How Will Proactive Network Maintenance Change Under DOCSIS® 4.0?

A Technical Paper prepared for SCTE by

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1. Introduction

DOCSIS® 4.0 specifications introduced two important changes beyond DOCSIS 3.1 specifications: extended spectrum, and full duplex transmission. As a result, the assumptions change around the interpretation of proactive network maintenance (PNM) data, how the PNM tests and queries may work, and the sensitivity of some frequencies to certain impairments. As such, PNM tools will likely evolve, and operator use of PNM will need to increase to assure service reliability is met.

This paper outlines expectations around how the network will change, and as a result how network operations may change. It can serve as the foundation for an industry project plan to develop network and service operations solutions to keep pace with new DOCSIS 4.0 technology.

2. PNM Overview

During SCTE's 2008 Cable-Tec Expo in Philadelphia, CableLabs' Alberto Campos, Eduardo Cardona, and Lakshmi Raman presented a paper titled "Pre-equalization Based Pro-Active Network Maintenance Methodology" [1]. The authors proposed using cable modem (CM) upstream transmitter adaptive pre-equalization coefficients to detect and localize plant impairments.

The basic idea involved (1) deriving complex frequency response signatures from pre-equalization coefficients, (2) looking for responses indicative of the presence of linear distortions,[1] and (3) overlaying CM location information from the cable company's customer database on a system topology display of some sort – for instance, digitized outside plant maps.

In 2009 CableLabs formed a PNM working group to implement the ideas presented in the Expo '08 paper. The output of the working group's efforts was a PNM best practices document published by CableLabs in 2010 (updated versions of the best practices document have since been published [2]), followed by a reference implementation.[2]

Using the CableLabs PNM best practices recommendations and sometimes also the PNM reference implementation, several cable operators and third parties were able to create software-based PNM applications. The PNM applications allowed operators to remotely identify and locate plant and drop impairments using data from CM upstream pre-equalization coefficients.

When the DOCSIS 3.1 specifications were created, a decision was made to incorporate provisions and "hooks" for PNM in those specs. PNM was revamped for DOCSIS 3.1 specifications from the ground up to provide downstream and upstream "test points" in the cable modem termination system (CMTS) and cable modem, allowing operators to characterize and troubleshoot hybrid fiber/coax (HFC) plant and subscriber drops; support remote proactive troubleshooting of plant faults; and improve reliability and maximize throughput in well-maintained plants. As shown in Figure 1, from [3], the cable network can be thought of as a device under test (DUT), and PNM measurements are virtual test equipment. For more information, see Section 9 of the DOCSIS 3.1 PHY Specification [3], which details PNM support and requirements.

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[1] Linear distortions in cable networks include micro-reflections, amplitude ripple, and group delay distortion.
[2] SCTE's Network Operations Subcommittee Working Group 7 (NOS WG7), created in 2017, also handles PNM. The CableLabs and SCTE PNM working groups collaborate on the subject, and each group's efforts complement the other's.

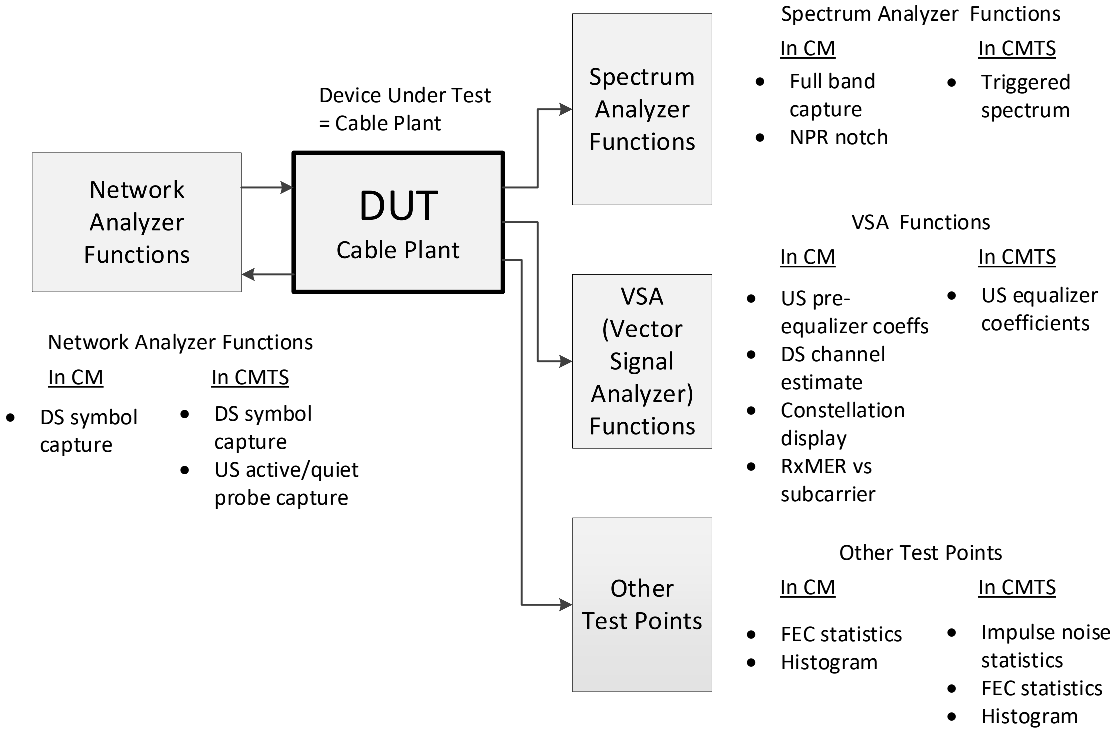


Figure 1 - DOCSIS 3.1 "test points" for an HFC network.

3. What is DOCSIS 4.0?

DOCSIS 4.0 specifications, released in 2019, are the latest in the DOCSIS family. The following description from the introduction in the DOCSIS 4.0 Physical Layer Specification [4] provides an overview:

> This generation of the DOCSIS specifications builds upon the previous generations of DOCSIS specifications (commonly referred to as the DOCSIS 3.1 and earlier specifications), leveraging the existing Media Access Control (MAC) and Physical (PHY) layers. It includes backward compatibility for the existing PHY layers in order to enable a seamless migration to the new technology. Further, the DOCSIS 4.0 specifications introduces Full Duplex (FDX) DOCSIS PHY layer technology as an expansion of the OFDM PHY layer introduced in the DOCSIS 3.1 PHY specification to increase upstream capacity without significant loss of downstream capacity versus DOCSIS 3.1. The DOCSIS 4.0 specification also builds upon DOCSIS 3.1 OFDM and OFDMA technology with an extended Frequency Division Duplex (FDD) DOCSIS alternative. DOCSIS 4.0 FDD supports legacy high split and also provides extended splits up to 684 MHz in an operational band plan which is referred to as Ultra-high Split (UHS). DOCSIS 4.0 FDD also introduces expansion of usable downstream spectrum up to 1794 MHz. Both the FDX and FDD DOCSIS 4.0 alternatives are based on OFDM PHY. Many sections refer to basic OFDM sublayer definitions described in [DOCSIS PHYv3.1].

Cable operators have for decades designed their networks to use sub-split band plans. A sub-split band plan is one that has most of the usable radio frequency (RF) bandwidth allocated to downstream signal transmission. A small portion near the lower end of the usable spectrum is allocated to upstream transmission. For example, a common sub-split band plan used in North America and elsewhere has the upstream operating from 5 megahertz (MHz) to 42 MHz, and the downstream operating from about 54 MHz to the highest downstream frequency limit (e.g., 750 MHz). In an effort to increase upstream capacity and data throughput, the industry has been migrating to mid-split and high-split band plans, with the former using 5 MHz to 85 MHz for upstream transmission, and the latter using 5 MHz to 204 MHz for upstream transmission. For more information on band splits and their history, see [5].

