DOCSIS 3.1 Operational Integration and Proactive Network Maintenance Tools

Enhancing Network Performance Through Intelligent Data Mining and Software Algorithm Execution (aka More with Less!)

A Technical Paper prepared for the Society of Cable Telecommunications Engineers
By

Brady Volpe
Founder
The Volpe Firm / Nimble This
3000 Old Alabama Rd., Suite 119-434, Johns Creek, GA 30022 USA
Ph: +1-404-424-8202 x.201
brady.volpe@volpefirm.com

Overview

This paper will first provide a brief primer on DOCSIS and DOCSIS pre-equalization. It will then discuss the high level changes in DOCSIS 3.1 which must be considered from a migration standpoint from today's networks. This will lead the reader into a conversation about being reactive versus proactive and venture into the greater discussion of Proactive Network Maintenance. Proactive Network Maintenance will be reviewed and how it can help identify impairments and assist the cable operator in DOCSIS 3.1 migration. Finally the paper will discuss the powerful new PNM features that have been integrated into the DOCSIS 3.1 specification. Examples are provided so that the reader will have a comprehensive understanding of the power PNM will have in a DOCSIS 3.1 network.

Contents

Section 1 – Overview

This paper will first provide a brief primer on DOCSIS and DOCSIS pre-equalization. It will then discuss the high level changes in DOCSIS 3.1 which must be considered from a migration standpoint from today's networks. This will lead the reader into a conversation about being reactive versus proactive and venture into the greater discussion of Proactive Network Maintenance. Proactive Network Maintenance will be reviewed and how it can help identify and locate impairments as well as assist the cable operator in DOCSIS 3.1 migration. Finally the paper will discuss the powerful new PNM features that have been integrated into the DOCSIS 3.1 specification. Examples are provided so that the reader will have a comprehensive understanding of the power PNM will have in a DOCSIS 3.1 network.

Section 2 – DOCSIS 1.x, 2.0, & 3.0 Primer (excludes 3.1)

Data Over Cable Service Interface Specification (DOCSIS) is effectively a transparent Ethernet bridge over a hybrid fiber/coax (HFC) network. There are two (2) functional components in a DOCSIS network, the cable modem (CM) on the subscriber side and the CMTS in the headend or hub site. The CMTS typically communicates with the CMs on one or more 6 MHz wide (8 MHz in Euro-DOCSIS deployments), 64- or 256-QAM (quadrature amplitude modulation) digitally encoded RF signals on the downstream path of an HFC network between 108 MHz and 1 GHz. The CMs communicate with the CMTS using one or more quadrature phase shift keying (QPSK), 8-, 16-, 32-, or 64-QAM digitally encoded RF signals, transmitted on an upstream HFC frequency between 5 to 85 MHz. The digital data, transported via digitally modulated carriers, contains Media Access Control (MAC) information, which enables the CMs to coexist with other CMs by using a Time Division Multiple Access (TDMA) scheme or synchronous code division multiple access (S-CDMA). In essence, the CMTS is the system scheduler, which coordinates the power level, frequency, transmit time, and pre-equalization of all CM signals on the DOCSIS network. By virtue of the fact that CMs and the CMTS are able to communicate digital data with each other over the HFC network for the purpose of "command-and-control" processes, they are also able to transmit packets containing other non-DOCSIS MAC related data. This is what fundamentally facilitates the ability to send Ethernet traffic bi-directionally over an HFC network. The CMTS-CM DOCSIS network transports IP based traffic in the same method that is used to communicate MAC protocol between the devices. Now that the IP traffic can traverse the HFC network, end users are also able to utilize this network for the purpose of transmitting content destined for the multitude of available data network services such as email, web browsing, IP video, and voice over IP telephony (VoIP).
In summary, each user is assigned a unique cable modem, which conforms to the DOCSIS specification. The CMTS works as a system scheduler enabling many cable modems to

reside on the same RF network. TDMA and/or S-CDMA are employed in cable modem communications so that each modem is allocated a certain finite time over which it may transmit and receive IP data. IP data destined for a particular user is sent to that user's modem by the CMTS on one or more downstream RF channels. This is the way an Ethernet network is able to be transparently bridged from a data backbone to a subscriber's home or business location.

Section 3 – What is DOCSIS Pre-Equalization

DOCSIS pre-equalization is a feature that was first added in the DOCSIS 1.1 specification. The objective of pre-equalization is to improve upstream performance in the presence of certain RF impairments. These impairments include, but are not limited to, frequency response, micro-reflections, and group delay.

The method in which DOCSIS pre-equalization improves upstream performance in the presence of these RF impairments is simple. The CMTS looks at messages coming from the cable modem and evaluates the signal quality of the messages. If the CMTS determines that the messages can be improved by pre-equalization, the CMTS sends equalizer adjustment values to the cable modem. The cable modem applies these equalizer adjustment values, called coefficients, to its pre-equalizer. The result is that the cable modem transmits a pre-distorted signal to compensate for impairments, causing the distortion, between the cable modem and the CMTS. As the pre-distorted signal traverses the HFC network it will experience the effects of RF impairments. By the time the pre-distorted signal from the cable modem arrives at the CMTS it will no longer have any of the original pre-distortion, as the RF impairments will have transformed it back into a near-ideal signal that the CMTS intended to see. If further adjustments are required, the CMTS will send more pre-equalizer coefficient values to the cable modem and the cycle repeats. This cycle repeats at least once every thirty seconds for every cable modem in the DOCSIS network, provided pre-equalization is enabled in the CMTS.

An illustration of a cable modem signal is perhaps the best way to demonstrate pre-equalization in action. Figure 1 below shows an upstream cable modem signal as seen at the CMTS. This RF signal shows significant roll-off due to plant impairments. This would cause the CMTS to have difficulty-demodulating signal, resulting in codeword errors, lost subscriber data and poor subscriber quality of experience (QoE).

