Get Smart: FDX Amplifiers and Completing the Brilliant Network

A technical paper prepared for presentation at SCTE TechExpo24

Dr. Robert Howald
Fellow
Comcast
robert_howald@comcast.com

Marc Morrissette
Senior Principal Broadband Hardware Engineer
Comcast
marc_morrissette@comcast.com

Nader Foroughi, Comcast

Mike Robinson, Comcast

Table of Contents

Title **Page Number**

List of Figures

Title **Page Number**

List of Tables

1. Introduction

The industry vision of 10G laid out in January 2019 became a reality in October 2023. Comcast upgraded the to a data over cable service interface specification (DOCSIS®) 4.0 full-duplex DOCSIS® (FDX) network in three markets, introducing "X-Class" symmetrical speeds up to 2 Gbps in those areas. The FDX footprint and X-Class customer connects have rapidly grown since that major milestone achievement.

The CableLabs-specified reference architecture for DOCSIS 4.0 (D4.0) FDX is based on a "Node+0 actives (N+0)" network. "N+0" is a hybrid fiber-coax (HFC) system consisting of no actives (i.e. amplifiers) between the coaxial port of the fiber node and the connected home or business. For D4.0 at Comcast, that node is a Remote-Physical Layer (RPHY) based node based on the Distributed Access Architecture (DAA). The DAA N+0 architecture is what Comcast's FDX production deployments are currently built upon.

The "Big Idea" of FDX is that it defines a common bandwidth (the "FDX Band") able to carry traffic both downstream (DS) and upstream (US). N+0 simplifies this key FDX feature. However, most operator networks, including Comcast, are pre-dominantly "Node + x actives (amplifiers) (N+x)," i.e. networks *with* amplifiers. Therefore, to broadly scale X-Class speeds, Comcast and key technology partners have developed FDX-capable Smart Amplifiers. These Smart Amplifiers have the ability to support FDX. Moreover, they have capabilities that transform network operations and visibility in profound ways.

In this paper, we will explore the essentials of FDX Smart Amplifiers, including:

- FDX-Enabling Technology
- Cascaded Performance
- Capacity and Traffic Engineering
- Activation and Alignment Automation
- The Amp Software Ecosystem
- Network Diagnosis and Reliability

As with the launch of DOCSIS 3.1 (D3.1) in 2017, the birth of D4.0 FDX represents the beginning of what is ahead for D4.0. Attendees of this session will leave with a deep understanding of this next D4.0 technology wave – the Smart FDX Amplifier that completes the Brilliant Network.

2. FDX Enabling Technology

Figure 1 illustrates the essential spectrum goal of FDX– enabling significantly more US capacity. More interestingly, these new FDX US bands (Red "FDX" in Figure 1) are also available for DS! This is quite different than typical Frequency Domain Duplex (FDD) operation, the approach taken in D4.0 FDD. How can both DS (Dark Blue in Figure 1) and US data exist in the same spectrum? There are two essential innovations in D4.0 that enable this.

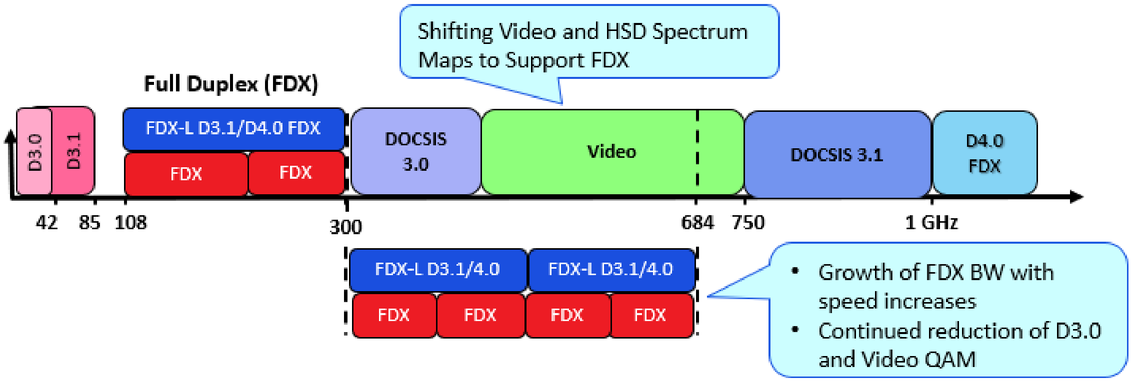

Figure 1 - Massive New US Bandwidth by Sharing DS and US in the Same Spectrum

2.1. Key FDX Innovations

Although more US bandwidth is defined, it is the same 96 MHz orthogonal frequency-division multiple access (OFDMA) physical layer (PHY) blocks that are defined in D3.1, except that the band over which they can operate is expanded. Thus, D4.0 leverages the power of the D3.1 PHY completely. Six additional 96 MHz blocks are added across the 108-684 MHz FDX band, complementing an 85 MHz "mid-split" system.

DS and US can occupy the same band using a technology known as Echo Cancellation (EC). EC, in general, is a mature technology used in other telecom networks, such as digital subscriber line technologies (xDSL) and wireless. Before D4.0 it had not yet been implemented in cable networks. The EC concept is very similar to those other applications, although the cable does introduce some new implementation challenges. EC is the first of the two critical innovations that power FDX.

The second key innovation is based on a fundamental architectural difference in cable systems compared to telco xDSL systems. Twisted pair telco networks are point-to-point connections from the DSL Access Multiplexer (DSLAM) whereas HFC is a point-to-multipoint system. This logical architecture difference creates the need for another layer of innovation for FDX. This is the creation of Interference Groups (IGs) and Transmission Groups (TGs) for the scheduler to manage.

Figure 2 illustrates these innovations using a passive coaxial network (i.e. N+0) for simplicity. N+0 is NOT a requirement for FDX. In fact, one of the drivers for this paper is the evolution of FDX for N+x networks, whereas the D4.0 specification uses N+0 model types only as reference architectures. FDX-capable amplifiers will support FDX signals over N+x networks, allowing FDX to be implemented over a much wider swath of the footprint more quickly, and more of which is N+x than N+0. As we know from standard HFC networks, radio frequency (RF) amplifier cascades impact end-of-line fidelity, and this is no different for FDX amplifiers. However, with FDX amplifiers, an additional effect comes from the formation of IGs and TGs. As a result, an additional trade space created by N+x FDX networks are maximum speed tiers that can be supported for what amount of user penetration versus amplifier cascade depth. We will briefly discuss FDX amplifiers themselves in a subsequent section.

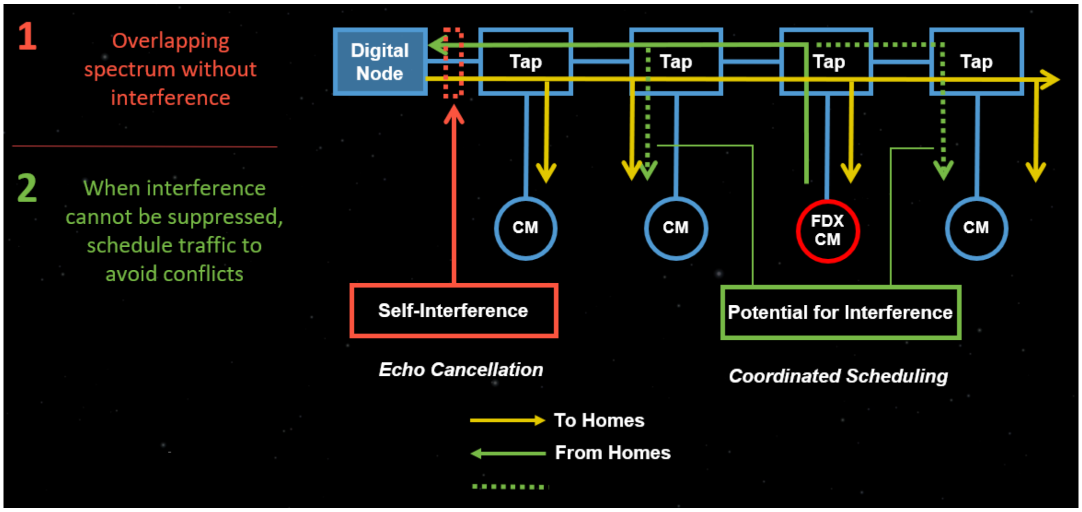

Figure 2 - Two Key New Innovations Power D4.0 FDX - EC and Coordinated Scheduling

2.2. A Closer Look: Echo Cancellation

Referring to Figure 2, adding US signals at frequencies where DS signals exist requires the DS signal be "subtracted" before the US OFDMA receiver. This requires high RF isolation and strong EC of the higher DS reflected back into the US receiver. While the implementation details may be complex, the EC concept is quite simple, and the digital signal processing (DSP) principles very mature. A simplified diagram illustrating the EC concept is shown in Figure 3.

The DS signal will have some energy imposed on the US Rx through imperfect isolation of real hardware in the Node. It will also have energy reflected back by imperfect (all!) RF interfaces as it travels down the coaxial plant. These are the "Echoes" that give the EC function its name. What is distinctive to EC for cable is the high cancellation required in real-time across a multi-octave bandwidth.

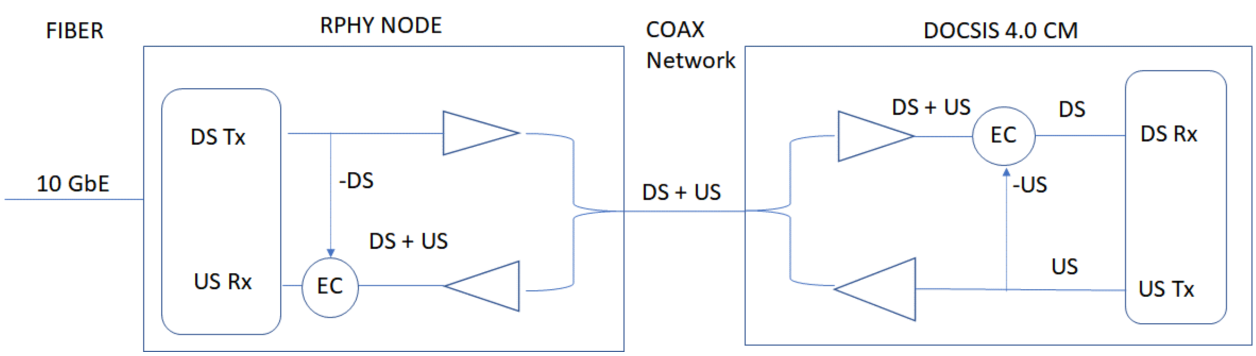

Figure 3 - Basics of Echo Cancellation

For more details describing EC and performance observed, please refer to [3][5][9][11].

