

Not Your Grandfather's Amplifier!

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1. Introduction

The era of smart amplifiers is officially underway!

In January 2025, Comcast began deploying next-generation FDX Smart Amplifiers, supporting DOCSIS® 4.0 FDX networks today. Unified DOCSIS 4.0 amplifiers support FDX, but also extending the Downstream to 1.8 GHz, among other features, will reach the field later this year. These deployments prove that FDX is not limited to N+0, despite that being the reference architecture in the DOCSIS 4.0 FDX standard. We will describe the experience and lessons learned deploying this first-of-its-kind technology at scale.

The rich telemetry of FDX Smart Amps provides deep network insight unlike anything before in the cable plant. These insights enable rapid notification, localization, diagnosis, and, coupled with event correlation engines in the cloud, can make source and root cause determinations. Where automated remediations can be applied, they can be quickly exercised. Where physical remediation is required, the increased visibility and data-driven diagnosis can ensure the right tech with the right tools arrives, informed, at the precise location as quickly as possible. Case study examples and operational models will demonstrate network efficiency and customer experience benefits when the FDX Smart Amp data ecosystem is real-time monitoring every coaxial span in the network.

Lastly, looking ahead, the opportunities enabled by this breakthrough technology are vast. This FDX Smart Amp becomes an edge compute location, empowered by its own AI engine. Extensive AI-based cloud compute is already at the heart of network operations today. With the FDX Smart Amp, the coaxial plant now augments the cloud compute with a distributed AI network, placing powerful processing capacity even closer to customers. We will describe the vision for leveraging this new capability.

2. What Makes DOCSIS 4.0 Full-Duplex Unique

Comcast launched DOCSIS 4.0 Full-Duplex (FDX) based network upgrades in October 2023. This launch introduced symmetrical speeds up to 2 Gbps in multiple areas. The FDX footprint and customer connections have grown significantly in the two years since this launch.

The CableLabs-specified reference architecture for FDX is based on a network without RF amplifiers as standalone actives, also known as “Node +0” or just N+0. The fiber node expected for a DOCSIS 4.0 FDX or DOCSIS 4.0 FDD system is part of a Distributed Access Architecture (DAA), and for Comcast and most other operators deploying DAA, that means a Remote-PHY based digital node (RPDs)

The unique quality of FDX is that it can use part of the HFC network bandwidth bi-directionally – it can support both downstream traffic and upstream (US) traffic in the same bandwidth, at the same time. The fundamental premise is shown in **Figure 1**. The details of this technology are described in many prior technical papers [1][3][5].

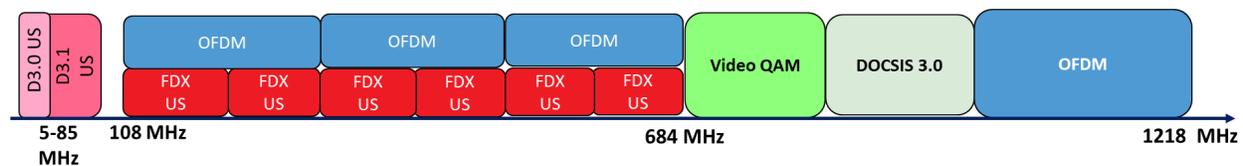


Figure 1 – DOCSIS 4.0 Full-Duplex Enables a Portion of the Bandwidth to be Bi-Directional

The N+0 reference architecture simplifies the implementation of FDX technology. And, indeed, the N+0 areas are where Comcast began its launch of FDX in 2023. However, because of the amount of deployed HFC that includes RF amplifiers (referred to as “N+x”) it was a practical imperative to extend FDX technology to systems beyond N+0. Comcast and key technology partners embarked on the development of FDX Amplifiers to meet this need and ensure multi-gigabit symmetric speeds could be rapidly deployed throughout the entire HFC footprint, whether N+0 or N+x. These amplifiers, of course, have the key technology ingredients to support FDX. However, they have additional, powerful capabilities that are transformative to network evolution and operations in unprecedented ways, and these aspects will be the focus of this paper.

3. By the Numbers: FDX Deployments

As of July 2025, Comcast has upgraded over 1.7M homes passed (hhp) to support FDX. The network upgrade is on track to cover nearly 8M homes passed by the end of 2025 and will continue at this rapid pace in 2026. The deployment comprises over 45,000 FDX RPDs. Most of these are part of Comcast’s N+0 footprint, as the launch of FDX-capable amplifiers began in January of 2025, about 15 months after the FDX launch itself. As of this writing (July 2025), over 33,000 FDX-capable amplifiers have been deployed in the network.

FDX-based services are available in each of Comcast’s 14 regions across the nation, including major metropolitan areas such as Atlanta, Boston, Chicago, Denver, Houston, Miami, Philadelphia, Portland, Sacramento, San Francisco, and Seattle, among others. The available symmetric tiers in the portfolio currently are 300/300, 500/500, 1G/1G and 2G/2G. Potential future FDX spectrum expansion can enable higher tiers, such as 3G/3G and beyond as business requirements dictate. Customers acquiring the newly available speeds continues to grow as the network upgrades in each area meet sufficient coverage criteria to enable sales.

The speed tiers identified above are delivered using the spectrum configuration shown in **Figure 2** below.



Figure 2 – Initial Spectrum Configuration Serving N+0 FDX Footprint (note that the unlabeled purple block represents spectrum set aside for maintenance tones and similar local origin use cases)

This spectrum configuration allowed Comcast to focus initially on operationalizing this expanded upstream band without the added complications associated with bi-directional features, such as in the RPD and vCMTS. Also, the approach provided a window of time, and of spectrum, to observe and characterize the FDX US performance before the full set of FDX-ready instrumentation and tools were available to support scale deployment. Notably, the spectrum configuration of Figure 2 is sufficient for the N+0 footprint only. However, as noted building FDX into N+x areas began in January 2025.

A consequence of the networks with amplifiers is an increase in the average size of the RPD. For example, whereas an N+0 node may pass 70 homes due to physical reach constraints, N+x nodes, because of the amplifiers, has the potential for much further reach, enabling systems to support a wide range of geographies and densities. As such, N+x nodes come in many shapes and sizes. Some can be as small as N+0, while more common sizes are on the order of 200 hhp, and large nodes can exceed 400 hhp.

The increased node size enabled by FDX Amplifiers has important ramifications to spectrum definition shown in Figure 2. In particular, for N+0 systems, Figure 2 is a careful balance of sufficient capacity for peak-busy-hour utilization of DOCSIS 3.0 and DOCSIS 3.1 users, while accommodating speeds up to 2G symmetric for DOCSIS 4.0 FDX subscribers, and 2G/300Mbps for DOCSIS 3.1 subscribers. Furthermore, Figure 2 supports existing QAM video services with a manageable amount of video QAM reduction, achieved often entirely through re-multiplexing.

However, the effective balance of High-Speed Data (HSD) service allocations that worked for N+0 networks is insufficient for the larger nodes of N+x networks. Broadcast video QAM, of course, can remain unchanged. However, with the high-speed data (HSD) subscriber count increasing by 5x or even more, a large increase of total traffic must be accounted for at peak busy hour, yet the network still must support the peak speed tiers. The result of this traffic engineering analysis for N+x footprint is that additional DOCSIS 3.0 and DOCSIS 3.1 network capacity must be allocated. How much can be quantified to develop the N+x production spectrum line-up, which is shown in **Figure 3** below.



Figure 3 – FDX Spectrum Configuration for the N+x Footprint

Of note is that the introduction of the bi-directional FDX band becomes a requirement to deliver multi-gigabit symmetric speeds in the generalized N+x footprint. Smaller N+x nodes and those of low utilization may not require this functionality, but the Figure 3 configuration must be supported for most. Also, for consistency and ease of automation, and with the necessary availability of the critical FDX technical features to support it, these networks will migrate to bi-directional configurations also.

4. FDX Upgrades are Building Upon a Solid Foundation

Comcast introduced DAA and Virtual CMTS (vCMTS) into its network over 7 years ago. As the technology matured, the pace of network upgrades accelerated accordingly. In 2023, Comcast announced details of the large-scale, multi-year network upgrade that was underway [2]. The objective of the upgrade was for a coverage of 50 million hhp by the end of 2025, which the company is tracking closely to. This DAA foundation is a specified architecture assumption of DOCSIS 4.0 systems per the standards for DOCSIS 4.0.

The vCMTS / DAA foundation makes for a straightforward upgrade process from standard, non-FDX RPDs to FDX technology. With the vCMTS core, switching infrastructure, and automated back-end registration and provisioning process established, the FDX Node becomes “just” another Ethernet terminating transducer with a new, greater set of RF and service capabilities, supported by new configuration and provisioning attributes. Incremental changes to configuration objects and provisioning parameters are made that support these new DOCSIS 4.0 FDX capabilities [7]. Full node and/or module swaps can be executed to upgrade from standard RPD to FDX, with individual OEM platform dependencies.

Upgrading the network with FDX Smart Amplifiers is quite different, however, over a traditional amplifier upgrade, and decidedly simpler. The install and activation of any individual amplifier by the technician has the same final objective as a traditional amplifier – align the amplifier by adjust the attenuation and conditioner values in the forward and return RF chains to meet the conditions of the HFC

design – but how to get there has been completely transformed. In addition to the forward and return band, there is now this new “FDX” band. The DOCSIS 4.0 FDX specification defines the incremental options through which the FDX band can be allocated to accommodate business needs evolving over time.

The amplifier does not “know” anything about FDX band allocation. The unique new RF work of the amplifier is processing the expanded upstream in an environment that includes downstream interference energy and delivering the US out of the amplifier heading towards the RPD with high fidelity. As with legacy US, there are elements of the FDX US band that must be aligned and calibrated. However, the technician installing the FDX Amplifier does not take any direct action to align the FDX Upstream during the upgrade, as will be described.

5. FDX Smart Amp Field Installations – Early Lessons

Tens of thousands of FDX Smart Amplifiers have been installed in the field, and the upgrade process has been scaled across the national footprint. This includes fully trained construction business partners actively upgrading N+x networks to FDX. A gradual ramp-up plan was in place to ensure that issues found did not multiply too quickly before they were able to be addressed. And, indeed, during the learning curve period, several valuable lessons emerged. Some of the most disruptive ones are described below.

5.1. Process-Centric

IT Management Comes to Amplifiers!

Having amplifiers that get online and register brings with it the incredible new features and capabilities of distributed processing, but also the burdens of CPUs in the field. Three particularly troublesome aspects were:

- 1) Business partners (3rd party contractors) obtaining and maintaining access to the Comcast Amp Application for activation
- 2) Business partners having access, but frequently getting kicked off the virtual private network (VPN) while calibrating because of rules governing VPN session length for non-employees
- 3) Threat assessment and security design of the new HW and the SW ecosystem for amplifiers becomes necessary, accounting for connectivity through the cable modem-like transponder and Ethernet accessibility within the platform for maintenance

Trust But Verify!