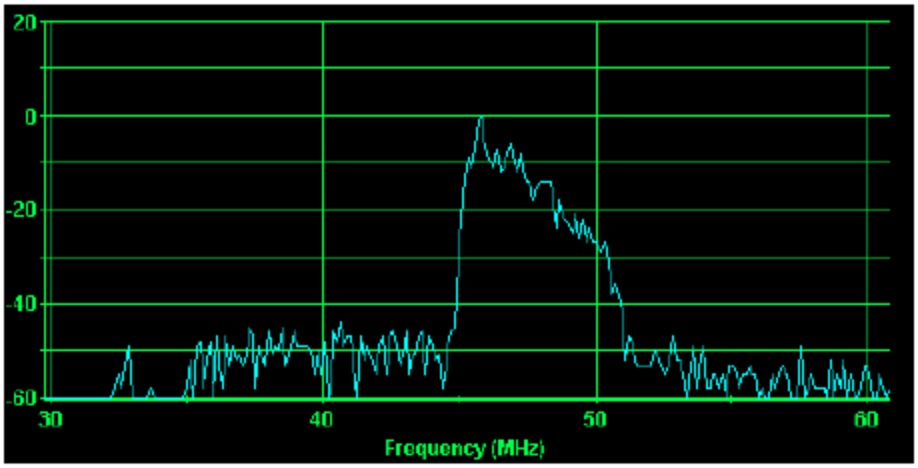

Figure 1: Cable Modem Signal without Pre-Equalization

Once DOCSIS pre-equalization is enabled on the CMTS for this particular upstream, the CMTS will instruct the cable modem to pre-distort the signals it is transmitting via its internal equalizer. The pre-distortion would result in a signal that has higher output at the high frequencies and less output at the lower frequencies. This would be a mirror image of the signal seen in figure 1. The result is the response shown in figure 2 below, where the signal at the CMTS is flat after going through the RF impairments.

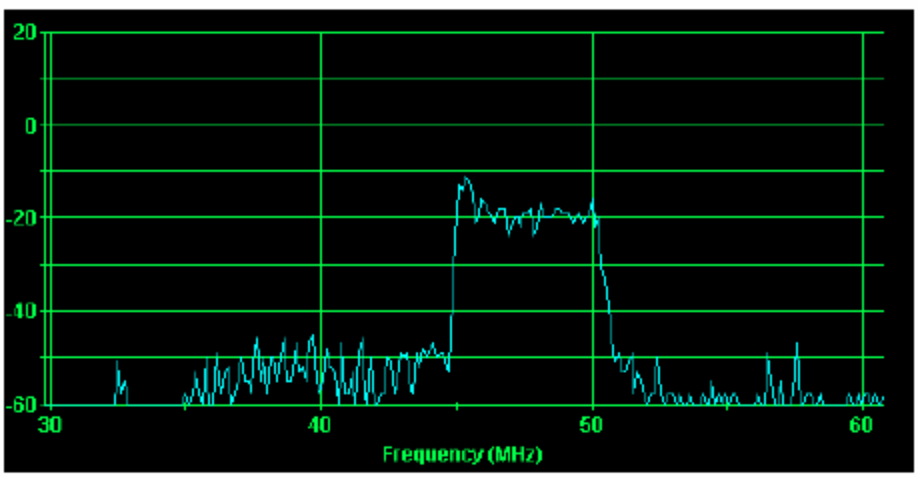

Figure 2: Cable Modem Signal with Pre-Equalization

Now the value of DOCSIS pre-equalization should be clear. What was once a very poor, looking signal at the CMTS (figure 1), is now a near-perfect signal at the CMTS (figure 2) thanks to pre-equalization in the cable modem.

Section 4 – DOCSIS 3.1 Challenges

DOCSIS 3.1 is the latest DOCSIS specification released in late 2013. Its primary goal is to extend the life of DOCSIS by providing substantially higher downstream and upstream data rates through high order modulations. The higher order modulations in an HFC network are achieved by using Orthogonal Frequency Division Multiplexing (OFDM) and an improved error correction technic called Low Density Parity Check (LDPC). The details of OFDM and LDPC are outside the scope of this paper, however we will focus on the modulation and bandwidth increases in DOCSIS 3.1 and how these will impact the plant operations.

The first key challenge in DOCSIS 3.1 is the aforementioned higher order modulation formats. In previous versions of DOCSIS the highest mode of quadrature amplitude modulation (QAM) used was 256-QAM. This means 2^8 or 8-bits per symbol are represented in the constellation. In DOCSIS 3.1, modulations of up to 4096-QAM will be supported. At 4069-QAM there are 12-bits per symbol or 2^{12}. This makes for a higher requirement on the downstream MER (roughly 35 dB MER) versus the current 31 dB MER needed for 256 QAM. It is easiest to visualize the physical difference between 256-QAM and 4096-QAM by looking at their respective constellation diagrams shown in figure 3 below:

