# Developing The DOCSIS 4.0 Playbook For The Season Of 10g

A Technical Paper prepared for SCTE by

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# 1. Introduction

Nearly three years after the introduction of 10G, industry activity tied to this foundational next generation cable technology, known in technical circles as DOCSIS 4.0, is accelerating rapidly. The timing is well-suited to the moment. DOCSIS 3.1 has been in production for over 5 years. Newer features are now being exercised, such as 8k FFTs (25kHz) for OFDM and ODFDMA, Mid-Split and High Split networks to expand upstream, and the revolutionary Profile Management Application (PMA), the automated form of DOCSIS3.1 Multiple Modulation Profiles (MMP).

As DOCSIS 3.1 deployments continue, so do capacity growth and speed expectations for the network. DOCSIS 4.0 was developed to support relentless bandwidth consumption and speed trends, leveraging the DOCSIS 3.1 PHY basis for its bandwidth efficiency, resiliency, and backwards compatibility.

As with most cable technology evolutions, there is no "one size fits all" solution among, or often even within, a single operator. Each operator's current as-built networks have different starting points and range of other variables – region of the country, geography and topology, municipal and state make-ready differences and a range of aerial/underground construction techniques, to name a few.

In this paper, Comcast and Charter will provide a unified point of view on the rapidly approaching cycle of DOCSIS 4.0 upgrades. We will address:

- Implementation options in DOCSIS 4.0, including Full Duplex/FDX and Extended Spectrum/FDD
- Common use cases, with guidance on how DOCSIS 4.0 options may be applied
- The range of network variables and anticipated impacts
- How key dependent variables may drive evolution path decision criteria
- The complementary nature of the technologies

This is a useful and timely session for all operators, suppliers, and industry partners interested in how DOCSIS 4.0 will shape tomorrow, as envisioned by engineering leads of two largest cable operators in North America.

# 2. 10G Overview

## 2.1. Objectives

Cable operators have steadily increased bandwidth and speeds to subscribers since the launch of the DOCSIS high speed data services (HSD). Compound annual growth rates (CAGRs) and the appetite for more bandwidth-intensive applications, has made continuous investment in the network the cost of doing business. These trends have been reasonably predictable, allowing operators to be very efficient with their network investments and develop standard practices to manage growth. HFC continues to show the ability to adapt and increase capabilities to meet the needs of today's subscribers and businesses.

MSOs have historically been conservative in talking about their network capabilities. For example, technical terms such as "DOCSIS 3.1" and "DAA" represent some of the language of today's industry technology advances and foundational initiatives leading to 10G. However, the terms themselves are not particularly effective for describing what the network is capable of and what it can deliver for customers.

Building upon DOCSIS 3.1 and DAA, among others, the 10G aims to represent a technical benchmark but also be associated with what these new advances mean to services and to the customer experience. So what is 10G? The "pillars" of the 10G networks are defined as:

- Speed – Enabling of multigigabit symmetric speeds, raising the bar for consumer broadband.
- Low latency – Low Latency DOCSIS (LLD) is now incorporated into the DOCSIS 3.1 specification and carried forward into DOCSIS 4.0. Delivers a better customer experience, in particular for applications such as gaming and AR/VR.
- Reliability – Methods to proactively identify and address network issues before consumers are aware of them
- Security – Improve the confidentiality, integrity, and availability of safe communications.

Summarizing, 10G will offer up to 10 Gbps of intelligent, reliable, secure bi-directional capability that, coupled with decreased latency, will enhance the customer experience of today. The 10G network will unleash a new generation of capability that will drive innovative applications and create new digital opportunities, novel services, and impact lifestyles for the better.

## 2.2. HFC Challenges to 10G

With such a grand vision, what will it take for operators to move from PowerPoint (and white papers(!)) to implementation and field deployment?

Well, if 10G was simple to obtain and pedestrian in its objectives, it might already be available and there would not be multi-years of play-by-play media coverage and industry-wide excitement about its promise. Furthermore, painting the end state of a next generation network evolution is relatively straightforward. It is the transition from the current state to that end state that creates the challenges, consuming most of the energy that access engineers and business planners spend when debating network path and technology direction. The starting point for 10G comes with several interrelated obstacles:

1) *Coaxial Bandwidth* – First and foremost, the cable network spectrum is very broad, but there are still limits to the easily accessible bandwidth. For most HFC systems today, that bandwidth is either 750 MHz, 860 MHz, 1 GHz, and more recently to 1.2 GHz. The limit that applies for a particular plant is typically determined by the generation of RF amplifiers installed. With a downstream limit such as 750 MHz, for example, there is simply not sufficient spectrum to achieve 10 Gbps even in a complete DOCSIS 3.1 migration.

2) *Upstream Allocation* – Despite the scenario described above, the path to 10Gbps on the downstream is not too difficult to envision, even for 750 MHz. Simply add more very efficient DOCSIS 3.1 spectrum extending to 1 GHz or 1.2 GHz with readily available amplifier replacements, for example, and it is within reach, depending on other EOL fidelity variables. However, 10G is really setting its sights on massively expanding upstream bandwidth, which in North America is typically 42 MHz. Some MSOs have trialed upgrading to a Mid-Split Upstream, extending the return band to 85 MHz, to increase the capacity runway of the network and defer node splits. As can be observed above, the downstream-to-upstream (DS/US) ratio is highly asymmetrical. It is the primary goal of 10G to develop a more symmetrical DS/US ratio.

3) *Current DOCSIS Production Spectrum* – An assumption made above on the route to 10 Gbps is a "complete DOCSIS 3.1 migration." This is an unlikely scenario for many years. There will be relatively inefficient video QAM signals on the network for many years to support broadcast video services over many millions of existing set-top boxes (STBs) in the field today. In addition, while DOCSIS 3.1-capable devices are increasing in the field, DOCSIS 3.0 Cable Modems (CMs) still represent the majority in Comcast's footprint, and of the millions of DOCSIS 3.1 CMs in the field operate today, most operate in DOCSIS 3.0 mode, carrying the majority of traffic and accounting for most of the HSD spectrum. Other operators, including Charter, have activated more DOCSIS 3.1 upstream and are taking advantage of these additional efficiencies to add capacity and defer node splits. Existing services based on 256-QAM signals (as well as QAM VOD signals) put limits on how much spectrum can be allocated for DOCSIS 3.1, burdening some of the spectrum with less bandwidth efficiency.

4) *DOCSIS Capability* – The DOCSIS 3.1 standard limits the upstream spectrum to a maximum of 204 MHz – the "High Split" configuration. This configuration is designed to enable up to 1Gbps of upstream when carrying all DOCSIS 3.1 OFDMA signals. In this configuration, it is capable of up to about 1.5 Gbps. The definition of the DOCSIS 4.0 standard sets about to expand the amount of spectrum made available for Upstream, up to 684 MHz for either DOCSIS 4.0 option. This expansion is the major change that the standard is targeting towards the 10G network.

5) *Distributed Access Network (DAA)* – DAA is a definite "good" guy, so why is it listed here as a challenge? Well, the DAA journey has not begun with many operators, and is also fragmented in approach taken. For all of the discussion of DOCSIS 4.0, it is a consensus agreement that it will only be implemented via DAA. DAA is itself a complex, multi-faceted journey to production scale and as a prerequisite to DOCSIS 4.0, presents a large obstacle of a DAA plan is not first established and executed on.

6) *Business Case* – Plant upgrades have been part of cable network evolution for decades. Each upgrade cycle has undergone typical analysis of pro/con and meeting criteria for return on investment. Well-understood guidelines have been established over the years for node splits, spectrum addition, and other network augmentations, such as FTTH. Similar modeling will take place for DOCSIS 4.0 and be honed over time using empirical data.

## 2.3. Still Early in the Life of DOCSIS 3.1

Before expounding in the exciting technology and opportunities ahead with 10G, it is important to recognize that the DOCIS 3.1 journey is still early. Planning ahead for DOCSIS 4.0 does not mean things are standing still in the meantime – on the contrary, operationalizing and optimizing the advanced features enabled with DOCSIS 3.1 has really just begun.

### *2.3.1. 2020: Everything Changes*

When it comes to the evolution of DOCSIS, each version seems to have a longer runway than the prior. That is certainly the case when we talk about DOCSIS 3.1, which can easily be considered to be in the infancy of its life span. Some operators began to roll out DOCSIS 3.1 OFDM downstream a few years ago, primarily to provide a Gigabit service offering. Like all versions prior, it is backwards compatible; however not until DOCSIS 3.1 CPE reaches meaningful penetration rates will operators be able to use it to its fullest capacity.

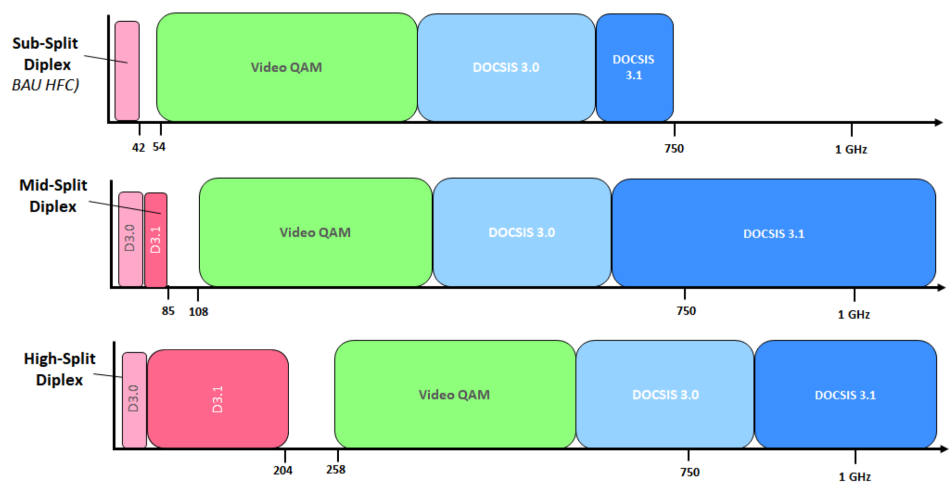
 

Recently with the COVID-19 pandemic we saw an increased number of people working from home and learning from home using video conferencing and real time communications tools. The industry shined in its ability to handle the increase in traffic due, but the pandemic did highlight the significance to optimizing how we leverage DOCSIS 3.1 increased bandwidth.

### 2.3.2. Pulling the Levers

A significant example of what is possible and still ahead for DOCSIS 3.1 is the expanded downstream and upstream spectrum it provides over DOCSIS 3.0. Current DOCSIS 3.1 has the capability to support a downstream frequency range up to 1.2 GHz and an upstream frequency range up to 204 MHz, better known as High Split. Today, a 42 MHz upstream bandwidth is the most common for North American cable operators, although some migrations to Mid-Split (85 MHz) have taken place. The expansion of frequency capability will allow operators more flexibility in how to leverage their networks for offering enhanced service tiers.

**Figure 1** illustrates the differences between a standard HFC spectrum allocation today and the Mid-Split and High-Split architectures.




The majority of North American operators have deployed DOCSIS 3.1 downstream OFDM blocks. Some operators have also begun to leverage OFDMA in the upstream, which provides higher modulation schemes and greater bits per second per hertz (bps/Hz) when compared to the DOCSIS 3.0 A-TDMA Single-Carrier QAM (SC-QAM). As operators continue to increase the penetration of DOCSIS 3.1 CPE, some are opting to gradually remove ATDMA one service group at a time, replacing this spectrum with OFDMA because of the higher modulation profiles and increased throughput, and therefore longer capacity runway. Most node splits are driven by the upstream capacity utilization associated with the limited available 42 MHz of spectrum.

In the downstream path, operators are using the increased CPE penetration to further expand OFDM blocks and increase the total throughput made possible with 4096-QAM (12 bps/Hz) OFDM subcarriers as compared to 256-QAM (8 bps/Hz) of the legacy single carrier QAMs, a 50% increase in inefficiency. As downstream growth trends continue, there will be a reclamation of the legacy single carrier QAMs in the spectrum that are currently supporting DOCSIS 2.0/3.0 devices that, through attrition, are currently being replaced with DOCSIS 3.1 CPE. The decreasing penetration of these legacy devices can be supported with fewer SC-QAMs occupying the downstream.

#### *2.3.3. Increasing the Spectrum and Moving the Split*

As shown in **Figure 1**, most HFC networks today are built with a 750 MHz or 860 MHz upper frequency range utilizing a 5 – 42 MHz "Sub-Split" return. This bandwidth cap of 42 MHz means a limited amount of DOCSIS carriers, and the amount of spectrum used for the upstream falls far short of the capabilities available in DOCSIS 3.1 devices that have now been available and deployed for years. There is ample opportunity to replace active components in the field with new nodes and amplifiers that support a downstream to 1.2 GHz, with either a Mid or High Split configuration. This extra spectrum will allow for the expansion of both OFDM and OFDMA carriers and greatly increase the total throughput capacity of the network in both directions.

Most operators, feeling the upstream growth constraints, now accelerated by COVID-19 and its implications [1][4] are already executing on these frequency expansion upgrades. Some are making these bandwidth changes in coordination with their Distributed Access Architecture (DAA) rollouts, minimizing outside plant impacts and making most efficient use of construction opportunities.

DAA itself can be considered another lever operators can use to increase signal fidelity and, with the available optimizations of bandwidth efficiency with DOCSIS 3.1, deliver greater capacity to the network, benefitting customers.