When technicians go into the field to upgrade the amplifiers, it is not uncommon for the existing levels observed at the amplifier to be upgraded to not be consistent with the design levels. This leaves the technicians in a difficult position of determining if the design levels were changed and not updated in the tools, or if local action (i.e. crank up the levels) was taken to accelerate an installation or overcome a bad span, for example, to get customers healthy quickly – always a high priority.

This phenomenon is being addressed in two ways, which we will see snapshots of later in this paper:

- 1) Utilize the FDX Smart Amps Echo Cancellor’s telemetry to identify a troubled span during the upgrade as soon as it is online line and telemetry is flowing.

- 2) During end-to-end cascade alignment, the criteria for the amplifier's output is set to be governed by its directly connected devices as observed pre-cut-over. This will go a long way towards ensuring stable customer experience after cutover.

5.2. Training / Technical Complications

Power Up

A major lesson of digital nodes was that power glitches would reset them and, in doing so, disconnect services to customers on the node until the RPD finished rebooting and modems completed re-ranging. Power sensitivity lessons now come to amplifiers, albeit reboots are much shorter in duration and much simpler functionally and with respect to state for amplifiers. A sound understanding of the power grid feeding the area to be upgraded is important, as FDX Smart Amps can impact the power design. Also, it is important to make sure it is a 90V system – which should have occurred before the FDX upgrade was approved but has proven not always to be guaranteed.

Lastly, being careful not to reset RPDs and not flash power while an amplifier is calibrating requires some “air traffic control” that previously did not require as much attentiveness. Amplifier balancing and self-alignment requires an uninterrupted RF input. The upgrade also potentially involves adjustments to the powering subsystem, and these adjustments can remove RF at the wrong location if not coordinated.

Spectrum Snowflakes

While the company has made excellent strides standardizing spectrum maps, most of the progress has been made on the DOCSIS side of spectrum allocation. There are still hundreds, if not thousands of unique spectrum variants in the footprint of 200k+ nodes. Most are minor deviations of video QAM carrier channel counts and frequency bands, out-of-band signaling, leakage tones, AGCs, local channel insert, etc. However, over so many spectrum map variants, some spectrum allocation cases were observed to create calibration errors. These were traced to the handling of non-uniform regions of the spectrum such as tones and gaps for the more extreme cases where these were present. Initially these were worked around by characterizing the limitations of accurate calibration but were ultimately resolved with firmware (FW) upgrades to the sampling and interpolation/extrapolation algorithms. The result was dependencies tied to spectrum line-up variations were vastly reduced

Amplifiers Driven at Levels Below their Design Limitations

A small percentage of amplifiers (estimated at 1-2%) in N+x are driven by out-of-compliance, excessively low design levels that will compromise performance in FDX operation. A common scenario of this type is a very long express span of old, high loss, trunk from a node to the amplifier, beyond which the N+x cascade feeds a neighborhood with a typical range of design levels. While traditional amplifiers may just pay an SNR penalty, just as an FDX amplifier would when operating in standard Mid-Split mode, for FDX operations there is an additional consideration associated with the level ratio of the incoming (low) DS and outgoing US in the FDX band to balance and align with high fidelity.

Most of these cases are remedied with physical network changes upstream of the amplifier, such as coupler values and RF profile changes. Others may be best suited to adding a mid-span amplifier. Awareness of this phenomenon is important to drive resource allocation properly for upgrades of these scenarios. Field guidance was issued to clarify the acceptable boundary conditions.

6. 2nd Generation FDX Amp Roadmap

The first full year of production FDX Smart Amplifier deployments are winding down, and tens of thousands are now deployed in the field. This pioneering, first-generation amplifier design had straightforward major milestones and objectives:

- 1) Develop conceptual design and requirements
- 2) Develop and prove the HW technology
- 3) Develop the FW/SW architecture and code
- 4) Produce a robust, predictable large volume platform meeting requirements

Put simply, ensuring a working 1st-generation platform, manufacturable and deployable at scale was essential. By pivoting from N+0 only footprint and into N+x areas, the amplifiers were essential to increasing the growth and reach of FDX-capable homes passed.

Lessons learned during hardware and software development, as well as in field trials exercising new tools and processes, provide input for areas of opportunity to improve the amplifier. Among areas under development for the 2nd generation hardware design are lower power, increased automation, and Unified DOCSIS 4.0 chips. These will be touched on briefly below.

6.1. Power Reduction

With a functioning platform that is fully characterized, some efficiency gains are expected by reviewing the existing design for areas of improvement. With the top priority being a working production platform, existing tried-and-true designs were the foundation of the amplifier, on top of which FDX functionality was integrated. With a renewed focus on power efficiency, there are savings available, and some have already been observed in initial lab testing.

The introduction of a System-on-a-Chip (SoC) adds an inherent increase to the power consumption of a standard amplifier. However, the availability of the SoC also adds capability that can be used to reduce power consumption above and beyond hardware design optimization. Traditional options, such as self-contained digital pre-distortion (DPD) can be activated. DPD is a relatively well-understood technology, made simpler to implement with the presence of the SoC that can host the Digital Signal Processing (DSP) that is part of implementing the DPD function, as well as support adaptive adjustments for variations that impact amplifier linearity, such as temperature variation.

Because the amplifier can communicate with back-end operational tools and be configured remotely, more sophisticated methods leveraging centralized machine learning algorithms that can convert traffic utilization data into actionable adjustments to spectrum allocation (channel reduction) or Power Amplifier (PA) bias control can be considered. Development and proof of concept for the bias control approach has shown excellent early returns, as shown in **Figure 4**.

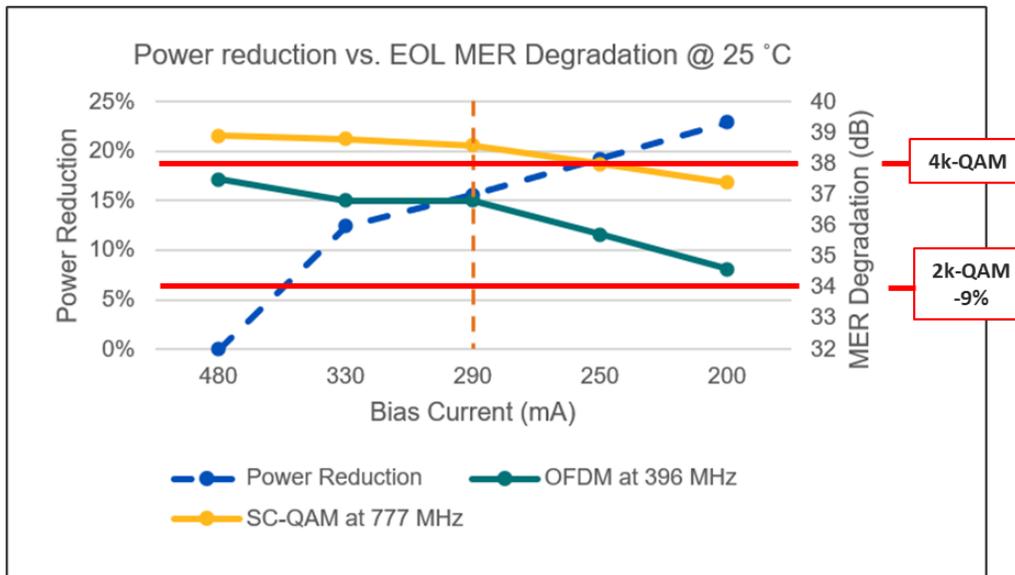


Figure 4 – Bias Control vs MER Performance in an N+6 Amplifier Cascade

Using the vertical red dotted line as a reference set point for the PAs in the chain, there is 15% available power reduction with a very modest MER degradation – nary enough to affect the modulation index that can be supported. Even if extended to the most efficient data point (blue curve) at 23% (200 ma) the MER loss does not cross the threshold of a QAM profile downgrade. However, even if it does drop beneath the threshold, the capacity loss of such a drop for the OFDM block is only about 9%. When considering the use of this operation in a simple case such as power savings that can be recovered during low utilization hours, such as overnight, the traffic reduction during these periods is typically much higher than 9%. Furthermore, 9% is not enough total capacity loss to impact speed tiers. These results are thus very encouraging.

Note that bias control and DPD are not fully complementary since they exercise common variables to operate. In other words, efficiencies attributable to each cannot be “added” together to obtain a total efficiency gain. Net power savings if leveraging both due to their interaction is future optimization work.

6.2. Increased Automation

Today’s standard line amplifiers are designed to drop into a wide variety HFC architectures. For a single platform to accommodate the variety of networks, there are, within the amplifier, multiple locations along the downstream path and upstream path that accept plug-in components to set levels and frequency selective conditioning properly for any network design. When installing amplifiers, technicians choose these attenuation and conditioning values for each amplifier depending on where it is in the design, with measurements taken at the location to guide them. A “tackle box” of plug-in components accompanies the line technicians to support this alignment.

The 1st Generation FDX Amplifier eliminates most of these plug-in components [4][6]. However, some plug-ins remain, as shown in **Figure 5** [4]. In particular, it was recognized immediately that the top priority of a self-aligning amplifier is to get the embedded cable modem transponder online.

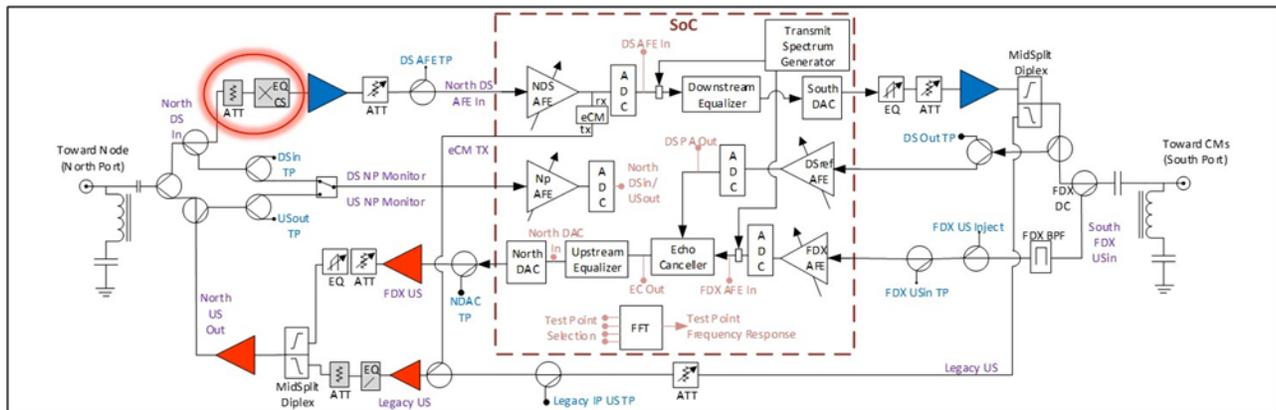


Figure 5 – First Generation FDX Smart Amp Platform Eliminates Most (but not all) Plug-In Components

To de-risk the activation operation before there was an opportunity to exercise the embedded CM during the design phase or characterize the SoC’s internal digital conditioning, the input front section of the amplifier was left with its native plug-in options available as shown in Figure 5 (red circle), at least until the transponder function and RF dynamic range were able to be characterized. Also, a line technician’s first step today is to set these plug-in values at the input to drive the first stage amplifier at a recommended level and with a flat spectrum. The operation is nearly identical for the FDX Amp, except that the recommended level is different due to the drive level of the analog-to-digital converter (A/D) is not the same as the first amp stage of a typical non-FDX amplifier.

