Operational Considerations & Configurations for FDX & Soft-FDX

A Network Migration Guide To Converge The Cable Industry

A Technical Paper prepared for SCTE•ISBE by

Ayham Al-Banna, Ph.D.
Engineering Fellow, CTO Office – Network Solutions
Commscope
2400 Ogden Ave., Suite 180, Lisle, IL 60532, USA
630-281-3009
Ayham.Al-Banna@Commscope.com

Frank O'Keeffe, Ph.D.
Distinguished Systems Engineer, CTO Office – Network Solutions
Commscope

Tom Cloonan, Ph.D.
CTO – Network Solutions
Commscope

Table of Contents

Title **Page Number**

List of Figures

Title **Page Number**

List of Tables

Introduction

There are many available technologies that will extend the life of hybrid fiber coaxial (HFC) networks. These include Full Duplex DOCSIS (FDX), Soft Full Duplex DOCSIS (Soft-FDX), and Extended Spectrum DOCSIS (ESD). This paper will provide an overview of these technologies along with capacity simulation results and a gradual migration strategy. It will be shown that HFC networks have enough capacity to meet the demand and address competition for the next two decades.

HFC networks are in the best position to create the future 10G networks, which are needed to support symmetrical services through the Data Over Cable Service Interface Specifications (DOCSIS). Multiple technologies are available to augment the current capacities of HFC networks, such as FDX and ESD. Some of the early deployments of the FDX & ESD technologies can be focused on increasing the upstream (US) throughput. This can be done by utilizing a special mode of FDX, where the FDX node and modem technology are used to move the US split to a higher frequency. This deployment scenario is called Soft-FDX and is suitable for cascaded N+x (i.e., Node followed by x amplifiers) networks.

This paper shows how these technologies are complementary in nature and explains how the Soft-FDX technology can deliver similar performance to that of the traditional FDX while using the same node technology and modem silicon chips that are currently being developed for first generation of FDX products. The paper also explains the inefficiencies in spectrum usage that results from configuring FDX grids with small allocated FDX spectrum sizes. Furthermore, it proposes operational modes and spectral configurations that will allow FDX modems that are running in FDX mode to efficiently utilize the spectrum regardless of the size of the allocated FDX spectrum.

The paper additionally shows some simulation results of potential capacities that can be achieved in cascaded N+x Soft-FDX networks when using first generation FDX node and modem silicon. It also compares this capacity to the capacity that can be obtained from running the network in a native N+0 traditional FDX operation. ESD simulations to 1.8 GHz and 3 GHz are also provided.

Another operational complexity that is studied in this paper is the topic of video delivery and out-of-band (OOB) signal handling in both N+0 traditional FDX and N+x Soft-FDX networks.

The paper also discusses various network migration strategies that will help the multiple service operators (MSOs) in selecting gradual evolution steps to reach the desired goal architecture.

The paper is organized as follows. Section 1 provides high-level FDX overview. FDX grids and potential inefficiencies are discussed in Section 2. Section 3 discusses FDX for cascaded networks, which is followed by the Soft-FDX overview in Section 4. Section 5 provides simulations results for FDX & Soft-FDX systems. FDX Taxonomy is proposed and discussed in Section 6. Section 7 discusses video OOB delivery mechanism. ESD is discussed and simulations results are provided in Section 8. Finally, Section 9 proposes a network migration diagram and discusses various network migration strategies.

Content

1. Full Duplex DOCSIS (FDX)

This section provides a high-level overview of the FDX technology. Readers that are familiar with topic may skip to the next section.

The FDX specifications [FDX_PHY] were created to provide the MSOs with ways to increase the offered US speeds without sacrificing the valuable downstream (DS) spectrum. This is done by overlapping the US & DS spectra as shown in Figure 1, where range of overlap is from 108-684 MHz and makes the FDX band.

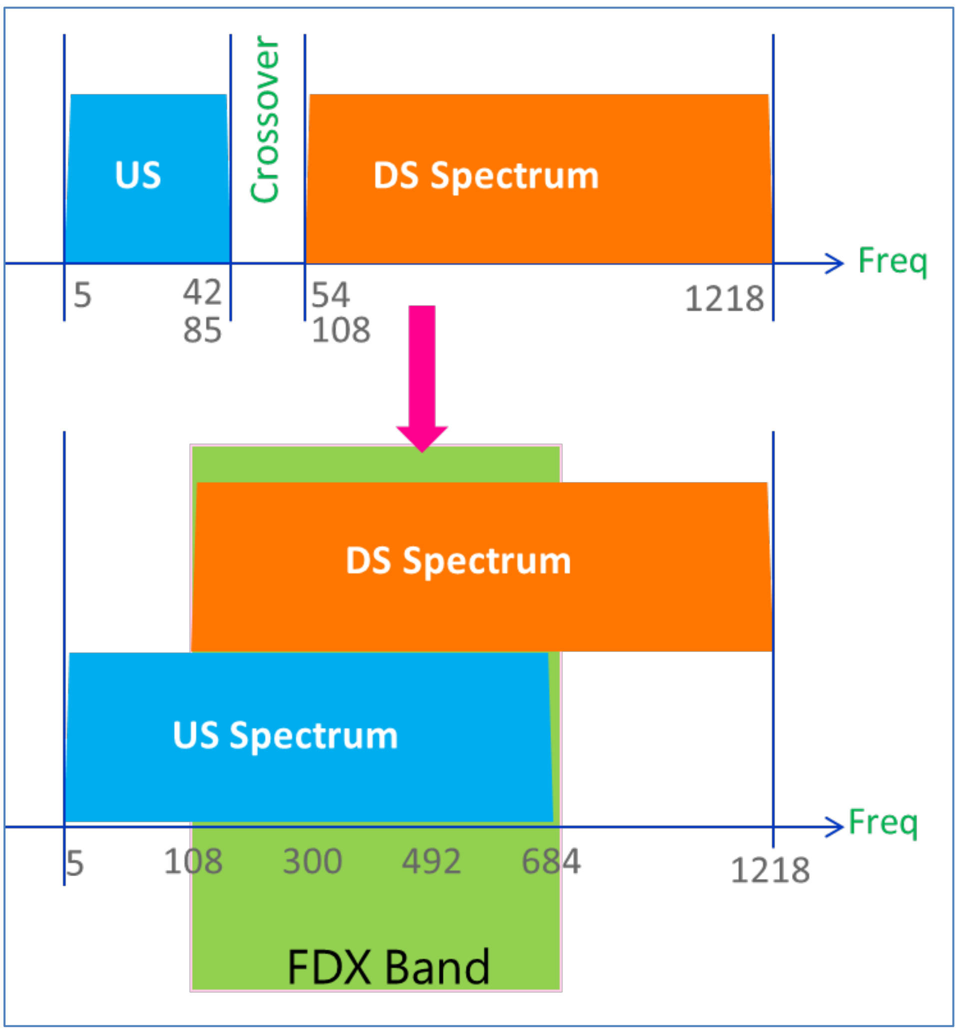

Figure 1 - Overlapping US & DS spectra in FDX systems

A key assumption that was made while creating the FDX specifications was that the target FDX network architecture is a fiber deep (FD) distributed access architecture (DAA) N+0 network and therefore new node designs are needed to offer the FDX functionality. Note that N+0 means that the plant is completely passive (i.e. no amplifiers) between the node and the cable modem (CM) and therefore the plant echo cancellation (EC) functionality will need to be implemented in the DAA node, which can be based on either remote PHY (RPHY) or remote MAC-PHY (R-MAC-PHY) architectures.

The FDX functionality in the node is achieved by the node's ability to perform echo cancellation. Echo cancellation is needed because the node is using the same spectrum for simultaneous DS transmissions and US receptions as shown in Figure 2. Additionally, the DS signals are transmitted at much higher levels than the levels of the received US signals at the node leading to negative signal to noise ratio (SNR) values for US transmissions received by the node. Node and plant micro-reflections need to be cancelled in order for US signals to be successfully demodulated by the node burst receiver.

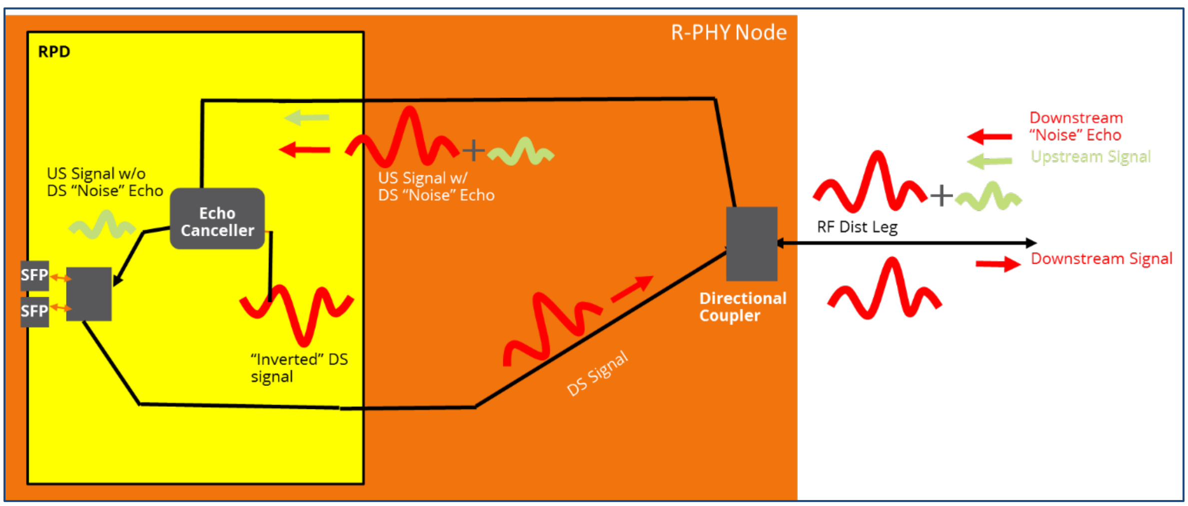

Figure 2 - FDX Node Echo Cancellation

HFC plants are subject to environmental and non-environmental changes which can affect the performance of FDX systems. An example of these changes include wind, temperature, repair incidents, damage, etc. The EC will need to update its coefficients frequently in order to compensate for the plant changes, which is essential to maintain good quality of experience (QoE) service to customers in different weather and maintenance events. An example of this process is shown in Figure 3 and Figure 4, which show the errors of an EC during a plant maintenance event (tap faceplate removal) from a field trial activity. Observe that the EC quickly converged and updated its coefficients to cancel the new micro-reflection pattern and continue to provide error-free operation.

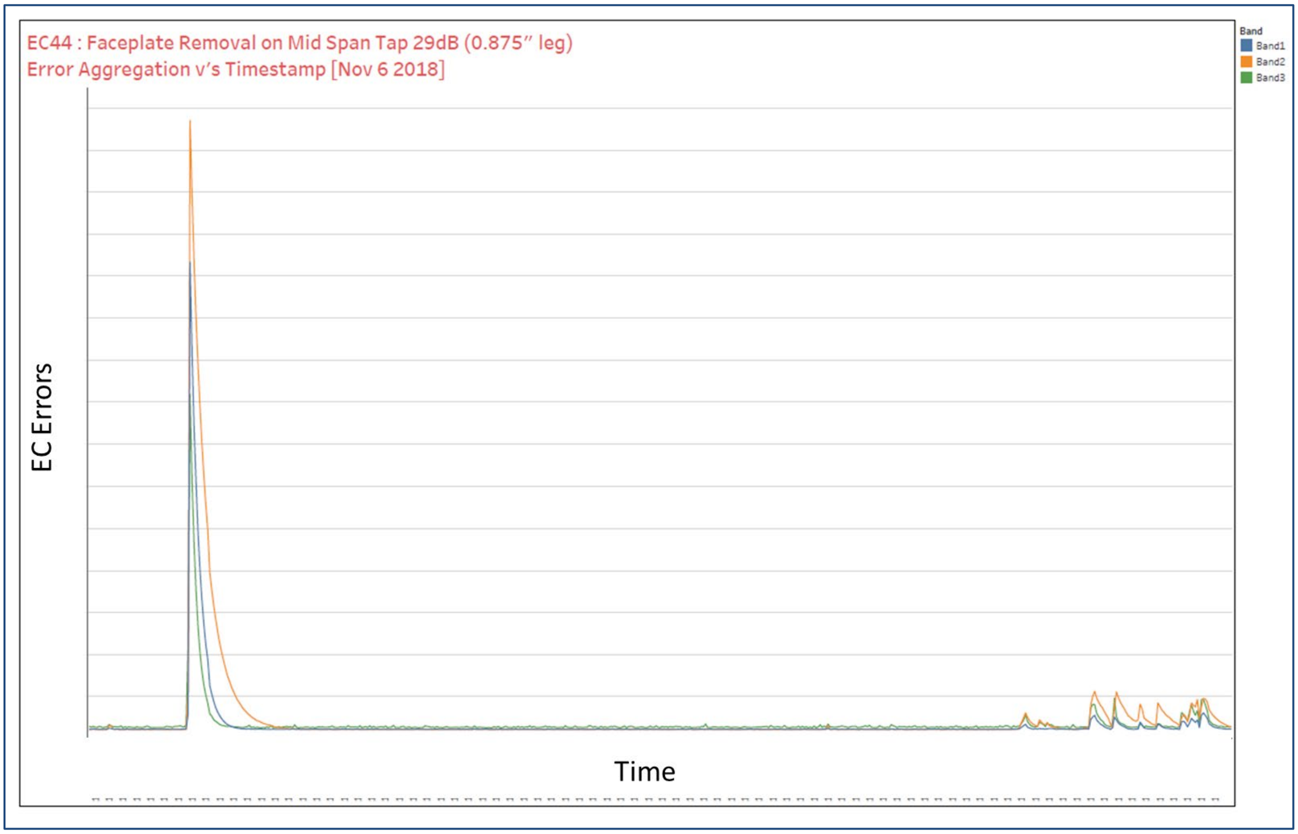

Figure 3 - EC errors in a plant maintenance event from a field trial

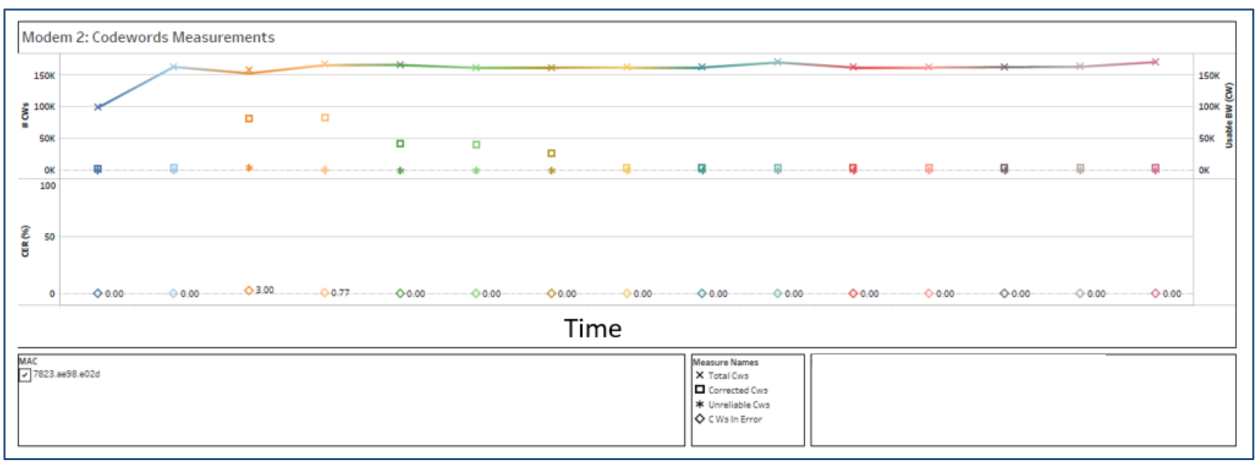

Figure 4 - Performance during the plant maintenance event from a field trial in Figure 3

Another challenge with cable systems is that these systems are point-to-multi-point systems as shown in Figure 5. This topology causes interference between modems. The problem in cable systems is that many cable modems share the same medium in a point-to-multipoint network, which causes a lot of trouble in an FDX environment, where the high-level US transmission of one modem can damage the DS reception of the next-door neighbor (the DS signal is weak at the CM). The US signal is coupled into the DS path through the finite isolation between tap ports causing US signal leakage into the DS signal and thus leading to low or negative DS SNR values at the neighboring CMs as shown in Figure 6.

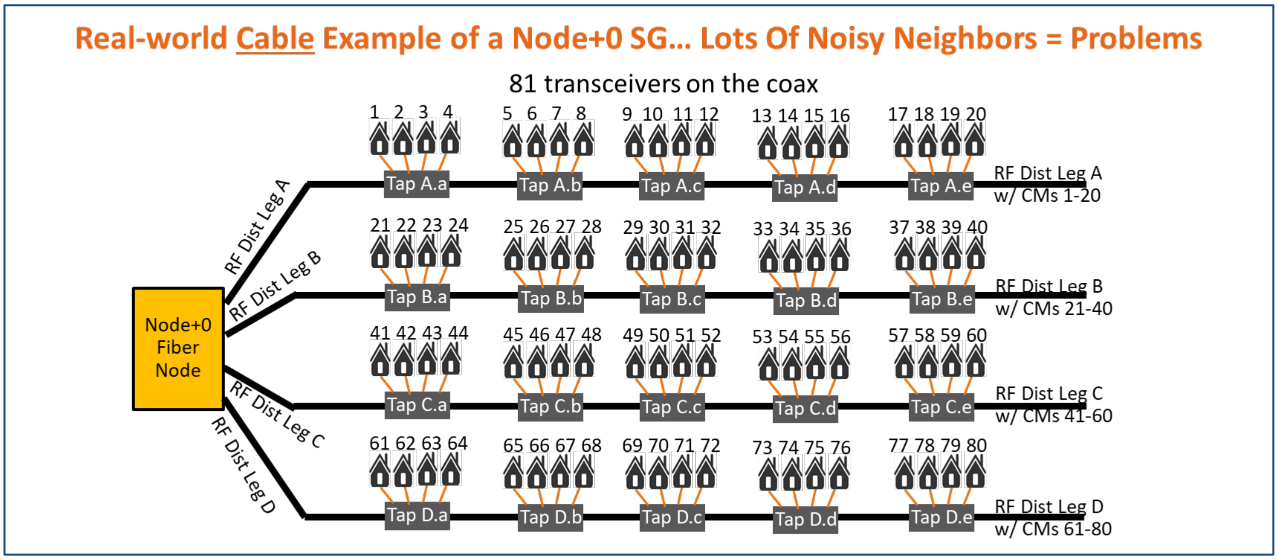

Figure 5 - FDX Challenges with Cable Plants

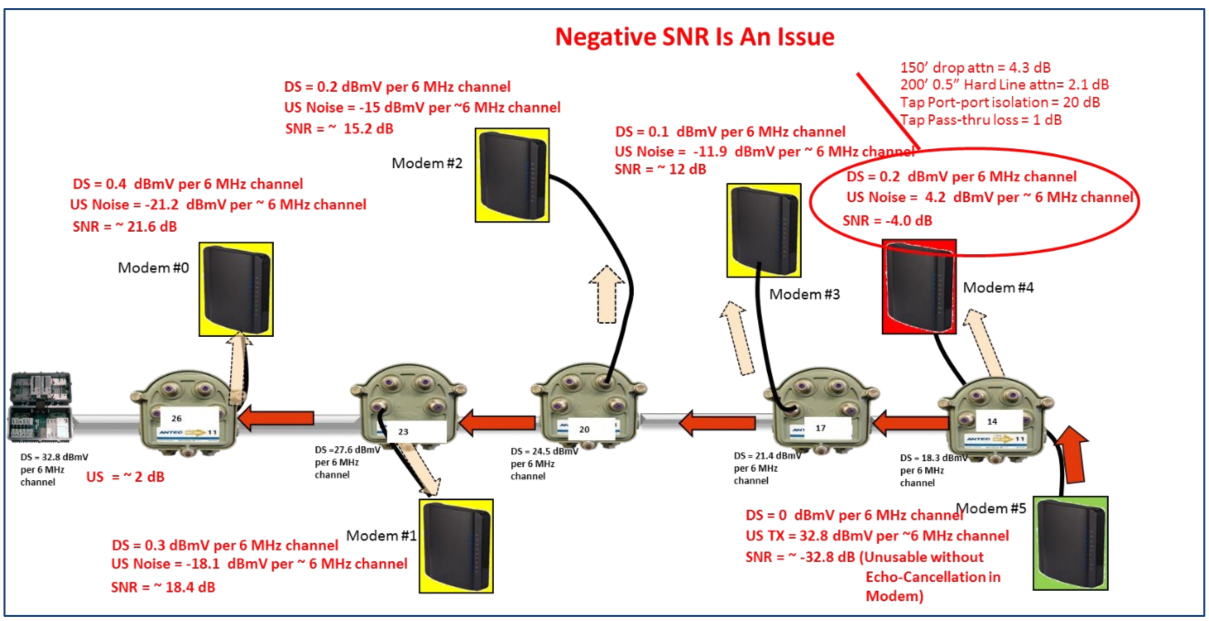

Figure 6 - Example of FDX Challenges with Cable Plants

Enabling the FDX functionality requires removing the diplexer from the node and modems. This poses a key challenge because the DS and US signal power on the device become related and affect each other. In the FDX environment, there are different types of interference which are described below and shown in Figure 7.

- **ALI (adjacent leakage interference)**: Occurs when a transmitter injects energy next to the frequency band where energy is being tuned to in a receiver, and the tails of that transmitted energy leak into the receiver's tuning spectrum (top of Figure 7).
- **ACI (adjacent channel interference)**: Occurs when a transmitter injects energy outside of the frequency band where energy is being tuned to in a receiver, but the transmitted energy is still within the passband of the automatic gain control (AGC) circuit and/or analog to digital converter (ADC) causing potential blinding (middle of Figure 7).
- **CCI (co-channel interference)**: Occurs when a transmitter injects energy on top of the frequency band where energy is being tuned to in a receiver (bottom of Figure 7).

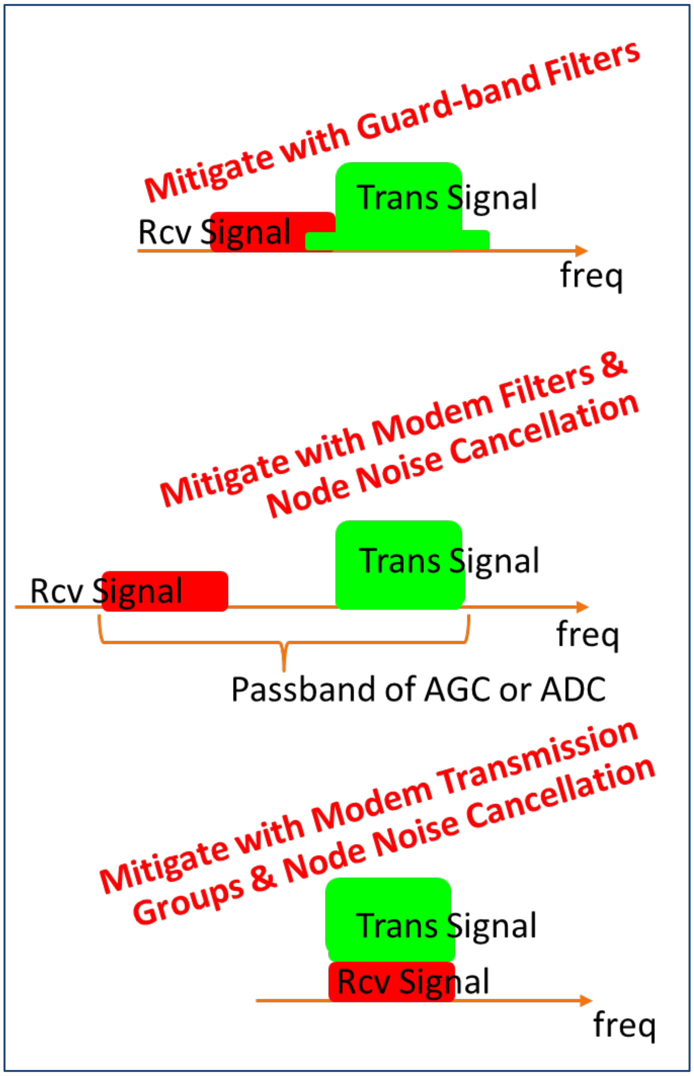

Figure 7 - Different types of FDX Interferences (ALI, ACI, and CCI)

Given the above inter-modem interference problem, one of the challenges with the FDX environment is to figure out which modems interfere with each other so they can be logically separated. MSOs do not normally have access to a database that contains the modems' physical locations relative to the plant (i.e., which tap, tap port etc.). Therefore, a method needs to be developed to give the media access control (MAC) Domain controller function within the remote MACPHY device (RMD) or cable modem termination system (CMTS) the ability to identify the interfering modems without requiring a database of modems' physical locations. This method was developed in the FDX specifications [FDX_PHY] [FDX_MULPI] and is called sounding.

The sounding algorithm is a technique by which each modem transmits a signal in the US direction while other neighboring modems in the service group (SG) listen to the transmission and determine the signal strength of that US transmission. Measurements are used to determine the CCI-based signal to interference ratio (SIR) levels that would result if a modem tried to receive a DS signal in the presence of the US interfering signal from its neighbor (when the DS signal & US signal are in the same frequency band). A few notes about sounding are listed below:

- Particular pairs of neighbors who find that their resulting CCI-based SIRs would be inadequate to permit the reception of the DS signal are declared to be "noisy neighbors"
- Note that even if Modem X has a good DS SIR when Modem Y transmits in the US, if we find that Modem Y has an inadequate DS SIR whenever Modem X transmits in the US, then Modem X & Modem Y are still declared to be "noisy neighbors" (even though the noise problem is only manifested in one direction (X is noisy to Y). This is shown in Figure 8
- Chains of "noisy neighbors" can be created by the "noisy neighbor" list… for example consider the following list, also shown in Figure 8:
    - B is noisy to A
    - A is noisy to B
    - B is noisy to C
    - D is noisy to C
    - F is noisy to E
    - G is noisy to H
- An interference group (IG) is the list of modems in a contiguous noisy-neighbor chain (e.g., {A,B,C,D} represent one IG, while {E,F} is another IG, and {G,H} is yet another IG.) as shown in Figure 8

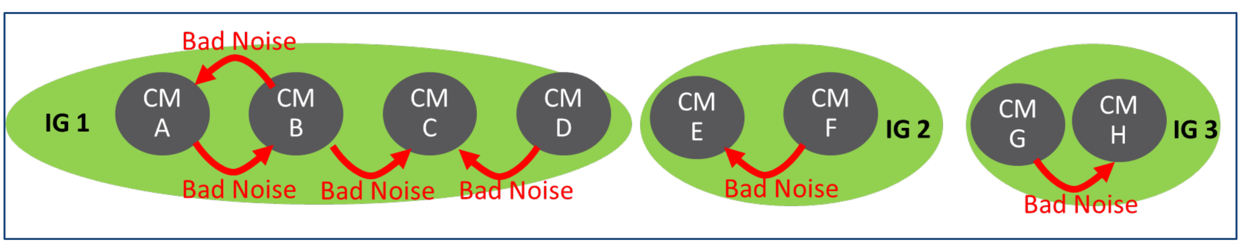

Figure 8 - Interference Groups concept in FDX

The logical separation of interfering modems is done by mapping the IGs to transmission groups (TGs).

- <u>Interference group (IG):</u> PHY-level concept that represents a group of modems that interfere with one another's performance when operated in an FDX mode of operation (with DS & US transmissions occurring simultaneously in the same frequency band). The interference is usually due to CCI issues resulting from US signal energy from a "noisy neighbor" modem distorting and corrupting the reception of DS signals arriving at another modem within the Interference Group

- Transmission group (TG): MAC-level concept that represents a combination of one or more IGs to create a larger group of modems that can be treated as a single managed entity on the HFC plant as shown in Figure 9 and Figure 10. This reduction in entity counts (from Igs to TGs) can help to reduce the workload on the MAC Domain controller. Resource blocks (RB), which are chunks of non-overlapping US & DS FDX bandwidth, will actually be assigned to TGs (not Igs). A TG can be thought of as a Super-Big IG

The formation of the TGs described above enables the ability to form RBs that can be assigned to TGs, via resource block assignment (RBA) messages. An example of the assignment is shown in Figure 11 & Figure 12, where the following can be noted:

- Each of the US/DS (Green/Red) combinations corresponds to an RB configuration
- Assigning one RB configuration to a particular TG creates a half-duplex transmission channel and accompanying US/DS scheduler function that keeps the modems from transmitting US & DS on the same frequency at the same time, and therefore prevents co-channel interference from occurring between modems within the same IG/TG.

