software are tightly integrated and sourced from the same supplier.

A key goal of service function chaining (SFC) being defined by the IETF is to deliver a topologically independent service plane. Through SFC, network packets matching designated criteria can be subjected to service functions in a prescribed order without changing the topology of the underlying network and without the need for service functions to be topologically aware. The term "service function" is loosely equivalent to "network function" in the context of the current paper.

When taken together, these new capabilities bring tremendous flexibility and dynamism in how network services can be designed, deployed, and operated, but these benefits come at the cost of complexity. The usual methods of the past are no longer sufficient in the face of this complexity, so a new breed of tools and techniques is emerging.

2.1. Hierarchical Automation

Pervasive, layered automation is key to the successful operation of network services in the new reality that is SDN/NFV.

The ETSI NFV ISG has defined a hierarchically layered functional architecture for automated management and network orchestration (MANO) associated with virtualized network services. The hierarchy includes (top to bottom) the network functions virtualization orchestrator (NFVO), virtualized network function manager (VNFM), and virtualized infrastructure manager (VIM). The first two are concerned with the orchestration of NFV-based network services and the management of virtualized network functions, respectively, in association with their deployment on NFVI. The VIM is responsible for the management of the NFVI itself. Rounding out this group of automation entities is the SDN controller, which addresses the network configuration for the NFVI underlay and overlay networks. These four entities work together to provide for dynamic and flexible NFV-based network service deployment and automated operation on an NFVI instance.

Large network operators will have numerous NFVI instances, and will wish to deploy more complex NFV-based network services across them. There are also numerous other aspects of end-to-end service operation and inter-provider automation to be addressed above ETSI NFV MANO. The service orchestrator (SO), a.k.a. inter-domain resource orchestrator (IDRO), fulfills this need by addressing the global, end-end, multi-domain, and inter-provider automation concerns of network service operation. Representative examples of this type of orchestration function can be found, for example, in the Metro Ethernet Forum (MEF) Lifecycle Services Orchestration (LSO) architecture, the Zero Touch Network Service Management initiative and also in open source projects such as the Open Network Automation Platform (ONAP), among others.

In a similar manner, a hierarchical pattern for SDN control has emerged whereby a top-level SDN control function works in concert with the SO and can interface with SDN control functions within SDN domains lower down on the hierarchy or with peer top-level SDN control functions of other service providers.

These multiple layers of automation are arranged into a hierarchy of orchestration and control functions working together to deliver a tremendous jump in operational agility and flexibility that could not be achieved by employing the traditional techniques of the past. This statement is certainly true in relation to manual methods, but also applies to typical legacy operations support system approaches.

2.2. Data Model-Driven

With the rise of the automation ecosystem described in the previous section comes an approach to automated network service deployment and operation that mixes capabilities from the cloud orchestration world and the network management and operations world. This approach uses data models to describe the characteristics and composition of VNFs and NFV-based network services, as well as capabilities, dependencies, and other aspects important to automated orchestration, operation, and configuration. These data models are delivered into the automation ecosystem to direct and control all aspects of NFV-based network service instantiation and operation.

Standardization efforts for these NFV/SDN data models is taking place based on two key schema languages, namely, OASIS TOSCA and IETF YANG. The former was initially developed as a standard for cloud orchestration while the latter arose in the network management arena as a much-improved replacement for Simple Network Management Protocol (SNMP) Management Information Base variables (MIBs).

These data models are designed for flexibility and composability. A VNF implementation is accompanied by a data model describing, among other related information, its capabilities, dependencies, and deployment artifacts. Network service types are defined by a data model describing its composition in terms of VNFs and other network services and their interconnection. The same VNF types can be combined and interconnected in different ways to serve the needs of disparate network service designs.

Within the context of the service orchestration/MANO/SDN automation stack and NFVI on which to deploy VNFs, the definition, deployment, and operational control of NFV-based network services is largely driven with an exercise in data model creation and manipulation, which in turn, is directly actionable by automation.

Consequently, changes to these data models can happen frequently in support of a much more agile and automated approach to network service deployment and operation.

2.3. Network Service Design

New network service designs targeted to the NFV/SDN environment have the potential to be more varied, flexible, and dynamic. These new network service designs are created with automation in mind, rather than independent of it. In fact, the specification of the automation-related service deployment and operation aspects of a network service becomes as important at design time as are the functional aspects.

In addition to incorporating automation into these service designs, explicit layering of capabilities is also key. Such network service designs explicitly separate the underlying infrastructure (NFVI, underlay networks, etc.), the substrate onto which the new network services are deployed, from the services themselves. The resulting dependencies on, and the expected dynamic configuration of, the underlying infrastructure are also necessary parts of the network service design. The more agile and automated the underlying infrastructure can be, the better will be the agility and flexibility of the network services from design to deployment and operation.

3. The Problem

A key problem to be solved is the gap between the operations environment for legacy/physical network services and infrastructure, with its typical lack of agility and flexibility, and the need to interwork with the more agile and flexible SDN/NFV-based services and infrastructure.

A common approach for configuring devices and networks has been the use of the command line interface (CLI). Over time, the increase in network complexity and the introduction of new technologies made manual configuration with CLI alone a much less attractive approach for the task. Consequently, scripting was introduced to simulate the interaction of a human with the network for device and service configuration. Scripting is effective for straightforward repetitive tasks that are carried out in high volume and can be initiated by a human operator.

The scripting approach can be sufficient for a static network having very few changes after the network is fully deployed. However, with the introduction of NFV and SDN, the technologies involved are becoming progressively more sophisticated and dynamic; configuration changes are frequent instead of the exception. The network is no longer static in nature, but instead has become a very dynamic environment that can see devices inserted and removed from the network automatically many times each day. The paths through the network that services take can be even more dynamic than this, with the introduction of event-driven configuration changes becoming a reality for the legacy/physical network just as it is with SDN/NFV-based network services.

Much like the network itself, the management tools overseeing the legacy/physical network were designed to be static as well. It has been a challenge to maintain the synchronization of inventory to network, even with infrequent changes, as evidenced by the less-than-ideal accuracy rate found in most network inventory systems today. In some cases, a change to the network can involve almost as much time updating the OSS as it takes to do the change itself. This is not ideal, but is manageable if changes happened infrequently enough. The dynamic nature of future networks mentioned above breaks this model.

In addition to the networking evolution they bring, SDN and NFV also increase the operational complexity level with the introduction of new automation tools. These include VIM to manage the NFVI layer, VNF managers (VNFM) to manage the VNFs themselves, and NFV orchestrators (NFVO) managing the interactions between all of the components discussed above for a given domain. The real possibility of multiple NFV domains leads to multiples of each of these tools, contributing to the increased complexity of interactions with legacy tools in the operations environment. The new SDN/NFV tools must be integrated with legacy toolsets in order to enable effective management and control of the future network. To be successful, the combined toolset must manage all of the PNFs and VNFs involved in a coordinated manner.

An additional complexity added to the current environment is that service providers frequently choose specific tools for specific use cases, such as virtual customer premises equipment (vCPE) or SD-WAN. Each of these solutions comes with its own NFVO, VNFM, NFVI, and controller in most cases. This proliferation of duplicate tools increases the number of management touchpoints, sometimes even within a single network domain.

This divergence of management between physical and virtual domains has created an ‘operations gap’ or ops gap, as shown in Figure 1 below. The benefits of adopting virtualization and cloud technologies introduced by SDN and NFV are many, but the tooling that comes with that is challenged to extend effectively to existing physical networks. This operations gap will grow as operations teams are required to support modern technologies, while continuing to support existing ones.

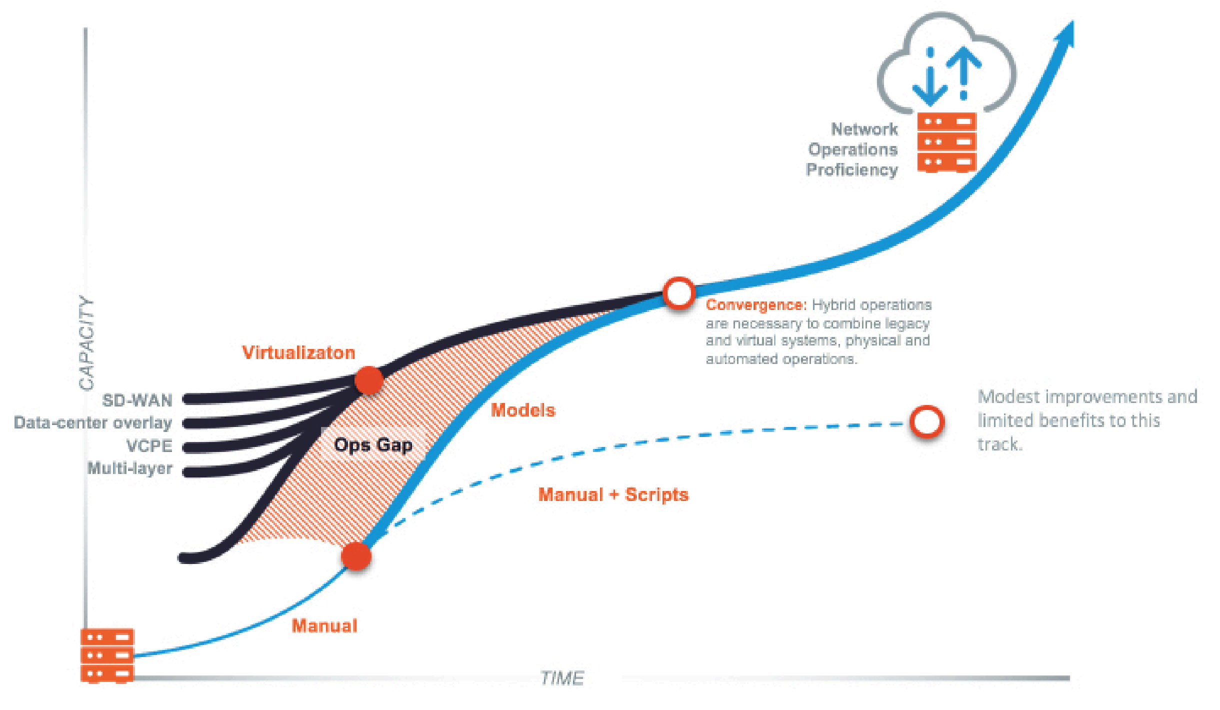

Figure 1 - The Operations Path

Figure 1 depicts both the ops gap, along with an indication of a path forward. There must be a convergence of toolsets and processes. This convergence needs a common management platform for the operations teams to utilize that will allow for management of the multiple siloes across physical and virtual domains that will exist. Also, the areas of the network where minimal value can be achieved with further automation must be allowed to remain on their path of today.

4. A Way Forward

An earlier section of this paper identified the SO, also known as the inter-domain resource orchestrator (IDRO), as a key part of the automation stack for managing network services operations across multiple network domains. While this orchestrator can be used to coordinate across SDN/NFV domains, we suggest that it can also be an effective part of the solution to address the operations gap. This section expands upon the approach and explains the characteristics needed for a successful solution. These include:

- The solution must be model-based when it comes to service design
- The solution must accommodate physical and virtual elements in its design
- The solution must be able to define services that traverse the physical and the virtual, resulting in service designs that leverage both PNFs and VNFs
- The solution must enable programmability across both legacy and new network technologies

The solution must utilize industry defined standards for modeling, such as TOSCA and YANG, and integrate with domain-specific automation entities (ex. orchestrators). These models will be distributed to the appropriate automation entities for service definition, provisioning, monitoring, and automatic remediation.

The end goal is a solution that is as agile in its management of the network as the networks themselves are becoming. In order to better define this path, the following sections will discuss where this activity is now and a possible path it could take in the future.

4.1. Legacy Automation and Orchestration

The CLI is designed specifically for human interaction with the complex functionality of device operation and service provisioning in the network. If one were to pull the full configuration of a device it would include both the device and service-specific aspects of that configuration.

In order to scale this management technique, it became necessary to produce scripts that simulated a person keying into the CLI, but that were capable of doing so in a repetitive manner much faster than any human could. Figure 2 depicts this process. These scripts were then called by northbound systems to introduce the first rudimentary forms of network automation. In some form or other, this is largely where the industry is today.

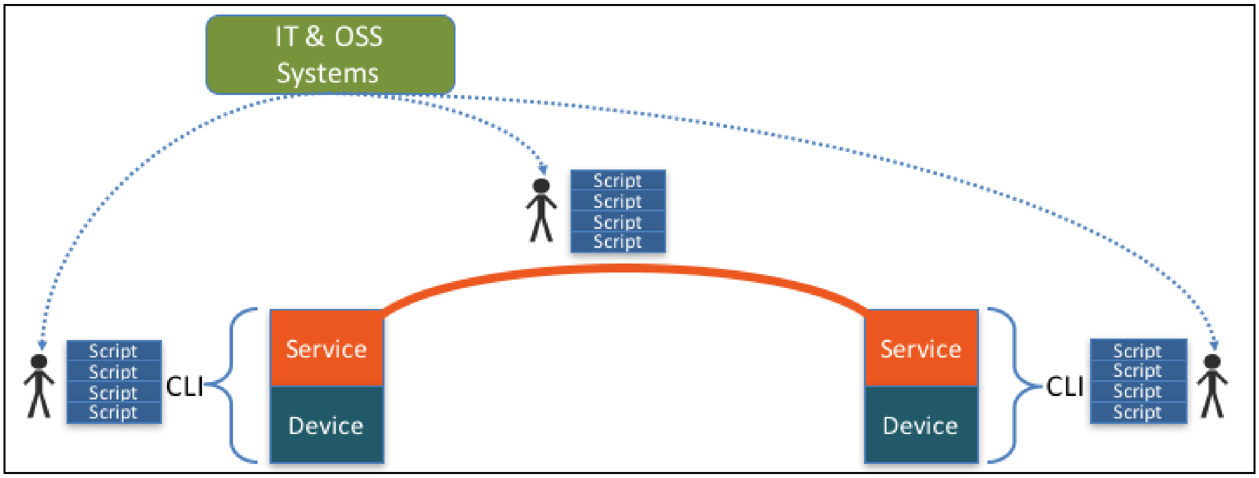

Figure 2 – Traditional Network Automation

This approach is very effective in smaller environments that do not have multiple network domains, such as an enterprise network. However, in the service provider space the network quickly becomes much more complex. These networks are composed of access networks, core networks, backbone networks (that can span countries), etc., resulting in an automation picture like that shown above being replicated for each of them. In the multiple system operator (MSO) space this can be increased by an additional factor when you consider the different access methods involved with fiber-based, DOCSIS-based, and MEF technologies.

As more sophisticated automation has emerged, separate domain orchestrators have been put in charge of each of these networks. These domain orchestrators do a very good job of management and control of the specific environment they were designed for, but it is becoming increasingly more common for services to cross these domains. The result is an operational environment requiring manual steps executed by an engineer moving between multiple systems, sometimes logging in and out of each, in order to provision and maintain services.

In an attempt to accommodate this issue some OSS implementations have used a basic workflow over the top of the various domain orchestrators to allow for automation. That approach works for most “sunny day” scenarios where everything functions perfectly, but, unfortunately, it is not reality in a production network. Due to that reality, these solutions become cumbersome to manage and maintain as the issues discovered are addressed with the same approach to automation. Something with more intelligence and flexibility is required to effectively automate services across domains.

4.2. Cross-Domain Orchestration

The idea of an “orchestrator of orchestrators” is not necessarily new in the industry, but the outlined approach is firmly rooted in the application of layered model-based service definition and management made actionable by multi-layered automation with the SO/IDRO as the topmost entity. Models provide a level of flexibility that scripting cannot. This is not to say there isn’t still a place for scripts; but an approach that relies solely on vendor-centric scripts for each device type and service involved does not scale. The model-based approach, and one which increasingly can use standards-

based models, accommodates multi-vendor and multi-device type environments in a much more effective manner.
Of interest are three data model levels employed across the layered automation stack: device models, service configuration models, and service control models. These three models are depicted in Figure 3 below, and are described in detail here:

- Device models separate the device specific configuration from the service configuration. This allows for life-cycle management at the device layer that is abstracted from the services that traverse them. In the PNF domain these models are based on the device configurations we are all familiar with but abstract the variation of vendor differences. In the VNF domain these are the VNF descriptors (VNFD) that define a VNF and how it should be deployed. At this layer, the modeling is typically YANG or XML template based.
- Service configuration models, likewise, are specifically focused on the configuration of the services and not concerned with the configuration of the devices they reside on. This allows for another layer of life-cycle management focused on the services. The service configuration model must be able to accommodate services “chained” across multiple devices, whether they be PNF, VNF, or a combination of the two. In the PNF domain these are the service related aspects of the configuration, and can traverse multiple PNFs. Likewise, in the VNF domain these will include VNF deployment and configuration concerns. At this layer, the models are typically YANG- or TOSCA-based.
- Last is the concept of service control models. These models consider the underlying models, but also include process/workflow and other policy-based elements to provide a model-based approach to operationalizing the network.

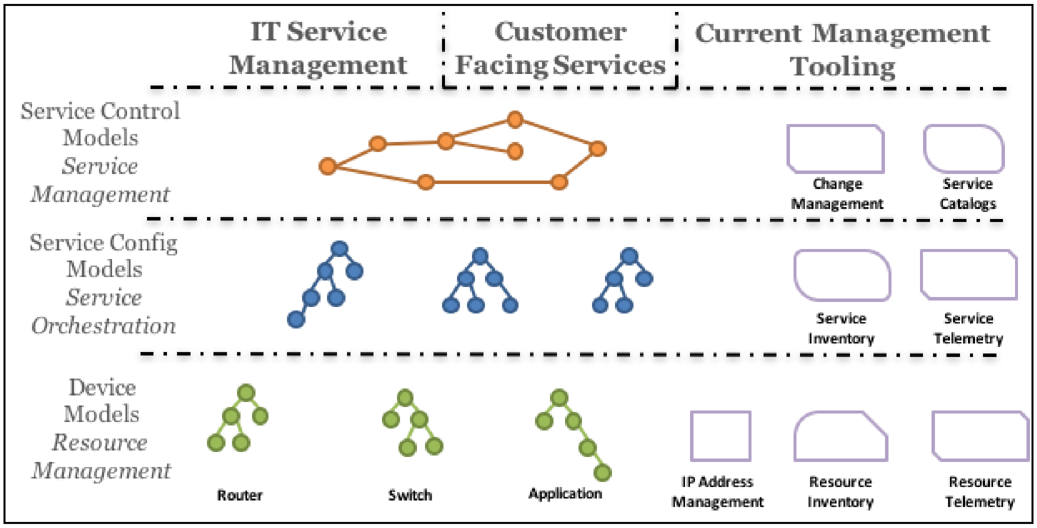

Figure 3 – Model Hierarchy

When the approach is applied to the network, a model-based approach similar to what is depicted below in Figure 4 results:

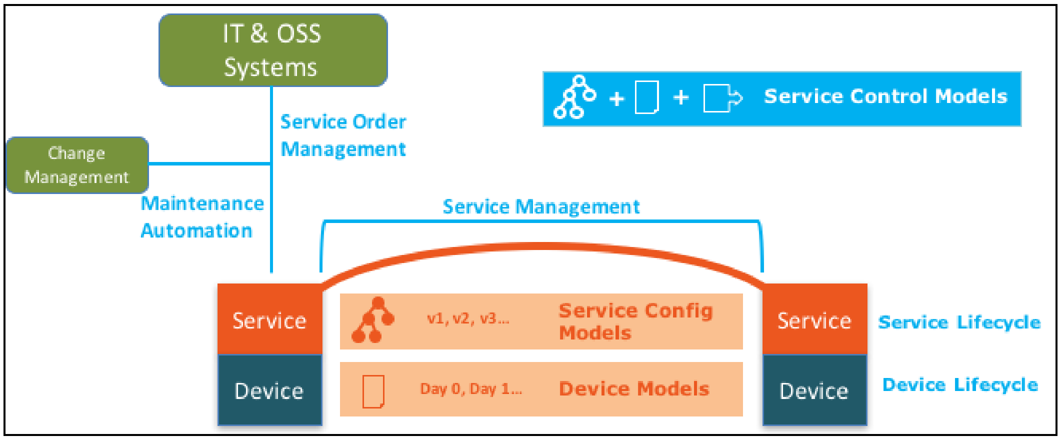

Figure 4 – Model-Based Approach

Device models may exist in a single domain's management systems, or many systems each containing the device models for its domain. For example, a PNF manager would operate according to device models in a standard format (YANG, XML, etc.) for the devices it manages and a VNF manager would do the same for an NFV environment. The same is true for the service configuration models. The important point here is that the models are coordinated and managed by the top-level cross-domain orchestrator that maintains the overall, end-to-end view of the services.

A key point of the approach is that the Service Control models address the end-end dynamic control of the composition, deployment, and operation of network services and are well-matched with the service orchestrator role of the multi-level automation stack. The service control models relate to the other identified models and can even address the ways those models should be composed and activated given current operational conditions.

As shown in Figure 5 below, the two lower levels very well may have multiple controllers or orchestrators in place that manage specific domains. This is especially true at the device layer, which would also include infrastructure managers, such as the VIM from NFV MANO. Each domain may have controllers/orchestrators with a span of control limited to that domain. Rather than requiring domain controllers/orchestrators to directly integrate with one another (between domains), the approach is to have them integrate with the service orchestrator at the top level.

At the lowest layer, legacy devices and their management entities, if any, will likely not have the necessary programmability capabilities to achieve this approach. For these devices, a programmability layer must be inserted to provide this interface to those devices. In the cases of newer devices emerging today, application program interfaces (APIs) are almost always supplied to provide this capability. An important point to notice is that there are legacy physical and virtual, as well as more modern programmable, devices. One should not assume that "virtual" equals "programmable".

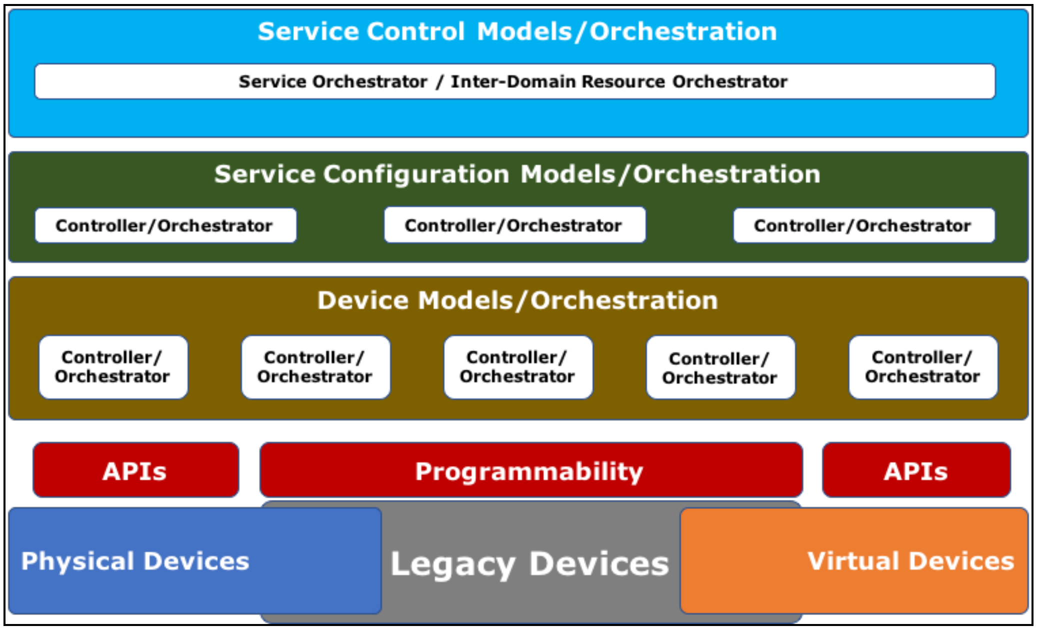

Figure 5 – Orchestration Layers

While the domain orchestrators that house the underlying models will likely also contain the capability to manage many functions, such as golden configuration, configuration drift/compliance reporting and remediation, device turn up, etc., the cross-domain orchestrator must have access to these functions in order to enable it to manage the complete end-to-end service lifecycle.