At this point, having brought online tens of thousands of FDX amplifiers, and having characterized the embedded CM and the RF dynamic range, it is clear that these physical components can be effectively exchanged for a combination of digitally controlled components supported by SoC firmware control, augmented by digital conditioning within the SoC itself. This enables a 2nd generation design to be further simplified, with the ultimate objective being for a technician’s role to be to physically install and connect the amplifier, after which it will come up and self-align the downstream and the FDX Upstream without technician involvement. The benefits that accrue with these design updates are faster installation and activation time, and elimination of human error in the selection of component values. **Figure 6** shows this updated front end design.

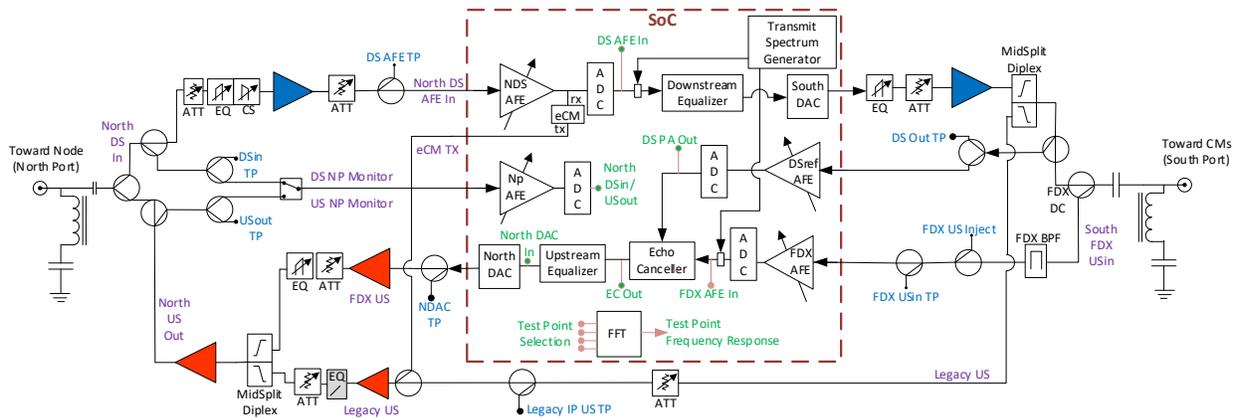


Figure 6 – Eliminating Front End Plug-in Components for Increased Activation Automation in a Second-Generation Design

6.3. Unified DOCSIS 4.0

Earlier this year, the DOCSIS 4.0 standard was updated to incorporate changes to support Unified DOCSIS 4.0. Harkening back to the earliest days of the DOCSIS 4.0 standard and its emergence as the 10G industry initiative, the creation of two DOCSIS 4.0 options for operators was identified as a weakness that could slow industry adoption. At that time, however, numerous papers and talks were given noting how the two DOCSIS 4.0 technologies – DOCSIS 4.0 FDX and DOCSIS 4.0 FDD – were in fact complementary technically [1][3][5]. Figures such as shown in **Figure 7** were used to illustrate this point.

It was hard in those early days of the 10G era (circa 2019) to look ahead to the convergence into a single silicon solution with both DOCSIS 4.0 options. But this is in fact what is now available for operators to leverage as DOCSIS 4.0 solutions with the ultimate in flexibility. Unified capable silicon is available today for the RPDs, CMs, and the Amplifiers. Given that most operators have taken limited steps, if any, towards deploying DOCSIS 4.0, this development turns out to be very timely.

Today, Comcast is deploying Digital Nodes, FDX Smart Amps, and DOCSIS 4.0 CPE, all with unified silicon. While the current focus of production scale-up is 1.2 GHz FDX outside plant (OSP) platforms, upgrading these platforms to be fully unified solutions will enable the downstream to be expanded to 1.8 GHz at some future date if this direction is taken. This direction, of course, then entails a commitment to the replacement of millions of passives deployed. But the optionality is there with the deployment of unified silicon.

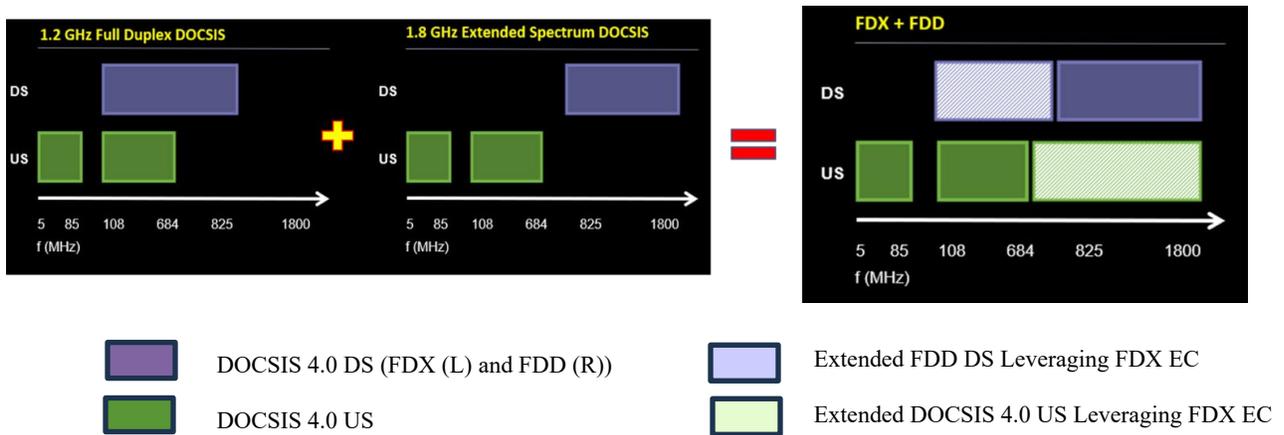


Figure 7 – Unified DOCSIS 4.0 Supports Both FDX and FDD and Other Complementary Variants

Maximally Flexible and Efficient FDD via Flex Band

A new feature of the unified architecture is a DSP-based FDD architecture, referred to as Flex Band (FB) and developed by Broadcom, whereby physical diplex filter selection options in nodes and amps are instead implemented digitally, as shown in **Figure 8** below. Digital filters are of course a very mature technology, and a DSP-based approach to implementing FDD increases the flexibility of operators to adjust the spectrum split between upstream and downstream as needed, without ever needing to visit each platform to change components as capacity and service requirements change. In practice, as a remote configuration change versus a HW swap, more spectrum options become available. Additional flexibility comes with DSP in that a physical filter will draw a line between US (lower) and DS (higher). A DSP-based filter does not necessarily have to follow those rules when it selects whether a Flex Band (FB) should be a DS or an US band, as shown in Figure 8.

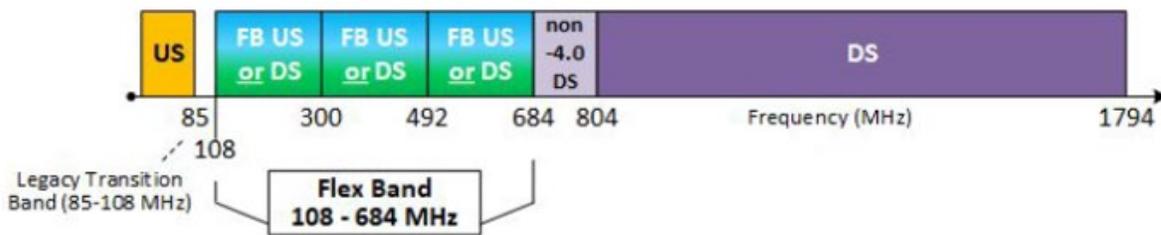


Figure 8 – Unified DOCSIS 4.0 Supports “Flex-Band” – a DSP-Based Implementation of FDD (figure courtesy of Broadcom)

Essentially, Flex Band (FB) can be considered a version of FDX with a single transmission group using a static Resource Block Assignment (RBA) setting.

An additional unique option of the unified solution (not shown in Figure 8) is the extension of Figure 8 to include the FB functionality on top of a foundation of High Split instead of Mid Split. This extends the

components for a new DS/US frequency split plan. This SoC feature adds approximately 400 Mbps of DS capacity in the prime 108-684 MHz band.

In addition to the increased spectral efficiency of a DSP-based split in the SoC compared HW-based FDD systems, the RF circuits surrounding the SoC include SW controls for gain, positive tilt, and cable simulator functions throughout the RF chains, items that are commonly implemented by plug-in components in standard HFC amplifiers. This adds yet another layer of efficiency, in this case operational efficiency, by eliminating the need to return to the amplifier in person if further balance or alignment adjustments are needed. It also enables fully automated balancing and alignment, eliminating the need for manual measurements and calculations, followed by error-prone component changes and adjustment settings to achieve the desired transmit and receive power profiles. As shall be described, the technician simply interacts with the amplifier via an iOS application for its DS transmit and US receive power profiles, and the FDX Smart Amp automatically makes all the necessary measurements and adjustments that are required to produce the desired power profiles.

7.1. A Closer Look at the SoC DSP

Within the SoC, both the DS and US signals are terminated into a high-speed, high-precision Analog-to-Digital Converter (ADC). The ADC is high-speed to sample the complete DS spectrum (up to 1.8 GHz). The complete DS spectrum is placed within the 1st Nyquist band of the ADC. This is often referred to as baseband mode or full-band capture. The ADC maintains a very high SNR, capable of supporting up to 16,384 QAM modulation. Before the ADC samples the signal, there is an Analog Front End (AFE), which consists of a variable-gain Low Noise Amplifier (LNA) that sets the RF level into the ADC to prevent clipping or saturation of the ADC and loads the signal into the ADC for maximum available fidelity.