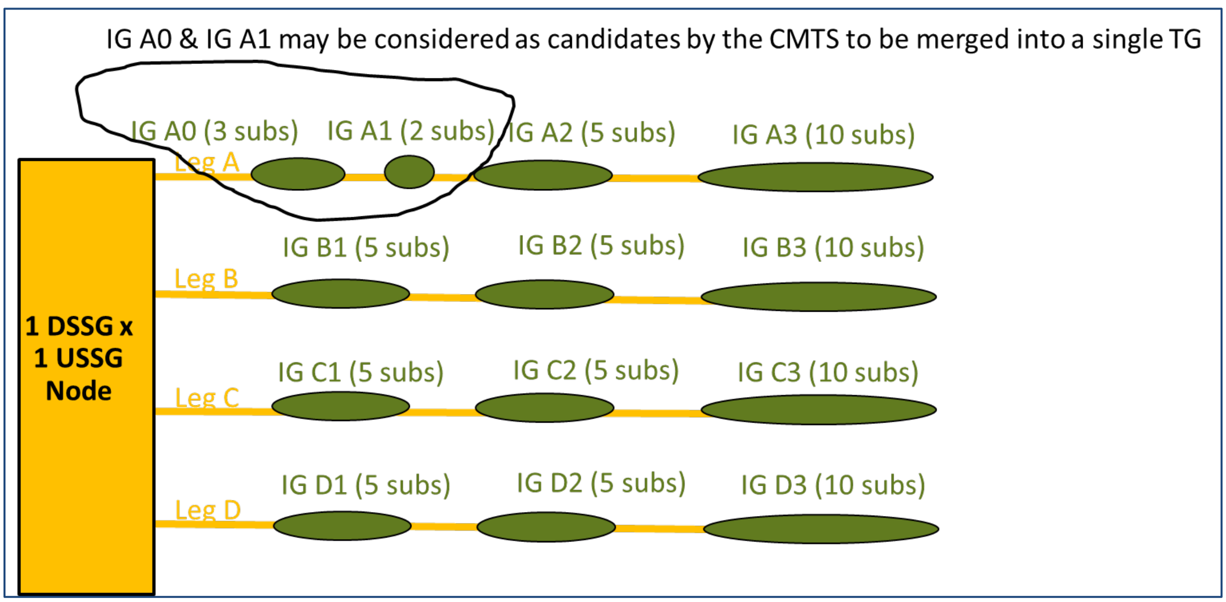

Figure 9 – Forming TGs from Igs

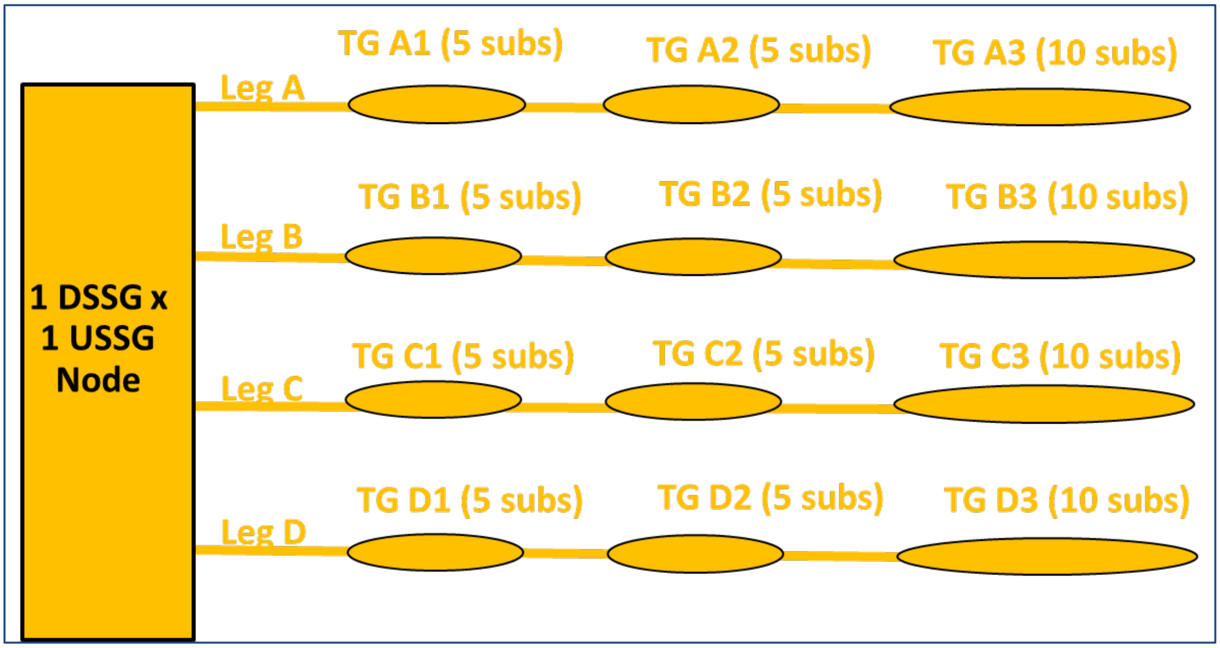

Figure 10 – TGs in FDX Systems

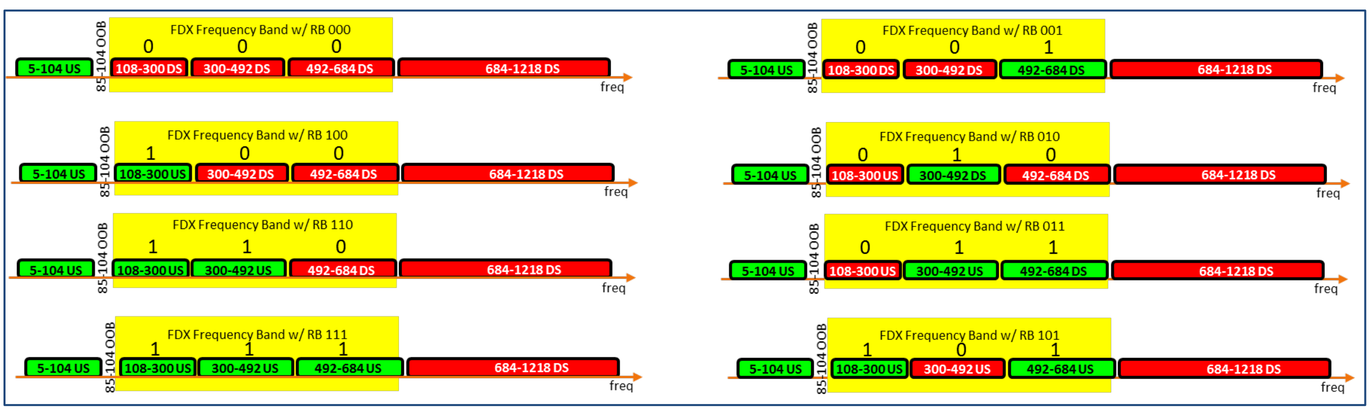

Figure 11 – RBAs in FDX Systems

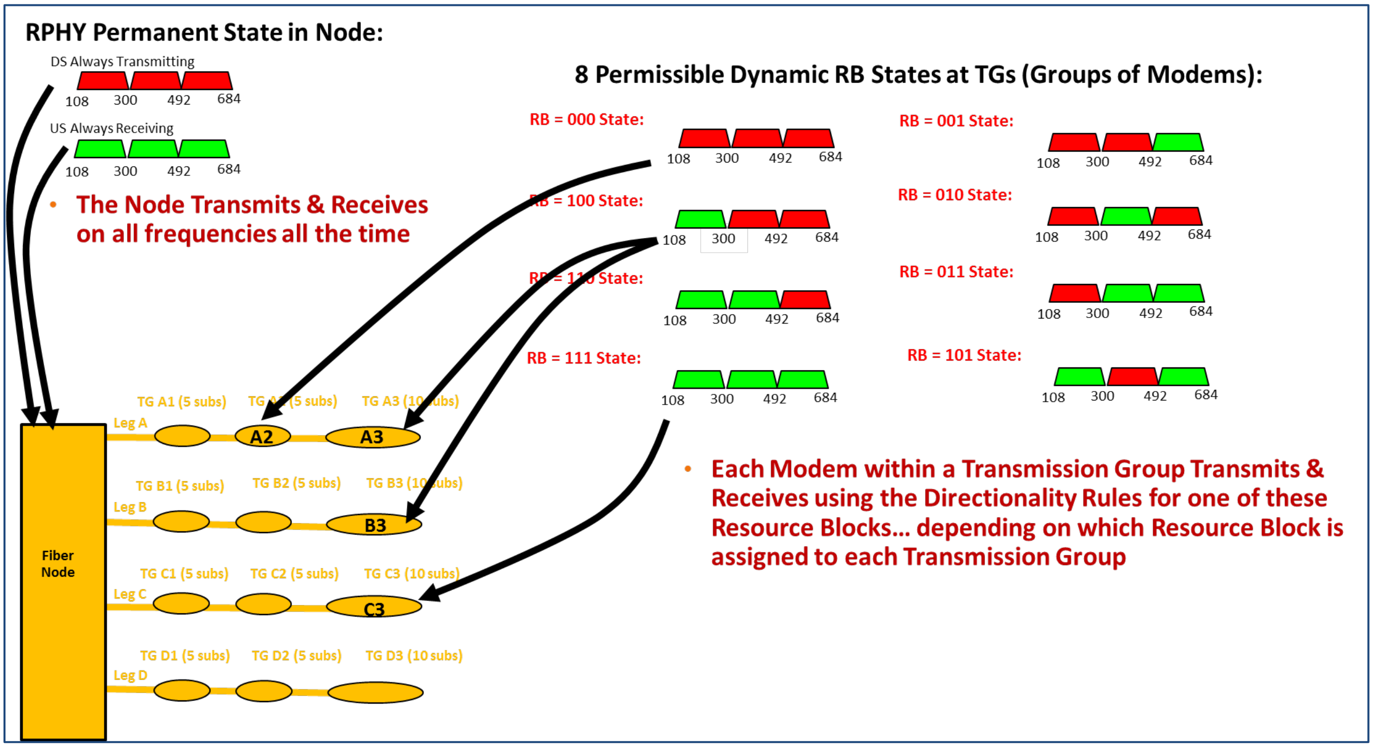

Figure 12 – RBA assignments in FDX Systems

Note that the concept of Dynamic RBA is defined in the FDX specifications [FDX_MULPI] which enables the ability to dynamically change the directionality of a particular portion of the spectrum for a TG from DS to US and vice versa. This comes in handy to accommodate grants in response to bandwidth (BW) requests for very high-throughput US speed tests.

For example, Figure 13 shows that TG A1 did not have enough US BW to reach 3 Gbps and therefore a change in the RBA was needed to meet the speed test request. Note that the RB assignments may change over time. So, it is a dynamic environment that changes to meet the customer throughput demand. An example of the time domain variations is shown at the bottom of Figure 14 for TGs D1/D2/D3.

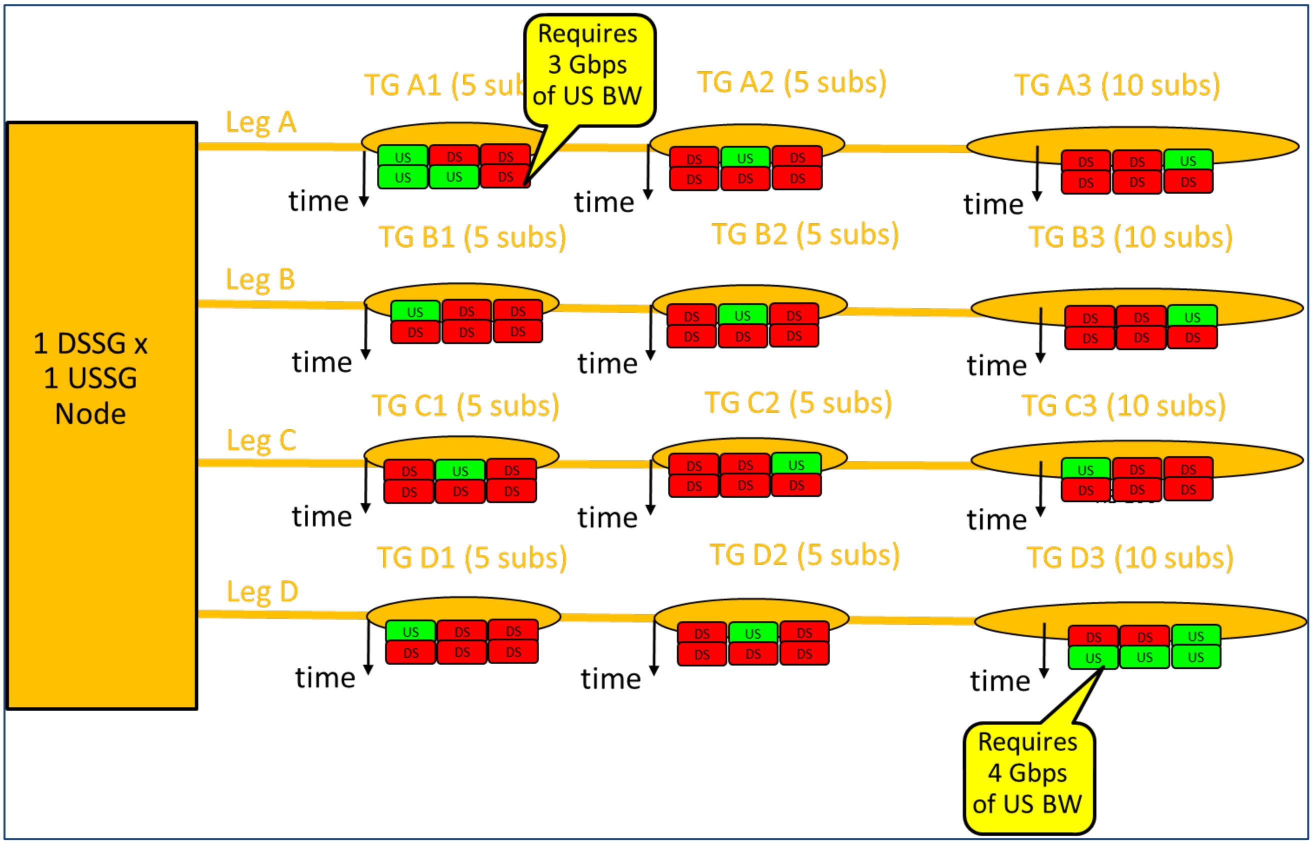

Figure 13 – Changing the RBAs assignments in FDX to meet the traffic demand

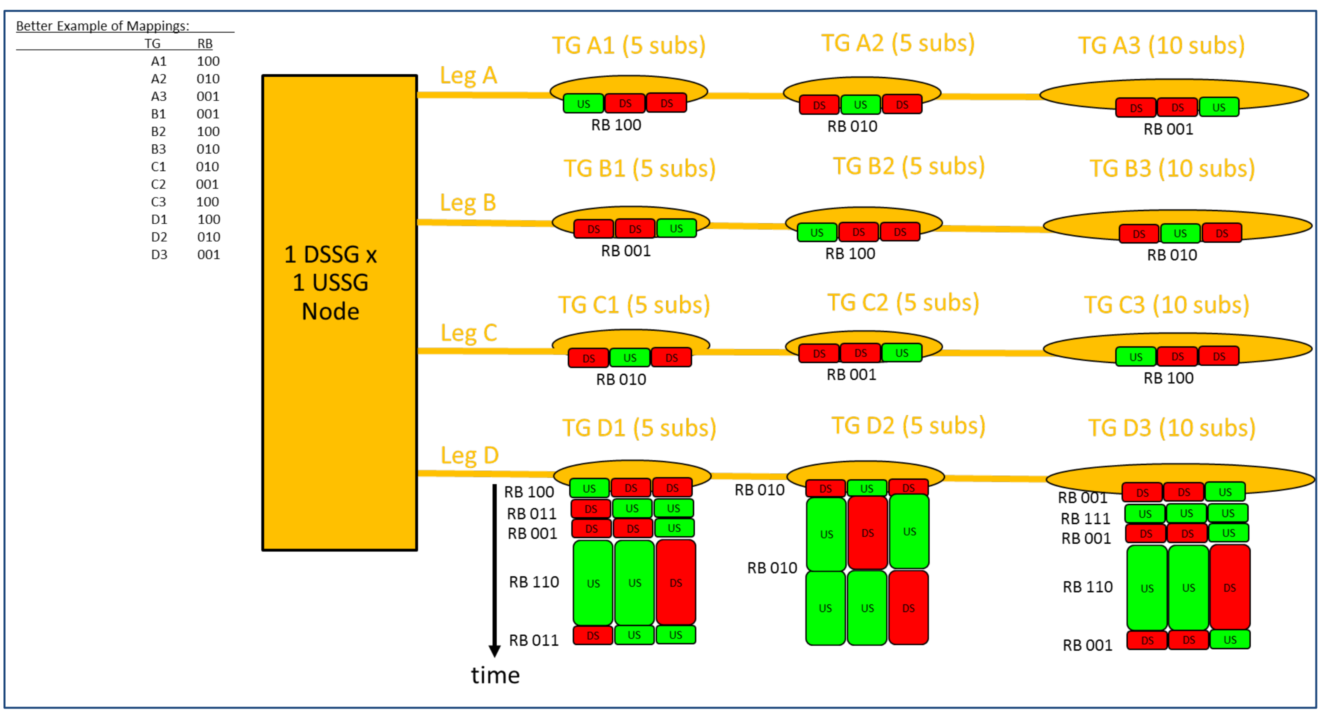

Figure 14 – Dynamic nature of RBAs in FDX

It might be obvious now from the above discussions that the directionality of any portion of the spectrum from a TG (or modem) view point is DS or US only and the FDX operation only occurs from the node viewpoint as shown in Figure 15. Therefore, the modems' operation will be strictly frequency divison duplex (FDD-based) as shown in Figure 16, which shows the dynamic nature of the FDD assignment of a spectrum to a modem over time. The node, on the other hand, is transmitting and receiving simultaneously using the same spectrum (due to concurrent communication with multiple TGs) and therefore the node offers true FDX functionality.

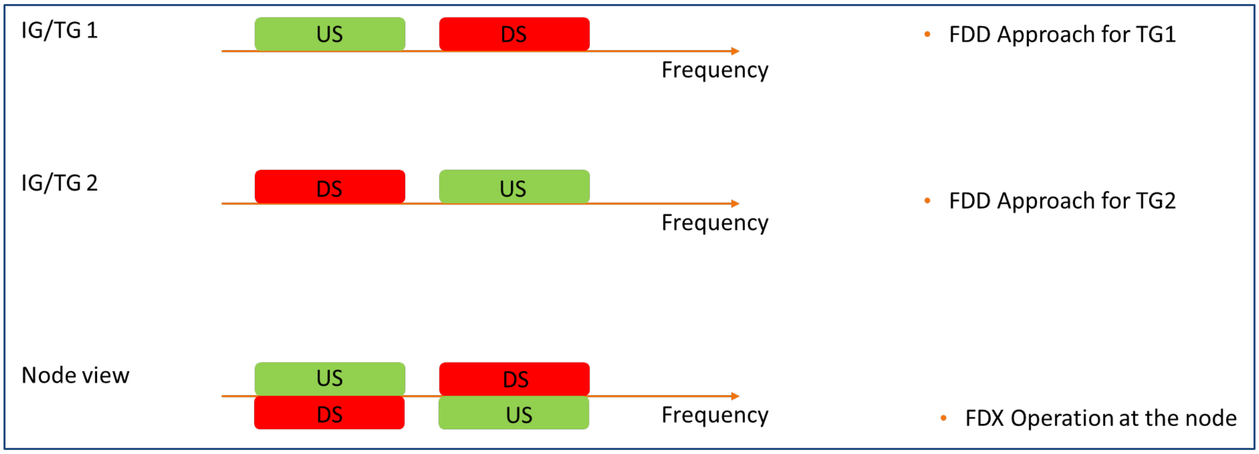

Figure 15 – TGs (and modems) work in FDD or half-duplex operation. Node runs in a true FDX mode

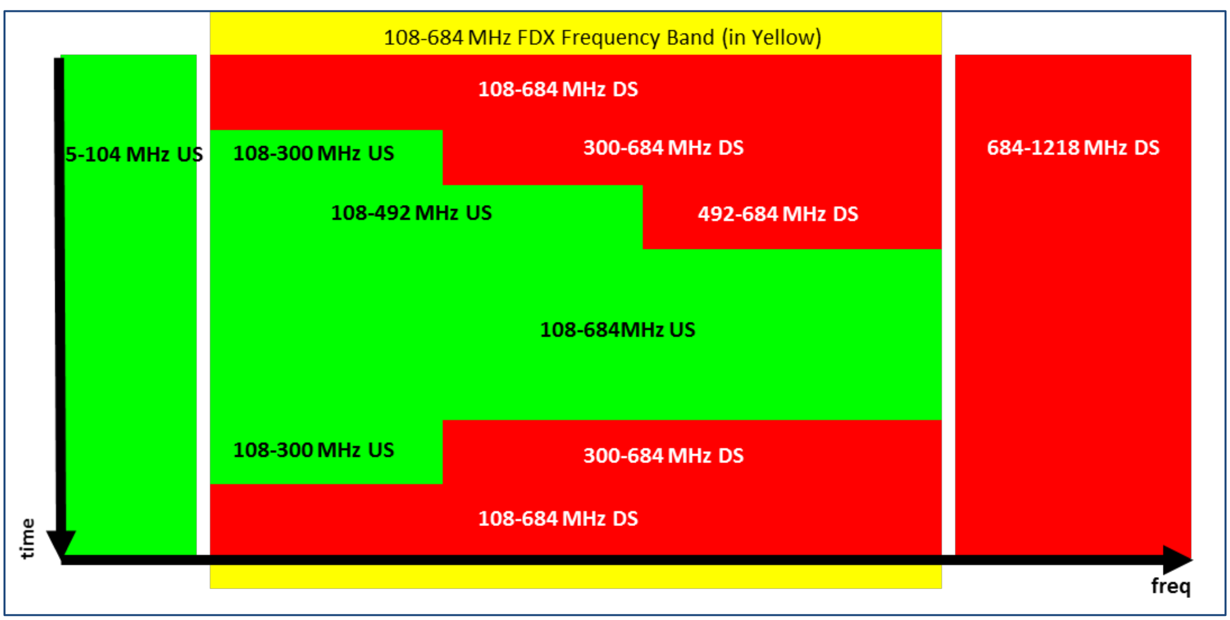

Figure 16 – FDX Operation from the modem view point (or RBA/TG view point)

In order to achieve the desired capacities of 10 Gbps DS & 5-6 Gbps US, the FDX specifications require quadrature amplitude modulation (QAM) orders up to DS QAM4K and US QAM1K overlapping in the FDX band. With that in mind, multiple plant models were characterized and simulated during the specification process to study the potential performance of the FDX systems. In particular, three plant models were investigated: typical, multi-dwelling unit (MDU), and rural. The parameters and setup of these models are shown in Figure 17 and Figure 18 – Figure 20, respectively.

Inputs	Model 1 Typical, or Average HHP Density	Model 2 High HHP Density (i.e. MDU)	Model 3 Rural, or Low HHP Density
Initial Feeder 1 In (Node) to Tap Spacing	175'	50'	500'
Express Cable	N/A	N/A	0.875
Group-of-2 Taps Spacing	N/A	50'	N/A
Subsequent Tap-to-Tap Spacing	175'	0'	300'
Tap Ports	4	8	4
Trunk Cable Type	0.625	0.625	0.625
Drop Cable	RG6	RG6	RG11
Drop Length	100'	100'	200'

Figure 17 – Parameters of various plant models studied during the FDX specifications process

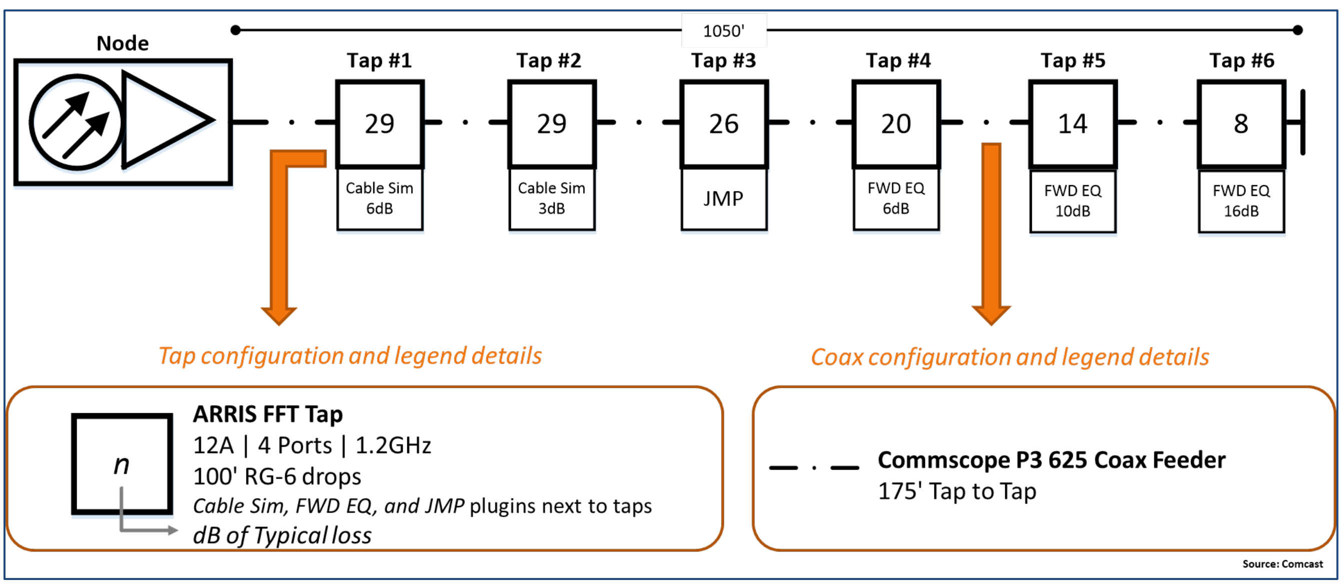

Figure 18 – Model 1 that was studied during the FDX specifications process

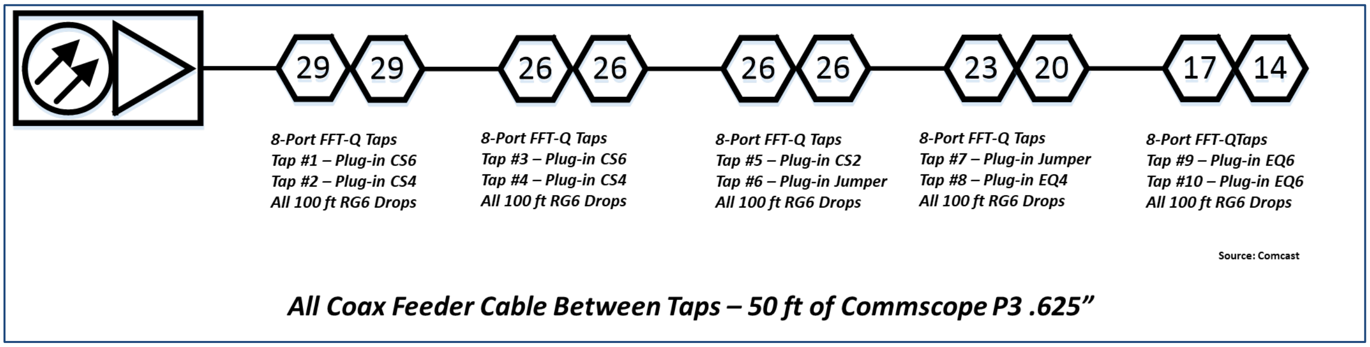

Figure 19 – Model 2 that was studied during the FDX specifications process

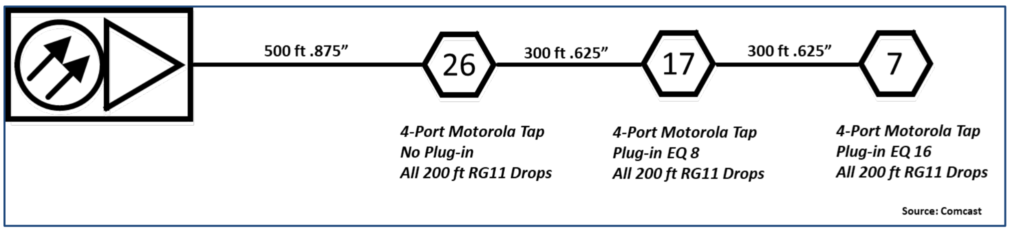

Figure 20 – Model 3 that was studied during the FDX specifications process

While simulations were performed for all models showing that simultaneous DS QAM4K and US QAM1K operation is feasible, this section will only provide sample analyses for Model 1. All models were characterized over various temperatures and the characterization data was used in the simulations. Model 1 characterization data at 25C temperature is shown in Figure 21 for the plant attenuation or insertion loss in dB between the node port and each of the modems on the 6 taps. The return loss data, which is shown in Figure 22, is critical for characterizing the EC performance which is affected by the micro-reflections that reflect from the plant to the node while overlapping with the desired US signal. Finally, the isolation data between the various modems, which is shown in Figure 23, is used to estimate the IGs and interference between different modems.