Introduced at the 2019 CES, the cable industry's 10G Platform [6], [7] will deliver speeds of 10 gigabits per second (Gbps) with improved reliability, security, and lower latency, using DOCSIS 3.1 and DOCSIS 4.0 technologies, passive optical networks (PON), coherent optics, dual channel Wi-Fi®,[3] and more.

In particular, the 10G Platform will take advantage of DOCSIS 4.0 technology's expanded spectrum usage – to 1794 MHz (aka 1.8 gigahertz, or GHz) or higher – and more efficient use of parts of the RF spectrum with FDX operation.

3.1. Frequency division duplexing

Originally called "extended spectrum DOCSIS" (ESD), the term frequency division duplexing (FDD) is used in the DOCSIS 4.0 specifications. The reason it's called FDD is because, just like DOCSIS 3.1 and earlier technology, downstream signals operate in one frequency range and upstream signals operate in a different frequency range. The DOCSIS 4.0 upstream RF spectrum can operate to as high as 684 MHz, and the downstream to as high as 1.8 GHz or more. Figure 2, from [4], shows the configurable FDD upstream allocated spectrum bandwidths.

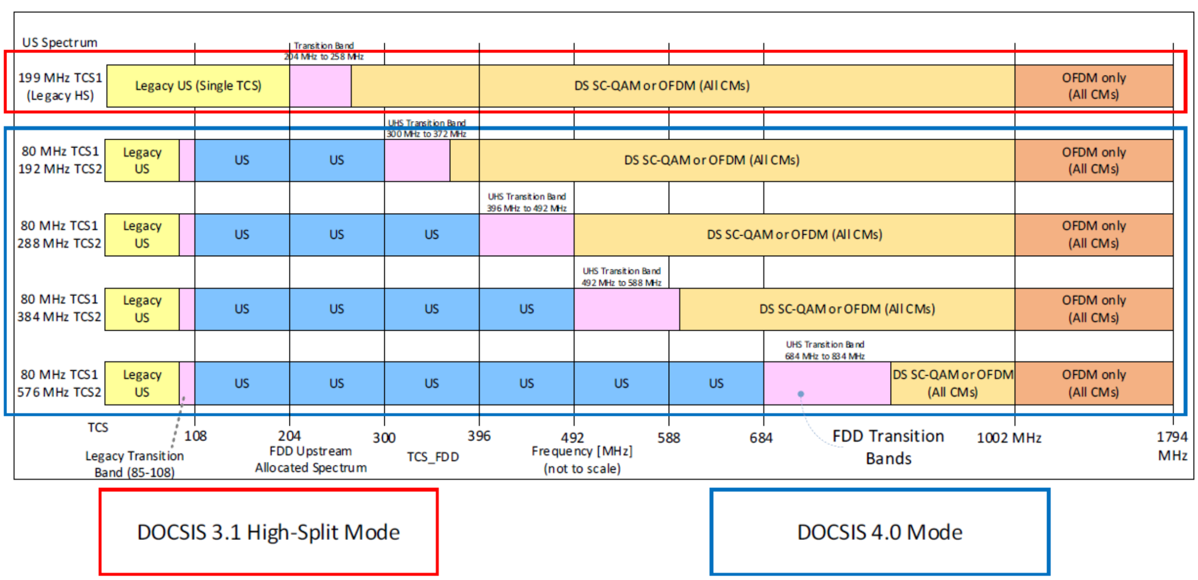


Figure 2. FDD frequency maps.

[3] Wi-Fi® is a registered trademark of the Wi-Fi Alliance®. Wireless local area networks (WLANs) are commonly called Wi-Fi.

3.2. What is full duplex?

FDX – commonly known as "FDX DOCSIS" – was originally introduced as an annex in DOCSIS 3.1 specifications, and is now part of the DOCSIS 4.0 specifications. Through the magic of echo cancellation (EC) and other technologies, FDX allows the carriage of downstream and upstream signals on the same frequencies at the same time. The graphic in Figure 3, from [4], shows configurable FDX allocated spectrum bandwidths, including what is called FDX allocated spectrum. The latter comprises the frequency ranges where downstream and upstream signals can simultaneously occupy the same frequencies, allowing increased data speeds in both directions.

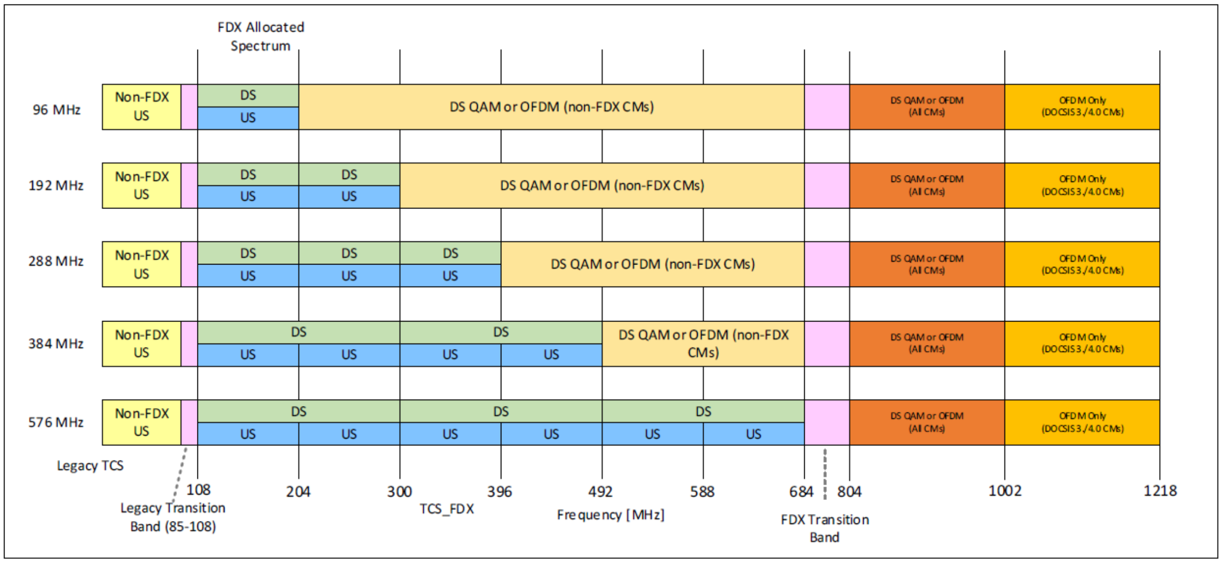


Figure 3. FDX frequency maps.

3.3. PNM in DOCSIS 4.0 networks

As mentioned previously, [3] includes a full section (section 9) covering PNM. "Section 9 PROACTIVE NETWORK MAINTENANCE" in [4] simply says "See [DOCSIS PHYv3.1] section 9."

While the PNM parameters in [3] are for the most part directly applicable to DOCSIS 4.0 technology deployments, there are some important differences and some new challenges. For example, full band capture (FBC) in cable modems will have to support a higher upper frequency limit in the downstream, to 1.8 GHz in FDD applications. Indeed, all of the downstream PNM parameters described in [3] and referenced in [4] will need to support operation to 1.8 GHz, and the upstream PNM parameters will need to accommodate operation in all of the supported frequency ranges to as high as 684 MHz.

Cable network operation on higher frequencies in both the upstream and downstream will be susceptible to new sources of ingress, as well as services with which signal leakage can interfere. Other challenges include such things as management of total power at active device outputs; isolation requirements for FDX; additional attenuation at higher frequencies; PNM test and query; and more. Developers and users of PNM tools and applications will need to understand these challenges, many of which are discussed in subsequent sections of this paper.

4. Plant Preparation and Transition path

The best proactive network maintenance is that which happens when the network is being prepared for DOCSIS 4.0 technology, well before an impairment occurs.