This introduces a core concept of life-cycle management. It is reasonable to assume that a domain orchestrator will own the life-cycle of the device specific actions, but this capability must be accessible to the cross-domain orchestrator as mentioned above.

The life-cycle of a service, however, should be controlled by the cross-domain orchestrator. The reason for this is that in most cases, if not all, a service will not be wholly contained within a single domain. Today this cross-domain function is very manual, especially in assurance and repair scenarios.

There is a large amount of triage that can be automated by the cross-domain orchestrator that engineers must do manually today. Additionally, it is often the case that auto-remediation can be performed to get a customer back in service or a network element functioning again, and then reported on for follow up as needed. In this scenario, it is possible that the engineer never has to be involved in the remediation action.

To enable this capability, it should be a goal to implement modeling discipline across the service provider organization in a manner that considers all of the above from both top down and bottom up views. There is a very important role to fill for those who intimately understand the device layer, and this capability could be centralized within an engineering group focused on modeling or distributed to engineering groups more closely associated with those devices.

Similarly, service modeling can be performed by distributed or centralized organizations within a service provider. The particular approach depends on the organizational structure of each company embarking on this approach.

The service modeling engineers should define the service, including the technical aspects of each PNF and VNF type involved, how those elements are chained together, and the policy definition of how those services are deployed, maintained, and decommissioned. This modeling of service and operations should be tightly integrated with the capabilities exposed by the device models used in the service composition.

5. Conclusion

As service providers look to enjoy the benefits and opportunities of service design and operation enabled by SDN and NFV, we will be employing data model-driven techniques more pervasively than in the past. The operations gap between the legacy network environment and these new approaches can be closed, but doing that will be a process of on-boarding, or adapting, the legacy network onto the new toolsets. In this way, a data-model driven approach can be used uniformly across the entire network, thereby better unlocking the value that still exists within these legacy deployments.

In addition to enabling the legacy network to be controlled with automation driven by standardized data models, the relationship of the various automation stacks should be managed so that an explosion of interdependencies does not result. Consequently, the use of end-to-end service orchestration across these domains is an important aspect to closing the operations gap.

Work in the industry to date across standards and open source organizations is addressing the NFV and SDN approaches as outlined in this paper. Even so, there is a danger that fragmentation of data modeling standards and practice will limit our collective ability to deliver the kind of network service provider customers will expect going forward. It is hoped that a unified set of SDN/NFV data model standards can be achieved. It is also encouraging to see developing industry traction around end-to-end service orchestration leveraging data model-driven techniques.

These are but some of the important pieces in the puzzle of designing and operating the service provider networks we all desire to achieve. It is hoped that the perspectives brought in this paper are helpful in advancing toward that goal.

6. Abbreviations and Definitions

6.1. Abbreviations

CLI	command line interface
ETSI	European Telecommunications Standards Institute
IDRO	inter-domain resource orchestrator
IETF	Internet Engineering Task Force
ISBE	International Society of Broadband Experts
LSO	lifecycle service orchestration

MANO	management and orchestration
MEF	Metro Ethernet Forum
MIB	management information base
NFV	network function virtualization
NFVI	network function virtualization infrastructure
OASIS	Organization for the Advancement of Structured Information Standards
OSS	operations support system
PNF	physical network function
SCTE	Society of Cable Telecommunications Engineers
SD-WAN	software defined wide area network
SDN	software defined networking
SFC	service function chaining
SNMP	simple network management protocol
SO	service orchestrator
TOSCA	topology and orchestration specification for cloud applications
vCPE	virtual customer premises equipment
VIM	virtual infrastructure manager
VNF	virtual network function
VNFD	virtual network function descriptor
VNFM	virtual network function manager
YANG	yet another next generation

6.2. Definitions

MANO	Management and orchestration is the architecture that was defined by ETSI to account for the NFV orchestrator, the VNF manager, and the virtual infrastructure manager.
NFVO	Network function virtualization orchestrator is the component in the MANO stack responsible for defining the service to be deployed in the NFV environment. This tool is also responsible for the instantiation of instances of those services, and the management of that lifecycle within the NFV domain.
PNF	Physical network function is a physical instantiation of a network functions such as a switch, router, CMTS, etc.
VIM	Virtual infrastructure manager is the component in the MANO stack that manages the storage, compute, and networking infrastructure of an NFV environment.
VNF	Virtual network function is the virtualized instantiation of a network function such as routing, firewall, etc.
VNFM	Virtual network function manager is the component in the MANO stack that is responsible for defining the VNFs involved in the virtualized service to be deployed. These VNF definitions are atomic components that can be combined in the NFVO to define that higher-level service. Additionally, the VNF manager is responsible for instantiation of instances of the VNFs involved in the service, and lifecycle management of those individual VNF components. The NFVO is responsible for orchestrating the lifecycle management of each of the VNFs involved for full lifecycle management at the service level.

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OFDM Cyclic Prefix Elimination

A Technical Paper prepared for SCTE•ISBE by

Tom Williams, Principal Architect, Cable Television Laboratories, Inc.
SCTE/ISBE Member
858 Coal Creek Circle
Louisville, CO 80027-9750
t.williams@cablelabs.com
+1 303-661-3486

Greg White, Distinguished Technologist, Cable Television Laboratories, Inc.
SCTE/ISBE Member
858 Coal Creek Circle
Louisville, CO 80027-9750
g.white@cablelabs.com
+1 303-661-3822

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1. Introduction

Cyclic prefixes (CPs) are overhead that can be eliminated, or at least greatly reduced. CPs, also known as guard intervals, are used on orthogonal frequency division multiplexing (OFDM) transmissions to facilitate equalization at a receiver. The equalization is typically accomplished in the frequency domain with a single complex multiplication of each frequency domain subcarrier. For this simple equalization method to work accurately, the cyclic prefix needs to be longer than any echo in the signal path. By using an overlapped Fourier transform, the cyclic prefix can be removed and frequency domain equalization can be performed with negligible inter-symbol interference (ISI). This linearization can also be accomplished entirely in the time domain with a finite impulse response (FIR) filter or an overlapped circular convolution.

Key messages of this paper include:

- Less or no CP means data rates increase. The gains for wireless applications are greater than wired applications.
- CP elimination means that the length of an OFDM block no longer needs to be long to minimize CP percentage overhead
- An FIR filter and an overlapped Fourier transform can produce the same frequency domain equalization result
- CP elimination works for single carrier and multicarrier
- Reduction in chip geometry increases speed and functionality, and makes additional processing practical

This paper describes the signal processing and provides an analysis of simulation results for a variety of channel conditions involving random noise and multipath.

2. Background

Distortions are generally categorized into two categories, linear and non-linear. Non-linear cable distortions include such impairments as amplifier clipping, amplifier compression, composite triple beat (CTB), common path distortion (CPD), second and third order distortion, and intermodulation. Linear distortions include such impairments as multipath distortion (also known as echoes, ghosts, or dispersion), amplitude tilt, and group delay (also called chromatic dispersion in fiber optic cable). Linear distortions may be caused by a delayed arrival of copies of an original signal due to reflections, such as radio waves bouncing off a water tower, or cable line impedance mismatches. They can also be caused by non-linearity of phase response, which may occur in filters. While the non-linear distortions demonstrate the characteristic of increasing the bandwidth of noise-like digital signals, linear distortions do not. This paper focuses exclusively on the linear distortions.

The three most commonly employed digital modulation techniques are single carrier, multicarrier, and spread spectrum, and all three need to somehow have linear distortions canceled to achieve best performance in the presence of random (or Gaussian) noise. If an un-equalized received signal has excessive linear distortion, it can’t be demodulated, even with no random noise present. At some point, all three modulation techniques have been used on cable systems.

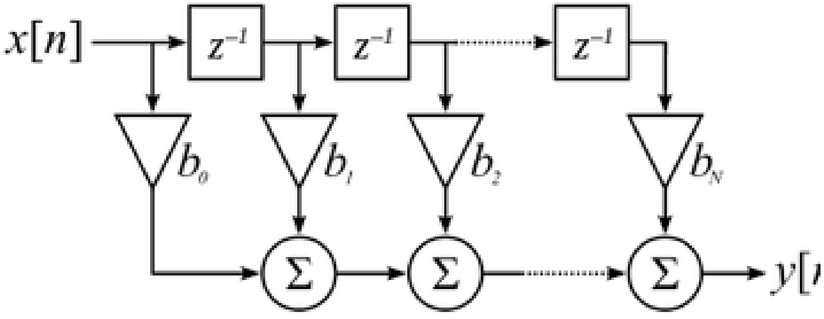
The basic method of linear distortion, or distortion elimination, is linear convolution. Equation 1 is the discrete form of the convolution integral. This convolution process operates on two time domain (TD) sequences of numbers, one which is periodic discrete samples of a received signal and one which is a correctional sequence of numbers. A time response that removes echoes is an impulse response called an inverse channel response. Looking at Equation 1, the time limits of -∞ to +∞ present an implementation problem. Generally, the channel impulse response may be limited in time, but a received signal may be continuous. An inverse channel response can generally be computed from a channel response, but sometimes an inverse channel response cannot be calculated, such as when a frequency response goes to zero at one or more frequencies.

Figure 1 is a block diagram of one type of echo canceling digital filter that implements Equation 1. It is called a FIR filter and it removes linear distortion by convolving a continuously received signal in the TD with a time-limited inverse of the channel's response (impulse response). The received signal passes through the delay elements (z^{-1}) and the multipliers' outputs are summed. The multipliers are programmed with coefficients b_0, b_1, b_2… b_n, which comprise the impulse response of the inverse channel response. This makes a distortion-free received signal if the taps are accurately programmed and there are enough of them. This TD equalizer is commonly implemented in silicon (hardware), but can also be implemented in software for low data rates. Sequences typically comprise complex numbers with real and imaginary components, or equivalently, magnitude and phase. A measure of a digital signal processor (DSP) chip's processing power is the number of multiply and accumulate operations it can perform per second.

$$\begin{aligned}(f * g)[n] &\stackrel{\text{def}}{=} \sum_{m=-\infty}^{\infty} f[m]\, g[n-m] \\ &= \sum_{m=-\infty}^{\infty} f[n-m]\, g[m].\end{aligned}$$

(commutativity)

Eq 1



A direct form discrete-time FIR filter of order *N*. The top part is an *N*-stage delay line with *N* + 1 taps. Each unit delay is a z^{-1} operator in Z-transform notation.

Figure 1 - FIR Filter of Order *N*

Figure 1 shows a filter that performs a linear convolution in the time domain.

However, there is an implementation problem with the elegant FIR filter of Figure 1 when a bandwidth is wide and there is a long echo: the number of taps becomes very large and the clocking rate is high. (A tap is a multiply and accumulate operation.) For example, if a 190 MHz wide DOCSIS 3.1 signal is distorted with a 5 µs echo, the TD symbol rate is 204.8 megasamples per second (Msamples/s). This is a time period of only 1/204.8e6 = 4.88 ns. So, a required number of taps to equalize a 5 µs echo is 5e-6/4.88e-9, which is 1024 taps, and they are all clocked at more than 200 megacycles per second. That is 205 giga complex multiply and accumulate operations per second for equalization! So, something more efficient and less costly in terms of hardware and power consumption was needed for wideband reception.

The convolution theorem states essentially that a convolution of two time sequences can also be accomplished by a multiplication in the frequency domain, as shown in Equations 2 and 3.[2][2]

Eq 2

$$\mathcal{F}\{f * g\} = \mathcal{F}\{f\} \cdot \mathcal{F}\{g\}$$

where · denotes point-wise multiplication. It also works the other way around:

Eq 3

$$\mathcal{F}\{f \cdot g\} = \mathcal{F}\{f\} * \mathcal{F}\{g\}$$

This theorem suggests an alternate solution to the FIR filter complexity: do equalization in the frequency domain (FD) by multiplying each FD subcarrier by a single complex correction coefficient. The conversion of the time sequence into a FD sequence can be done using a discrete Fourier transform, however the time to frequency conversion process is computationally intensive. Equation 5 is the formula for the discrete Fourier transform, and Equation 4 is the formula for an inverse Fourier transform, which converts a FD signal back into the TD. Fortunately, an efficient method of performing the discrete Fourier transform was discovered in the mid-1960s by Tukey and Cooley, and it is called a fast Fourier transform (FFT)[4]. By using a fast transform, the number of multiply steps is drastically reduced from N^2 down to N/2log2N, where N is the FFT size. There has been a sequence size requirement for performing a Fourier transform, and that is that the size of the sequence of numbers be limited to 2^N, where N is an integer number. There are now fast transforms that can efficiently transform sequences whose length is a prime number.

$$f[k] = \frac{1}{N} \sum_{n=0}^{N-1} F[n] e^{+j \frac{2\pi}{N} nk}$$

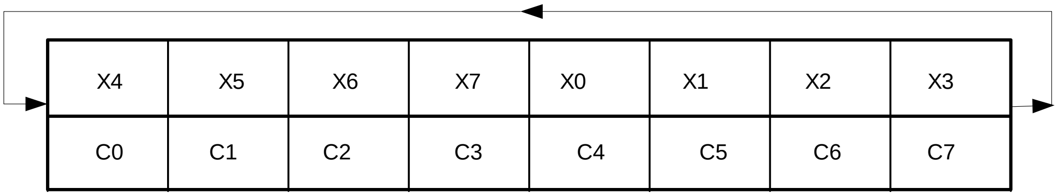
Eq 4

$$F[n] = \sum_{k=0}^{N-1} f[k] e^{-j \frac{2\pi}{N} nk}$$

Eq 5

Another observation that should be made is that the formula for the FFT and IFFT are nearly the same, except for two details, the IFFT has a scale factor of 1/N, and a negative exponential on *e*.

There is a second issue with using FD equalization. Equation 5 implements the equivalent of a circular convolution, not a linear one. See Figure 2, which is a block diagram illustrating an eight-element circular convolution. With a circular convolution, the convolution result is obtained by multiplying each term in the X sequence by a matching term in the C sequence and summing all products. This is followed by shifting the X sequence to the right one step and repeating. At the end, the rightmost term is barrel shifted back to the left. In other words, what is needed is a continuous efficient convolution process, and what is available is an efficient batch (or block) circular convolution process.



X4	X5	X6	X7	X0	X1	X2	X3
C0	C1	C2	C3	C4	C5	C6	C7

Figure 2 – Eight-Element Circular Convolution Block Diagram

In Figure 2, each Xn term is multiplied by the Cn term underneath it, and the products are summed. Next a circular shift to the right is performed on the top row and the process is repeated.

Two FD equalization options are available, form the data into blocks for block processing, or make a linear process out of a pipelined block process.

OFDM is a multicarrier technology that uses the first option, but a problem is encountered with extraneous energy from echoes entering a circular convolution. Figure 3 (top) illustrates three successive signal sequences, W, X, and Y, (as transmitted) where sequence X is preceded by sequence W, and followed by sequence Y. Figure 3 (bottom) illustrates the real-world problem of sequence contamination from echoes. A time-delay (and attenuated) copy of W’s waveform enters the X transform block, due to a trailing echo. This unwanted energy causes ISI and must be removed. The conventional solution is illustrated in Figure 4, where a CP is formed by copying time samples from the end of X and pasting them onto the front of X, making it longer. The numbers included in a transform are not influenced by the echo because the echo dies out before transform samples are captured.

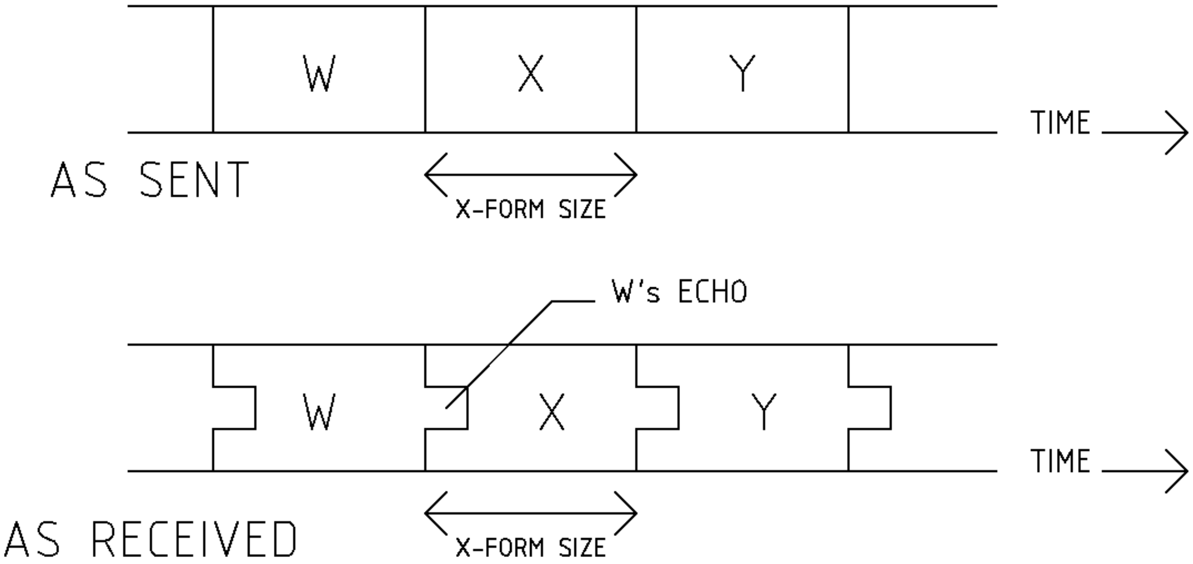


Figure 3 - Problem When Extraneous Energy (from W) Gets into X's Transform

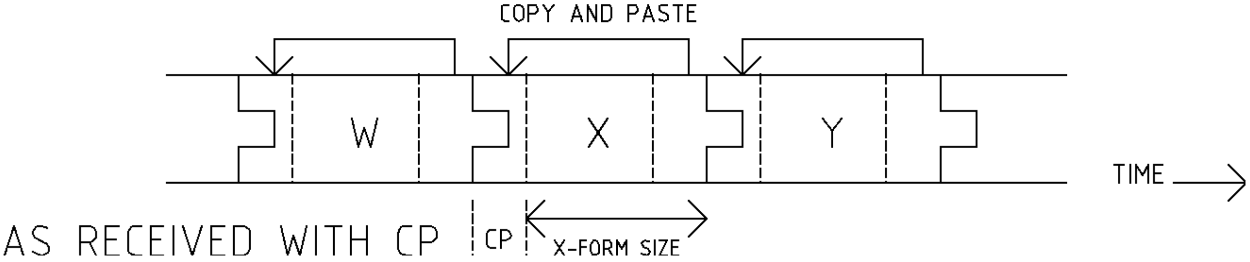


Figure 4. Conventional Solution

When a CP is copied from the latter part of the X TD sequence and pasted onto the front of the X TD sequence, the transmission is made longer by the length of the CP. The echo from W dies out during the CP, which not included in the transform process.

Note that this illustration applies to trailing echoes. In RF channels, leading echoes are sometimes encountered due to propagation characteristics. So, a CP must be long enough to accommodate both leading and trailing echoes. The CP also needs to be long enough for group delay variation in the channel.

Figure 5 depicts a way to eliminate the CP by using a longer overlapped circular convolution, and tossing the symbols on the beginning and end when the TD convolution is finished. So, an overlapped circular convolution starts capturing time samples in the middle of W, captures all of X, and stops capturing in the middle of Y. When the equalization is finished, the ½ of W and ½ of Y are discarded and the equalized X block is saved. The process is repeated next on the Y block. Saved equalized symbols are pasted together to make a clean output stream.

If the number of symbols in X is large, this same process can be done more efficiently in the FD. The TD samples are converted to the frequency domain, where equalization takes place on the entire sequence, followed by a conversion back into the time domain where the contaminated ends are eliminated. This overlapped transform is subsequently repeated with Y in the middle, and the good center symbols are combined to make a continuous flow in the TD.

If the underlying modulation in W, X, and Y is a single carrier type, the symbols are sliced and forwarded to the forward error correction (FEC). If the underlying W, X, and Y blocks are multicarrier (OFDM), another FFT must be performed on the de-ghosted sequence before slicing, followed by FEC. If the underlying W, X, and Y blocks are spread spectrum, they must next be de-spread.

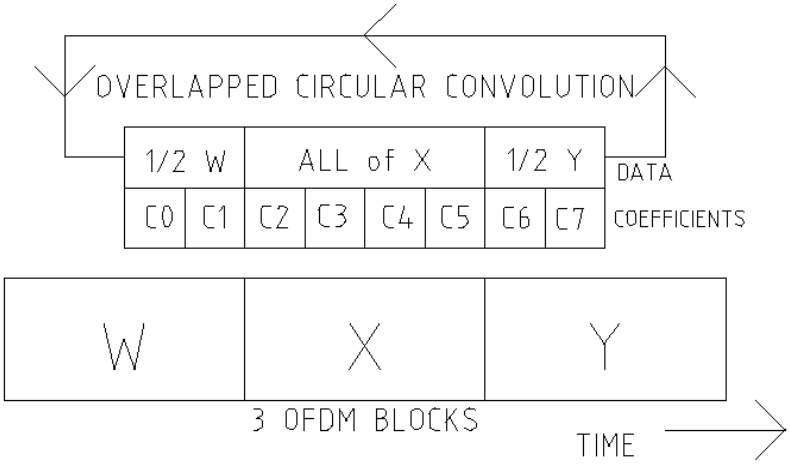


Figure 5 - Overlapped Circular Convolution

An enlarged circular convolution (or equivalently overlapped Fourier transform), combined with TD equalization, recovers the X sequence without a CP.

Note: An overlapped Fourier transform is just one way to achieve a linear convolution and is equivalent to an enlarged circular convolution. Furthermore, the process linearly operates on any sequence of information-bearing numbers in a non-discriminatory fashion. Likewise blocks W and Y can be vacant (dead air time), another type of signal, or a training signal.

Figure 6 is a block diagram of the processing associated with an overlapped Fourier transform equalizing an OFDM symbol with no CP. The block diagram of Figure 6 performs the identical operation as the FIR filter in Figure 1. A continuous TD stream of symbols is received, formed into blocks of Nc symbols and converted to the FD, where an equalizing single complex multiply occurs at each subcarrier frequency. The equalized FD overlapped transform is next converted back into the TD, where symbols (shaded in gray) are discarded. This process repeated and the equalized center parts are pasted together for an equalized TD symbol stream. (ref. [6] Kudo NHK paper)

Figure 7 is a block diagram with an additional FFT step added on the bottom of the figure. This puts the equalized signal back into the FD which is required if the underlying modulation is OFDM.

Note that this process has considerable flexibility:

1. The equalization process is modulation agnostic as to what type of data is being linearized. The input data may be continuous or made into blocks.

2. The (frequency domain) equalization can be done on multiple blocks at the same time, across block boundaries. A large block can also be broken into sub-blocks for equalization.
3. The size of the transform block can be made larger or smaller as desired. In the case of conventional OFDM, the length is made large so that the overhead of the CP is not too burdensome of a percentage of the total time. However, phase noise stability becomes more difficult when a transform length is long.
4. If a very long echo is encountered, Nc symbols can be enlarged at the receiver. This is a valuable feature for terrestrial broadcast signal, which can suffer from very long echoes.
5. A too-short (or stubby) CP can be used for synchronization, if desired. Too-short is defined as not long enough to compensate for the longest expected echo in a channel.
6. Another signal can be used for receiver synchronization with better properties than a CP, like lower crest factor, or better autocorrelation properties. A chirp or a Zadoff-Chu sequence are good candidates. (ref [7] on ZC)
7. Continuous pilots can also be used for synchronization. Timing for start of block can done by putting a set of captured pilots into an IFFT, with zero for all data subcarriers. A resulting TD impulse response will show if the timing was early or late.