## 3. DOCSIS 4.0 Technology Options

### 3.1. Full Duplex DOCSIS (FDX)

**Figure 2** illustrates the essential spectrum goal of FDX– enabling significantly more upstream. More interestingly, these new FDX upstream bands (Red "FDX" in **Figure 2**) are available for downstream. Huh? This is quite different than typical Frequency Domain Duplex (FDD) operation, the approach taken in DOCSIS 4.0 FDD. It is also begs the question – how can both downstream and upstream data exist in the same spectrum?

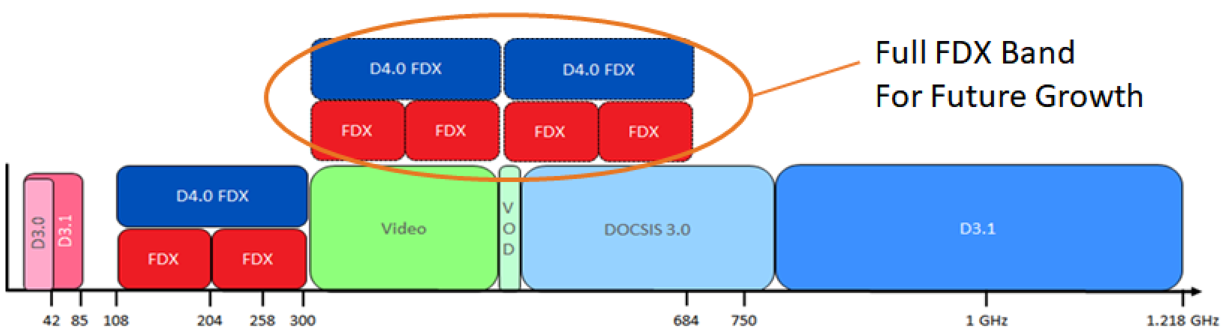



**Figure 2 - Upstream Spectrum Added for DOCSIS 4.0 Full Duplex (FDX)**

### *3.1.1. Key FDX Innovations*

Although more upstream bandwidth is defined, it is the same 96 MHz OFDMA physical layer blocks as defined in DOCSIS 3.1. Thus, DOCSIS 4.0 leverages the power of the DOCSIS 3.1 PHY completely. Six additional 96MHz blocks are added across the 108-684 MHz band, complementing an 85 MHz "mid-split" system.

Downstream and upstream can occupy the same band with a technology known as Echo Cancellation (EC). Echo Cancellation in general is a mature technology used in other telecom networks, such as xDSL and wireless. It has not yet been implemented in cable networks. The EC concept is very similar, although the cable does introduce some new challenges. EC is the first of the two critical innovations that power FDX.

The second key innovation is based on an architectural difference in cable systems when compared to telco xDSL systems. Twisted pair telco networks are point-to-point from the DSL Access Multiplexer, or DSLAM, whereas HFC is a point-to-multipoint. 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 3** illustrates these innovations from the CMTS perspective, using a passive coaxial network (i.e., N+0) for simplicity. N+0 is NOT a requirement for FDX, but the specifications were developed with N+0 as a baseline. FDX-capable amplifiers are being developed to support FDX signals over N+x networks, allowing FDX over a broader range of architectures. As in standard HFC networks, an RF amplifier cascade impacts quantifiably the network performance. With amplifiers for FDX, one of the impacts is the effect on IGs and TGs. As a result, additional considerations that account for the relationships among of maximum speed tier, penetration, and cascade depth have been developed. We will discuss FDX amplifiers in a subsequent section.

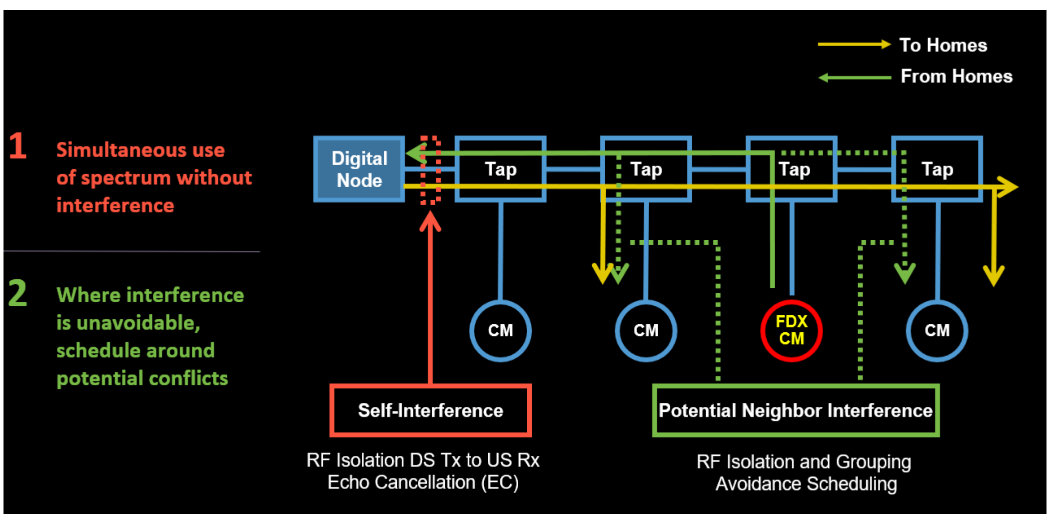



**Figure 3 - Two Key New Innovations in DOCSIS 4.0 Full Duplex**

### *3.1.2. A Closer Look Part 1 – Echo Cancellation*

Referring to **Figure 3**, adding upstream where downstream exists requires that the downstream signal be "subtracted" before the US OFDMA receiver. This requires high RF isolation and strong EC of the much higher downstream signal. While the implementation details may be complex, the EC concept is a quite simple, and the digital signal processing (DSP) principles to build it very mature. A simplified diagram illustrating the EC concept is shown in **Figure 4**.

The node downstream transmit signal will have some of its energy reflected back by the imperfect RF interfaces, such as described by the return loss of a tap, for example. These are the so-called "Echoes" that give the EC function its name. What is distinctive to EC for cable is the high cancellation required across a broad bandwidth. These cable specifics push the envelope.

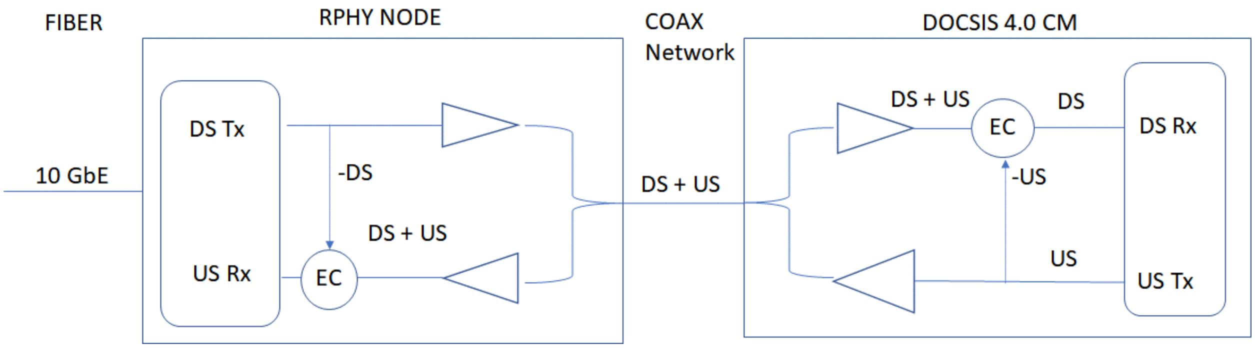



**Figure 4 - Conceptual Basics of Echo Cancellation in a non-DAA Configuration**

### 3.1.3. *A Closer Look, Part 2: Interference Groups and Transmission Groups (IGs/TGs)*

As noted, for HFC, the network is a point-to-multipoint architecture. While an FDX modem knows its own upstream transmission, it cannot know that of his neighbor. It requires sufficient RF isolation among neighbors to prevent FDX-band upstream users from interfering with a neighbor using that band for downstream. Unfortunately, RF isolation among homes cannot always be guaranteed to be high enough. The isolation relationships among homes a shared RF leg are determined as part of FDX "sounding" process.

Without sufficient RF isolation we can have the vCMTS scheduler designed to avoid this scenario. In an FDD system, the scheduler does not need to pay particularly close attention to the relationship of downstream and upstream access to the wire. This changes in FDX. During FDX "sounding," the FDX system determines these isolation relationships. Potentially interfering users are lumped into "Interference Groups," or IGs. A logical set of IGs is called a Transmission Group (TG), because not every IG needs to be treated independently – it depends on traffic. This scheduler assures that potentially interfering pairs are not subscribing the same spectrum in the same time slot.

Because there are six OFDMA blocks, the vCMTS can service multiple IGs with uniform capacity and speeds by assigning different Resource Block Assignments (RBAs) to each IG. **Figure 5** shows an example of how the 108-684 MHz FDX band might be allocated to simultaneously support a case with three TGs. These RBAs can adapt with time based on traffic demand.

Note that the FDX band is not all the DOCSIS spectrum available. Non-FDX DOCSIS 3.1 spectrum and DOCSIS 3.0 spectrum will also exist.

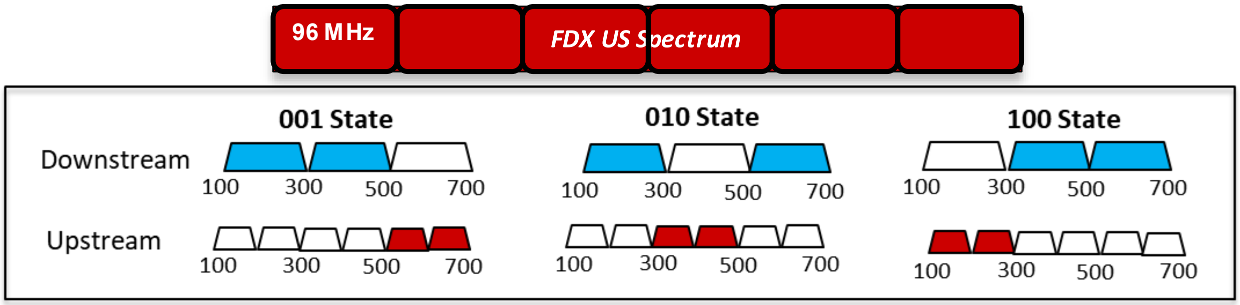



**Figure 5 - OFDMA "Resource Blocks" Enabled in the FDX Band**

### *3.1.4. DOCSIS 3.1 Compatibility / Coexistence*

Because FDX is fundamentally based on DOCSIS 3.1, the FDX band can only be activated where the DOCSIS3.1 downstream is allocated. Existing DOCSIS 3.1 devices should be aware that they are part of an FDX system in order that they partake in IG/TG sounding and thereby be well-behaved co-existing devices in an FDX-enabled plant. This DOCSIS 3.1 device mode is known as "FDX-Light" or FDX-L. Obviously, DOCSIS 3.1 devices do not support FDX. They cannot transmit in all of the FDX band higher than 204 MHz. Nonetheless, it is important that the device be aware that it is operating on an FDX system. In this way, it can participate in network sounding, allowing the vCMTS to determine when it can schedule packets to be received by the device and avoid being interfered upon with by an FDX device that may be transmitting in the same band and at the same time.

FDX-L is a software-only upgrade to existing DOCSIS 3.1 devices. Without this mode, a separate DOCSIS4.0 band would need to be set aside, similar to what is done today with DOCSIS 3.0 and DOCSIS3.1 spectrum. Launching FDX and the much higher upstream speeds therefore implies a commitment to an amount of DOCSIS 3.1 downstream spectrum, within which the FDX upstream can operate. As with any spectrum allocation, this must be managed within the constraints of the HFC network's overall spectrum plan. Networks supporting FDX will all be a 1 GHz systems or 1.2 GHz systems, which are bandwidth upgrades from today's 750MHz systems and 860MHz systems. So, at first, the challenge to "find" spectrum is not as daunting considering that new spectrum that will be added as FDX becomes deployed when an amplifier is installed that adds new bandwidth above 750 MHz or 860 MHz.

### *3.1.5. DOCSIS 4.0 FDX is Coming to Life*

The first DOCSIS 4.0 FDX RPD bring-up and characterization began in March of 2021, and the results were described in various media publications the next month [2].

Some hardware images of the first FDX RPD are shown in **Figure 6**. The RPD module shown on the right plugs into an FDX node, which is not shown.