As networks are being upgraded, consider drop tests as well, to find potential leakage, poor drop performance, and potential sources for non-linear impairments. Passive intermodulation (PIM) distortion is anticipated to be worse in DOCSIS 4.0 networks with higher operating levels. Plant preparation is a convenient opportunity to find and remove any older distribution and drop passives that will not perform well at higher frequencies, find and remove bad or detrimental filters (including in-line equalizers), and find and remove any house amplifiers that will impact service. Degraded and poor performing drops may also have difficulty carrying signals at higher frequencies.

In-depth guidance on plant preparation is beyond the scope of this paper, but the authors acknowledge its importance for PNM. In particular, operators must address plant quality before upgrading to and deploying DOCSIS 4.0 technology.

The next section discusses some of the challenges related to managing impairments, and the potential impacts of those impairments on DOCSIS 4.0 technology deployments. Other potentially impacting topics, such as FDX-capable amplifiers and smart amplifiers, are also discussed.

5. Impairment Management and Other Challenges

5.1. Challenges in legacy plants

Figure 4 shows the results of end-to-end testing of a tapped feeder leg (active device output to last tap) using legacy components designed for a maximum downstream frequency of 1 GHz to perhaps 1.2 GHz. The coaxial cable has a standalone attenuation at 1 GHz of about 24 decibels (dB), typical of just under 1000 feet of 0.500 hardline coax. Looking at the S_{12} and S_{21} traces,[4] the combined insertion loss (cable plus passives) is about 45 dB at 1 GHz, typical of a span of feeder with taps and other passives. Of particular concern is the sharp frequency response rolloff starting at about 1.3 GHz in the S_{12} and S_{21} traces (circled in red in the figure), indicating that attenuation at higher frequencies is substantial. That rolloff is caused by the passives. The S_{11} trace, from which return loss can be derived, also indicates poor performance above about 1.3 GHz. From this example, operation above 1.3 GHz would be impossible using the legacy passives.

Cable operators contemplating operation to 1.8 GHz will need to evaluate their networks to determine to what extent upgrades or changes will be necessary to support higher downstream frequencies. PNM tools will need to support operation at the higher frequencies, too.

[4] The S_{11}, S_{12}, S_{21}, and S_{22} parameters in the figure are scattering parameters, or S-parameters. For more on S-parameters, see [13]

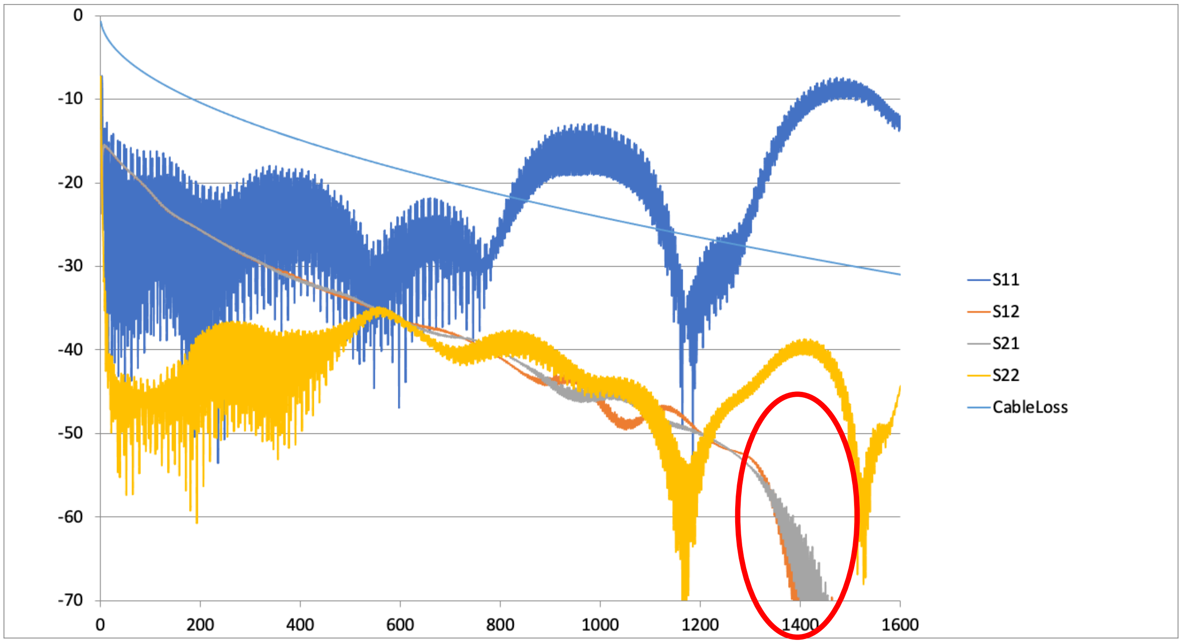


Figure 4: End-to-end test results for a legacy tapped feeder. Graphic courtesy of CableLabs.

5.2. Potential sources of ingress at higher frequencies

Cable operators are already familiar with sources of ingress and over-the-air signals affected by signal leakage in the 5 MHz to 1 GHz frequency range. Most operators have little or no experience with ingress and leakage at frequencies above 1 GHz, though. Figure 5, from [10], shows over-the-air frequency allocations in the United States from about 900 MHz to 1850 MHz (frequency allocations in other countries may be different). This frequency range includes the 902 MHz to 928 MHz industrial, scientific, and medical (ISM) band (shared with amateur radio); the 23 centimeters amateur radio band (1240 MHz to 1300 MHz); six aeronautical radio navigation bands (960 MHz to 1215 MHz, 1300 MHz to 1350 MHz, and four smaller bands from 1559 MHz to 1626.5 MHz); some long term evolution (LTE) bands; among others. GPS frequencies[5] are in the 1100 MHz to 1600 MHz frequency range, too. Signals on some of the aforementioned frequencies are potential sources of ingress interference to the cable network, and can be interfered with by signal leakage.

PNM's full band capture and receive modulation error ratio (RxMER) will continue to be valuable for identifying and helping to locate potential ingress, especially at the higher frequencies discussed here.

[5] Global Positioning System (GPS) frequency L1 is 1575.42 MHz (15.345 MHz bandwidth); L2 is 1227.6 MHz (11 MHz bandwidth); and L5 is 1176.45 MHz (12.5 MHz bandwidth). See https://www.nist.gov/pml/time-and-frequency-division/popular-links/time-frequency-z/time-and-frequency-z-g

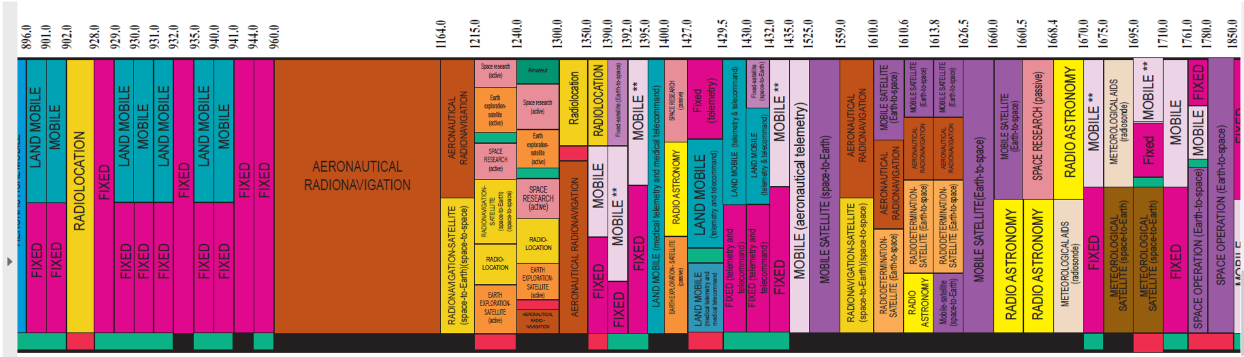


Figure 5. Over-the-air frequency allocations in the U.S. from about 900 MHz to 1.85 GHz.

5.3. Distribution and drop impairment impacts on FDD and FDX

A comprehensive list of plant and drop impairments and their impacts on FDD and FDX operation could easily be the basis for a standalone paper. The following are some of the more important considerations.