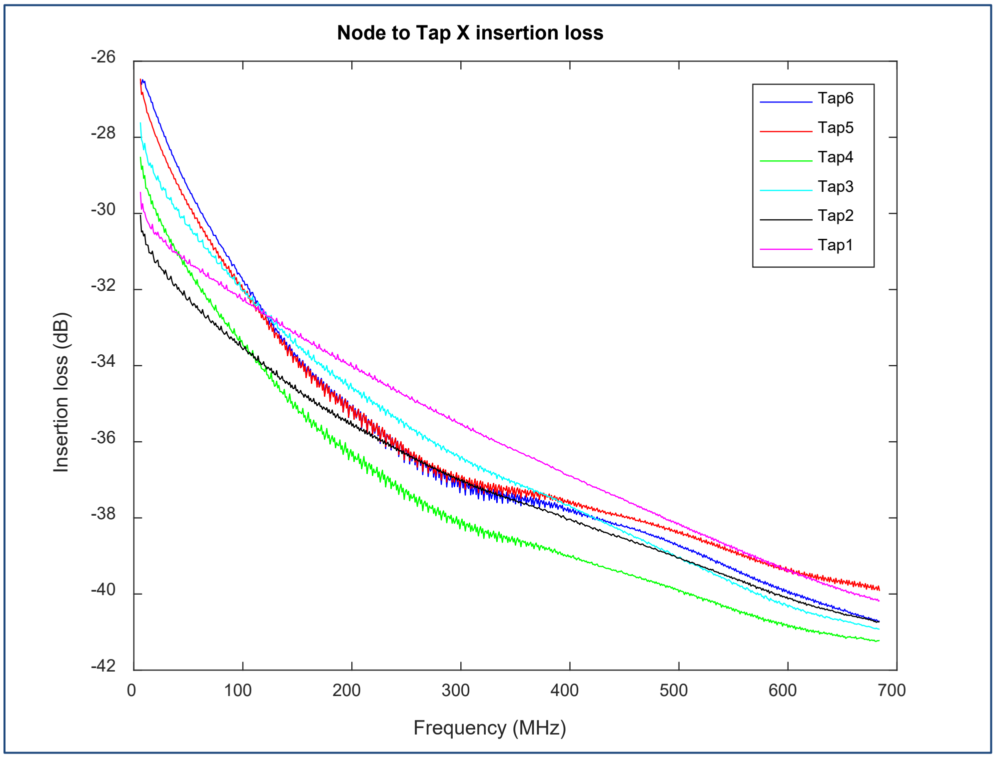

Figure 21 – Model 1 insertion loss from the tap to each of the modems on the 6 taps

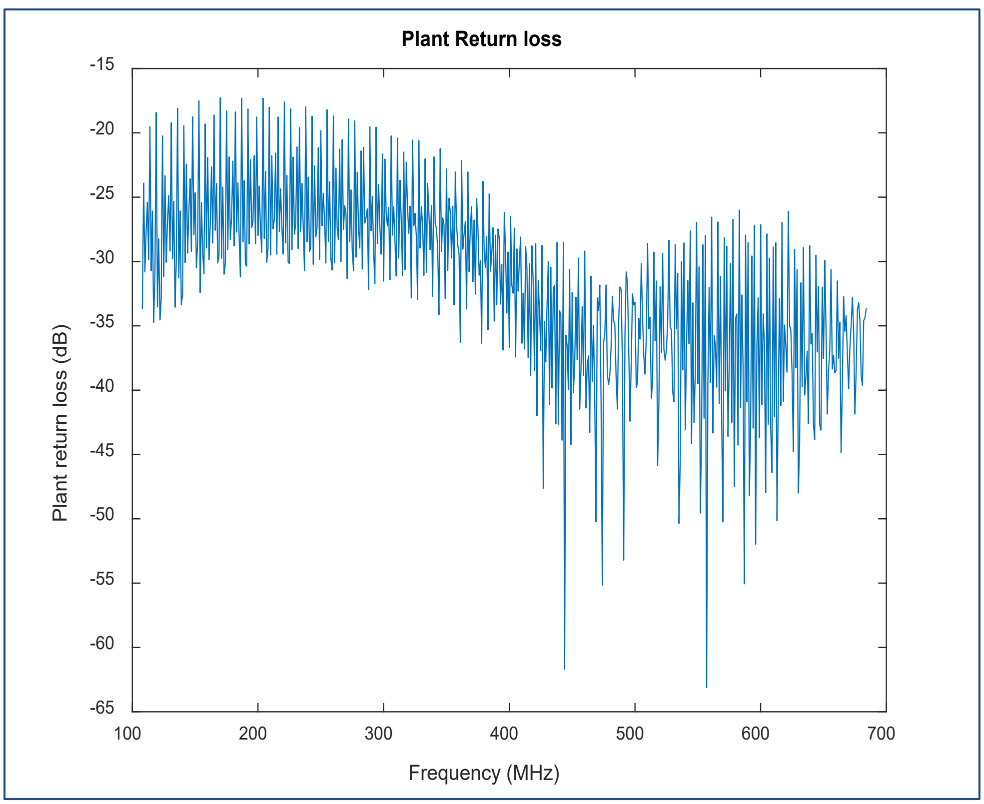

Figure 22 – Model 1 return loss

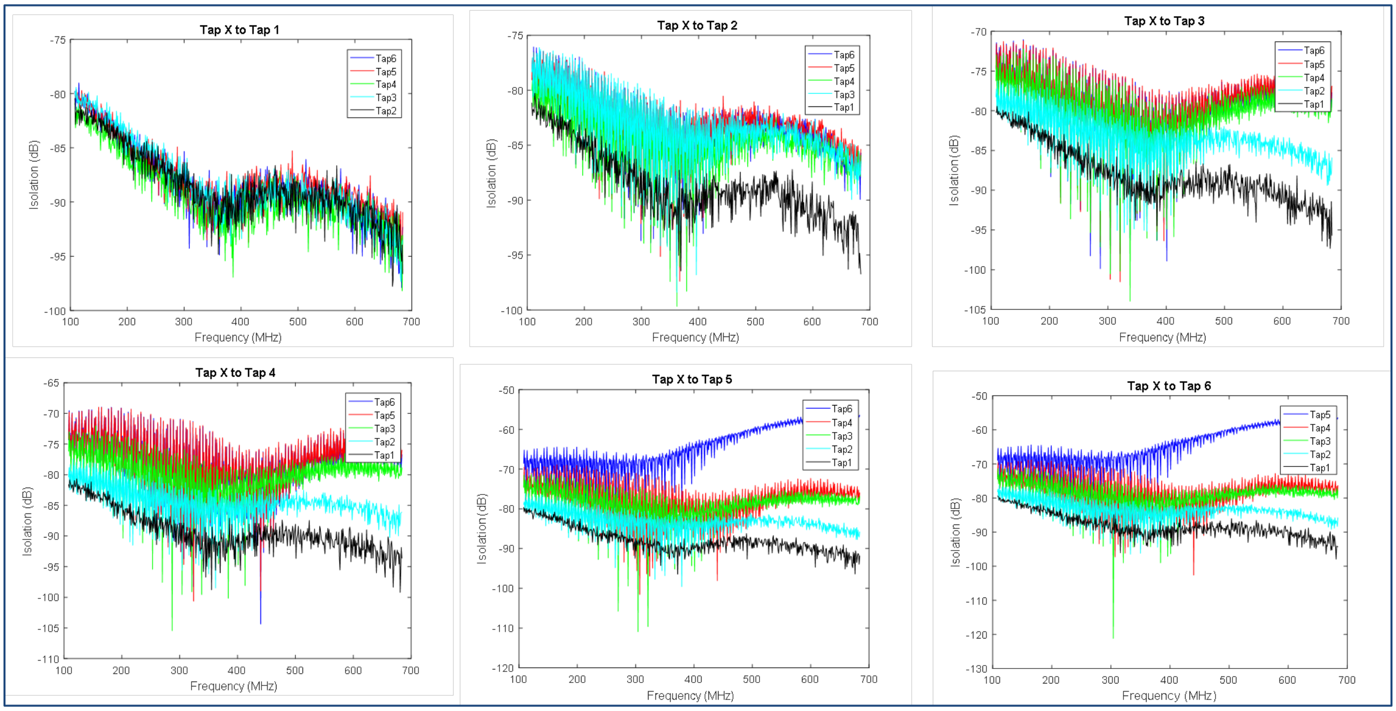

Figure 23 – Model 1 isolation between modems on different taps

Various simulation runs were performed, and it was found that the optimal IG arrangement for Model 1 is as shown in Figure 24. In particular, each of the first three taps makes its own IG while the last 3 taps form a single IG. The simulation methodology described below:

- Do the following:
  - Find all of the combinations of receive (Rx) US tilt and power level per 6 MHz @ node input where
    - The CM transmit (Tx) power does not exceed the maximum CM total composite power (TCP) of 65 dBmV & no more than 10% degradation for the DS throughput in the FDX band
  - Out of the above combinations, select the combination that yields a maximum average US SNR at the US burst receiver and therefore maximum US capacity
    - An US Rx tilt of 0 was selected if it yields an SNR performance at the burst receiver within 1 dB of the global maximum
  - Generate the statistics for that combination (e.g., CM Tx power, IG matrix, etc.)

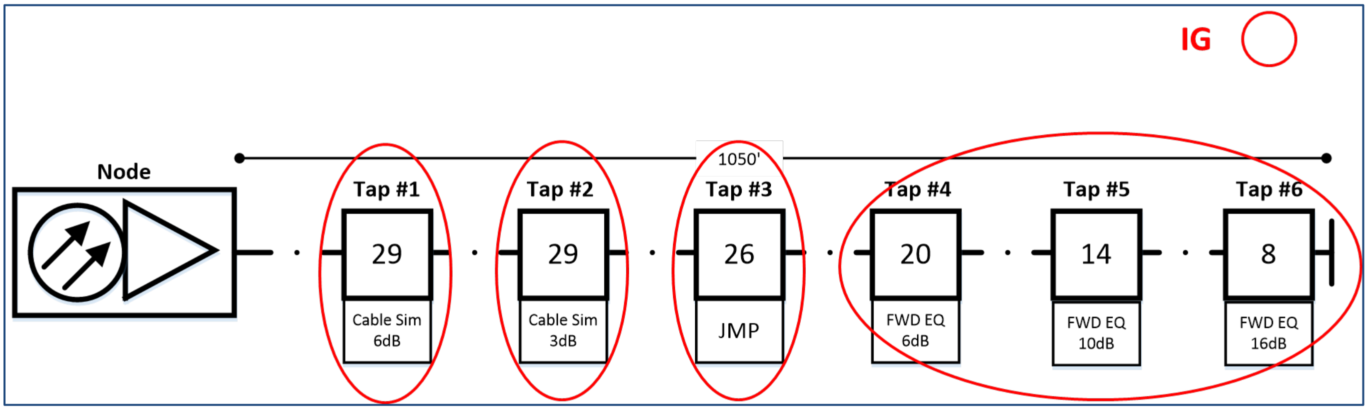

Figure 24 – Optimal IG configuration for Model 1

Based on the above methodology, invalid combinations as well as the SNR values for valid Rx US tilt and Rx US signal levels combinations are show in Figure 25. Observe that the highest SNR values occur along the diagonal line separating the valid and invalid combinations. The optimal solution point for this case was selected to correspond to an US Rx tilt of 0 dB, which corresponding to an US Rx power level per 6 MHz at lowest frequency (i.e., 5 MHz) of 5.8 dBmV. At this optimal solution point, none of the modems exceeded the TCP limit of 65 dBmV because this was one of the simulation constraints as was explained earlier. The modem TCP (in dBmV) on the 6 taps is [63.1, 64.1, 63.8, 64.8, 63.4, 63.8].

The resultant interference values between modems for the optimal case agree with the assumed optimal IG arrangement and are shown via the IG matrix provided in Table 1. Each entry of the IG matrix represents SIR value at the receiving modem as a result of an interfering signal from another transmitting modem. Observe how the last three modems/taps form a single IG, where the SIR values ideally drop below the necessary threshold to provide DS QAM4K operation with 10% loss. The Tx & Rx signal levels and leakage between modems for the optimal case are shown in Figure 26.

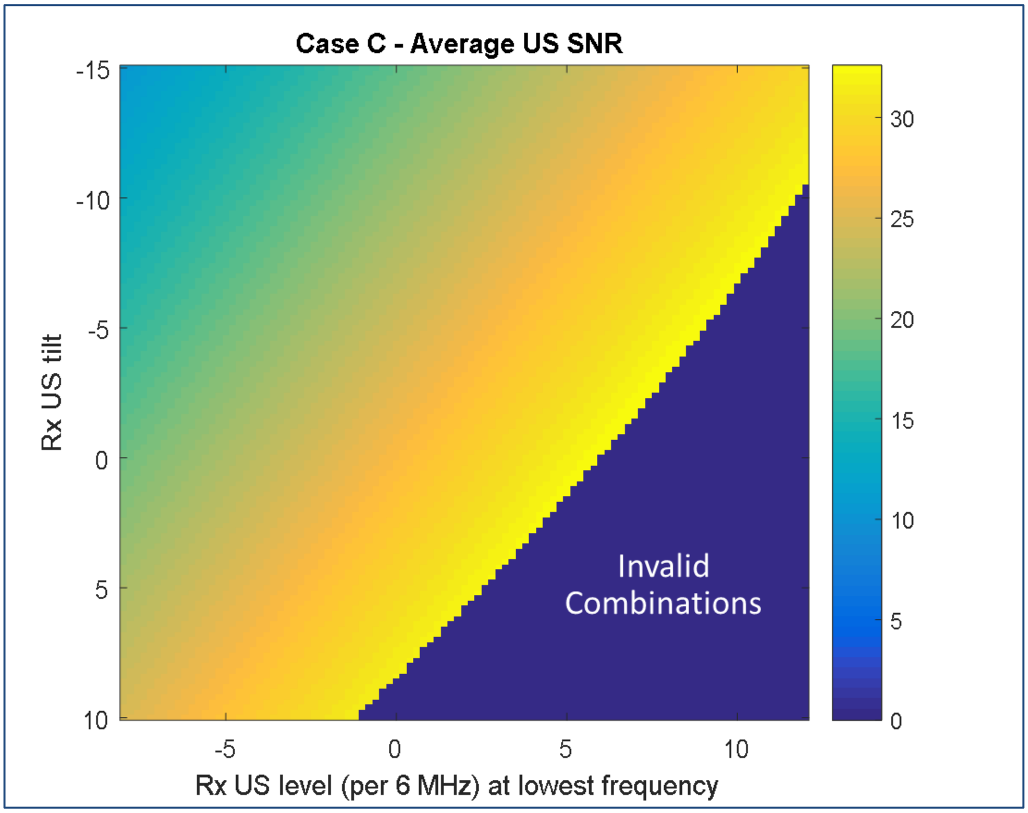

Figure 25 – SNR heat map for various Rx US tilt and Rx US signal levels

Table 1 – IG matrix (SIR in dB) for the optimal case of Model 1

	SIR (dB)	Rx Tap1	Rx Tap2	Rx Tap3	Rx Tap4	Rx Tap5	Rx Tap6
Tx	Tap1	0	42.2	42.2	42.1	42.2	42.2
Tx	Tap2	42.2	0	40.6	40.6	40.6	40.6
Tx	Tap3	42.2	40.6	0	38.4	38.4	38.4
Tx	Tap4	42.2	40.6	38.4	0	36.7	36.7
Tx	Tap5	42.2	40.6	38.4	36.7	0	26
Tx	Tap6	42.2	40.6	38.4	36.7	26	0

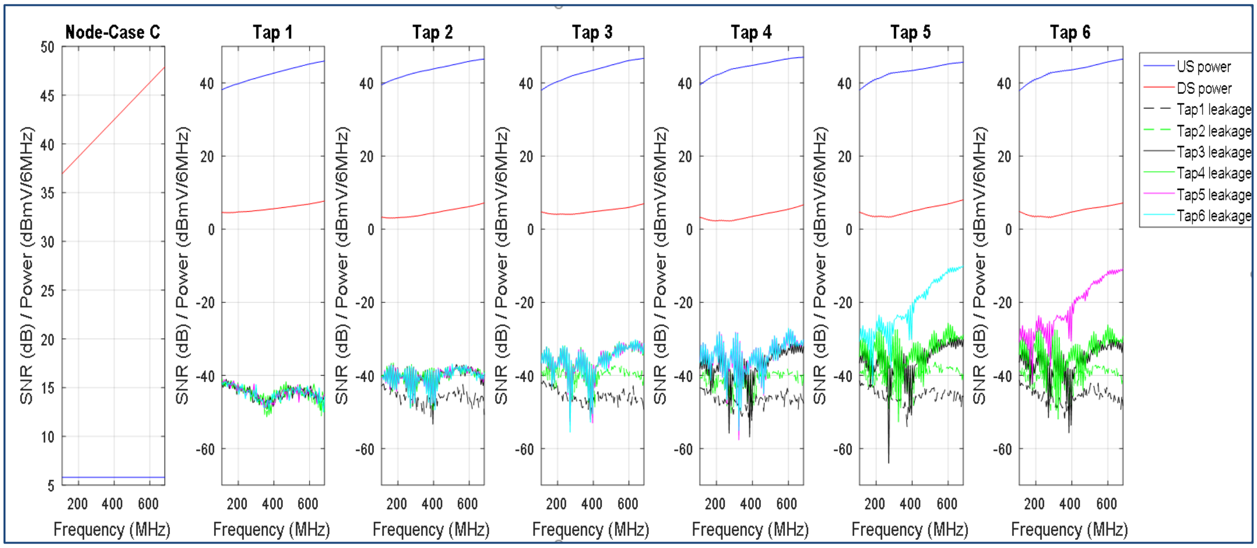

Figure 26 – Tx & Rx signal levels and leakage between modems for Model 1 optimal case

2. FDX Grids & Associated Inefficiencies & Potential Solutions

The FDX specifications were created to support a smooth migration strategy as MSOs start considering FDX deployment. In particular, the specifications enable the MSOs to start with a small part of the spectrum allocated to FDX and increase it over time as they reclaim more spectrum from other services. For example, the MSO may choose to use a smaller FDX grid (i.e., allocated FDX spectrum) to accommodate large number of video, DOCSIS single carrier quadrature amplitude modulation (SC-QAM) channels, and potentially orthogonal frequency division multiplexing (OFDM) channels. The allocated FDX spectrum is defined as the portion of the FDX Band that the access network allocates for FDX operation [FDX_PHY]. The FDX grids corresponding to various allocated FDX spectrum sizes are shown in Figure 27, where the grid to the allocated FDX spectrum mapping is as follows

- Grid #1: Allocated FDX spectrum of 96 MHz (from 108-204 MHz)
- Grid #2: Allocated FDX spectrum of 192 MHz (from 108-300 MHz)
- Grid #3: Allocated FDX spectrum of 288 MHz (from 108-396 MHz)
- Grid #4: Allocated FDX spectrum of 384 MHz (from 108-492 MHz)
- Grid #5: Allocated FDX spectrum of 576 MHz (from 108-684 MHz)

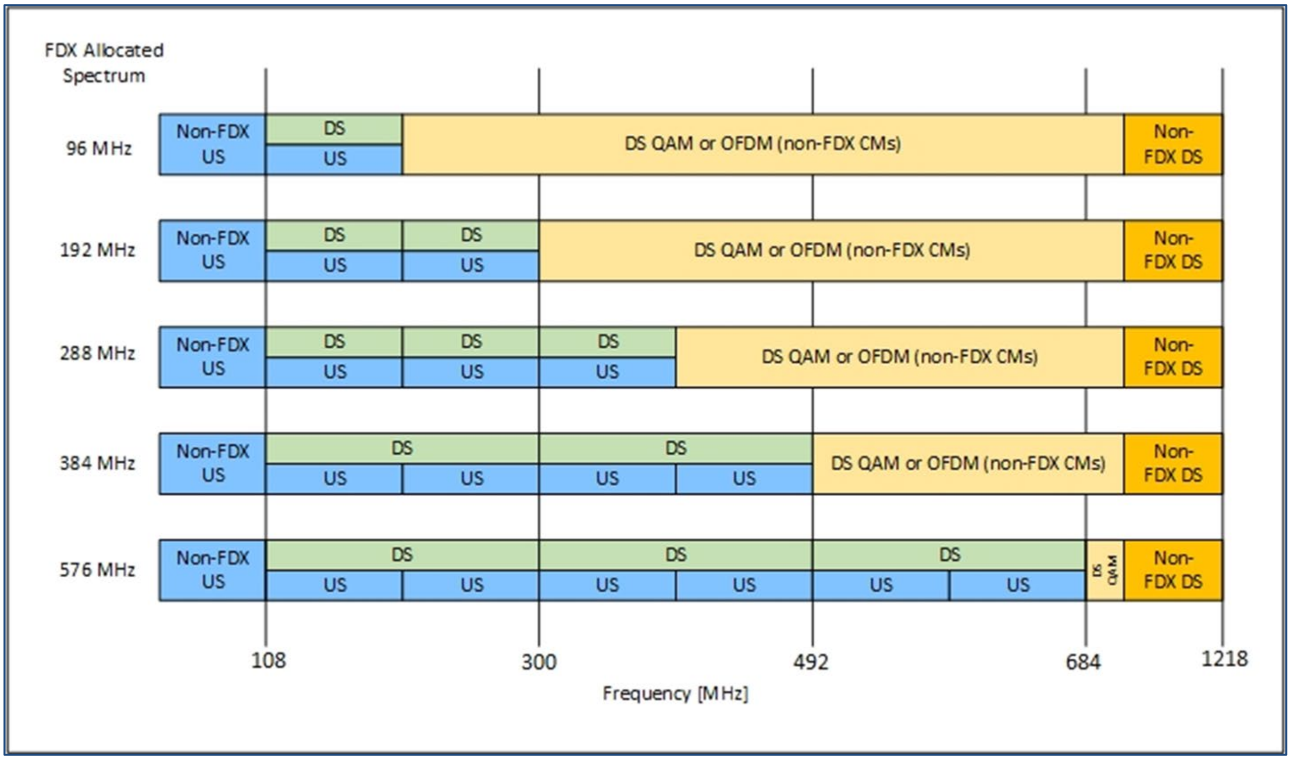

Figure 27 – All FDX Grids supported in the FDX spec

Note that the channels within the allocated FDX spectrum must be OFDM channels. That is, all FDX channels must be OFDM channels. Also, the spectrum that is above the allocated FDX spectrum and below 684 MHz (in beige color in Figure 27) cannot be used by FDX modems. This spectrum can contain video channels, SC-QAM data channels, and OFDM channels. However, the SC-QAM data and OFDM channel can only be used by legacy modems FDX modems that are running in legacy mode (not FDX mode). Additionally, FDX modems also contain a diplexer with a transition band from 684 -804 MHz where it cannot receive any channels in that band.

The above constraints will cause some spectrum inefficiencies for FDX modems. That is, if an MSO starts with Grid #2 (labeled 192 MHz in Figure 27) as an example, FDX modems will not be able to use the spectrum between 300-804 MHz. However, there are ways that can be used to reduce these inefficiencies in certain cases, especially when the MSO is planning on using one or more OFDM channels in spectrum above the allocated FDX spectrum and below 684 MHz. In this case, some tricks can be applied by using a larger FDX grid. For instance, the MSO can choose to use Grid # 3 (labeled 288 MHz in Figure 27) and configure the third FDX OFDM channel (from 300-396 MHz) to be DS only. Since it is configured as an FDX channel (even thought it is always in the DS direction), the FDX modem will be able to use it. Similarly, if the MSO uses Grid # 4 (labeled 384 MHz in Figure 27) instead of Grid # 2 (labeled 192 MHz in Figure 27) and configure the second FDX channel (300-492 MHz) to be an FDX channel that is always in the DS direction, then the FDX modem will be able to use it. Note that while the configuration of the last FDX channel as DS-always does not affect legacy D3.1 modems, it will help enable FDX modems to have access to that channel.

The configuration of an FDX channel as an always-DS channel can be done via the RBA messages which can specify the direction of a particular FDX channel. In this case, the RBA messages communicate to FDX modems that this channel will always be in the DS and not switch its direction to the US.

3. FDX for N+x Networks?

As mentioned earlier, the FDX specifications were optimized for N+0 (i.e. zero amplifiers between the node and the CM) network architectures. However, it is very costly to reduce the number of network cascades to zero, where no amplifiers exist in the whole network. Questions started to arise regarding the ability to deploy FDX in cascaded networks in order to reduce the projected cost per subscriber. CableLabs started an FDX amplifier committee where some work was done to specify a half-duplex or time division duplex (TDD) amplifier that will quickly switch the direction based on traffic demand and RBA messages. An example of the TDD amplifier is shown in Figure 28.

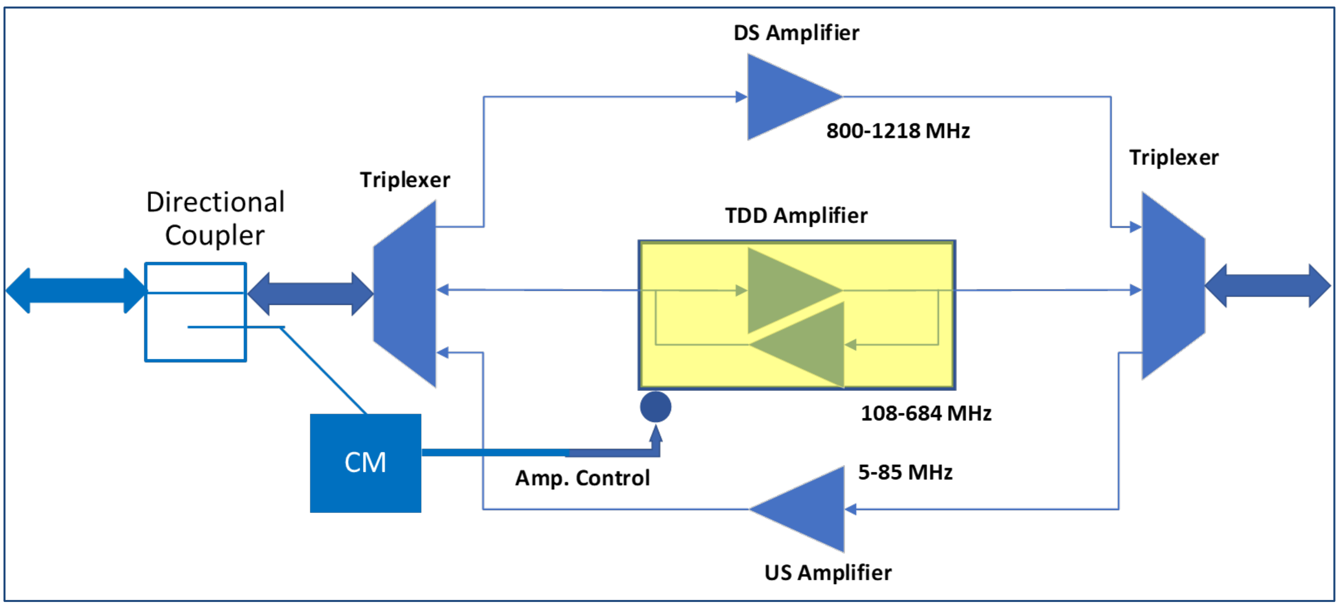

Figure 28 – Half-Duplex/TDD FDX Amplifier Example

Some operators started then asking about the feasibility of true FDX amplifiers in an effort to unlock the full potential of the FDX technology. The Cablelabs committee already started discussing this flavor of FDX amplifiers that is based on the EC technology. An example of True FDX amplifier is shown in Figure 29.