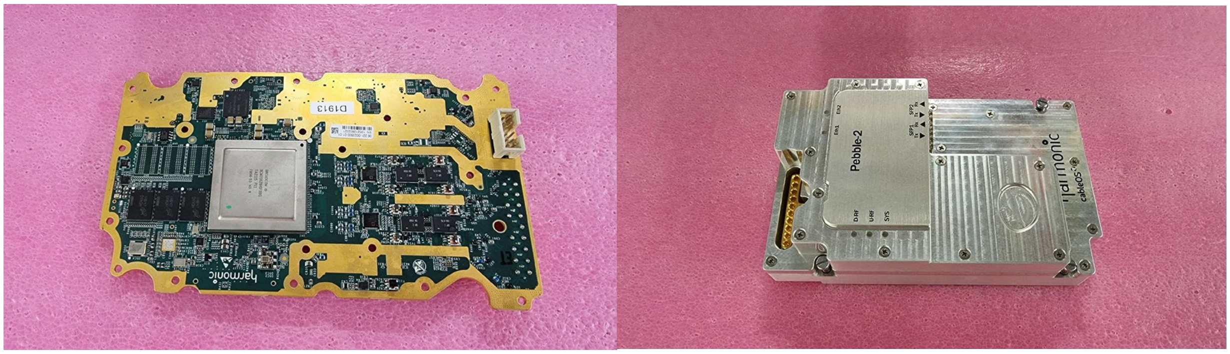
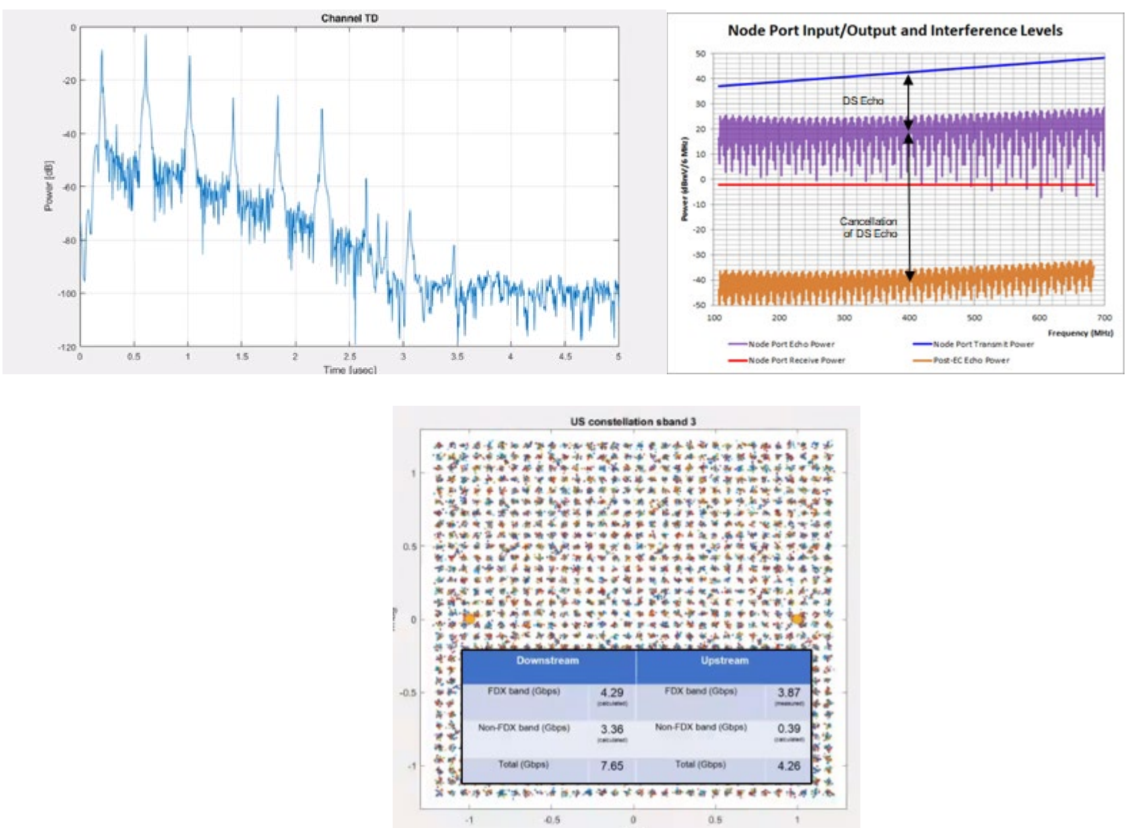



**Figure 6 - DOCSIS 4.0 FDX RPD Hardware**

**Figure 7** shows the sample network's echo characteristics used for the test, as well as a simulation of how the FDX Band operates with both downstream and upstream present in such an environment. Also shown is the measured downstream and upstream throughput from the test, which includes block of DOCSIS 3.0 spectrum downstream and upstream (legacy), plus video carriers akin to today's channel line-up. The network achieved 7.6 Gbps downstream and 4.3 Gbps upstream, both in terms of net throughput. 1024-QAM was able to be successfully activated in the upstream, as shown, with performance similar to a typical DOCSIS 3.1 upstream receiver. The latter is of defined only to 204 MHz upstream.




| Downstream | | Upstream | |
|---|---|---|---|
| FDX band (Gbps) | 4.29 (calculated) | FDX band (Gbps) | 3.87 (measured) |
| Non-FDX band (Gbps) | 3.36 (calculated) | Non-FDX band (Gbps) | 0.39 (calculated) |
| Total (Gbps) | 7.65 | Total (Gbps) | 4.26 |

**Figure 7 - DOCSIS 4.0 FDX RPD in Operation (clockwise from upper left): a) Plant Echo Response from Node Port b) Simulated Node Tx, Tx Echo, Node Rx, Cancelled Echo c) 1024-QAM US**

The DOCSIS 4.0 specified minimum upstream MER requirements are higher than DOCSIS 3.1 in anticipation of noise contributions in the form of residual echo from the FDX band. Nonetheless, the test results observed and shown here using a "Model 1" plant and echo environment is delivering performance similar to a straight DOCSIS 3.1 US receiver, without needing any additional headroom for MER loss.

There will surely be more to come from the labs and shortly in the field as FDX is birthed in 2021!

### 3.1.6. FDX-Capable Amplifiers

The FDX system specifications were written using the assumption of an N+0 network. However, FDX is not technically limited to an amplifier-free plant and the specification does not prevent it. In fact, shortly after the FDX specifications were compiled, a CableLabs Study Group was formed to evaluate methods for implementing amplifiers that support FDX. The foundational EC technology developed for the FDX RPD can in principle apply at any point in the network to manage overlapping spectrum, and this can include amplifiers. Of course, these are therefore not traditional amplifiers, but a new class of device that includes this new digital signal processing (DSP).

An EC-based amplifier concept is shown in **Figure 8**. The nature of overlapping spectrum and gain in both directions creates a full-circle loop gain path. The EC must be capable of suppressing the FDX loop gain, such that the net gain around the path is < 0 dB to maintain a stable device. The EC must further be designed to act on the echo it is suppressing sufficiently that the aggregate residual echo noise, which becomes part of the amplifier's own noise floor, supports the US MER requirements effectively for DOCSIS4.0, without introducing unacceptable MER degradation and subsequent loss of bandwidth efficiency.

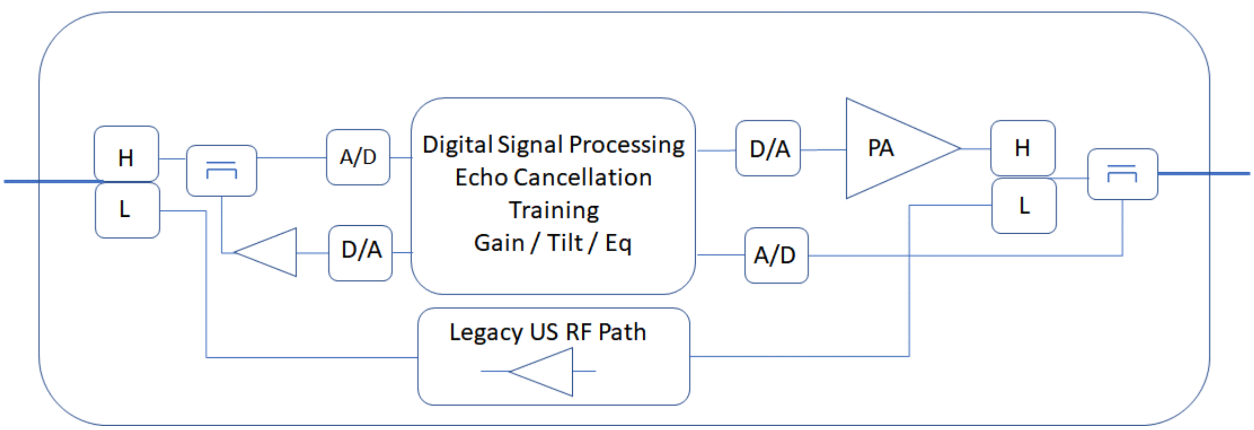



**Figure 8 - FDX Over N+X Using an Echo Cancellation-Based Amplifier**

The Echo Cancellation function required is similar to that of the node, except that for an amplifier it can exist on both sides. A sample of the upstream signal is taken so that an opposite phase, equal magnitude version can be added in front of the downstream amplifier. Similarly, the signal from the downstream amplifier is sampled and an anti-downstream version added at the input to the upstream amplifier.

As in HFC, as the cascade increases, noise contributions aggregate and the MER decreases. For an FDX amplifier, in the FDX band, there is an additional noise contributor to account for in the form of residual echo. The amount of acceptable degradation due to the amplifier is a system engineering parameter that flows from performance specifications ultimately to the performance of the EC itself. A significant advantage for amplifier EC when compared to N+0 is that the levels on the DS port are lower, and on the

US port higher. Thus, the DS to US level ratio is smaller, which is favorable for the EC that must subtract the downstream.

While noise analysis is relatively straightforward for N+x with FDX, the traffic engineering requires additional scrutiny due to the shared DS and US and the effects amplifiers can have in expanding the size of an IG.

Consider the N+1 system shown in **Figure 9**. When an amplifier is included, there is an expansion of Interference Group 4 (IG4) to the "south," or home-facing, side of the amplifier. These users become part of the last IG of the tap string before the amplifier. This is because of the limited drop-to-output isolation characteristics of today's taps. This parameter can be optimized for high drop-to-output isolation, but until there was FDX to consider, there was no reason to do so. Work in this area shows promise if the logistical and operational challenges can be managed.

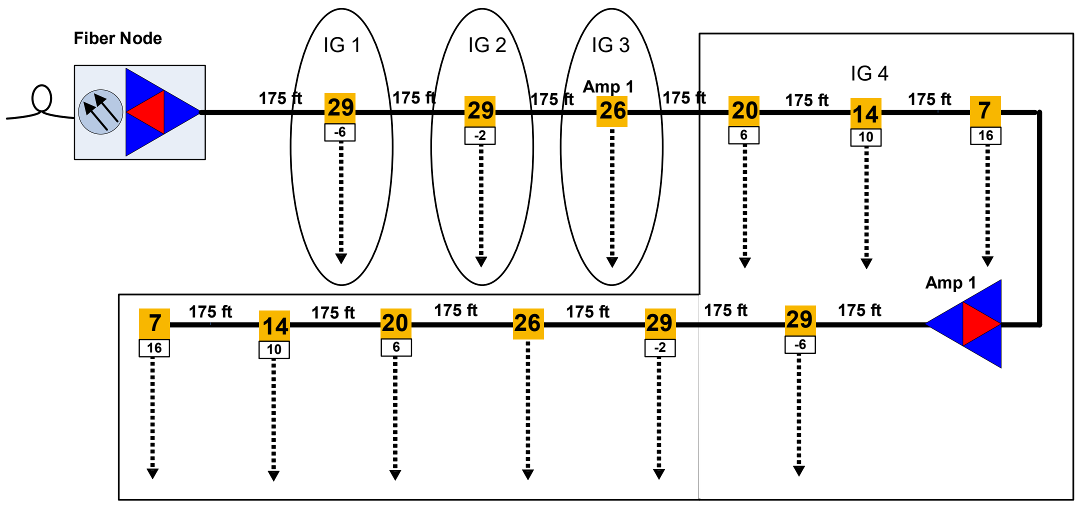



**Figure 9 - Potential Interference Group Expansion due to Amplifier on an FDX Network**

If we think about network segmentation triggers in current HFC networks, rules have been developed that link service group size, speeds, and percent capacity utilization and define total capacity required. Then, with an awareness of device penetrations, this can be translated to DOCSIS 3.0 and DOCSIS 3.1 spectrum requirements and the numerical thresholds that trigger a network augmentation.

Similar capacity-based analysis and empirical rule making will now apply to FDX, with one additional nuance. The FDX band is allocated for both downstream *and* upstream. The infrequent bursts of peak speeds can therefore be called upon to service the downstream *or* the upstream, but they have a new shared bandwidth dependency. Although from the node perspective there is full duplex spectrum operation, from the CM perspective the introduction of IGs places constraints on who can simultaneously access the spectrum. **Figure 10** depicts this observation.

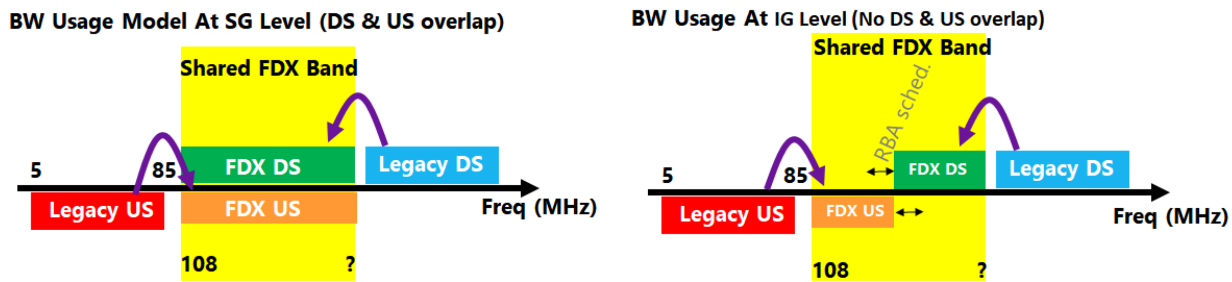



**Figure 10 - Managing FDX Bandwidth to Guarantee Peak Speed Bursts [Courtesy CommScope]**

The traffic engineering questions become:

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 downstream and upstream traffic engineering become co-mingled in FDX?