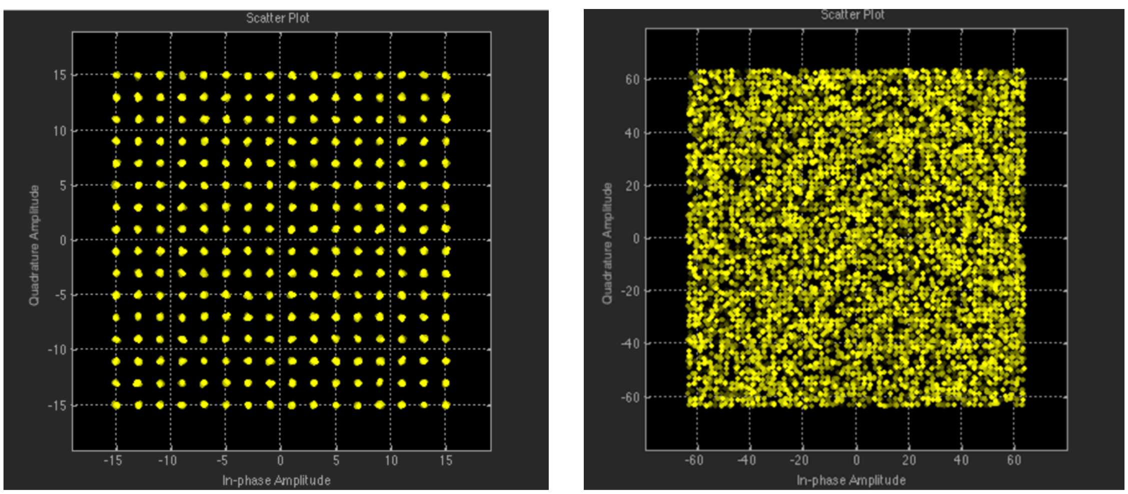

Figure 3. 256-QAM vs. 4096-QAM Constellation Diagram

Here we see that 256-QAM has a great deal of spacing between constellation points while 4096-QAM looks more like a blurry mess. This necessitates a very clean downstream. In other documents one can read how LDPC will help during the recovery process in compensating for errors that may occur, however it must be understood that there is no fixing a noisy downstream.

Similarly in the upstream the current highest order modulation is 64-QAM. In DOCSIS 3.1 up to 1024-QAM will be supported. Just as in the downstream the upstream must improve from an MER standpoint in order to support 1024-QAM. Figure 4 provides a visual indication of the difference between 64- and 1024-QAM.

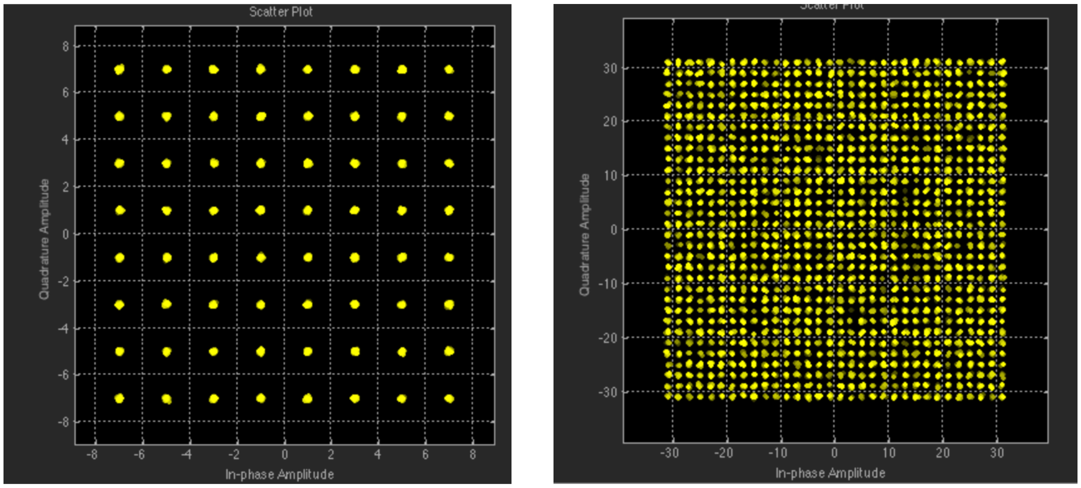

Figure 4. 64-QAM vs. 1024-QAM Constellation Diagram

For 64-QAM we see even larger spacing between constellation points than in 256-QAM. This is expected in the upstream due to the larger ingress and impairments typical of the upstream. The 1024-QAM constellation is not nearly as congested as the 4096-QAM constellation in figure 3 as individual symbols can still be recognized. However 1024-QAM is still a very complex modulation to be used in upstream transmission on an HFC network.

Further, upstream DOCSIS 3.0 and lesser channels have a maximum bandwidth of 6.4 MHz. In DOCSIS 3.1 the minimum bandwidth of a DOCSIS channel will be 24 MHz. This is roughly the equivalent of four (4) legacy DOCSIS channels stacked side-by-side. It will represent a substantial RF energy increase to analog return path optical lasers resulting in potential laser clipping. Figure 5 shows a comparison between an existing 6.4 MHz DOCSIS channel and a 24 MHz DOCSIS 3.1 channel.

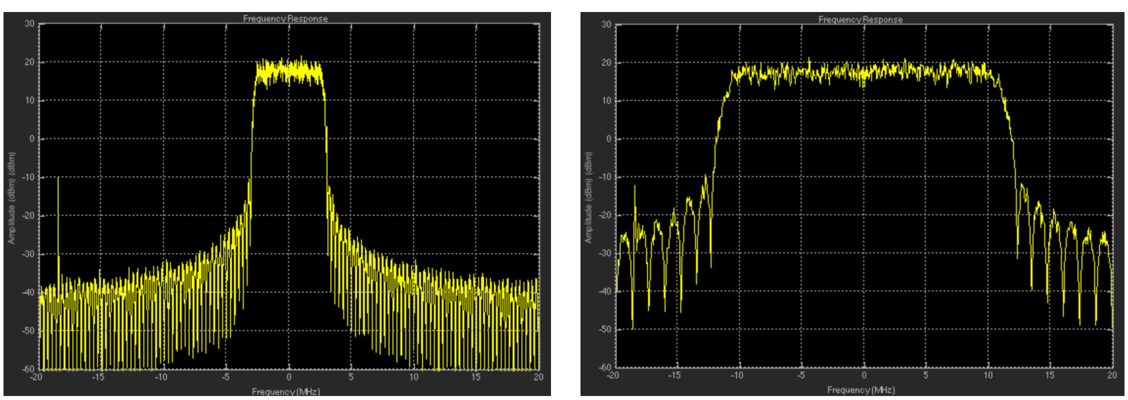

Figure 5. 6.4 MHz Upstream vs. 24 MHz Upstream Channels

To be successful it is clear that upstream improvements and preparations will be required. This is the opportunity for Proactive Network Maintenance (PNM) now, long before the first DOCSIS 3.1 network is turned up.