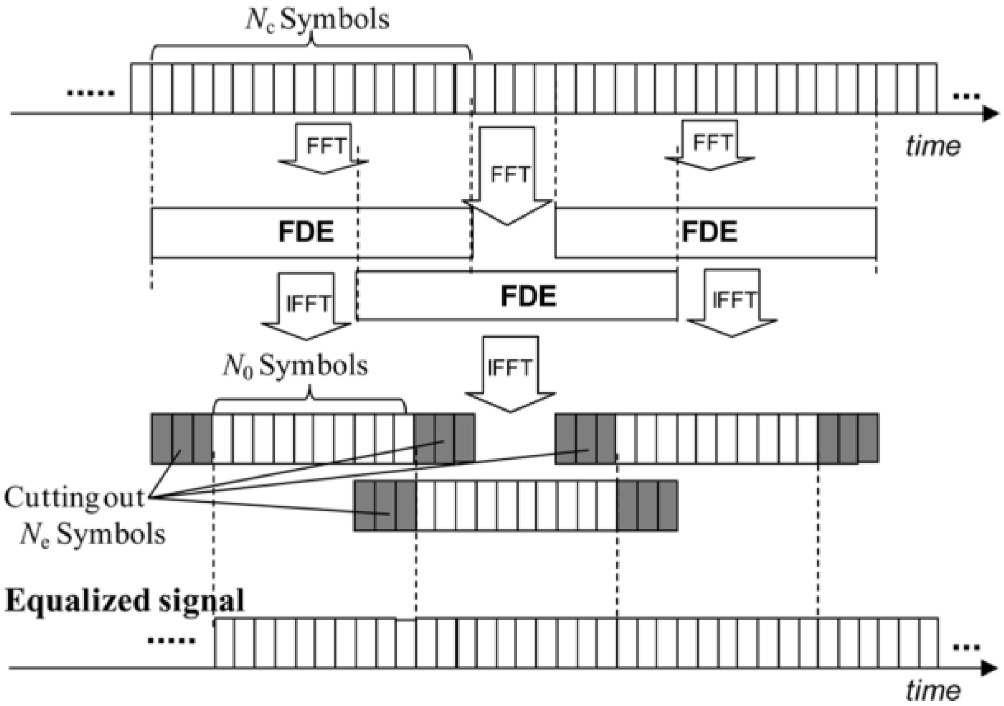


Figure 6 - Processing Block Diagram Associated - Overlapped Fourier Transform Equalizing an OFDM Symbol with no CP ref. [6]

An overlapped Fourier transform is used to equalize a signal. An equalized TD signal is made by combining the center N_0 symbols of the overlapped transform.

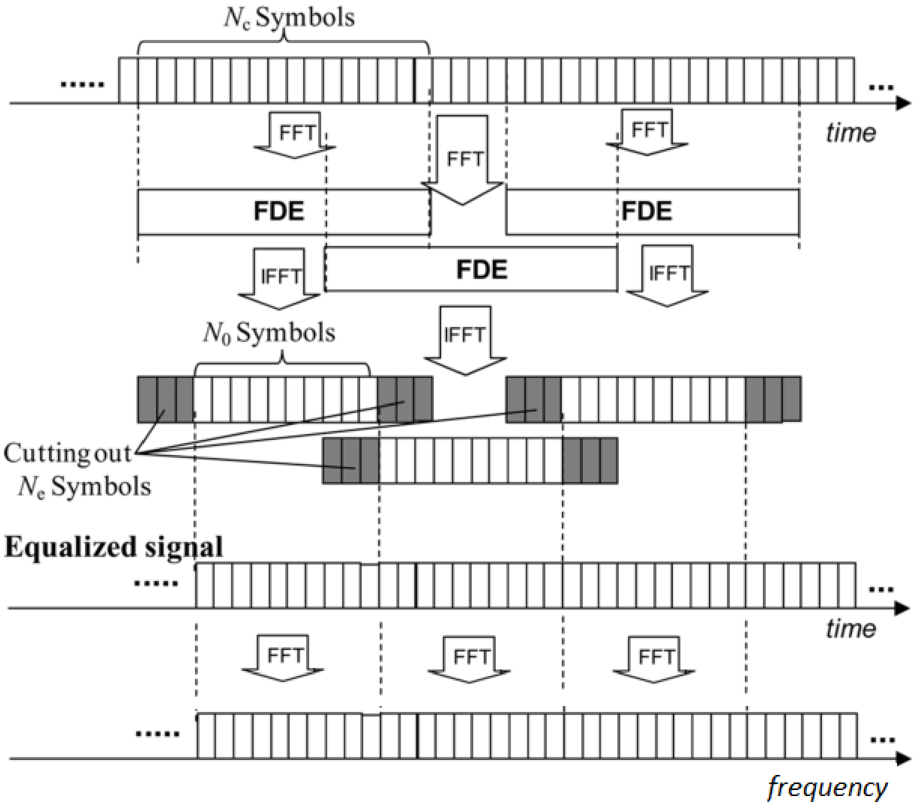


Figure 7 - Block Diagram with Additional FFT Step for OFDM(A)

Figure 7 is the same as Figure 6 except another step has been added (on the bottom) to form TD stream data into blocks and transform them into blocks of FD symbols.

3. Demonstration

This idea has been implemented in two hardware demos and in software using Matlab. **Error! Reference source not found.** has the Matlab code with in-line comments.

The first wired hardware demonstration was done with a LeCroy Arbitrary Waveform Generator transmitting through an echo-generating coaxial network into a LeCroy HDO digital oscilloscope acting as a receiver. This same demo can also be done on upstream cable plant. This equipment's wiring diagram is shown in Figure 8. Figure 9 is a photo of the test equipment. The received burst is illustrated in Figure 10 (top) and contained a QPSK training signal, followed by three 64-QAM OFDM blocks CPs. Figure 10 (bottom) shows the spectrum of the transmitted signal impaired by a severe echo. The transmitted OFDM had an FFT size of 2048 and a subcarrier spacing of 36 kHz. The signal occupied the band between 5 MHz and 85 MHz. Equalization was performed on the middle burst, using an overlapped Fourier transform. A linear frequency response is shown in the left side of Figure 11 and constellation plot is shown in the right side of Figure 11. The constellation plot shows a number of impairments, such as a small frequency offset between transmitter and receiver, and phase noise jitter. But without equalization, the constellation diagram (not illustrated) looks like random noise. The code for the hardware demo was written in C/C++.

The second wireless hardware demonstration was done with two Ettus B200 software defined radios, one used for transmissions and one used for reception. The transmit hardware is illustrated in Figure 14. Using separate transmitter and receiver introduces a frequency offset between the two separated devices. The demonstration burst consists of a 64-sample Zadoff-Chu (ZC) sequence, followed by fifteen 64 sample OFDM blocks without pilots and without CPs, followed by another Zadoff-Chu sequence. The transmitted signal is illustrated in Figure 15. Two Zadoff-Chu sequences were used for determining the timing offset between transmitter and receiver, channel estimation, and start of block timing. The modulation order was QPSK. The Zadoff-Chu sequence frequency domain components are plotted in Figure 16. Note that while the Zadoff-Chu time domain energy is flat, the spectral energy is almost flat. The demo was run around 800 MHz and around 2.4 GHz, and with symbol rates of 8 and 16 Msym/s. Figure 17 is a demo plot showing the received signal, channel estimation from the first Zadoff-Chu sequence, and a recovered constellation.

Figure 12 is a plot of 1024-QAM from the included Matlab code with a 1 µs echo at -6 dB and -40 dB random noise. The left plot is a received signal before equalization and the right plot is the received signal after equalization using an overlapped FFT.

Figure 13 is a plot from Matlab simulations that shows the resulting MER in dB (vertical axis) vs. the strength of a 1µs echo in dB (horizontal axis) as echo strength changes. Background noise was kept at a constant 50 dB SNR for this simulation. Even with a severe echo, the MER after correction is close to input background noise.

Simulations in Matlab reveal experimentally that an overlapped Fourier Transform is not an approximate substitute for a FIR filter, but can be a mathematically exact replacement for a FIR filter.

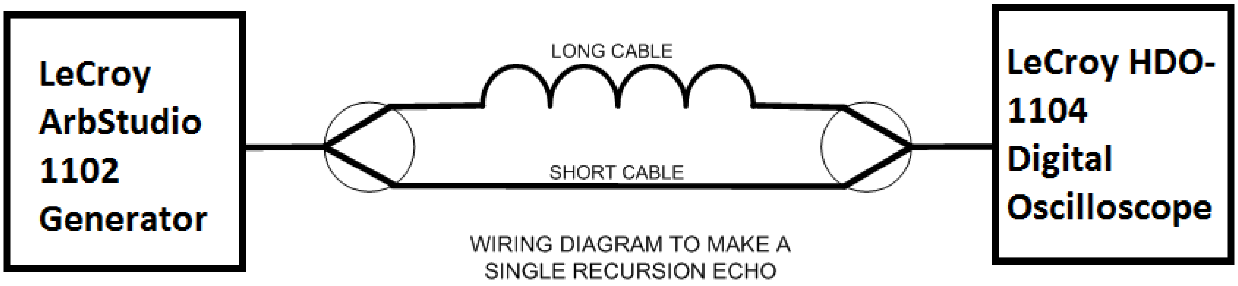


Figure 8 - Hardware Simulation Wiring Diagram

Note: An echo is created with two splitters and two pieces of cable, one short and one long. The duration of the echo is the delay difference between the two cables.

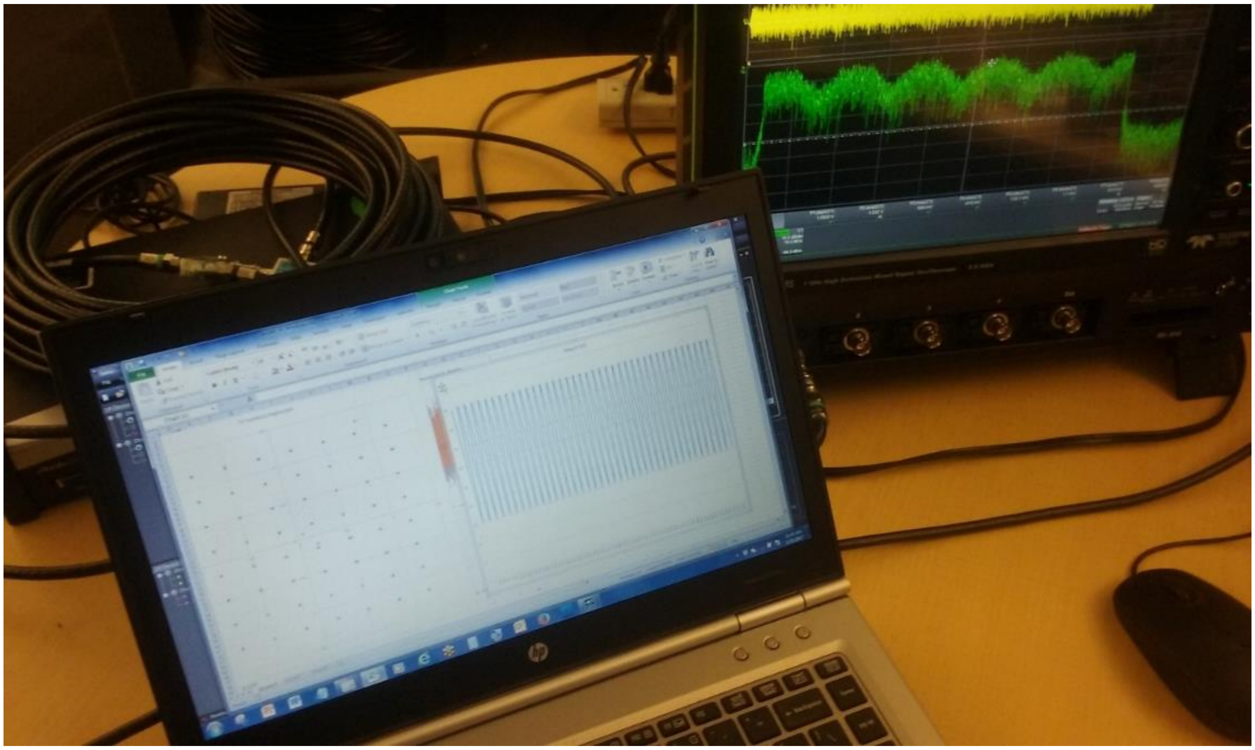
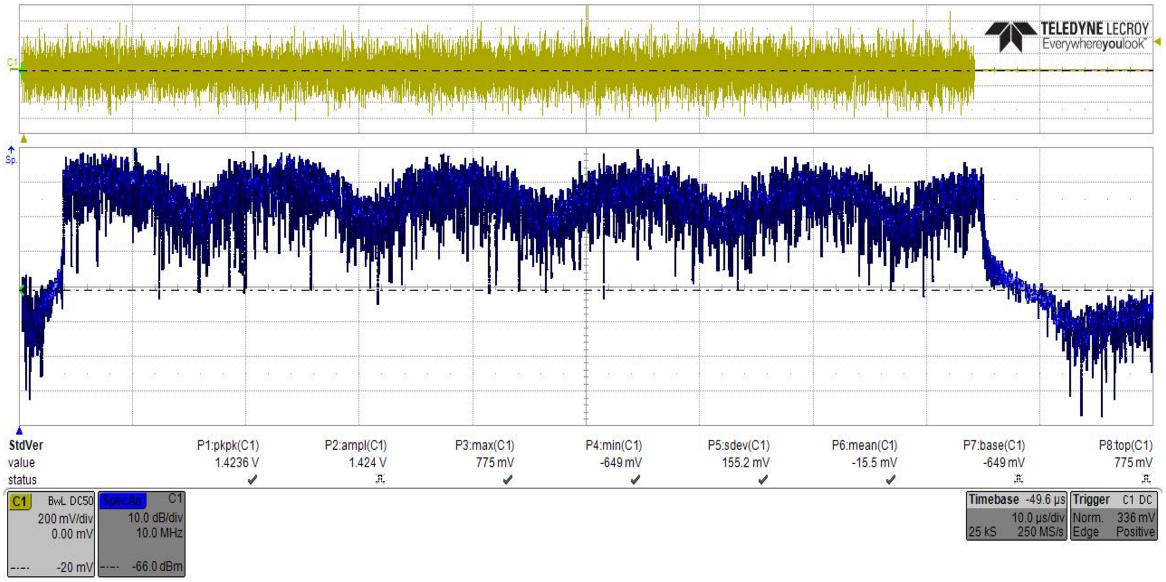


Figure 9 - Equipment Used in wired Hardware Simulation



StdVer	P1:pkpk(C1)	P2:ampl(C1)	P3:max(C1)	P4:min(C1)	P5:sdev(C1)	P6:mean(C1)	P7:base(C1)	P8:top(C1)
value	1.4236 V	1.424 V	775 mV	-649 mV	155.2 mV	-15.5 mV	-649 mV	775 mV
status	✓	⎍	✓	✓	✓	✓	⎍	⎍

C1 BwL DC50 200 mV/div 0.00 mV -20 mV

SpecAn C1 10.0 dB/div 10.0 MHz -66.0 dBm

Timebase -49.6 µs 10.0 µs/div 25 kS 250 MS/s

Trigger C1 DC Norm. 336 mV Edge Positive

Figure 10 - Time and Frequency Plots of the Received OFDM Burst

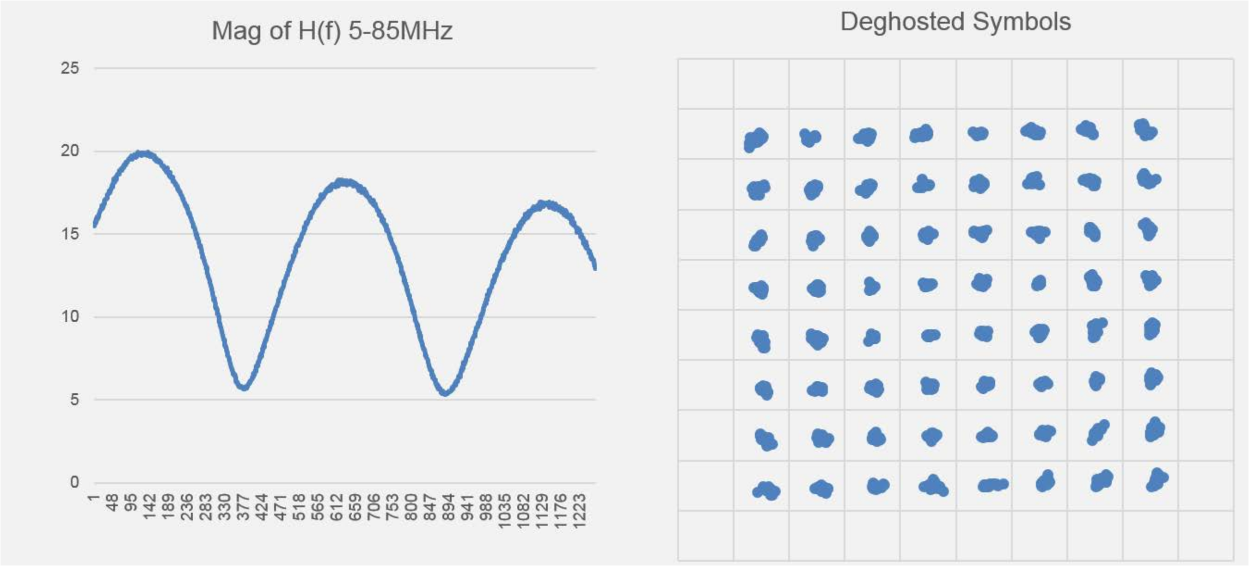


Figure 11 – 5 MHz to 85 MHz Channel Response (on left); Constellation Plot (on right)

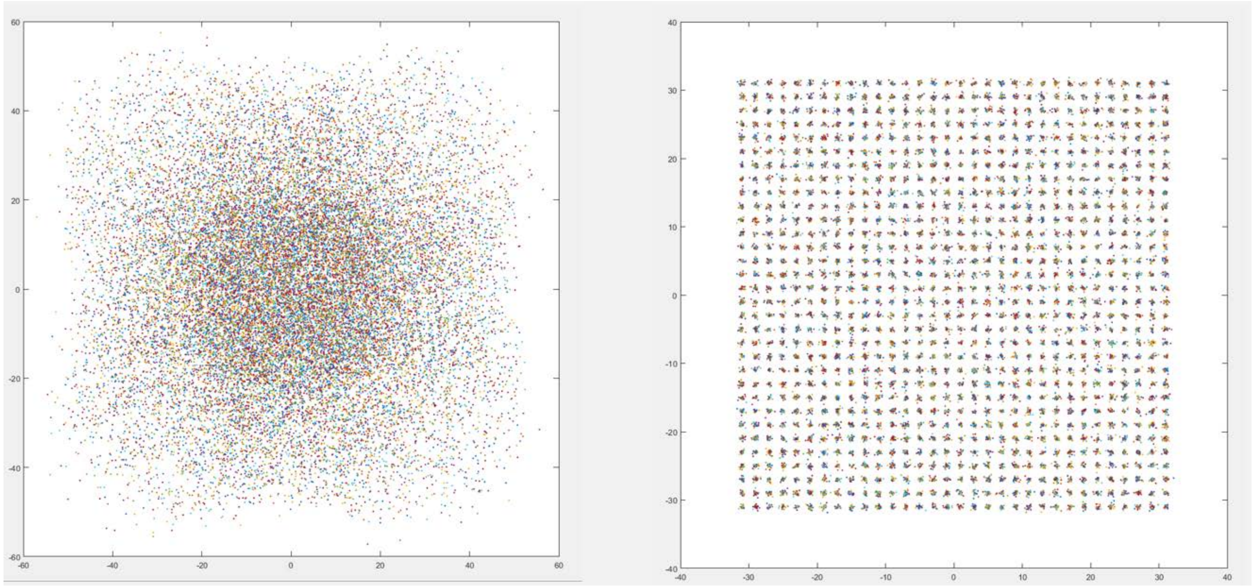


Figure 12 - Matlab plots of Code in Appendix A with 1 μs Echo at 6 dB

Note: The left plot is with equalization off and the right plot is with equalization on. An overlapped Fourier transform was used with no CP.

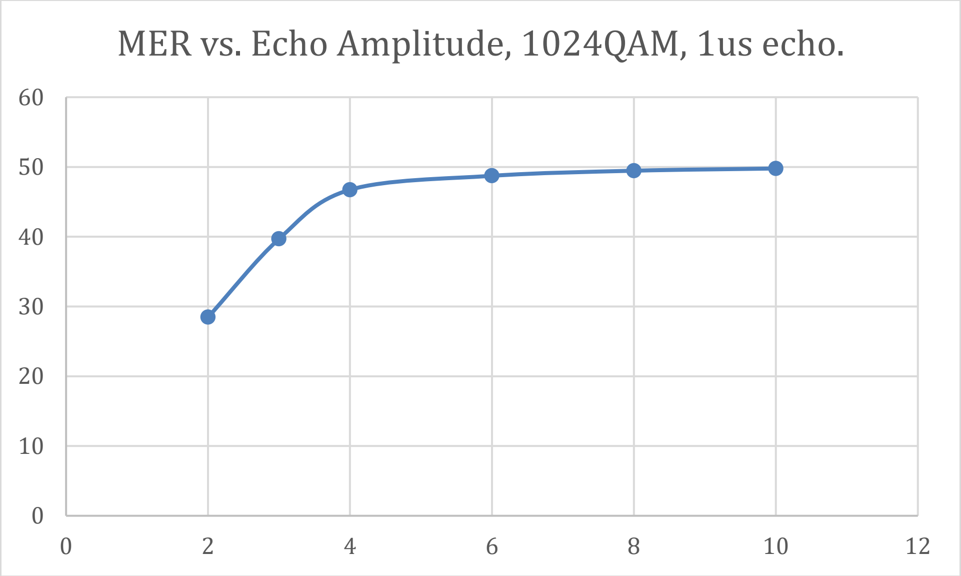


Figure 13 - Matlab Simulation Result, with 1024-QAM and a 1 µs Delay Echo

Figure 13 shows resulting MER in dB after echo cancelation vs. the strength of the echo in dB.