2.3. A Closer Look: Coordinated Scheduling, Interference Groups and Transmission Groups

FDX Cable Modems have their own EC's to avoid self-interference. That self-interference is a combination of adjacent leakage interference and noise floor contributions from the output power amplifier (PA). They do not use common bandwidth simultaneously but rely on dynamic resource block assignments (RBA) to support traffic demands. While an FDX modem knows about its own US transmission, it cannot know that of the neighbor, and thus has no way to “cancel” that interference. It requires sufficient RF isolation among the homes sharing a coaxial segment to prevent FDX-band US users from interfering with others’ DS. Unfortunately, sufficient isolation cannot always be guaranteed. Isolation relationships among homes per the FDX standard are determined by the “sounding” process for D4.0 and D3.1 devices that support FDX-Limited (FDX-L) functionality. Comcast has devised other techniques [6] to determine this.

Without sufficient RF isolation, the virtual cable modem termination system (vCMTS) scheduler is used. Potentially interfering users are lumped into IGs. A logical set of IGs is a TG treated as one for scheduler purposes. The scheduler assures that potentially interfering pairs are not accessing the same spectrum in the same time slot.

The vCMTS can assign different RBAs to different TGs. Figure 4 shows an example of how the 108-684 MHz FDX band might be allocated to simultaneously support two TGs. RBAs can adapt with time based on traffic and peak speed demand.

Note that the FDX band is not all of the DOCSIS spectrum available. Non-FDX D3.1 spectrum and DOCSIS 3.0 (D3.0) spectrum will also exist. Furthermore, not all of the FDX band needs to be assigned–more US bandwidth is allocated to FDX as peak US speed requirements increase.

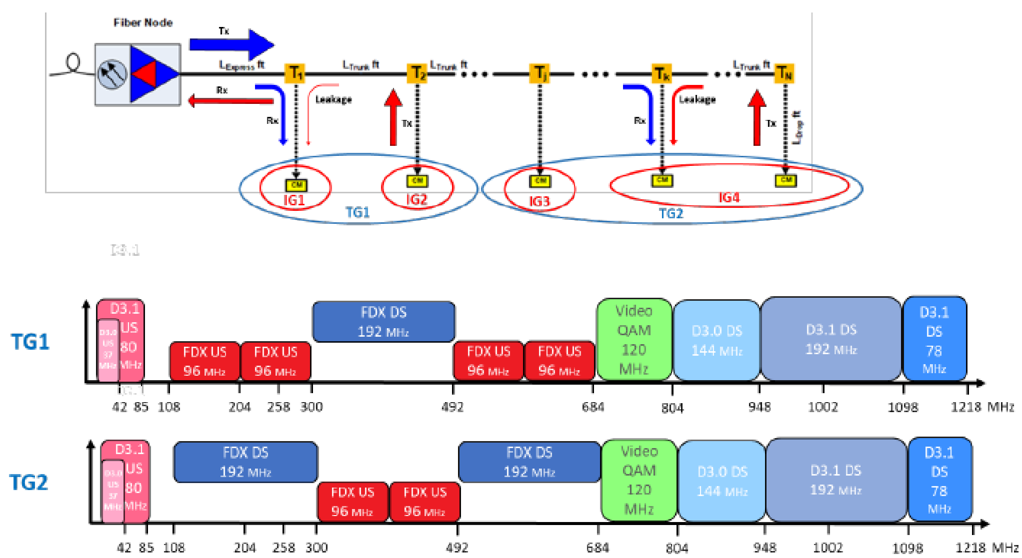

Figure 4 - IG and TG Example and Complementary Spectrum Usage [12]

2.4. Do FDX Amplifiers Impact Traffic Engineering?

The FDX system reference architecture assumes an N+0 network. However, the foundational EC technology developed for the FDX RPD can apply at any point in the network to manage overlapping spectrum, including amplifiers. This is the implementation approach in today’s FDX Amplifiers.

The signal to noise ratio (SNR) analysis is straightforward for N+x with FDX and has been previously published [12]. However, the traffic engineering is less straightforward due to the shared DS and US. The effect of an FDX Amplifiers is to expand the size of an Interference Group (IG), as shown in Figure 5. Nonetheless, the work has also been done and the results published debunking concerns over IG sizes significantly limiting FDX capacity and speeds [8].

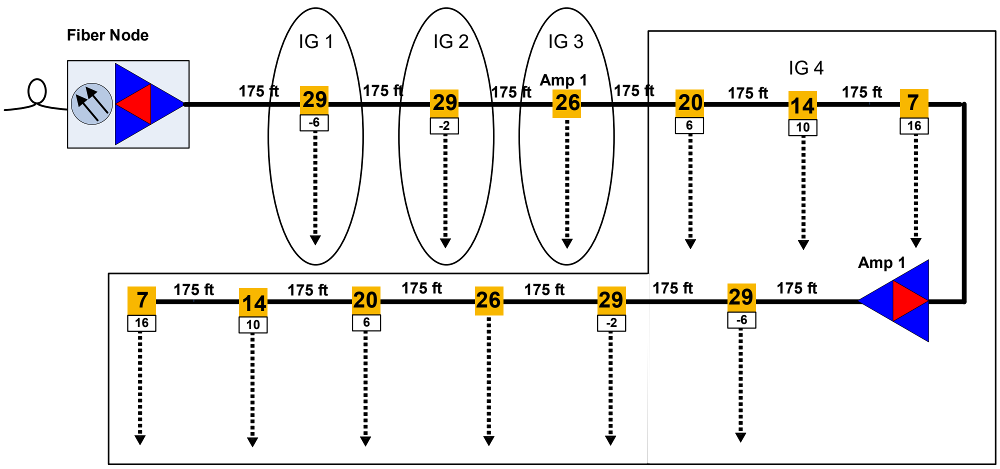

Figure 5 - Interference Group Elongation Aspect of FDX Amplifiers [8]

When an amplifier is added, there is an expansion of Interference Group 4 (IG4) to the "south" side of the amplifier. These users become part of the last IG of the tap string before the amplifier. This is because of the imperfect drop-to-output isolation characteristics of today's taps. This parameter can be improved upon by design changes, and Taps upgraded to prevent the phenomenon, but this is costly and there is no compelling reason to do that based on results herein. During development of the standard for D4.0 FDX, all of the effort around IG/TG definition was focused on RF isolation. None of it focused on how much it matters to practical broadband usage. Thinking of it from that perspective, the traffic engineering questions became:

1. How large can an IG be before there is an impact to the customer experience?
2. What service speed / IG size / spectrum rules exist when DS and US traffic engineering become co-mingled in FDX?

These questions were answered in [8].

When FDX was conceived, it was assumed that there would be significant utilization overlap between the US and DS in the FDX band, as shown in Figure 6. The more that the DS and US consumption overlaps, the more important it is to have multiple FDX TGs.

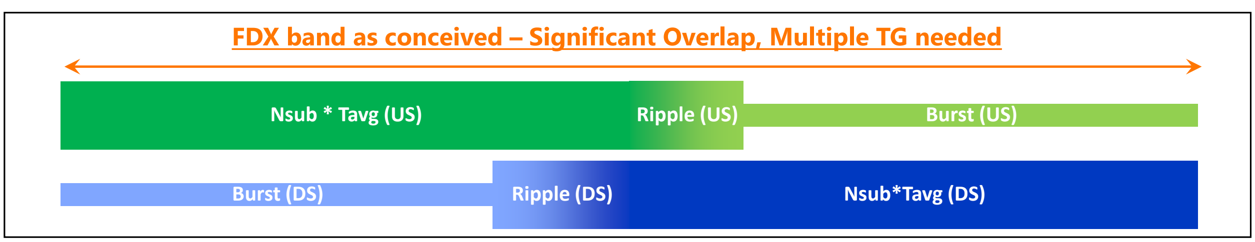

Figure 6 - FDX Band as Originally Conceived with Significant DS/US Use Overlap [8]

What has subsequently been learned and proven is that the FDX band traffic engineering is driven by simultaneous burst probabilities, and therefore DS/US utilization overlap is extremely unlikely. This is shown in Figure 7.

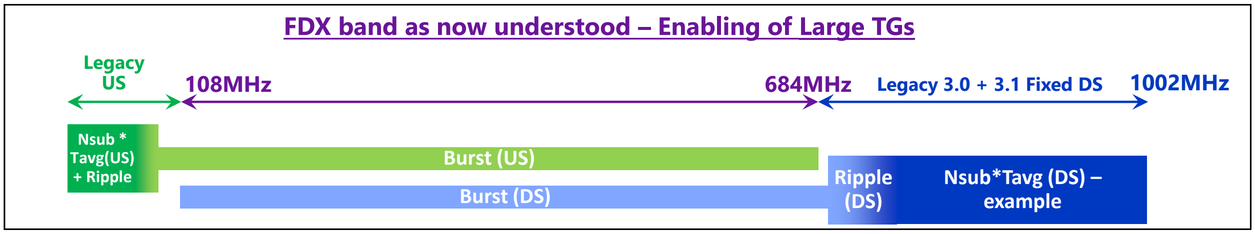

Figure 7 - FDX Band as Understood Today with Rare, Burst Overlap [8]

In one example, the US stays below 85 MHz for 99.8% of the time and needs to access the FDX band only 0.2% of the time. Meanwhile, 99.9% of the time, DS stays above 684 MHz time, and only accesses the FDX band 0.1% of the time. Refer to [8] for additional scenarios.

The principle enabling large TGs is that networks are and have always been oversubscribed for real traffic, taking advantage of statistical multiplexing. Many customers can effectively share capacity much less than the sum of their individual service speeds. As the peak speeds to average utilization skew to larger ratios, peak bursts occur even more infrequently. The output of this is how much oversubscription can take place – how big can a service group (SG) be, in this case because peak speeds (specifically, speed test results) may otherwise be compromised. These results are shown in **Table 1**. Average sizes of fiber nodes are 300-350 households passed (HHP), not all of which are subscribers, and getting smaller. Results show that large TGs can be supported and that the TG sizes align well with current node sizes and planned node splits.

Table 1 - TG Size Summary: Spectrum, Scenarios, and Speeds [8]

TG Size Summary*

	Scenario	2G / 2G	3G / 3G	4G / 4G
Near Term	1	>350	306 / X	157 / X
Near Term	2	>400	250	157 / X
Near Term	3	> 400	>400	>400
Longer Term	4	310	225	150
Longer Term	5	350	290	230

*4k-QAM DS / 1k-QAM US

Scenario 5:
5 Gbps DS @ TG Size = 218
6 Gbps DS @ TG Size ~ 125
7 Gbps DS @ TG Size ~ 60

60

Explaining these results qualitatively, the smaller number of users that are the FDX population can be seen as two sets of "users" – DS and US. For US, they appear as less aggressive users looking to infrequently access frequency and time resources (whether those be down or up) than the FDX DS "users" or the D3.1 DS users. Similar to independent DS and US criteria, thresholds can be quantified for

TG size versus peak speeds, as shown in **Table 1.** Infrequent peak bursts and DS Avg bandwidth (BW) >> US Avg BW means the FDX Band's RBAs will be deployed as DS blocks the vast majority of the time.