Section 5 – Proactive Network Maintenance (PNM)

Proactive network maintenance or PNM is the practice of maintaining a network in a non-reactive method. This statement is not meant to be sarcastic, as only until the past several years' cable operators have relied on reactive tools. Such tools provide metrics such as FEC statistics, MER, SNR, or even offline modem counts. The challenge with these metrics are that they often provide too little information too late. In many cases when the metrics arrive they are customer impacting.

Through the advent of the PNM initiative and the InGeNeOs working groups at CableLabs, proactive network maintenance has become a viable alternative. This is primarily accomplished through the data acquisition of cable modem pre-equalization data. Upon obtaining the data, it is processed through algorithms and upstream impairment taps, distance to impairments and correlation of modems with common impairments can be determined. The resulting output can be summarized in a typical PNM application as shown in figure 6 below.

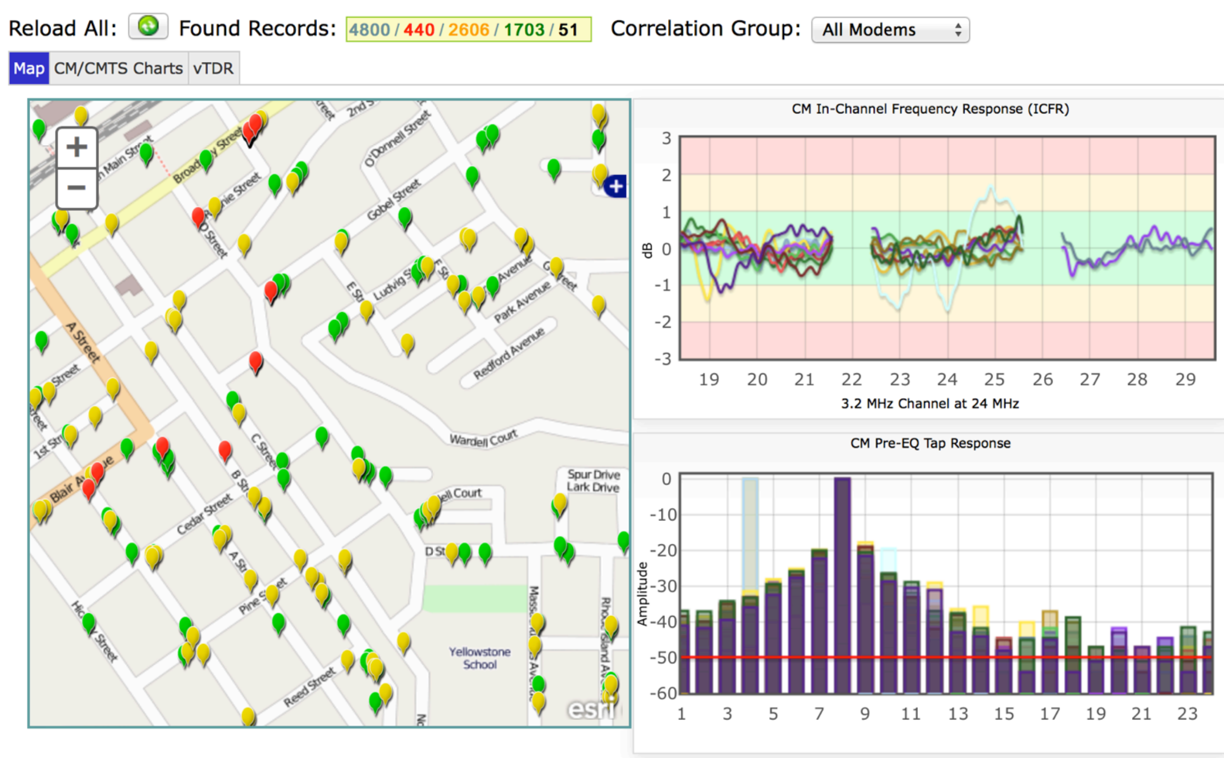

Figure 6. Commercial PNM Monitoring Solution

As can be seen, the cable modems on a given CMTS are quantified as red, yellow and green based on the criticality of upstream impairments analyzed by the pre-equalization data stored in the cable modems. A red modem shown on this dashboard is very different than a red modem, which would be shown on a standard SNMP or NMS dashboard. The SNMP dashboard will tell you when a modem is reporting problems, like bad SNR, MER or uncorrectable codeword errors. This PNM-based dashboard is proactive because it shows when a modem may have problems in the future. This is because pre-equalization in the cable modem is compensating for upstream impairments. Ideally the modem is able to fully compensate for the impairments and the subscriber and the SNMP monitoring system is not aware of the existence of the impairment. One thing is certain, however; cable plants do not get better over time. Corrosion, water, wind, and time will take their toll. The tap values and in channel frequency response will deteriorate over time. So it is safe to assume that most of the red modems will eventually start showing up on the SNMP monitoring systems and / or result in subscriber calls. Similarly the yellow modems will become red modems. So it is a conscious decision to decide to be proactive instead of reactive.

Small and large cable operators have realized the power of PNM and its adoption rate is rapidly growing. The goal in all of this is using PNM technology is to be proactive and identify and fix problems before the subscriber knows they exist. Even further, it is desirable to take this opportunity to focus on improving the HFC plant in preparation for DOCSIS 3.1. This can be with the insight to impairments that were not previously visible.

Section 6 – PNM Spectrum Analysis

While not quite as proactive, some of the outcomes from the PNM working groups were advanced functionalities that took advantage of existing DOCSIS hardware to provide more insight to the HFC plant. Most notably are upstream and downstream spectrum analyses.