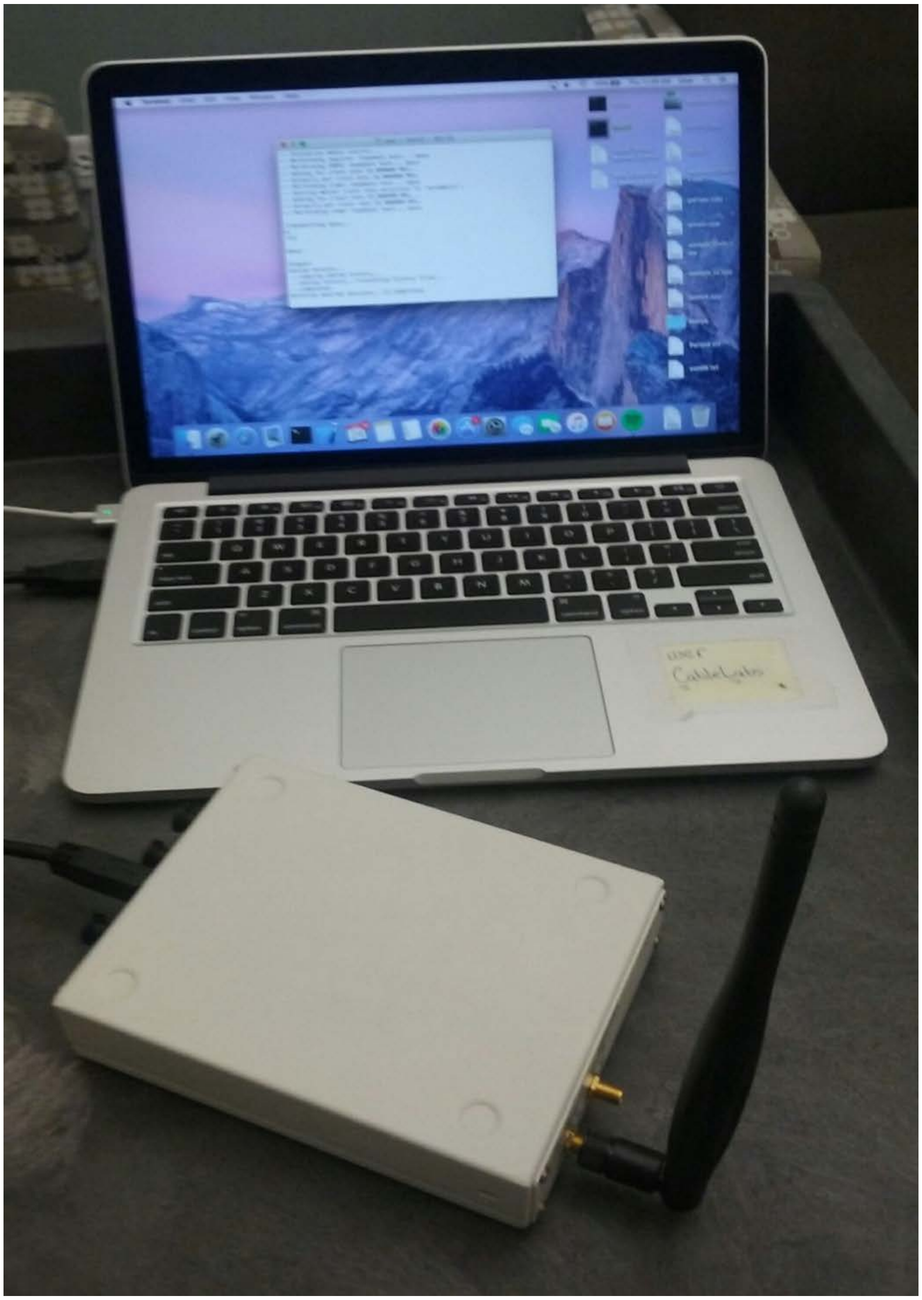


Figure 14 - Transmitter Hardware with Computer

Note: Driving an Ettus B200 SDR, connected to an antenna.

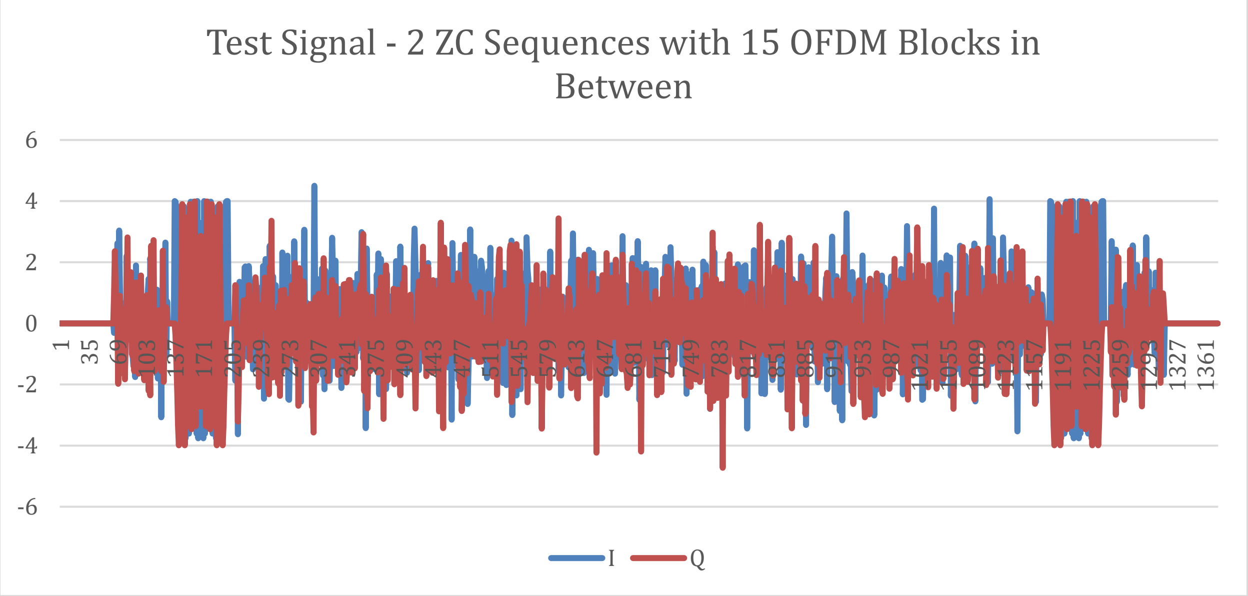


Figure 15 - Wireless Test Signal

Note: Illustrating two 64 symbol Zadoff-Chu sequences with 15 64 symbol OFDM blocks, with no pilots and no cyclic prefixes.

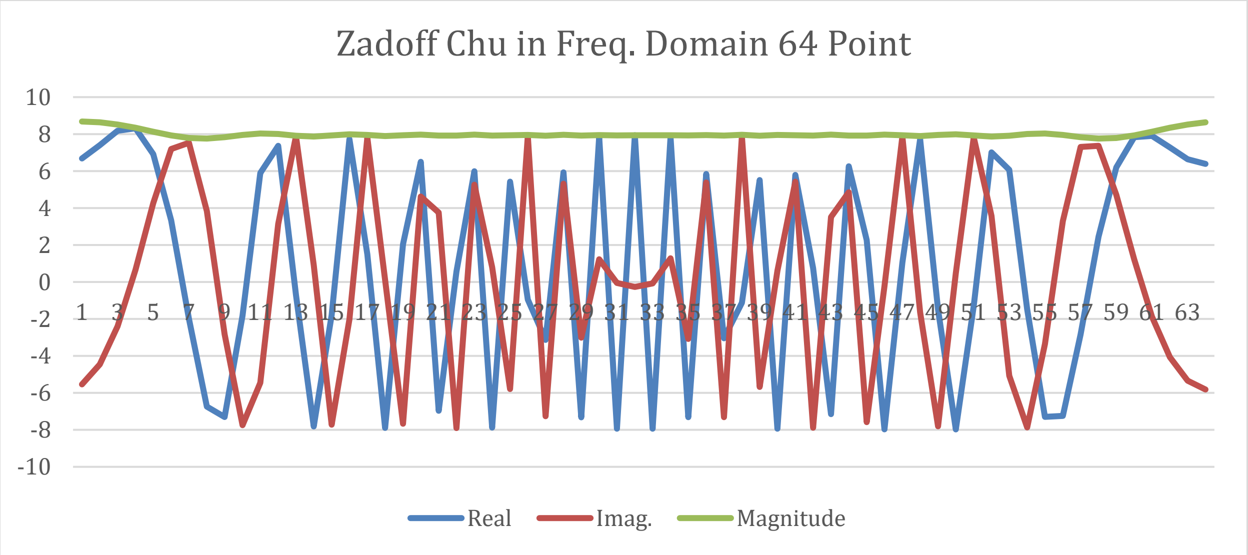


Figure 16 - The 64-Symbol Zadoff-Chu Sequence in Figure 14

Note: Viewed in the frequency domain. Time domain signal has a flat magnitude, and frequency domain components are nearly flat (green trace), so it makes and excellent training signal with zero crest factor.

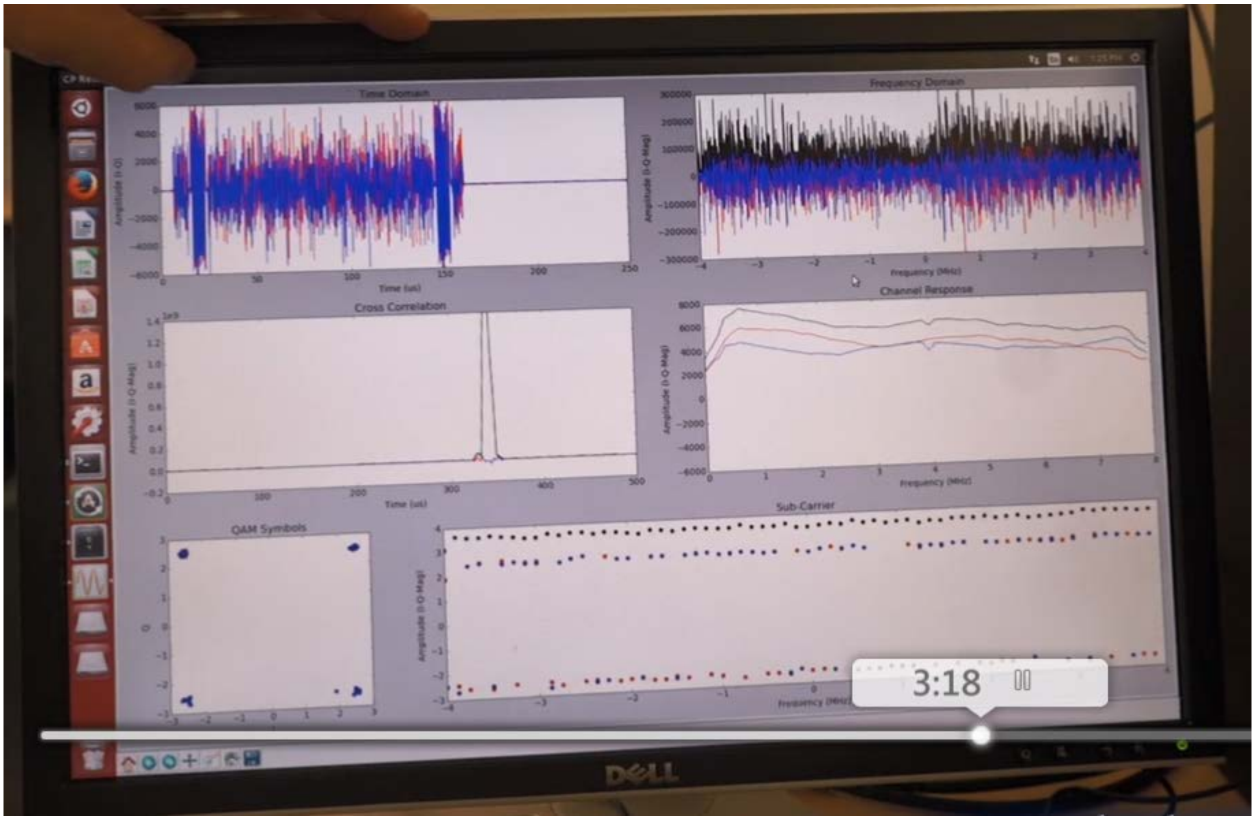


Figure 17 - Receiver Display Screen for Wireless Demo

Note: Upper left is a time plot of the received test signal. Upper right is FFT of received test signal (spectrum), middle left is correlation peak between two ZC sequences for finding frequency offset and timing. Middle right is training signal spectrum, magnitude, real, and imaginary. Lower left is equalized constellation, 64 points on one of 15 OFDM bursts. Lower right is real and imaginary samples vs. frequency for 64 subcarriers.

4. Applications

Equalization using an overlapped Fourier transform, or equivalently an overlapped cyclic convolution, can be used in wired or wireless applications. Keep in mind, the processing steps just replace a FIR filter with a pipelined process using frequency domain equalization. In a terrestrial broadcast environment, OFDM has generally proven superior when there are deep fades, but extremely long echoes can be encountered, requiring very long CPs, and hence an inefficient transmission system.

In cable, with a large population of DOCSIS 3.1 cable modems (CMs) deployed, the legacy downstream units would need to be relegated to a downstream carrier with a CP, but future units could operate with a stubby CP, or no CP whatsoever. CMs operating in the 1.2 GHz to 1.8 GHz band have not yet been deployed, so that is a possibility for CP elimination. The upstream OFDMA modulation is a more interesting case, where pre-distortion is used by CM upstream transmitters. If the channel is correctly equalized, the cable modem termination system (CMTS) receiver should not be doing anything with the CP except discarding it. So, a CP doesn’t need to be sent by a CM.

Multimedia over Coax Alliance (MoCA) is another good coaxial technique that could enjoy increased data rates by eliminating CPs. In this case. MoCA terminals can be installed house-by-house, so there are no legacy issues.

In wireless applications, such as long term evolution (LTE) cell phones or Wi-Fi, multiple input, multiple output (MIMO) is used to increase the data capacity of a band. Cyclic prefixes can be eliminated here also, as the pipelined overlapped Fourier transform works the same as existing FD or TD equalizing filters.

Note that the signals preceding and trailing the OFDM signal can be any type of signal, including non-OFDM signals, training signals, and no signal (dead air time). However, preceding and trailing signals should experience the same linear distortions.

5. Conclusions

1. Using an overlapped Fourier transform, which is equivalent to an overlapped (too-long) circular convolution, a sequence of numbers without a CP can be exactly equalized.
2. One can also de-ghost a single carrier received signal, without a CP, in the frequency domain.
3. The sequence of numbers can be from any type of modulation, including single carrier, multicarrier, or spread spectrum.
4. One can also de-ghost an OFDM transmission by running it through a correctly-programmed FIR filter, but for wide bandwidth the required number of taps may be excessive.
5. The sequence linearization process is separate from the other necessary steps a receiver must perform, such as discovering the carrier frequency, finding the start of a block, and finding the channel response. The second hardware demo showed solutions for all these steps.
6. Once a signal is de-ghosted, in the time domain or the frequency domain, it can be Fourier transformed or inverse Fourier transformed, and the echo will still be gone.
7. While a CP, which is a repeated waveform that is useful for synchronization, other sequences such as Zadoff-Chu sequences have better correlation properties and lower crest factors relative to CPs, which are repeated random energy. Zadoff-Chu sequences are a constant amplitude zero autocorrelation (CAZAC) function.
8. System adapts for exceedingly long echoes, as the overlapped transform size can be made arbitrarily long at the receiver.
9. The length of the overlapped transform is not constrained to OFDM block size. For example, two OFDM blocks can be linearized in the FD inside the same overlapped transform. While linearized, and back in the time domain, the two blocks may be separated for two block-by-block final FFTs.
10. Works for multiple combined transmissions, such as orthogonal frequency division multiple access (OFDMA) and single carrier frequency division multiple access (SC-FDMA). Note that in the receiver, FD customized multiplication coefficients (by the transmitter) must fix each transmissions’ impairment, subcarrier by subcarrier.
11. As an implementation detail, a too-short CP, which can be called a “stubby” CP, can be used to assist receiver synchronization. Stubby is defined as too short relative to the longest channel echo.
12. Pipelining can be used to speed up reception.

13. Technology works for all types of data links including optical, coaxial cable, MoCA, twisted pair, DSL, microwave, non-line of sight RF, terrestrial broadcast, 5G systems, and in MIMO wireless applications.
14. Moore's law, combined with the efficiency of FD equalization, make very high-speed implementations practical.
15. CP length need to compensate multiple recursions if echo is single recursion. Ref PNM Best Practices: HFC Networks (DOCSIS 3.0), appendix V.
16. It works!

Key messages

1. CPs are overhead that can be eliminated, or at least greatly reduced.
2. A FIR filter and an overlapped Fourier transform can produce a same result
3. Overlapped Fourier transforms work for single carrier and multicarrier
4. Reduction in chip geometry increases speed and functionality, and makes additional processing practical
5. CP elimination means that length of OFDM block no longer needs to be long to minimize CP percentage overhead.

6. Abbreviations and Definitions

6.1. Abbreviations

CAZAC	constant amplitude zero autocorrelation
CM	cable modem
CMTS	cable modem termination system
CP	cyclic prefix
CPD	common path distortion
CTB	composite triple beat
dB	decibel
DOCSIS	Data-Over-Cable Service Interface Specifications
DSL	digital subscriber line
DSP	digital signal processing
FD	frequency domain
FDE	
FEC	forward error correction

FFT	fast Fourier transform
FIR	finite impulse response
GHz	gigahertz
IFFT	inverse fast Fourier transform
ISBE	International Society of Broadband Experts
ISI	inter-symbol interference
LTE	long term evolution
MER	modulation error ratio
MHz	megahertz
MIMO	multiple input multiple output
MoCA	Multimedia over Coax Alliance
Msym/s	megasymbols per second
ns	nanosecond
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
RF	radio frequency
SC-FDMA	single carrier frequency division multiple access
SCTE	Society of Cable Telecommunications Engineers
SNR	signal-to-noise ratio
TD	time domain
ZC	Zadoff-Chu
µs	microsecond

7. Bibliography and References

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Appendix A - MATLAB Code

```
% Copyright (c) 2017, Cable Television Laboratories Inc.
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%
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% modification, are permitted provided that the following conditions are met:
%
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% of the authors and should not be interpreted as representing official policies,
% either expressed or implied, of the FreeBSD Project.
%
% Implementation of CP-less OFDM transmission and Freq. Domain EQ.
% based on T.Williams proposal
%
% Author:  Greg White 2/2/2017

% Simulation of idealized tx-rx chain for OFDM with no cyclic prefix

%% Configuration Values

% system configuration
Tsymbol=20e-6; %20us symbol time
fftsize=4096;
T_sub=Tsymbol/fftsize; % sub-symbol time
numsymbols=102; % how many sequential OFDM symbols to simulate, note: the first and
last will be discarded
QAM=1024; % Modulation Order

% channel configuration: the model here is an AWGN channel with a single echo
snr_db=50;  % AWGN SNR
echo_db=-6;  % echo amplitude relative to the direct signal amplitude
echo_t=1e-6; % echo time delay (in seconds)

% calculated values
N=sqrt(QAM); % number of unique symbol values in each dimension
E_symbol=2*mean((2*((1:(N/2)))-1).^2); % average subcarrier-symbol energy
E_noise=E_symbol*10^(-snr_db/10); % average noise energy per subcarrier-symbol


%% Generate transmitted signal
Xr=2*round(rand(fftsize,numsymbols)*N+0.5)-N-1;  % generate random symbols (real
component)
Xi=2*round(rand(fftsize,numsymbols)*N+0.5)-N-1;  % generate random symbols (imag
component)
X=Xr+j*Xi; % combine real+imag
x=sqrt(fftsize)*ifft(X); % Perform IFFT of each symbol to convert to time domain
x=x(:); % reorganize x into a 1-dimensional time sequence

%% Generate channel
echo_m=10^(echo_db/20);  % convert echo_db into linear quantity
T_echo=round(echo_t/T_sub); % convert echo delay into a sub-symbol index

%channel impulse response
channel=zeros(T_echo+1,1); % start with all zeros
channel(1)=1; % add a 1 at the zero-lag tap
channel(end)=echo_m; % add the echo at the appropriate tap

% AWGN noise sequence
noise=sqrt(E_noise/2)*(randn(length(x),1)+j*randn(length(x),1));

%% calculate received signal
y=conv(x,channel);  % convolve transmitted signal (x) with the channel impulse
response
y=y(1:length(x))+noise; % trim the resulting convolution back down to the original
length and add the noise

%% Show what the result would be if no equalization was done
```

```
Y=fft(reshape(y,fftsize,numsymbols))/sqrt(fftsize); % do the FFT to convert to
freq. domain

figure(1);
plot(real(Y),imag(Y),'.'); % plot the constellation
axis square; % plot formatting
axis(max(abs(axis))*[-1 1 -1 1]); % plot formatting

E_error=mean(mean(abs(Y-X).^2)); % calculate the average subcarrier-symbol error
energy
MER_noEQ = 10*log10(E_symbol / E_error); % calculate the MER with no EQ

%% Frequency Domain Equalization
%
% This is an omniscient FDE, i.e. it knows precisely what the channel response was

% pad the channel impulse response out to equal 2x the OFDM FFT size
% note: this code will break if echo_t is more than 2x the OFDM FFT size
channel_resample=zeros(fftsize*2,1);
channel_resample(1:length(channel))=channel;
CHANNEL_RES=fft(channel_resample);  % and convert the channel response into the
freq domain

%generate overlapping fft blocks that are 2x the OFDM FFT size
z_temp=reshape(y,fftsize,numsymbols);
z=[z_temp(fftsize/2+(1:fftsize/2),1:end-2);
    z_temp(:,2:end-1);
    z_temp((1:fftsize/2),3:end)];

Z=fft(z)/sqrt(2*fftsize); % convert to freq domain
Z= Z ./ repmat(CHANNEL_RES,1,numsymbols-2); % equalize
zz=ifft(Z)*sqrt(2*fftsize); % convert back to time domain
zz=zz(fftsize/2+(1:fftsize),:); % discard overlaps

%% OFDM receiver
ZZ=fft(zz)/sqrt(fftsize); %convert equalized time sequence to freq domain

%% Plot the resulting constellation
figure(2)
plot(real(ZZ),imag(ZZ),'.');
axis square

%% Display some statistics
% calculate the MER for each OFDM symbol and then give summary stats
E_error=mean(abs(ZZ-X(:,2:end-1)).^2);
MER = 10*log10(E_symbol ./ E_error);
disp('MER per OFDM symbol (in dB)');
disp({'Min','Mean','Max','Std'});
disp([min(MER) mean(MER) max(MER) std(MER)]);
```

Understanding the Limitations of Cable Modem-Based Upstream Interference Measurements

Impact of the home network and ways to get around the limitations of CM-based measurements

A Technical Paper prepared for SCTE•ISBE by

Jack Moran
Senior Director – Cable Access Networks Research
Futurewei Technologies Inc,
SCTE/ISBE Member

Table of Contents

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1. Introduction and Background

Historically the cable TV industry has struggled mightily for at least the past 25 years regarding how to perform measurements through the coaxial cable plant that provide meaningful and accurate estimates for signal quality. Perhaps more importantly this pursuit of meaningful signal quality measurements has always been accompanied by the immortal mantra that the measurement approach must be economical and easy to perform and, above all, automated.

In the last 15 years or so, the rise of DOCSIS 2.0 and beyond, with its significantly increased constellation sizes that provide major increases throughput capabilities, is a double edged sword in that the higher constellation sizes require much higher modulation error ratio (MER) to attain error free operation. It should be no secret to anyone reading this paper that these higher constellations come at a price, which is they are less robust to noise interference and, more importantly, the larger the constellation size the more the susceptibility to system non-linearity.

Therefore, the need for accurate signal quality measurements is virtually demanded with the more demanding larger constellation size modulations to determine if the MSO network signal quality is sufficient to support a given target goal for error free transmission of the larger constellation size modulations that are now commonplace with the introduction to DOCSIS 3.1.

One can understand the need for performing meaningful signal quality measurements routinely over the MSO network, but the real dilemma facing the MSO world is how to accomplish that task -- and how to do it economically.

In 2009 a committee was formed within CableLabs that was eventually named the Proactive Network Maintenance Committee (PNM) to begin the process as how to best utilize DOCSIS signals and DOCSIS measurements capabilities to accurately assess the network performance capabilities.

PNM today has proven to be quite successful in that using DOCSIS signaling and measurements of DOCSIS signals has been proven to be both reliable and, yes, automated for the most part.

In fact, one could argue the biggest breakthrough for PNM was when the concept of the CM performing FFT spectrum measurements appeared on the scene. It has proven to be perhaps the most successful measurement technique introduced since the 2009 start of the PNM work. With this powerful feature, the MSO gets to observe what the downstream signal looks like when it arrives at the location in the home where the CM is installed.