**Figure 11** shows a model assessing the subscriber count, spectrum, and QAM efficiency trade space for a set of input parameters projected to 2028 that includes average utilization with CAGRs of 35% downstream and 30% upstream, and speed tiers up to 4 Gbps/4 Gbps subscribed to by *every* user. The subscriber group (or IG size) sharing FDX spectrum can be as large as 64 and stay within 1200MHz of total spectrum, or even within 1 GHz for a relatively inefficient (for DAA) 9 bps/Hz net downstream throughput. The upstream, even for the 4 Gbps/4 Gbps (green) case, stays within the FDX band allocation for an IG size above 128.

What these studies reveal is that FDX bandwidth can be used extremely efficiently. Peak bursts are extremely infrequent and the collision of bursts from concurrent peaking users is rarer still. With an 85MHz legacy upstream, the upstream bandwidth is sufficient for peak-busy-hour (pbh) average utilization for up to 200 subscribers – where the red arrow points to the FDX bandwidth breach in **Figure 11**. The FDX upstream band turns out to be primarily a spillover reservoir for the occasional burst peaking user. Meanwhile, most of the daily grind for the FDX band is in delivering downstream capacity. This represents an extremely efficient use of precious HFC spectrum, which is precisely the principle that FDX was created on.

Reviewing, today's capacity management is based on assessing service group size vs available capacity vs utilization. At a certain empirically derived utilization threshold, a network augmentation is triggered. Typically, these are triggered by upstream utilization, and is a node split. However, it can also be new spectrum, more DOCSIS 3.1, or QAM reclamation.

The effect of FDX and the IG phenomenon is that now, in addition to the parameters above, network augmentation may be triggered by introduction of a new *speed tier*, and as a secondary factor the penetration of that tier over time. This will also ultimately be empirically derived, but initially be based on guidelines such as those given above. Network segmentation rules have been developed for services levels of 2/2 Gbps, 3/3 Gbps, and 4/4 Gbps.

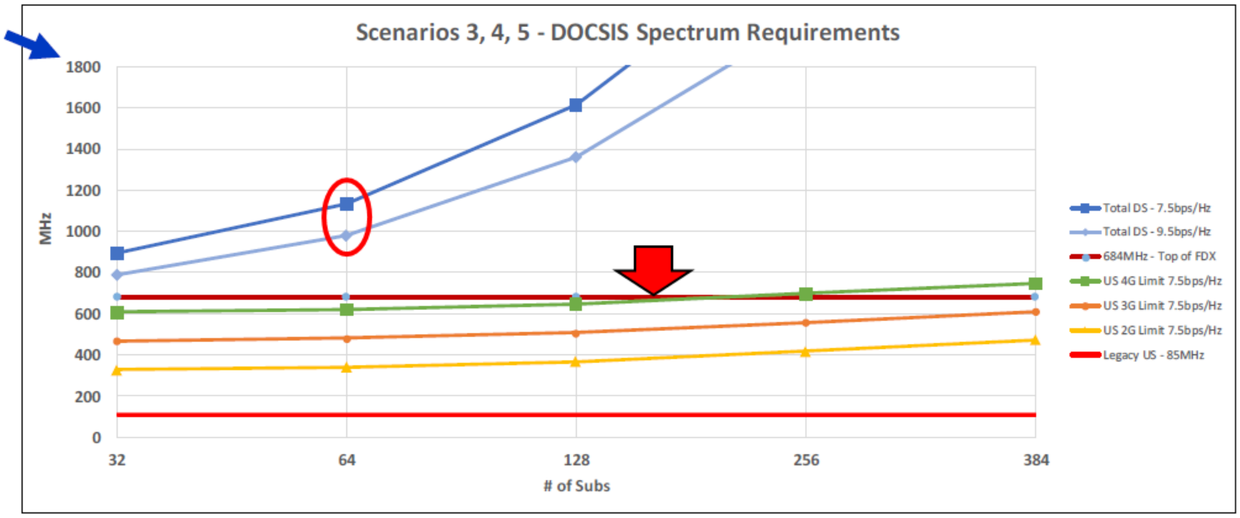



**Figure 11 - Total RF Spectrum Required vs Subs Sharing a TG [3 Gbps/3 Gbps, 4 Gbps/2 Gbps, and 4Gbps /4 Gbps]**

## 3.2. Extended Spectrum DOCSIS

### *3.2.1. What Is Extended Spectrum in the Plant?*

The answer is simple! The cable industry has been executing HFC bandwidth expansion path for decades, so moving the spectrum to 1.8 GHz can be considered simply the next step in a well-established network evolution model. The next step in this path to higher bandwidth HFC has been coined *"Extended Spectrum"*. Looking back at the history of HFC plants, it was not so long ago that the upgrade was to 550MHz, then to 750 MHz, closely followed by 860 MHz, then 1GHz, and most recently to 1.2 GHz. Many "old-timers" can probably remember some of the incremental steps prior to 550 MHz, with long amplifier cascades – prior to adding the "F" in HFC. A step to 1.8 GHz from this perspective is just the next step in a spectrum and capacity expansion on the way to potentially a 3.0 GHz HFC network. In this manner we continue to leverage our valuable assets as has been done in HFC successfully for decades.

Recognizing the fact that HFC is going to be around for a very long time, cable operators are looking at what to do to keep moving on the path to 10G (10 Gbps). Prior spectrum expansion in the last two decades were primarily driven on the need for more downstream channel capacity; now, it is primarily upstream capacity, creating a more complex set of questions for what to do next.

There is increasing pressure on the physical layer of the network to create incremental capacity. Many networks may need additional interventions to keep up with new product and service offerings, but mostly to keep pace with the data traffic growth. The increase in Internet bandwidth demand is one of the primary reasons we touch the outside plant network today. Internet connectivity has become a very competitive landscape over the last decade, with the majority of the operators increasing data speeds on a consistent cadence. Had the role of data growth on network augmentation been understood 20 years ago at the dawn of HSD services, a more methodical and capacity engineering-based approach to place nodes could have produced more balanced service groups, evenly distributing data capacity. Nevertheless, over the last decade operators have learned the nature of capacity engineering and have been performing node segmentations, node splitting, and in some cases more aggressive steps, such as N+0 upgrades.

As expected, the results of these activities have benefited operators by systematically driving fiber deeper into their networks and closer to customer premises, thus reducing amplifier cascades and ultimately improving network performance and reliability. The segmentations have shrunk service group sizes sharing the bandwidth. Combined with aforementioned spectrum allocations, operators have a set of tools at their disposable to manage capacity, and with a range of impact suited to the incremental capacity upgrades of a simple node split, to tools suited to high growth, competitive footprint preparedness that include new spectrum, deeper fiber, and DAA.

### 3.2.2. Why Extend the Spectrum?

Leveraging the current assets of the HFC network in a manner that does not greatly change how operators invest capital is the key fundamental premise of *"Extended Spectrum."* Keeping network operations simple and familiar for the field operations teams is a key advantage of this approach. Extended Spectrum will allow cable operators to defer capital investments over a much longer period of time by using the "Business As Usual" (BAU) approach, while pragmatically driving fiber deeper into their networks. The improvements to amplifier technology will allow for continued use of most existing amplifier cascades, which fits into the current tree and branch topology of HFC networks.

**Figure 12** shows how and Extended Spectrum allocation compares to today and to the High Split scenario that was shown in **Figure 1**.

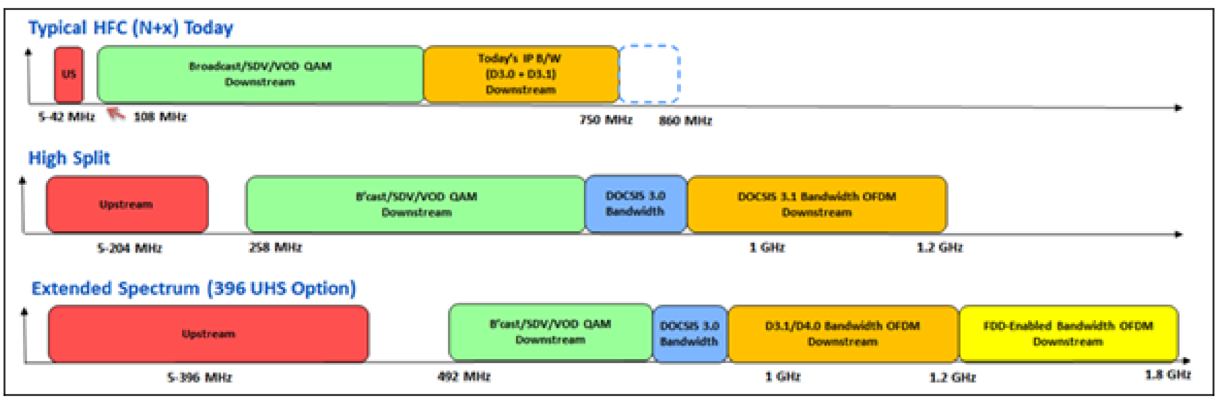



**Figure 12 - Typical HFC vs High Split vs DOCSIS 4.0 Extended Spectrum**

One of the biggest changes in future HFC plant upgrades will be pushing the upper limit of the carriers higher in the spectrum. Many details are still being worked out, but the goal is to perform drop-in upgrade to systems that were properly designed and built to a true 750MHz or higher. A properly designed and built system is highly dependent on the accuracy of the plant maps, the designer doing the work, the line equipment being used, and the distances in the spans of the coaxial cable. All of these potential uncertainties, plus the variables that went into the last system upgrade, can have an impact on this next step. With this in mind, operators will have flexibility to offer increased bandwidth in select locations to increase their speed to deployment.

So, how are operators looking at implementation of Extended Spectrum in practice? Below are some examples from an operator point of view in addressing some of the key changes introduced:

- *When is the right time to replace taps and passives*? The objective is for the frequency response of the housing to support 3.0 GHz now, with a 1.8GHz capability built into the device from day one. There is not an urgent need to put 1.8 GHz in place today, as most network upgrades are beginning with a 750 MHz plant. Thus, even after an upstream split change, there is typically open and useable spectrum up to 1.2 GHz to consume, buying time to phase in taps and passives upgrades as the downstream bandwidth gets utilized.

- *How best to manage Total Composite Power over the extended bandwidth?* Maintaining a realistic Total Composite Power (TCP) while extending the spectrum to 1.8 GHz requires thinking about the tilt and output levels, because of the need to maintain legacy RF levels into legacy CPE. Working closely with the silicon vendors has been an important step to understand trade-offs between level and performance.

  Note that the RF amplification is being designed to drop into the current amplifier spacing and location currently utilize for 750 MHz plant. This creates the need for new RF hybrids that are capable of amplifying at much higher frequencies while maintain a Total Composite Power (TCP) that is acceptable to minimize all distortions while not exceeding a power budget. Given the magnitude of this challenge, alternatives are being considered while the amplifier efficiencies catch up, looking at ways to not exceed the TCP capabilities of the amplifier. A simple way this can be accomplished is to use a step-down approach of the signal at either 1 GHz or 1.2 GHz. This step down will maintain a TCP, while not impacting the amplifier linearity that would otherwise degrade amplifier MER we want to achieve.

- For the upstream split, what is the "right" ratio? 204, 396, 492, 684 MHz or beyond are all flexible and effective solutions for whichever direction various operators choose for their markets. Each must be evaluated comprehensively within the market of interest to ensure they do not break powering boundaries of the network, reduce overall performance, or dramatically increase complexity. **Figure 13** and **Table 1** [6] show the spectrum allocations for downstream and upstream based on the DOCSIS 4.0 standard "Ultra High Split "(UHS) options.