Typically upstream and downstream spectrum analysis required expensive hardware from test equipment vendors. In addition return path monitoring in the headend involved extensive headend splitters and cabling. The addition of these splitters and cables add loss, points of failure and ingress and add OPEX for the manpower to install and maintain the equipment.

The PNM solution for upstream spectrum analysis is to use the built-in spare FFT in every CMTS. This adds virtually no extra processing to the CMTS. Further since it uses the intelligence of the CMTS one is able to filter on any cable modem MAC address with the additional power of seeing ingress under the DOCSIS channel. Seeing ingress under the DOCSIS channel is accomplished because the CMTS knows both when modems are transmitting data as well when modems are not transmitting data. As the CMTS knows when no modems are transmitting it can provide RF data on these no-transmit periods. This provides RF spectrum of ingress noise under the DOCSIS channels, which is virtually impossible to obtain using conventional headend monitoring equipment. Figure 7 shows an example of a PNM-based upstream spectrum analyzer using CMTS hardware for the capture of the upstream.

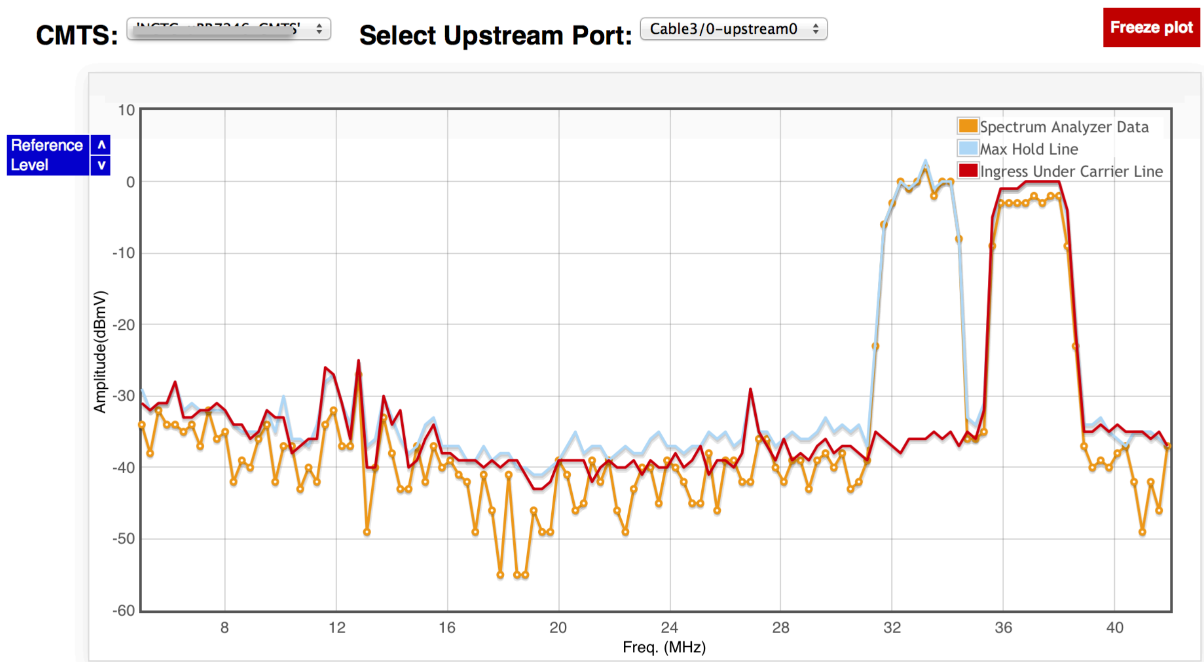

Figure 7. PNM-based Upstream Spectrum Analyzer

For downstream spectrum analysis the cable modem is used. Only newer generation DOCSIS 3.0 cable modems support this functionality, which is called full-band capture. This advanced capability in modems provide the ability to capture the frequency spectrum from 54 MHz to 1 GHz and sometimes higher.

This means that every subscriber having one of these modems becomes an end-of-line probe with spectrum analysis capability. Consider a subscriber calling about not being able to view ESPN. One could quickly pull up the RF spectrum going to the subscriber's home and see there is a big suck-out where the ESPN network is. It would then be possible to look around neighboring homes and find if the impairment is only at the subscriber's home or if it is a plant issue. This enables the cable operator to know whether to send a tech to the subscriber's home or to an RF amplifier feeding the group of homes effected. This powerful functionality enables one to find the problem and narrow its location down to a specific location in a matter of minutes. Figure 8 shows an example of a live capture from a Comcast plant courtesy of Larry Wolcott of Comcast.

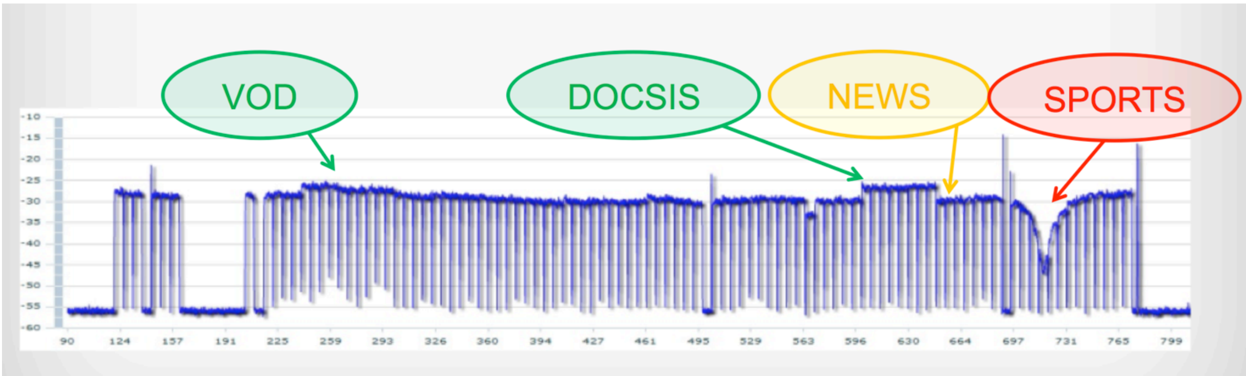

Figure 8. PNM-based Cable Modem Downstream Spectrum Analyzer

In the above capture it is evident that a suck-out is present directly where the sports channels are being broadcast. Other minor impairments can be visualized in the spectrum as well, indicating the power of this feature.