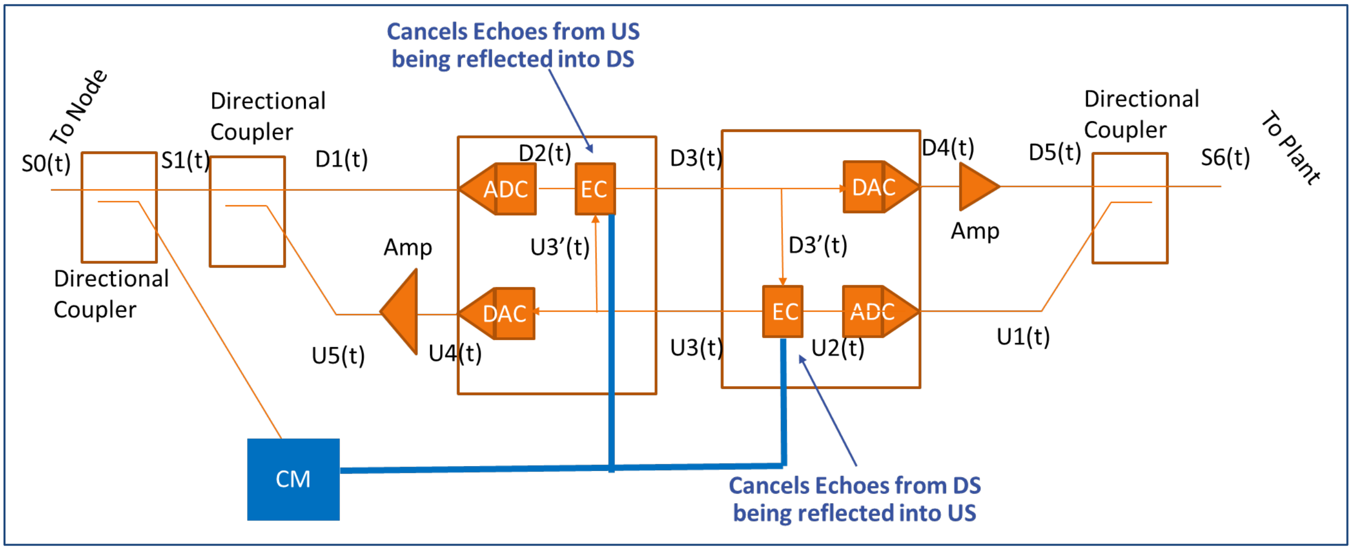

Figure 29 – True FDX Amplifier Example

There are many issues that still need to be studied and resolved when it relates true FDX amplifiers. These include power consumption, thermal dissipation, real estate allocation in amplifier housing, radio frequency (RF) performance, EC performance, good isolation between the amplified US & DS paths, operation in long cascades, and most importantly, cost!

Apart from all the above issues that still need to be addressed, FDX amplifiers, if feasible, present a key challenge to FDX operation in cascaded cable networks because of the IG Elongation problem. IG elongation is the expansion of an interference group to cover taps on both sides of the amplifier. This is caused by the interference of all taps behind the amplifier into the last few taps before the amplifier which have low tap-output isolation. In particular, the US transmissions from modems connected to taps behind the amplifier will leak into the DS path of signals arriving at modems connected to the taps before the amplifier. Note that the US signal levels from all taps behind the amplifier is the same at the input of the amplifier due to the ranging process of modems. This US signal level is amplified and leaked into the DS signal path of the last few taps before the amplifier causing all taps behind the amplifier to be in the same IG as the last few taps before the amplifier.

In order to further illustrate the IG elongation problem, consider an N+0 system that represents Model 1 HFC network which was shown earlier in this paper (see Figure 18). In this plant model example, the optimal arrangement of the Igs was determined to be as shown in Figure 24, where the each of the first three taps represents its own IG and the last three taps represent a single IG. Converting the N+0 system to N+1 system by replacing the last tap with an FDX amplifier yields new IG arrangements and interactions as shown in Figure 30. In particular, each of the Igs behind the amplifier will have mutual interference with the last IG before the amplifier. Therefore, in this N+1 configuration, the last interference group before the amplifier expands to cover all Igs behind the amplifier leading to the final IG arrangement shown in Figure 31. Increasing the size of the IG significantly preclude a proper FDX operation because the spectrum allocation within a single IG (or TG to be more accurate) is based on an FDD operation, where overlapping US & DS spectra within a single TG is not permitted.

Note that adding more amplifiers to yield an N+2 or N+x system will only make it worse from an IG elongation point view. In particular, the large interference group will further expand to cover all taps behind all of the subsequent amplifiers.

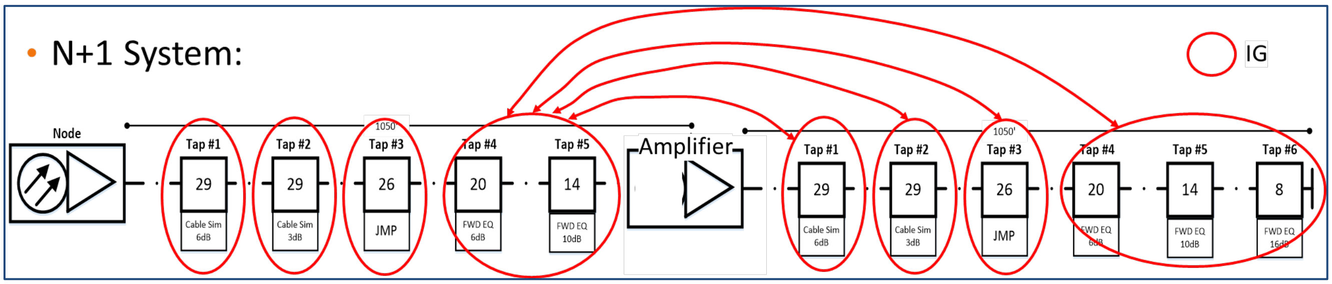

Figure 30 – IG Elongation with FDX Amplifiers in an Example N+1 Network

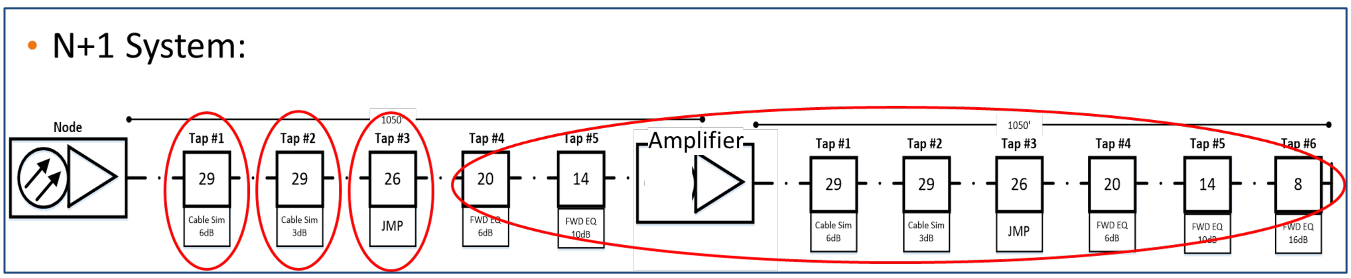

Figure 31 – Final IG Configuratio in an Example N+1 Network

There is no easy way to solve this IG elongation problem. One potential solution is to cut the distance between the amplifiers in half and use an amplifier followed by high-value taps, which possess high inter-connector isolation. Unfortunately, this is an unrealistic solution that can be very costly. Another potential problem for the IG elongation is to use very sophisticated & complicated RBA scheduling where the large IG is viewed to be a collection of smaller IGs with one-on-one interference from some of the IGs to the others. Scheduling simultaneous US & DS for IGs (or TGs) that independently interfere with a common IG (and IG that connects both IGs) can only occur when there is no traffic destined to the connecting or common IG. Not only this is complicated scheduling but also it suffers from inefficiencies and does not permit true FDX operation.

The ultimate solution for the IG elongation problem is to treat the network architecture as an FDD or TDD network where US & DS spectra do not overlap at any instant of time, which is the main operational aspect of an IG.

Since rearchitecting the N+x network to an N+0 network is very expensive, most MSOs would rather continue using their cascaded networks as is. However, as mentioned earlier, the use of FDX amplifiers will not support a true FDX operation due to the IG elongation problem, which will yield half-duplex FDD or TDD operation. This may work just fine for the MSOs with cascaded networks because they prefer to keep working in the familiar FDD mode where spectrum management and operation is easy.

Therefore, for cascaded networks, we propose to use the FDX technology in a Soft-FDX mode, where the network continues to operate in the FDD approach but the split between the US & DS can be changed via software.

4. Soft-FDX: Introduction, Implementation, and Deployment

Soft-FDX is a special operational mode of traditional FDX and is proposed to enable the FDX operation in cascaded N+x networks.

Soft-FDX is based on operating each of the node radio frequency (RF) legs in an FDD mode such that the US & DS spectra do not overlap (just like today!). The 'Soft' adjective refers to the ability to change the location of the US/DS split via software. Soft-FDX helps in supporting high US speeds, which are occasionally demanded by users, without permanently locking the spectrum to the US which can severely affect the valuable DS spectrum that is used to offer many services including video and high DS speeds which are demanded more frequently than the US. The various RF legs on a single node can have different US/DS split configurations leading to overlapping US & DS spectra at the node MAC level, which translates to an FDX operation at the node MAC level. In other words, the Soft-FDX mode is equivalent to a traditional FDX mode with an IG size of one RF leg.

Soft-FDX can be either Static or Dynamic. Static Soft-FDX refers to the case where the US/DS split location does not change without operator-initiated configuration changes, which causes the split to stay in a given configuration for months or years. On the other hand, Dynamic Soft-FDX refers to the case where the US/DS split location changes in real time based on traffic demand (on the order of milliseconds or seconds). For instance, in the Dynamic Soft-FDX mode, when there is a need for more US spectrum as a result of subscriber-initiated US speed test, the US/DS split changes automatically to accommodate that and when the need for the added US spectrum goes way, the split changes back to reclaim the valuable DS spectrum. Both Static and Dynamic Soft-FDX can be implemented using special assignment of the FDX RBA messages as will be explained via the examples illustrated later in this section.

We propose to use the FDX node and modem technologies for cascaded (i.e., N+x) FDD networks via utilizing the Soft-FDX mode that is compliant with the FDX specifications. The question becomes: How do we use the FDX grids to support the FDD operation in cascaded HFC networks? An example can help in explaining the proposed approach. Consider a 204 MHz US split network. The exercise at hand is to use the FDX grids in order to support the 204 MHz network architecture. The first task is to select the appropriate grid out of the available FDX grids that were shown in Figure 27. This is function of multiple variables:

- Number of video channels
- Number of SC-QAM channels
- FDX CM usable spectrum

When a large number of video and/or SC-QAM channels need to be supported, then a low-numbered FDX grid may be more appropriate and vice versa. As for the FDX CM usable spectrum, the traffic demand of the FDX modem need to be evaluated and contrasted against the available BW that can be accessed by the FDX modem. In particular, the FDX modem can only access DS channels above 804 MHz and OFDM channels within the allocated FDX spectrum. It cannot access any of the channels located above the allocated FDX spectrum and below 804 MHz. Therefore, if the FDX CM needs DS throughputs that exceed what can be offered by the combination of the DS FDX channels within the assumed allocated FDX spectrum and legacy (SC-QAM or OFDM) channels above 804 MHz, then a larger grid option will need to be selected such that the allocated FDX spectrum is larger and therefore the accessible BW for the FDX CM is increased.

Let us assume that the FDX modem requires DS BW beyond what is offered in the non-FDX DS spectrum (i.e., spectrum above 804 MHz). If we select grid # 1, in order to accommodate a 204 MHz network, that will not work because of the lack of enough DS BW for FDX CMs. Therefore, only grid options #2-5 can be used. If we assume that Grid #3 is selected, as shown in Figure 32, to satisfy the criteria described above (number of video/SC-QAM channels and enough DS BW for FDX CMs), then the following procedure can be followed in order to configure the FDX node configured with Grid #3 for 204 MHz FDD operation:

- While the node is an FDX-capable node, it needs to be configured to 'know' that the plant has a 204/258 MHz diplexer. The node will avoid transmitting any DS energy or receiving any US bursts in that band
- Configure an exclusion zone in 204-258 MHz as shown in Figure 33. This exclusion zone is configured such that it applies to both DS & US directions. This spectrum overlaps with the diplexer transition band
- All DOCSIS 3.1 and FDX modems are assigned to the same IG/TG. Recall that the operation of the current system is FDD and therefore no FDX is required. In this case, it will be more appropriate to assign all modems that understand RBA messages to the same TG
- Node configures the RBAs messages such that:
    - 108-204 MHz is always in the US direction
    - 300-396 MHz is always in the DS direction. Note that this part of the spectrum is accessible to FDX CMs (which is the main reason for selecting a grid #3 as opposed to grid # 1, for example)
- Decide on what to do with 258-300 MHz. It can be one of the following options:
    - Assigned to be always in the DS direction. This will be accessible to FDX CMs
    - Exclude it via making the exclusion zone from 204-300 MHz & use video and/or data SC-QAM (42 MHz can fit 7 6 MHz channels or 5 8 MHz channels)
- Configure video and/or data SC-QAMs in 396-804 MHz
- Configure SC-QAM and/or OFDM channels above 804 MHz

Using the above configuration steps, it becomes obvious that the final spectrum configuration is as follows: 5-204 MHz is always US while 258 MHz-1.2 GHz is always DS. This matches the current configuration of today's 204 MHz FDD networks. In this configuration, DOCSIS 3.1 high-split modems will work just fine and will have access to all the non-video spectrum between 258 MHz and 1.218 GHz. Observe that FDX CMs cannot access the 396-804 MHz spectrum.

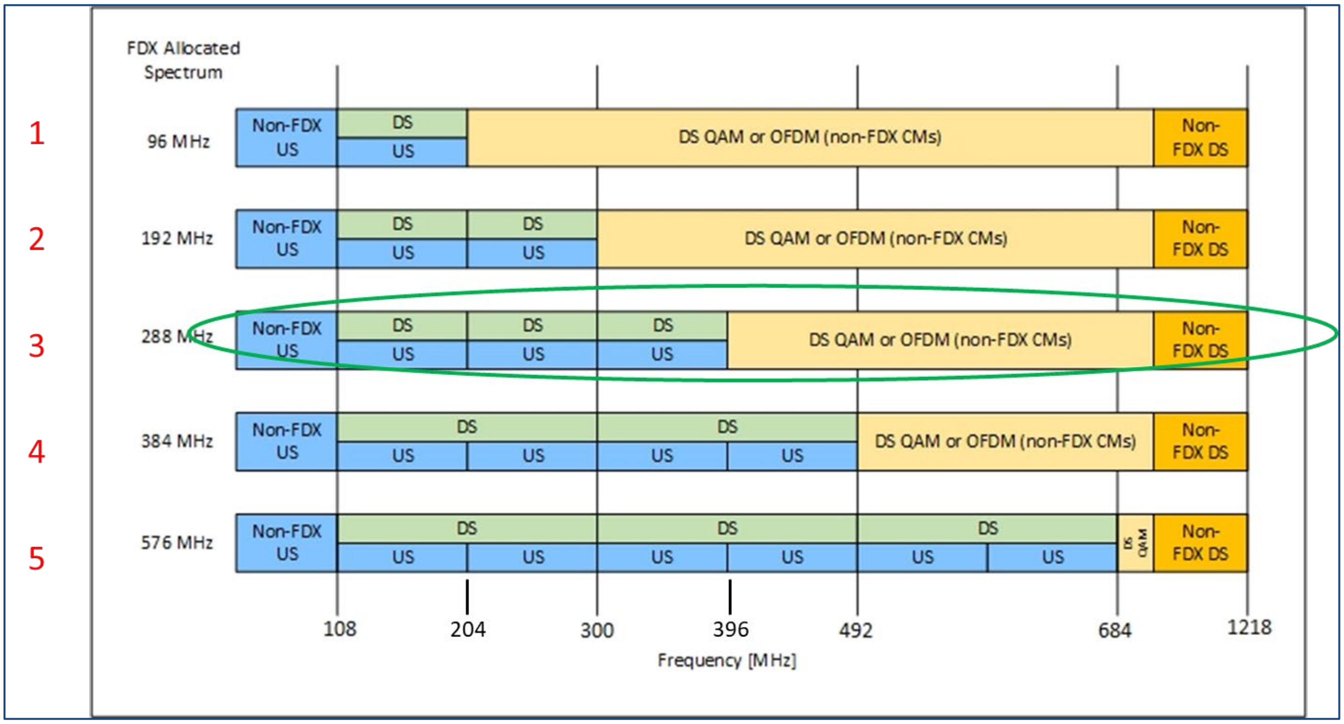

Figure 32 – Soft-FDX: FDX Grid #3 is selected to support 204 MHz FDD operation

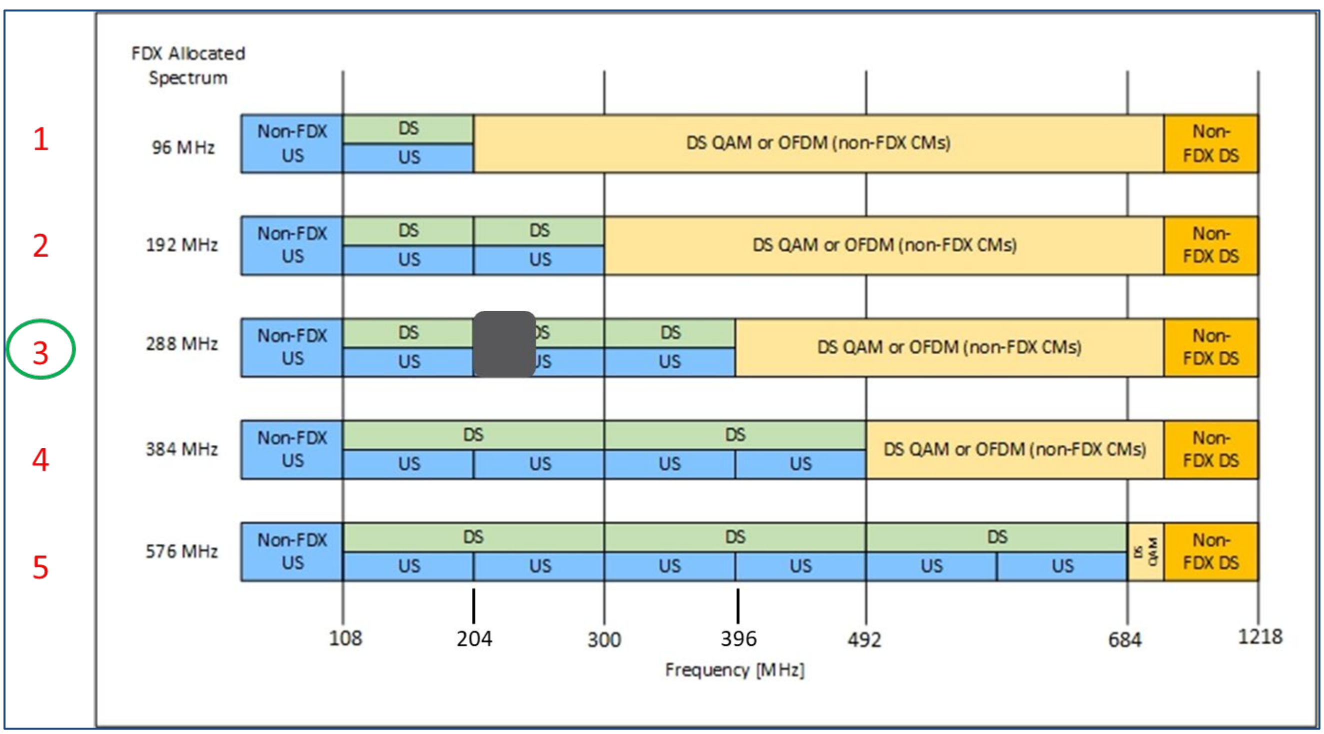

Figure 33 – Soft-FDX: Configuring 204-258 MHz exclusion zone in the FDX Grid #3 to support 204 MHz FDD operation

The above example used Grid # 3 as the basis for configuring an FDX system to support 204 MHz FDD network operation. Same concept applies if other grids are selected. To further clarify the concept, the above exercise is repeated using Grid # 4, as shown in Figure 34.

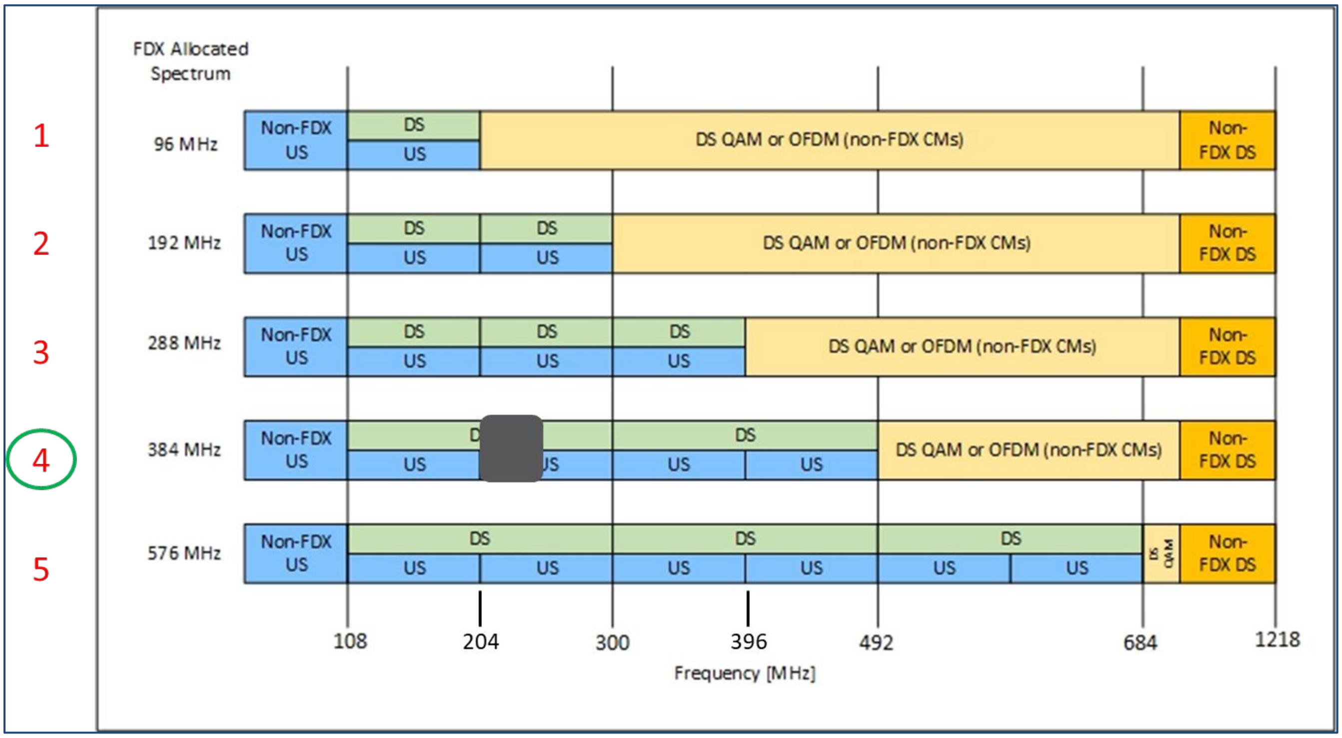

Figure 34 – Soft-FDX: Configuring 204-258 MHz exclusion zone in the FDX Grid #4 to support 204 MHz FDD operation

The procedure for configuring grid #4 to support 204 MHz FDD operation is very similar to the procedure that was provided earlier for grid # 3 and is briefly listed below:

- While the node is an FDX-capable node, it needs to be configured to 'know' that the plant has a 204/258 MHz diplexer
- Configure an exclusion zone in 204-258 MHz as shown in Figure 34
- All DOCSIS 3.1 and FDX modems are assigned to the same IG/TG
- Node configures the RBAs messages such that:
    - 108-300 MHz is always in the US direction
    - 300-492 MHz is always in the DS direction. Note that this part of the spectrum is accessible to FDX CMs
- Decide on what to do with 258-300 MHz. It can be one of the following options:
    - Exclude it via making the exclusion zone from 204-300 MHz & use video and/or data SC-QAM (42 MHz can fit 7 6 MHz channels or 5 8 MHz channels)
    - Lose it?
- Configure video and/or data SC-QAMs in 492-804 MHz

- Configure SC-QAM and/or OFDM channels above 804 MHz

Note that in this configuration, DOCSIS 3.1 high-split modems will work just fine and will have access to all the non-video spectrum between 258 MHz and 1.218 GHz and FDX CMs will not be able to access the 492-804 MHz spectrum.

Going back to Grid # 3. What if the MSO chooses to change the US/DS split to 300/353 MHz (for a 17.5% diplexer, which is similar to the one used in the 684/804 MHz split)? That can be easily done via the following high-level configuration shown in Figure 35:

- While the node is an FDX-capable node, it needs to be configured to 'know' that the plant has a 300/353 MHz diplexer
- Configure an exclusion zone in 300-353 MHz as shown in Figure 35
- All DOCSIS 3.1 and FDX modems are assigned to the same IG/TG
- Node configures the RBAs messages such that:
  - 108-300 MHz is always in the US direction
- Decide on what to do with 353-396 MHz. It can be one of the following options:
  - 353-396 MHz is always in the DS direction. Note that this part of the spectrum is accessible to FDX CMs
  - Exclude it via making the exclusion zone from 300-396 MHz & use video and/or data SC-QAM (43 MHz can fit 7 6 MHz channels or 5 8 MHz channels)
- Configure video and/or data SC-QAMs in 396-804 MHz
- Configure SC-QAM and/or OFDM channels above 804 MHz

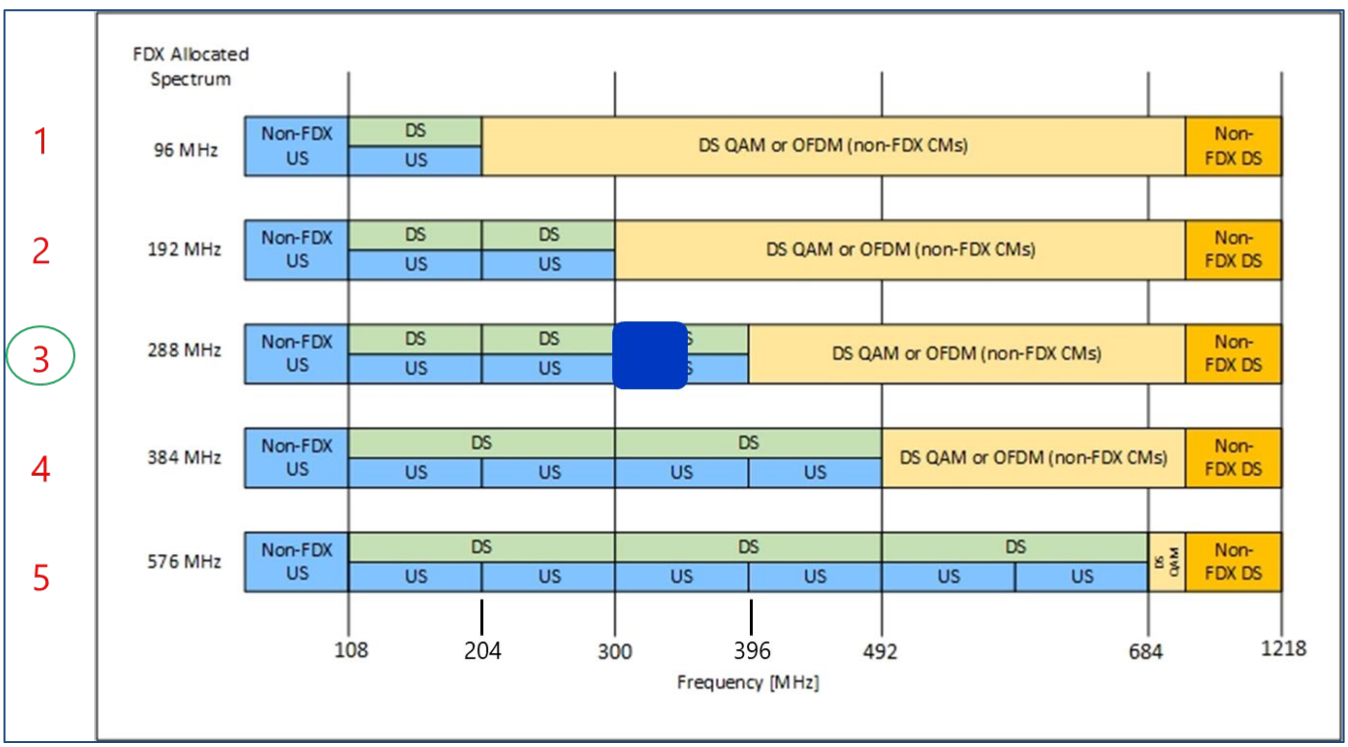

Figure 35 – Soft-FDX: Configuring 300-353 MHz exclusion zone in the FDX Grid #3 to support 300 MHz FDD operation

It can be seen from the above examples that FDX-compliant procedures can be used to enable the use of the FDX technology to support cascaded networks with FDD operation. The FDD operation can be Static Soft-FDX (Static RBA assignments) or Dynamic Soft-FDX (Dynamic RBA allocations). Note that the exclusion zone effect in the above examples can also be implemented via 'unused' subcarriers if the node does not support exclusion zone reconfiguration/movement without shutting down the channels. This is needed if the location of the split needs to be changed dynamically (i.e., with the Dynamic Soft-FDX mode).