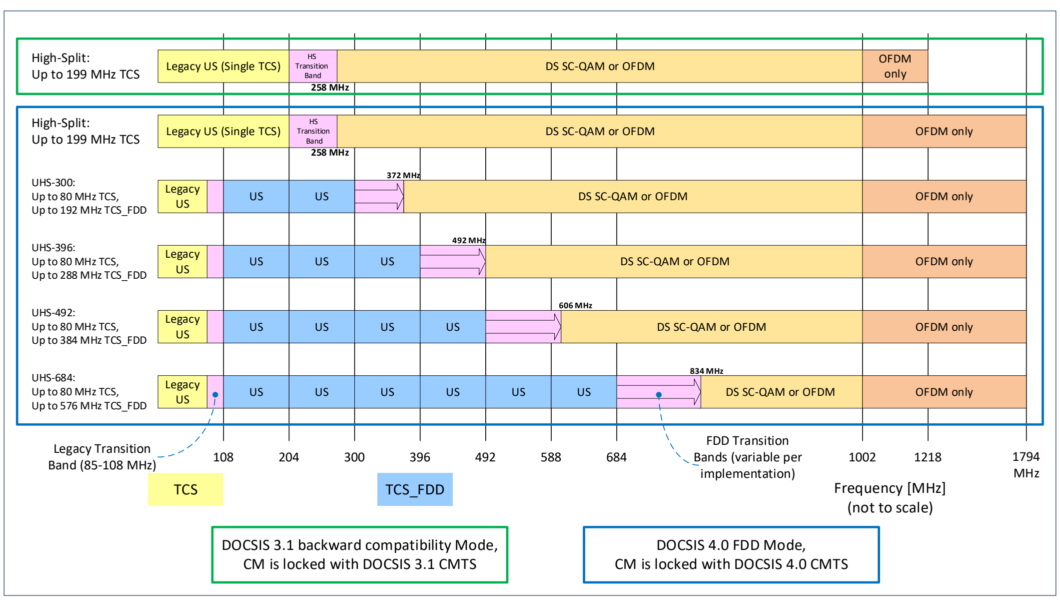



**Figure 13 - DOCSIS 4.0 Extended Spectrum Allocation Options for Downstream and Upstream**

**Table 1 - DOCSIS 4.0 Extended Spectrum Ultra High-Split Options**

| Split Name | Diplex Filter Start Frequency (Upstream upper band edge) (MHz) | Diplex Filter Stop Frequency (Downstream lower band edge) (MHz) |
|---|---|---|
| High-Split | 204* | 258 |
| UHS-300 | 300 | 300 MHz–372 MHz |
| UHS-396 | 396 | 396 MHz–492 MHz |
| UHS-492 | 492 | 492 MHz–606 MHz |
| UHS-684 | 684 | 684 MHz–834 MHz |

Changes are coming to HFC networks over the next few years in order to deliver more bandwidth and prepare for 10G. Extended spectrum ensures that operators have a long-term cost-effective option. Continuing to leverage these assets in a strategic manner is one way in which we will remain competitive while meeting the growing demands and insatiable subscriber's appetite for more bandwidth. The path to 10G initiative announced by CableLabs has accelerated efforts to deliver 10 Gbps service over coaxial cable networks. This makes strategic research efforts a big part of how operators are planning to reach the 10G vision and which technologies will be best to use. **Figure 14** shows the first DOCSIS 4.0 Extended Spectrum DAA node SoC, now being brought up in labs.

As an industry, it is imperative to have a large selection of tools that allows cable operators flexibility and scalability for their specific operating models. When looking at all the different architectures and scenarios that exist across the globe, operators must consider how to best scale the available assets and when to do so. As has been the case for decades, this will include a mixture of tools that support implementing roadmaps, such as the path to 10G, with anticipation for key technologies on the horizon.


**Figure 14 - First DOCSIS 4.0 FDD SoC**

Recently CableLabs completed the specification work on DOCSIS 4.0, which includes Full Duplex DOCSIS (FDX) and Extended Spectrum DOCSIS (ESD). These DOCSIS 4.0 variants will support different options to increase bandwidth and capacity, and furthermore support convergence of the technologies over time.

## 3.3. FDD-FDX Synergies and Key Differences

The most important commonality between DOCSIS 4.0 FDX and DOCSIS 4.0 FDD is the use of the DOCSIS3.1 technology as the basis for their Physical Layers. DOCSIS 3.1, of course, was a major shift away from what had been exclusively Single-Carrier QAM (SC-QAM) modulation formats of limited maximum efficiency for both the downstream (256-QAM) and the upstream (64-QAM), and using a combination of Convolutional and Reed-Solomon coding for Forward Error Correction (FEC) to increase the robustness. DOCSIS 3.1 broke the precedent of compatible SC-QAM based versions of DOCSIS, embraced the fast-growing adoption of multicarrier modulation (OFDM/OFDMA), and updated the FEC to Low Density Parity Check (LDPC) that was, despite its computational complexity, now able be implemented in real time, delivering significant new coding gain.

Both DOCSIS 4.0 FDX and DOCSIS 4.0 FDD rely on these powerful DOCSIS 3.1 modulation formats and FEC. Furthermore, the same OFDMA and OFDMA "numerology" details are unchanged in DOCSIS4.0 – subcarrier spacings options, range of cyclic prefixes, FFT size, windowing, exclusion bands, pilots, PLC channel, etc.

Of course, the focus of DOCSIS 4.0 is the expanded spectrum range that these "DOCSIS 3.1" signals can be extended over, into frequency allocations where they had not been allowed before.

### *3.3.1. The Same Except Where they are Different*

The discussion to follow will mostly take place from a network and DAA node point of view. However, a parallel discussion with many of the same characteristics apply on the CPE side, although the economic equation for CPE devices is very different. Technology parallels notwithstanding, the commercial differences and the premium value on the customer-facing LAN interfaces may lead to different business decision points on implementation and feature priorities.

For both FDX and FDD, upstream signals can extend beyond 204 MHz, up to 684 MHz. The required amount of OFDM and OFDMA resources is similar, as shown in **Table 2**. This is by design, enabling system-on-a-chip (SoC) suppliers to design and manufacture their chips which highly common blocks and functions for the most complex elements of the SoC. The common technology basis makes for an efficient and cost-effective ecosystem.

Where DOCSIS 4.0 differs from DOCSIS 3.1 more significantly are the differences between FDX and FDD that force changes at the "edge" of the SoC and outside of the SoC. However, the massive DOCSIS 3.1 processing engines required for either FDX or FDD are dominant features of these SoCs. Coupled with the common processing resources required, manufacturers of these devices may choose to implement the more moderate differences at the edge of the chip within a common SoC as configurable elements. This could be the case in the DAA node, or the CPE, or both.

**Table 2 - Common DOCSIS Resources are Defined for FDX and FDD [6]**

| Item | Device | FDX OFDM/OFDMA | ESD OFDM/OFDMA | SC-QAM |
|---|---|---|---|---|
| Downstream Channel Support | CM | 5 total OFDM channels;<br>3 channels capable of FDX operation;<br>All channels capable of non-FDX operation up to 1218 MHz | 5 total OFDM channels;<br>All Channels capable of operation up to 1794MHz | 32 |
| | CMTS | 6 total OFDM channels;<br>3 channels capable of FDX operation;<br>All channels capable of non-FDX operation up to 1218 MHz | 8 total OFDM<br>All channels capable of operations up to 1794MHz | 32 |
| Upstream Channel Support | CM | At least 7 total OFDMA channels;<br>6 channels capable of FDX operation;<br>2 channels capable of non-FDX operation within the legacy diplexer configuration.<br>(Some channels can be configurable to support either FDX or non-FDX operation. When supporting 6 FDX OFDMA channels, only 1 non-FDX OFDMA channel is required.) | 7 total OFDMA channels | 4 (or 8) SC-QAM channels, operating within the legacy diplexer configuration |
| | CMTS | 8 total OFDMA channels;<br>6 channels with FDX operation;<br>2 channels capable of non-FDX operation based on operator deployment requirements. | 8 total OFDMA channels | 4 (or 8) SC-QAM channels, operation dependent on operator deployment requirements |

The nature of the differences on the Original Equipment Manufacturers (OEMs) who build the FDX or FDD components around the SoC technology is more challenging than the SoC vendors. In FDD systems, the DAA node and CPE extends to 1.8 GHz, and includes diplex options for upstream settings. In FDX system, the typical 1.2 GHz bandwidth suffices, and there are no additional diplexers in the node beyond the standard Mid-Split one isolating the legacy upstream from the FDX band. FDX upstream is added by remotely configuring the vCMTS for the FDX band to activate the desired number of OFDMA blocks and extending the EC technology across these new blocks. The "Big Idea" is that this new massive upstream is added but where there is also downstream in use, thereby creating an extremely efficient use of coaxial spectrum without a large guardband penalty.

However, since OFDMA activation in the FDX band is not filter-based, an RF path at a node port, as shown in **Figure 15**, uses a *directional coupler* before the legacy diplexer in order to siphon off the upstream signal to send to an FDX band receiver. Thus, RF layout for an RF board in an FDX node is very different than in an FDD system.

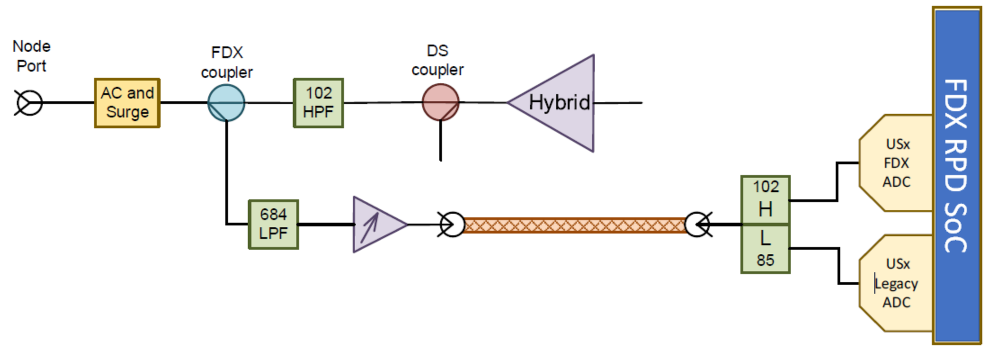



**Figure 15 - RF Processing in FDX is Different than in FDD systems**

Another change on the RF layout for FDX (not shown in **Figure 15)** are RF feedback traces from the downstream RF path, such as from the "DS Coupler" to sample and enable the signal so the EC can learn the interference and subtract it.

As described, in an FDD system, the RF processing chain is similar to today's nodes except for the much wider frequency response, and that it is expected that FDD nodes will incorporate a subset of the DOCSIS4.0 specification-defined diplexers to address upstream speeds by adjusting the diplex filter value remotely. The FDD "Big Idea" is then to enable this extended upstream-only spectrum, and downstream signals are extended up to 1794 MHz to make room for the shifted downstream to sit above the higher upstream plus ensuing guardband. FDD guardband is approximately 20% of the upstream diplex edge, for a maximum of 150 MHz in the 684 MHz case at the top end of the range. While 684 MHz is an available option, current usage and speed trajectories indicate this maximum upstream band edge may not be required, or at least not for many years.

Technically, 1794 MHz is the upper band limit defined initially for the DOCSIS 3.1 downstream. However, it had been largely deferred as DOCSIS 3.1 was developed (circa 2012) and the "I01" first release published. During that time, it was determined that quantifying the specification to this forward band limit could be deferred. This quantification is now taking place, and because of this, while the band edge of the frequency was identified by the DOCSIS 3.1 specification, it is the DOCSIS 4.0 work that is completing the requirements. Thus, 1794 MHz is typically identified with DOCSIS 4.0 Extended Spectrum and similarly, DOCSIS 4.0 FDX is associated with the 1218 MHz limit.

**Figure 16** illustrates the commonality of DOCSIS processing resources from a spectrum utilization point-of-view between FDX and FDD.

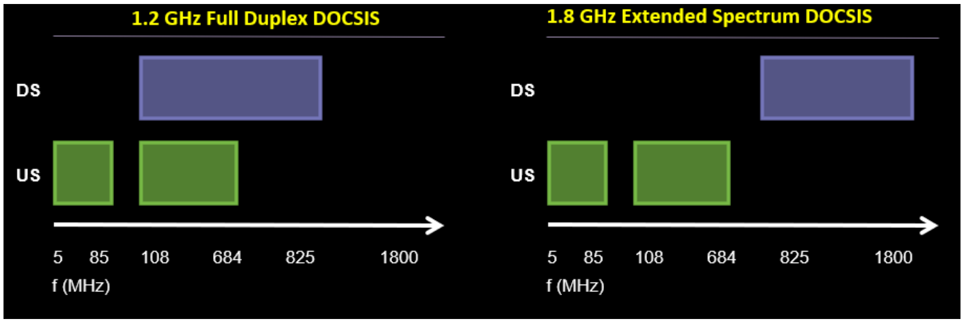



**Figure 16 - DOCSIS Resources Downstream and Upstream are Common in FDX and FDD**

### *3.3.2. Is this What DOCSIS 4.1 Might Look Like?*

Observing the two DOCSIS 4.0 options, we see that both add a common set of upstream OFDMA blocks over a common frequency range. One, FDD, pushes a significant physical bandwidth extension into the network relying on common RF practices executed for several generations of HFC migration. The other, FDX, relies on the introduction of new DSP technology to complement the existing plant technology in order that the spectrum asset be operated more efficiently over a bandwidth that the plant is built to support.

Importantly, these are not mutually exclusive approaches! In fact, they are complementary technologies that, in principle, could be merged in some future DOCSIS extension, perhaps as shown in **Figure 17.**

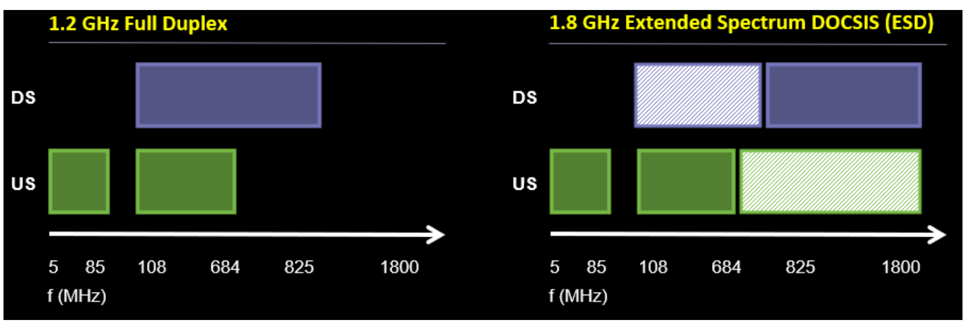



**Figure 17 - The Potential Complementary Nature of FDX and FDD**

With the DOCSIS 4.0 upstream capacity as defined for FDX or FDD in the 5-6 Gbps range, merging the two technologies may be next step toward push the upstream also towards the 10 Gig goalpost.