Section 7 – PNM in DOCSIS 3.1

So far the discussions of PNM have strictly been associated with DOCSIS 1.x through DOCSIS 3.0. Without question PNM is extremely power and many cable operators are finding CAPEX & OPEX savings in addition to tremendous subscriber satisfaction. During the development of the DOCSIS 3.1 specification the CableLabs InGeNeOs working group collaborated with the DOCSIS 3.1 working group to ensure that PNM hooks were integrated into the 3.1 standard. This has resulted into some very powerful PNM features in the DOCSIS 3.1 standard that will enable PNM functionality far beyond what is currently available today.

The entire Section 9 of the DOCSIS 3.1 PHY specification is dedicated to "Proactive Network Maintenance". Figure 9 below shows the corresponding figure 9-1 from the DOCSIS 3.1 PHY, which represents an overview of test points in the CM and CMTS providing network analyzer, spectrum analyzer and vector signal analyzer functionality from a PNM perspective.

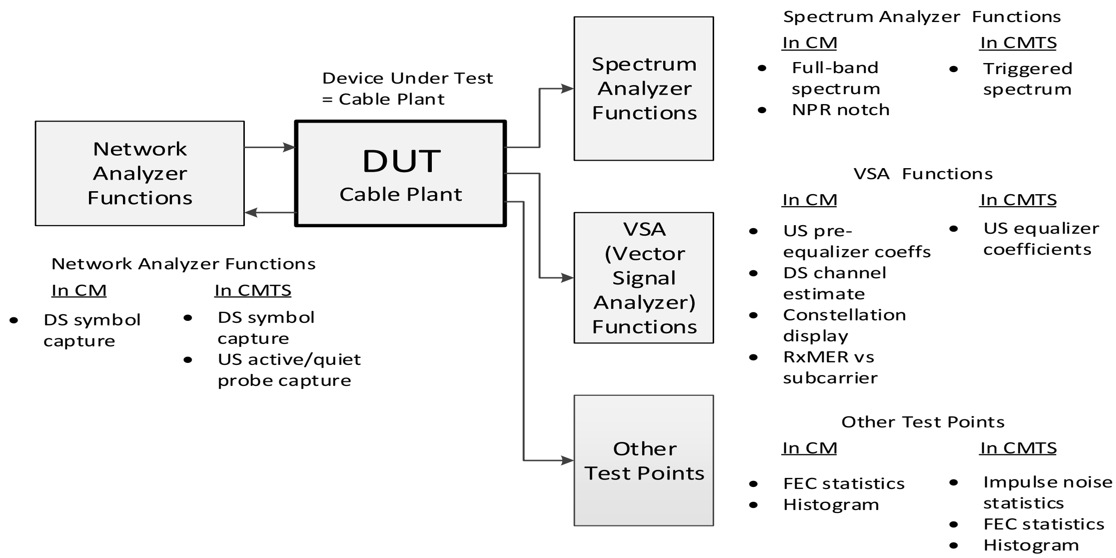

Figure 9. DOCSIS 3.1 PHY Figure 9-1 Test points in CM and CMTS Supporting Proactive Network Maintenance

The above diagram and PHY specification includes PNM metrics such as downstream transmit and receive symbol capture, wideband spectrum analysis, noise power ratio, in channel estimation, constellation display, MER, histograms and a ton of statistics

Similarly for the upstream there is a feature called a quiet probe, giving the ability to do live plant NPR testing, more spectral analysis, the same upstream taps just like today, lots of statistics, histograms and MER. There is unprecedented insight to upstream signal quality and more importantly impairments. Some detailed examples of how these types of tools will be used in practice are modeled in the following paragraphs.

Figure 10 shows the downstream symbol capture in practice. Since the the transmitted and received symbols at the CMTS and cable modem are known, the exact quality of the transmitted and received DOCSIS signal can be determined. If there is an impairment it will be visible and determinant. The impairment type, degree of impairment and impact on the network will also be evident. Impairments such as ingress under the carrier will not require test equipment to estimate the ingress. Cable modems will provide this information to the user or application with extreme detail. In the case of figure 10, the in channel frequency response is being derived by the symbol recovery, however much more detail can and will be derived.