There are limitations nonetheless that must be recognized when one is viewing the results of a wideband spectrum measurement performed in the home environment and they are as follows:

- The FFT spectrum measurement is performed after the entire downstream spectrum or signal has made its way through the directional coupler (hardline street tap), the drop coaxial cable, the ground block connection, and finally the home coaxial cable wiring and coupling device. The signal measured has been impacted by this home environment connection.
- When one considers both the signal and the potential noise and/or system non-linearity that may be present, the CM can only see the noise (spurious energy) that has occurred in front of the tap location that the CM path is connected to and never what is further

beyond (after) the tap location. While this limitation is real and a function of the street or hardline coaxial cable tap design, it does become convenient in determining where a noise source or system non-linearity entered the plant.

- Finally, and perhaps a point that is often neglected, the slope of the spectrum that is received and hence measured by the CM is more a function of the home environment than the plant environment that the MSO wishes to understand better. The level and slope in the spectrum measured by the CM in any given home location is unique to the drop coaxial cable and home coupling device and coaxial cable wiring used in the particular home. Therefore, while the spectrum measurement performed by the CM is a very real condition for that particular CM, the measurement doesn't necessarily reflect what the MSO network response truly looks like at the input to that particular hardline tap.

2. Challenges in Characterizing Home Interference with a Cable Modem

The spectrum measurement issues discussed so far pertain only to the downstream or forward path direction of the plant and don't cover the problems unique for any CM that is now offering support of a full bandwidth spectrum measurement which includes the return path direction of the same plant.

Consider the home environment where the CM is connected to home coaxial cable wiring and the coupling device used to connect the CM also contains separate TV connections with or without a STB being used. Assume that there is a noise source in the home that is emanating from the TV or STB area of the home and that the CM performs an FFT spectrum measurement that includes the return path spectrum region. Three issues occur when attempting to measure upstream signals or upstream signal interference from the home coupling device that the CM is connected to and they are as follows:

- The CM spectrum measurement is misrepresenting what the real noise interference response truly looks like because the CM is seeing the interference signal through the port-to-port isolation (or shall we say lack port-to-port isolation) of the home coupling device and never the signal directly. The response of the noise source and the level of the noise source being captured with the FFT spectrum measurement is in fact the isolation response and level of the home coupling device. Reality comes into play here as the isolation response is generally unknown for any given CM connected in the network and reporting a return path direction spectrum measurement.
- While the hardline tap is designed to pass all downstream signals on to the CM, the same is not true at all for the upstream or return path direction of the plant. All the CM can see is any noise or interference source from within the home or, on rare occasion, a poor shield condition drop cable letting over-the-air transmissions signals enter via the drop coax cable. In the case of the over-air-transmission signals this return path FFT spectrum measurement would be successful and present itself to the CM as it appears on the drop coax. Additionally, for any wideband transient noise source (noise or system non-linearity) that is occurring from within the home, all the CM FFT spectrum measurement can capture is the isolation response of the noise or non-linearity spurious energy.
- The third major issue for the CM is that the noise and/or system non-linearity that may exist in the home is signal dependent. Due to the burst nature of return path signal transmissions, a spectrum measurement that is instantaneous and that also possesses the dynamic range capability to be able to perform an instantaneous spectrum measurement

while in the presence of its own return path transmission is required. It is nearly impossible to have an additional ADC that is both high-speed and at least 12 bits available at a low cost. This type of measurement function that can capture transient noise and burst signal transmission is more like the ADC design of the CMTS upstream receiver circuitry and not that of the CM.

So as one can see, the challenge of any CM performing even a reasonably accurate measurement of any transient noise or burst signal transmissions in the home is formidable at best and in truth virtually impossible.

The DOCSIS 3.1 CMTS has now available, to assist in the return path signal analysis, a set of test sequences (signals) that do improve the situation just described above. The test signal will afford the CMTS the ability to estimate the signal-to-interference ratio present when the given DOCSIS 3.1 CM is transmitting the test signal, but the test signal and interference signal must both travel through the remaining sections of the return path before arriving at the node and eventually the hubsite where the CMTS receiver is located.

Simply put, while the CMTS upstream receiver possess the ability to measure a wideband signal upstream, the CMTS is unfortunately only seeing this signal after it has been combined with all other paths and coupling devices on the entire return path. This makes the task of the CMTS determining the origin of this noise source again impossible.

3. Actual Home Interference vs. What the Cable Modem Measures

Before continuing with how to resolve this problem for all CM-based measurement systems, let us demonstrate what the interference signal truly looks like (response and total power) and what the CM spectrum measurement reports through the isolation response of the home coupling device.

In this section, a series of network analyzer measurements will be presented and compared to what would be observed by a CM-based approach. The results depict what the input signal of interference looks like at the port of the home coupling device versus what the CM FFT measurement input will look like of the same signal as seen through the isolation response of the same home coupling device.

3.1. Home Network Architectures and Their Impact on CM-Based Measurements

Prior to measurement responses, it will be quite useful to review a series of figures that show the actual connection and where the CM is in relationship to the TV or STB or noise source.

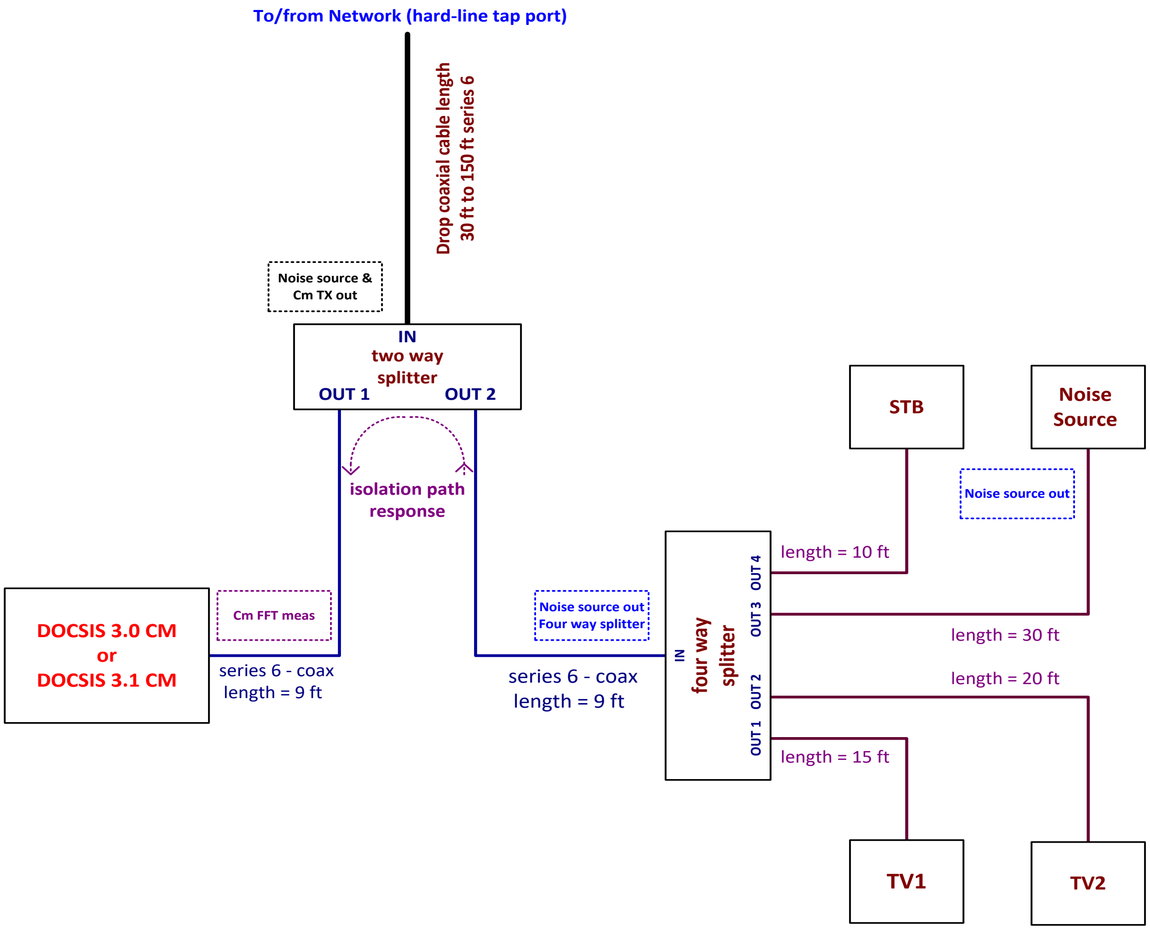


Figure 1a. Typical home connection environment – Using two-way splitter connection to ground block entry point

In this particular example of a home connection configuration the four-way splitter may or may not be amplified depending upon desired loss goals of a given MSO, but for the purpose of the example I have opted to use a passive four-way splitter. In this first example the noise source is arbitrarily assigned to port 3 of the four-way splitter but it wouldn’t make any difference which of the four ports the noise source was connected.

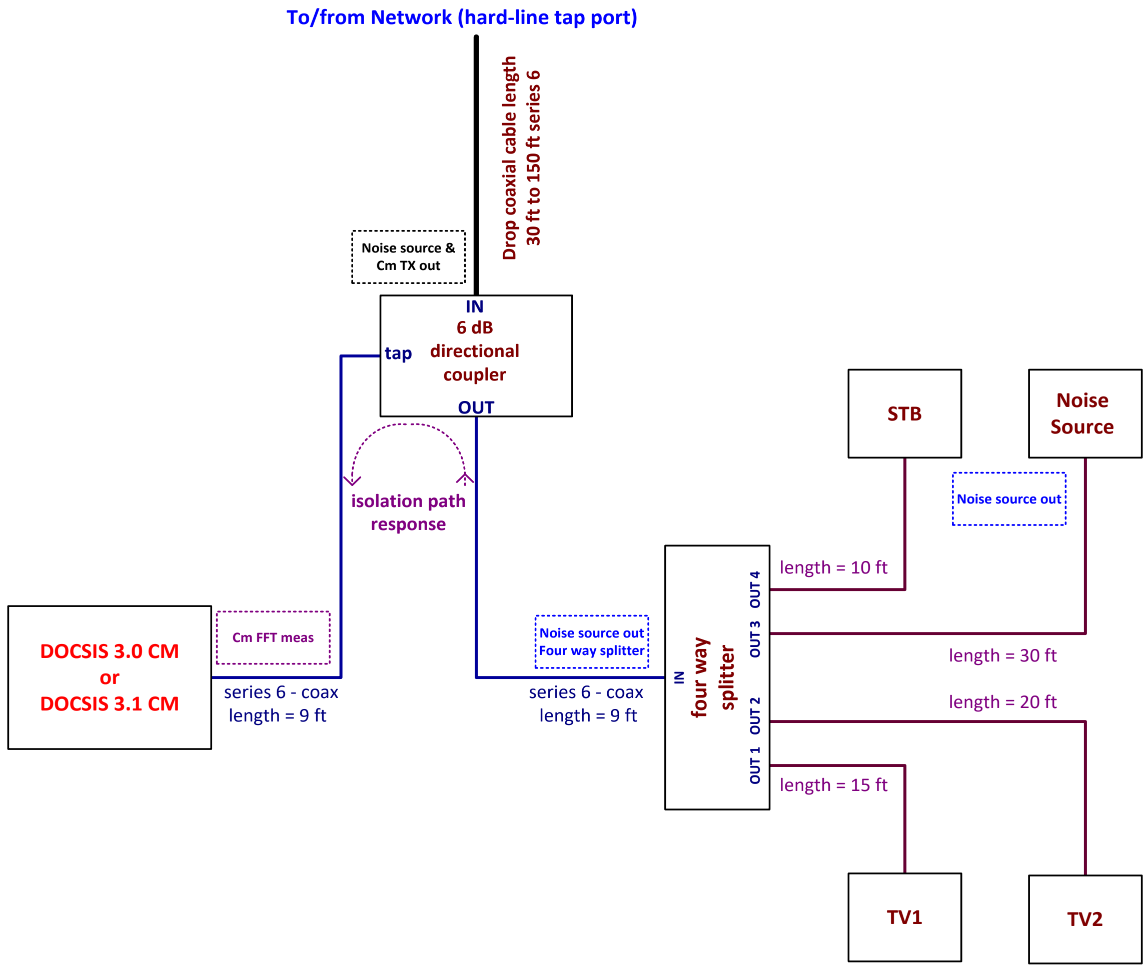


Figure 1b. Second typical home connection environment – Using 6 dB directional coupler connection to ground block entry point

Again in this example of a home connection configuration, the four-way splitter may or may not be amplified depending upon desired loss goals of a given MSO, but for the purpose of the example I have opted to use a passive four-way splitter. In this second example again the noise source is arbitrarily assigned to port 3 of the four splitter but it wouldn’t make any difference which of the four ports the noise source was connected.

The one major difference here is the isolation of a directional coupler is better than the two-way splitter used in the first example. With that said it is my understanding that although this configuration was once commonplace, it is seldom used by most MSOs today.

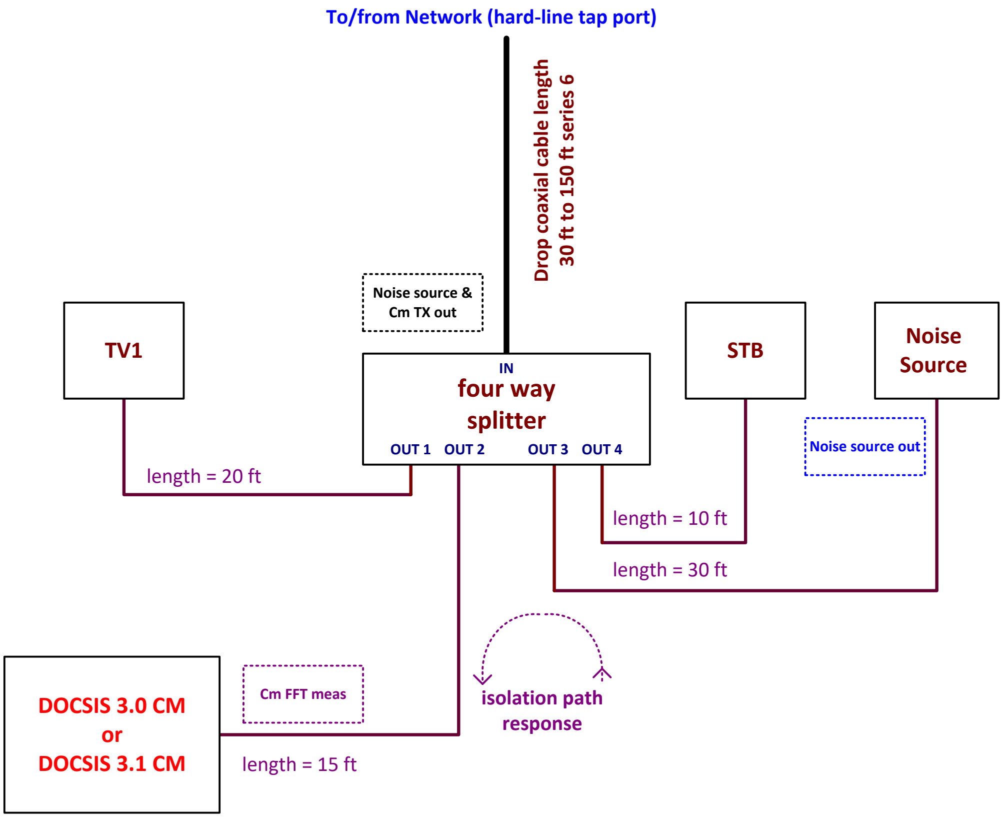


Figure 1c. Third typical home connection environment – Simply using a four-way splitter as the connection device to ground block entry point

In this third and final typical home configuration, the MSO has opted simply to use a single four-way splitter and be done with it. The obvious trade-off, as will be clearly shown in the response below, is that the CM has more loss to deal with.

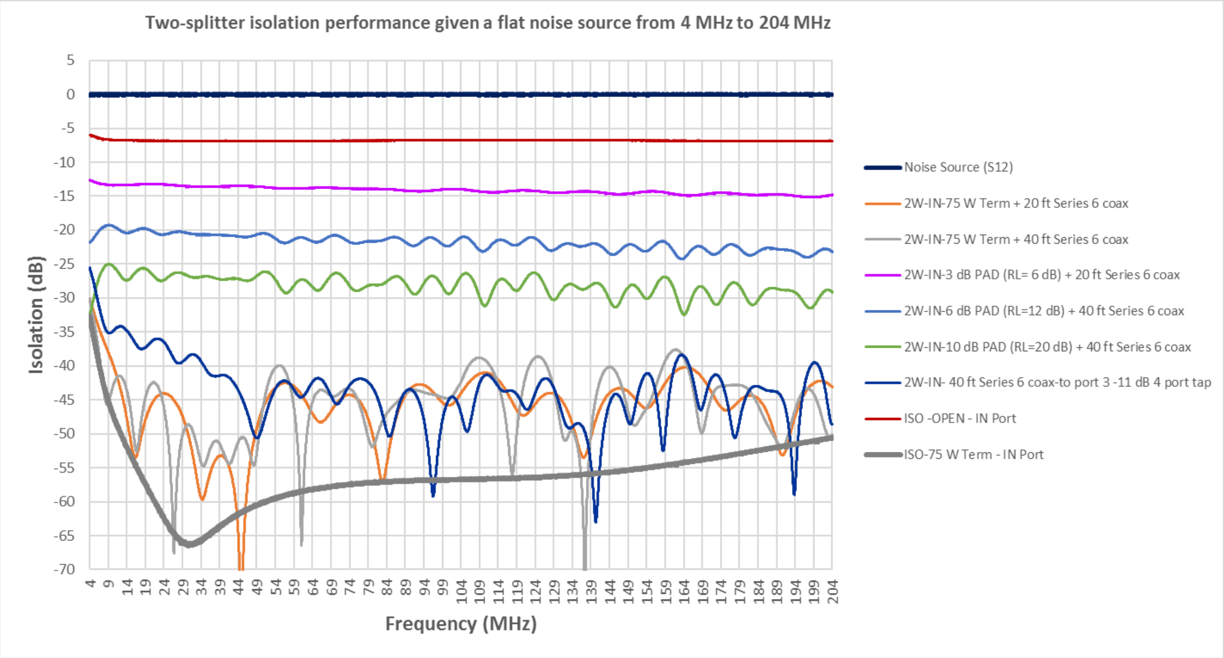


Figure 1d. Isolation response of typical two-way splitter given various termination characteristics connected to the input (output) port of two way splitter

The figure above demonstrates that the only variable that is key in determining the amount of CM FFT spectrum measurement error resulting from the CM only seeing the noise source through the isolation response of the splitter is the characteristics of the termination of the input (output) of the two-way splitter.

In fact one could argue that the only hope any MSO has of the CM reporting at least a representative sample measurement of the noise source is when the characteristics of the termination connecting to the two way splitter are poor. Ironically the better the termination characteristics are the more likely the MSO will remain clueless as to the actual characteristics of the noise source response and the accuracy of the level measurement of this interference signal (simply referring to it as noise for this paper) being reported by the CM FFT measurement. It is in jeopardy of being in serious error, especially as the return loss improves to just 12 dB, as Figure 1d clearly demonstrates.

For a better understanding of what one is observing in Figure 1d, perhaps I should take the time here to explain how Figure 1d results were actually measured by displaying Figure 1e below. But, before discussing Figure 1e it is important to stress the requirements of how to properly characterize any network component connected in the coaxial cable plant and or home environment coupling device, as is being performed in Figure 1e below.

3.2. Vector Network Analyzer Measurements as a Reference

A vector network analyzer is the definitive measurement instrument for characterizing linear characteristics of components in a network. When measuring an MSO coaxial cable plant or network, the following limitations / precautions must be followed:

- The use of a network analyzer is by definition a disruptive measurement and therefore the network signals must be either shut down for the duration of the test or the component being evaluated must be removed first from the network.
- Under no circumstance can any network analyzer be subject to network power! This means a galvanic isolation measurement technique must be utilized to save the network analyzer from being blown up.
- Generally speaking, the network analyzer is limited to a very local measurement and so it is generally never used to perform an end-to-end characterization measurement in the field as the distance would require two network analyzers to be used and synchronized together. There are two schools of thought as how to best do this, but it is beyond the scope of this paper. It is far easier to use a vector signal generator at one end of the connection and a vector signal analyzer at the other end of the connection to perform reasonably accurate characterizations without requiring two network analyzers would need to be synchronized together. Additionally, when using a vector signal generator it is possible to leave the network signals on, as the vector signal generator simply fills in the blank spectrum spaces and the vector signal analyzer can measure the existing signals as well as the signals the vector signal generator added when performing a characterization.
- The network analyzer is only the definitive choice for characterization of individual components (directional couplers, splitters etc. & hardline coax and drop coax portions of any given connection) on a test bench and not really in the field. I did take the network analyzer out to the field once and found it to slow the characterization process down by a factor of 3 times minimum. Sadly, the definitive accuracy that comes with using the vector network analyzer was simply not worth the amount of time necessary to complete a single node characterization.
- If one truly wishes to understand the hardline tap (directional couplers), home splitter characteristics, and all the associated coaxial cable connected to it in the home to a high level of certainty, than the correct measurement tool is clearly the vector network analyzer. Therefore, Figure 1e below is a test set up for how the measurements were performed that are displayed in Figure 1d.

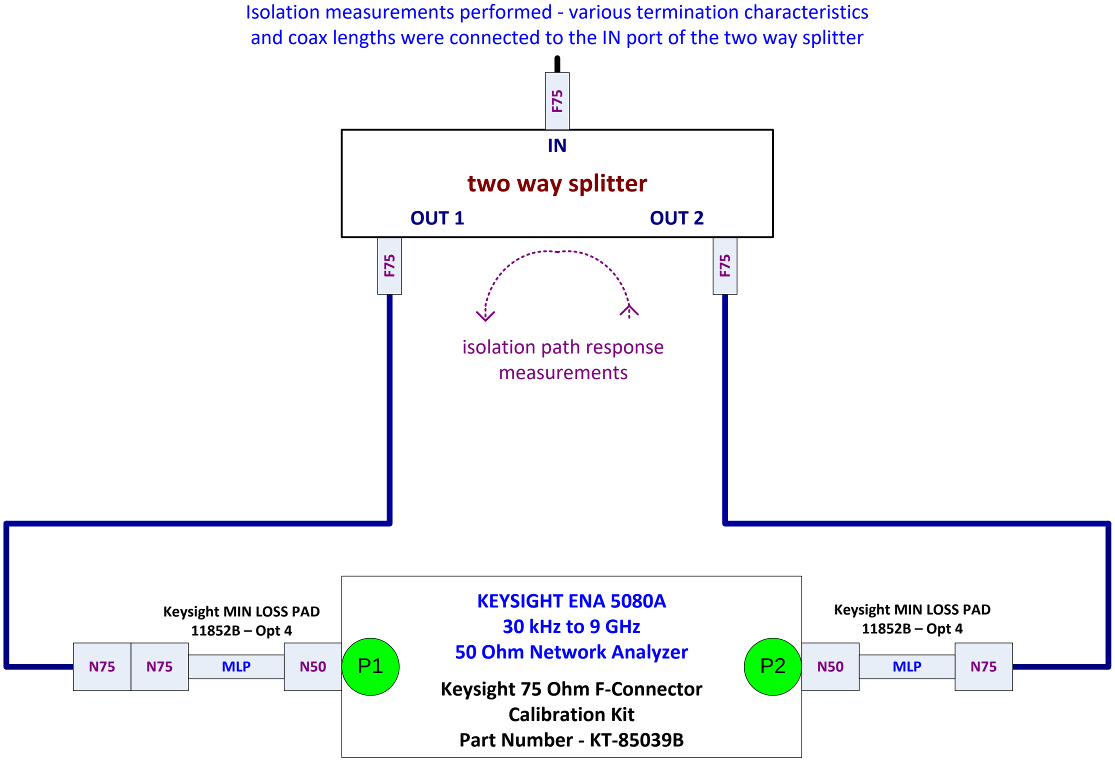


Figure 1e. Isolation response measurements performed using the KEYSIGHT ENA 5080A 50 Ω Vector Network Analyzer configured to perform 75 Ω measurements

For the purposes of this characterization of a two-way splitter, one can see that port 2 of the network analyzer is serving as the ideal wideband noise source signal for the isolation measurements performed.