By contrast, if a large chunk of the coaxial spectrum such as 5-204 MHz, 5-300 MHz, 5-396 MHz, etc., is dedicated to US traffic as in D4.0 FDD, it will be ***idle the vast majority of the time***. This phenomenon is visualized in Figure 8**.**

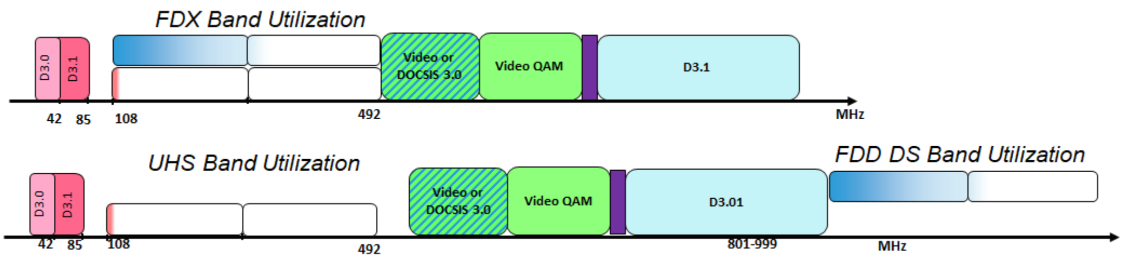

Figure 8 - FDX vs FDD Traffic Utilization

Furthermore, for the increasingly high "ultra-high split" options, while this high-quality spectrum mostly idles as an outlet for an occasional US burst, more DS is forced into the least predictable, never previously activated, spectrum above 1 GHz, and only *after* all taps and passives have been upgraded.

Summarizing, traffic analysis of the FDX bandwidth has shown that

- The initial instinct to minimize the size of an IG turns out is evidentially unfounded
- Large TGs can be supported, similar to how oversubscription models have worked for operators for decades
- TG sizes for the multi-gigabit symmetric speed tiers align well with current node sizing and planned network augments in the years ahead

Capacity, speed, penetration, and TG relationships can be used, as they are used today, to provide guidance to network operators' capacity and speed planning

3. FDX Smart Amp Cascaded Performance

Network subscriber device connectivity is provided to the FDX RPHY node through a tree-and-branch amplifier connection structure. At the head of the network, multi-port bridger (MB) amplifiers are used to provide wide network connectivity for each node launch point. MB amplifiers provide multiple hardline connection ports ("South Ports") connecting parallel RF network segments for devices which are located further away from the node. As the RF network expands out, devices are then connected through Line Extender (LE) amplifiers, which provide a single South Port connection for devices located further away from the node. Test results of two different cascade structures are described below.

The first cascade that was evaluated connects an FDX subscriber device to the FDX RPD through two amplifiers in series (N+2). Both amplifiers are MB type amplifiers. The second cascade that was evaluated extends the first cascade network through a series of four additional LE amplifiers, as shown in Figure 9.

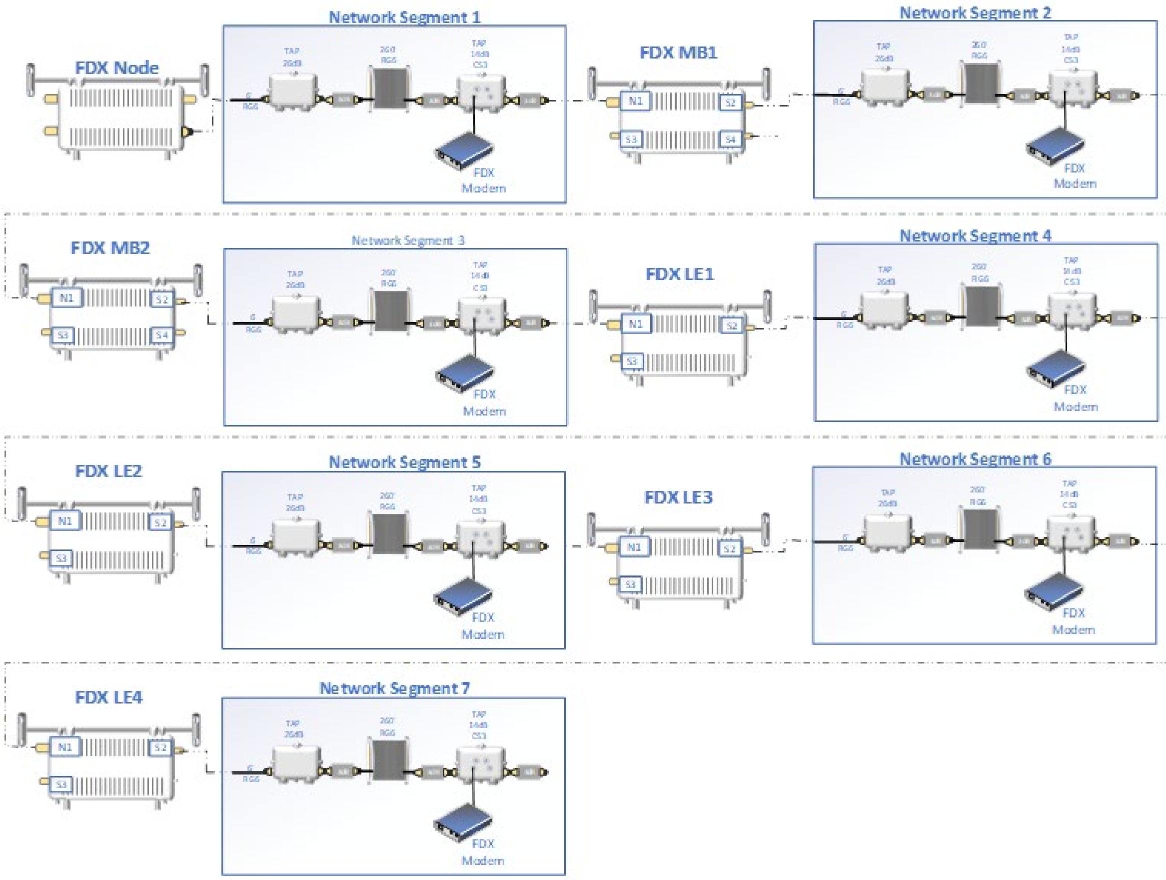

Figure 9 - N+6 FDX Amp Cascade Performance (2xMB+4xLE)

Before cascade performance was quantified, each amplifier was first put through a process of self-alignment, the approach for which is described in [10]. During this process, the amplifier software (SW) adjusts various controls within the amplifier. This is automatically performed under SW control, and these adjustments correct for any RF response anomalies that are occurring in each network segment. In this way, these RF anomalies are not allowed to build up as the cascade expands, and signal fidelity is optimized through the cascade network.

Cascade performance was assessed with FDX activated to the maximum bandwidth of 576 MHz (108 MHz-684 MHz). The vCMTS was configured to provide overlapped spectrum within the FDX band, with both DS orthogonal frequency-division multiplexing (OFDM) and US OFDMA channels active and occupying the 108-684 MHz band simultaneously. Figure 10 shows the DS configuration, providing three FDX band OFDM carriers. The FDX US band was configured with 6x96 MHz OFDMA carriers. In addition, above the FDX band, there are two OFDM carriers and 12 single carrier quadrature amplitude modulations (SC-QAMs) providing additional DS bonding capability for both D4.0 and D3.0/3.1.

Very Common Aggressive N+x TX Power Profile

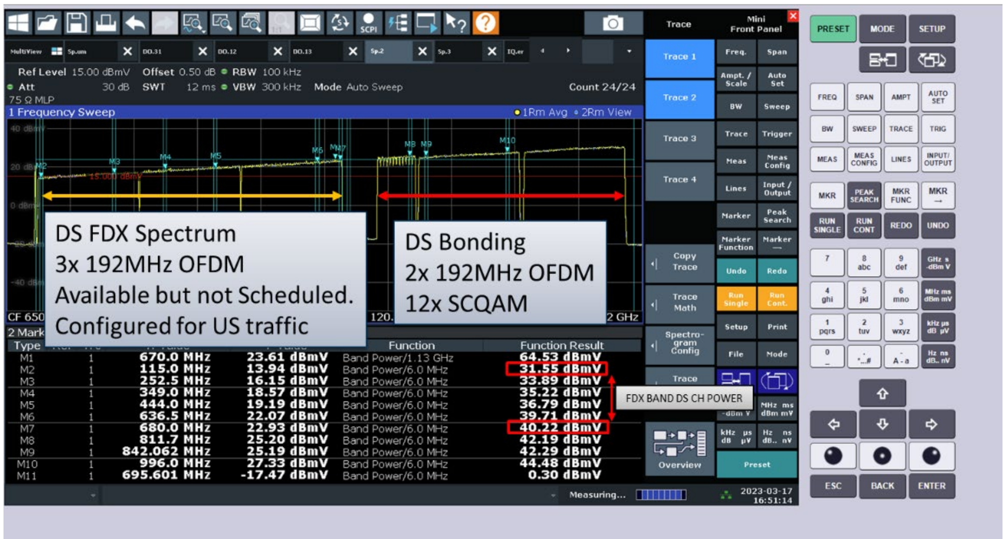

Figure 10 - DS Lineup Configured for FDX + Legacy D3.0/D3.1

US performance was assessed on both the N+2 and N+6 networks. Figure 11shows the modulation error ratio (MER) per band for the FDX OFDMA mini-slots for the N+2 network. All MER measurements support 2K-QAM, for a raw throughput of over 6 Gbps.

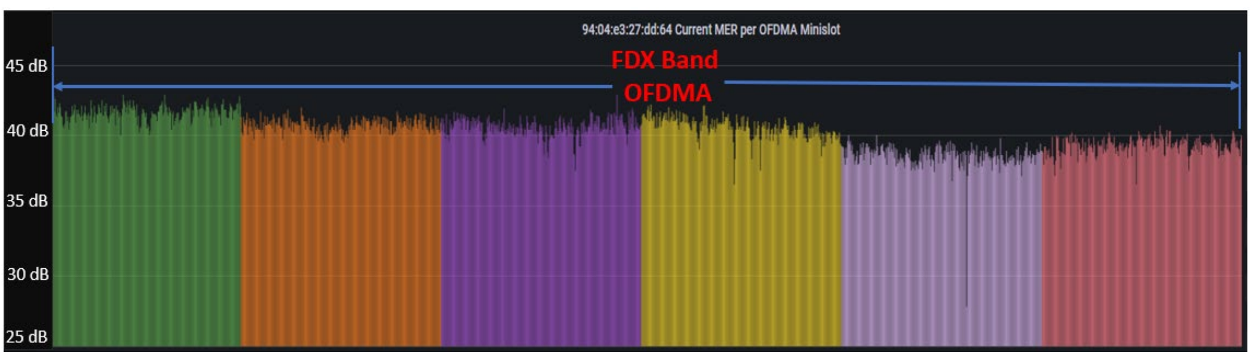

Figure 11 – N+2 FDX OFDMA Channels' MER Measurement

While the N+2 case is indeed a short cascade, this particular case of "N+2" is of a specific design criterion that is one of the more challenging scenarios for FDX and amplifiers. The design criteria, internally referred to as "Tier 1," represents an iteration of the Fiber Deep network upgrades, whereby up to two amplifiers in cascade were allowed into the design if the node size HHP target was unable to be supported with N+0. Essentially, N+0 became the target architecture in the very high-density areas, while N+1 and N+2 become more common elsewhere.