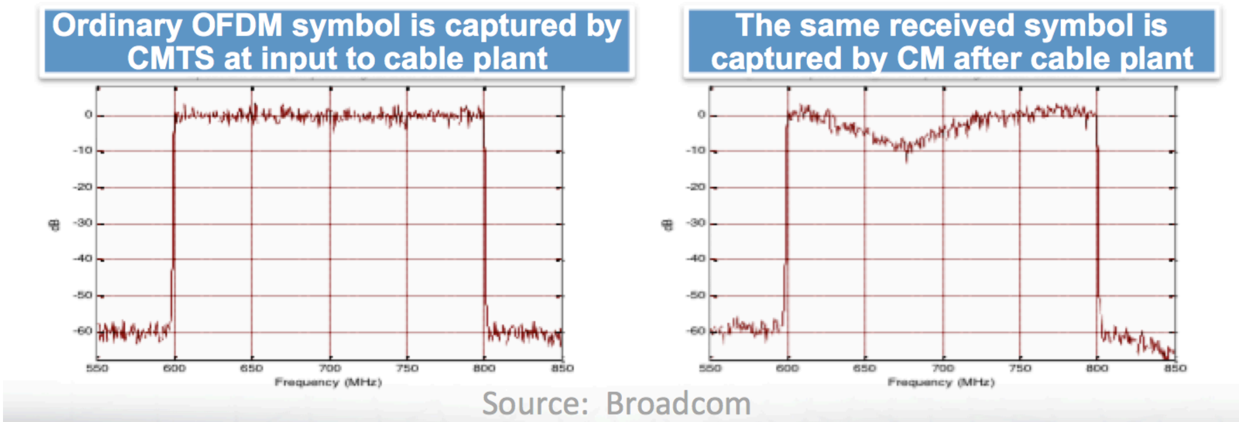

Figure 10. PNM DS Symbol Capture

On the upstream, it will be possible to tell exactly how much dynamic range is left in the return path laser. This will be accomplished with Noise Power Ratio or NPR testing. Using exclusion bands, non-linearity's will fill up the open notches as shown in figure 11 and then it will be possible to precisely determine the amount of available dynamic range. Previously NPR was only something that could be accomplished in the laboratory, but with PNM in DOCSIS 3.1 it will be practical to do in live DOCSIS networks.

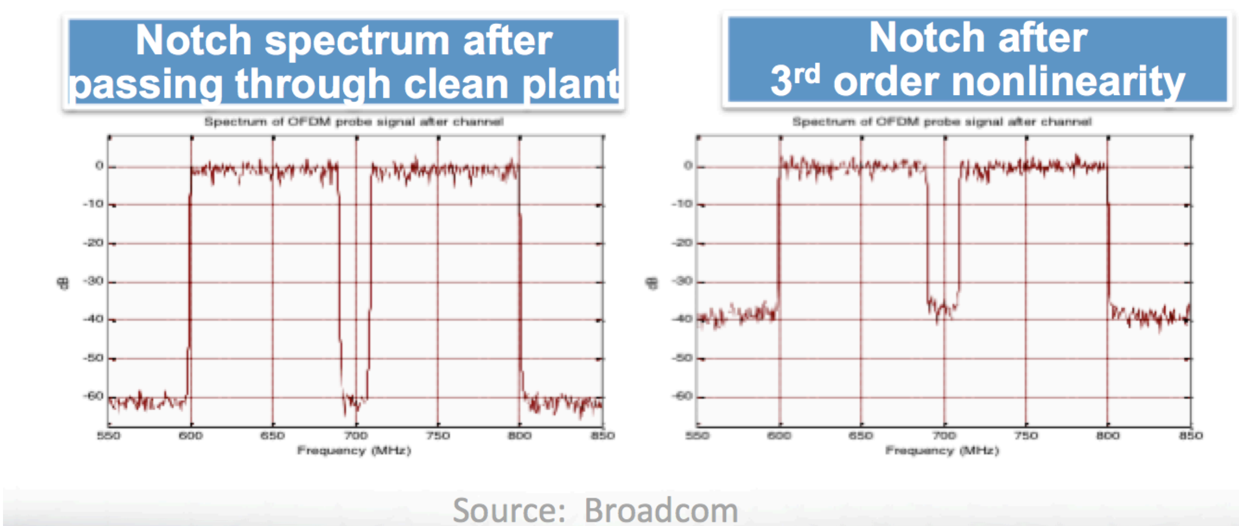

Figure 11. NPR Testing in Live DOCSIS Networks

The final example is the ability to definitively know anytime the laser clipped on a symbol-by-symbol basis. Further it will be possible to plot this in a histogram and create simple thresholds to set-off traps when laser clipping occurs. This will be easily to implement with PNM in a DOCSIS 3.1 network with the new hooks in place. Figure 12 provides an example of how this is possible.