- Proper attenuation/insertion loss, frequency response, return loss, port-to-port isolation (where applicable), and other characteristics of network and drop actives, coaxial cable, passives, connectors, etc., across the full operating bandwidth are critical. Out of spec performance for any of the aforementioned could negatively affect FDD and FDX operation.
- Ingress in FDX bands causes errors in channel characterization, and the RF bandwidth of the spectrum affected by noise funneling can be larger in an FDX architecture than in others because of its wider upstream bandwidth. Noise funneling remains a problem because one source impacts all. That is, severe ingress from just one drop can significantly impair a node’s upstream performance, regardless of the size of the node’s service area or the number of homes passed – decreasing the size of the serving area does not necessarily decrease the noise problem. As well, drop ingress in an FDX band could impair downstream (in the drop) and upstream performance.
- Common path distortion (CPD), originating from inside customers’ homes, might be increased by high transmit levels of FDX and FDD CMs.
- An FDX or FDD CM located on unconditioned house wiring, rather than the point of entry, could experience more problems on average. This outcome is due to additional complexity of the inside wiring, presence of drop passives and actives, the number of connectors, etc.

5.4. Managing total composite power

To overcome increased attenuation at higher frequencies in FDD networks, active device output power – including output total composite power (TCP) – will be higher. Figure 6, from [11], illustrates three examples of signal level-versus-frequency in an FDD network. PNM tools can be an important part of the management of active device signal levels and TCP. Section 30.14 and Appendix J of [11] include additional discussion about TCP.

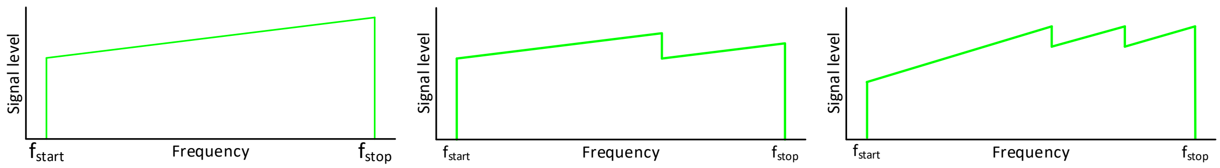


Figure 6. Examples of active device output signal level versus frequency in an FDD network.

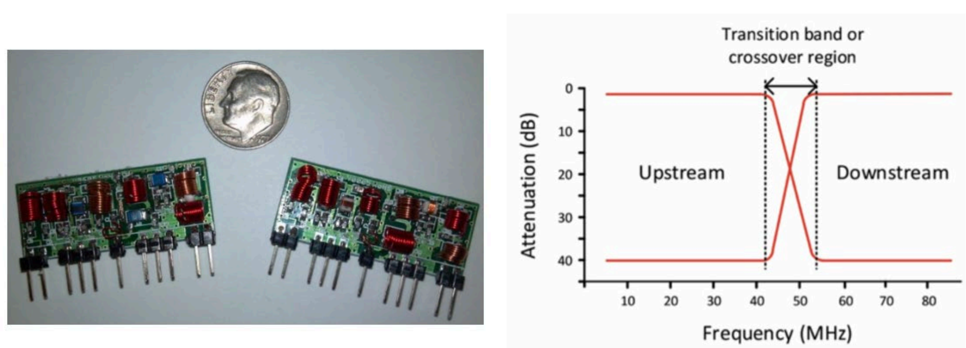
5.5. OUDP leakage detection

While signal leakage detection is generally not part of a PNM toolset, ingress detection is, and the two are often related. That is, if leakage exists ingress usually does, too. In high-split and ultra-high-split band plans, the 108 MHz to 137 MHz aeronautical band overlaps part of the cable network's upstream spectrum. Leakage detection and measurement are more challenging, since a continuous downstream leakage test signal cannot easily be transmitted in or near aeronautical band frequencies. One promising method is to use OFDMA upstream data profile (OUDP) for leakage detection and monitoring. This approach is discussed in [12], and recent lab and field test results are encouraging.

5.6. Outside plant amplifiers and impacts on PNM

5.6.1. FDX amplification and PNM

RF amplifiers are an integral part of any HFC network. Their primary purpose is to amplify and condition RF signals so that they may propagate through subsequent spans of coaxial cable. Coaxial cable attenuates RF signals in a non-uniform manner (that is, cable attenuation is greater at higher frequencies than it is at lower frequencies), thus requiring the next RF amplifier to again amplify and condition the RF signals. Rinse and repeat. RF amplifiers and fiber nodes have one or more devices in them called a diplex filter. Two diplex filters are shown in Figure 7(a) and a simulated transition band of the frequency response of a sub-split diplex filter is shown in Figure 7(b). The purpose of the diplex filter is isolate the downstream from the upstream path in the active device, helping to prevent problems such as oscillation.



(a) (b)

Figure 7: Example diplex filter (a), diplex filter transition band (b).

Diplex filters are not compatible with FDX operation. This is because upstream and downstream signals are present on some frequencies at the same time. The diplex filter prevents this from occurring, so FDX networks require one of two considerations:

- A network design with a fiber node and no active devices after the fiber node (aka Node + 0).
- A design with a fiber node and amplifiers capable of amplifying in both directions without diplex filters, or dedicated FDX-capable amplifiers with echo cancellation.

In the case of FDX amplification and PNM, a Node + 0 network in theory makes for a much simpler network to maintain and troubleshoot. Since it lacks any actives after the fiber node, one only need be concerned with the node (and perhaps power supply), the hardline coax, passive devices, and subscriber drops and their components. When considering troubleshooting using such things as correlation groups and echo cavities, the following are important:

- The number of subscribers available in a correlation group will typically be smaller due to smaller service groups.
- Echo cavities will always be formed between the fiber node and passive devices and/or damaged coax/connectors. Actives after the node will no longer play a role in echo cavities.
- The number of impairments in a given plant segment will decrease because the number of connectors, coax, etc. will be fewer.
- Node + 0 will not fix pre-existing distribution coax and drop issues. RF failure group sizes may be reduced, and some causes of failure eliminated, but the number of overall service issues may or may not be greatly reduced.

While the general maintenance requirements for a Node + 0 network are not substantially expected to go down, the overall performance is expected to improve. This is because RF downstream signals from the fiber node will be nearly equivalent to those in the headend from a quality perspective. Further, upstream signals from the CM will be received and demodulated at the fiber node, assuming a DAA deployment with digital fiber links.

PNM will be a key troubleshooting tool in an FDX deployment to monitor performance, impairments and EC performance. It is assumed that for FDX to be successful some amplification may be required in HFC networks. It will be essential for PNM to have visibility into FDX amplified networks, especially at the amplifier level. See the next section on smart amplifiers.

5.6.2. Smart amplifiers and FDD

FDD is very different than FDX in its requirements for diplex filters and amplification, but there is one commonality discussed this section: smart amplifiers.

FDD will still require diplex filters to separate the downstream from the upstream in actives and certain passives. However, diplex filters in an FDD environment will need to at a minimum be upgradable and ideally programmable (or remotely switchable). Similarly, the RF conditioning circuitry in RF amplifiers should also be programmable. Vendors are producing new amplifiers with diplex filters and conditioning circuitry which can be remotely configured or locally configured with a mobile app.

This leads into the concept of smart amplifiers. Smart amplifiers not only include the ability to eliminate legacy plug-in pads and equalizers, but they are also adding PNM functionally such as full band capture so that one can remotely see the output of the amplifier to configure its padding and conditioning. PNM can take advantage of FBC in the fiber nodes and amplifiers as yet another monitoring point in the field to identify and localize RF impairments. This is useful for both FDD and FDX deployments.

Because the FBC capability in smart amplifiers is built on CM technology, other PNM tests can use the CM in the amplifier. Now the amplifier can be used for all PNM tests supported by the CM chipset. Of particular importance is that this functionality operates over the extended upstream and downstream RF bandwidths.