The operational implications are that nodes that ran at very high output levels (to support maximum N+0 HHP coverage) where in both N+0 and N+2 systems. N+0 is the most challenging RF profile for FDX, because it combines the highest DS RF power spectral density (PSD) and tilt profile with the lowest US receive level (US Rx). For N+0, of course, this is the only Echo-to-Signal that plays a role in the system fidelity. For N+2, that is not the case. Cascaded with this most challenging node RF profile are up to two FDX amplifiers. These are also run at relatively high levels – less than Fiber Deep, but higher than the very common, aggressive N+x profile. While the cascade is very short, this combination makes it one of the more challenging N+x permutations, so performance in this environment is included in specification validation.

The most common RF profiles common on the Comcast plant bucketized into the six shown in Figure 12.

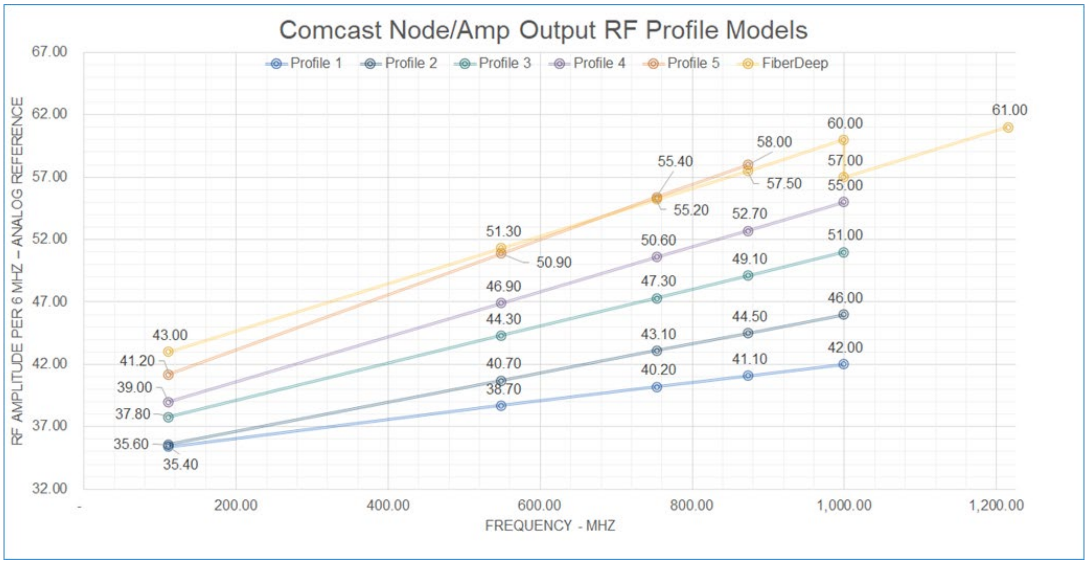

Figure 11 - Comcast Node/Amplifier Range of DS Profiles

Figure 13 shows the FDX wideband probe MER measurements for the modem placed at the end of the N+6 cascade. For N+6, the wideband probe MER results indicate support for 1k-QAM for all 6 OFDMA channels, for a raw throughput of over 5.7 Gbps.

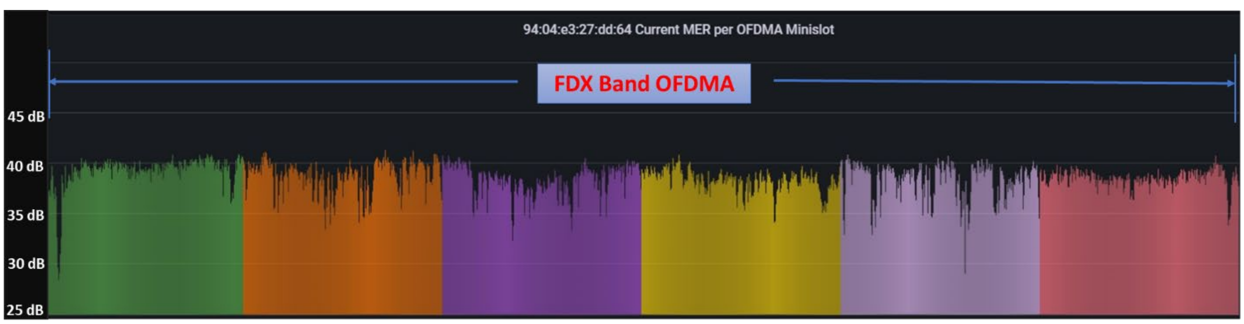

Figure 12 - N+6 FDX OFDMA Channels' MER Measurement

4. FDX Smart Amplifier Ecosystem

4.1. Activation Flow and Implementation Approach

Introducing the FDX Smart Amplifier is much more than understanding how an RF platform operates with FDX technology. This is, in fact, the simpler problem having had years of experience with the FDX RPD and understanding the similarities on the "south" port (DS output side) of the amplifier, as well as the relative simplifications on the "north" port (DS input side). The migration from a basic line technician install and well understood manual process of balancing undergoes a complete overhaul because of the addressability, remote access, integration with cloud applications on the back end, and move to full automation of activation and lifecycle management.

As such, the software and process development is being done in multiple phases. This will help manage training and knowledge acquisition, mature SW components themselves, and increase functionality incrementally, building on priority functions on the way to end-to-end automation and network management.

In parallel to developing greater and greater automation, for example, corresponding efforts are taking place to update existing technician tools to accommodate manual entry for pad and equalizer (EQ) settings that formerly would be done via hardware plug-ins. In this way, line technicians can follow similar processes as today to align an amplifier – birthing the amplifier as a Mid-Split device Day 1 – just with more advanced tools. Meanwhile, this capability in known applications, such as quick response (QR) scanner and meter applications, to "override" automated processes provides a cushion for the SW to be tested and matured, but not be a cause for slowing construction. The SW can catch up with continued releases as bugs are found, but it is imperative to keep the construction machine operating efficiently at full scale.

Note that "Day 1" Mid-Split activation could mean FDX enablement – which is always a remote command and alignment – on Day 1000, Day 100, Day 10, or also Day 1, shortly after the network upgrade is complete.

In addition, with the range measurement, self-test, communication, and DOCSIS functionality of the amplifier, there are multiple potential solutions possible for alignment, topology discovery, periodic calibration, and network monitoring and alerting. Algorithms being developed will be evaluated and the optimal routines implemented. The following sections describe in detail the primary development activities for each functional component. **Table 2** summarizes the core cloud application-centric SW components and their role in bringing the FDX Smart Amplifier online, aligning, discovery, and end-to-end optimization.

Table 2 -FDX Smart Amp Install to FDX Activation

INSTALL AND ACTIVATE STANDALONE AMP

- Physically install platform
- Common tech next steps: Input plug-ins - match AFE RF in and legacy band US (future SW automation)
- Amp CM comes online, Amp registers with "Amp Central" back end for **automated cal:**
  - Amp Config (DS PSD, US RLSP) pushed
  - Alignment initiated: meas DS freq response; residual RF in path corrections applied in SoC
  - Apply corrections to pre-eq the FDX US path in SoC
  - Meas and align DS RF out, SoC, EQs, Pads
  - Config FDX US path Eqs, Pads

NETWORK TOPOLOGY DISCOVERY

- Method 1 (100% automated)
  - Poll all CMs on a node leg (customer + Amps)
  - Fluctuate level or tilt slightly to induce delta form initial state
  - Record devices effected by delta
  - Repeat for every Amp as delta source; 2D results matrix uniquely defines topology
- Method 2 (100% automated)
  - Identical 2D matrix derivation of relationships
  - Relationships themselves determined via time coordinated Amp CM Tx / Amp South Rx measurements

ACTIVATE FDX MODE – DS E2E FINE TUNING

- Method 1 (100% automated)
  - Use Topology Discovery knowledge to fine-tune E2E DS alignment
  - "Standalone" cal steps repeated "front-to-back" for each Amp on each branch
  - Eliminates single amp error or build-up, installs without reference RF input, deltas of new connect operations
- Method 2 (100% automated)
  - Capture Rx levels for Amp and customer CMs as "optimum" state, pre-alignment
  - Exercise non-linear constrained gradient algorithm (defined acceptable) RF constraints to return post-upgraded network to initial operating state

FINE TUNE FDX US AND BUILD COMPLETE CHECK

- Method 1 (100% automated)
  - Use Topology Discovery knowledge to fine-tune E2E US FDX band alignment
  - SoC Test Pattern generator injects FDX US test signal onto EOL amp(s) US North Port
  - "Standalone" cal steps "back-to-front" each Amp, each branch, adjusting cal if needed
  - Eliminates single amp error or build-up, installs without reference RF input, deltas of new connect operations
- Method 2 (100% automated)
  - Replace or complement active test signal injection with customer FDX CMs
  - Standalone FDX config – update cal as CMs come online and are identified and located

Of course, in order to have cloud applications do magical new things with Smart Amplifiers, the amplifier itself must itself have a mature embedded platform that enables it to come alive, communication and be effectively interfaced with, as described in the next section.

4.2. Embedded Software

Traditional amplifiers deployed in HFC networks have been primarily hardware-driven platforms. Once installed and the technician walks away, the performance of an amplifier can only be indirectly monitored through the behavior of other components in the network. All direct measurements and adjustments must be made by physically accessing the device. This limitation results in the network being tuned with a static configuration that is sufficient to support the design variations as well as plant dynamic variations such as temperature, component aging, plant maintenance impacts, etc. Plant variations tend to be slow, and are accommodated by hardware components meant to compensate, such as recognizing thermal changes and adjusting accordingly and implementing automatic gain control (AGC).

Enter the FDX smart amplifier, where SW is a critical, essential component of the system, bringing much more visibility, control, and computational support to the historically "dumb" amplifier. A sophisticated software stack paired with remote access allows the operator to optimize the plant configuration while monitoring its performance – both the amplifier itself and the plant on either side. The SW, combined with an integrated back-office suite, will enable triggering alerts and notifications as necessary, and is the basis for multiple automation routines to be described in subsequent sections.