At the South Port, post-ADC, the SoC includes the critical Echo Canceller (EC) function. The SoC US Rx in the FDX band captures a digital representation of the desired US, as well as undesired interference created by DS in the form of a composite of all echoes created by the cable plant. Every device (node, tap, splitter, amplifier, power inserter) in the cable plant will create an echo, or signal reflection. Each of the echoes is a version of the same DS RF waveform, but shifted in amplitude, phase, and time. The result of the echoes is an undesired composite signal, which is interference or noise on the desired US. However, since these echoes are correlated with the DS signal that is generated in the amplifier, this interference can be largely eliminated or “cancelled” by the amplifier via Digital Signal Processing (DSP) techniques. This results in a high-fidelity post-EC US receive signal suitable for supporting bandwidth efficient QAM modulations despite the “overlapping” DS and US transmissions in this common bandwidth as was shown in Figure 3.

Once sampled, the DS and US processing described above occurs in the digital domain within the SoC. Note, however, that the legacy US band of 5-85 MHz does not pass through the SoC, as shown in Figure 9. Of course, what amplifiers transmit onto the coaxial cable are RF signals, not digital, in both the DS and US directions. The digitized and processed RF signals are then used to regenerate the DS and FDX US signals, reversing the sampling capture by feeding these filtered, digitized samples to high-speed/high-precision Digital-to-Analog Converters (DAC) in the SoC. Digital correction is provided to the incoming DS signals, as well as the outgoing DS (South Port) and US (North Port) signals. These various digital domain corrections, along with the external SoC RF circuits, which provide additional balancing and conditioning, allow the FDX Smart Amplifier to accurately transmit and maintain the desired DS and US output spectrum and RF profiles (output level vs frequency). This results in consistent receive levels at the desired design levels to the active devices directly connected on either side of the amplifier.

Another performance and efficiency opportunity enabled by FDX Smart Amp resources is the introduction of temperature compensation using a digital Bode function. Traditional Bode circuits require hands on manual alignment by a technician using external equipment and measurements. It is subject to initial setup issues, which can result in limited temperature compensation effectiveness. A digital temperature compensation method has several advantages:

- 1) It is fully SW controlled
- 2) There are no measurements or adjustments performed by the technician, so fewer error opportunities
- 3) If the span loss substantially changes, the digital temperature compensation function can be automatically recentered remotely, without technician hands-on interaction. Truck rolls are not needed to re-center a Bode circuit subject to post-installation construction.

One extremely powerful benefit of having these signals processed in the digital domain is that detailed signal analysis can be completed at each amplifier in the network, capturing configuration and diagnostic information about every span in the network! Example tools/analyses/functions include:

- Wide Band Fast Fourier Transform (WBFFT) engine
- EC streaming telemetry metrics
- Telemetry for automated Network Topology Discovery
- Time Domain Reflectometer “TDR” analysis
- RF wideband power monitoring
- Temperature Monitoring
- Digital BODE function
- Anomaly and plant ingress detection
- Noise identification and filtering

These and other opportunities exist within each FDX Smart Amp – without the need to connect external test equipment or subsequent technician truck rolls to support onsite measurements, plug-in value changes, maintenance of amplifier balancing, etc.. By converting the signal into the digital domain, the amplifier now has a rich set of telemetry to draw from. This will be discussed in greater detail later in this paper. The SoC communicates in real time through the embedded CM transponder, providing the FDX Smart Amp with command, control, configuration, and telemetry interfaces to back-office entities.

8. FDX Smart Amp Installation and Activation

The FDX Smart Amp introduces a completely new approach to the concept of “Amp Activation.” Everything described in the upcoming paragraphs is accomplished within the FDX Smart Amp under software-control. Even basic RF output configuration is set via software-control, as are traditional amplifier balancing functions. As the Amp Connect App (ACA) was developed, various functional controls had to be available to the technician.

There are two differences to the fundamental approach when setting up the FDX Smart Amp compared to a traditional amplifier:

- 1) The FDX Smart Amp is based on the input setpoint requirement of the SoC, with output RF profile independently set, rather than station gain. This simplifies the role of the tech for amplifier balancing through the automation that becomes enabled.

- 2) Based on the above the function of the Automatic Drive Unit (ADU) becomes maintain steady SoC input and no longer has responsibility for maintaining a constant output – the independently set RF profile is there to perfect this output and with self-measurement, keep it maintained.

For the SoC to regenerate the signal with high fidelity, it needs the proper TCP at its input from the North Port, and a well-balanced RF chain implementation driving an appropriate output level vs frequency profile for the design feeding the South Port. All necessary FDX Smart Amp configuration objects and telemetry described in the subsequent paragraphs are available on this first-generation platform today to set up the FDX Smart Amps. Additional configuration objects and automation are already under development for the next generation platform, simplifying activation further. For example, as discussed in the roadmap section, today's initial step towards RF balancing requires physical intervention in the form of North Port DS forward (FWD) pad and equalizer (EQ) adjustments, as well as the legacy 5-85 MHz US attenuation. A key new functionality of 2nd generation platforms mentioned will be to eliminate these plug-ins and the traditional balancing exercise it entails in favor of SW-controlled devices. Today, only after the initial physical step to balance the RF signal to the SoC AFE is completed is software able to take over via the ACA to complete the activation.

Lastly, note that the process of upgrading and activating the network for FDX operation, in fact, always begins with installing the FDX Smart Amp into a legacy Sub split or Mid-Split network. Then, after all amplifiers are installed and activated, enabling FDX capability can occur – whether that be minutes, hours, days, weeks, or even months later. Importantly, the task of the on-site technician installing the FDX Smart Amp through the ACA is limited to standalone amplifier, legacy operation activation only. Subsequent activation of FDX mode itself, FDX US alignment, and network cascade alignment, are all fully automated with no technician intervention required.

8.1. FDX Smart Amp iOS Application

Refer to **Figure 9** for elements described in this section relative to their positioning within the FDX Smart Amp architecture.

Figure 10 shows several of the basic screens of the ACA, highlighting the initial scan and connection functionality. As previously mentioned, scanning initializes the connections to back-office entities via the amplifier's embedded transponder.

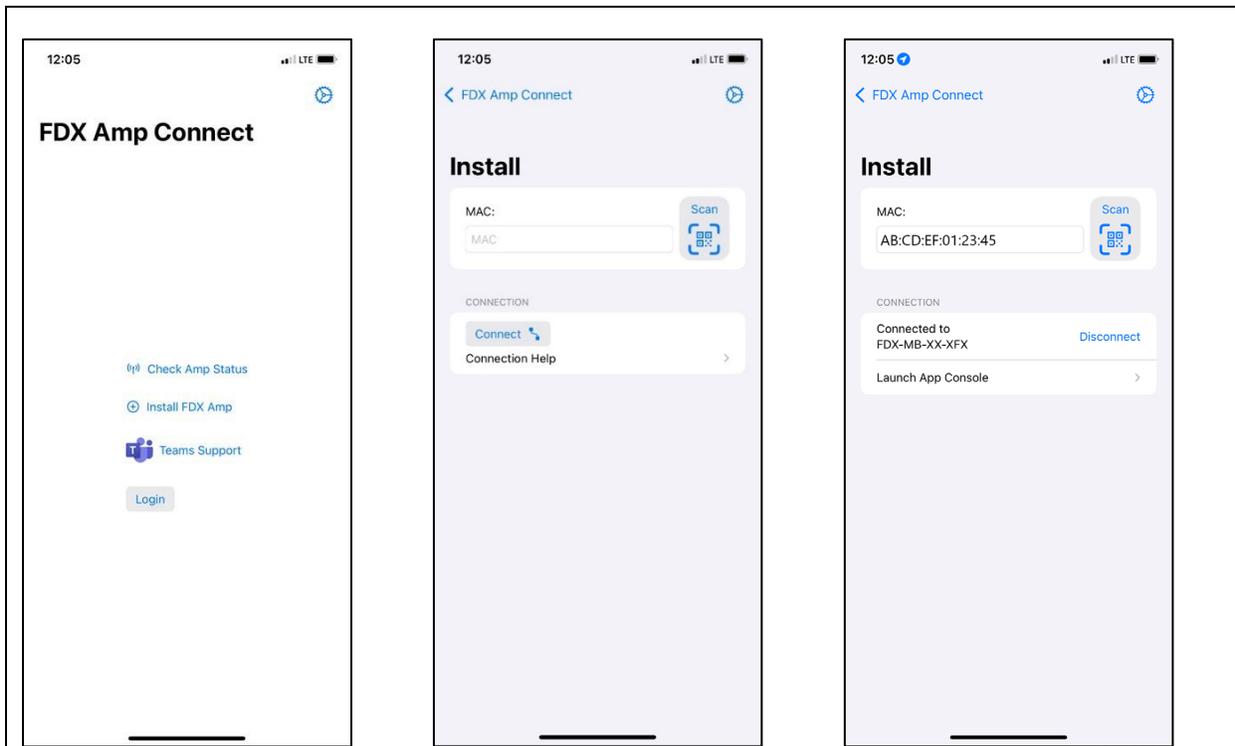


Figure 10 – Amp Connect Application (ACA) Screenshots

One of the new functionalities possible with the FDX Smart Amp noted previously is Network Topology Discovery (TD), which will be described later in detail. Note here that Registration of the FDX Smart Amp to the back-office is essential for TD, and TD is the foundation for many additional capabilities associated with network and FDX alignment, as well as operational diagnosis and localization.

As the first step of the ACA-driven activation process, the technician installs the FDX amplifier to be Registered, as shown in **Figure 11**, adding the device to our database. Back-office automation allows various tools to obtain and display the amplifier names intended for the installations. Geo-tagging the amplifiers during installation improves the location validation.

Topology Discovery is MAC domain-based; the amplifier registration process adds the flexibility of name association to MAC address for field personnel to easily find any given amplifier later if necessary.

Lastly, the ACA can be connected to the amplifier directly through an Ethernet dongle carried by technicians, should an issue arise that compromises DOCSIS connectivity.