6. DOCSIS 4.0 Technology

6.1. Triggered RxMER

As stated in [4], FDX modems can measure RxMER over all subcarriers at the same time. This measurement is triggered by events including time triggers, echo canceller training (ECT) probe triggers, and OUDP sounding triggers.

Time triggers could be the most useful for PNM because they are triggered at a specific time, and that time could be correlated to certain events by the CMTS or converged cable access platform (CCAP). For example, a CM can measure RxMER per subcarrier while a specific test downstream signal is sent, and while another upstream signal is sent by another CM. This could be used to find nonlinear impairments. Also, it could be used to synchronize data collection on multiple CMs at once, or to coordinate with a test device signal or measurement, or to time an external radio signal to potentially look for ingress sources, for example.

ECT RxMER probe triggers measure a modem's receive capabilities during worst case conditions, used for setting bit-loading after echo cancellation training. As such, it could be useful for PNM as an indication of the environment for transmission, and will provide a peek at the bit loading that the CM is capable of achieving.

OUDP sounding triggers allow measurement of the interference between CMs. With a measure and a sounding CM pair, the information could be very useful for PNM, particularly for fault localization. The information may even be useful to verify relative location information.

While these alternate forms of RxMER are described for the DOCSIS 4.0 protocol in both the PHY [4] and MULPI [8] specifications, the OSSI [9] specifications have not yet outlined how the data would be reported for fault management purposes.

6.2. Interference group information

The CMTS or CCAP determines a given FDX modem's participation in an interference group (IG) and transmission group (TG) after modems have performed sounding. This process helps the CMTS to identify which CMs interfere with other CMs on a given HFC plant segment. During sounding one CM is granted time to transmit and surrounding CMs are told to measure the per-subcarrier RxMER for the FDX sub-band being used for the sounding. Future enhancements in the OSSI specifications are planned to address the reporting of which CMs have been placed into specific IGs and TGs. Because CM membership in a given IG or TG is not operator-configured, the CMTS/CCAP is the source of truth for these associations.

Additionally, FDX manages the usage of a given FDX sub-band through the use of what is called a resource block (RB). It is possible to assign a given RB in a given TG as either static (always one direction, usually upstream) or dynamic (scheduled by the CMTS or CCAP, the block operates in both directions in a given sub-band for a specific TG). In the dynamic resource block assignment (RBA) scheduling, RBA switching can happen at an extremely fast rate which makes tracking and reporting of the RBA metrics challenging.

6.3. Echo cancellation in the node

To maintain increased capacity, and to meet 10G goals, greater reliance on echo cancellation is to be expected. When echo cancellers do not perform as needed, RF impairments may impact service.

FDX-capable nodes support simultaneous upstream and downstream communications over each FDX channel. FDX-compliant CMs will operate in FDD mode, where on any FDX channel or sub-band, the CM is either transmitting in the upstream or receiving in the downstream direction. To avoid the risk of co-channel interference (CCI) and adjacent channel interference (ACI) between CMs, the CMTS schedules transmissions and grants such that a CM does not transmit at the same time as other CMs that are susceptible to interference from the transmitting CM. CM to CM interference susceptibility is measured through a sounding process that is defined in the specification. Even with the CMTS determining interference groups, there is still a need to manage the impacts of upstream and downstream signals at the node. The FDX node has to employ echo cancellation methods to help remove the reflection of the downstream transmitted signals that are reflected back from components in the node and in the plant which impact the reception of upstream signaling. This echo cancellation can be done in both the analog and digital domains. In the analog domain, traditional techniques can be utilized that copy the DS carriers and then manipulate phase and magnitude and then apply that as a filter on the receiver path. EC conducted in the digital domain allows for near signal regeneration, depending on the node design. At the node, the DS signals are at their strongest so this method can be effective at cancelling out echoes in the FDX node itself.

From a PNM point of view, more work and definition need to be performed to determine how to measure and report echoes, and the signals after echo cancellation has been performed. As more FDX plant and nodes are deployed, these challenges will be met, and new management objects will be created which will aid in better performance of these plant segments.

A pre-EC RxMER measurement, possible at the node, could provide some information about the signal before EC, which may be partially informative toward gauging the EC effectiveness.

Generally, there are four approaches for providing this information, which could be useful for PNM and operations tools and applications:

- a measure in the specification that is based on what is described here;
- a measure in the specification that is based on some combination of US and DS RxMER and maybe more to describe some equivalent of the effort spent on echo cancellation and how much more could be corrected, without getting into manufacturer-specific intellectual property;
- a best practice based on one of these approaches, doing what is best to use external testing and available measures to provide equivalent information; and
- new requirements to collect and hold the information for future use.

A fiber node typically feeds up to four legs of coax. Management of the FDX spectrum and EC process in nodes with multiple legs can vary among vendors, with potentially different implementations. Actual capabilities and details are beyond the scope of this paper. However, from a PNM perspective there would be value if per-leg EC data were available.

The authors suggest that the DOCSIS specifications teams develop an engineering change to provide management objects that describe the limits and performance of ECs.

6.4. Echo cancellation in the CM

As with the node EC, a couple of parameters should be reported for the FDX CM EC. However, the FDX CM is a lower cost device and may not have the horsepower to provide all the measurements that a node could.

- EC is trained or not trained—In the OSSI and MULPI specifications, a trained EC is sufficiently converged. Reporting on the state of training is important for PNM. For instance, if the EC is not converged, reception of the channel(s) in the sub-band might not be usable, and knowing that the EC is not converged provides valuable information for troubleshooting why the channel/sub-band is not usable.
- Echo before and after cancellation—Operators need a way to express this so they can characterize the plant and find when and where changes happen in the network.
- Margin remaining before EC begins to have problems—Operators need a way to express this parameter. The specifications development organizations could suggest measurement and reporting methods.
- Any indication of why an EC cannot train or is on the margin—For example, if there is a particular echo that is too big, then data on that echo could be used to provide the echo's distance, which would allow an operator to troubleshoot. The industry will need to determine how that information would be communicated and what the data would look like.

7. Telemetry

With increased complexity and the expectation of new service-impacting failure modes being revealed in the network, new telemetry, and more frequent telemetry in some cases, will be needed. PNM fault management requires identification of faults from the telemetry, and then use cases for localizing the fault must follow. Fault identification requires a broad scope covering the entire network, with an initial granularity for the next step of fault management; fault localization requires several different groupings and finer resolution of telemetry. PNM fault management will require ways for operators to manage their operations and maintenance costs, so improvements in tools will follow the improvements in telemetry delivery.

PNM telemetry today consists of queries (polling data that are intermittently collected) and tests (requiring configuration to enable the data collection). In DOCSIS 3.0 networks, Simple Network Management Protocol (SNMP) was the primary method in use. The need for larger data sets occurred with DOCSIS 3.1 technology. Trivial File Transfer Protocol (TFTP) was introduced to enable more optimal data transfer than what is possible with SNMP. TFTP was adopted by CM vendors, but had limited adoption by CMTS vendors.

DOCSIS 4.0 technology brings new possibilities with telemetry from CMTS equipment. With R-PHY architectures, there are new tunneling protocols such as Layer 2 Tunneling Protocol (L2TP) pseudowires presenting a packet streaming protocol (PSP). DOCSIS 4.0 technology brings requirements for more data, more measurements, more often. SNMP will continue to increase our "technical debt" that limits the full capabilities of monitoring platforms. L2TP is one such protocol that is in use by CMTS vendors for transporting large amounts of data fast.

With R-MACPHY, YANG data models describe the methods for acquiring telemetry, delivered through TFTP, HTTP, and other means. Like L2TP, YANG models eliminate limitations with SNMP and bring data aggregation from DOCSIS devices into the 21st century. YANG models are an interesting discussion topic but are not a requirement for CMTS vendors to support, therefore, similar to TFTP it could be unlikely that CMTS vendors will adopt YANG models.