Software Design Requirements

As noted, the addition of a remotely accessible software stack opens a new world of capabilities to the amplifier. This brings a host of requirements to the software platform. Beyond the feature requirements themselves, the software architecture must consider the following design requirements:

- Support for hardware architectures across multiple manufacturers
- Support for various SoC architectures
- Provide a framework for collaborative development with multiple partners
- Implement a control interface that utilizes common network management protocols

Figure 14 below shows the high-level architecture of the embedded amplifier software. A description of each component follows.

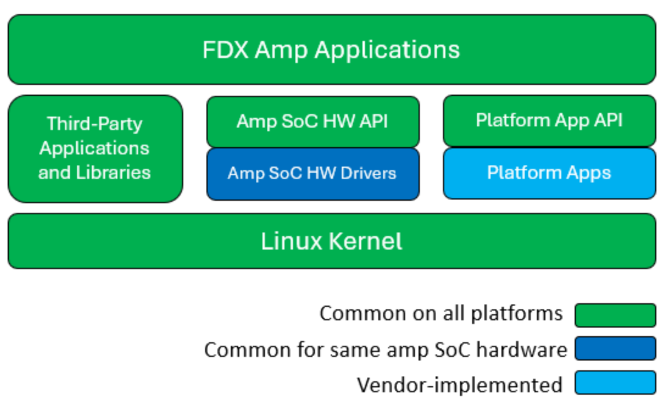

Figure 13 - FDX Smart Amplifier Embedded SW Architecture

Linux Kernel

This is the kernel for the operating system. Linux was chosen for its proven history of hardware support, network protocol support, customization ability, open source, and developer community involvement.

Third-Party Applications and Libraries

Third-party applications include common open-source software functionality. Below are a few examples:

- DHCP – Network identity exchanges
- SSH – Remote shell access
- generic network management interface (gNMI) – Remote configuration and monitoring
- HTTP – Software downloads

<u>FDX Amplifier Applications</u>

FDX amplifier applications provide the primary system management features. These include:

- System startup orchestration
- Device configuration (e.g. port configuration)
- Device monitoring (e.g. statistics, status, alarms)
- Software upgrades
- Device reboot

<u>Amp (SoC) Hardware Application Programming Interface (API)</u>

This layer defines a common interface for all amp-specific features provided by the SoC. This interface is the same for all platforms.

<u>Amp SoC Hardware Drivers</u>

This layer is the SoC-specific implementation of the features defined in the Amp SoC Hardware API. The same implementation is shared across all platforms using the same SoC.

<u>Platform App API</u>

This layer defines a common interface for all features that are implemented by the manufacturer. This interface is the same for all platforms.

<u>Platform Apps</u>

This layer is the manufacturer-specific implementation of the features defined in the Platform App API. This is specific to a manufacturer's platform.

4.3. Standalone Installation and Alignment

This section describes the steps for amplifier initialization and activation, which occur immediately after installation into the network.

Figure 15 shows the block diagram for the FDX amplifier, labelled with various points used in the alignment description below.

After the amplifier is installed, the technician configures the DS in plug-ins, to achieve the desired channel power at the Downstream Analog Front End Test Point (*DS AFE TP*), providing optimal North Port DS AFE signal loading. This is similar to what a technician does today to align to a flat, defined level, only in the FDX Amp case, the level itself is set per SoC input level recommendation rather than a pre-amplifier stage of a traditional amplifier.

Note that this plug-in component and step is slated for future elimination (among others). An electronically controlled pad is also in line with this DS input. However, as part of the operational transition from all-manual to 100% automated, steps between to manage that transition and incrementally introduce new SW features include semi-automation phases with some manual functionality and measurement verifications until both HW and SW on the platform are fully mature.

Similarly, the legacy Mid-Split band US plug-ins are installed which will allow the embedded cable modem (eCM) to range and register. At this point, both the eCM and the amplifier itself have obtained internet protocol (IP) addresses, and the amplifier supports gNMI connections to the back office for control and status during the initialization and activation process.

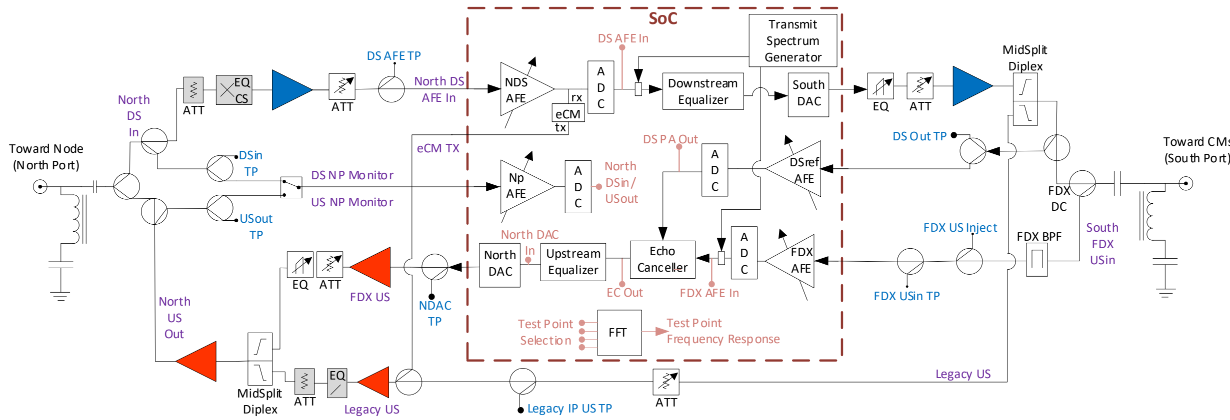

Figure 14 - FDX Amplifier Block Diagram [10]

Once the eCM is online, the amplifier then receives a configuration profile though gNMI messaging. This defines the DS transmit (TX) power profile including any DS power stepdown points (typically > 1 GHz), and the US receive level set point (RLSP). With this information, the process of standalone alignment is initiated to complete the amplifier activation.

On the DS input side, the frequency response of the DS input is measured and analyzed under software control. This information is used to correct any frequency response anomalies which may exist on the network segment connected to the amplifier North Port, as well as any residual tilt or power offset that has not been corrected with the DS plug-ins. This prevents these anomalies from being propagated to the network segments connected to the amplifier South Port(s). This correction is performed within the SoC, *to a degree of precision that is not possible with either plug-in or electronic controlled EQ and attenuators*.

This same correction is also used to *pre-equalize* the FDX US, correcting for the same north network segment frequency response anomalies that are occurring within the FDX band of the north side plant segment. In FDX mode, of course, the frequency response and path loss become the FDX US frequency response and path loss.

The DS output side is then aligned by the software which analyzes the frequency response measured at the *DS PA out*. This measurement is used to determine the final values of DS attenuator, DS equalizer, and SoC DS filter settings, which in combination drive the amplifier south port accurately to the configured DS transmit power profile. Note that this capability also enables the amplifier to hold a "perfect" output, preventing cascaded propagation of small misalignments over time and temperature, in a way not possible in a traditional amplifier

The last step of standalone alignment uses the configuration profile, along with the DS input frequency response measurement. Software configures the FDX US output attenuator, FDX external equalizer, and the SoC US equalizer to their final values. These controls are set to provide flat US RLSP to the amplifier/node connected at the other end of the north side network segment.

One final note on the FDX alignment operation. As noted, the DS measurements provide the means to pre-set the FDX US, using the network symmetry aspect of passive coax. In addition, however, as show in Figure 15, the SoC contains a transmit spectrum pattern generator that can be used in the FDX band. The SoC enables this pattern generator to be flipped around and transmit out of the FDX US. By launching this pattern generator from the last amplifier, the FDX alignment "back to front" can be fine-tuned via measurement span-to-span, eliminating any offsets that may occur from the presetting of the FDX US in the prior steps.

More powerful than FDX fine-tuning, however, is that this pattern generator injection process will uncover any errors in the upgrade process that missed an amplifier and left a Mid-Split only amplifier in place. In fairness to our excellent business partners, often this occurs because an amplifier is not on the design map due to a recording error. Regardless of the reason, with this capability, and before construction teams move onto the next job, they can detect whether they finished the first one.

At this point the amplifier is fully activated, and all control settings that were configured during the activation process are saved in non-volatile memory for use during subsequent amplifier boot cycles.

4.4. Topology Discovery

Understanding the topological relationship between nodes, amplifiers in cascade, and connected cable modems is crucial for maintaining optimal network performance. Because FDX Smart Amps are uniquely addressable, can fully measure on all ports, and be controlled remotely and with automation, they provide a very powerful topology discovery capability that cannot be done using today's amplifiers.

One effective approach to this discovery is to analyze minor, controlled, power fluctuations throughout the network. These power fluctuations can provide valuable information about the behavior of amplifiers and the performance of cable modems, helping to identify potential issues and optimize configurations. By closely monitoring power fluctuations at various points in the network, particularly at the outputs of amplifiers and the inputs to cable modems, network operators can identify patterns that indicate how well the amplifiers are performing and how effectively the signal is being transmitted to end-user devices.

K-means clustering is a powerful technique for analyzing these power fluctuations. This method partitions the data into k clusters, where k is a predefined number of clusters. The steps involved in k-means clustering are as follows:

1. Initialization: Choose k initial cluster centroids, which can be selected randomly or using specific methods, such as k-means++.
2. Assignment: Assign each data point to the nearest centroid based on the Euclidean distance
3. Update: Recalculate the centroids as the mean of all data points assigned to each cluster
4. Iterate

By applying k-means clustering to the power fluctuation data collected from amplifiers and cable modems, operators can determine exactly which amplifiers are feeding others, as well as determine which end-devices are connected to the amplifiers that are feeding them. Moreover, by analyzing the centroids and the distribution of data points within each cluster, operators can gain insights into the typical behavior and performance of different parts of the network.

To demonstrate the concept above, a randomly generated topology, consisting of Amplifiers and Cable Modems and shown in Figure 16**,** has been utilized to determine the topology of amplifiers and connected cable modems.

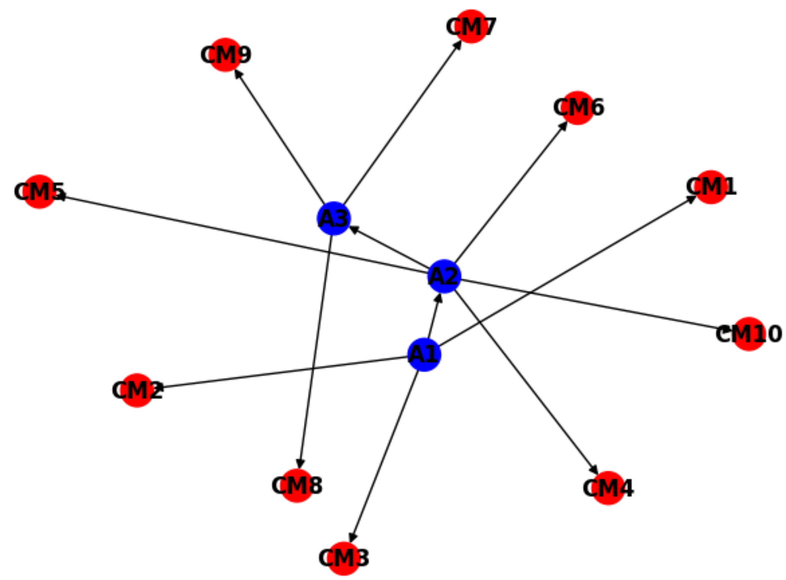

Figure 15 - Random Topology Discovery Example

Running the K-means clustering algorithm outputs the results shown in **Table 2**.