## 3.4. Characteristics and Attributes Summary

**Table 3** summarizes DOCSIS 4.0 FDD and FDX comparative attributes discussed herein (most of them), side-by-side. This is a useful cheat sheet to have on a whiteboard (perhaps a relic of a pre-Covid era) to generate dialogue, inspire feedback, identify where information gaps exist, zero in on those that carry the most weight, and generally spark debate and pro/con scorecards . We will use it later to re-form from a side-by-side comparison into DOCSIS 4.0 NFEAQs – Not Frequently Enough Asked Questions.

**Table 3 - FDD-FDX Attributes Comparison**

| Attribute | FDD/ESD | FDX |
|---|---|---|
| Strategy/Philosophy to 10G | • Based on access network BW extension upgrade, up to 1.8GHz, for existing actives and passives<br>• Introduction of DAA to migrate to 10G, similar to previous HFC plant upgrades with a choice of diplex split configurations | • Based on access network technology upgrades to introduce new DSP (EC) into RPHY nodes and Amplifier platforms<br>• Build on DAA production and scaling of vCMTS as the foundation for 10G |
| Migration Factors | • 1.8 GHz DOCSIS 4.0 DAA Nodes, Amps, Taps and Passives<br>• Allows for cascade of amplifiers<br>• New CPE | • RPD Nodes with DOCSIS 4.0 EC function<br>• FDX-capable amps with DSP<br>• New CPE |
| Complexity | • New tech challenges – BW and TCP extension<br>• Use of "low power" amp extender for edge cases | • New tech challenges – EC function, CMTS scheduler, DSP-based amps<br>• New capacity mgmt rule for IG/TG size for peak speed |
| Spectrum/Capacity | • 1536 MHz DS/656 MHz US (see **Figure 13** and **Table 1**)<br>• Up to 15G/5G (all-DOCSIS 3.1)<br>• DS/US: BW and Capacity per diplex selection | • 1110 MHz DS / 656 MHz US (see **Figure 2**)<br>• Up to 11G/5G (simultaneous, all-DOCSIS 3.1)<br>• FDX BW/speed by SW config |
| Operations | • Utilize existing common operational practices – FDD system with different possible split choices<br>• New field tools | • New operational practices for handling of spectrum overlap and amplifier installations<br>• New field tools |
| Network | • N+X<br>• Cascade reduction/trade-off based market capabilities | • N+0 (optimal)<br>• N+X – Cascade reduction/trade-off based on market speeds |
| As-Built Migration | • Continue node split and introduce DAA node splits, leverage for HFC migration activity, introducing components of FDD over time<br>• Migration path and timing considerations for Underground vs Aerial and MDU vs SDU cost implications | • Introduce DAA for node splits with vCMTS, leverage for HFC migration activity and platforms that enable FDX activation<br>• Migration path and timing considerations for Underground vs Aerial and MDU vs SDU cost implications |

While capacity and data speeds often garner the most of the attention when discussing access network, other important attributes from **Table 3** that consume more attention when comparing the options above are alignment to long-term strategy for the access network, network upgrade costs, and operational implications. The latter two have corollaries the attributes "as-built" and "complexity," which we will dip into a bit deeper in the next section.

# 4. DOCSIS 4.0 Migration – Key Variables

Across a single MSO are a range of HFC architectures. Larger MSOs, such as Comcast and Charter, tend to have a very wider range of network variants, owing to the consolidation of many smaller operators over time and the exchanging of properties among MSOs to gain operating efficiencies. There are opportunities to reel in the range of variations with the introduction of new technology and defining new architectures as part of a Next Generation migration plan. It is an opportunity to build a more common end state. However, as noted, the difficult part is always in the transition *to* a desired end state. Several important network characteristics play a role in the cost, complexity, reliability, and performance of the end state achieved from a given HFC baseline architecture and physical network.

## 4.1. Network Bandwidth

Today's HFC networks come mostly in the 3 varieties of maximum bandwidth described earlier – 750 MHz, 860 MHz, and 1 GHz – with a fourth emerging at 1.2 GHz, which nearly all new actives and passives support today. Many of these networks, in particular 750 MHz networks, likely began their lives designed for much lower total bandwidth, such as 450 MHz or 550 MHz (even 330 MHz). RF signal loss over coaxial is frequency-dependent and has a predictable inverse root-frequency relationship. As such, the construction of the network led to a physical distance between actives and passives as well as feeder cable requirements that could deliver a desired target end-of-line (EOL) performance – modest by today's standards – although at that time built around analog video requirements. Analog video is sensitive to noise and distortion, but these are pre-High Definition (HD) days with what would be considered low video quality expectations today.

This "spacing" generally was able to be held intact as RF amplification technology over time overcame the limitations of long spacing that was associated to an assumption of RF loss that may have fit for 450 MHz, but not for 750MHz. Bandwidth increments were relatively small steps, and broadband power amplifiers got better through the evolution from Silicon-based to Gallium Arsenide-based (GaAs) to Gallium Nitride (GaN)-based. By "better," we mean able to extend in bandwidth, but also able to extend in Total Composite Power (TCP), since more bandwidth to cover means more power to transmit. In addition, because RF transmission is launched on a tilt, the TCP is impacted disproportionately higher to the bandwidth added.

Lastly, most taps and passives on the network have upper frequency specifications such as 1GHz or 1.2GHz over which their RF parameter must be met. Passive devices can carry signals without guarantee of performance beyond these ranges with generally parasitic additional loss, to a point. With specification guaranteed only to 1.0 GHz or 1.2 GHz, there is a point above that at which the technology used in the design becomes incapable of supporting reasonable transmission with predictable loss.

The above variables have been part of the considerations for every HFC plant bandwidth upgrade over the years, and will be again as the network extension to 1.8 GHz is developed. How capable is the existing plant for supporting 1.8GHz and what are the cost / performance trade-offs and implications to prepare the network for this extension. There are no current HFC plants built with 1.8 GHz spacing in mind, and the disproportionate TCP due to tilted RF loading to 1.8 GHz places some constraints on the power spectral density profile.

On the FDX side, the RF design at the port of a node adds new passive components for feedback EC and a directional coupler to support the FDX band operation in both directions. These additional passive losses occur right at the output of the PA on the way to the port, contributing to launch power decreases that can reduce reach to homes on a passive network or decrease levels at the next active. The coupler designed loss also impacts the upstream signal at the node port in the FDX band that must be accounted for in the design and system engineering. These effects must be compensated for in the overall node design and accounted for in the system engineering. The trade-off space is typical in many ways - gains, levels, distortion, noise – towards an optimized FDX node design. What is different is that in the FDX band the trade-offs must have both DS and US in mind, since they share that part of the spectrum.

### 4.2. Cascade Depth

VERY long amplifier cascades were eliminated with the invention of HFC, allowing fiber to cover long distances and limit the coaxial cable portion of the plant. "Long" cascades today are much different. **Figure 18** shows a distribution of cascade depths across a sample within a region of the Comcast network used for a business modeling exercise. These distributions vary across regions with an operator as well as across operators. Comcast has builts million of homes passed to date in an N+0 configuration [3]. The sample selected in **Figure 18** is specifically outside of these N+0 build areas, but of course include some natural N+o as-built cases, such as MDUs. For this subset of the network, over 5 amplifiers in cascade would qualify as "a "large" cascade. Note that the "5" in N+5 merely refers to the maximum series cascade in the RF design. There could be 15 amplifiers off of a node port (near the median), but the number in cascade would be a maximum of 5.

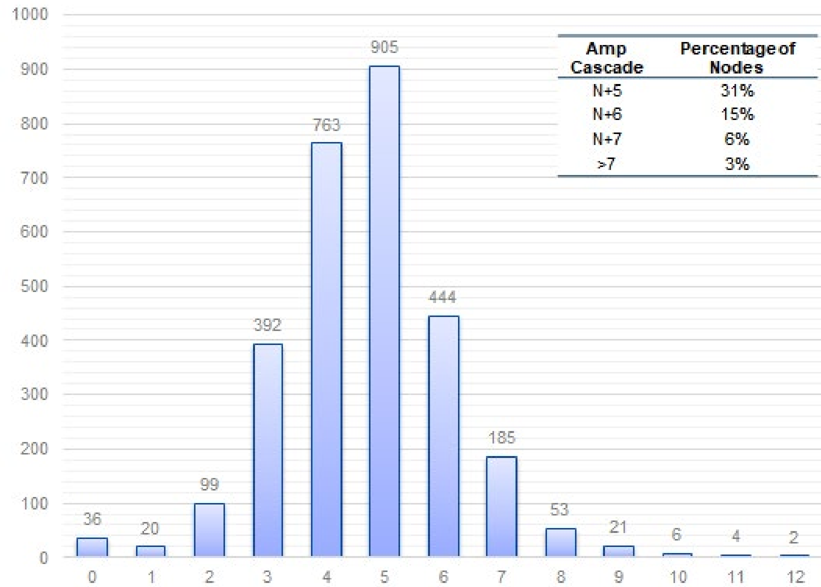



**Figure 18 - Cascade Distribution – Comcast Sample**

Cascade depth effects the same things it always has – MER degradation, frequency response, serving groups size (when combined with homes passed density).

For DOCSIS 4.0 cascade depth impacts are the same, only different. For FDX, as discussed, cascade depth includes the contribution of any residual noise of echo cancellation in addition to natural thermal noise. And, by the nature of the service group size relationship, cascade depth has a relationship to IGs and speed offering.

For FDD, the cascade depth drives the frequency response roll-off associated with the increased RF loss with frequency of existing feeder and drop cable, and taps and passives. Projected performance and the frequency extreme drive the minimum receive levels and ultimately bandwidth efficiency expectations.

For both cases, setting a maximum cascade design rule to offset the negative consequences of deeper cascades will drive cost into the migration plan in order to accomplish the segmentation needed. These costs can be modeled based on target objectives for the DOCSIS 4.0 network and the implications of those objectives on the cost of the network augmentation. In addition, as is always the case with network architecture, it can be phased over time to balance the deferment of upgrade cost with the need to achieve certain capacity and speed targets on Day 1 vs Day 1001. The flexibility to easily deploy new downstream and upstream capacity then becomes a consideration, always looking to eliminate or minimize physical plant touches.

## 4.3. Aerial or Underground Construction

For any network augmentation that involves pulling fiber or coax cable, there is a significant difference in the labor cost of this work between aerial and underground construction that is very favorable to the aerial plant style. The availability of conduit with unused carrying capacity underground helps to minimize this difference, where that is the case. Of course, not all underground is created equal either, such as augmentations that require tearing up concrete and crossing busy streets in metropolitan cores.

Operators know their own labor costs for these physical and regional variables, as well as any overhead costs associated with different municipalities, which can also vary widely. Sample network migration models can be created based on these known construction types. And, as pointed out in the discussion on "cascade depth," network augmentation can be phased as a function of time tied to capacity targets versus time, governed by CAGRs, and speed capability versus time, governed by the HSD business. The phasing has to be balanced by the opposing force of not creating too many network disruptions that are customer-impacting, and not creating excess inefficiency with too many ventures into the plant to take steps that were not sufficiently consequential the last time around in buying time to support traffic demand.

### 4.4. Homes Passed (HHP) Density

Not surprisingly, all else the same, it is more cost effective to upgrade a high-density area than a low density area, simply because the denominator is larger. Secondarily, there is a relative uniformity of higher density footprint that has a stabilizing effect on metrics, the customer experience and simplifying operations.

The boundary case of high density is the Multi-Dwelling Unit (MDU) environment. Unfortunately, and somewhat counterintuitively, such environments are also prone to be among the more challenging from an RF standpoint for a variety of reasons. MDUs will be discussed in more detail in the next section.

### 4.5. Network Powering

We will likely be asking more from the network power supplies that power the HFC plant when moving to DOCSIS 4.0. The DAA foundation of DOCSIS 4.0, the DSP that is introduced as part of FDX, or the extended bandwidth that is part of FDD all point towards taking a close look at the state of the existing network powering – voltage and amperage – as well as back-up power requirements.

Available power supply monitoring information has allowed Comcast to determine the percentage of upgraded footprint will require more current from existing supplies in a modest plant upgrade, and how many drive all-new power supplies to be added. Sensitivity analysis has been done around how many new amps of current drive power supply upgrades ($) or new power supplies altogether ($$$) given the known supply capacity margin going in.

### 4.6. Multi-Dwelling Units

When it comes to Multi Dwelling Units (MDUs), the "Good and Bad" are closely coupled. On one hand, an MDU can be considered the low hanging fruit for a DOCSIS 4.0 deployment given the high density and minimized cable lengths. It is that high density that makes these environments targets for competition. To add to the complexity, the FCC has rules (usually referred to as the "Inside Wiring Rules" 47 CFR 76.802) designed to enhance competition in MDU buildings. The FCC rules allow the MDU owner to gain control over Inside Wiring in order to make it available for use by a competitive service provider. It is these rules that make operators more reluctant to rewire the MDU or upgrade with fiber to each unit. A caveat to the FCC rules is that they are technology-agnostic and do not distinguish between the types of wiring that comprises the inside wiring. The applicability of the rules does not depend on whether the Inside Wiring is CAT-5, RG-6 or fiber optic cable.