Vendors have developed proprietary solutions, based on protocols and techniques such as L2TP, CMTS SSH direct READ access, Kafka bus access, and more. Proprietary solutions have proven to be substantially more effective than SNMP and deliver critical data in near-real time. Examples of this are upstream spectrum analysis and OFDMA RxMER per subcarrier data. Vendor implementations of streaming telemetry using proprietary solutions enable upstream spectrum analysis which rival hardware-based spectrum analyzers in terms of trace update response time. Further, OFDMA RxMER data can be obtained on a fully loaded CMTS chassis every 15 minutes for every active CM connected to that CMTS. This can be done simultaneously while running other PNM tests. For cable operators considering upstream profile management application (PMA), this is a game changer. Those familiar with standard PNM tests know that running OFDMA RxMER typically prevents one from running any other PNM test, such as upstream triggered spectrum capture (UTSC).[6]

The advent of smart amplifiers will add a new telemetry opportunity. This paper previously discussed the FBC capability in smart amplifiers, but there is far more to it. DOCSIS 4.0 amplifiers are expected to run hotter, provide more gain, operate at higher frequencies, and contain sophisticated internal electronics. Having an on-board CM enables the ability to monitor the modem's internal temperature sensor(s), voltages, and any other on-board sensor the vendor may choose to include. All this data gets communicated directly back to the CMTS and the monitoring system. Vendors could, for example, give access to mainline power supply monitoring, RF probing, and more. Each amplifier becomes another telemetry point in the network. How the telemetry is retrieved is again up to DOCSIS 4.0 specifications and vendor implementation. Ideally it will not use SNMP.

What does all this this mean? There are many solutions being tested on the open market for DOCSIS 4.0 data collection. Further, new solutions are being proposed by CableLabs. It will ultimately be up to the cable operator community to drive which technologies are adopted and implemented. This paper has identified the need that DOCSIS 4.0 technology has for PNM. However, it should be apparent to the reader that a gap exists. That gap is the lack of a clear path between how vendors and operators will align to a consistent PNM implementation and how PNM will function across multiple vendor platforms to meet the expectations of cable operators. It is recommended that operators understand this gap and align to address it.

8. Test and Query

As discussed previously in this paper, DOCSIS 4.0 technology brings new opportunities and challenges from a PNM perspective. New test methods and data analytic queries must be created and optimized for new spectrum changes and new technologies, such as echo cancellation. As data speeds increase, bandwidths expand and complex technologies are introduced, PNM will be increasingly more important to ensure continued quality of experience (QoE) to subscribers. There is no doubt that subscribers will continue to be more dependent on high-speed data, and competition will continue to apply pressure to improve network quality.

[6] Rather than track per-modem OFDMA RxMER per subcarrier (and preclude the use of UTSC by field personnel), some operators monitor port average RxMER and other data at the upstream input to the CMTS/CCAP. If a problem is detected, then data from individual modems can be looked at more closely.

8.1. Challenges and Opportunities with FDD

In FDD, the upstream band can extend to as high as 684 MHz. In DOCSIS 3.1 technology, the highest upstream frequency is 204 MHz. Higher frequencies mean much more data to aggregate and store in databases from cable modems and CMTSs. Further, large data sets require significantly more CPU (or GPU) processing power from an analytics standpoint when identifying impairments. Today, most modems and CMTSs still rely on SNMP to retrieve data from them. While SNMP has been a great protocol for the cable industry for more than a decade, it is a very slow and outdated protocol. Fortunately, CableLabs specifications are moving towards other methods of obtaining large data sets, such as TFTP and streaming telemetry. It is critical that adoption of these methods by vendors occurs quickly.

The downstream spectrum in FDD will also be increasing from 1.2 GHz to 1.8 GHz with visions of one day supporting up to 3 GHz (or higher!). As in the upstream, this will require cable modems to support FBC up to the highest frequency supported in the network. Currently, DOCSIS 3.1 modems support FBC up to 1.2 GHz while DOCSIS 3.0 modems only support FBC up to 1 GHz. One can see the disparity of a 1.8 GHz network supporting a mixture of DOCSIS 3.0, 3.1 and 4.0 cable modems. As DOCSIS 4.0 modems are initially deployed, one will have limited visibility to impairments in the RF spectrum above 1.2 GHz, assuming significant deployment of DOCSIS 3.1 modems. It is expected that many passive devices, and subscriber drop cables and components, will have various impairments above 1.2 GHz because the 1.2 GHz to 1.8 GHz spectrum has never been widely tested. It may sound trivial when speaking in terms of "GHz," but this is 600 MHz of largely untested spectrum that PNM will be essential in analyzing and testing. DOCSIS 4.0 modems with FBC capabilities up to 1.8 GHz are essential. Further, a method of quickly obtaining the FBC spectrum from 5 MHz (or lower) to 1.8 GHz will be critical.

Upstream spectrum analysis is a "meat and potatoes" feature of any PNM application. Technicians rely on it every day to identify and resolve return path ingress and other impairments. The state-of-the-art return path upstream spectrum analysis relies on a CableLabs-based specified measurement called UTSC. UTSC enables compatibility across vendors and platforms whether it is integrated CCAP (iCCAP) or distributed access architecture CCAP (dCCAP). CCAP vendors and PNM vendors will need to ensure their platforms support upstream spectrum analysis up to the highest frequencies supported in FDD. Further, vendors must be able to support fast refresh speeds on upstream spectrum analysis over a much wider bandwidth in order to capture transient noise events, many of which may occur at higher frequencies not previously seen. The current state of DOCSIS 3.1 UTSC across the vendor space is non-optimal in that each CCAP vendor has partial adoption of the CableLabs UTSC specification. This state creates challenges for adoption by cable operators, and a lack of feature sets with some vendors means that not all tests are supported. It will be important that vendors fully adopt UTSC in DOCSIS 4.0 networks so that operators are able to troubleshoot more complex problems as frequency expansion will certainly bring unanticipated complexities.

8.2. Challenges and Opportunities with FDX

Like its counterpart FDD, FDX has similar upstream and downstream frequency expansion challenges for PNM. However, FDX adds more technical hurdles which PNM will be critical to help solve. For instance, downstream FBC at the CM may contain upstream and downstream transmissions within the same interference group in the FDX band (108 MHz to 684 MHz). Visualization and troubleshooting of simultaneous upstream and downstream will lead to new challenges for both vendors and technicians.

Having visibility into the level of EC and reserve EC capacity will be essential. As previously discussed, the CMTS and CM have EC functionality. The authors believe that it will be possible to determine some amount of impairment between the CMTS and the CM by utilizing the information provided by the EC operation in the CM and FDX node.

In general, PNM tests for FDX will be more challenging overall than FDD. A general summary of this can be seen later in Table 1.

8.3. DOCSIS 4.0 Impact on Standard PNM Tests

As defined in the DOCSIS 3.1 and 4.0 specifications, there exists a standard set of PNM test and query features designed to enable cable operators and vendors to obtain optimal troubleshooting data from the CMTS and CMs. Those specifications are designed in order to establish consistent inter-operability among vendors of CMTS, CM and PNM software. This section provides a brief description of each PNM test followed by table that summarizes the gaps for full support of DOCSIS 4.0 FDD and FDX.

DS Symbol Capture (CM and CCAP)

Description:

- The DsOfdmSymbolCapture object provides partial functionality of a network analyzer to analyze the response of the cable plant. A symbol is generated at the CCAP and also captured at the CM, and then the results compared.

DsOfdmNoisePowerRatio (CCAP/Spectrum)

Description:

- The purpose of downstream NPR measurement is to view the noise, interference and intermodulation products underlying a portion of the OFDM signal. As an out-of-service test, the CCAP can define an exclusion band of zero-valued subcarriers which forms a spectral notch in the downstream OFDM signal for all profiles of a given downstream channel. The CM provides its normal spectral capture measurements per [PHYv3.1], or symbol capture per [PHYv3.1], which permit analysis of the notch depth. A possible use case is to observe LTE interference occurring within an OFDM band; another is to observe intermodulation products resulting from signal-level alignment issues. Since the introduction and removal of a notch affects all profiles, causing possible link downtime, this feature is intended for infrequent maintenance.