Table 3 – K-Means Clustering Determining Topology

Amplifiers Baseline and Fluctuated Power Levels:

	Amplifier_ID	Baseline_Power_Level	Fluctuated_Power_Level	Fluctuation
0	A1	77	76.5	-0.5
1	A2	96	95.5	-0.5
2	A3	79	78.5	-0.5

Modems Baseline and Fluctuated Signal Levels:

	Modem_ID	Baseline_Signal_Level	Signal_Level	Fluctuated_Signal_Level
0	CM1	0.050321	1.357635	0.857635
1	CM2	-0.090028	-0.033199	-0.533199
2	CM3	0.685309	-1.082924	-1.582924
3	CM4	-0.459605	0.370693	-0.129307
4	CM5	0.238362	0.390806	-0.109194
5	CM6	-0.356148	1.282287	0.782287
6	CM7	-0.724889	1.398819	0.898819
7	CM8	-0.228087	-0.647016	-1.147016
8	CM9	0.923108	-0.666961	-1.166961
9	CM10	1.446142	-2.929003	0.000000

```
Derived Modem to Amplifier Mapping:
CM1: A1
CM2: A1
CM3: A1
CM4: A2
CM5: A2
CM6: A2
CM7: A3
CM8: A3
CM9: A3
CM10: A2

Cascade Structure:
A1: CM1, CM2, CM3, next A2
A2: CM4, CM5, CM6, CM10, next A3
A3: CM7, CM8, CM9
```

The results are as expected, the algorithm can properly determine the logical architecture of the Amplifiers and cable modems (CM) in Figure 16.

Again, this is all made possible by the FDX Smart Amp capabilities to be addressed, coordinate, communicate, and interact with cloud applications.

4.5. End-to-End Cascade Alignment and Optimization

Node and amplifier output levels are one of the key attributes to delivering high-quality and reliable services. Design levels in the field may have varied over time, mostly because field technicians may have to tweak and repair the infrastructure to ensure customers' services are kept running smoothly. These adjustments are essential because they directly impact how well end-user devices perform since these devices depend on receiving a specific range of input power level and signal quality. If the levels and fidelity deviate from what is expected, it can cause service impairment or disruption, and effect the reliability and efficiency of the entire network.

Traditional designs methodologies match a fixed, single, configuration for node and amplifier levels to the HFC design span losses, passive losses, and assumptions about the drop-home network losses. Levels are also, of course, based on the capabilities of the amplifier technology itself, in particular the broadband PA. This traditional approach offers convenient simplicity for operating and managing the network, and its success offering more and more advanced services over the years is a testament to the sound principles used in this approach.

Deviating from a fixed-output design constraint in the HFC cascade has some risk, but also offers great rewards with respect to automation, operations, and future optimization. Simply deriving the current levels of amplifiers in the network itself and managing the variations is a complex non-linear optimization problem. This complexity arises from the interdependencies among various network parameters and the inherently non-linear nature of signal amplification processes. To accurately model these relationships, a thorough understanding of the network topology is essential. Knowing topology of the HFC network – as noted above is discoverable by FDX Smart Amps themselves – including the locations and specifications of nodes, amplifiers, and end-devices, allows for precise modeling of signal transmission and power distribution.

To tackle this non-linear optimization challenge, equality and inequality constraints are essential tools. Equality constraints enforce specific conditions that must be met exactly, such as maintaining a precise signal strength at certain points in the network. For example, an equality constraint might ensure that the signal level at the input of a particular amplifier is exactly within a specified range to guarantee optimal performance DS. These constraints are crucial for consistently maintaining critical parameters, which is vital for the stable operation of the HFC network.

Equality Constraints

Equality constraints ensure that specific conditions are met exactly. These can be used to derive precise signal levels or power requirements at certain points in the network. Mathematically, equality constraints can be expressed as follows:

$$hi(\boldsymbol{x}) = 0, \forall i \in \{1,2, \dots, m\}$$

where x is the vector of variables we are optimizing (e.g., amplifier gains, input power levels), and hi represents the i-th equality constraint.

For instance, in an HFC network, if we need to ensure that the total output power at a specific amplifier output in the network is exactly Ptarget, we can formulate this as:

$$10log[Pin, iGi + Ne] - Ptarget = 0$$

$$where\ the\ ith\ amp\ effective\ noise\ added\ to\ the\ output\ is$$

$$Ne \ = \ (F \ - \ 1)\ Gi\ (kToB)\ and$$

$$noise\ factor\ F \ = \ 10\text{^}(NFi/10);$$

$$NFi\ is\ ith\ amp\ noise\ figure$$

$$since\ for\ amp\ i$$

$$F \ = \ SNRin/SNRout$$

$$= \ (Pin/Nin)(Nout/Pout)$$

$$= \ (Pin/Nin)(Gi\ Nin \ + \ Ne)/(Gi\ Pin)$$

$$= \ 1 \ + \ Ne/(Gi\ Nin)$$

Where:

- Pin, i is the input power to the $i - th$ amplifier
- Gi is the gain of the $i - th$ amplifier
- Ni is the noise figure of the $i - th$ amplifier

- $Ptarget$ is the desired output power level
- n is the number of amplifiers
-

Note that F (hence NF) depends on the input noise level and is calculated using a reference thermal noise level at room temperature To with Nin = k To B, where:

- k: $Boltzmann's\ constant\ (1.374 * 10^{\wedge}(-23))\ joules/°K$
- T: $absolute\ temprature\ in\ °K$
- B: $the\ bandwidth\ of\ the\ measurement\ in\ Hz$

Given that signal power in the cable television in typically shown in dBmV in a 75 Ohm environment, the thermal noise power at 62°F is approximately:

$$N_p(dBmV) = -125.2 + 10logB$$

For QAM and other digital carriers, such as OFDM, the noise floor is typically assumed to be at:

$$N_p = -57.4\ dBmV$$

Inequality Constraints

On the other hand, inequality constraints offer the flexibility needed to accommodate variations while keeping parameters within acceptable limits. For instance, inequality constraints can set permissible ranges for signal power variations, ensuring that while some fluctuations are allowed, they remain within safe bounds to prevent signal quality degradation. This flexibility is crucial for adapting to the real-world conditions and changes that occur in the field.

Inequality constraints provide permissible ranges for various parameters, ensuring they stay within operational limits. These constraints can be expressed as inequalities:

$$gi(\boldsymbol{x}) \leq 0, \forall i \in \{1,2, \dots, p\}$$

For HFC networks, inequality constraints can be used to limit the power output and to ensure the amplifier is operating in an optimal range. For example:

$$Pmin, i \leq Pout, i \leq Pmax, i$$

- $Pout, i$ is the output power of the i-th amplifier
- $Pmin, i$ and $Pmax, i$ are the minimum and maximum allowable output power levels for the i-th amplifier

Combining Both

By using both equality and inequality constraints, the non-linear optimization process can effectively find a solution that balances all requirements. This approach is deterministic, meaning that given the same initial conditions and constraints, the optimization process will always reach the same solution. Unlike statistical methods, which may produce varying results based on probabilistic factors, this deterministic approach ensures consistent and reliable outcomes. Therefore, leveraging equality and inequality constraints in non-linear optimization provides a solid framework for managing amplifier output levels in

HFC networks. This ensures that network performance remains optimal despite ongoing changes and challenges, resulting in a more reliable and efficient HFC network for end-users.

The optimization problem can then be formulated as:

$$minx\boldsymbol{f}(\boldsymbol{x})$$

$$subject\ to:$$

$$hi(\boldsymbol{x}) = 0, \forall i \in 1,2,\dots,m$$

$$gj(\boldsymbol{x}) \leq 0, \forall j \in \{1,2,\dots,p$$

In the example below, existing amplifier output levels can be calculated based on the plant design shown in Figure 17.

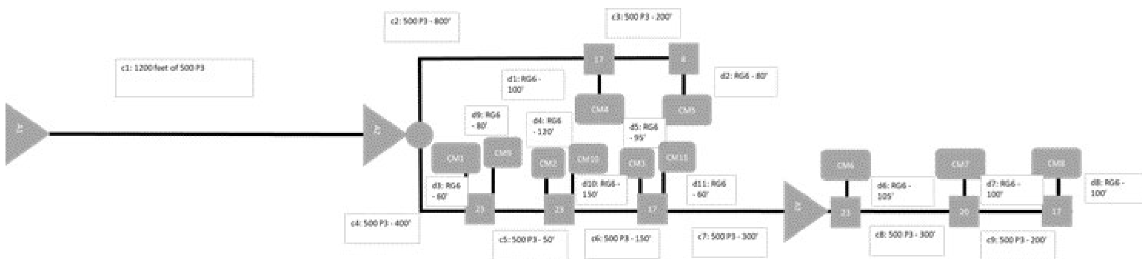

Figure 16 – Calculating Amplifier Levels of an Example Cascade

Today's CMs provide for full-band capture (FBC) capability. Each device is essentially a spectrum analyzer view of what it sees at its coaxial input port. From this, various calculations can be done, including DS levels. Figure 18 is an example of what various CMs on an amplifier might report. Assume these are the devices reporting in the network and shown in Figure 17.

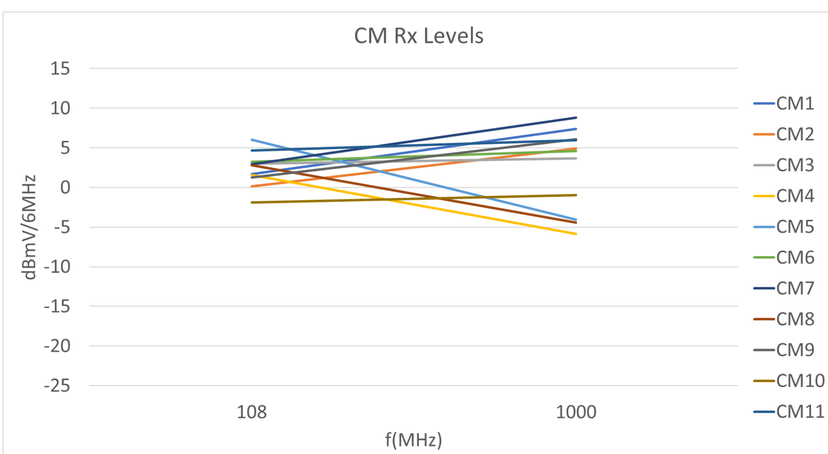

Figure 17 – Hypothetical CM DS Rx Reporting

If a plant upgrade induces a change and it forces all amplifiers to output the same level, e.g. $31dBmV/6MHz$ at 108 MHz and $45dBmV/6MHz$ at 1002 MHz, the new spectrum captures will look as shown in Figure 19.