The follow-up questions are: What about the amplifiers? How can the split be changed in those amplifiers? Changing the split in the amplifier can potentially be done via multiple ways such as:

a. FDX amplifiers (TDD/Half-Duplex and EC-based amplifiers explained earlier in Section 3)
b. Switchable diplexer amplifiers
c. Pluggable diplexer amplifiers
d. Embedded diplexer amplifiers

The first two options above can allow changing the split via software configuration (Soft-FDX). The last two options will require a visit to the amplifier location in order to change the diplexer or the module that contains the diplexer. Obviously, complexity and cost will be a factor in deciding which option the MSO may select. If the MSO chooses to use one of the first two options, then Soft-FDX operation on a system level can be supported. The US/DS split can be changed as needed via software, and therefore supporting either a Static Soft-FDX or Dynamic Soft-FDX operation, without rolling a tuck to the amplifier location. Note that the above amplifiers exhibit a guardband between the US & DS spectra except for the EC-based amplifier that can potentially support the feature of guardband reduction/removal.

It is worth noting that Half-duplex DOCSIS (HDX) refers to the case where the *whole* allocated FDX spectrum is switched between the US or DS directions. That is, all channels in the allocated FDX spectrum are assigned the same direction at any moment of time. Note that HDX is a subset or a special case of the Soft-FDX scheme. In particular, HDX is actually a Soft-FDX mode with only two options: the US/DS split is at 108 MHz or at the end of the allocated FDX spectrum. For example, looking at Grid # 3 of the FDX grids that were shown in Figure 27, the Soft-FDX approach has four choices for the US/DS split: 108 MHz, 204 MHz, 300 MHz, and 396 MHz. On the other hand, the HDX scheme, where the direction of the whole allocated FDX spectrum switches between US & DS, can be represented as a Soft-FDX mode but with only two choices: 108 MHz and 396 MHz. Since the HDX scheme has less frequency domain resolution for the split movement, it may need to switch faster between the two available split choices in order to yield comparable performance to the superset Soft-FDX system.

The discussion in this section shows that the Soft-FDX mode enables the use of the FDX technology for cascaded FDD networks, which can help converge the cable industry again. In particular, MSOs that are with N+0 and are planning to use traditional FDX will enjoy better pricing due to higher volumes of the FDX products/chipsets while MSOs with cascaded networks will be able to enjoy deploying a future-proof technology, where the US/DS split can change dynamically (if needed) on their existing cascaded networks. Observe also that using the EC technology can potentially lead to the removal of the guardbands between the US & DS spectra. It is also worth noting that the feature of changing the split location dynamically will also delay the need to deploy 1.8 GHz or 3 GHz HFC equipment in the outside plant (OSP). All MSOs will have additional benefits from this convergence in the cable industry which will lead to less complex network migration decisions and faster features delivery from systems vendors.

5. Simulations Results of FDX & Soft-FDX Systems

Computer simulations were performed to estimate the potential capacities that can be achieved with FDX and various Soft-FDX systems. The key simulation assumptions are listed below. Note that the network assumptions are based on information that was provided by a major MSO in North America (i.e., proposed scenario for MSO X):

- Node+4 network architecture. Taps are equalized. Two-way splitter in the home
- RG-6 drop cable length is 150 ft
- Hardline coax distance between amplifiers (i.e., stage length) is 176 m. All stages are of equal length
- All stages have 5 cable segments. Stages between amplifiers contain 4 taps in the sequence 23-20-17-14 dB) and the last stage has 5 taps in the sequence 23-20-17-14-8 dB (all 4-way). All taps are 1.2 GHz taps
- US split is at 396 MHz. DS starts at 465 MHz (17.5% guardband)
- 32 SC-QAM channels. The rest is occupied by OFDM channels. No video channels
- US starts at 20 MHz and stops at 396 MHz. DS starts at 456 MHz. Static Soft-FDX operation
- Tx TCP is 68 dBmV
- Up-tilted power spectral density (PSD) over the frequency range covering SC-QAM channels and flat above that (i.e., over the frequency range converting OFDM channels). See the ESD section later in this paper (Section 8) for the rationale behind this PSD spectral signature that optimizes the performance
- D3.1 allowed DS & US QAM modulation orders and SNR thresholds & power levels are used to estimate the variable bit loading profile. That is, D3.1-compliant unmodified levels were assumed to estimate the variable bit loading profile
- DS OFDM PHY efficiency of 78%. This is based on the following assumptions: 192 MHz OFDM channel size, 4K Fast Fourier Transform (FFT) with 50 kHz subcarrier spacing, 1.25 usec cyclic prefix (CP), large forward error correction (FEC) codeword (CW), etc. Note that these values are very realistic and more aggressive assumptions can be made
- DS SC-QAM spectral efficiency of 6.33 bps/Hz with the highest QAM order of QAM256 [D3.1_Tech]
- US orthogonal frequency division multiple Access (OFDMA) PHY efficiency of 75%. This is based on the following assumptions: 96 MHz OFDMA channel size, 2K FFT with 50 kHz subcarrier spacing, 2.5 usec CP, large FEC CW, frame size of 16 symbols, etc. Note that these values are very realistic and more aggressive assumptions can be made
- End of line (EoL) net DS throughout (after removing DS PHY overhead) is reported

Based on the above assumptions, the net DS throughput is 6.021 Gbps and the net US throughput is 2.827 Gbps for MSO X's Static Soft-FDX system. These values can be easily increased if the SC-QAM channels are reclaimed and OFDM channels are deployed instead. Also, the capacities can be further increased if more aggressive OFDM/OFDMA assumptions are made.

In order to fully understand the above results, more detailed curves are provided for both DS & US simulations. As for the DS, the Tx PSD & TCP are shown in Figure 36, the Rx SNR & power levels are shown in Figure 37, and the variable bit loading modulation profile & cumulative DS net throughput are shown in Figure 38. As for the US, the Tx PSD & TCP are shown in Figure 39, the Rx SNR & power levels are shown in Figure 40, and the variable bit loading modulation profile & cumulative US net throughput are shown in Figure 41.

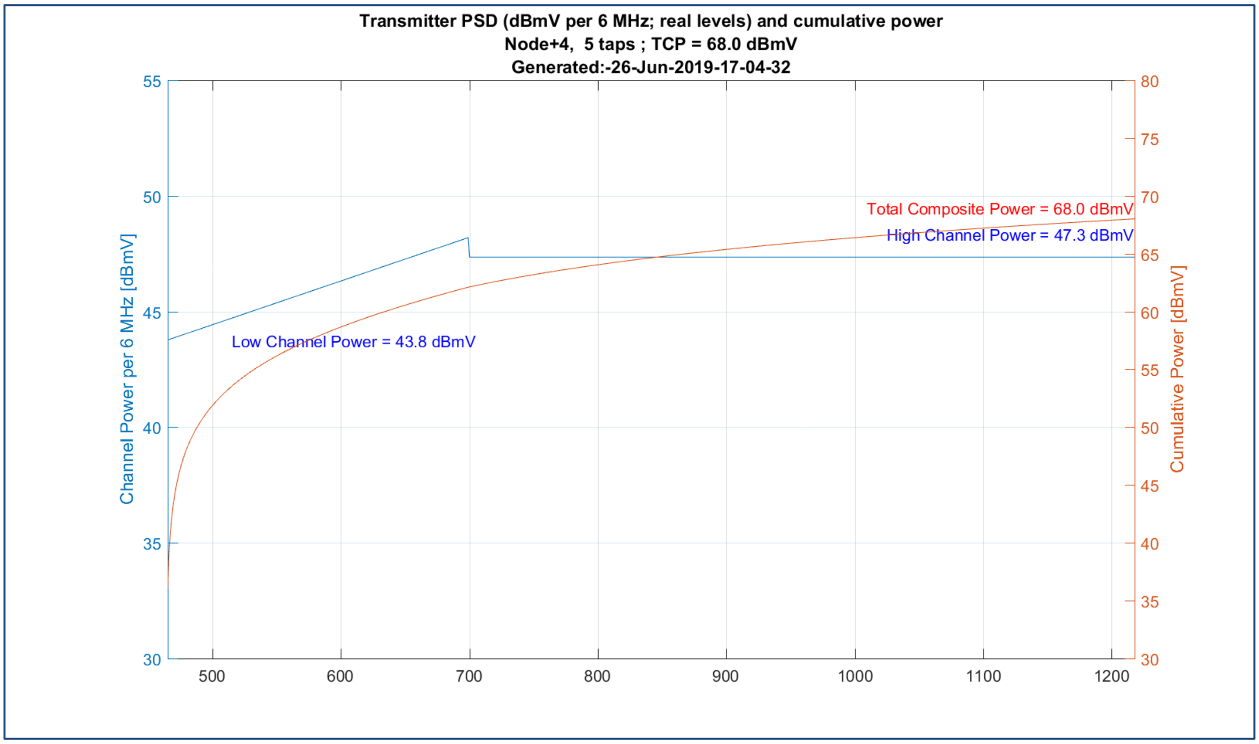

Figure 36 – Tx DS PSD & TCP for the Static Soft-FDX system with 396 MHz split for MSO X

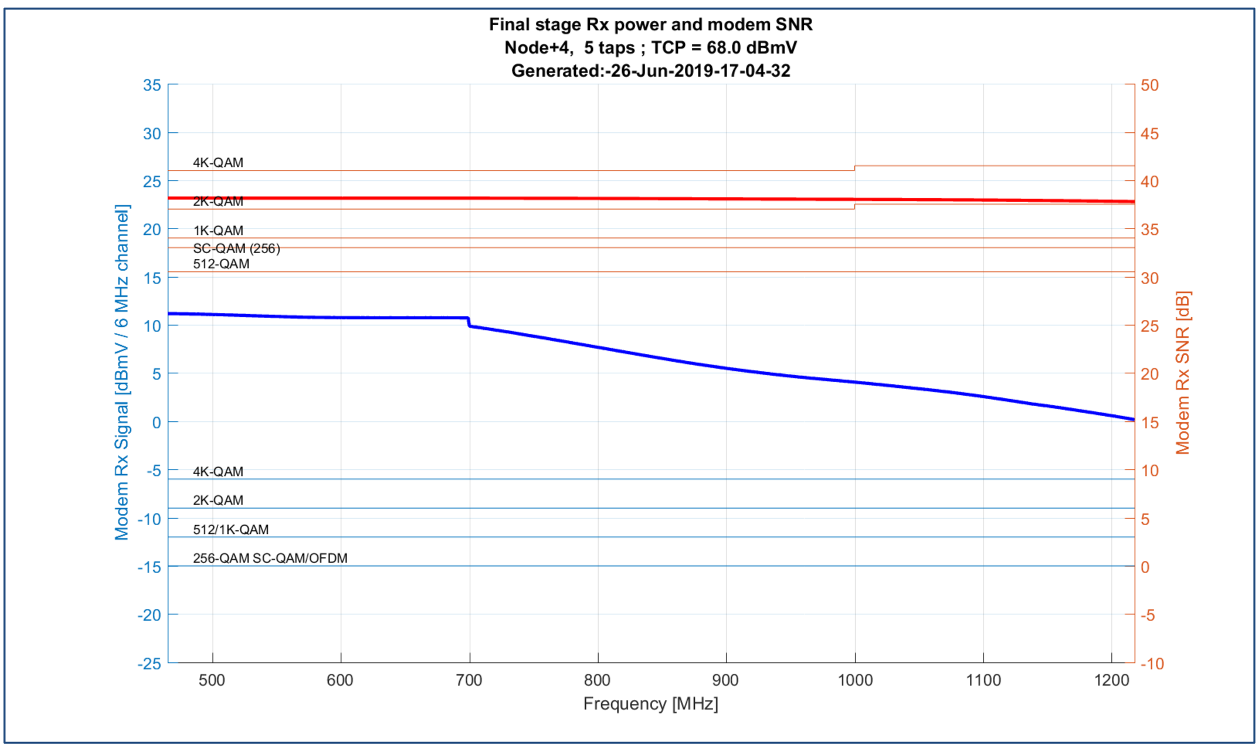

Figure 37 – Rx DS SNR (red) & power levels (blue) & TCP for the Static Soft-FDX system with 396 MHz split for MSO X

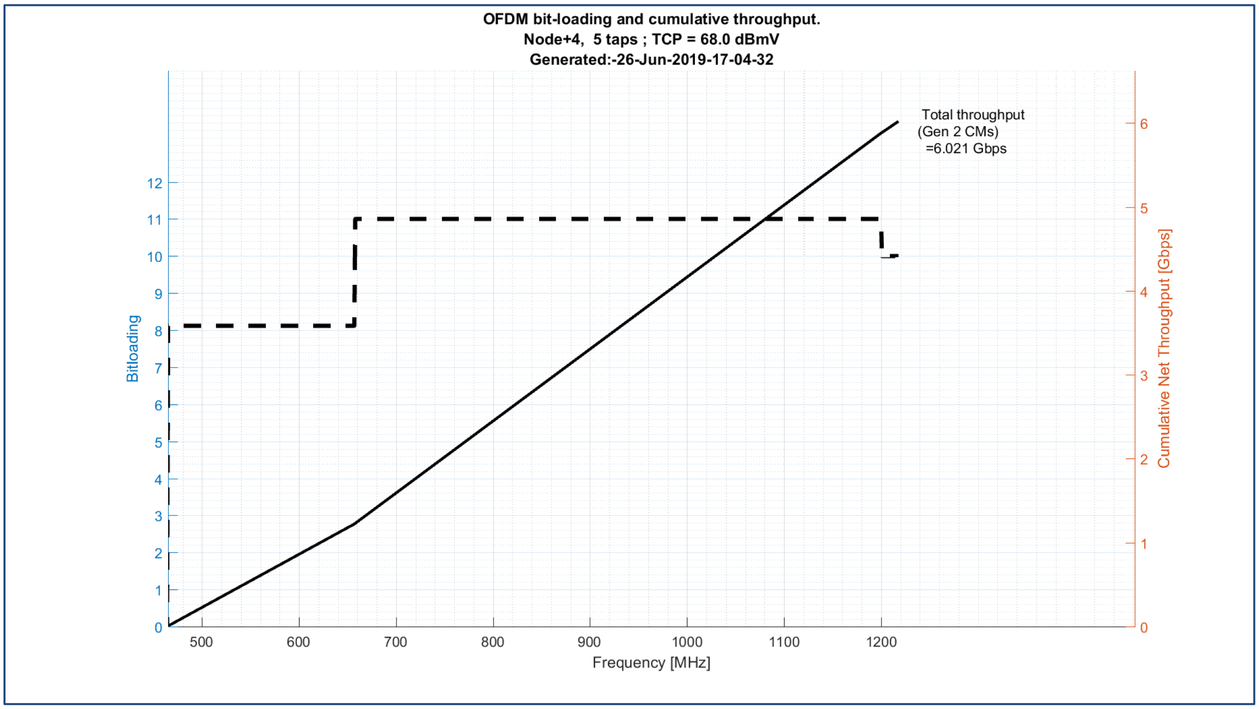

Figure 38 – Rx DS variable bit loading modulation profile and cumulative net DS throughput for the Static Soft-FDX system with 396 MHz split for MSO X

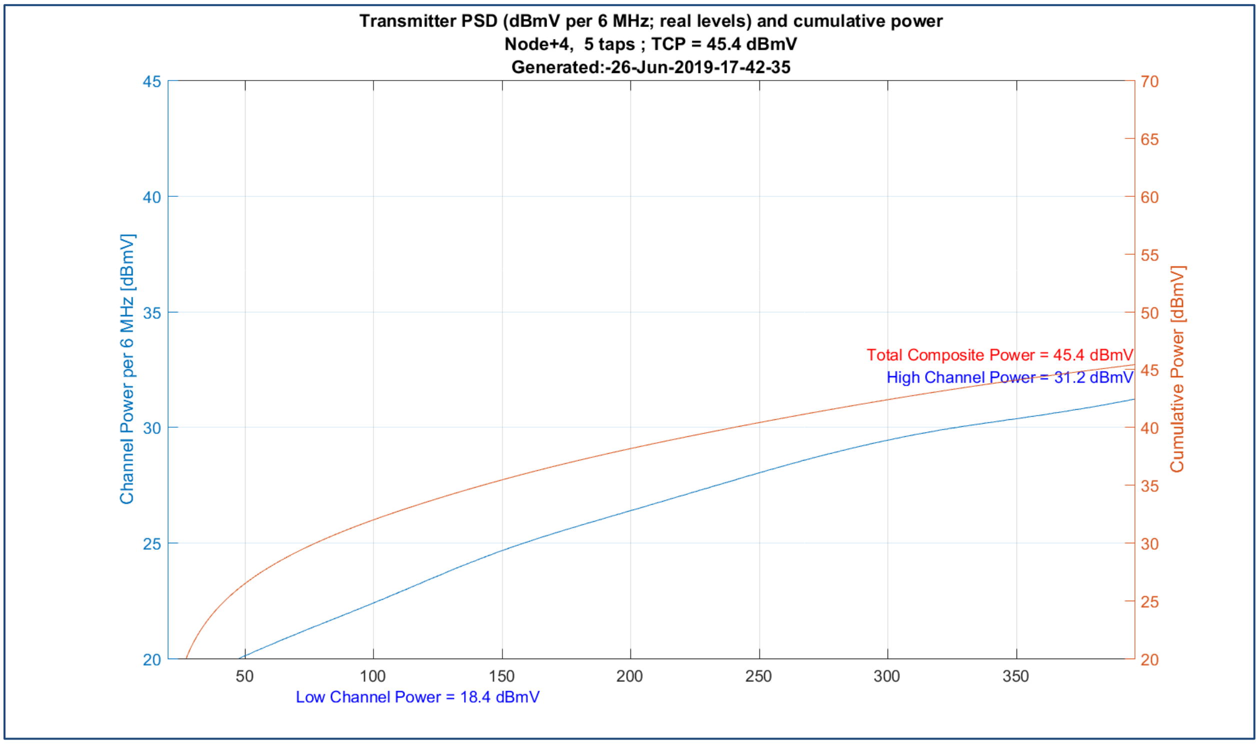

Figure 39 – Tx US PSD & TCP for the Static Soft-FDX system with 396 MHz split for MSO X

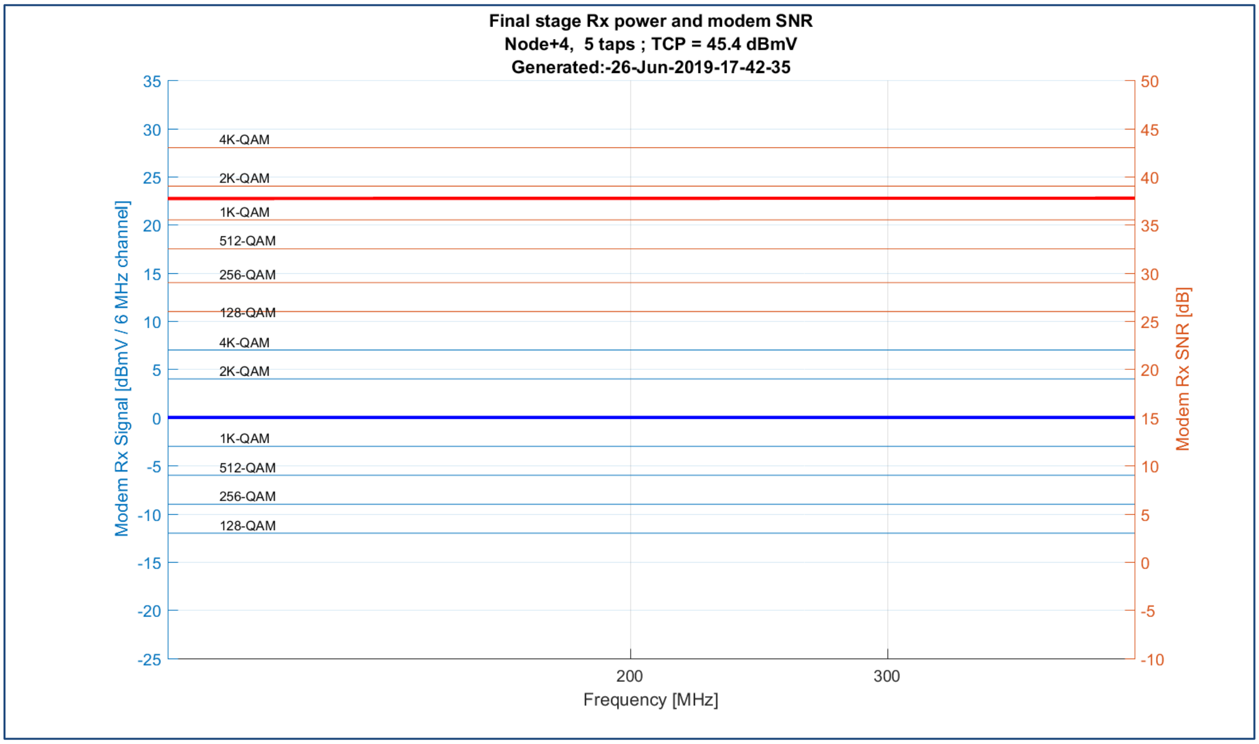

Figure 40 – Rx US SNR (red) & power levels (blue) & TCP for the Static Soft-FDX system with 396 MHz split for MSO X

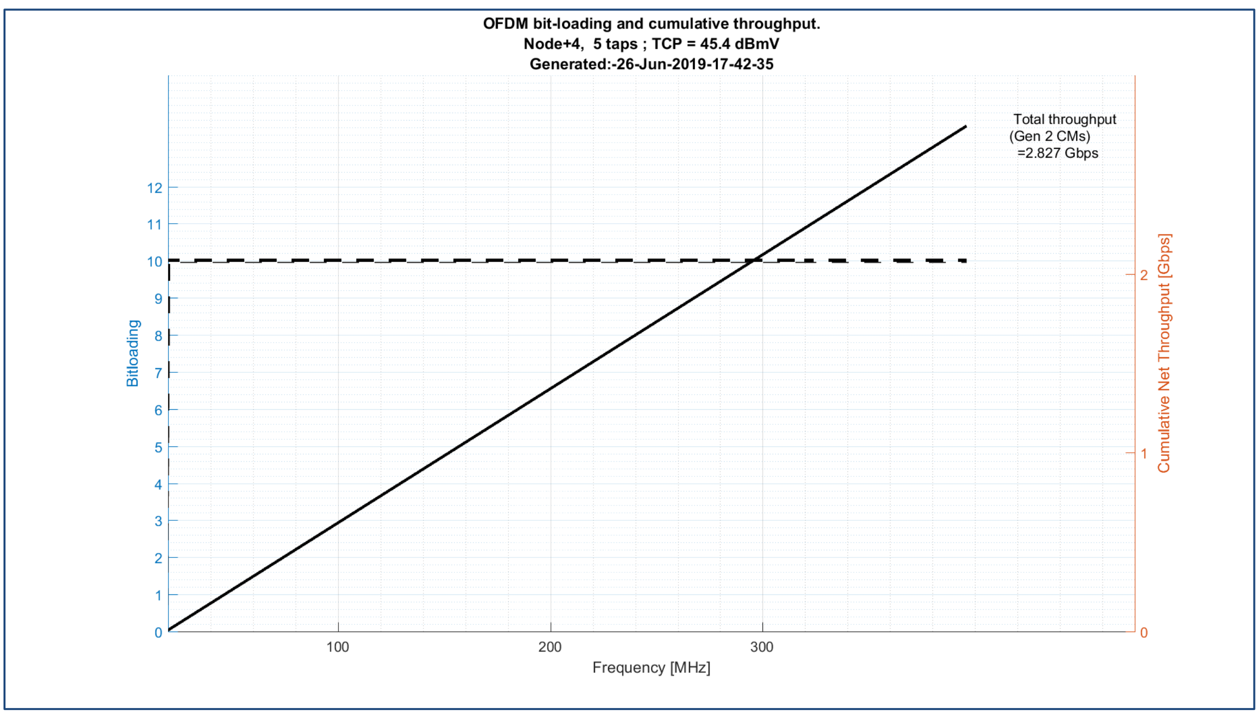

Figure 41 – Rx US variable bit loading modulation profile and cumulative net DS throughput for the Static Soft-FDX system with 396 MHz split for MSO X

The above analysis is for a single scenario of a proposed 396 MHz split in a Static Soft-FDX system. It will be informative to estimate the potential achievable capacities for other splits in a Static Soft-FDX systems. This was simulated using the same assumptions that were assumed for the MSO X scenario except for the DS SC-QAM channels that are eliminated and replaced with OFDM channels. The results for 204/258, 300/353, 396/465, 492/578, and 684/804 MHz splits are shown in Figure 42. Note how the net DS throughput decreases as the US split size increases because this is a Static Soft-FDX system where the US & DS spectra do not overlap and therefore the US spectrum will grow at the expense of the DS spectrum.

In a Dynamic Soft-FDX system where the split can change dynamically, the DS spectrum can be assumed to start at 108 MHz for all split options. While the DS & US spectra do not overlap, switching the split dynamically and quickly over time will allow the DS to burst with frequencies from 108-1218 MHz and the US to burst over frequencies between 20 MHz and the top of the split whenever is needed (provided that the switching occurs fast enough to accommodate the traffic demand). Therefore, the DS capacity can be approximated to be equal to the capacity achieved as if the system had access to the 108-1218 MHz spectrum permanently. As for the US, the results will be identical to the Static Soft-FDX case. The achievable DS & US net throughputs for a Dynamic Soft-FDX system are shown in Figure 43. Note that the net DS throughput is about 10 Gbps (9.5 Gbps to be exact) and the net US throughput is about 5 Gbps. Finally, observe that user requests for higher US throughputs will likely be very infrequent and therefore the switching of the split will likely occur very infrequently as well.

As for the throughputs of FDX systems, their net throughputs can be approximated to be similar to the capacities achieved with Dynamic Soft-FDX systems if we assume that the infrequent switching overhead is roughly equivalent to the overhead incurred by the sounding process, RBA switching, DS throughput degradation due to residual interference from other Igs, etc. Therefore, it is safe to conclude that the DS & US throughputs of FDX systems are roughly equivalent to those shown in Figure 43.

Finally, recall that the parameters provided by MSO X assume N+4 network architecture. In order to study the effect of the number of amplifiers in a cascade on the achievable capacities, DS & US simulations were performed using the same assumptions listed above but for various number of amplifiers in the cascade and the results are shown in Figure 44. Observe that the throughput values for the 396 MHz split case are identical to those shown earlier. The results here show that the number of amplifiers in a cascade did not have a significant effect mainly because the assumed plant hardline coax length (176 m) is relatively short.