The demographics of these properties vary greatly from location to location. Some utilize a campus layout, also known as a "garden style." Of course, the high-rise single building is usually what people think of when they hear "MDU." In any case, the density is typically much higher than serving single family units (SFUs), so an operator typically has opportunity for lower investment per living unit.

Servicing the MDU space is also unique in that the owner has the ability to grant exclusivity to the use of the inside wiring. This allows operators to sign "Bulk Agreements" to serve the entire building. Until recently buildings were often wired with coaxial cable. It is this wiring that DOCSIS 4.0 looks to leverage with symmetrical Gigabit speeds similar to fiber, without the costly expense of rewiring the building.

As with any HFC outside plant upgrade to increase bandwidth there will be some network and design challenges. With respect to MDUs, when compared to aerial or underground plant in easements or rights of ways, some of the challenges are similar. There are typically two types of environments, classified as either "Greenfield" new build or "Brownfield" existing network. The latter is the area that gives the greatest benefit to utilizing DOCSIS 4.0, given the re-use of the coaxial infrastructure that exists in a majority of buildings. The higher density of the MDU environment will allow operators to easily deploy in a cost effective and strategic manner. Operators have taken note of the power of fiber to the building, and thereby many sites are fed from a "Dedicated Node" that serves the complex only. These dedicated nodes can be upgraded incrementally by only making changes to that location. Even in the garden style layout there are very few actives and much less cable than single family units. The latter is of high importance given the higher attenuation of coaxial cable at upper frequencies. These shorter coaxial runs would also benefit from a future 3.0 GHz Extended Spectrum for the same reason.

In Greenfield, more builders and owners are opting to install fiber or Ethernet cable as they build the units. These will typically be fed using a Passive Optical Network (PON) technology which is not the focus for this paper. However, cable operators have equalized the conversation around fiber vs coax with respect to HSD speed offerings with DOCSIS 3.1 and DOCSIS 4.0.

Experienced field personnel will attest to the fact that MDUs have their own set of challenges related to maintaining the integrity of the RF performance. These units typically have high churn with people moving in and out more often. This creates more opportunities for loose connectors, open terminations, damaged inside wiring, etc. These types of issues can result in a trouble call or truck roll to resolve. Note for DOCSIS 4.0 Extended Spectrum, the new bands will be occupied by OFDM carriers only, which are much more resilient than SC-QAM signals, with better error correction and with the ability to change modulation profiles when needed.

The above MDU variables can be considered in the MDU design during the deployment. DOCSIS 4.0 has some requirements that will change how these buildings are served. Two of the biggest DOCSIS 4.0 changes are:

1) DOCSIS 4.0 must be deployed as part of a *Distributed Access Architecture* (DAA). With this requirement, there will no longer be a reliance on analog optics that serve nodes today. This will result in improved signal fidelity to the property and into the unit, and thus more DOCSIS 4.0 capacity.

2) The DOCSIS 4.0 modem will be a *Point of Entry device* when used in DOCSIS 4.0 mode, meaning that it will be the sole HFC-terminating device in the unit. There will be no need to be concerned with the splitter network to feed other boxes, such as STBs, and in many cases also the cabling inside the unit. These fundamental changes reduce the concern that we typically have when dealing with insertion and attenuation loses.

As stated in the beginning, MDU environments could be considered the low hanging fruit for initial DOCSIS 4.0 deployments to provide multi-gigabyte services without the need to re-wire the inside of the units. We even see a possibility of leveraging 3.0 GHz in the future in the MDU space.

## 4.7. The Home Network

With increasing numbers of Wi-Fi devices within home networks (on average, there are currently 15.8 Wi-Fi connected devices per home, and current projections have these numbers doubling to above 36 devices per home by 2025), the strong preference for the convenience of wireless over wired by customers, the increase in IP traffic to and within the home, and the move to higher speed WAN solutions such as DOCSIS4.0, it is imperative that the industry collectively start assessing the various options for in-home devices to meet these evolving customer needs. Operators and technology partner experts who are focused on the customer experience, premise equipment, technical operations, and fulfillment operations are well aware of one of the fundamental questions around in-home device architectures; whether to deploy a single integrated Gateway box (device) or a dual box solution that separates the WAN modem from the LAN gateway. The advent of DOCSIS 4.0 has reignited that discussion, largely due to the value of locating the DOCSIS 4.0 modem near the home's demarcation for improved DOCSIS performance.

In considering the CPE options for a DOCSIS 4.0 solution, there are a number of tradeoffs that need to be contemplated. The primary consideration is the customer experience from ordering the service, to unboxing the devices(s), to installation and activation, to performance and reliability, and if there is an issue, how the customer can identify and quickly resolve the issue. Other key considerations include the cost of the device(s), as well as operational costs of managing SKUs including supply chain, Technical Operations, and care.

When talking about a 1-Box or 2-Box solution, the first consideration is to decide what functionality goes in each device. For the 1-Box solution, everything is integrated into a single device, so this is more straightforward. However, when this functionality is split across two boxes, the split of the integrated functionality across two devices as well as the connectivity between those devices must be considered. **Table 4** below shows one option for the separation of functionality; however, other options are possible depending on specific services that need to be supported as well as operational considerations.

**Table 4 - DOCSIS 4.0 CPE 1-Box vs 2-Box Considerations**

| | | |
|---|---|---|
| Integrated Modem, and WiFi Router<br>• DOCSIS 4.0<br>• Telephony<br>• Routing<br>• LAN connectivity<br>  • Ethernet<br>  • WiFi<br>• IoT | Box 1-D4.0 Modem<br>• DOCSIS 4.0<br>• Telephony | Box 2-Ethernet Gateway<br>• Routing<br>• LAN connectivity<br>  • Ethernet<br>  • WiFi<br>• IoT |

As noted previously, there are pros and cons to either the 1-box or 2-box approach. A single box configuration enables the Service Provider to offer a single device (gateway) to deliver the customer's connectivity and all of their IP-based services. This option makes an SIK installation process relatively simple, assuming no RF-related issues at the premises (note – a 2-box solution can also be based on an SIK model). However, it also can introduce some additional complexity around in-home/Wi-Fi connectivity. The connectivity issues are generally related to the location of the RF outlet within the premise, which is often not centrally located within the dwelling. The advancement in Wi-Fi and mesh technologies has helped alleviate the wireless connectivity challenges of the past.

Consider **Figure 20**. When considering a 2-box solution, one of the advantages, if properly executed, is that it can allow the router to be placed in a more central location in the home. This will likely provide a better in-home connectivity experience, as the Wi-Fi functionality in the gateway can be more centrally located within the home. Another advantage of the 2-Box configuration is the ability of the DOCSIS 4.0 device to be located at the demarcation, which will improve DOCSIS 4.0 performance by avoiding any additional passive losses or impairments from actives withing the home, as the in-home wiring is uncontrolled and can create installation and troubleshooting challenges. Avoiding this potential unnecessary degradation to the DOCSIS 4.0 solution can be beneficial to both operators (consistent performance, straightforward operations) and customers (higher speeds, more consistent performance, fewer technician visits). This is true from DOCSIS 3.1 as well, but the value of a demarcation installation with DOCSIS 4.0 is amplified since we are pushing the limits of the RF capabilities of the coax network.

The industry has been fortunate for some time in that the core WAN and Wi-Fi technologies have not been changing (individually or jointly) historically at the pace being observed today. The recent launch of WiFi6 (2019), the approval for Wi-Fi 6E (2020), and pending Wi-Fi 7 specification ratification suggest Wi-Fi is iterating at an accelerated pace, which is a good reason to consider a 2-Box solution. A 2-box solution allows the WAN and LAN functionality to be updated independently since this functionality is physically separated between two devices. As always, however, it comes with a cost that must be considered. These costs could manifest negatively on the operator side and the customer experience side. Some of these implications are discussed below.

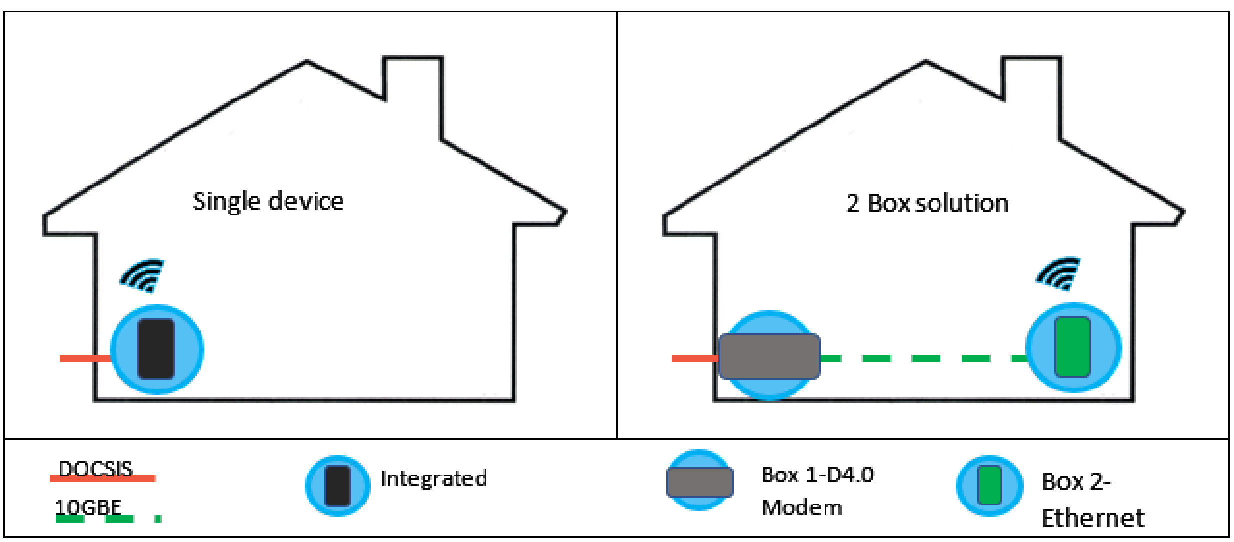



**Figure 19 - DOCSIS 4.0 CPE 1-Box vs 2-Box Installation**

As an example, an interesting challenge with a 2-box configuration is related to the connectivity between box 1 and box 2. As we look to moving to multi-gigabit speeds within the home we are faced with a couple of choices.

1. Leverage a 10Gbit Ethernet connection between the devices, which provides a robust connection but introduces complexity around running Ethernet cables and could compromise the ability to locate box 2 (router) with Wi-Fi in a central location within the home. This potentially undermines one of the key advantages of a 2-box solution, which is flexibility in the location of the Wi-Fi AP.

2. Consider leveraging a wireless medium (mmWave or Wi-Fi) for backhaul. Wireless backhaul introduces other challenges from cost on each device to managing Wi-Fi congestion within customer premises and guaranteeing reliable multi-Gigabit performance.

Another interesting item for consideration in the 2-box architecture, with its own "pros" and "cons," is whether the WAN (box 1) could be hardened and sit outside the customer premise or if it should be located within the dwelling. Locating the DOCSIS 4.0 eMTA outside the home has operational benefits as the Technician is now able to troubleshoot DOCSIS issues without having to enter the customer's home. However, in addition to the cost of hardening a modem to work in an outdoor environment, powering this device and how to get the LAN connected from outside the home to the Wi-Fi router in the home can be a challenge. Having the DOCSIS 4.0 eMTA outside the home also has some potential security risks because the LAN will be exposed outside the home. With all of these constraints in mind, it has been difficult to date to justify mounting the DOCSIS device outside the home.

With the increasing demands on our networks, the need to move to DOCSIS 4.0 longer-term is clear, and while this will take some time, it is important to plan how this technology will be deployed. While there are significant considerations for the DOCSIS networks as part of this transition, we must also be thoughtful about the CPE solution, as it is not likely to be cost-effective initially to deploy only DOCSIS 4.0 devices as this new technology is being launched. With that in mind, the customer impact and operational impact of the CPE decisions must be considered.

## 5. Planner's Guide to DOCSIS 4.0 Migration

There are reasons that North American cable operators, although generally aiming for similar service objectives, operating in similar competitive environments, and with common ecosystem technology options to choose from, have deviated in their architectural solutions and directions over time. Looking back to the mid-2000's, the popular debates of the era were many. Perhaps most prominent was around how to future-proof the downstream – the concern of the time – with increasing demand for HD channels, which consumed significantly more bandwidth per HD program (4-5x) than standard definition (SD) video. Back then, the discussions were around upgrading plant spectrum, deploying Digital Terminal Adaptors (DTAs), deploying Switched Digital Video (SDV), and transitioning to IP Video. Note these are also mostly complementary initiatives (SDV or IP Video being the exception).

More broadly, invest in FTTH now or double down on coax technologies was a hot topic. This perhaps sounds odd, given the 15+ years of continued successful coaxial strategy. But this period of time was also the launch of major Telco-based FTTH initiatives that signaled the "end" of cable services, again.

For MSOs, and again in particular large MSOs with broad and diverse geographical footprint, there are also many different starting points of HFC networks. Other initial conditions include existing portfolios of CPE devices with ranges of capabilities, critical OEM partners with varying roadmaps and unique expertise, different internal viewpoints on where the investment focus should be, and different perspective on near term and long-term architecture. Capacity-building investment does not have simple, direct revenue tied to it the way new service opportunities do. Yet supporting capacity growth and demand is the cost of doing business as a network provider.