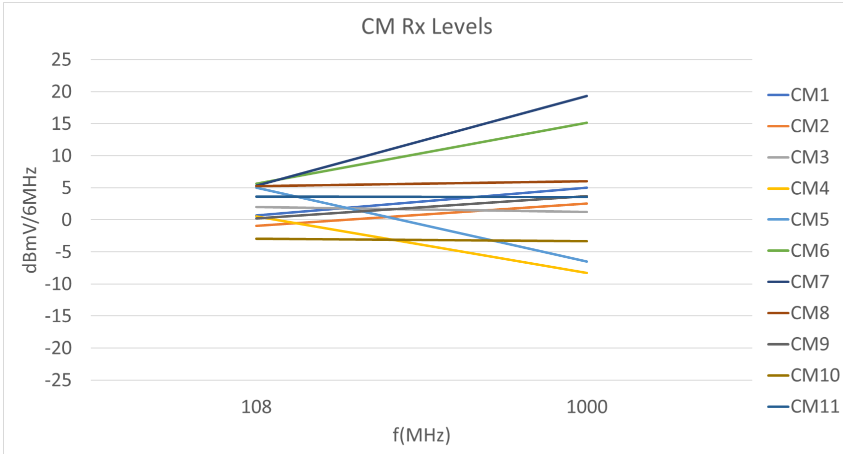

Figure 18 – CM Levels Stimulated by Change in Amplifier Profile

The difference between the two figures can easily be seen. Utilizing the equality and inequality constraints mentioned above, we can derive the exact historical amplifier output levels, and summarized in **Table 4**.

Table 4 – Derived Amplifier Levels Based of Figure 17 Network

Design Levels:	**dBmV/6MHz**
@ 108 MHz	31
@ 1002 MHz	45
Historical Levels:	
@ 108 MHz	34.14
@ 1002 MHz	49.51

With these capabilities available, coupled with the information available at the CMs (including the Amplifier's own CM), each installed FDX Amplifier can algorithmically determine what level to operate at to drive its span to the next amplifier and to the customer connected CMs to maintain the CM existing baseline conditions (initially) – both customer CM and amplifier eCM. This ensures FDX amplifier upgrades can be automated, returning the pre-FDX Amp HFC network to its original, stable operating point to complete the upgrade.

Over time, additional criteria can be added by defining what is "optimal" performance with weighting given less to current baseline and more to additional measurable parameters. Examples include maximum average fidelity, maximum total capacity, maximum FDX US capacity, maximum OFDM capacity, minimum neighbor interference, maximum self-install success, minimum power consumption, etc. In practice some (or no) weighting can be given to each. Whatever combination of criteria make business sense, and how to quantify them into a metric input, this type of algorithm allows automation of end-to-end cascade alignment as its most basic and minimum function, and opportunities to continually make the network smarter and more flexible by replacing manual and fixed operations and functionality with automatable processes and potential machine learning (ML)/artificial intelligence (AI) based multi-variate optimization.

4.6. Amplifier Lifecycle and Manager

Taking a step back now into the realities of network operation, the amplifier lifecycle and manager (ALCM) component will manage and orchestrate the day-to-day, week-to-week, and otherwise non-steady state operational modes of amplifiers.

Examples that exist today that must be accounted for differently because of the SoC and SW-centric nature of the FDX Amplifier are power outages and glitches, amplifier maintenance, amplifier swaps, cable cuts, etc. All of these scenarios and more must be accounted for now also in SW processes and desired behaviors resulting from these events. Other possible negative use cases also should be considered for amplifier desired behaviors and built into the design. For the most part, all of these involve storage of amplifier configuration state, including EC coefficients and convergence status, and handling unplanned re-boots

In addition, the automated alignment described above can theoretically be run at any time. Amplifiers can maintain their outputs "perfectly" by monitoring their output profiles and holding them within a tight window of operation. However, individual amplifiers adjusting independently may align themselves differently than an End-to-End complete cascade alignment in order from the node toward the end of an amplifier cascade, as the latter step involves measurements and adjustment at both amplifier input and output. A periodic refresh may provide better operating points.

Lastly, it has been described how amplifiers can help to keep themselves aligned perfectly at their outputs. Some amount of variation versus time being accommodated is expected. However, larger swings of variation of input level, perhaps indicative of a bad span to the North port, should generate a notification when measured at the amplifier input test point. Perhaps the amplifier can correct for it (or not), but thresholds should be set beyond which the observed behavior suggests something beyond normal variation and in need of repair.

5. Smart Amp Network Telemetry and Diagnosis

The FDX Smart Amplifier SoC has an embedded AI/ML engine. Incorporating AI/ML capable chips into amplifiers offers a revolutionary approach to real-time anomaly detection and mitigation. By embedding these advanced chips, the amplifiers can continuously monitor and analyze network performance, detecting irregularities as they occur. The AI/ML models, pre-trained on extensive datasets of network behavior, can identify deviations from the norm in real-time rather than relying on statistical inference.

A prime example of this is the detection of ingress noise, which can be deemed as one of the most difficult impairments to detect for many, if not all operators. Example of broadcast ingress into the Mid-Split OFDMA band is shown in Figure 20 **[2]**.

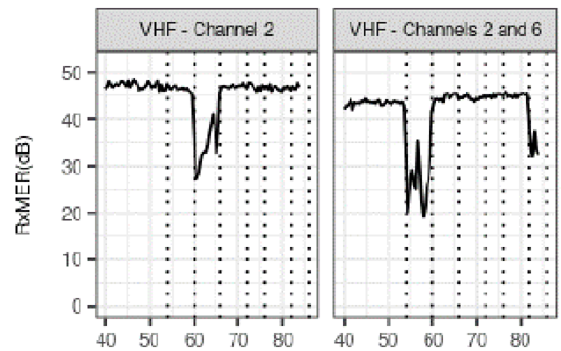

Figure 19 - Mid-Split OFDMA VHF Ingress [2]

A pre-trained model, exposed to various noise profiles during its training phase, can derive the characteristics of ingress noise. When deployed in an amplifier, the AI/ML chip can continuously compare real-time noise levels with the expected model. Given the bursty and intermittent nature of US ingress noise, having the chip doing real time analysis on the spectrum can lead to pinpoint accuracy for detecting impairments.

Upon detecting unusual noise patterns, the system can immediately isolate the affected segment and take corrective actions, such as applying attenuation to the impaired leg of the node or amplifier, while alerting maintenance technicians for physical inspections.

Incorporating AI chips within amplifiers in an HFC environment can also significantly enhance the efficiency and effectiveness of other deep learning models for real-time anomaly detection and mitigation. This can be achieved by building upon transferring a pre-trained model from a training environment to the real-world. Such models and ML/AI algorithms are operating at Comcast today on a library of anomalies trained for and shown in Figure 21 **[1]**.

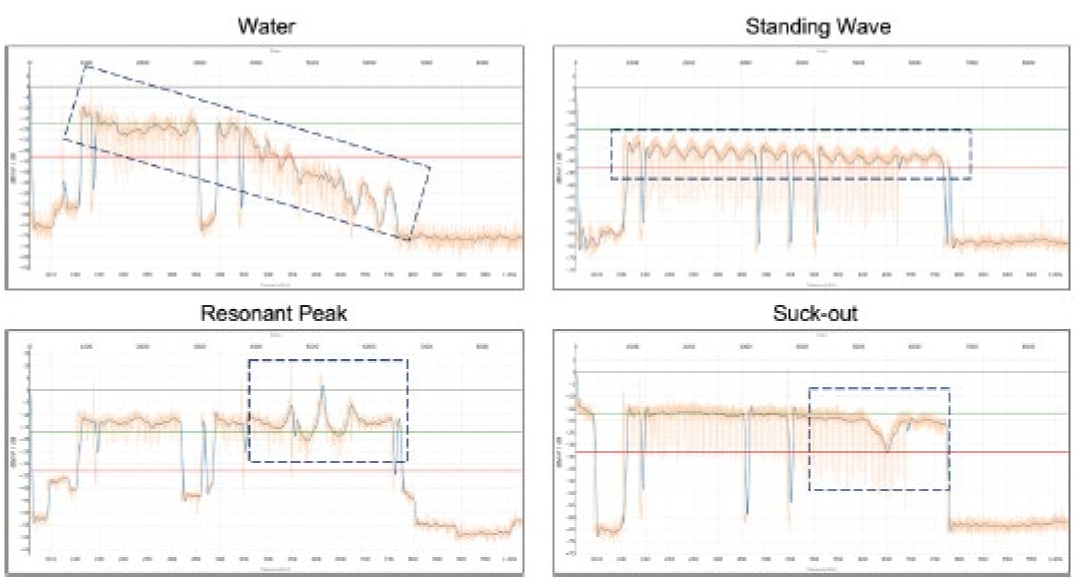

Figure 20 - AI/ML-based Anomaly Detection Library [1]

Today, cloud-based algorithms use this data to zero-in on probable causes of these plant impairments as shown in Figure 22. An issue identified in Figure 21 and commonly seen in amplifiers that causes resonant peaks is present in FBC data. The root cause analysis (RCA) algorithm only calculates the score for each of the amplifiers found in the node's topology. In Figure 22, the modems impacted by resonant peaks are clustered on the left side of the graph (highlighted in pink), with no modem in the cluster reporting having normal spectrum. Therefore, the amplifier highlighted in the figure has an RCA score equal to the maximum possible.