DS CM Spectrum Analysis Full Band Capture

Description:

- This test allows for the full band capture of the DS RF spectrum that the modem is configured to use.

CmDsOfdmChanEstimateCoef

Description:

- The purpose of this table is for the CM to report its estimate of the downstream channel response. The reciprocals of the channel response coefficients are typically used by the CM as its frequency-domain downstream equalizer coefficients. The channel estimate consists of a single complex value per subcarrier. The channel response coefficients are expressed as 16-

bit two's complement numbers using 2.13 nibble format. The CM samples are scaled such that the average power of the samples is approximately 1, in order to avoid excessive clipping and quantization noise.

- Summary metrics (slope, ripple, and mean) are defined in order to avoid having to send all coefficients on every query. The summary metrics are calculated when the corresponding MIB is queried. A Coefficient filename and trigger are provided to obtain the channel coefficients.
- The CM will report these metrics for each OFDM channel it has been assigned.

CmDsConstDispMeas

Description:

- The downstream constellation display provides received QAM constellation points for display. Equalized soft decisions (I and Q) at the slicer input are collected over time, possibly with subsampling to reduce complexity, and made available for analysis. This measurement is intended for data subcarriers only. Up to 8192 per OFDM channel samples are provided for each query; additional queries can be made to further fill in the plot.

ModulationOrderOffset

Description:

- This attribute specifies an offset from the lowest order modulation for the data subcarriers in any of the profiles in the downstream channel. If the lowest order modulation order that the CM was receiving was 1024-QAM and the ModulationOrderOffset was zero, then the CM would capture the soft decision samples for all of the subcarriers which were using 1024-QAM. If the ModulationOrderOffset was 1, then the CM would capture the soft decision samples for all of the subcarriers using the next highest modulation order in use for the profiles in the downstream channel.

CmDsOfdmRxMer

Description:

- Provides measurements of the RxMER for each subcarrier.

CmDsOfdmMerMargin

Description:

- Provide an estimate of the MER margin available on the downstream data channel with respect to a modulation profile. The profile may be a profile that the modem has already been assigned or a candidate profile. This measurement is similar to the MER Margin reported in the OPT-RSP Message [MULPIv4.0].

CmDsOfdmFecSummary

Description:

- The purpose of this item is to provide a series of codeword error rate measurements on a per profile basis over a set period of time.

CmDsHist

Description:

- The purpose of the downstream histogram is to provide a measurement of nonlinear effects in the channel such as amplifier compression and laser clipping. For example, laser clipping causes one tail of the histogram to be truncated and replaced with a spike. The CM captures the histogram of time domain samples at the wideband front end of the receiver (full downstream).

Upstream Histogram

Description:

- The upstream histogram provides a measurement of nonlinear effects in the channel such as amplifier compression and laser clipping. For example, laser clipping causes one tail of the histogram to be truncated and replaced with a spike. When the upstream histogram enable attribute is set to 'true', the CCAP will begin capturing the histogram of time domain samples at the wideband front end of the receiver (full upstream band). The histogram is two-sided; that is, it encompasses values from far-negative to far-positive values of the samples. The histogram will have a minimum of 255 or 256 equally spaced bins. These bins typically correspond to the 8 MSBs of the wideband analog-to-digital converter (ADC) for the case of 255 or 256 bins. The histogram dwell count, a 32-bit unsigned integer, is the number of samples observed while counting hits for a given bin and may have the same value for all bins. The histogram hit count, a 32-bit unsigned integer, is the number of samples falling in a given bin. The CCAP will report the dwell count per bin and the hit count per bin. When enabled, the CCAP will compute a histogram with a dwell of at least 10 million samples at each bin in 30 seconds or less. The CCAP will continue accumulating histogram samples until it is restarted, disabled or times out. If the highest dwell count approaches its 32-bit overflow value, the CCAP will save the current set of histogram values and reset the histogram, so that in a steady-state condition a complete measurement is always available.

US Impulse Noise

Description:

- The UsImpulseNoise object provides statistics of burst/impulse noise occurring in a selected narrow band. A bandpass filter is positioned in an unoccupied upstream band. A threshold is set, energy exceeding the threshold triggers the measurement of an event, and energy falling below the threshold ends the event. An optional feature allows the threshold to be set to zero, in which case the average power in the band will be measured. The measurement is time-stamped using the DOCSIS 3.0 field of the 64-bit extended timestamp (bits 9-40, where bit 0 is the LSB), which provides a resolution of 98 ns and a range of 7 minutes.
- The CCAP provides the capability to capture the following statistics in a selected band up to 5.12 MHz wide:
  - Timestamp of event
  - Duration of event
  - Average power of event
- The CCAP provides a time history buffer of up to 1024 events. In steady state operation, a ring buffer provides the measurements of the last 1024 events that occurred while the measurement was enabled.

Us OFDMA Active and Quiet Probe

Description:

- The purpose of upstream capture is to measure plant response and view the underlying noise floor, by capturing at least one OFDMA symbol during a scheduled active or quiet probe. An active probe provides the partial functionality of a network analyzer, because the input is known, and the output is captured. This permits full characterization of the linear and nonlinear response of the upstream cable plant. A quiet probe provides an opportunity to view the underlying noise and ingress while no traffic is being transmitted in the OFDMA band being measured.
- When enabled to perform the capture, the CCAP selects a specified transmitting CM, or quiet period when no CMs are transmitting, for the capture. The CCAP sets up the capture as described in [MULPIv3.1], selecting either an active SID corresponding to the specified MAC address or the idle SID, and defining an active or quiet probe. The active probe symbol for this capture normally includes all non-excluded subcarriers across the upstream OFDMA channel, with pre-equalization on or off as specified in the MIB. The quiet probe symbol normally includes all subcarriers, that is, during the quiet probe time there are no transmissions in the given upstream OFDMA channel. For the quiet probe, the CCAP captures samples of at least one full OFDMA symbol including the guard interval. The CCAP begins the capture with the first symbol of the specified probe. The sample rate is the FFT sample rate (102.4 megasamples per second).

Us OFDMA MER per Subcarrier

Description:

- This item provides measurements of the upstream RxMER for each subcarrier. The CCAP measures the RxMER using an upstream probe, which is not subject to symbol errors as data subcarriers would be. The probes used for RxMER measurement are typically distinct from the probes used for pre-equalization adjustment. For the purposes of this measurement, RxMER is defined as the ratio of the average power of the ideal QAM constellation to the average error-vector power. The error vector is the difference between the equalized received probe value and the known correct probe value. If some subcarriers (such as exclusion bands) cannot be measured by the CCAP, the CCAP indicates that condition in the measurement data for those subcarriers.

Us Triggered Spectrum Capture

Description:

- Capture of upstream spectrum through a number of triggering means including free run, time stamp value, mini-slot number, MAC-SID, idle SID, symbol, event trigger, and IUC.
- Note that reliable US triggered spectrum capture is a top priority for PNM in general, as this has not yet been implemented following the specifications.

8.3.1. Summarizing the gaps

With a high-level understanding of each of the PNM test queries, Table 1 provides an overview of the needed support in DOCSIS 4.0 tools for FDD and FDX as of the writing of this paper. As can be seen in Table 1, it is expected that PNM testing on FDD channels will be less impacted than PNM testing on FDX channels due to the intrinsic complexities of FDX. In general, when PNM tests are run on a channel configured in the FDX band, to perform downstream PMN tests like DS Symbol Capture and

NoisePowerRatio, the RBA for the sub-band must be set in the downstream direction, and upstream PNM tests will need the sub-band to be configured in the upstream direction while the test is performed. Cable operators deploying FDD or FDX will experience new challenges. Having proper tools, especially proper PNM tools, will enable cable operators to be better positioned to effectively and quickly troubleshoot complex problems in their HFC networks.