Port 1 of the network analyzer is serving in the role of being connected where the DOCSIS 3.0 or DOCSIS 3.1 CM would be connected and performing a FFT spectrum measurement as is being requested by the MSO NOC at any given moment.

It must be clearly pointed out to all that the CM FFT spectrum measurement is not subject to two-way port to port isolation on the forward path direction as this is ONLY a return path direction phenomenon due to the design and usage of the two-way splitter.

Details of the components displayed in Figure 1e:

- **Keysight ENA series E5080A 50 ohm impedance Type-N connector vector network analyzer from 30 kHz to 9.0 GHz:** I now only use a 50 ohm vector network analyzer because it was getting nearly impossible to make any vector network analyzer measurement above 3.0 GHz with industry standard 75 ohm vector network analyzers that all stop at 3.0 GHz. The next step below makes 75 Ohm measurements easy to perform.
- **Two Keysight minimum loss pad kits 11852B Opt 4:** The Keysight minimum loss pad is a precision 50 ohm N-Type connector to 75 ohm N-Type connector with a minimum

return loss of 40 dB over the entire frequency range of interest. The pad is virtually a flat response over the range of interest and possesses a 5.7 dB flat loss by design.

- **Precision network analyzer phase stable test coaxial cables:** Type N male to Type F male coax cables that are 30 inches in length and are part of the calibration preformed before any measurements are made.
- **Keysight KT85039B mechanical 75 ohm Type F calibration kit or Keysight KT85099E electronic 75 ohm calibration kit:** For speed and convenience I tend to use the electronic calibration kit unless I need accuracy of better than 50 dB beyond 3.0 GHz in which case I use the mechanical calibration kit. Regardless of which kit is used, all measurements S11, S21, S12 & S22 must be calibrated before a single measurement is performed on the two-way splitter in Figure 1d.

During the measurement in Figure 1e, the network analyzer is actually generating a signal that is traveling from port 2 of the network analyzer to port 2 of the two-way splitter. That signal is intended to travel on to the node and/or hubsite via the two-way splitter’s input port (output port for the return path direction). If one were to simply remove the network analyzer port 1 connection from port 1 of the two-way splitter and reconnect it to the input/output port of the same two-way splitter one would be performing a through loss response of the two-way splitter. (Port 1 of the splitter would need to be terminated for an accurate measurement.)

With the measurement technique discussed and displayed in Figure 1e, it is time discuss the results displayed in Figure 1d:

- The isolation capability of any two-way, three-way or four-way splitter in the home is a direct function of how closely the termination impedance matches the ideal 75 ohm impedance the splitter is internally balanced to. As one can observe in Figure 1d, the isolation ranges from as poor as 6.9 dB in the case the input port is left open circuited to much better than 60 dB when the input termination is terminated with a near ideal 75 ohm termination impedance (the impedance that matches the internal design). In this case the isolation is roughly 66 dB at 30 MHz.
- The isolation response of the home coupling device is directly impacted by the characteristics of the termination over frequency that is provided by the MSO network.
- Therefore, all the MSO can do to begin to bound the isolation variability problem would be to create a calibration process during the installation of the DOCSIS CM in the home. The installer would be carrying a second CM that would be a diagnostic CM capable of transmitting a constant carrier narrowband set of modulated carriers that both the CMTS could measure and the DOCSIS CM could measure via the FFT spectrum measurement. The constant carrier signals are used to estimate the accuracy of the CM FFT spectrum measurement by placing these narrow band carriers in key gaps, intended to not to interfere with the normal DOCSIS carriers that are assigned. This provides up to four identifiable very narrow band carriers that both the CM FFT spectrum measurement and the CMTS can capture. A delta value would be assigned for the response reported from the CM to the measured response from the CMTS. This difference could be saved and applied to future measurements from this CM. Alternatively, if the installation could be allowed to become interruptive, the second diagnostic CM could become a second DOCSIS 3.1 CM supporting a specific DOCSIS 3.1 PNM test sequence. In this way the DOCSIS customer CM (CM1) and the installer technician DOCSIS 3.1 CM (CM2) could each transmit identical signals but with CM1 going first and recording the response and loss and then when CM2 transmits the identical signal at the TV or STB connection

point, CM1 performs an FFT spectrum measurement. Now the CMTS has what level CM1 signals arrived at and then CM2 signals arrived at. The CM1 FFT spectrum measurement of the CM2 test signal is also sent to the CMTS. Then one can calculate what error exists for reporting a CM FFT spectrum in the return path direction out of this particular home.

- The easiest way to calibrate is to transmit the DOCSIS 3.1 PNM based test sequence from CM2 and have the CM perform the FFT manually performed by the installer and then go outside and with the ground block disconnected measure the signal at the ground block with the installer meter and now you have the MSO network termination impedance CM FFT spectrum measurement as well as the ground block terminated by the meter measurement. It is then a simple matter to save both traces and then go in the home and shut off the diagnostic CM and reconnect the ground block and resume the installation.
- Unfortunately, I have no solution presently for how the MSO would handle self-installations. That is beyond the scope of this paper.
- The problem of isolation calibration becomes more severe with discussing the possibility of using a 6 dB directional coupler instead of a two way splitter. In the case of the 6 dB directional coupler, the through loss would be about one dB less. More significantly, the isolation performance of the directional coupler is, on average, about 10 dB better versus frequency and over a much wider range of characteristic termination impedances provided by the MSO network.

4. Analysis of Results and Examples

In this section, I will detail why it’s not possible to make accurate return path measurements from inside the home and why possible solutions are limited by the design of the HFC network.

4.1. A Review of the Basic Problem

It has now been demonstrated in Figure 1d that it is virtually impossible for any CM to accurately estimate the amplitude response and or overall interference power of any given noise and/or signal source that is originated from within the home environment by performing a PNM based wideband FFT spectrum measurement in the return path signal direction. The inaccuracies will hopefully be clear to all after reviewing the realities listed below:

- The DOCSIS CM performing a PNM based wideband FFT spectrum measurement of the return signal path direction, can only do so by viewing the offending device and/or noise source that is connected to a different port of the home coupling device than the port that the DOCSIS CM is connected to. Therefore, the DOCSIS CM PNM based FFT spectrum measurement intended to capture the return signal path interference to begin with, can only do so by viewing the interference signal through the isolation response of the home coupling device. The DOCSIS CM performing the FFT spectrum for the purposes of capturing the noise characteristics within the home can never measure the signal directly.
- Given that the DOCSIS CM performing a PNM based FFT spectrum measurement of the return signal path interference can only be performed through an isolation response, the real or actual noise response and/or level remains unknown. This is clearly evident in the isolated response variability displayed in Figure 1d above.
- As a practical matter regarding the home environment isolation response path, the following paths can exist:

- **Figure 1a – two-way splitter example:** The isolation response is determined by the termination characteristics connect to the input port of the same two way splitter.
- **Figure 1b - 6 dB directional coupler example:** This example is submitted for completeness, as I have been informed this configuration, though once commonplace, is seldom used anymore.
- **Figure 1c – four-way splitter example:** Since a four-way splitter is simply three two-way splitters connected together, the biggest difference in isolation is simply the second two-way splitter ports and again the three two-way splitter ports are quite similar to a normal two-way splitter with perhaps a little less sensitivity to the input impedance termination characteristics. However, the ports from the second two-way splitter to the third two-way splitters port isolation should be approximately 7 dB better due to the additional path loss for any port connected to the second two-way splitter to make itself over to the third two-way splitter ports.

In conclusion, thus far every single home environment has the potential of the isolation response being entirely different which of course makes the reliability of anything reported in the return signal path direction a crap shoot at best. I am concluding this because the isolation response per home is generally unknown.

As mentioned above, a calibration process or procedure could be performed by an installer to be able to state with some certainly that at least the levels of the noise signal interference captured by the DOCSIS PNM return path signal FFT spectrum measurement can be begin to be treated as a likely representative of the interference signal present.

In the end, no matter what any MSO decides to do there are three basic issues that must be dealt with one way or the other:

- Given the reality that all FFT spectrum measurements in the return signal path direction are isolation only, then a process or procedure must be put in place to minimize the inaccuracy of reporting the noise characteristic response indirectly through the isolation response!!
- Given the reality of only isolation responses being generally available today, the MSO can opt to perform controlled isolation response determinations at installation by using a second and independent noise source as part of the installation procedure. While a procedure like this is a reasonable approach for MSO installed locations, there would have to be a pretty flexible procedure put in place in order to satisfy self-installation customers!!
- If the MSO is placing real value on the return signal path DOCSIS PNM based FFT spectrum measurements, then dare I suggest that the MSO might consider changing the rules for CMs moving forward to take advantage of the return path spectrum measurements. Again, there is nothing wrong with the forward path FFT spectrum measurements today, save that they can only measure specifically the input to the home environment. While this type of solution is possible it is quite complicated and involved and beyond the scope of this technical paper.

4.2. The Better Way to Measure Return Signals

A better way is achievable to accurately and directly measure return signal path noise and all other upstream DOCSIS signals for that matter. More importantly, this novel approach does not require entering the home and dealing with the home environment at all.

Consider the fact that, by design, the home environment is the last place one wants to go to measure any return path signal interference because the HFC network is designed to isolate each customer and hence virtually all or at least most of the noise within the home. The hardline tap and the home coupling devices utilized are all designed to do the following:

Hard-line taps

- Allow all forward path signals to freely enter the customer home & allow all return path transmit signals to enter the network in the direction of heading back towards the node and eventually the hubsite
- Significantly attenuate all return path direction transmit signals (>40 dB attenuated) from heading further downstream of the CM FFT measurement point
- Summary: Virtually nothing from any other home on the node can be measured by the Home DOCSIS CM performing a return path FFT spectrum measurement.

Home coupling devices (two-way, three-way, four-way & eight-way splitters)

- Allow all forward path signals to freely pass through the coupling device to the CM or STB/TV & allows all return path transmit signals that are connected to its respective port to pass through and on to the node and hubsite eventually
- Isolates upstream signals and noise from reaching a DOCSIS CM that attempts to perform an FFT spectrum measurement in the return path area of the spectrum. The amount of attenuation (isolation) is a function of how well the network termination matches the home coupling device impedance. Unlike the hardline tap example above that almost always provides greater than 40 dB of attenuation and/or isolation, the home coupling device typically isolates (attenuates) in the range of 14 dB to 40 dB.
- Summary: DOCSIS CM return path signal FFT spectrum measurements range from being 14 to 40 dB inaccurate of the actual level and the response can look dramatically different from the actual noise response.

The home is the last place one ought to be making measurements for all the reasons cited above.

Let’s summarize what any MSO really wants to know regarding the return path signal direction of their plant:

- The actual characteristics of the impairment occurring in the return path signal direction including where is it occurring in the spectrum and what is the bandwidth, power and duration of the transient or spurious event
- The specific location of the noise source. I know with certainty that far too much time is spent tracking down transient noise sources to the point that I would be willing bet that transient noise is occupying greater than 65% of the entire field teams’ resources on a daily basis.
- The difference between noise sources and system non-linearity. Not all transient events occurring today are noise related but rather a significant portion of transient events are

really system non-linearity events that are occurring all the time and no one can even tell the difference. The simple and sad truth is two-fold:

  - The DOCSIS CM FFT spectrum measurements are averaged, even if it is a small amount of averages that were rightfully designed to ensure that the actual noise floor is displayed correctly on the downstream or forward path direction of the plant.
  - Since the CM is always viewing the noise in the home through the eyes of an isolation response it is virtually impossible to tell the difference between signal-dependent noise (system non-linearity) and transient noise as all the signal analysis one holds dear in viewing any waveform is already greatly jumbled up by the port to port isolation response and complicated with a small amount of averaging added.

So here we are faced with finding a better way to analyze the return path signal direction and stay also within the realm of the DOCSIS based PNM measurement concept. The answer is as astoundingly simple. Let’s review the problem as a system measurement challenge that all MSOs must face:

- Like the forward path (downstream direction) the return path (upstream direction) has signals that each pass by all the taps
- Unlike the forward path in which each tap allows for being able to accurately measure the entire forward path spectrum via a DOCSIS FFT spectrum measurement, the return path signal direction enjoys no such luxury, as not a single tap in the cable TV plants deployed today affords the RF technician any ability to measure anything in the return path signal direction. In fact, the only the measurement capability in the return path signal direction today is either at the CMTS in the hubsite or the D-CCAP or R-PHY devices at the node. OK, the RF technician could open the amplifier cover (heaven help us) and create a massive noise problem in the forward path direction while trying to figure out what is going on in the return path direction and so we all know that is not happening.
- While the D-CCAP or R-PHY or even the traditional CMTS of today in all hubsites can measure all the return path transient events accurately, they have no ability to discern where the noise source is located. They are powerless to inform the RF Technician in the field exactly where the noise source is occurring. Furthermore, there could be multiple noise sources participating in each event.
- The entire industry will be facing this return path signal problem more and more as time goes on as the demand for more throughput will require higher constellation modulations, which will force the issue.

So, what is the solution? Deploy a reverse direction test tap function in the network! Let’s start off with the simplest and most direct approach, which I personally performed in the many MSO networks that I have performed characterizations on over the past 5 to 8 years.

5. A New Approach to Measurements: The Dual Window Test Tap

5.1. The Simple and Direct Approach

The simplest and most direct approach that has always been available to all MSOs in the world for more than 20 years is to install a two-port tap backwards during a maintenance window. The tap should have low through loss and be highly directional with high tap port loss. A backwards tap has the output port facing the node and the input port facing the rest of the taps. Let's examine the diagnostic power this unleashes to the RF technician in the field:

- Installing a 23 dB or higher two-port tap backwards on each major leg or branch out of the node immediately affords the ability to isolate which major branch the noise is coming from. It should be obvious that reducing the noise funneling effect that makes the noise source virtually impossible to locate from the node or hubsite becomes a rather straight forward process once the measurement point is further down the coaxial cable plant path.
- A little deeper approach would be to install a 23 dB or higher two-port tap backwards directly at the output of the first amplifier of each major branch out of the amplifiers.
- Technicians can immediately and accurately measure the return path signal branches in a way that has never been possible.
- While the emphasis so far is on measuring the return path signal path I must point out the second benefit of a reverse tap and that is the ability for the RF technician to transmit a special test signal downstream, for instance when trouble-shooting a structural micro-reflection problem. If one thinks about this advantage very carefully this allows the RF technician in the field to trouble-shoot on his or her own by sending an out-of-band signal back down the line to start demodulating at various tap location looking for a root cause for a structural micro-reflection. Without a local injection point, the current process can become quite involved as the NOC must be involved, etc.

While I am suggesting that this approach could be done immediately by every MSO reading this paper, I will acknowledge that this approach, though very effective and possibly should be considered anyway on very difficult nodes (every MSO has them), is far too costly in both resources and time due to having to cut in a brand new tap which mandates a maintenance window and a bunch of customers out for roughly 1 to 3 hours.

However, when one is installing a node everyone is out anyway and, furthermore, the tap placed backwards doesn't even require cutting it in as the hardline is already disconnected. The RF technicians at a major international MSO just discovered the benefits immediately, and installation was practically no effort at all.

One could make a move to resolve a difficult node or two immediately by doing the above mentioned backwards installed tap approach. It works! Serious transient noise events already occurring on the trouble node could be located by the poor RF technician assigned to figuring out what the heck is wrong with a given node!!!

However, we all know that this concept is not likely to become a widespread practice and we hope there must be a better way. Yes, there certainly is!

5.2. The Dual Window Test Tap

Marc Morrissette formerly of Huawei and I had been working with a major tap vendor for well over a year to develop the concept of what I have been referring to for at least a year or more and that is now being referred to as a dual window tap that would require a simple faceplate change and so no major outage at all. Conceptually this tap has already been demonstrated in the SCTE CableTec EXPO 2015 show and in in several labs.

I am strongly recommending suggesting that the faceplate tap change also include a test forward path port and a reverse tap for the DOCSIS upstream receiver function. Consider the fact that both the CM and upstream receiver functions are clear of the home environment and now one should be understanding that for the first time the DOCSIS diagnostic CM function measurements being performed at this point are free from all customers and the home environment. Measurements at the test tap will reveal the actual system response of the network without having to subtract out the home environment contribution including the loss and frequency response limitations of the typical coupling devices used in the home.

5.2.1. Reverse Tap Characteristics

First prior to reviewing the reverse tap characteristics it would perhaps be beneficial to observe a functional block diagram of the proposed reverse tap.

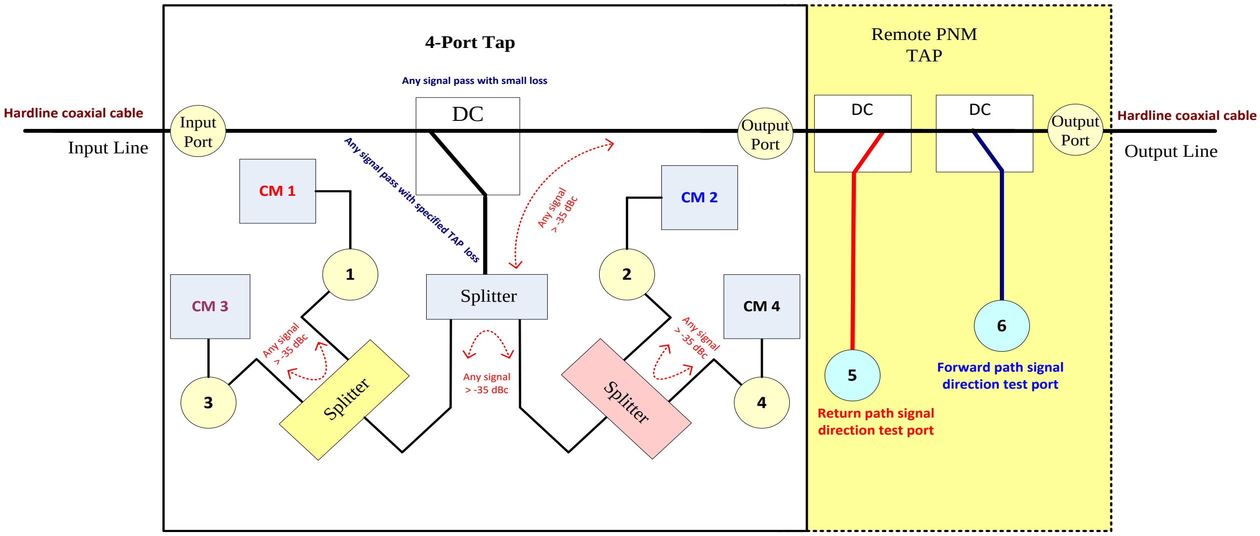


Figure 2a. Functional Block Diagram – New Faceplate Change ONLY – Dual Window Test Tap

The new proposed dual window test tap in Figure 2a replaces what was a standard 23 dB tap with four normal forward direction ports and a new dual window 23 dB test tap port. This is only a functional block representation and the actual system circuit design would likely be quite a bit different. The dual window tap could be temporary installed or left permanently. The objectives are as follows:

- All four customers are unaware of any testing being conducted with the one brief outage to replace the faceplate.
- Because it is a faceplate change only the four customers are impacted for about 5 minutes or less and the remainder of the node continues in operationally other than the four customers that are out briefly as both the signal and power feed is passed through while the faceplate is off.
- Once the new faceplate is screwed down the four customers are back and of course the two test ports are now available for measurement
- As one can see port 5 would be the new return path signal direction tap port and port 6 would be the new forward path direction signal tap port.

- Port 6 could also be power passing in the event the MSO were to use an automated measurement system operating off of network power.

The test tap arrangement shown in Figure 2a would have to introduce a small amount of additional loss in the through path as there are more directional couplers now present as opposed to prior to the faceplate change. However, I feel it is a very small price to pay for unleashing the power of having full diagnostic measurement capability outside of the home environment and the ability to have wideband spectrum capability in the return path signal direction that never existed before.

The measurements of a four-port faceplate change test tap prototype are displayed in Figures 2b through 2d.

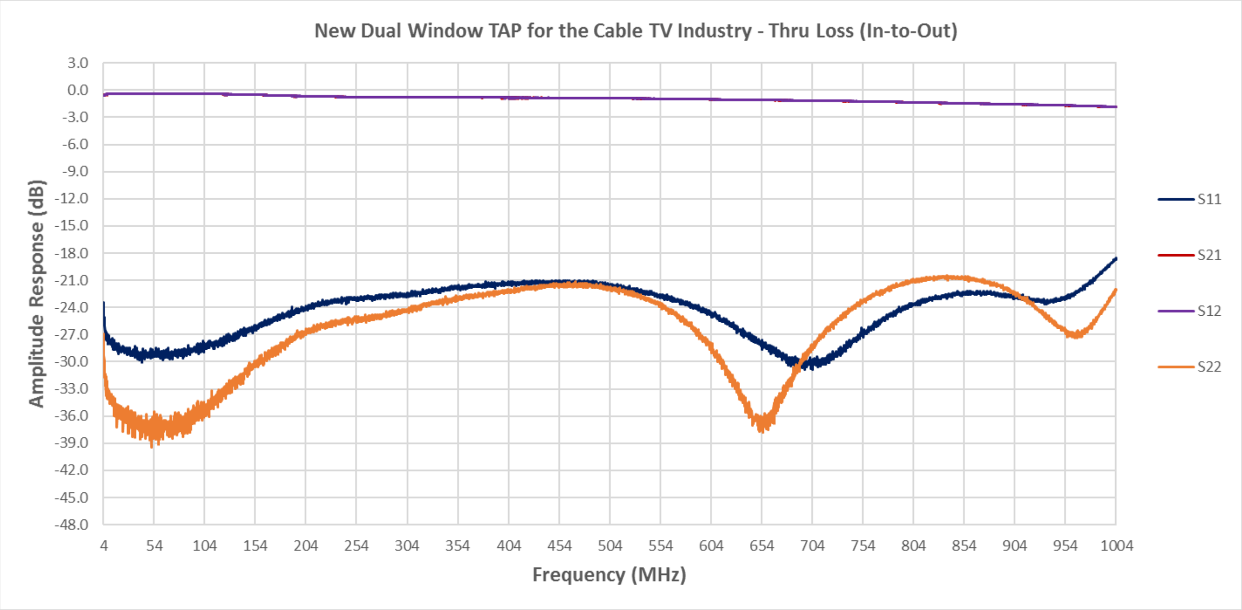


Figure 2b. New Dual Window Test Tap- In to Out (Thru) loss

As one can see the return loss characteristic objective > 18 dB have been achieved up to the 1002 MHz tap design that the prototype dual window tap was held to for characteristics. Honestly, given the world population of taps today and given the fact that a faceplate only change would be seriously considered, there was no point in doing any prototype tap for real world DEMOs in the near future that go beyond 1002 MHz.