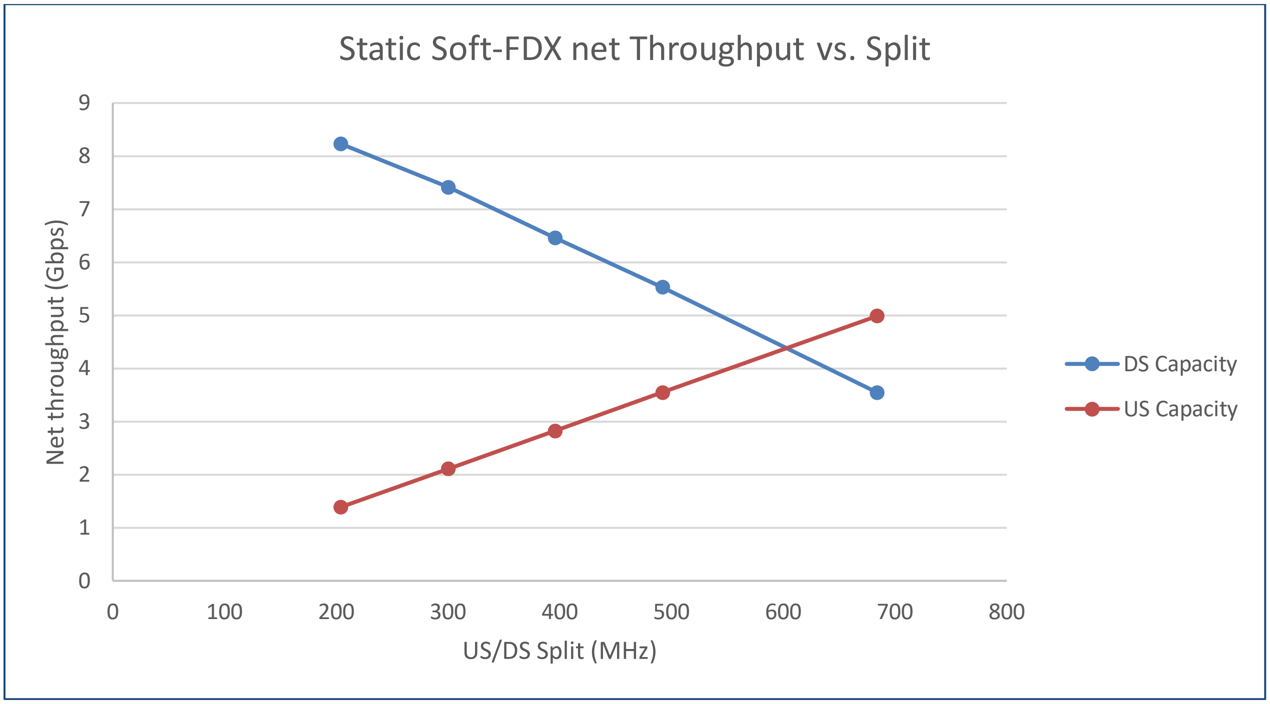

Figure 42 – DS & US net throughputs for Static Soft-FDX systems (different US/DS split options)

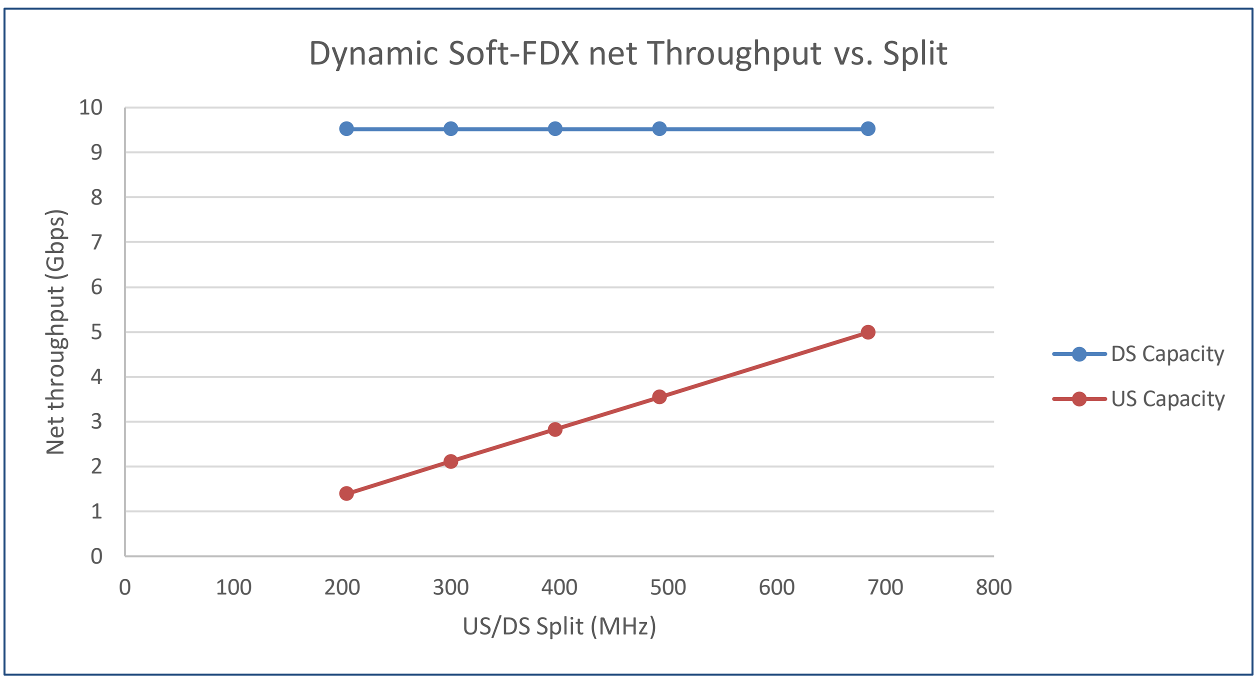

Figure 43 – DS & US net throughputs for Dynamic Soft-FDX systems (different US/DS split options) & FDX systems

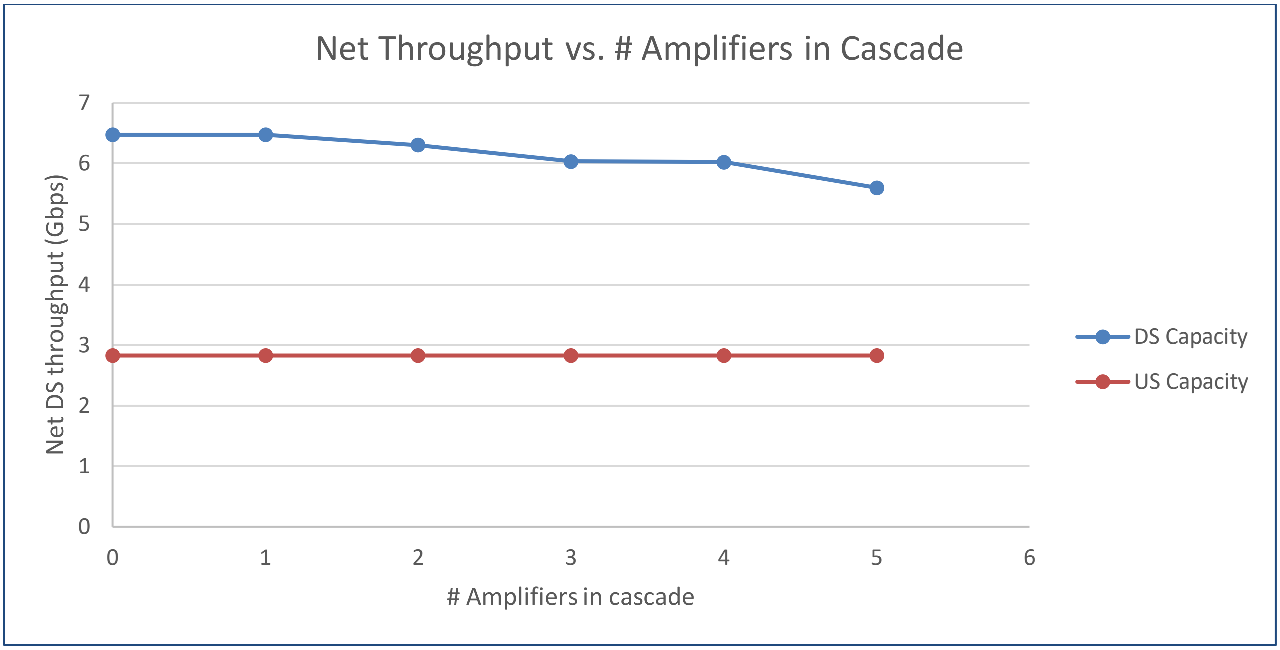

Figure 44 – DS & US net throughputs for a Static Soft-FDX system (396 MHz) with variable cascade depth

6. FDX Taxonomy

Given that many modes are supported by FDX & FDD, confusion can easily occur when discussing migration strategies. This section attempts to define and study the various FDX/FDD options which are proposed in Figure 45. Note that in Figure 45, the term Ultra-Split refers to cases where the US BW can go beyond 204 MHz (i.e., up to 300, 396, 492, 588, and 684 MHz).

The US BW augmentation strategies in Figure 45 are listed from the least flexible option (on the left) to the most flexible option (on the right). These strategies can be divided into the following categories.

FDD: refers to an FDD operation where split does not change during normal operation.

> **Hard-FDD:** refers to an FDD operation where the split does not change during normal operation. Moreover, if the split needs to be changed, then a truck-roll visit to the node/amplifier is needed.
>
> > **Mid-Split Hard-FDD 5-85 MHz:** refers to an FDD operation where the split 85/108 MHz does not change during normal operation. Moreover, if the split needs to be changed, then a truck-roll visit to the node/amplifier is needed. This option works with amplifiers that contain embedded or pluggable diplexers.
> >
> > **High-Split Hard-FDD 5-204 MHz:** refers to an FDD operation where the split 204/258 MHz does not change during normal operation. Moreover, if the split needs to be changed, then a truck-roll visit to the

node/amplifier is needed. This option works with amplifiers that contain embedded or pluggable diplexers.

Ultra-Split Hard-FDD: refers to an FDD operation where the split 300/353, 396/465, 492/578, 588/691, or 684/804 MHz does not change during normal operation. Moreover, if the split needs to be changed, then a truck-roll visit to the node/amplifier is needed. This option can work with amplifiers that contain embedded or pluggable diplexers.

FDX: refers that the BW augmentation is achieved by using FDX-based technology for the node and/or amplifiers.

Static Soft-FDX (Node-Level FDX): refers to an FDD operation where the split does not change during normal operation. However, if the split needs to be changed, then it can be done remotely via software configuration and a truck-roll visit to the node/amplifier is not needed. This mode supports FDX operation at the node MAC-level. Each node RF leg can operate with non-overlapping US & DS spectra (i.e., FDD mode) configuration. Various legs can have different spectrum assignments/split configurations leading to overlapping US/DS spectra at the node MAC level. That is, this mode runs in FDD operation at the leg level (it can also be run as FDD at the node level)

Ultra-Split Static Soft-FDX: refers to an FDD operation where the split 300/353, 396/465, 492/578, 588/691, or 684/804 MHz does not change during normal operation. However, if the split needs to be changed, then it can be done remotely via software configuration and a truck-roll visit to the node/amplifier is not needed. This option can work with FDX amplifiers or amplifiers that contain switchable diplexers.

Dynamic Soft-FDX (Node-Level FDX): refers to an FDX operation at the node MAC-level. Each node RF leg will operate with non-overlapping US & DS spectra (i.e., FDD mode). For each leg, the direction of any particular spectrum portion changes dynamically over time (TDD) and therefore various legs can have different spectrum assignments at any moment in time leading to overlapping US/DS spectra at the node MAC level. That is, this mode runs in TDD/FDD operation at the leg level (it can also be run as TDD/FDD at the node level)

Ultra-Split Dynamic Soft-FDX (HDX): refers to the operation where the direction of the whole allocated FDX spectrum on any RF leg is either US or DS at any moment of time. This corresponds to RBAs of 111 or 000, where 0 refers to the US direction and 1 refers to the DS direction. This assignment can change dynamically over time. This approach is referred to as HDX and can be viewed as a special case of the Ultra-Split Dynamic Soft-FDX (Sliding-Split) option below. This option requires FDX amplifiers or amplifiers with switchable diplexers.

Ultra-Split Dynamic Soft-FDX (Sliding-Split): refers to the operation where the US/DS split within the allocated FDX spectrum on any RF leg move or 'slide' over time. In this configuration, the US channels will always be at frequencies less than those for DS channels in the allocated FDX spectrum. This corresponds to RBAs of 111, 011, 001, and 000, where 0 refers to the US direction and 1 refers to the DS direction. This assignment can change dynamically over time. This option requires FDX amplifiers or amplifiers with switchable diplexers.

Ultra-Split Dynamic Soft-FDX (Subband): refers the operation where the assignment between US & DS within the allocated FDX spectrum on any RF leg is not constrained by any limits. That is, the direction of each of the subbands on the leg can arbitrarily be set to either in the US or DS direction at any moment of time. This corresponds to all possible RBAs RBAs of 000, 001, 010, 011, 100, 101, 110, and 111, where 0 refers to the US direction and 1 refers to the DS direction. This assignment can change dynamically over time. This option requires FDX amplifiers.

Traditional FDX (Leg-Level FDX): refers to the operation where the US & DS spectra can overlap on the RF leg of the node. This mode runs in TDD/FDD operation at the IG level.

Ultra-Split Traditional FDX: refers to the true FDX operation where the US & DS spectra can overlap on the RF leg of the node. In this case, multiple Igs on the leg are expected to enable a true FDX operation. This will require N+0 network architecture. As discussed earlier, if this option is used with cascaded networks, FDX amplifiers will lead to the IG elongation problem, which may preclude the cascaded system from supporting a true FDX operation.

Observe that Figure 45 shows a future vision for the US BW, where BWs above 684 MHz may be required if US speeds beyond 5-6 Gbps are needed.

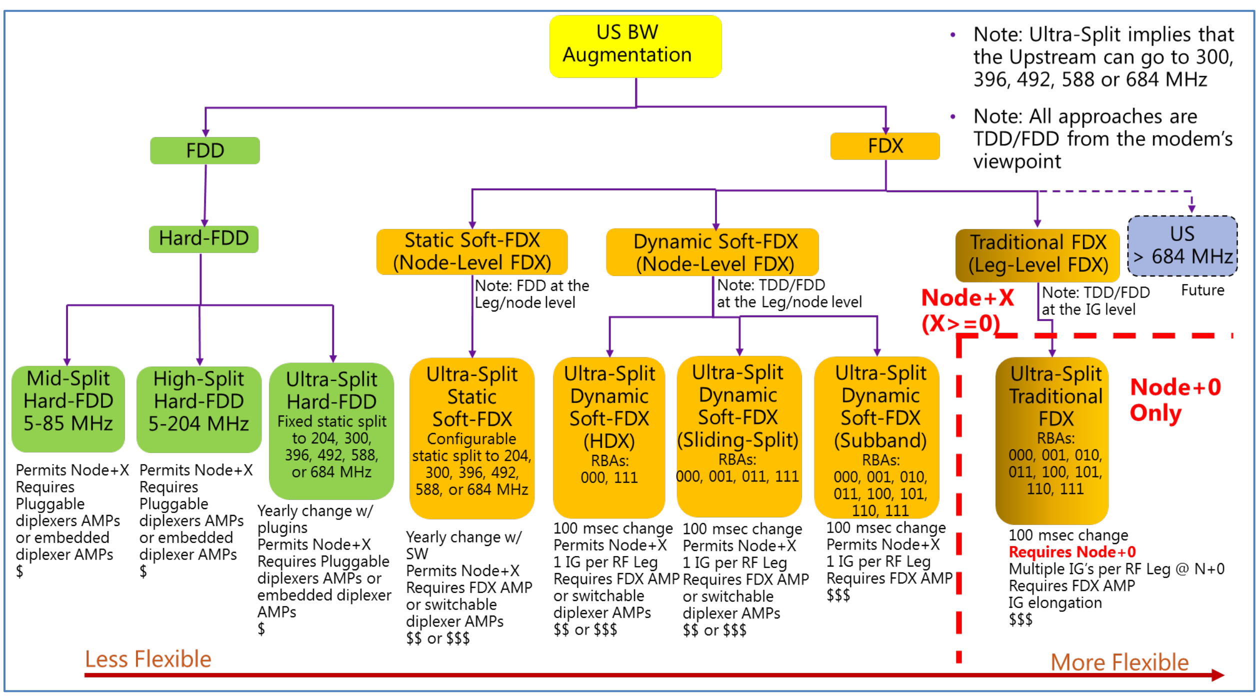

Figure 45 – FDX Taxonomy

7. Video Signals & Video OOB Signaling Issues with Potential Solutions

The delivery of legacy video signals and video OOB signals can become tricky whenever the US/DS split needs to be increased to a value above 85/108 MHz. This is because video OOB DS signals are typically within the 85-104 MHz frequency range and increasing the US/DS split beyond 85/108 MHz would cause that portion of the spectrum that is typically used for DS OOB signals to be within US frequency range. Also, legacy video signals tend to be placed in the lower part of the DS spectrum and increasing the split will require moving those legacy video channels to higher frequencies.

In the FDX specifications, it was assumed that FDX homes to be internet protocol (IP) video homes. That is, houses with FDX gateways are not required to receive legacy video signals. Additionally, since the FDX specifications assumed N+0 network architecture, it was assumed that the node can insert the DS OOB signals in the frequency range between 85-104 MHz (that spectrum is not used for the US, which ranges from 5-85 MHz for legacy and 108-684 MHz for US FDX signals). The delivery of those OOB signals in amplifiers was not discussed, because it seemed irrelevant with the N+0 network architecture. However, given that MSOs are considering increasing the US split to 204/258 MHz or using the Soft-FDX options (based on FDX technology) in cascaded networks, the topic of legacy video signals and OOB signals delivery becomes critical.

As for FDX nodes, the delivery of video OOB signals does not present a challenge due to the fact that FDX nodes tend to use couplers as opposed to diplexers as shown in Figure 46. As for the delivery of legacy video signals, those channels will need to be placed above the allocated the allocated FDX spectrum and they will be received by houses with non-FDX modems. As for legacy nodes (prior to FDX) with high-splits or Ultra-high-splits diplexers, those nodes will need to be modified to potentially use quad-plexers or combination or filtering and diplexers and couplers in order to be able to inject DS video OOB signal within the US frequency range. In some alternative schemes, the node can upconvert the OOB signals to a high frequency range that will need to be down-converted somewhere in the network for proper consumption of the legacy video devices. Alternatively, DOCSIS Set-Top Gateway (DSG) signaling can also be used.

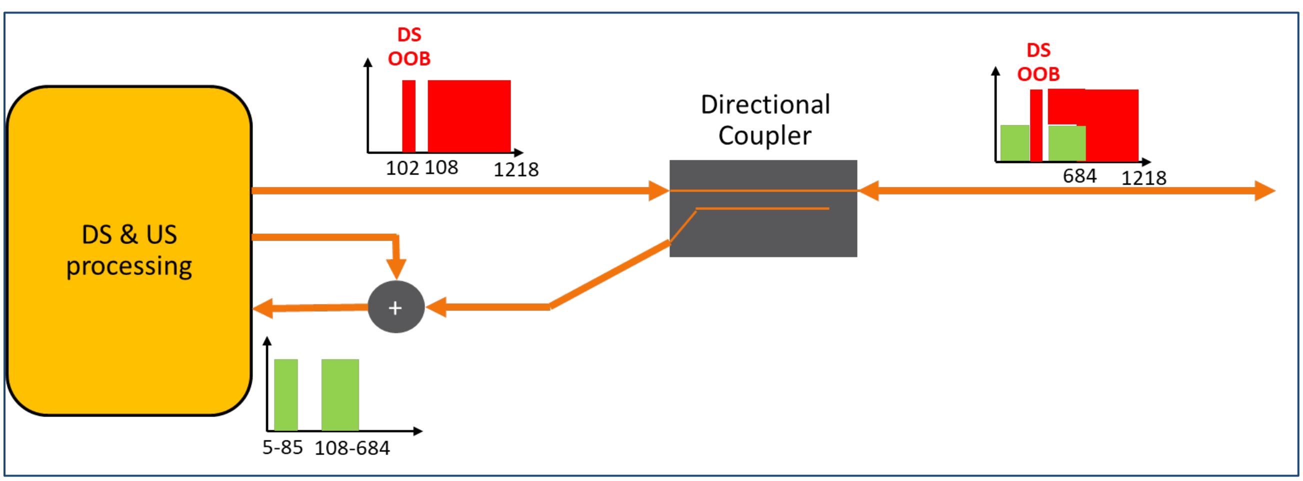

Figure 46 – OOB signal delivery in FDX Nodes

As for houses served by high-split or ultra-high-split networks, there are potentially various ways to solve the legacy video signals and video OOB signals. For OOB signals, if the node/network transmit those signals in the appropriate frequency range, then no additional work is needed by the house gateway (i.e., only some filtering to make sure those signals get delivered to the set-top boxes (STBs) inside the home). On the other hand, if the node or the network upconverts the video OOB signal, the house gateway will need to down-convert it to the appropriate frequency range and send it to the STBs inside the home. If the network sends those signals via DSG signaling and the STBs inside the home do not support that, then the home gateway will need to decode those signals and convert them to regular OOB signals to be delivered to legacy STBs inside the home.

As for the home reception of legacy video signals, where the gateway is at the point-of-entry (PoE) of the house, few approaches are possible: those houses could use IP video, or the gateway can use filters to allow QAM video signals to pass through into the home network. Alternatively, the gateway can receive QAM video signals and re-generate them as IP video for IP STBs inside the home. Another alternative is for the gateway to receive video QAM signals and re-generate those QAM video signals for delivery over the home network for legacy STBs.

As for amplifiers, delivering legacy video signals in high-split and ultra-high-split networks does not present any challenge. On the other hand, delivering legacy video OOB signals will need to be resolved. Amplifiers can use quad-plexers in order to support the delivery of legacy video DS OOB signals inside the US frequency range. Alternatively, the amplifiers may need to down-convert the OOB signal (if the node/network use upconverted OOB signals) and inject it within the US spectrum for delivery to houses connected south of this amplifier. Finally, the amplifiers can use some filtering schemes where the OOB signals can be extracted, amplified, and re-injected back to the network.

8. Extended Spectrum DOCSIS (ESD)

ESD refers to the extension of the DS frequency range beyond the 1.2 GHz limit that can be supported with DOCSIS 3.1. Observe that the use of Dynamic Soft-FDX will postpone the need to extend the DS spectrum upper limit to higher frequencies because Dynamic Soft-FDX enables reclaiming the lost DS spectrum as soon as the demand for increased US BW is over. Extending the DS spectrum to very high frequencies can also be delayed if the DS roll-off region is used. In particular, taps can typically work at frequencies beyond their specified limit.

For example, Figure 47 shows a simulation of N+ 3 network using characterization data of a real-world 1 GHz tap. Note that the EoL net cumulative capacity of the system at 1 GHz (i.e., the specified limit of the tap) is slightly less than 6 Gbps. However, about 7.5 Gbps of capacity can be achieved if the roll-off region is used in this example. This particular tap was able to support reduced bit loading values even beyond 1.2 GHz. Obviously, the performance in the roll-off region will depend on the type/make/model/value of the tap, but there will always be some untapped capacity that can be reclaimed when pushing some spectrum in the roll-off region using reduced bit-loadings against frequency which is already supported with the variable bit loading feature of DOCSIS 3.1.

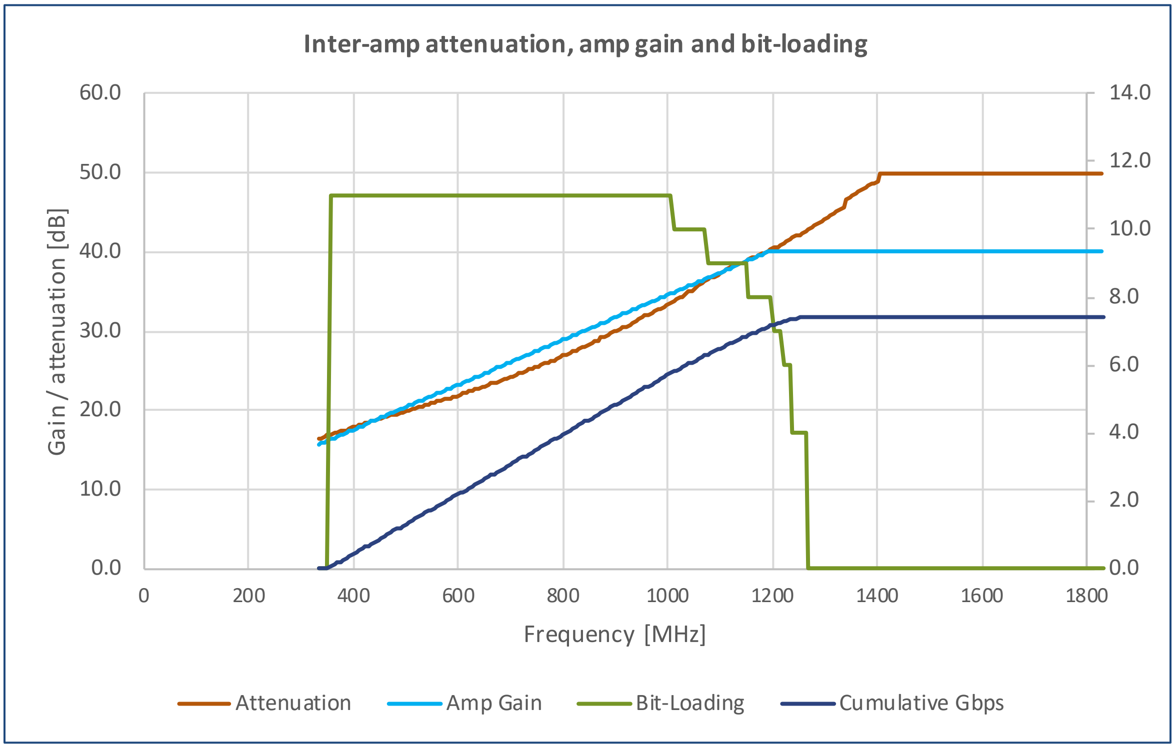

Figure 47 – N+3 Network simulation in the roll-off region

Going to higher DS frequency values beyond the roll-off region such as 1.8 GHz or 3 GHz (or even more) will likely become a necessity if Static Soft-FDX is used where increasing the US spectrum will occur at the expense of the available DS spectrum. If legacy video channels are not reclaimed and the demand for high DS peak rates persists, then there will be a need to extend the DS spectrum as shown in Figure 48.

ARRIS (now part of Commscope) studied the topic of extending the DS spectrum in previous work [ESD_SpForum] in fiber to the last active (FTTLA) and fiber to the tap (FTTT) systems illustrated in Figure 49. In that paper, ARRIS showed that N+0 FTTLA system can offer up to 30+ Gbps and FTTT systems can offer up to 200+Gbps. This significant capacity should not be overlooked! The capacity simulation results for the FTTLA and FTTT systems from [ESD_SpForum] are shown again in Figure 50 and Figure 51 for convenience. Note that these simulations [ESD_SpForum] represent the theoretical Shannon/Hartley capacities of the coaxial cable on its own without considering the effect of other equipment like tap losses, receiver performance, etc which will reduce the achievable capacities. The effect of these equipment is incorporated in the simulation results shown later in this section.