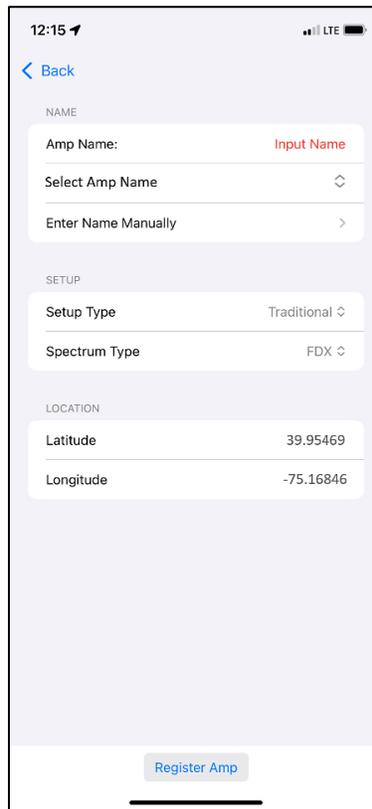


Figure 11 – Amp Connect App Registration Screen

The next step of the activation process is to provide the FDX Smart Amp’s RF profile to be transmitted from the South Port as the DS output. This is a simple interaction from the technician, selecting or setting the design output levels for their active device. In legacy amplifiers, these levels were achieved by changing the input and output attenuation based on the amplifier's station gain. **Figure 12** illustrates this simple interface for setting the power and frequency of the lower and upper bands of the spectrum. The selectable low and high channels allow the amplifiers to be installed in various deployments and, of course, are not limited to FDX systems.

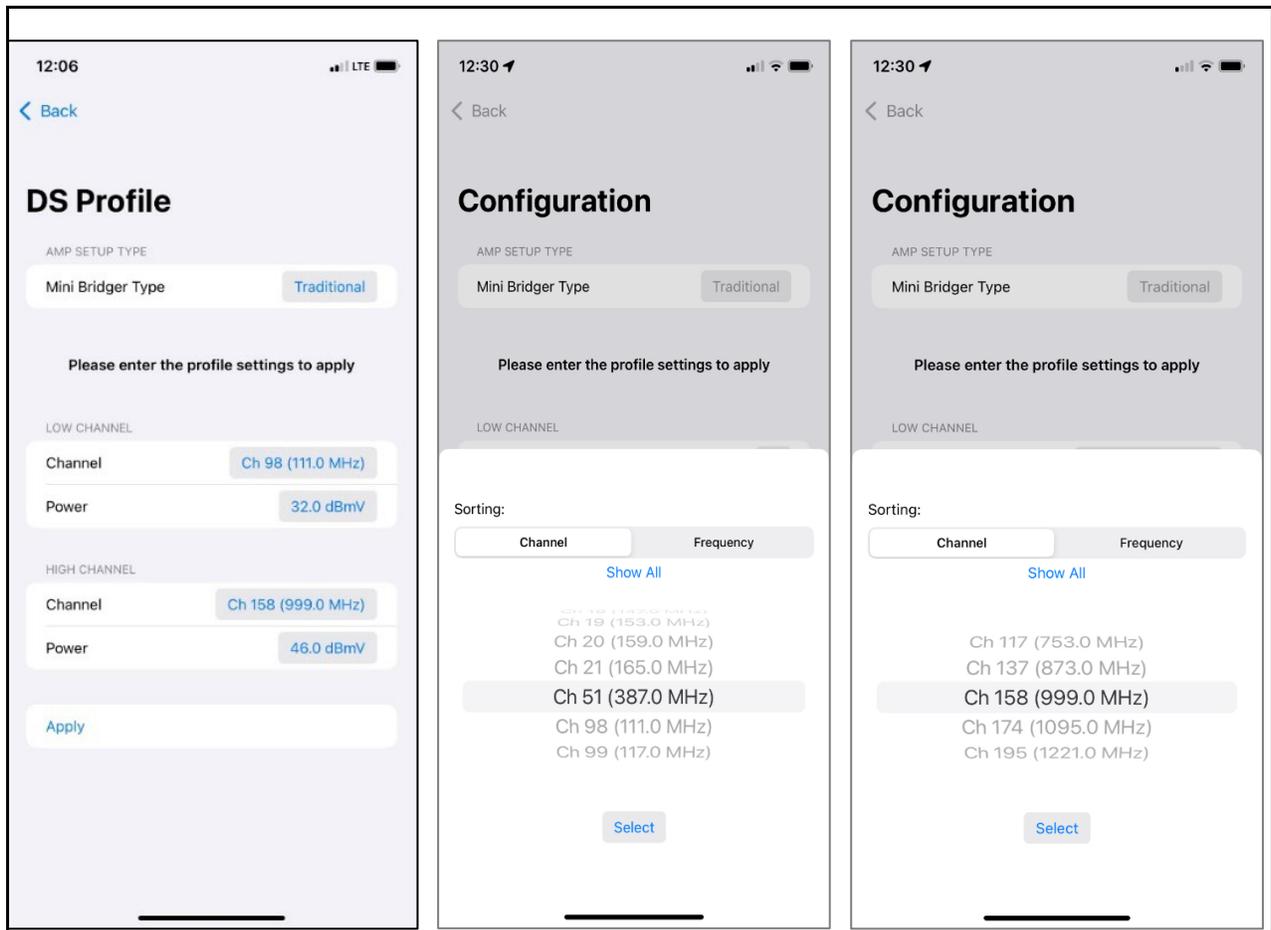


Figure 12 – Amp Connect App Output Profile Selection Screens

Another significant change with the FDX Smart Amplifiers is that there are just two HW platform types: a line extender (LE) and a bridger. While that might seem to be a design limiting constraint, the SW controls of the RF chain leading to the South Ports and the DS output TCP capability of the HW platform allows it to emulate various module configurations found in traditional amplifiers. This applies in particular to the Balanced and Unbalanced Triple output amplifier. **Figure 13** illustrates the field selectable options of these “virtualized” module types. The ACA sends the appropriate commands to the FDX Smart Amp to adjust various attenuation settings to achieve the desired profile and module type at each South Port.

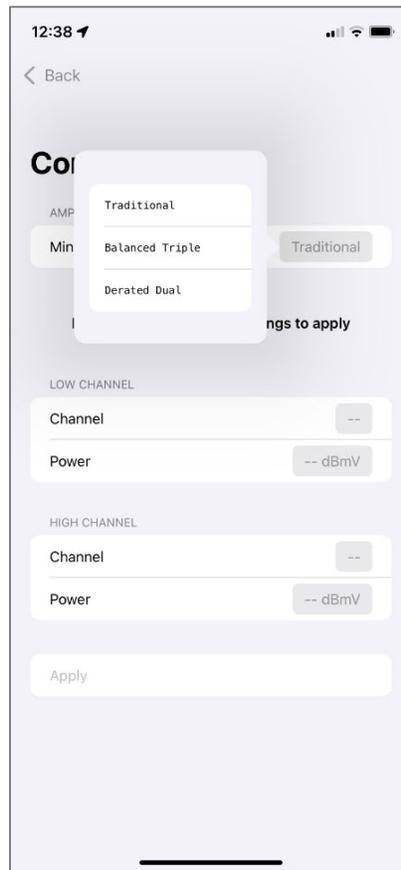


Figure 13 – Amp Connect App Module Configuration Selection Screen

8.2. Overview of FDX Smart Amp Automated Calibration

With the South Port output profile set, the next step is for the amplifier to make various measurements and adjustments, conditioning and shaping the gain and tilt of the spectrum, as part of the automated calibration process. Self-correction is also part of this process, and calibration ultimately leads to the proper regenerated high-fidelity signal at the proper level and tilt expected at the SoC’s DAC output.

An illustrative example of the power of the automated calibration process is shown in **Figure 14**. This figure demonstrates the correction of a frequency response issue from the North Port segment, reproducing a highly remediated signal passed to the next segment of the network from the amplifier South Port output. As shown, the internal DSP and regeneration capability substantially improve MER, correcting most of the previous reduction from the North Port segment’s impairment, and reducing the blast radius of customers exposed to the more sizeable impairment, resulting in a net improvement to aggregate customer experience. In common examples such as suck-outs, customer modems behind the impairment can fall into partial services mode of operation due to bonding challenges. This will compromise some customer speed tiers, leading to potential trouble calls. The Profile Management Application may serve to reduce the exposure of modems in partial, but in doing so will derate QAM profiles and reduce network capacity – a similar phenomenon but generally a less impactful loss of throughput.

Lastly, note that the telemetry available from the FDX Smart Amp can notify and alert on this discovered impairment at the speed of the operating telemetry ecosystem, which is a design choice once information is available to be streamed. This can ensure that even while remediating around as best that the DSP algorithms can, awareness is created where physical remediation is necessary. The “level” of awareness can be driven by data-driven thresholds set against these telemetry metrics, which can be based on impact to the customer experience and/or scale of impacted customers, for example. Such notifications are automatically routed to the operations center responsible for maintaining the network, along with the metadata necessary for the repair – diagnosis by signature analysis, node name, amp name, location of amp, location of impairment in the segment if that can be determined, etc. This maximizes efficiency of the repair and minimizes mean-time to repair (MTTR) by sending the right technician with the right tools to the right location – better for customers and better for operational resource management and costs.



Figure 14 – FDX Smart Amp DSP and Regeneration Enables Network Self-Correction

The FDX Smart Amp calibration process creates a new amplifier default configuration. This configuration is stored in non-volatile memory, which is essential so that the amplifier can auto-recover configuration state from any power interruption or system reboot.

8.3. FDX Smart Amp Calibration Mechanics

The calibration process has several steps. The steps configure many settings, including the North Port Downstream Equalizer, the South Port Output Attenuation, FDX Upstream DAC transmit levels, North AFE LNA gain, and other coefficients. The analyses performed by the SoC has the added benefit of providing a feedback loop to the technician with respect to the accuracy of the signal at the SoC’s AFE during the calibration process. This feedback eliminates guesswork and accounts for signal meter accuracy by providing real-time data. **Figure 15** illustrates the calibration along with the feedback process.