Table 1. Impact of FDD and FDX on DOCSIS 4.0 PNM tests

DOCSIS PNM Test	FDD Impact	FDX Impact
DS Symbol Capture (CM and CCAP)	None	RBA configured for DS, Testing required – investigation required
DsOfdmNoisePowerRatio (CCAP/Spectrum)	None	RBA for sub-band used on target DS – investigation required
Spectrum Analysis Full Band Capture	More bins, more data	Dual direction, more bins, more data, more complexity, filters in modems may differ by vendor – investigation required
CmDsOfdmChanEstimateCoef	None	Only possible when RBA for TG is set in DS direction, other dependencies involved
CmDsConstDispMeas	None	Uncertain. There may be an ability to capture I and Q values in two directions – investigation required
ModulationOrderOffset	None	None expected
CmDsOfdmRxMer	None	None Expected
CmDsOfdmMerMargin	None	None Expected
CmDsOfdmFecSummary	None	Test runs for several minutes which may be impacted based on RBA scheduling – investigation required
CmDsHist	None	Undetermined what happens with this test when in FDX operation – investigation required

Upstream Histogram	None	Uncertain how to measure the FDX band from 108 MHz to 684 MHz and how to account for any co-channel interference and echo cancellation
Us Impulse Noise	None	Recommend that this test does not apply to the FDX band
Us OFDMA Active and Quiet Probe	None	Multiple issues to address such as configuring all RBAs for the TG and configuring active probes – investigation required
Us OFDMA Rx Power	None	None expected
Us OFDMA RxMER per Subcarrier	None	If other transmission groups are operating in a DS direction, the RxMER values for the tested OFDMA channel could be lower – investigation required
Us Triggered Spectrum Capture	Wider spectrum, more bins, more data	Wider spectrum, more bins, more data, in addition, for SID filtering all TGs and channels must be sync'd to same TG to get a valid measurement

8.3.2. What is required?

As shown in Table 1, several PNM tests are impacted when FDX has been configured for operation. The most obvious impact is seen in the FDX allocated spectrum and the need for the test to be performed when the specific sub band that the channel is configured to use is set in the correct direction. As more FDX segments are brought into service over the next 12 to 24 months, these issues will be overcome and the specific impacts, and their workarounds, will be better understood through additional testing and use. FDX also has the concept of sounding, and the usage of that data for PNM related activities has yet to be explored fully and will be studied once enough DOCSIS 4.0 FDX modems and nodes are deployed.

FDD, in contrast, does not have as significant of an impact to the PNM testing because these channels are all in place today; the issue here is that there are more of them and a greater frequency span to cover for tests including FBC in the modem.

Another class of products will be employed for DOCSIS 4.0 deployments: smart amplifiers. These updated components in the plant will be more bi-directional and have capabilities for sampling and some PNM testing as well, which will allow the operator to have another valuable testing point in the network for measurement and troubleshooting analysis.

There will be challenges that will be met during this period. Some of the challenges are outlined as follows, and are expected to serve as the foundation of an industry project plan to resolve these challenges:

- Vendors of PNM tools must adapt some of the testing to accommodate the FDD and FDX impacts and the implementation of smart amplifiers that are added to the plant.
- Cable company operations and back-office teams dealing with the increased amount of data coming from devices in the field.
- Scheduling of testing for FDX channels.
- Compliance of FDD- and FDX-capable CMTSs and CMs with the DOCSIS 4.0 specifications
- Interoperability among vendors' products (CMTSs, nodes, CMs, etc.) with both FDD and FDX
- Clearly defined FDD and FDX PNM test and query specifications from the standards and specifications development organizations
- Adoption of FDD and FDX PNM test and query DOCSIS specifications by vendors
- Standards and specifications development groups exploring further the usage of FDX sounding data for PNM testing; the addition of test capabilities in smart amplifiers and other plant equipment is an area ripe for study and requirements creation that will likely see more activity as more FDX plant and modems become available.

In order to address the challenges identified above and develop the proposed industry project plan, the following groups will need to collaborate as has historically been done in specifications development:

- Chipset vendors
- CMTS vendors
- CM vendors
- PNM tool vendors
- Standards and specifications development organizations
- Cable operators

Input and collaboration from all parties are essential for bridging the gaps identified in this document.

9. Conclusion and Future Outlook

The past several years have seen significant progress in the use of equipment and PNM tests. This has provided a new level of capability for cable operators to offer more services at higher data rates to more subscribers. As the industry looks to the near future with DOCSIS 4.0 technology and FDX and FDD updates to the plant, these well-known tests will continue to provide significant insight into the health and operation of our cable networks. Operators can rest a little easier knowing that the same applications and methods being used today can be extended, with modifications, into the DOCSIS 4.0 networks that will soon be deployed. While there are still areas for continued innovation and standards work, the authors feel optimistic that the groundwork that has already been implemented will continue to provide operators with actionable data that can help to keep our networks healthy.

However, there is an opportunity for improvement. Many PNM tests were defined in the DOCSIS 3.1 specifications and implemented by equipment vendors. Some of those tests have been invaluable, such as downstream RxMER per subcarrier. However, other tests, such as UTSC giving insight into return path noise and upstream RxMER per subcarrier have been inadequately adopted by vendors. In preparation for deployment of DOCSIS 4.0 technology, this paper has identified gaps in PNM which are needed to support DOCSIS 4.0 deployments. While specifications can include recommendations, it is up to the cable operator community to decide if PNM test functionality, such as return path monitoring (e.g., UTSC) and extended frequency FBC are valuable tools or not. It is incumbent on cable operators to hold discussions with vendors and determine the priorities. Should enhancing PNM be a priority or not? This is a question cable operators must determine and communicate to their vendor partners.

Abbreviations

ADC	analog-to-digital converter
CCAP	converged cable access platform
CCI	co-channel interference
CM	cable modem
CMTS	cable modem termination system
CPD	common path distortion
CPU	central processing unit
DAA	distributed access architecture
dCCAP	distributed CCAP
DOCSIS	Data-Over-Cable Service Interface Specifications
DS	downstream
DUT	device under test
EC	echo canceller
ECT	echo canceller training
ESD	extended spectrum DOCSIS
FBC	full band capture
FDD	frequency division duplexing
FDX	full duplex [DOCSIS]
FEC	forward error correction
FFT	fast Fourier transform
Gbps	gigabits per second
GHz	gigahertz
GPS	Global Positioning System
GPU	graphics processing unit
HFC	hybrid fiber/coax
HTTP	Hypertext Transfer Protocol
I	in-phase
iCCAP	integrated CCAP
IG	interference group
ISM	industrial, scientific, and medical
IUC	interval usage code
L2TP	Layer 2 Tunneling Protocol
LSB	least significant bit
LTE	long term evolution
MAC	media access control
MER	modulation error ratio
MHz	megahertz
MIB	management information base

MULPI	MAC and upper layer protocols interface
NPR	noise power ratio
ns	nanosecond
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OSSI	operation(s) support system interface
OUDP	OFDMA upstream data profile
PHY	physical layer
PIM	passive intermodulation
PNM	proactive network maintenance
PMA	profile management application
PON	passive optical network
Q	quadrature
QAM	quadrature amplitude modulation
QoE	quality of experience
RB	resource block
RBA	resource block assignment
RF	radio frequency
R-PHY	remote PHY
R-MACPHY	remote MAC PHY
RxMER	receive modulation error ratio
SCTE	Society of Cable Telecommunications Engineers
SID	service identifier
SNMP	Simple Network Management Protocol
SSH	secure shell
TCP	total composite power
TFTP	Trivial File Transfer Protocol
TG	transmission group
US	upstream
UTSC	upstream triggered spectrum capture
WLAN	wireless local area network
YANG	yet another next generation

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