Furthermore, across operators and within a single operator, there are

- Different network architectures, often related to the range of per-homes passed (hhp) densities
- Different construction practices
- Zip-code, neighborhood, and property-specific demographics
- Different municipal operating environments
- Regionally varying competitive environments

These variables make it challenging for simple-to-state guidelines to easily apply and be executed. For example, a Comcast axiom previously mentioned was that the upgrade approach selected for an area must ensure at least a 5-yr lifespan before it would project to be augmented again. These types of principles are based on a combination of both network traffic and business modeling of executing various upgrade options.

The list above could surely be expanded upon, but it suffices to say, as the clichés go:

1) Cable solutions are rarely one-size-fits-all
2) Operators need a variety of "tools in the toolbox"
3) Evolution over Revolution

DOCSIS 4.0 is aligned to these well-worn principles.

## 5.1. DOCSIS 4.0 Begins with DAA

A major technology upgrade consensus "mandate" among operators is that the DOCSIS 4.0 roadmap will be based on DAA. Of course, this itself has tentacles that have been covered many times over in previous technical conferences, panels, the media, etc. There are different options within DAA. Comcast chose the Remote PHY (RPHY) path over 5 years ago, and has been successfully deploying DAA via RPHY in production scale for over 3 years. Some of this success can be attributed to moving the RPHY platform onto a virtualized CMTS core (vCMTS), decreasing interoperability permutations, and simplifying SW upgrades and changes through this centralized platform. With a node platform significantly more SW-based than its predecessors, this direction and migrating to agile development within the vCMTS was viewed as a critical step.

Since the standardization and deployments of RPHY, the Flexible MAC Architecture (FMA aka R-MACPHY) initiative at CableLabs has continued and matured. Some MSO's envision FMA as their DAA vehicle. There is a pro-con set of attributes to weigh between RPHY and FMA that is well-worn. For the topic of this paper, it is considered mostly orthogonal – DAA of one form or another must be in place for DOCSIS 4.0. RPHY vs R-MACPHY is not a significant consideration with respect to the DOCSIS 4.0 options. FDX or FDD can be implemented without any major dependencies.

## 5.2. Building a DOCSIS 4,0 Plan? Ask these Questions….

The debate over whether to move ahead with FDX or FDD is not likely to result in a crisp answer soon (if ever.) The reason is simple – there is no statistically meaningful data from which to make comparisons of the two, or to compare the projected results versus actual. There has been excellent DOCSIS 4.0 progress, as we have discussed herein, but sample size and trial variety progress, not results of scale or statistical significance. FDX proof-of-concept field trials were executed in 2018 and 2019 using modified DOCSIS 3.1 devices with FDX EC designs from key technology partners. In addition, FDD field characterizations across multiple MSO networks to quantify the extended bandwidth behavior of various architectures and passive components of today's networks have also been completed.

A major milestone in 2021 shed some light on how the slideware is comparing to the reality using the first true DOCSIS 4.0 FDX RPD production SoC vehicle. Thus, the era of minimal information is coming to an end. The DOCSIS 4.0 RMD for FDD is now also in labs today. By the end of 2021, we will see DOCSIS4.0 FDX end-to-end modem registration, and in 2022 have a first look at FDX performance in the field from vCMTS to RPD to CPE. So….we are on the verge of learning A LOT about the reality of both of these DOCSIS 4.0 options technically over the next 12-18 months.

Genuine technical capability and more confident, empirically-based extrapolations, based on real measurements, against the range of environments and conditions described will add significant insight in this time frame. However, it will be longer than 12-18 months to compare projected versus actual with respect to upgrade costs and operational challenges, since production at scale takes a few iterations to get right and production field teams take time to get ramped up, while incubation teams manage early technology introductions. Scale is a slowly ramping process where new technology and operational processes are concerned, as efficiency is a lower priority early on. And many fundamental components of construction, and upgrade costs, *are* well-understood. This includes items such as BAU node splits, DAA node splits, RF amplifier swaps, tap swaps, pulling fiber, upgrading coaxial cable, power supply augments, CMTS ports, spectrum addition, CPE installs, etc. Most MSOs have a good handle on these activities and mature budgeting around them. It is because of this that MSOs are able to form reasonable models, adding assumption figures or ranges to capture unknowns and sensitivity to unknowns of a DOCSIS 4.0 upgrade. And, like any new technology, DOCSIS 4.0 FDX and DOCSIS 4.0 FDD will bring their share of unknowns.

With this in mind, lets return to the attributes comparison of **Table 4** and try to reduce the broad implications of a single table of high-level attributes into a few succinct questions that can be used as a guide, as shown in **Table 5**. From there, we'll attempt to narrow these to what's really at the junction of Analysis Paralysis Avenue and Religious Belief Boulevard.

**Table 5 - DOCSIS 4.0 Attributes Comparison - FAQs**

| Attribute | FDD/ESD | FDX |
|---|---|---|
| Strategy/Philosophy to 10G | • Based on access network BW extension upgrade, up to 1.8GHz, for existing actives and passives<br>• Introduction of DAA to migrate to 10G, similar to previous HFC plant upgrades with a choice of diplex split configurations | • Based on access network technology upgrades to introduce new DSP (EC) into RPHY nodes and Amplifier platforms<br>• Build on DAA production and scaling of vCMTS as the foundation for 10G |
| Key Questions | • What is the confidence level for efficient, quality spectrum to 1.8 GHz?<br>• Is changing every active and passive in the plant non-regrettable capital? | • What is the confidence in broadband Echo Cancellation?<br>• Is adding new EC to RF amplifiers too complex a device? |

| Attribute | FDD/ESD | FDX |
|---|---|---|
| Migration Factors | • 1.8 GHz DOCSIS 4.0 DAA Nodes, Amps, Taps and Passives<br>• Allows for cascade of amplifiers<br>• New CPE | • RPD Nodes with DOCSIS 4.0 EC function<br>• FDX-capable amps with DSP<br>• New CPE |
| Key Questions | • What are the projected new costs, cost premiums, and construction cost for FDD migration? | • What are the projected new costs, cost premiums, and construction cost for FDX migration? |

| Attribute | FDD/ESD | FDX |
|---|---|---|
| Complexity | • New tech challenges – BW and TCP extension<br>• Use of "low power" amp extender for edge cases | • New tech challenges – EC function, CMTS scheduler, DSP-based amps<br>• New capacity mgmt rule for IG/TG size for peak speed |
| Key Questions | • What are the practical limits of freq response and TCP for most of the targeted upgrade area?<br>• Do all Taps and passives get swapped? | • What is the risk associated with the new technology of FDX?<br>• What are the new algorithms for Capacity mgmt? |

| Attribute | FDD/ESD | FDX |
|---|---|---|
| Spectrum/Capacity | • 1536 MHz DS/656 MHz US (see **Figure 13** and **Table 1**)<br>• Up to 15G/5G (all-DOCSIS 3.1)<br>• DS/US: BW and Capacity per diplex selection | • 1110 MHz DS / 656 MHz US (see **Figure 2**)<br>• Up to 11G/5G (simultaneous, all-DOCSIS 3.1)<br>• FDX BW/speed by SW config |
| Key Questions | • What are the real BW efficiencies in the new US bands and DS bands for FDD? | • What are the real BW efficiency in the new overlapping US and DS bands for FDX? |

| Attribute | FDD/ESD | FDX |
|---|---|---|
| Operations | • Utilize existing common operational practices – FDD system with different possible split choices<br>• New field tools | • New operational practices for handling of spectrum overlap and amplifier installations<br>• New field tools |
| Key Questions | • What are the alignment and maintenance implications for support downstream bandwidth to 1.8 GHz? | • What are the setup and maintenance implications to supporting FDX actives and overlapping spectrum on the plant? |

| Attribute | FDD/ESD | FDX |
|---|---|---|
| Network | • N+X<br>• Cascade reduction/trade-off based market capabilities | • N+0 (optimal)<br>• N+X – Cascade reduction/trade-off based on market speeds |
| Key Questions | • What are the realistic N+x limitations for 1.8 GHz?<br>• For different generations of plant design?<br>• How does that translate to Capacity Q above? | • What are the realistic N+x limitation for FDX?<br>• For what service speeds and penetration?<br>• How does that translate to Capacity Q above? |

| Attribute | FDD/ESD | FDX |
|---|---|---|
| As-Built Migration | • Continue node split and introduce DAA node splits, leverage for HFC migration activity, introducing components of FDD over time<br>• Migration path and timing considerations for Underground vs Aerial and MDU vs SDU cost implications | • Introduce DAA for node splits with vCMTS, leverage for HFC migration activity and platforms that enable FDX activation<br>• Migration path and timing considerations for Underground vs Aerial and MDU vs SDU cost implications |
| Key Questions | • How are actives and passives upgraded over time?<br>• How much additional cost is associated with N+x caps, new cabling, or remediating poor frequency response | • How are amplifiers upgraded to FDX?<br>• How much additional cost is associated with Amplifier DSP or N+X caps? |

**Table 4** and **Table 5** cover many variables, and yet, as anyone who has engaged with field teams and network construction personnel can attest, beneath each of these are additional layers of detail owing to the aforementioned variability of architecture and plant in an MSO network. DOCSIS 4.0 implementation will at least establish an HFC demarcation at the DOCSIS 4.0 CPE device and eliminate all or most of the home coaxial network variability, which today is technically, unfortunately, part of the HFC network.

If we were to consolidate the 20,000 ft. list of **Table 5** list into what "really really" are DOCSIS 4.0 FDX and FDD decisions hinging on – what consumes the majority of the dialogue when drawing up the internal pro-con table for the mighty offsite whiteboard sessions (in a nod to the impact of Covid – this actually sounds attractive!)– it might look like **Table 6**.

**Table 6 - Debate Kindling Top 3**

| Challenges | FDD/ESD | FDX |
|---|---|---|
| 1 | Total Composite Power limitations for 1.8 GHz | N+0 foundation implications for cost |
| 2 | As-built freq response over N+x | New technology risk |
| 3 | Upgrade and replacement of all taps and passives | FDX amp and N+x operation |

## 6. Summary

The 10G network is perhaps the most recognizable industry-wide initiative today. Its vision has been organized around four key pillars of service – capacity/speed, latency, reliability, and security. For the access network, it is the capacity and speed objective, in particular symmetrical multi-gigabit capability that represents the most directly addressable. It is a shift from existing BAU network migration strategies, because of its dependence on physical network changes over and above node splits, and because of the massive service payoff in the form of significantly more capable HSD services.

From the first established at the Consumer Electronics Show (CES) in 2019, the details of the visions gave way to the development of the technical requirements to achieve it, which is DOCSIS 4.0. The FDX specification actually began its life as an Appendix to the DOCSIS 3.1 specification aimed at optimization capability for N+0 systems. The DOCSIS 4.0 specifications are now completed and released for both FDX and FDD. For "FDX, the Appendix," was a "lift and shift" operation into DOCSIS 4.0. The FDD specification was then completed, with the latest release that includes both (I03) publishing in December 2020.

In this paper, we tried to objectively, but (of course) through individual company lenses, articulate common and differentiating characteristics of FDD and FDX, compare the implications of the most important characteristics beyond the slideware and into real upgrade consequences, and bring to the external whiteboard some of the discussion points that have been occurring in internal and cross-MSO network brainstorming sessions. Hopefully this paper has provided a peek into these dialogues.

Lastly, while some of these activities are clearly multi-year endeavors and apt to adapt with learnings over time, there is always a need for a "North Star" target. Among most (but not all) cable operators, DOCSIS 4.0 is this North Star. There is an early fork of implementation paths, but many MSOs have assessed which trail makes sense for them at the outset of their DOCSIS 4.0 journey. Breadcrumbs recommended!

# Abbreviations

| | |
|---|---|
| A-TDMA | Advanced Time-Division Multiple Access |
| BAU | bits per second |
| CAGR | forward error correction |
| CES | high definition |
| CM | hertz |
| CMTS | International Society of Broadband Experts |
| DAA | kelvin |
| DS | Society of Cable Telecommunications Engineers |
| DSL | Digital Subscriber Line |
| DSLAM | Digital Subscriber Line Access Multiplexer |
| DSP | Digital Signal Processing |
| EC | Echo Cancellation |
| ESD | Extended Spectrum DOCSIS |
| EOL | End-of-Life |
| FDD | Frequency Domain Duplex (aka DOCSIS 4.0 ESD) |
| FDX | DOCSIS 4.0 Full Duplex |
| FDX RPD | FDX Remothe PHY Device |
| FDX-L | FDX-Light |
| FEC | Forward Error Correction |
| FTTH | Fiber-to-the-Home |
| HSD | High Speed Data |
| IG | Interference Group |
| LDPC | Low Density Parity Check Code |
| LLD | Low Latency DOCSIS |
| MDU | Multi-Dwelling Unit |
| MER | Modulation Error Rate |
| MMP | Multiple Modulation Profiles |
| OFDMA | Orthogonal Frequency Division Multiple Access |
| OEM | Original Equipment Manufacturer |
| OFDM | Orthogonal Frequency Division Multiplexing |
| pbh | Peak Busy Hour |
| PMA | Profile Management Application |
| PON | Passive Optical Network |
| RBA | Resource Block Assignment |
| SDV | Switched Digital Video |
| SoC | System-on-a-Chip |
| STB | Settop Box |
| TCP | Total Composite Power |
| TG | Transmission Group |
| UHS | Ultra High Split |
| US | Upstream |
| xDSL | [any variant of] Digital Subscriber Line |

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