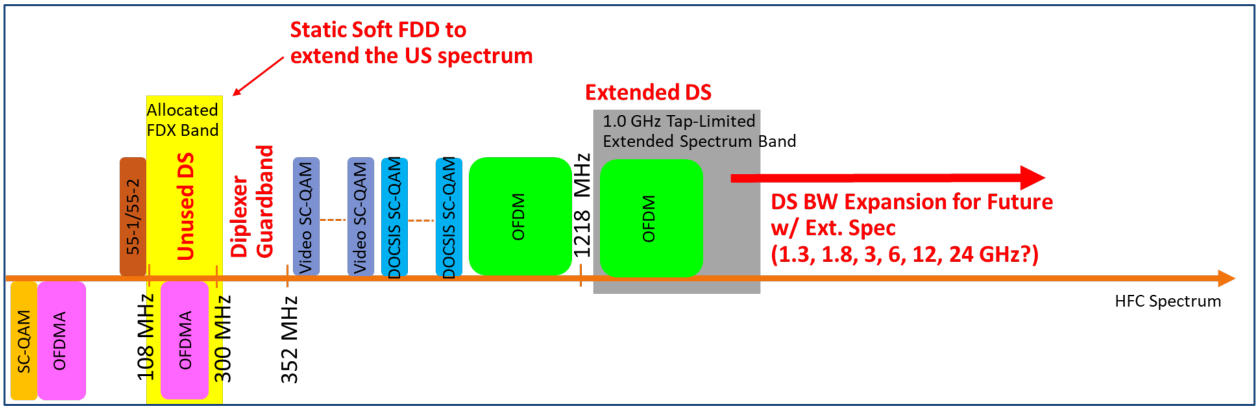

Figure 48 – Extending the DS spectrum when Static Soft-FDX is used

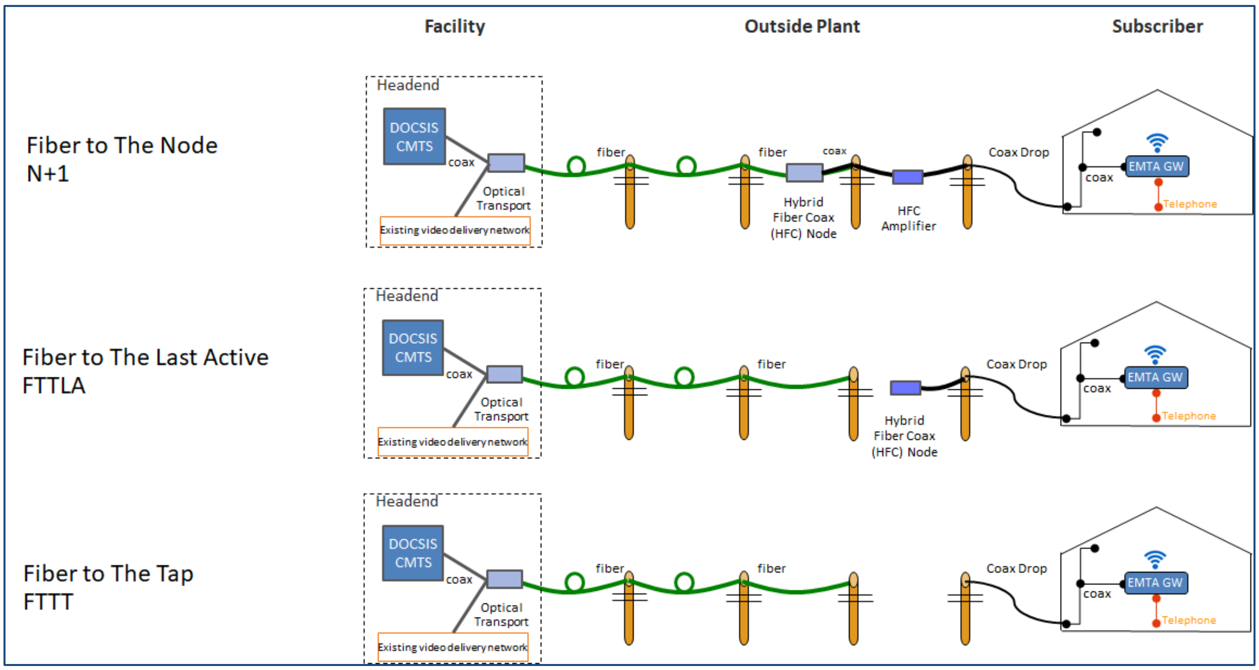

Figure 49 – Illustration of various HFC networks configurations, N+1, FTTLA, & FTTT systems

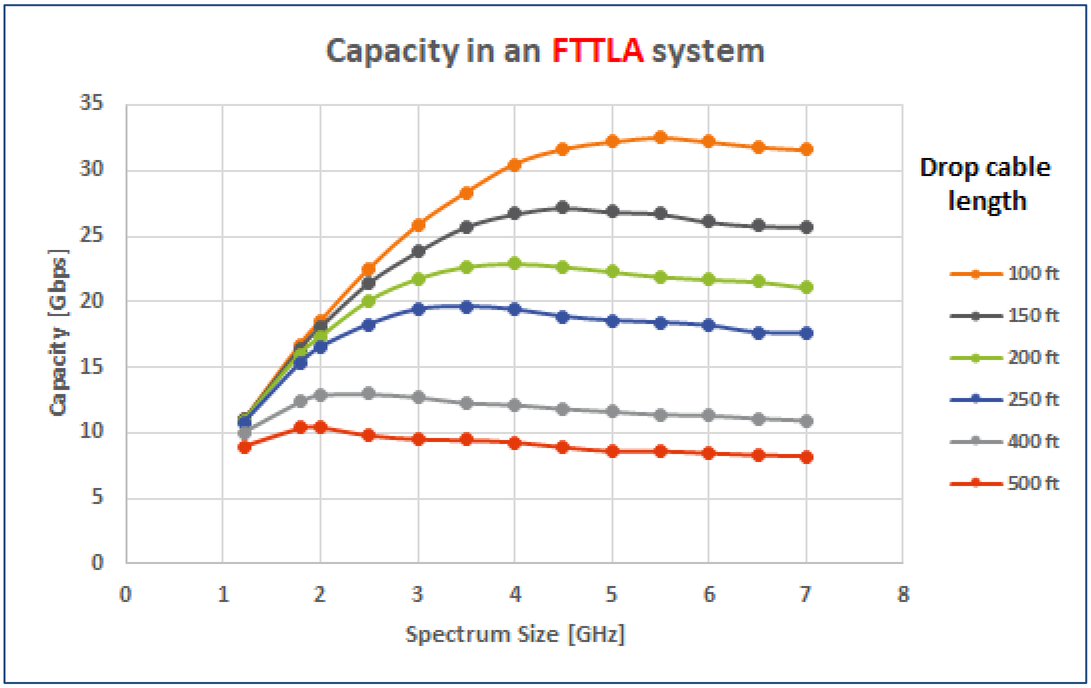

Figure 50 – Potential capacity achieved in FTTLA systems

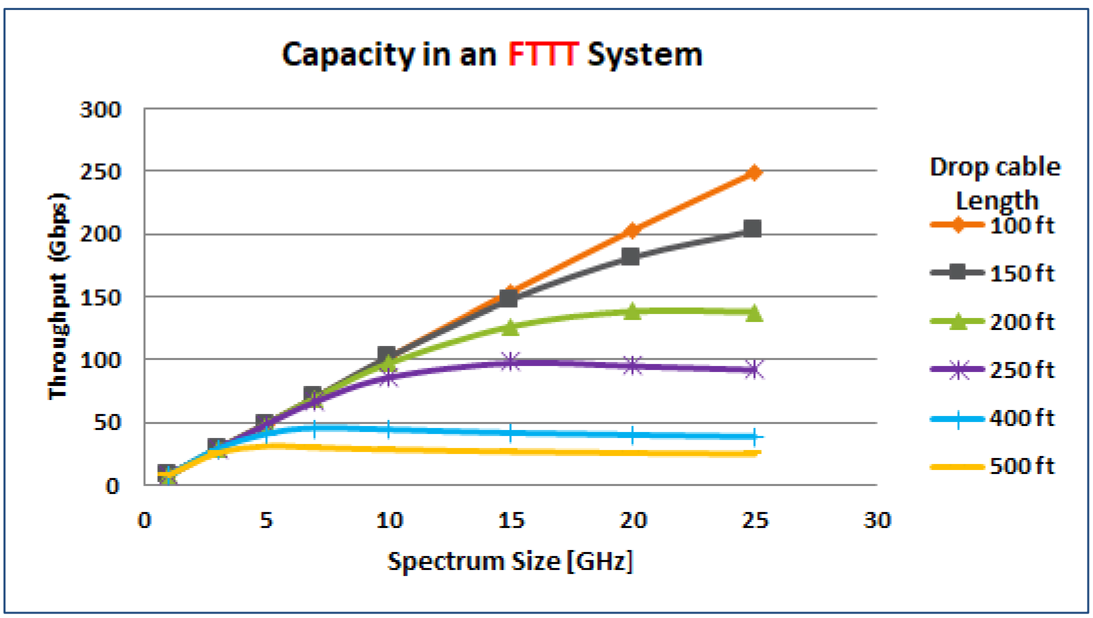

Figure 51 – Potential capacity achieved in FTTT systems

The topic of extending the DS spectrum to higher frequencies can be accompanied with various challenges that will need to be addressed. A list of such challenges and potential solutions is provided below:

- **Total Composite Power:** It might be intuitive to think that increasing the spectrum to higher values will require higher TCP values from the nodes and power amplifiers. While this might be ideal and may yield the highest possible capacities, keeping the TCP to levels that are comparable to the TCP levels supported in current nodes and power amplifiers is highly desired. The authors propose to keep the TCP roughly fixed at an equivalent TCP used in normal HFC operation today in order to facilitate realistic node and power amplifier implementation. Computer simulations showed that keeping the TCP values to current levels will not lead to significant losses in capacity with current plants lengths as will be shown later in this section
- **Tilt:** Modems and video STBs expect relatively flat PSD levels. Therefore, in today's deployments, up-tilted PSD levels are transmitted from the nodes and power amplifiers. Since extending the DS spectrum is proposed to be a backward compatible scheme, it is proposed the node and power amplifiers to transmit normal PSD levels and normal tilt values for the range of frequencies covering SC-QAM DOCSIS channel & SC-QAM Video channels. On the other hand, the transmit PSD would use flat tilt for frequencies covering DS OFDM channels above the SC-QAM channels as shown in Figure 52. This scheme is thought to be the optimal configuration to provide the highest throughputs given the limited Tx TCP values [ESD_SpForum]. Note that as SC-QAM channels for Video or DOCSIS are retired, more OFDM channels are added, and the flat region of the spectrum will expand and can have higher flat PSD levels and therefore higher SNRs, higher QAM orders, and higher throughputs. Observe that the received signal at the modems receiving those DS OFDM channels will be down-tilted and therefore the variable bit loading feature of DOCSIS 3.1 is required to reduce the QAM orders to levels that work with the reduced SNR values due to the down-tilted signal levels, and therefore guarantee an error-free operation in the presence of the down-tilted SNR values
- **Re-spacing of Amps**: Some might think that amplifier re-spacing may be necessary when extending the DS frequency range. However, given the proposed schemes of keeping the normal tilt & PSD levels in the frequency range covering video and SC-QAM channels and flat tilt PSD in the frequency range covering OFDM channels, re-spacing is not necessary. This is because legacy video and SC-QAM channels will continue to receive the expected levels and only OFDM are received with down-titled levels due to the increased attenuation leading to down-tilted SNR values which can be compensated for by using the variable bit loading feature of DOCSIS 3.1 as discussed earlier
- **# of Amps in Cascade:** Concerns are raised regarding whether the extended frequency range can be supported over the typical number of cascades that are used in today's networks. Some performance degradation may be expected as the distortions are added and accumulated at each amplifier stage. However, computer simulations showed that this effect was not significant performance degradation factor for N + 4 network architectures [FDX_ESD_IBC]
- **Multimedia over coax alliance (MoCA) in the home:** The overlapping frequency range of DOCSIS ESD signals and MoCA signals can present a challenge. To solve this issue, it is proposed to place the ESD CM as a portal gateway (GW) with 2 isolated RF ports at the PoE of the house. This will create and isolation between the OSP Network and the home network (just like what is proposed in the FDX specifications)
- **Legacy Video:** The topic of video signals and video OOB signals delivery is a challenge that is introduced by increasing the size of the US spectrum split which is typically accompanied with ESD deployments. This topic was addressed in section 7 of this paper

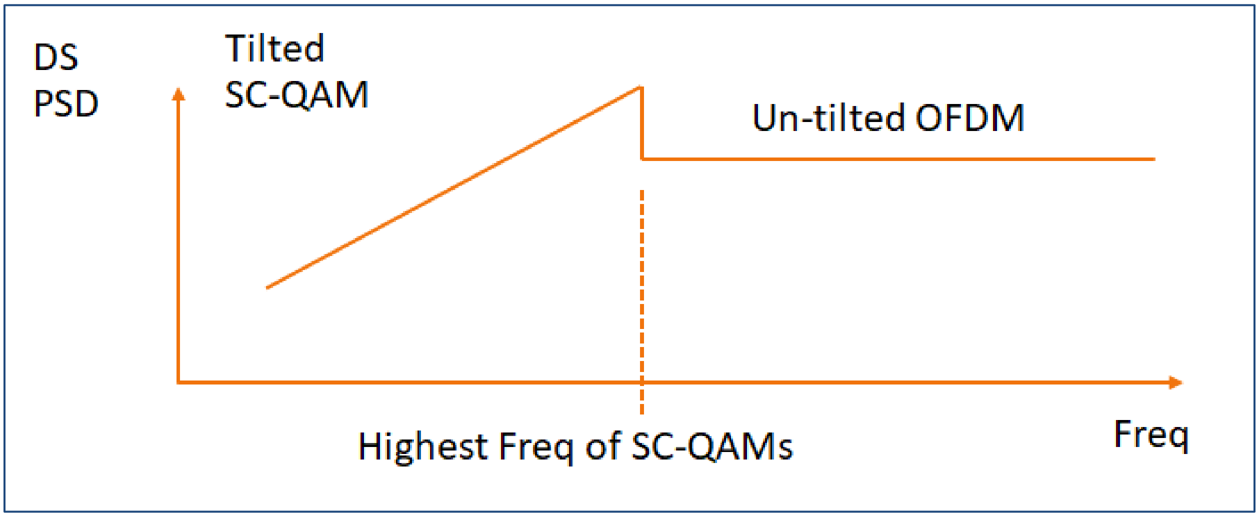

Figure 52 – Proposed Transmit PSD signature for ESD systems

Note that while hardlines and drop cables can support frequencies up to 7 GHz and 25 GHz [ESD_SpForum], respectively, a more natural intermediate step for increasing the DS frequency range could be 1.8 GHz or 3 GHz. Those frequency ranges will be able to satisfy the customer traffic demand and offer high peak rates that can address the Telco competition for the next two decades [Capacity_Tech]. In order to have an estimate of the potential capacities that can be achieved on 1.8 GHz and 3 GHz systems, computer simulations were performed, and the results are shown in Figure 53 & Figure 54 for 1.8 GHz systems and Figure 55 & Figure 56 for 3 GHz systems. Below are the key simulations assumptions, which are mostly similar to the assumptions used in the FDX & Soft-FDX simulations but are provided here again for convenience:

- Node+4 network architecture. Taps are not equalized. Two-way splitter in the home
- US starts at 20 MHz and stops at 684 MHz. DS starts at 804 MHz
- RG-6 drop cable length is 150 ft
- All stages are of equal length. Stage length represents the total hardline coax length between two amplifiers. Multiple hardline stage lengths cases were simulated
- All stages have 5 cable segments. Stages between amplifiers contain 4 taps in the sequence 23-20-17-14 dB) and the last stage has 5 taps in the sequence 23-20-17-14-8 dB (all 4-way)
- Flat PSD (i.e., no video/SC-QAM – assuming all OFDM channels to estimate the full potential capacity)
- All amplifiers except the final stage use 68 dBmV TCP to minimize the accumulated distortion. The last amplifier may have a higher TCP power to overcome final-stage losses. Signal to distortion ratio (SDR) is assumed to decrease as TCP values are increased (e.g., SDR of 41.4 dB at 73.3 dBmV TCP). Multiple TCP values were simulated
- Frequency response curves for a real (proposed sample) 1.8 GHz tap were used for the 1.8 GHz case. For the 3 GHz case, the 1.8 GHz tap characteristics were “stretched” out to 3 GHz to make 3 GHz tap data
- D3.1 allowed DS QAM modulation orders and SNR thresholds are used to estimate the variable bit loading profiles, but the modem is assumed to incorporate a pre-amp so D3.1 Rx power levels are not used

- DS PHY efficiency of 78%. EoL net DS throughout (after removing DS PHY overhead) is reported

Note that Figure 53 & Figure 54 are composed of the same data, yet show it differently (similar comment applies to Figure 55 & Figure 56). Observe that while the effect of the TCP level is less prevalent, the plant length is key for performance. Note also that the net DS throughput drops for short plants when the TCP value is increased to high levels, which leads to increased distortion levels. In a nutshell, these simulations results show that net DS throughputs of up to 8.5 Gbps and 18 Gbps can be achieved with 1.8 GHz and 3 GHz systems, respectively, given the above assumptions.

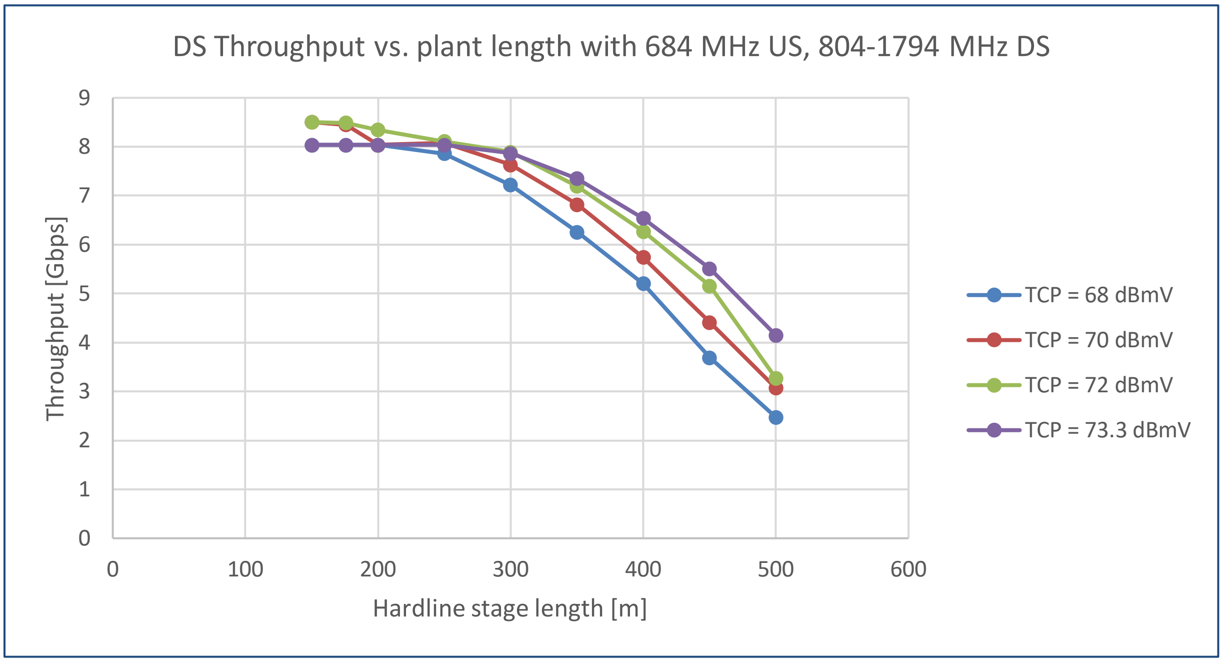

Figure 53 – Net DS throughput vs. plant length for 1.8 GHz systems (with different TCP levels)

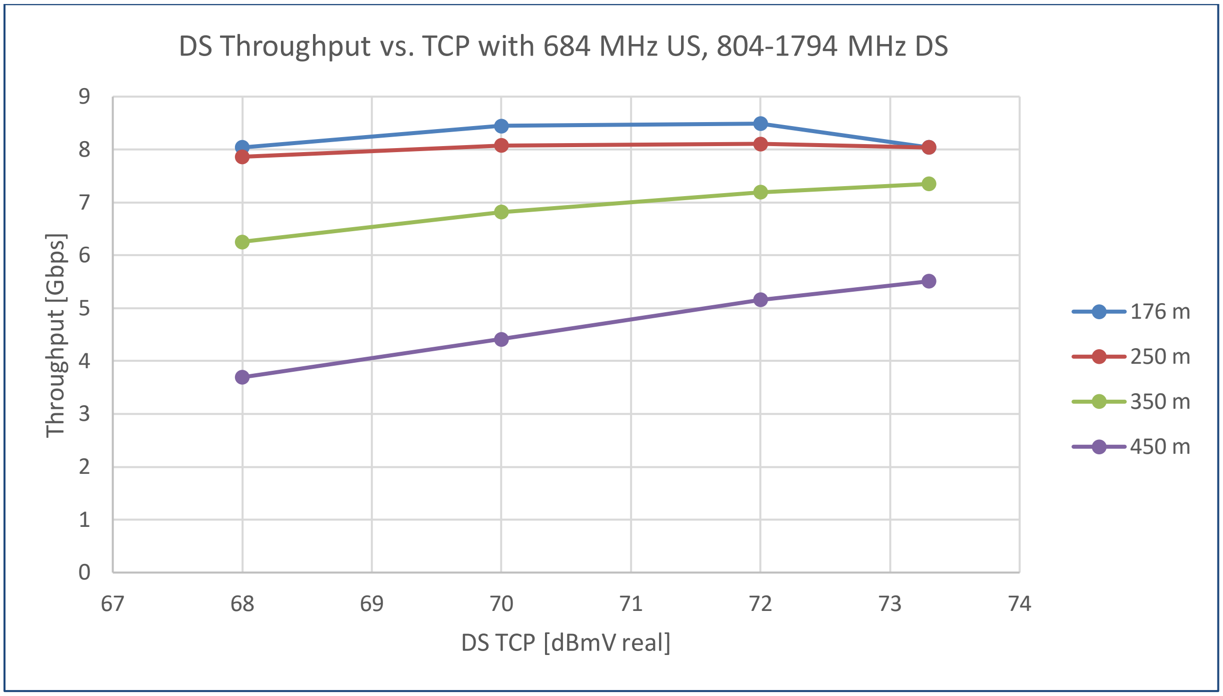

Figure 54 – Net DS throughput vs. TCP level for 1.8 GHz systems (with plant stage lengths)

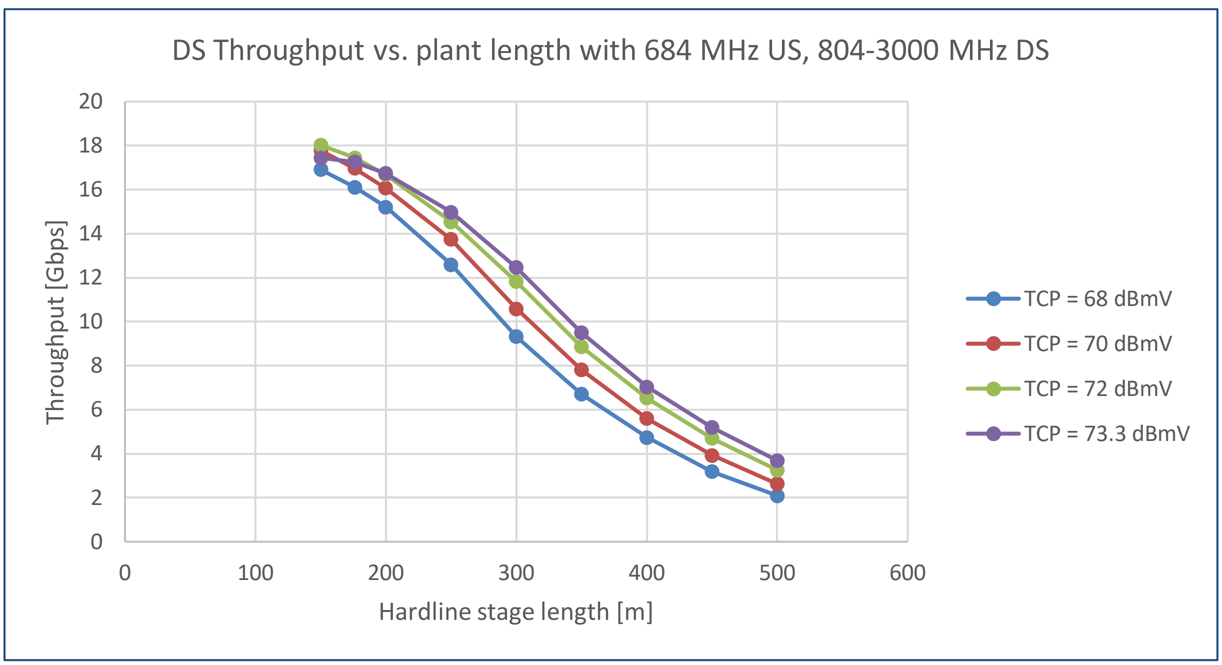

Figure 55 – Net DS throughput vs. plant length for 3 GHz systems (with different TCP levels)

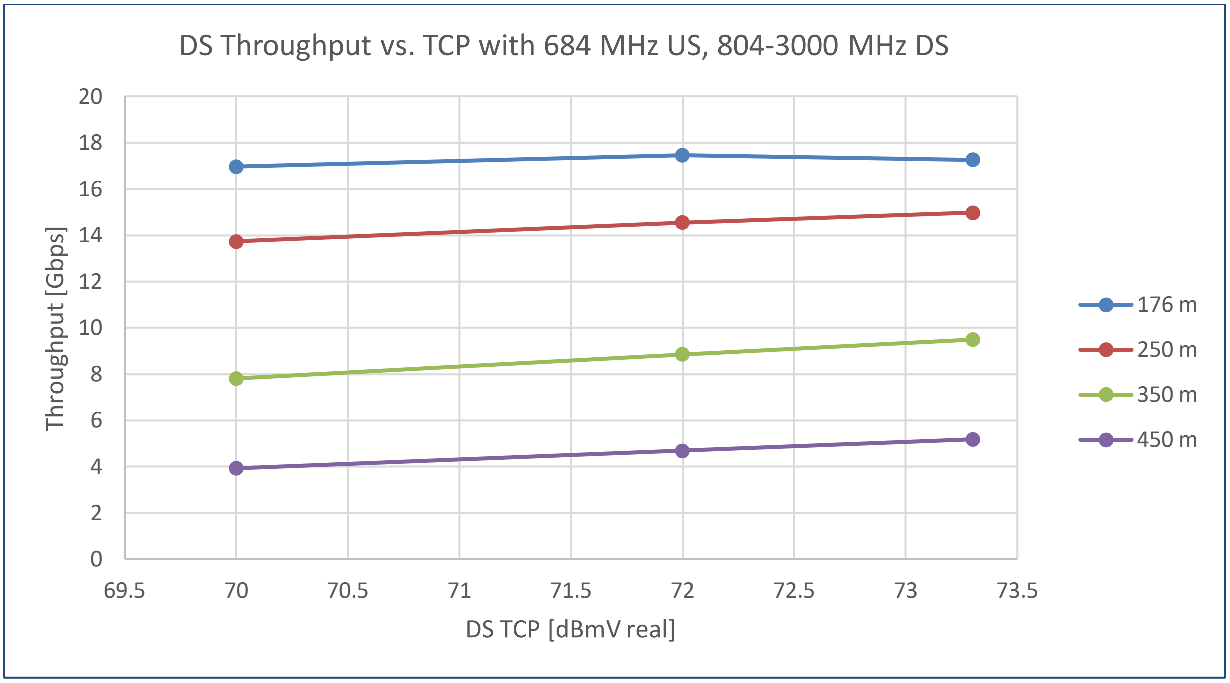

Figure 56 – Net DS throughput vs. TCP level for 1.8 GHz systems (with plant stage lengths)

To further illustrate the mechanics of the simulations, let us consider a single data point from these curves and provide the detailed simulation results that yielded that data point. Let us consider the case of 300m stage length with TCP of 70 dBmV in the 3 GHz system which produced a net DS throughput of 10.581 Gbps. For this case, Tx PSD & TCP are shown in Figure 57, the Rx SNR & power levels are shown in Figure 58, and finally the variable bit-loading modulation profile & cumulative net DS throughput are shown in Figure 59.