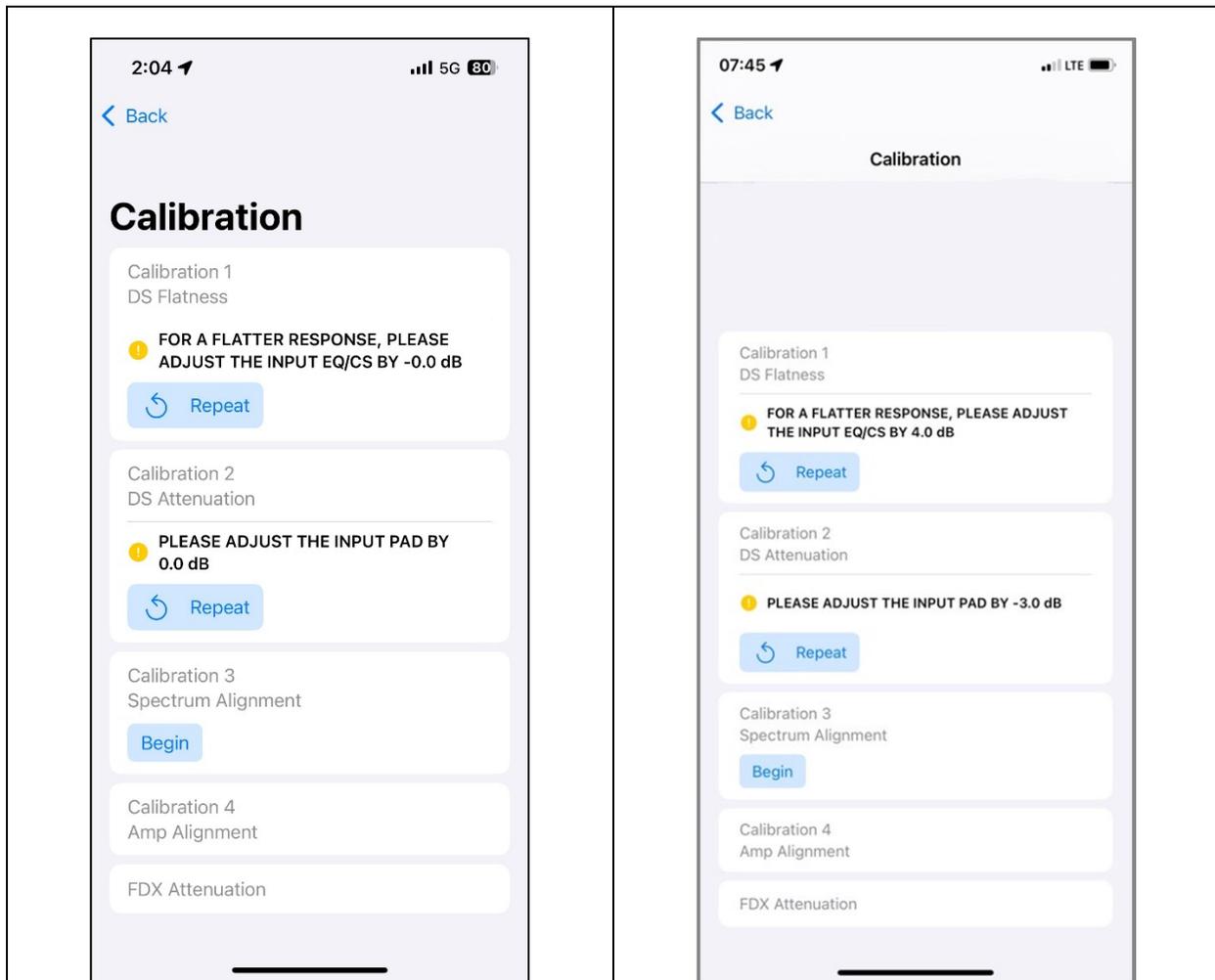


Figure 15 – Calibration Step Examples with Tech Feedback

During the current calibration process, the first two steps provide feedback indicating whether adjustments are needed for a flatter response or TCP at the SoC to operate with the best performance. In the above examples, there are different levels of technician accuracy during these initial balancing steps.

Upon completion of these calibration steps, the amplifier now outputs the desired profile, allowing for optional self-checks to confirm a valid calibration and allowing the technician to move on and calibrate the next amplifier in line.

9. Telemetry

In previous sections, anecdotal examples have been provided of the value of this telemetry, such as for self-correction, operations integration, and Topology Discovery. Indeed, the FDX Smart Amplifier has a suite of rich telemetry that provides the ability to automatically perform comprehensive network and amplifier health checks during and after deployment. The sources of the amplifier telemetry and the various key metrics are shown in **Figure 16**. This telemetry provides a means of aiding the technician in activating and aligning the amplifier simply and reliably. It is also the foundation for identification of service impacting network issues and the geolocation of these issues, including data to be made available

to a centralized AI/ML engine for diagnosis and subsequent alerting and alarming as necessary, or the AI/ML engine embedded on the SoC for local analysis. This ability to immediately identify and locate service impacting network issues in an automated way is one of the major benefits of FDX Smart Amplifier deployment. It enables efficient use of valuable technician time, allowing them to focus on mitigating actual plant issues, rather than spending large amounts of time trying to locate the network faults themselves. As the amplifiers get deployed at scale and the optimal mix of centralized versus distributed AI/ML becomes clearer, models can be independently updated on the amplifier to expand its capabilities. Most effective and efficient use of capabilities will be learned as these new capabilities are exercised and outcomes observed.

Examples of network segment telemetry of various common phenomenon are shown in **Figures 17-21**.

Figure 17 shows several connected network segments which have consistent narrowband ingress interference. **Figure 18** shows a single network segment which has transient impulsive noise interference. **Figure 19** shows a network segment which has a broadband rise in the noise floor. In this example, the cause for the broadband noise floor can be discovered by observing the time domain reflectometry (TDR) telemetry view.

In **Figure 20**, it is illustrated how the FDX Smart Amp geolocates faults to a much greater degree, saving valuable resources and time, which now can be used fixing the fault. Lastly, in **Figure 21**, it is illustrated how the telemetry detects narrowband ingress, and subsequently how the FDX Smart Amp contains the effect of that interference to the network segment where that noise source is located. This demonstrates how the telemetry is being used to enhance the overall network fidelity and reliability.

These examples illustrate the power of FDX Smart Amp telemetry being used to identify network issues, localized to every network segment. Such issues can be identified either locally on the Amp using the embedded SoC AI engine in a distributed AI/Edge Compute environment, or remotely by sending the telemetry to back end centralized AI agents. Most likely, a combination of centralized and distributed capabilities will be used, delivering an unprecedented granularity of network visibility and leading to operational efficiencies, higher reliability, and better overall customer experience.