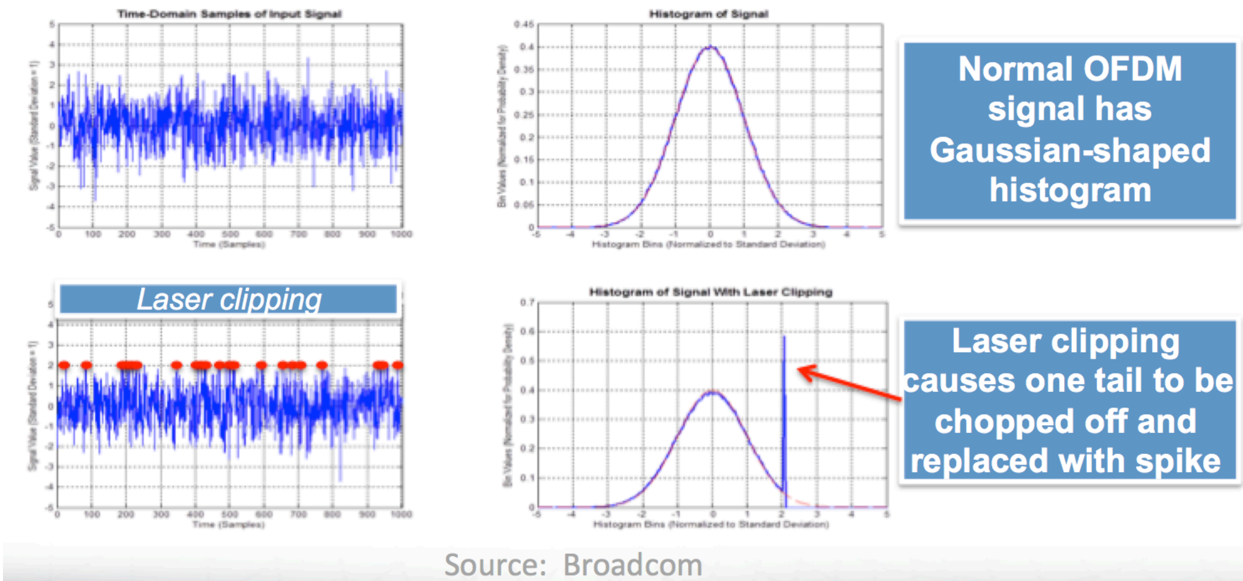

Figure 12. DOCSIS 3.1 PNM Laser Clipping Detection

The top row of figure 12 shows a normal OFDM signal with no laser clipping. The time domain chart (upper left) has no clipping events and the histogram (upper right) is perfectly Gaussian shaped. The bottom row shows what happens with PNM metrics when laser clipping occurs. The time domain chart on the lower left provides visible indication of signals being clipped as they do not rise above the y-axis where y=2. These are highlighted by red dots. When this is plotted on a histogram (lower right) one can see the significant change from the Gaussian distribution and the sharp peak at y=2. This sharp peak at y=2 on the histogram makes laser clipping events extremely easy to detect. This is a dramatic change from today's methods of laser clipping detection where one must look at the RF spectrum above 42 MHz (65 MHz for European networks) and try to identify non-linear RF energy. The later method is fraught with error and requires expensive RF spectrum analyzers. The PNM method in DOCSIS 3.1 simply requires the CMTS and cable modems along with a software algorithm.

Section 8 – Summary

This paper examined DOCSIS pre-equalization, Proactive Network Maintenance (PNM) and the new features that will come in PNM with DOCSIS 3.1. Further the paper discussed some of the key challenges in DOCSIS 3.1 and how proactively addressing your network today can help improve your network in order to prepare for DOCSIS 3.1. The reader should be able to take away a sense of the value of PNM as well as how PNM will continue to increase in value as DOCSIS 3.1 arrives.

Combined with upstream spectrum analysis in the CMTS, full-band capture modems for downstream spectrum analysis, the utilization of PNM to proactively troubleshoot networks is changing plant maintenance in a very positive way. A key step is first taking the initiative to "be proactive", the first habit in Stephen Covey's "7 Habits of Highly Effective People". The next step is to implement PNM if it is not already being done in one's DOCSIS network.

There are many success stories by large and small cable operators using PNM. The time is now to get proactive.

Bibliography

CableLabs, “Data Over Cable Service Interface Specifications DOCSIS 3.0-Physical Layer Specification,” CM-SP-PHYv3.0-I08-090121, 2009

B. Currivan, “Cable modem physical layer specification and design,” in Cable Modems: Current Technologies and Applications , IEC Compendium and IEEE Press, 1999.

CableLabs, “DOCSIS® Best Practices and Guidelines, Proactive Network Maintenance Using Pre-equalization”, CM-GL-PNMP-V02-110623, 2011

T. Wolf and C. L. A. Gatherer, “Low complexity equalization for cable modems,” in IEEE Proc. ISCAS, May 1998, vol. 5, pp. 522–524

CableLabs, “Data Over Cable Service Interface Specifications DOCSIS 3.1-Physical Layer Specification”, CM-SP-PHYv3.1-I01-131029, 2013

References of Honorable Mention:

- Larry Wolcott, Comcast
- Alberto Campos, CableLabs
- Tom Williams, CableLabs

Abbreviations and Acronyms

Adaptive pre-equalizer A circuit in a DOCSIS 1.1 or newer cable modem that pre-equalizes or pre-distorts the transmitted upstream signal to compensate for channel response impairments. In effect, the circuit creates a digital filter that has approximately the opposite complex frequency response of the channel through which the desired signal is to be transmitted.

Cable Modem (CM) A modulator-demodulator at subscriber locations intended for use in conveying data communications on a cable television system.

Cable Modem Termination System (CMTS) Cable modem termination system, located at the cable television system head-end or distribution hub, which provides complementary functionality to the cable modems to enable data connectivity to a wide-area network.
Channel A portion of the electromagnetic spectrum used to convey one or more RF signals between a transmitter and receiver.

Coefficient Complex number that establishes the gain of each tap in an adaptive equalizer.

Customer Premises Equipment Equipment at the end user's premises; may be provided by the end user or the service provider.
dBc Decibel below carrier
Downstream In cable television, the direction of transmission from the head-end to the subscriber.
Fast Fourier transform (FFT) An algorithm to compute the discrete Fourier transform (DFT), typically far more efficiently than methods such as correlation or solving simultaneous linear equations.

Fiber Node In HFC, a point of interface between a fiber trunk and the coaxial distribution.
Frequency response A complex quantity describing the flatness of a channel or specified frequency range, and that has two components: amplitude (magnitude)-versus-frequency, and phase-versus-frequency.

Group Delay The difference in transmission time between the highest and lowest of several frequencies through a device, circuit or system.
Micro-reflection A short time delay echo or reflection caused by an impedance mismatch. A micro- reflection's time delay is typically in the range from less than a symbol period to several symbol periods.
MR Level Micro-reflection level
Modulation error ratio (MER) The ratio of average symbol power to average error power. The higher the MER, the cleaner the received signal.

postMTT Post main tap tap

postMTTR Post-Main Tap to Total Energy Ratio

Pre-equalizer See *adaptive pre-equalizer*.

SNR signal-to-noise ratio

Tap (1) In the feeder portion of a coaxial cable distribution network, a passive device that comprises a combination of a directional coupler and splitter to "tap" off some of the feeder cable RF signal for connection to the subscriber drop. So-called self- terminating taps used at feeder ends-of-line are splitters only and do not usually contain a directional coupler. Also called a multitap. (2) The part of an adaptive equalizer where some of the main signal is "tapped" off, and which includes a delay element and multiplier. The gain of the multipliers are set by the equalizer's coefficients. (3) One term of the difference equation in a finite impulse response or a infinite impulse response filter. The difference equation of a FIR follows: $y(n) = b_0x(n) + b_1x(n\text{-}1) + b_2x(n\text{-}2) + \ldots + b_Nx(n\text{-}N)$

TDR Time domain reflectometer

Upstream The direction from the subscriber location toward the head-end.