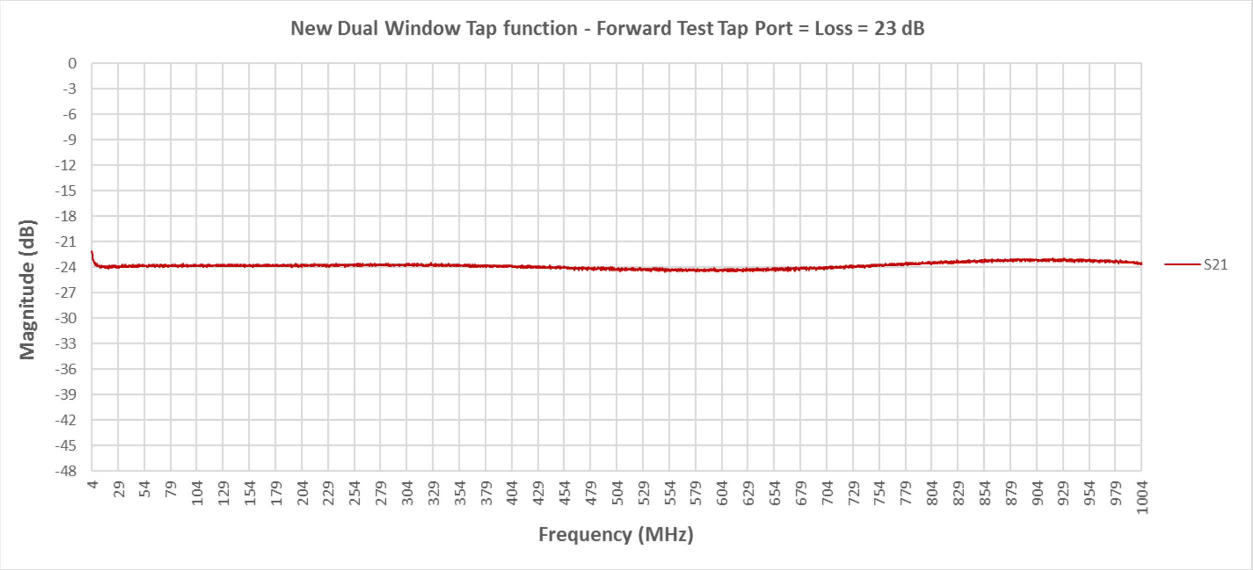


Figure 2c. New Dual Window Test Tap - forward tap Test port loss = 23 dB

Actual loss on a very first prototype dual window forward path direction test port = 24 dB, and note that the actual loss isn't as critical because one simply calibrates it out before the measurement.

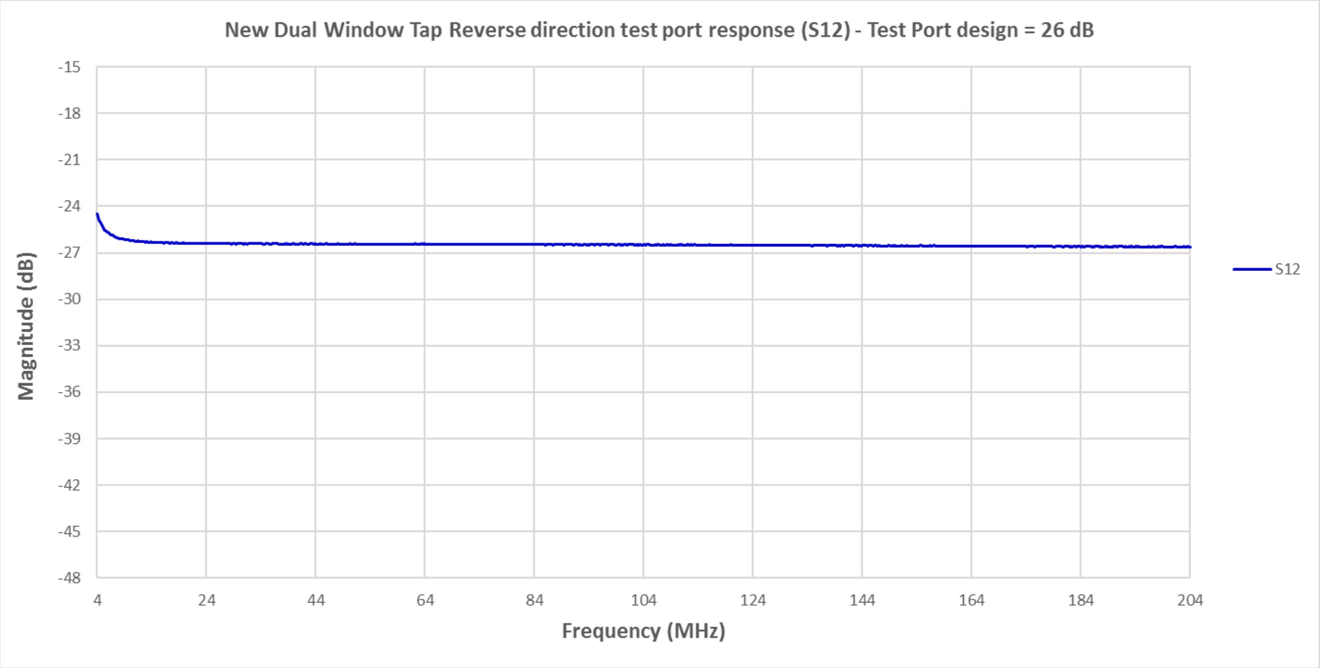


Figure 2d. New Dual Window Test Tap - Reverse direction Test port loss = 26 dB

In this prototype design, I opted for a small increase in loss to -26.5 dB to ensure excellent isolation characteristics.

Now having presented the concept of a faceplate changeable dual window test tap that every RF technician on the planet will be thrilled with by having direct access to both return path and forward path measurement access without interrupting customer service nor being impacted by customer transmission concerns, let me now continue on what I see is the future for the entire Cable TV industry.

5.2.2. Mobile Test Equipment

Let’s start out with the state of test equipment today in the cable TV industry:

- Cable TV installation technicians tend to now carry handheld devices.
    - The vast majority of time is spent measuring within the home environment or on the drop coax cable outside the home and so the levels tend to be more reasonable and the majority of the slope equalization that exists at the output of the node and amplifiers is at least approaching a near flat response.
    - For the most part all handheld test devices are based on a cable modem chip set which, of course, makes sense as the installer is very interested in how the home looks from a DOCSIS and digital video perspective.
    - I have only mentioned this large class of meters because while they serve the home installation purpose in an excellent manner they are not at all suitable for performing any measurements on the hardline coaxial cable plant and without question shouldn’t ever be considered.
- The next class of meters are handheld as well and are real FFT spectrum measurement CATV analyzers that are also legitimate spectrum analyzers as they do possess a digitizer for actual FFT spectrum measurements. The units are using a DOCSIS 3.1 CM chip set as well for power DOCSIS 3.1 measurement estimations. While I have yet to try one of this class on the node output or amplifier output I am being told that this class of CATV handheld analyzer was not designed specifically for the home installer and so I am truly hopeful. Clearly this class is far better than the above class that I already know doesn’t work well at all at the output of the node and/or amplifier. One such analyzer in this class is the DEVISER 2830 DOCSIS 3.1 CATV Analyzer with FFT spectrum capability. I am not discounting that there are a number of newer type test instruments coming out on the market soon, but simply put I am familiar with this particular FFT spectrum measurement capable instrument.
- There is of course the traditional non-handheld 2nd & 3rd generation design CATV analyzers that can operate off of battery for a short period of time but mostly require a truck to have an AC power inverter that has at least 900 to 1200 watts power handling capability. These instruments can indeed handle measuring directly at the output of the node and/or amplifier but unless the CATV analyzer is a late 3rd generation or even a fourth generation, i.e. FFT spectrum measurement capability as well as DOCSIS 3.0 and DOCSIS 3.1, having any estimate much beyond 43 dB is not likely.
- Finally on the horizon there is a new class of test equipment from Rohde & Schwarz that will be a replacement for the older ETL CATV Analyzer (above mentioned class of CATV analyzers) soon to be introduced as the DSA that is both sineswept and FFT spectrum measurement capable and yes is definitely not handheld but from my perspective it is designed for all node and amplifier output measurements and can even run on a battery though be it for a short period of time (I am guessing one would be carrying the battery pack). That would appear to be the measurement bridge I have been looking for between needing a pack mule to carry either the Keysight UXA series

N9040B DOCSIS 3.1 capable vector signal analyzer or the Rohde & Schwarz FSW DOCSIS 3.1 capable vector signal analyzer that I have been using for the last three years for DOCSIS 3.1 performance measurements. These two mentioned vector signal analyzers will perform every measurement the field will ever require now and in the future.

- The MSO would also need a van that is large enough to house the following:
  - Power inverter min wattage = 1500 watts and I would suggest 2000 watts
  - Min work bench to place the VSA on required is a 2 feet deep by 4 feet long by 30 inches max high to fit the VSA and the laptop PC connected to it to capture all measurement data in a windows remote desktop mode of operation – I would recommend a table that can easily carry up to 250 pounds to be safe and that the analyzer be properly secured at all times.
  - A chair that can be secured when traveling as well for the RF technician or engineer operating the VSA
  - A precision center pinned F-connector cable such as Belden 1694A (Series 6 - 4.5 GHz coaxial cable) about12 feet long with a Holland F81 F-female to F-female barrel connector attached to the head of the cable heading out of the Truck. I would strongly recommend a permanent arrangement for the exit point of the truck that would simply have the Holland Electronics F81 barrel terminated with a Holland F59th 75 Ohm termination when not in use.
  - The reason for the short length of Belden 1694A coax is because it is flexible and can be dressed in any manner necessary to get outside. However, I also strongly recommend a Belden 1694A type coax for drop lengths < 50 ft and seriously recommend the Belden 7731A type coax for all drop length connections > 50 ft.
  - The above configuration creates a useful truck/van workstation and portable pack mule necessary to cart either VSA around. The same configuration can be used for the considerably smaller and lighter and hence slightly portable Rohde & Schwarz ETL replacement now called a DSA. The real benefit of this arrangement is having it on all day in the van because of the power inverter. Power all day is a plus from a calibration perspective.

5.2.3. Field Operation Procedures

Having discussed the measurement problem for the return path direction of the plant, that the dual window tap is the answer to the RF technician’s return path measurement nightmares, and finally what test equipment RF technicians have at their disposal to perform key return path direction signal measurements, it is time discuss the operations side of the cable TV business.

We all know that when problems start occurring on any given node a bunch of attention is immediately paid to the node in question. In most situations with problems in the forward path direction, in less than two to four hours the root cause of the problem has been determined and, depending upon the problem, is either fixed immediately or a maintenance window is scheduled for the final repair. The forward path diagnostics of all the CMs that the NOC has access to, has already started the RF technician team in the right section of the node.

In return path direction it is an outstanding day for the RF technician crew dispatched if they have even begun to isolate the root cause of the noise and/or interference source in the return path direction in less than 8 hours.

Again, if the new dual window taps can be installed at various places in the node the RF technician can at least begin to isolate where the noise sources are originating from to begin to start looking for physical evidence of the problem.

The field technician can do the following if two dual window taps are installed:

- On the reverse direction (return) tap the RF technician can place a CATV analyzer in max hold sweep and then travel to the other dual window tap (I am assuming with the truck locked up with the meter running and while he or she walks to the next location -- hopefully not too far of a walk).
- On the second dual window tap that has a diagnostic (test) forward direction tap the RF technician can now transmit a test signal as a reference signal. This narrowband test signal can be at a frequency where no customer traffic is being generated and so, once again, no interruption in service.
- If there is only one technician available, he or she must secure this test instrument that is transmitting in constant carrier and return to the first dual window tap.
- Once back at the first dual window tap where he or she left the CATV analyzer in max hold, the RF technician then reviews what the measurements have revealed thus far and -- Murphy's Law always apply here -- nothing happened while you were present!!
- Now this poor technician has a major choice to make and that is call the NOC to see if another complaint came in while he or she was walking back and forth and if the answer is yes and you have nothing on this CATV analyzer to show for, then one has to make the determination to now leave that location sit and try another one.
- The dual window taps dramatically improved the situation in the field because the technician was able to at least perform return path measurements and definitively eliminate that path and move on the another one.
- Of course, all is well if the interference signal actually showed up on the max hold trace screen and the RF technician can capture the trace and move on to another site with a different technician coming in to trouble shoot the path in question or the RF technician can choose to move further down the path and install a third dual window in a third location behind the second dual window tap location. Now the second window connects to the return path test tap to the CATV Analyzer and the third dual window test tap further down the node now connects the signal generator to the forward test tap and sets the signal up identical to when it was located at the second dual window tap.
- The RF technician now returns to the second tap where the CATV Analyzer is in a max hold trace sweep mode of operation and observes if the event occurred again. If it has great, and if it hasn't one must decide how long to wait.

As one can see this process will eventually isolate the interference source, though it could take several days still and a little luck. Once the RF technician can see the interference event it is a matter of following it down towards the EOL location. I would state this as prodding along and methodically moving further down and eventually isolating the interference source. Yes, a two RF technician team could work this much faster!

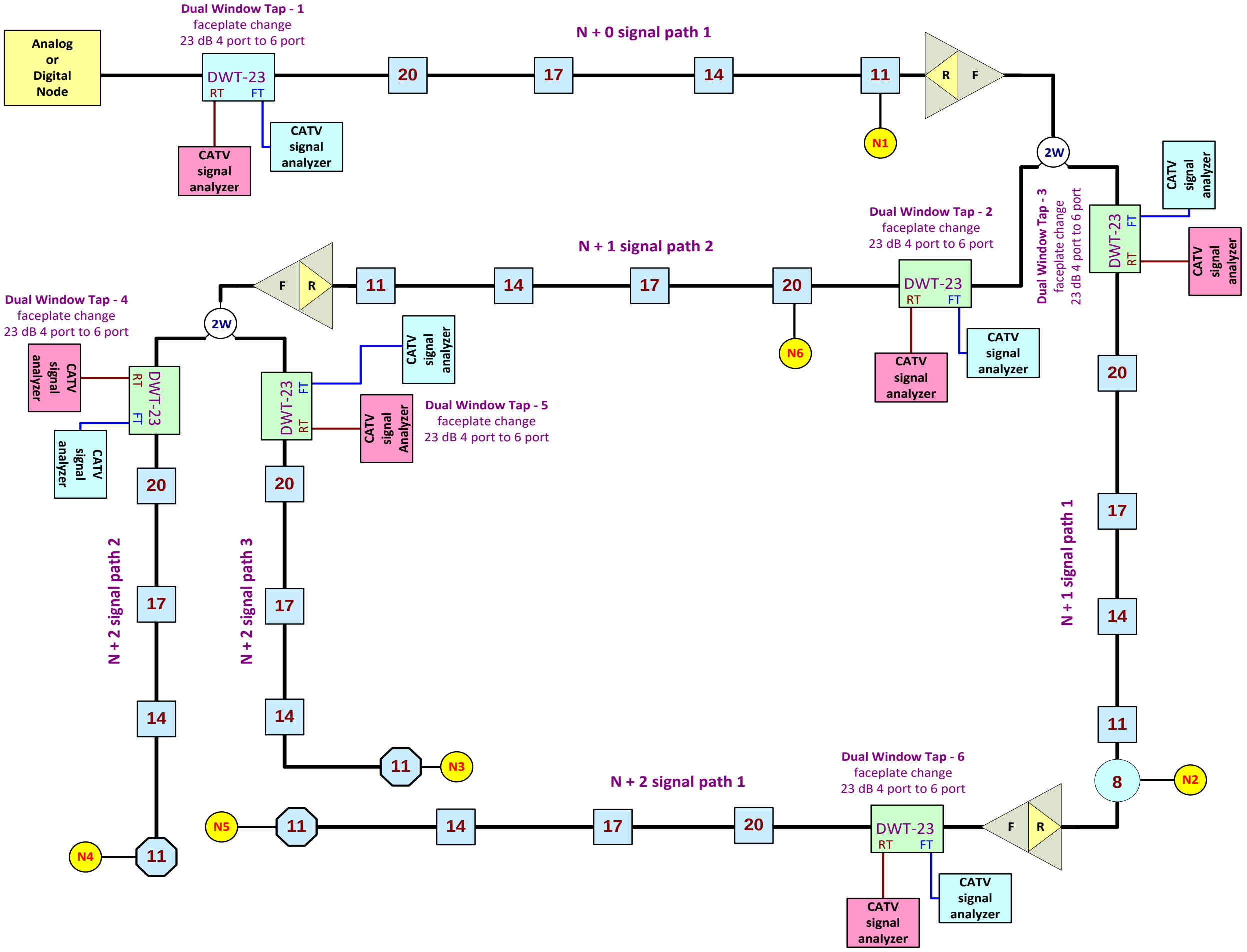


Figure 3a – Trouble shooting example using a dual window tap approach – node + 2 amplifiers

If one reviews Figure 3a above one will note that the dual window tap in this particular example could be installed in up to 6 tap locations if necessary to locate the noise source. Furthermore, the noises are displayed as simply a yellow circle with a noise source number associated with it from N1 (noise source 1) to N5 (noise source 5). Note that the noise locations are distributed so the CMTS in the hubsite (in the case of an analog node design) or the D-CCAP or R-PHY (in the case of a distributed digital node design) would not be able to locate each noise source.

The intent here is demonstrate that the RF technician can use two CATV signal analyzers (likely the handheld variety) to begin the search and hence isolate the noise source(s) that are causing performance issues on the node in question. The CATV signal analyzer depicted in red are the upstream or return path measurement functions of the CATV signal analyzer while the ones depicted in blue are the downstream or forward path CATV measurement functions. While there are a total of up to 12 CATV signal analyzer functions shown, only two at one time are envisioned by the author as being operational.

With the use of dual window faceplate capable taps and two handheld CATV signal analyzers all noise sources can be located by a systematic measurement approach that the dual window tap affords the RF technician.

5.3. Measurement Examples

5.3.1. *Downstream Example*

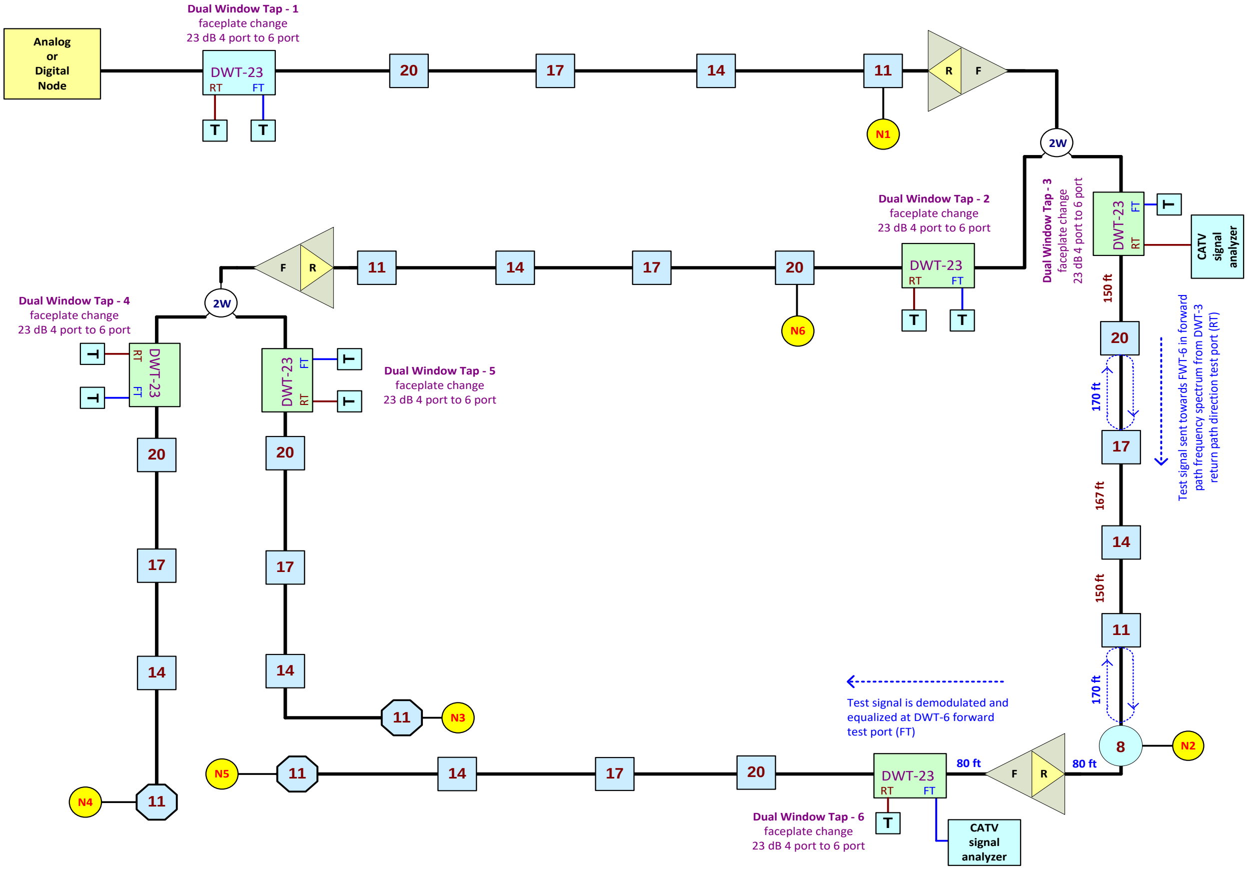


Figure 3b – Trouble shooting example – forward path micro-reflection isolation – node + 2 amplifiers

A suggested procedure for locating the forward path signal micro-reflection

Downstream test transmit signal set up

- As displayed in Figure 3b above start off with installing a dual window tap as shown as DWT-3. The test procedure is most effective if there are two people, one at each end.
- Connect the digital handheld CATV signal analyzer to the reverse test port as labeled RT in red font above. The CATV signal analyzer should be configured to transmit a modulated carrier frequency in the forward path direction. The carrier frequency and bandwidth must be selected to avoid impacting any customer downstream DOCSIS and/or video transmissions.
- To be safe I would recommend a power or level that is -6 dBc relative to existing carriers. The existing signals can be measured at the forward test port shown in blue font (FT). Be sure

to correct for the value of DWT tap being used. Since there is no shortage of available downstream carriers is it pretty easy to measure the downstream test signal with the second CATV signal analyzer connected further downstream at the DWT-6 location in this example.

- The channel bandwidth selected in this case should be a standard downstream channel, which is either 5.056941 Msym/s for 64-QAM or 5.350537 Msym/s for 256-QAM. Since the objective here is ensuring excellent equalization for discerning micro-reflections, I recommend the 64-QAM 5.056941 Msym/s option.
- Once the signal has been determined and is being transmitted at a selected known or observed level of -6 dBc and at the predetermined test carrier frequency and standard channel bandwidth offering for 64-QAM modulation, it is time to head to the location shown in Figure 3b as DWT-6. If one is alone, securing the meter properly to the test port tap for security reasons is an excellent idea prior to moving to the DWT-6 location

Downstream Test Receiver (DEMOD) set up

- When arriving at DWT-6, displayed in Figure 3b above in blue font (FT), the first objective is to connect a second digital handheld CATV signal analyzer to the forward direction test port.
- Set up the CATV signal analyzer as a demodulator that is set for the correct carrier frequency that was selected at the DWT-3 location. Unfortunately some of this type of set up is CATV signal analyzer specific and, therefore, specific settings are beyond the scope of this procedure. Ensure that the modulation that was selected while at DWT-3 is set up here for the demod operation and in 64-QAM mode.
- You should be seeing the transmit signal coming from the DWT-3 location.
- You should now be able to enable equalization on the meter. In some meters the equalization function is always enabled in demod mode of operation. If the EQ-MER estimate from the CATV analyzer > 33 dB one can be reasonably certain that the CATV signal analyzer has been successful in optimizing the response. 64-QAM needs only approximately 24 dB in Annex B mode or even 27 dB with no error correction enabled to be error free. Therefore, at a minimum, the equalized MER estimate is at least 6 dB better than required which would indicate the equalization has done a sufficient job.
- Now, look at the EQ Impulse response which is a bar graph response. Determine what tap location is displaying the largest bar level beyond the main tap (MT). There are several considerations to determine how much time and distance is associated with each tap.
  - All DOCSIS downstream equalizers use what is referred to as a concatenated equalizer structure of both a shorter time span feed-forward equalizer (FFE) structure to eliminate the effects of amplitude and group delay distortion and then the signal passes through a decision feedback equalizer (DFE) to deal directly with or mitigate micro-reflections. In most implementations that I know of the DFE is a T-Spaced Equalizer structure and most of the FFE equalizers are either a T/2 spaced and some are T-spaced.
  - Refer to the manual for the CATV signal analyzer being used as to how the micro-reflection delay response is displayed on the analyzer.
- It is reasonable to assume that the EQ-TAP locations are T-spaced on the DFE portion of the equalizer and so it should be approximately 1/5.056941 Msym/s = 197.748 ns per EQ-TAP location on the display. So, a 2 EQ-TAP delay = 169.2 ft as a one-way delay because 2*

197.748 ns = 349.5 ns and following a one-way delay equals 197.748 ns / velocity of propagation factor for hardline (1.168 ns per foot) = 169.2 ft.