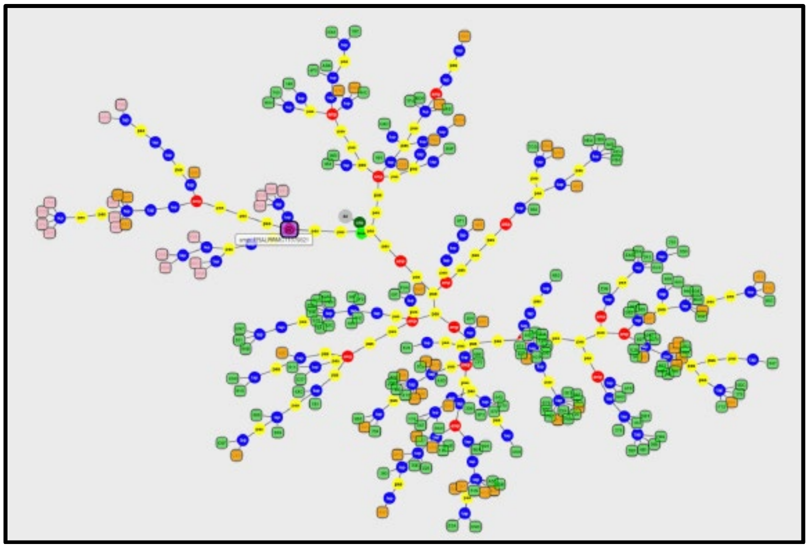

Figure 21 - Anomaly Detection Root cause Analysis [1]

There is now opportunity to have distributed AI functionality, making immediate decisions, minimizing the amount of telemetry exchanged between amplifier and cloud, and minimizing potential storage associated with a very high number of amplifiers when compared to nodes. In the example above, with FDX Smart Amplifiers, the visibility will be even more granular, extending from each amplifier itself between the node port and CM, rather than rely on inferences from CMs only, improving the RCA probability and diagnosis.

Generally, knowing that the AI chip is doing the analysis in real time, the fine tune and real adjustments to the detection/mitigation logic can also be done using real data in real time. Of course, there needs to be thresholds in place for the model to not drastically deviate from the norm, but the emphasis should remain on being able to train a model in real time, particularly when it comes to intermittent impairments.

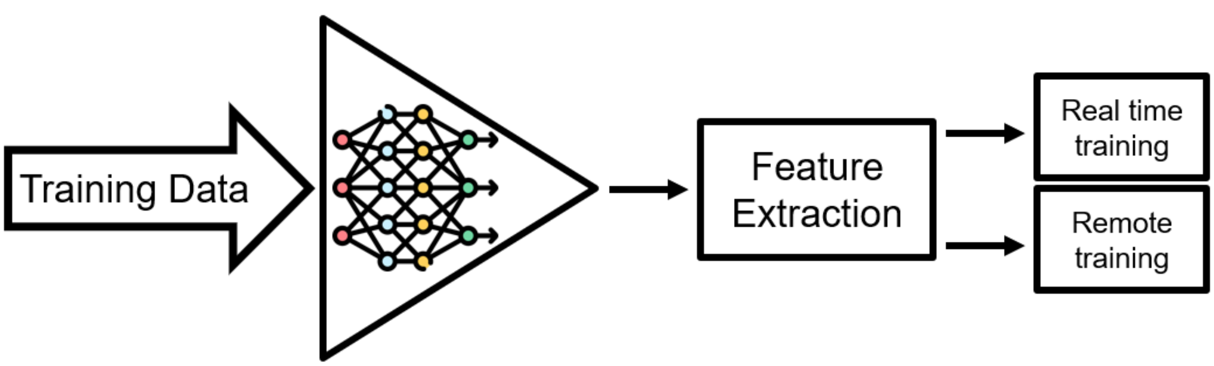

Figure 22 - Models are Continually Trained Iteratively with Real Data

The SoC is designed to handle deep learning models efficiently, enabling continuous monitoring and anomaly detection directly at the network edge. The computation limitations are bound by the following parameters:

- Computational capability of the AI engine
- Power consumption of the AI engine
- Memory capacity of the AI engine
- Bandwidth available for data transmission to and from the AI engine

Other benefits of real time analysis include:

- Reduced Latency: Edge processing ensures that decisions can be made quicker, enhancing the overall responsiveness of the network. This is crucial in maintaining high-quality service, as even minor delays can affect performance and user experience. For instance, in a situation where signal strength starts to drop, say due to rapid temperature changes, the chip can quickly adjust the amplifier's gain to maintain optimal signal quality.
- Resource Efficiency: By optimizing models for a distributed architecture, it is feasible to deploy sophisticated AI capabilities even in distributed and resource-constrained environments. As a result, the network can benefit from advanced anomaly detection and mitigation without incurring unnecessary costs or complexity.

6. Conclusion

Multi-Gigabit symmetrical broadband speeds powered by D4.0 FDX will enable operators to maintain their broadband leadership position for years to come. Comcast is proud to be leading this charge for the industry and paving a way forward for others to follow in terms of architecture and technology.

While the reference architecture for D4.0 FDX is based on an N+0 architecture, the same extraordinary EC technology that enables FDX in DAA fiber nodes can be used to implement FDX in N+x systems. Comcast has validated, via analysis and measurement, both the RF/fidelity of these systems, and the corresponding capacity, speed, and utilization aspects. This has all been extensively published and shared with the industry [3][5][8][9][10][11][12]. The FDX amplifier is the game-changing element of D4.0, as no longer are operators constrained by the additional time and cost associated with N+0 upgrades. The network can be rapidly upgraded with upgrades to actives alone. The entire HFC footprint is now addressable with FDX, and in doing so becomes capable of multi-gigabit symmetric speeds. Meanwhile, the time to find and upgrade or replace the entire set of network passives is likely to defer these upgrades for many years, limiting competitiveness against fiber speeds.

In addition to simply enabling FDX, the FDX Smart Amplifier opens a completely new world of network transparency and operational benefits. Amplifier activation and configuration can be fully automated, and amplifier performance self-correcting. Telemetry can stream in real time from many more points in the network, with granular health information at every point. Every single RF span between actives in the HFC network has its own spectrum analyzer to diagnose, localize, and alert on specific impairments, which have already been built into libraries trained on pattern detection algorithms. Finally, the AI/ML that currently provides this capability and feeds tools in the back end and to technician meters can be ported to run, and train, directly on the amplifiers themselves, providing even more benefits.

Indeed, the Smart FDX Amplifier is now here, and it is the industry game-changer that promises to drive the rapid, widescale success of D4.0.

Abbreviations

AFE	analog front end
AGC	automatic gain control
AI	artificial intelligence
ALCM	amplifier lifecycle manager
API	application programming interface
BW	bandwidth
CM	cable modem
CMTS	cable modem termination system
D3.0	data over cable service interface specification 3.0
D3.1	data over cable service interface specification 3.1
D4.0	data over cable service interface specification 4.0
DAA	distributed access architecture
DHCP	dynamic host configuration protocol
DOCSIS	data over cable service interface specification
DS	downstream
DSL	digital subscriber line
DSLAM	digital subscriber line access multiplexer
DSP	digital signal processing
EC	echo cancellation
eCM	embedded cable modem
EQ	equalizer
FBC	full band capture
FDD	frequency domain duplex
FDX	full duplex DOCSIS
FDX-L	full duplex DOCSIS limited
Gbps	gigabit per second
gNMI	generic network management interface
HFC	hybrid fiber-coax
HHP	Households passed
HTTP	Hypertext transfer protocol
HW	hardware
IG	interference group
IP	internet protocol
LE	line extender
MB	multi-port bridger
Mbps	megabit per second
MER	modulation error ratio
MHz	megahertz
ML	machine learning
N+x	node + x actives (amplifiers)
N+0	node+0 actives
OFDM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multiple access
PA	power amplifier
PHY	physical layer
PSD	power spectral density

QAM	quadrature amplitude modulation
QR	quick-response
RBA	resource block assignment
RCA	root cause analysis
RF	radio frequency
RLSP	receive level set point
RPHY	remote physical layer
SC-QAM	single carrier QAM
SG	service group
SoC	system-on-a-chip
SNR	signal to noise ratio
SSH	secure socket shell
SW	software
TG	transmission group
TP	test point
TX	transmit
US	upstream
xDSL	refers to all technology variants of DSL (x=S, A,V etc)

Bibliography & References

[1] Dugan, Kevin, and Justin Evans, Maher Harb, Deep Learning Approach for Detecting RF Spectrum Impairments and Conducting Root Cause Analysis, 2022 SCTE Expo, Sept 19-22, Philadelphia, PA.

[2] Ferreira, Jude, and Kevin Dugan, Maher Harb, Mike O'Dell, Larry Wolcott, Developing Machine Learning Models to Detect and Classify Impairments in OFDMA Channels, 2022 SCTE Expo, Sept 19-22, Philadelphia, PA.

[3] Howald, Dr. Robert, Roaring into the 20's with 10G, 2020 SCTE Expo, Oct 13-16 (Virtual Event).

[4] Howald, Dr. Robert and Jon Cave (Comcast), Olakunle Ekundare (Comcast), John Williams (Charter), Matt Petersen (Charter), Developing the DOCSIS 4.0 Playbook for the Season of 10G, 2021 SCTE Expo Oct 11-14 (Virtual Event).

[5] Howald, Dr. Robert L, Jeanne Ciampa, and Errol D'Souza, The First Anniversary of @Real10G – What Have We Learned, 2024 SCTE Expo, Sept 24-26, Philadelphia, PA.

[6] Howald, Dr. Robert L, John Chrostowski, Dr. Richard Primerano, and Chris Marinangeli, Hattery Will Get You Everywhere, 2024 SCTE Expo, Sept 24-26, Philadelphia, PA.

[7] Howald, Dr. Robert L, and Dr. Sebnem Ozer, Robert Thompson, Saif Rahman, Dr. Richard Prodan, Jorge Salinger, What is 10G – The Technology Foundation, 2019 SCTE Expo, Sept 30-Oct 3, New Orleans, LA.

[8] Howald, Dr. Robert L, and John Ulm, Saif Rahman, and Dr. Zoran Maricevic, Collision-Free Hyper-Speeds on the Bi-Directional FDX Highway, 2022 SCTE Expo, Sept 19-22, Philadelphia, PA.

[9] Prodan, Dr. Richard, 10G Full Duplex DOCSIS Implementation Exceeds Expectations, 2021 SCTE Expo Oct 11-14 (Virtual Event).

[10] Prodan, Dr. Richard, Full Duplex DOCSIS (FDX) Amplifier Automatic Configuration, 2023 SCTE Expo, Oct 16-19, Denver, CO.

[11] Prodan, Dr. Richard, Optimizing the Transition to Full Duplex DOCSIS, 2020 SCTE Expo (Virtual Event)

[12] Prodan, Dr. Richard, The Full Duplex DOCSIS Amplifier – Why, How, and When, 2022 SCTE Expo, Sept 19-22, Philadelphia, PA.

Press Releases

[13] *Comcast and CommScope Hit Major 10G Milestone,* Comcast Corporate Press Release February 23, 2023.

[14] *Comcast hits symmetrical 4-Gig speeds with CommScope's DOCSIS 4.0 FDX Amps,* lightreading.com October 16, 2023

[15] *Comcast and Broadcom to Develop the World's First AI-Powered Access Network with Pioneering New Chipset,* Comcast Corporate Press Release October 17, 2023.

Other

[15] *DOCSIS 4.0 Physical Layer Specification*, CM-SP-PHYv4.0-D01-190628, CableLabs 2019

Acknowledgements

Special thanks to Frank Eichenlaub, Benny Lewandowski, James Lin, for their contributions to this paper.