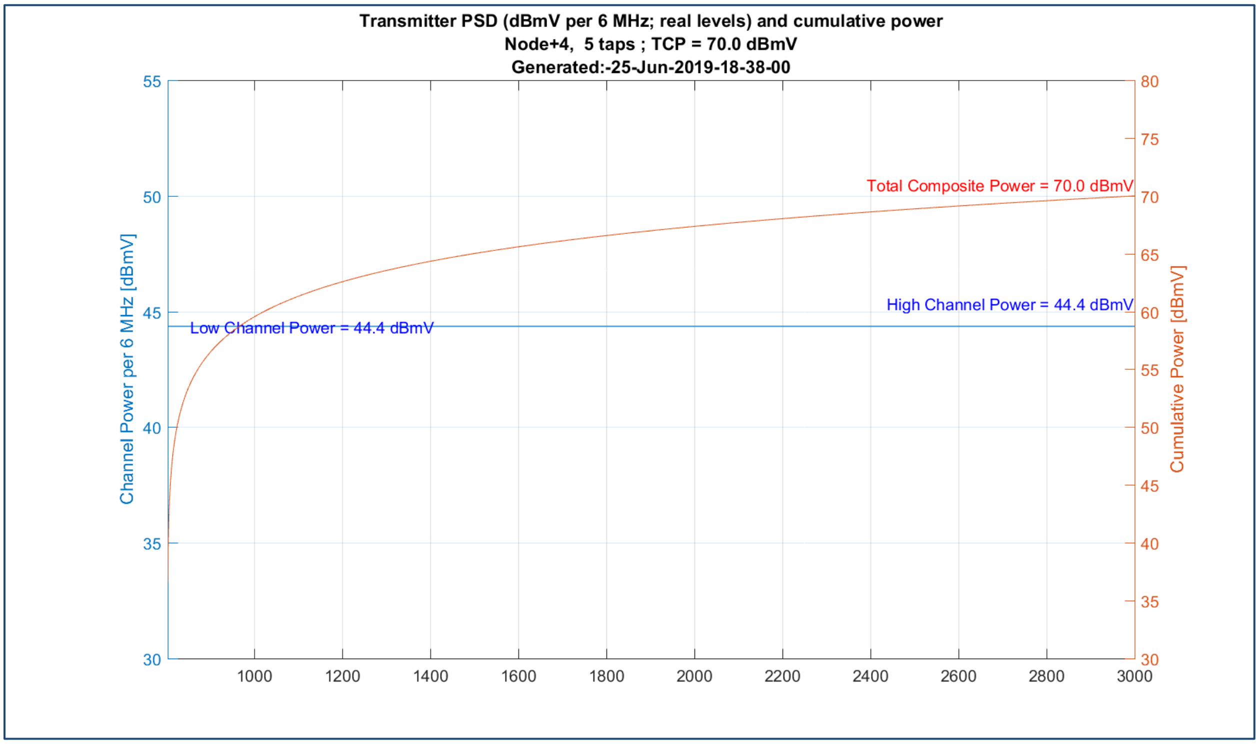

Figure 57 – Tx DS PSD & TCP for the 300m stage length with TCP of 70 dBmV in the 3 GHz system

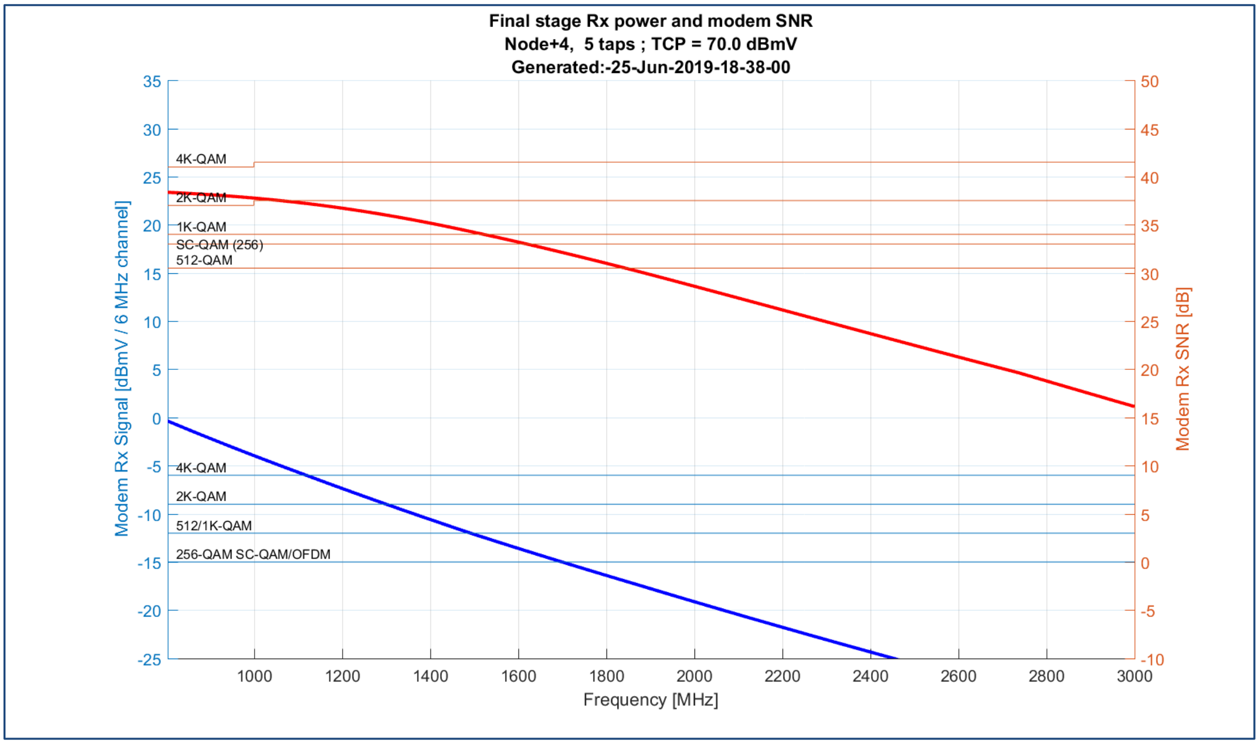

Figure 58 – Rx DS SNR (red) & power levels (blue) & TCP for the 300m stage length with TCP of 70 dBmV in the 3 GHz system

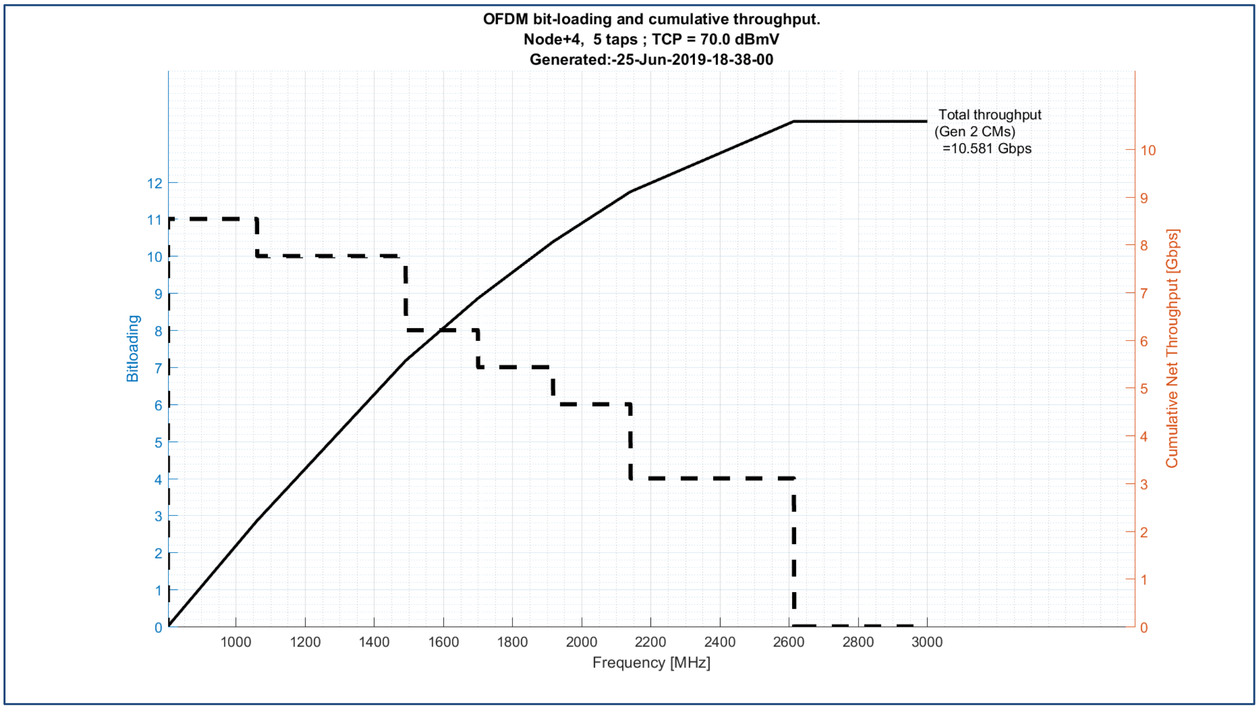

Figure 59 – Rx DS variable bit loading modulation profile and cumulative net DS throughput for the 300m stage length with TCP of 70 dBmV in the 3 GHz system

9. Network Migration Strategies

The previous sections of this paper described some of the available techniques that can be used to extend the life of HFC networks. These techniques include traditional FDX, Soft-FDX, and ESD. Other techniques that were discussed in other papers by the authors include DOCSIS 3.1 [D3.1_Tech], time and frequency division multiplexing (TaFDM) [TaFD_Tech], and FDD with channel bonding.

This section attempts to put the pieces together. In particular, it will introduce a migration methodology via proposing a network migration decision flow diagram as shown in Figure 60 [Migration2_ANGA]. This migration strategy work is an augmentation to the migration decision flow diagram that was initially proposed in [Migration1_ANGA].

It is critical for MSOs to start deploying DOCSIS 3.1 if they have not started already. This technology will increase the capacities that can be achieved on HFC networks in a given bandwidth due to the more noise-robust & efficient multi-carrier OFDM modulation and low-density parity check code (LDPC) FEC technologies [D3.1_Tech]. The additional US & DS capacities can postpone the next migration step and therefore ensure a smooth, timely, and cost-effective migration strategy.

As for the US, MSOs can use DOCSIS 3.1 with or without changing the split. However, some MSOs already started planning/deploying 204 MHz split in addition to DOCSIS 3.1 to enable symmetrical 1 Gbps services. MSOs that decide to stay at 42 MHz/65 MHz/85 MHz US splits can still deploy DOCSIS 3.1 in that part of the spectrum and either configure OFDMA channels in the vacant parts of the spectrum and bond it with US SC-QAM channels or use the TaFDM feature to overlap both types of channels. Although any of those options can be used, recent work [TaFD_Tech] showed that the FDD with channel bonding approach, where using just enough US SC-QAM channels to accommodate legacy services and reclaiming the leftover spectrum and assigning it to OFDMA channel(s) will provide similar or even superior performance than that of the TaFDM feature. This is mainly because the TaFDM feature suffers from some inefficiencies related to switching overhead, guard-bands between different channels, and guard-times between various grants [TaFD_Tech].

Note that the above steps (i.e., DOCSIS 3.1, split change, channel bonding, etc.) can be based on either an Integrated Converged Cable Access Platform (I-CCAP) or DAA platform. This is important to note because the next steps in the migration flow diagram are based on an FDX technology that requires a DAA network architecture.

As mentioned earlier, deploying DOCSIS 3.1 (regardless of changing the split or not) will postpone future network migration steps because the additional obtained capacity will enable the MSOs to meet more user traffic demand and address competition by offering higher Service Level Agreement (SLA) speeds. During this time extension, MSOs may continue to perform node splits in order to avoid traffic congestion on channels during busy hours. By the time there is a renewed need for larger US spectrum, MSOs will be positioned to evaluate their networks whether they are N+0 or not. If it is, then an MSO will have the option to use the traditional FDX or Dynamic Soft-FDX operation. On the other hand, if the network architecture is not N+0 (i.e., N+x), then the MSO may have to consider other alternatives.

When an MSO has an N+x network architecture and there is a need to increase the US BW, a decision needs to be made on the next step. The question becomes, "does exist FDX amplifiers that can support the traditional FDX operation?" This was discussed in section 3 of this paper, where it was mentioned that true FDX amplifiers will not be able to support a traditional FDX operation due to the IG elongation problem (unless the number of amplifiers is doubled, or less efficient workarounds are used which still will not permit a true FDX operation). If the FDX amplifiers are hypothesized to support true FDX operation, then the MSO can use them either in traditional FDX mode/Dynamic Soft-FDX especially if the DS spectrum is scarce, where the need to overlap US & DS is unavoidable, or in a Static Soft-FDX mode if the DS spectrum is abundant.

In the likely case where the available FDX amplifiers do not support traditional FDX operation, the MSO will have to use them in a Static Soft-FDX mode. If/when the DS BW gets scarce, the MSO will need to evaluate the next step by asking whether their network has arrived at N+0 or whether there are FDX amplifiers that exist and can support traditional FDX operation. If either is true, then the MSO can move to a traditional FDX/Dynamic Soft-FDX operation. If that is not the case, the MSO will have to begin using the roll-off region of the DS spectrum followed by extending the DS spectrum beyond the DS roll-off region (e.g., 1.8 GHz or 3 GHz).

If cost-effective, deploying active taps is another stepping stone that can be used to amplify the signals on hardlines, which can carry signals up to 7 GHz, and therefore enable higher capacities [ESD_SpForum]. This will buy MSOs even more time before the need to push the fiber deeper to the tap yielding the FTTT architecture, which will allow frequencies up to 25 GHz to be used [ESD_SpForum].

In the FTTT architecture, true FDX operation can occur for every subscriber because there will be point-to-point connection between the tap and every subscriber connected to it. Fiber to the home (FTTH) is the end goal architecture for many MSOs and can be reached as a follow-on step from the FTTT by laying fiber between the tap and subscriber home (i.e., laying fiber in the house backyard). Note that different MSOs may follow different migration paths depending on what makes sense for their financials and network architecture. Some MSOs may also try to skip some of the steps along the way as they see fit.

The above discussion can be further clarified by providing two network migration scenarios for two different MSO usecases. MSO A with an N+0 network may choose to follow the migration steps shown in Figure 61, while an MSO B with cascaded network is likely to follow the migration path shown in Figure 62.

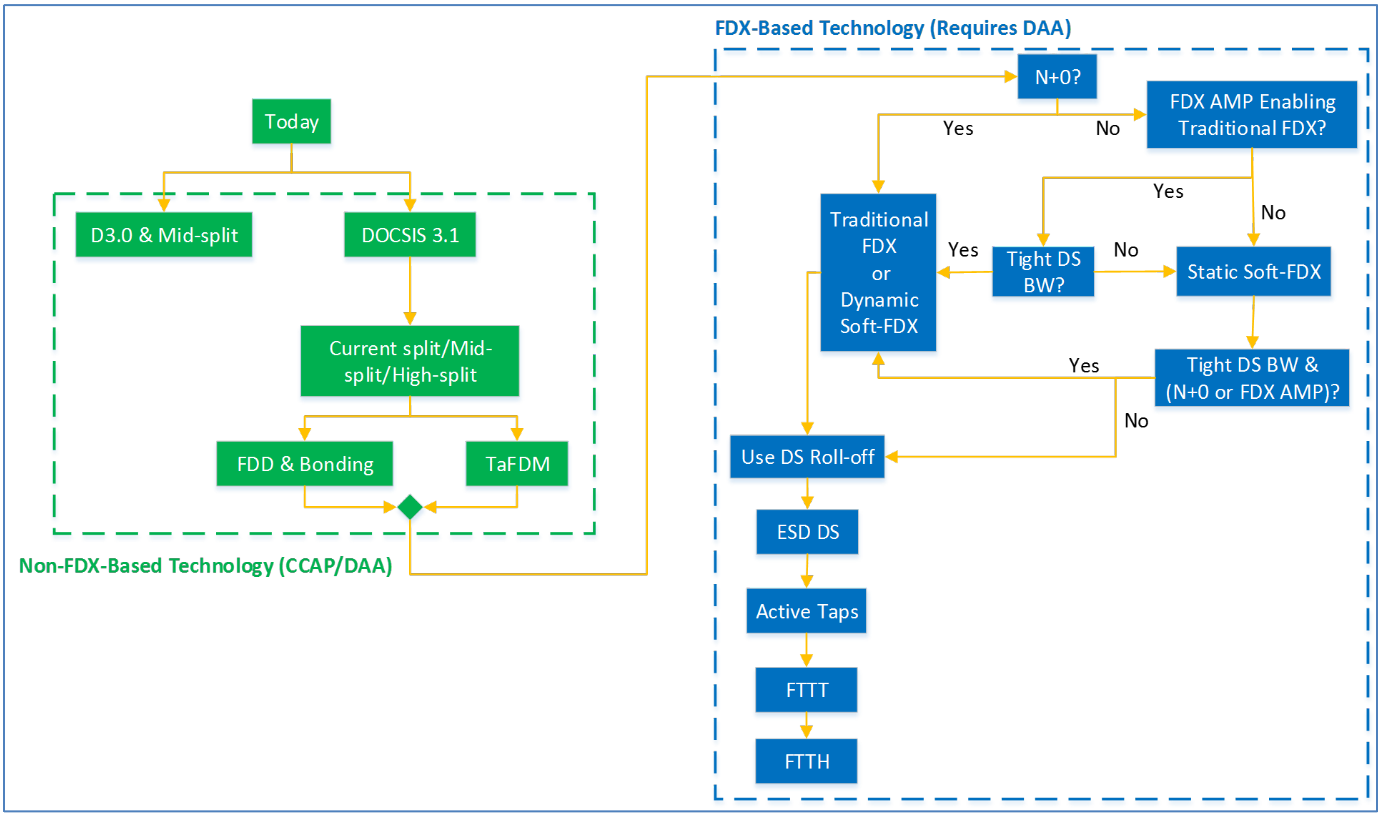

Figure 60 – Network Migration Flow Diagram

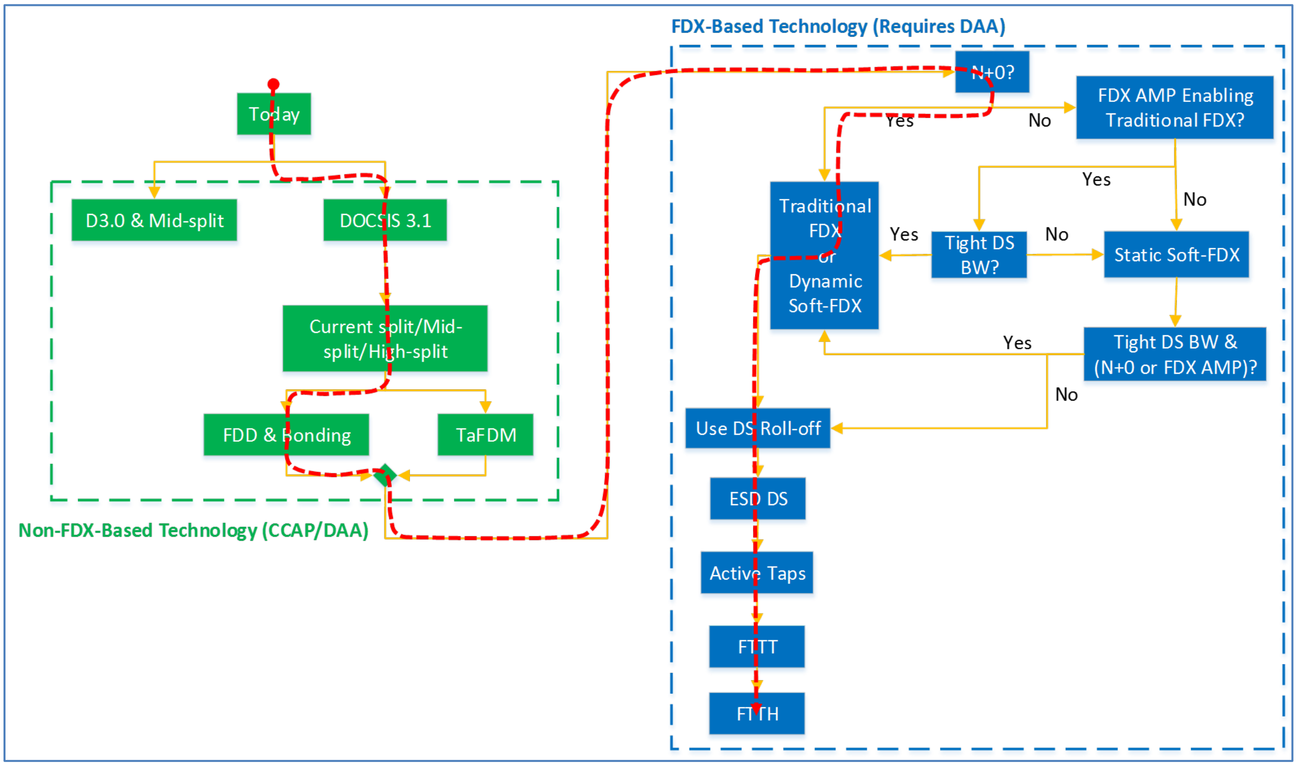

Figure 61 – Network Migration scenario for MSO A with N+0 network architecture

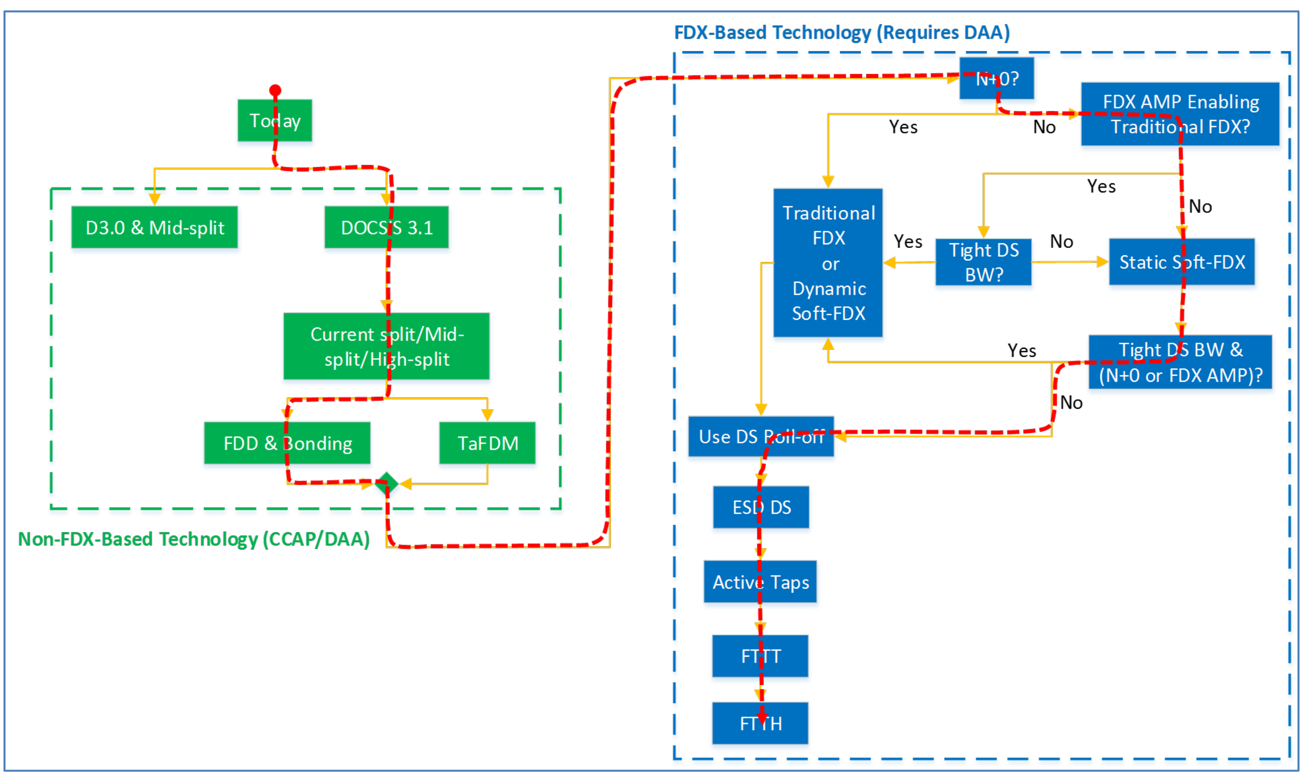

Figure 62 – Network Migration scenario for MSO B with N+x network architecture

It is obvious from the above discussion and there are many tools in the DOCSIS/HFC toolkit to enable multi-Gigabit US services via a smooth & gradual network migration over the next two decades! Those technologies and approaches are complementary in nature and they can be based on the same underlying technology (i.e., FDX chips). This is promising as it may lead to converging the cable industry which will benefit all its members including MSOs, chip vendors, and system vendors.

Conclusions

The paper provided an overview of the various available technologies that can be used to augment the capacities that can be achieved on HFC networks. These technologies included DOCSIS 3.1, traditional FDX, Soft-FDX, and ESD. The paper discussed the challenges presented by these technologies including but not limited to: small allocated FDX spectrum, FDX amplifiers, cascaded networks, and extending the DS spectrum. The paper then proposed appropriate solutions for these challenges. It was also shown that that Dynamic Soft-FDX systems and traditional FDX systems are roughly equivalent and can achieve net DS throughputs of about 10 Gbps and net US throughputs of about 5 Gbps.

The paper also discussed different video-related challenges when deploying high-splits and ultra-high-splits in N+0 as well as N+x cascaded networks. Workarounds were proposed to enable the delivery of video signals and OOB signaling in these environments.

It was shown that traditional FDX, Soft-FDX, and ESD are complementary technologies which can work together to converge the cable industry. Detailed network migration decision strategy was proposed, and various migration scenarios corresponding to different MSO usecases were studied. The paper concluded that MSOs will be able to augment their existing networks with timely investments via gradual migration strategies to reach the desired end goal architecture.

Abbreviations

ACI	adjacent channel interference
ADC	analog to digital converter
AGC	automatic gain control
ALI	adjacent leakage interference
bps	bit per second
BW	bandwidth
CCI	co-channel interference
CM	cable modem
CMTS	cable modem termination system
CP	cyclic prefix
CW	codeword
DAA	distributed access architecture
dB	decibel
dBmV	decibel per millivolt
DOCSIS	data over cable service interface specifications

DS	downstream
DSG	digital set-top gateway
EC	echo cancellation
EoL	end of line
ESD	extended spectrum DOCSIS
FD	fiber deep
FDD	frequency division duplex
FDX	full duplex DOCSIS
FEC	forward error correction
FFT	fast fourier transform
FTTH	fiber to the home
FTTLA	fiber to the last active
FTTT	fiber to the tap
Gbps	gigabit per second
GW	gateway
HDX	half duplex DOCSIS
HFC	hybrid fiber coax
Hz	hertz
I-CCAP	integrated converged cable access platform
IG	interference group
IP	internet protocol
kHz	kilo hertz
LDPC	low density parity check codes
MAC	media access control
Mbps	mega bit per second
MDU	multi-dwelling unit
MHz	mega hertz
MoCA	multimedia over coax alliance
MSO	multiple service operator
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OOB	out of band
OSP	outside plant
PoE	point of entry
PSD	power spectral density
QAM	quadrature amplitude modulation
QoE	quality of experience
RB	resource block
RBA	resource block assignment
RF	radio frequency
R-MAC-PHY	remote media access control and physical layers or remote MAC PHY
RMD	remote MACPHY device
RPHY	remote physical layer or remote PHY
Rx	receive
SC-QAM	single-carrier QAM
SDR	signal to distortion ratio
SG	service group
SIR	signal to interference ratio

SLA	service level agreement
SNR	signal to noise ratio
STB	set-top box
TaFDM	time and frequency division multiplexing
TCP	total composite power
TDD	time division duplex
TG	transmission group
Tx	transmit
US	upstream

Bibliography & References

[Capacity_Tech]	*"Capacity Planning, Traffic Engineering, & HFC Plant Evolution for the Next 25 years"*, by T. Cloonan et. al., SCTE Cable Tech Expo 2019.
[D3.1_Tech]	*"The Spectral Efficiency of DOCSIS® 3.1 Systems"*, by A. Al-Banna et. al., SCTE Cable-Tec Expo 2014.
[ESD_SpForum]	*"Using DOCSIS to Meet the Larger BW Demand of the 2020 Decade and Beyond"*, by T. Cloonan et. al., Spring Technical Forum, 2016.
[FDX_MULPI]	*"DOCSIS 4.0 MAC and Upper Layer Protocols Interface Specification"*, CM-SP-MULPIv4.0-D01-190628, Cablelabs, 2019.
[FDX_PHY]	*"DOCSIS 4.0 Physical Layer Specification"*, CM-SP-PHYv4.0-D01-190628, Cablelabs 2019.
[FDX_ESD_IBC]	*"Full duplex DOCSIS & Extended Spectrum DOCSIS Hold Hands to Form the 10G Cable Network of the Future"*, by F. O'Keeffe et. al., IBC 2019
[Migration1_ANGA]	*"Migration Strategies for Attractive Upstream Peak Rates"*, by A. Al-Banna, ANGA COM 2018.
[Migration2_ANGA]	*"Navigating the HFC Network Migration Maze into the 2020 Decade"*, by A. Al-Banna, ANGA COM 2019.
[TaFD_Tech]	*"When Does the DOCSIS 3.1 TaFD Feature Increase the Capacity of My Network?"*, by A. Al-Banna et. al., SCTE Cable Tech Expo 2017