- For a better understanding of the calculations in the preceding step, read the upstream section below.

5.3.2. Upstream Example

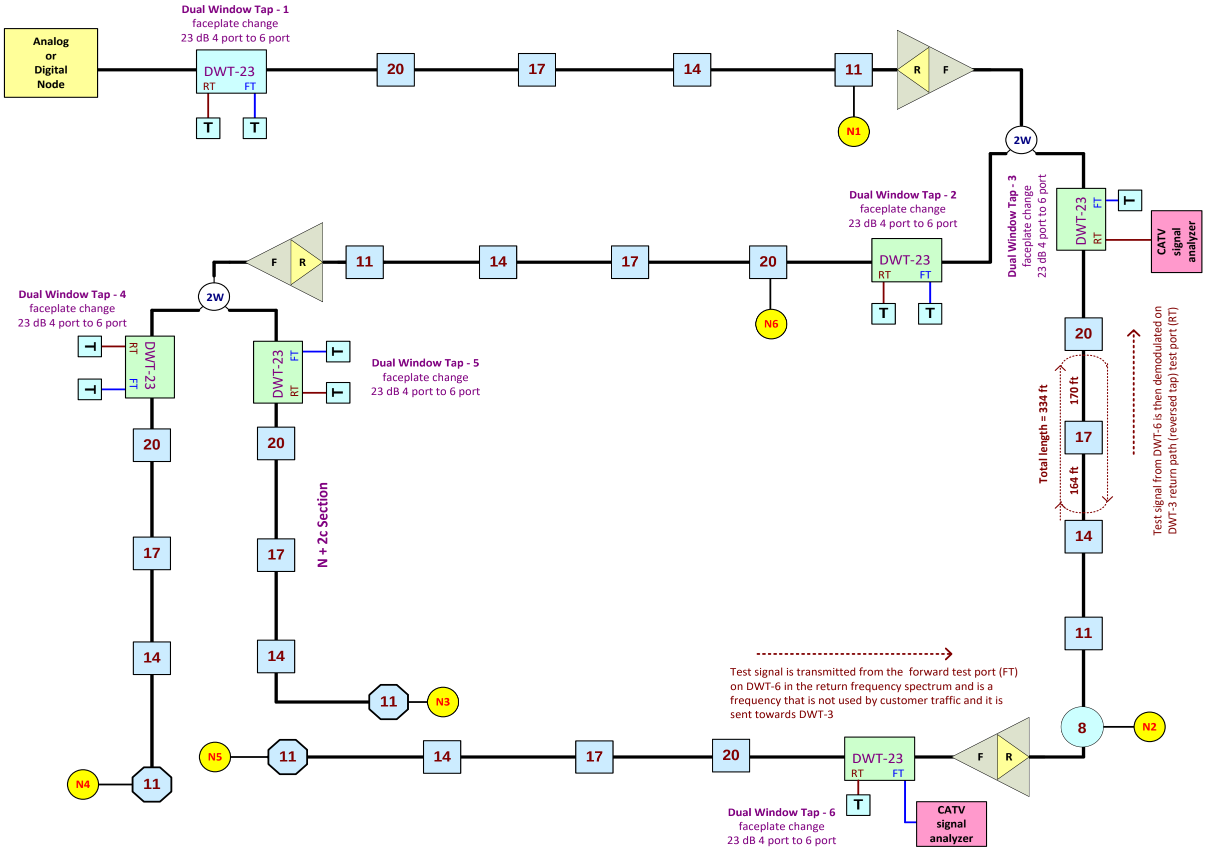


Figure 3c – Return path direction micro-reflection trouble shooting procedure

A suggested procedure for locating the return path signal micro-reflection

Upstream Test transmit signal set up

- As displayed in Figure 3c above start off with installing a dual window tap as shown as DWT-6. The test procedure is most effective if there are two people, one at each end.
- Connect the digital handheld CATV signal analyzer to the forward test port as labeled FT in blue font above. The CATV signal analyzer should be configured to transmit a modulated carrier frequency in the return path direction. The carrier frequency and bandwidth must be selected to avoid impacting any customer upstream DOCSIS transmissions.
- To be safe I would recommend a power or level that is -10 dBc the known DOCSIS transmit power for the value DWT tap being used. As a simple example if the normal DOCSIS TX level = +45 dBmV on a 23 dB tap (as shown above) than select +35 dBmV to be safe.

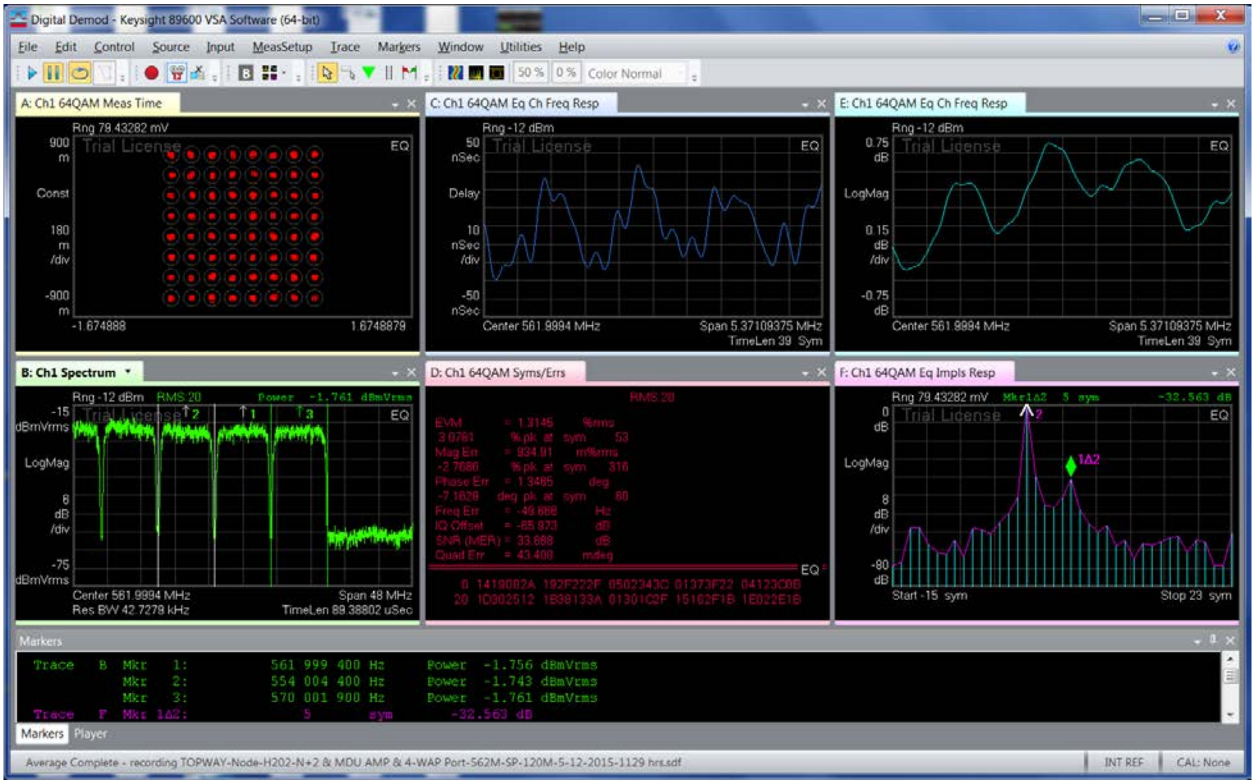
- The channel bandwidth one needs is really a function of how long a time delay is that makes up the micro-reflection and so a good rule of thumb is start off with a 2560 ksym/s symbol rate, which is a 3.2 MHz channel bandwidth.
- Since one is transmitting at -10 dBc, you should opt for 16-QAM or even QPSK modulation in order to ensure there is adequate dynamic range to ensure a solid equalization result from the demod operation of the CATV signal analyzer at the DWT-3 location.
- Once the signal is being transmitted at the selected level, carrier frequency and channel bandwidth, it is time to head to the location shown in Figure 3c as DWT-3. If one is alone, securing the meter properly to the test port tap for security reasons is an excellent idea prior to moving to the DWT-3 location.

Upstream Test Receiver (DEMOD) set up

- When arriving at DWT-3, displayed in figure 3c above in red font (RT), the first objective is to connect a second digital handheld CATV signal analyzer to the reverse test port.
- Set the CATV signal analyzer up as a demodulator that is set for the correct carrier frequency and modulation type, as was injected at the DWT-6 location.
- You should now be able now to enable equalization on the meter. In some meters it is always on. If the EQ-MER estimate from the CATV analyzer > 33 dB one can be reasonably certain that the CATV signal analyzer has been successful in optimizing the response. 16-QAM needs only 21 dB to be error free.
- Now, look at the EQ Impulse response which is a bar graph response. Determine what tap location is displaying the largest bar level.
- The equalizer will likely be a T-spaced equalizer, which means each tap location is a symbol time further in time out. Unfortunately, the remaining test procedure would have to be customized to the meter being used. However, the following comments on potential outcomes can be stated:
    - EQ Bar Graph Impulse Response – All micro-reflections are delayed in time and occur after the main tap location. All DOCSIS upstream EQs are using a 24-tap equalizer with the main tap location typically being EQ tap location 8.
    - Since the upstream EQ is T-spaced, each tap in time = 1/symbol rate.
        - For a 5120 ksym/s (CH BW = 6.4 MHz), each EQ-TAP = 1/5.12MHz = 195.3125 ns.
        - For a 2560 ksym/s (CH BW = 3.2 MHz), each EQ-TAP location = 390.625 ns.
        - For a 1280 ksym/s (CH BW = 1.6 MHz), each EQ-TAP location = 781.25 ns.
    - The micro-reflection delay is determined by counting how many EQ-TAP locations the highest energy tap is after the main tap location. For example, if the highest power or energy exists at EQ-TAP location 10, that means the round trip (RT) delay time is 10-8 or a 2 EQ TAP time delay.
        - For 5120 ksym/s, the time delay = 2*195.3125 ns or 390.625 ns.
        - For 2560 ksym/s, the time delay = 781.25 ns.
        - For 1280 ksym/s, the time delay = 1562.5 ns.
        - Since the example was stated with the 2560 ksym/s I will stay with that value.

- Given a RT delay of 781.25 ns it is extremely important to recognize that all micro-reflections must travel up and back to satisfy the RT condition. The signal must travel out and is reflected at the reflection point and then travels back the same path to the source where it is reflected off of the source termination and then finally is summed in with the original signal once again though delayed, in this case by 781.25 ns. Evaluating the impact to the transmitted signal by reflections is equivalent to the telephony world function long known as a “Listener Echo, ” which is when you hear the person talking to you a second time each time they speak.
- Since the signal must go out than then travel back, the distance that the reflection is away from the source is one half the RT time delay. A RT delay of 781.25 ns / 2 = one way delay time of 390.625 ns.
- The velocity of propagation for a hardline coaxial cable is roughly 1.16827 ns per foot of hardline coax traveled. Therefore, the RF technician need to start looking in this case at a distance of 390.625 ns / 1.16827 ns = 334.4 ft between reflections.
- Since the source is connected to DWT-6, simply start walking from DWT-6 until 334 ft has been covered and one should locate the physical problem creating the micro-reflection (MR). However, it is seldom that easy. Many times, the reflection is between two impairments, neither of which is the source. In this particular example, the micro-reflection lives between tap value 14 dB and tap value 20 dB and so the combination of 170 ft between the 20 dB tap and the 17 dB tap and again the 17 dB tap the 14 dB tap being 164 ft results in a total length of 334 ft. The resonant path is from the 14 dB tap through the 17 dB tap to the 20 dB tap and back again. While the process may take a little time, I am confident that once an RF technician with boots on the ground is already in the correct area the problem will be found.
- If one has a slightly more expensive CATV analyzer that can perhaps do a slightly larger symbol rate such as a 6.952 Msym/s (CH BW = 8.0 MHz), the time resolution improves from 195.3125 ns per EQ-TAP to 143.8435 ns, which would improve the location accuracy to some degree.
- Be aware that there can be error in the estimation up to 50%, so one goes to the distance indicated and then starts looking for the physical issue. It should be with +/-90 ft of the time delay. The RF technician will find the poor connector or crack in the hardline in no time.

5.3.3. *Other Examples of Measurement Results*



```
                RMS:20
EVM          = 1.3145      %rms
 3.0761       % pk  at  sym     53
Mag Err      = 934.91     m%rms
 -2.7680      % pk  at  sym    316
Phase Err    = 1.3485       deg
 -7.1628    deg  pk  at  sym    80
Freq Err     = -49.888       Hz
IQ Offset    = -65.873       dB
SNR (MER)    = 33.888        dB
Quad Err     = 43.408       mdeg
                                              EQ
  0  1419082A  192F222F  0502343C  01373F22  04123C0B
 20  1D302512  1B38133A  01301C2F  15162F1B  1E022E1B
```

```
Trace   B  Mkr   1:        561 999 400 Hz    Power  -1.756 dBmVrms
           Mkr   2:        554 004 400 Hz    Power  -1.743 dBmVrms
           Mkr   3:        570 001 900 Hz    Power  -1.761 dBmVrms
Trace   F  Mkr  1Δ2:              5      sym      -32.563 dB
```

Average Complete - recording TOPWAY-Node-H202-N+2 & MDU AMP & 4-WAP Port-562M-SP-120M-5-12-2015-1129 hrs.sdf

Figure 4a – Forward path direction micro-reflection example – carrier frequency = 562 MHz

EQ-MER = 33.9 dB

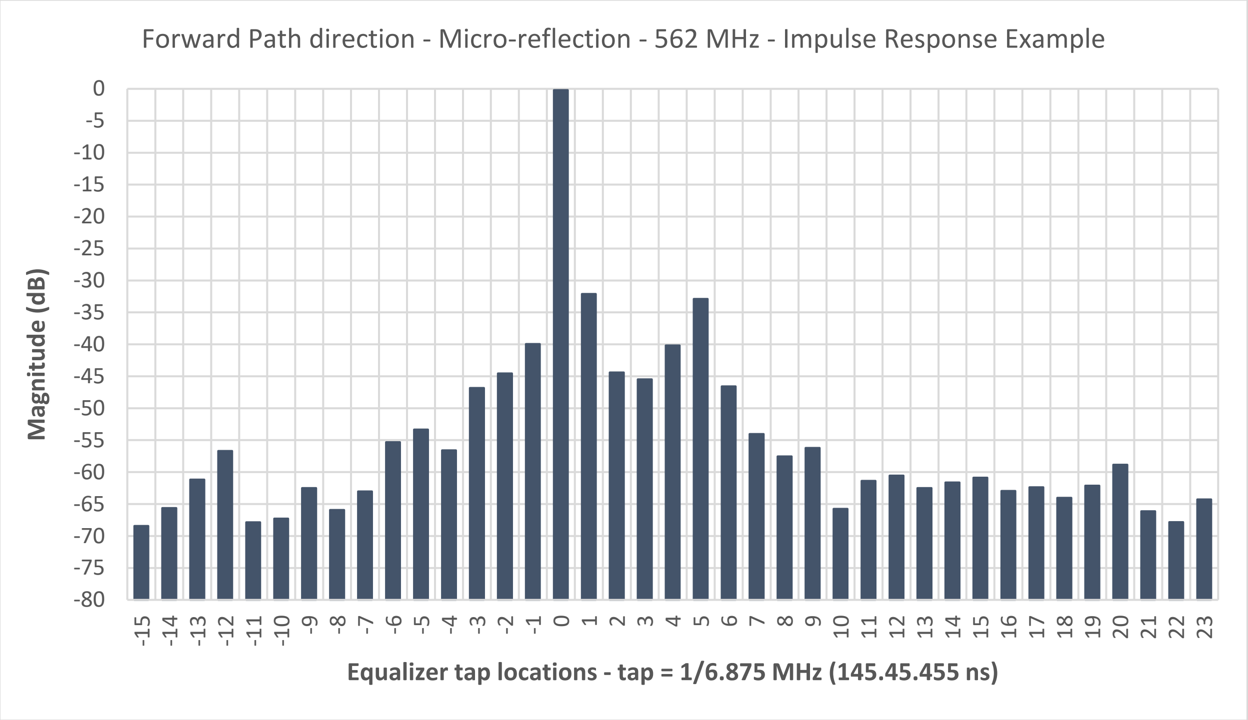


Figure 4b – Equalized impulse response of 562 MHz carrier with dual micro-reflections

- MR1 - Tap location MT+1 = -32.1 dB & one way length = 62 feet (possibly drop coax)
- MR2 - Tap location MT+5 = -32.9 dB & one way length = 311 feet (likely a structural MR)

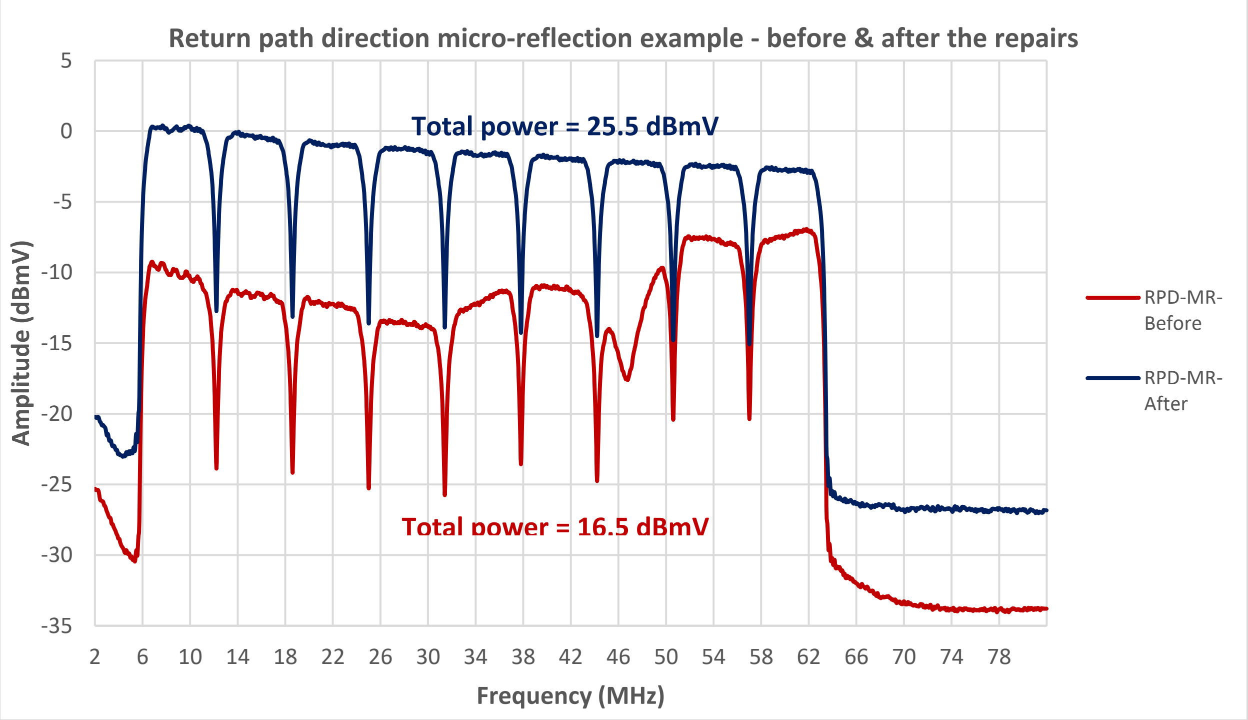


Figure 5 – Return path direction micro-reflection example

Please note the dramatic difference in the response as measured at the output of an 11 dB 8 PORT end-of-line TAP (input/output).

6. Conclusions

The cable TV industry requires methods to make accurate measurements of return path direction impairments anywhere on the coaxial cable network. The only place to make accurate measurements in the return path direction in today's networks is in the hubsite at the CMTS or at the distributed CCAP or R-PHY digital node.

The RF technician in the field has no real ability to measure any return path signal be it interference or actual DOCSIS signal transmissions directly anywhere in the coax network. The reason is simple and it is by design. All taps in the coaxial cable plant point towards the node/headend and don't allow for measurement of signals in the return path direction at all.

Moreover, the home coupling device provides only an isolation response for a diagnostic DOCSIS 3.1 CM performing an FFT spectrum measurement of the home. This is because the CM is not connected to the same coupling port as the interference signal attempting to be measured. Examples of this isolation response and how varied it can be from the actual signal response the CM is attempting to measure with the FFT spectrum measurement feature has clearly been demonstrated in this paper.

Given the limitations of both the hardline tap design and the home coupling device, it was painfully clear to this author that the entire cable TV industry needed dual window taps to resolve this hardline tap and home coupling device return path direction measurement discrepancy once and for all. The dual window tap allows the RF technician to perform return path signal and/or interference signal measurements directly without impacting customer service.

It is strongly recommended that the dual window tap provide two test ports: one the traditional forward path test port and the other a reverse direction (return path) test port. The dual ports allow the RF technician to make measurements in either direction without disrupting customer traffic.

The intent of the dual window tap is to provide the MSO with direct measurement access to the hardline coaxial cable network (plant) without having to disrupt service to the customer and, perhaps more importantly, to be able to perform return path signal measurements that are not influenced by the home environment, including the home coupling device.

This paper presented prototype dual window tap characteristics for the reader to view and hopefully understand the tremendous advantages of having a dual window tap capability at strategic locations in troubled plants.

Additionally, the dual window tap could be designed to resolve testing networks the utilize the emerging DOCSIS 3.1 Full Duplex specification that is presently in development at CableLabs.

Networks with dual window taps have the following characteristics that are highly valuable in both traditional and margining full duplex networks:

- The reverse path direction is not limited to any particular frequency.
- Even more importantly for the RF technician in the field, the reverse direction test port also provides the him or her the ability to generate an independent test signal downstream such that the same RF technician with a second CATV analyzer can demodulate the test signal further down the coaxial cable chain to search for structural micro-reflections and noise interference sources.
- The ability launch an independent test signal further downstream and of course out-of-band for the paying customer to avoid any interference is an extremely powerful diagnostic tool at the disposal of the RF technician in the field that has NEVER existed!
- Imagine attempting to resolve difficult echo and or noise issues entering in the middle of an N+0 bi-directional transmission and then trying to figure out where it is coming from. The dual window tap affords the MSO that ability. For example, installing the dual window tap mid-span allows a technician to observe what is being transmitted in both directions on the coaxial cable.

7. Abbreviations

bps	bits per second
CM	DOCSIS cable modem
CMTS	DOCSIS cable modem termination system
D-CCAP	distributed Converged Cable Access Platform
DWT	dual window tap
FEC	forward error correction
FFT	fast fourier transform
HFC	hybrid fiber-coax
ISBE	International Society of Broadband Experts
MR	micro-reflection
MT	main tap
R-PHY	remote physical layer terminal / node
RT	round trip
SCTE	Society of Cable Telecommunications Engineers

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