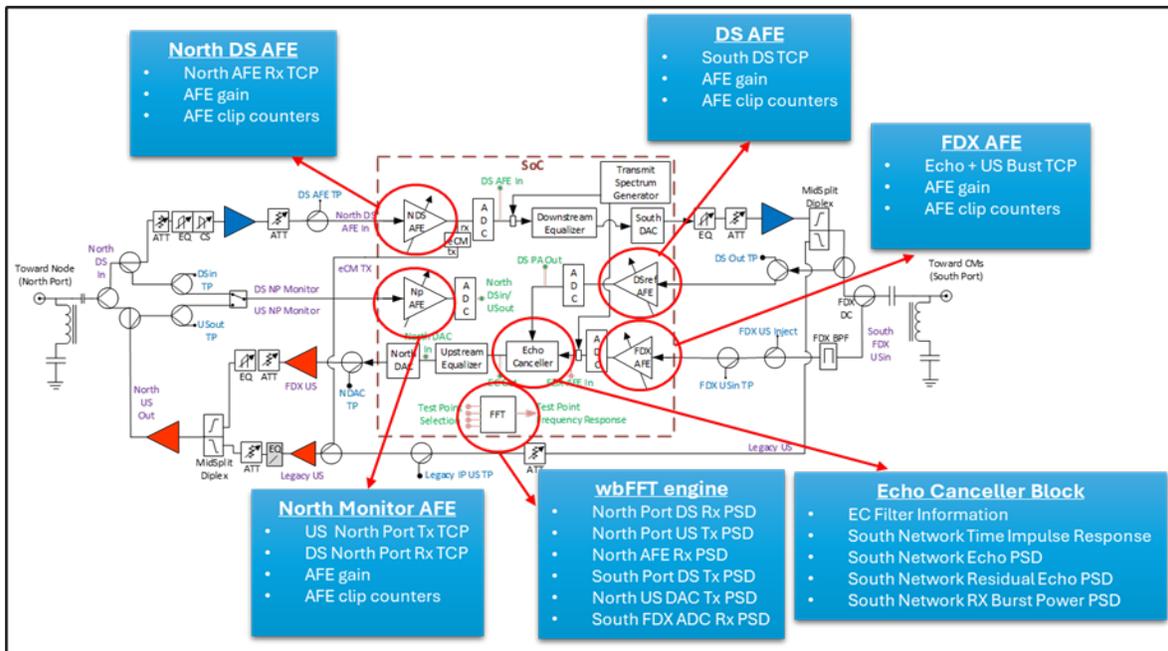


Figure 16 – FDX Smart Amp Telemetry Sources and Available Metrics

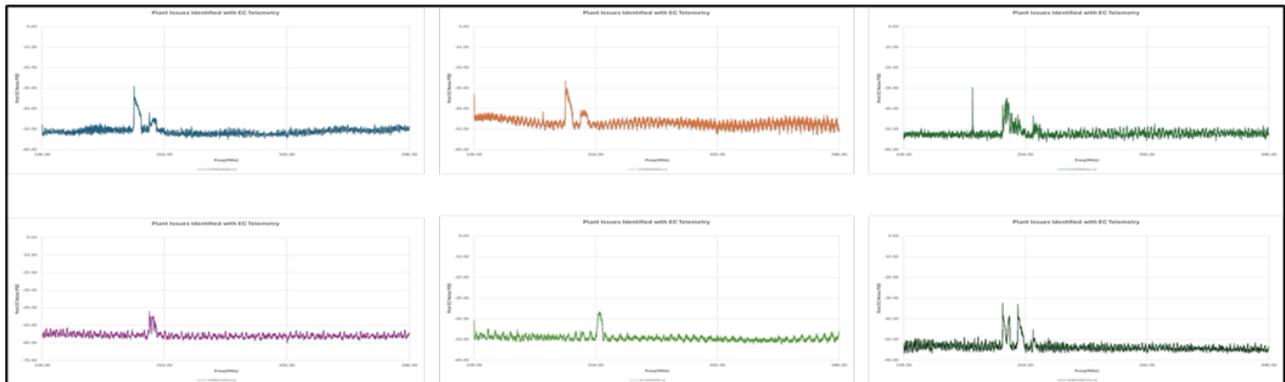


Figure 17 – Network Segments Identified with Consistent Narrowband Ingress

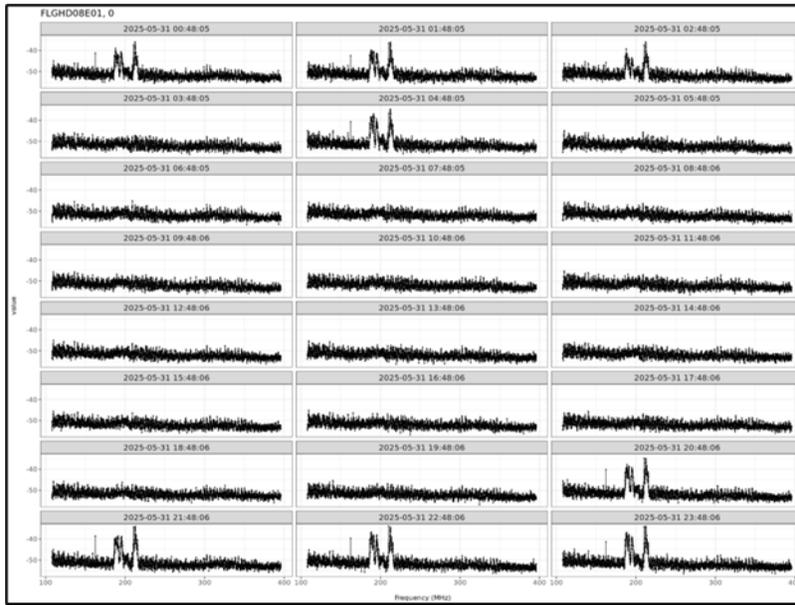


Figure 18 – Network Segments Identified with Transient Narrowband Ingress

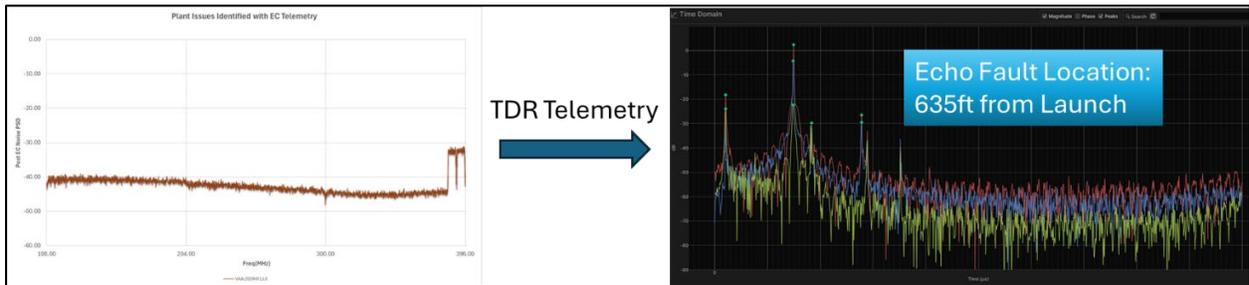


Figure 19 – Network Segment Showing Broadband Noise and TDR Analysis



Figure 20 – FDX Smart Amp Telemetry Enables Operations to Zero in on the Location of Network Faults

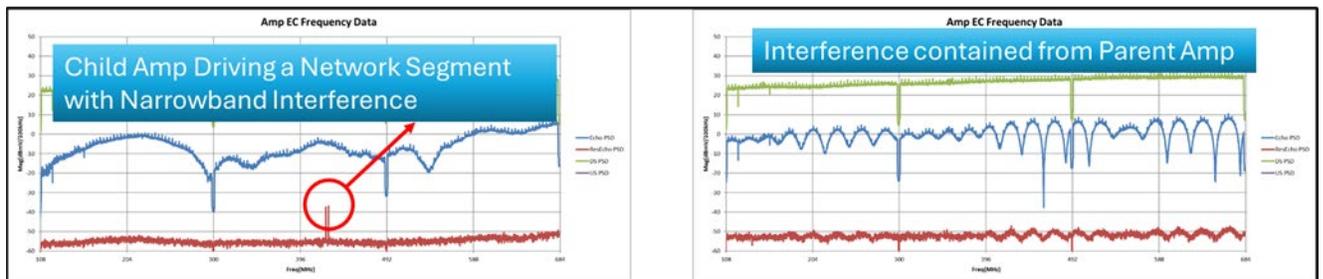


Figure 21 – FDX Smart Amp Telemetry Containing Narrowband Interference

10. Network Topology Discovery

The foundational feature of Network Topology Discovery, including its role in enabling system alignment optimization, and localization of identified plant issues, has been touched on several times in this paper. This section will describe the Topology Discovery output itself.

Discovering the topology relationship among FDX Smart Amps as well as to the subscriber devices enables the analysis and optimizations of amplifier interconnections and modem sub-populations. By sorting the modems into sub-populations, grouped by their connection to a parent amplifier, analysis can be performed and pattern recognition algorithms deployed on these individual modem sub-groups. This allows for a system wide alignment optimization of each individual network segment making up the tree and branch RF network, and it can also be used to augment the telemetry data from the amplifiers.

The method for determining the device interconnection of the amplifier tree and branch network of each node segment has been previously described [4]. This method has been implemented and successfully

deployed, becoming the first time that plant network components themselves were able to directly and deterministically capture their own logical topology on a live cable system. The approach has been validated on large networks of over 40 amplifiers, including accurate identification of each parent amplifier and its directly connected modem sub-populations.

Figure 22 shows a visualization of the actual topology discovery results of amplifiers and modems taken on a live cable network.

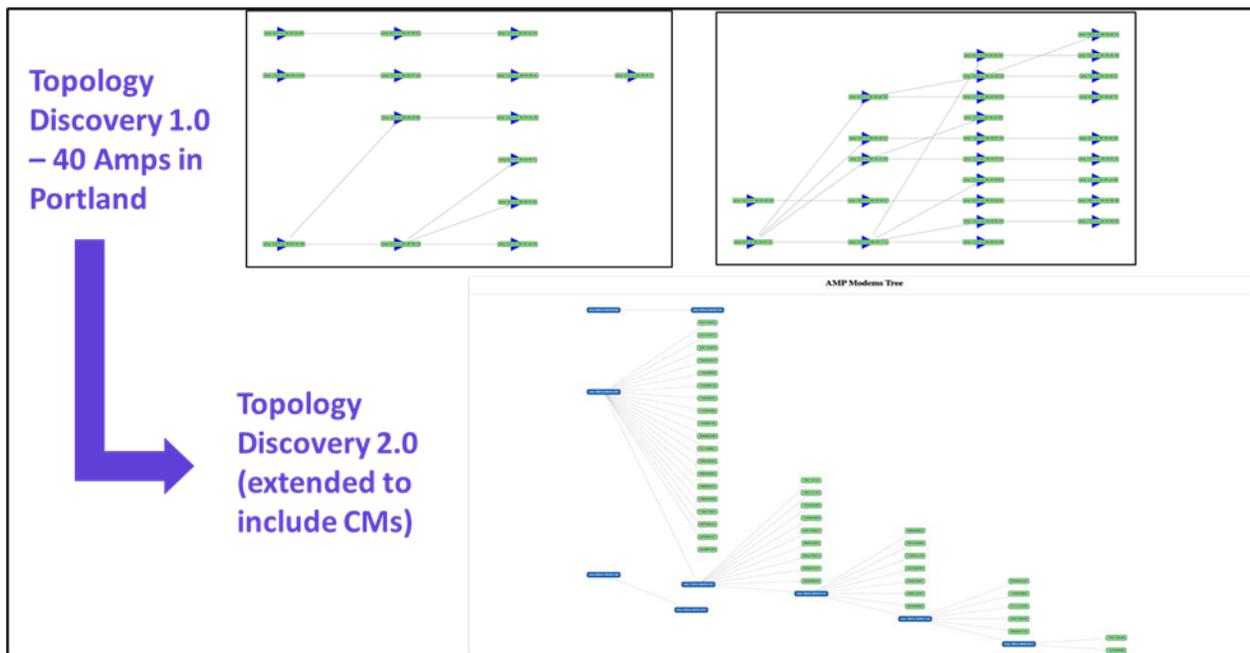


Figure 22 – Topology Discovery Result on a Cable Network with FDX Smart Amplifiers Showing both Amp-to-Amp and Amp-to-CM Relationships

11. Amplifier Cascade Alignment

There are multiple layers of amplifier alignment – single amplifier standalone alignment, alignment of the new FDX upstream band, and alignment optimization of the end-to-end cascade. Each of these are described below.

11.1. Individual FDX Smart Amp Alignment

System Alignment begins with the individual activation of the FDX Smart Amps in the cascade, which was previously described in the Amp Connect Application section. This section will describe what is going on in the amplifier during that process, how this individual alignment process can be extended to align the entire cascade, how it extends to FDX US operation, and how traditional temperature compensation circuits can be more effectively implemented with this technology.

Refer to **Figure 23** for the telemetry measurements and controls that are used for individual alignment.

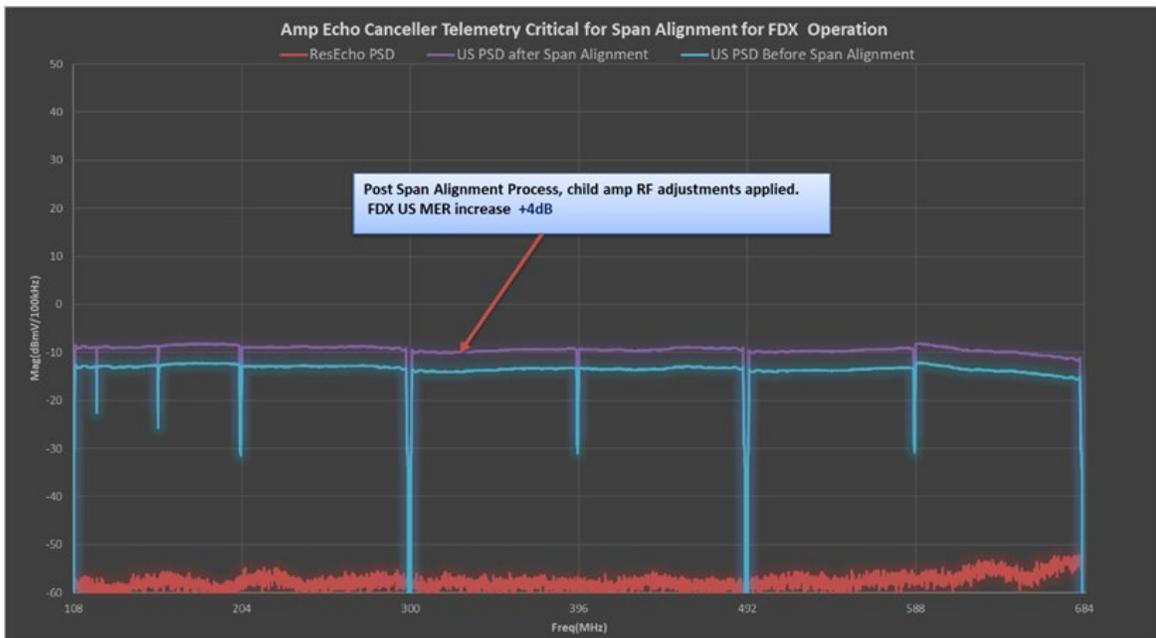


Figure 25 – US SNR Measurement Before (blue) and After (purple) Cascade Alignment Optimization – Showing a 4 dB Improved MER

The 2nd phase is aimed at fine tuning the alignment by considering the performance of subscriber devices connected to the FDX Smart Amps. With Topology Discovery completed, amplifier-to-amplifier relationships are known, as are the specific modems fed directly by each amplifier. This provides the capability to look at each modem subset group metrics, such as US transmit power and DS receive power, as well as the MER for the subset. These metrics can be used as the basis to modify the transmit and receive profiles of the parent amplifier to achieve the best fidelity (or other generalized “optimization” criteria) for the group of modems fed by that network segment. Of course, once a parent amplifier profile is adjusted, then all child amplifiers must be re-aligned to ensure that all amplifiers are aligned to the maximum fidelity (or alternative optimized criteria) following a parent amplifier adjustment. The digitized nature of adjusting configurable parameters of individual FDX Smart Amps, as was observed in the calibration process, allows these changes to be made in an automated and precise way. The result is an optimization of individual network segments and complete cascade in a way that has never been possible in a cable system. Furthermore, this can be exercised as a maintenance routine, either as a periodic re-calibration, or triggered by observing telemetry that exceeds a pre-determined threshold of acceptable drift.

12. Edge Artificial Intelligence (AI) and Deep Learning Applications

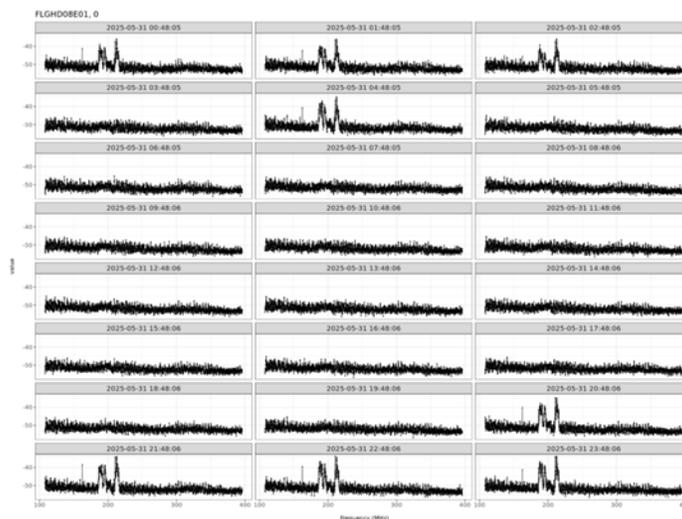
Many recent customer experience studies point to the fact that among the most important service attribute to the customer, if not the most, is reliability – just always be on, operating seamlessly, and at the paid-for service level. However, traditional centralized monitoring systems, while effective for steady-state analysis and static impairment detection, struggle with transient phenomena, which are common and become more so as wireless services densify and increase their spectrum usage. Even with massive amounts of data polled from every network element periodically, transient phenomenon can be extremely challenging due to clear visibility into the true root-cause of every event. This section explores how distributing AI capabilities throughout the network infrastructure, from amplifiers to nodes and CPE devices, can fundamentally transform the reliability of cable networks.

12.1. Temporal Sampling Limitations in Centralized Systems

Traditional centralized monitoring systems face a fundamental challenge: the inability to capture transient network events due to polling intervals. LTE and other over the air ingress signals present some of the most challenging impairments in modern cable networks, characterized by brief, high-intensity bursts that can severely degrade service quality.

Consider a typical LTE ingress event with a 50ms burst duration as an example of a common occurrence when mobile devices transmit near cable infrastructure that is not sufficiently hardened. In traditional centralized monitoring systems with 5-minute polling intervals, assuming that the operator polls every device in that segment every 5 minutes (which is a challenge on its own), the probability of detecting such an event is vanishingly small. With a 300-second polling cycle and assuming a 100ms sampling window per poll, the probability of capturing any portion of a 50ms burst is approximately 0.017% ($50\text{ms} / 300,000\text{ms}$). This means centralized systems on average will miss 99.983% of LTE ingress events, leaving operators blind to a primary source of customer-impacting interference. Even if the polling interval were reduced to one minute – a change that would increase backhaul traffic fivefold—the detection probability only improves to 0.083%, still missing over 99.9% of events.

Figure 17 (repeated below) is an example of real ingress captures from an FDX node, showing the stochastic nature of these signals and why they are so difficult to pinpoint with high accuracy using traditional, centralized models with periodic polls:



(Repeat of Figure 17)

Edge AI fundamentally transforms this by enabling continuous, intelligent monitoring at the point of impairment. When algorithms running on amplifiers or nodes detect spectral signatures indicative of potential LTE interference, they can dynamically adjust sampling rates to capture transient events. For instance, upon detecting elevated noise floor characteristics typical of LTE, the edge AI can increase polling to every 10-15 ms during high-risk periods. This adaptive approach yields a detection probability of effectively 100% for 50ms bursts, since $50\text{ms} > 7\text{ms}$ guarantees multiple samples during the event. Note that in this high-level example the stochastic nature of the LTE signal's duty cycle has not been considered.

This represents not just an incremental improvement, but a paradigm shift from reactive network management to proactive interference prevention, while simultaneously reducing unnecessary data transmission during quiet periods when aggressive monitoring isn't required. The reduction in the amount of data that is needed to detect transient noise on the edge in comparison to centralized models is another key benefit and will be explored further as these capabilities are developed and pushed into the field.

12.2. From the Field to Real Lab Training

The deployment of AI at the network edge enables a fundamental shift from rule-based detection to learned pattern recognition using actual spectral data. By training deep learning models directly on labeled WBFFT captures from the field, highly customized classifiers can be developed that distinguish between LTE ingress, power line interference, and any other impairment sources with great accuracy. The customization extends beyond simple classification; edge AI models can be trained to predict duration, and even likely root causes based on temporal patterns observed in historical data. For example, a model trained on captures from a specific neighborhood might learn that certain spectral patterns appearing at 6 PM correlate with increased LTE traffic from commuters, enabling preemptive mitigation.

Tapping Into Full-Duplex Superpowers

Full duplex amplifiers represent an advancement for edge-based ingress detection by eliminating the fundamental limitation of traditional frequency division duplex (FDD) systems. This is the ability to have full visibility into the underlying noise and location of a signal in the FDX band, due to the presence of an echo-canceller.

In conventional FDD amplifiers, accurate ingress detection is made very difficult due to noise funneling. Full duplex amplifiers are equipped with echo cancellers, each of which elegantly provides continuous access to the post-echo-cancellation noise floor. The echo canceller removes the amplifier's own transmitted downstream signal plus reflected copies from the received upstream path, revealing a clean view of the actual RF environment including any ingress signals at the post-EC sample point. This was observed in Figure 17, providing an exciting opportunity for edge AI algorithms to be hyper-customized based on the signal captured. This post-EC noise floor represents the true interference landscape without contamination from upstream or downstream traffic, enabling AI algorithms to perform continuous spectral analysis and pattern recognition. The importance of this cannot be emphasized enough for achieving incredibly high efficacy AI models.

When combined with the power of Topology Discovery, the combined intelligence transforms ingress troubleshooting from a manual, time-intensive process to an efficient, automated operation as observed in Figure 20. Beyond just narrowing down the guilty coaxial span allowing ingress onto the plant, the AI can correlate the interference signature with specific customer devices, identifying not just that interference exists and on which span, but also potentially if a home is the likely source as more and more AI-enabled CPE get into the field.

The combination of continuous post-EC monitoring and complete topology awareness makes FDX Smart Amps the ideal platform for distributed AI, providing both the clean signal environment and contextual intelligence necessary for autonomous network optimization.

13. Conclusion

The foundation of DAA and vCMTS was just the beginning of transforming the HFC network. With their introduction at Comcast nearly a decade ago, not only did the access technology take a huge leap forward, but the fundamental operational aspects of deploying and managing the broadband network changed completely. These architecture investments delivered unprecedented transparency, real-time monitoring, and automation. Digitization at the edge, coupled with increasingly granular telemetry available from CMs in the home, provides deep data analytic opportunities, and has allowed Comcast to pivot more and more of its network management and maintenance capabilities to AI/ML processes operating on expansive databases of metrics tracking customer experience, device health, and network health. DAA and vCMTS have truly revolutionized the cable architecture and the access network edge.

With the FDX Smart Amplifier, this foundation is empowered further in significant ways, as has been demonstrated in this paper. With the addition of a SoC supporting the Digital Signal Processing used by FDX, among other functions, the amplifier takes on a completely new personality. Rich telemetry deeper in the network keeps a careful watch on every single coaxial span in the cable plant, individually. Amplifiers know where they are relative to one another, and where the CMs on the leg of the node are relative to the amplifiers. This foundational Topology Discovery capability of the FDX Smart Amplifier begets many additional new and powerful capabilities and opportunities:

- The end-to-end network can be aligned and maintained with very high precision
- Coupled with other SoC features, FDX Smart Amps can execute a construction check on fidelity of the upgrade
- Awareness of network anomalies can be immediate and lead to rapid self-healing that maintains the customer experience and automated notification
- Localization of anomalies contributes to reduced MTTR
- AI/ML-trained pattern detection engines can evaluate amplifier telemetry streams for RF signatures to make source and root cause determinations
- The RF signature identification can take place directly on the amplifier itself, due to its embedded AI/ML engine, saving transport and storage resources
- Local AI inferencing can trigger immediate self-healing remediation, rapid alerts of events requiring physical remediation to the exact responsible maintenance center, and notifications to keep customers informed when necessary

The FDX Smart Amplifier has enabled the extension of DOCSIS 4.0 FDX anywhere in the Comcast footprint, whether N+0 or N+x. Customers can experience multi-gigabit symmetric speeds, while simultaneously the investment in FDX Smart Amps will lead to an increasingly visible network, a more operationally efficient network, a higher performing network, and ultimately a higher reliability experience for residential and business customers alike.

Abbreviations

ACA	Amp Connect Application
ADC	Analog-to-Digital Converter
ADU	Automatic Drive Unit
AFE	Analog Front End
AI	Artificial Intelligence
BW	Bandwidth
CM	Cable Modem
DAC	Digital to Analog Converter
DPD	Digital Pre-Distortion
DS	Downstream
DSP	Digital Signal Processing
EC	Echo Cancellation
EQ	Equalizer
FB	Flex Band
FDD	Frequency Domain Duplex
FDX	DOCSIS 4.0 Full Duplex
FWD	Forward
HHP	Households Passed
HW	Hardware
iOS	iPhone Operating System
LE	Line Extender
LNA	Low Noise Amplifier
MAC	Media Access Control
MER	Modulation Error Ratio
ML	Machine Learning
MTTR	Mean Time to Repair
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSP	Outside Plant
PA	Power Amplifier
PSD	Power Spectral Density
QAM	Quadrature Amplitude Modulation
RBA	Resource Block Assignment
RF	Radio Frequency
RLSP	Return Level Set Point
RPD	Remote PHY Device
SoC	System-on-a-Chip
SW	Software
TCP	Total Composite Power
TD	Touchdown or Topology Discovery
TDR	Time Domain Reflectometer
US	Upstream
VPN	Virtual Private Network
WBFFT	Wideband Fast Fourier Transform

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