Capacity Planning, Traffic Engineering, and HFC Plant Evolution for the Next 25 Years

How and When HFC Network Technologies Will Need to Adapt to Support Future Bandwidth Growth

A Technical Paper prepared for SCTE•ISBE by

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Introduction

Since their inception, Hybrid Fiber-Coax (HFC) networks have long been an evolving and changing infrastructure, continually adding new incremental changes in technology and delivering ever-increasing Bandwidth Capacities to accommodate the needs of their various services (Video, High Speed Data (HSD), and Voice). MSOs have long recognized that the HFC plant contains vast quantities of un-tapped Bandwidth Capacity, which can usually be enabled in a gradual, cost-effective, "just-in-time" fashion using minor evolutionary transitions applied intelligently to selected piece-parts of the network. This relatively low-cost, evolutionary approach to network transition has been quite successful and is usually preferred over more expensive revolutionary changes (ex: switching to FTTH) that attempt to change (or replace) a large amount of the HFC plant equipment and head-end equipment and in-home equipment all at once.

The last few years have produced a vast array of new and exciting technology ideas for the future, and they all have value. However, the list of options has been deemed to be too long and quite confusing by many MSOs. The following are examples of some candidates technologies being considered in the confusingly large list of options:

- Management/MAC Placement Variations
    - Centralized Access Architectures (CAAs)
        - Integrated CCAPs
        - M-CMTSs
        - Physical CCAP Cores + Remote PHY Shelves
        - Virtual CCAP Cores + Remote PHY Shelves
        - Chassis-based OLTs
    - Distributed Access Architectures (DAAs)
        - Physical CCAP Cores + Remote PHY Devices (RPDs)
        - Virtual CCAP Cores + Remote PHY Devices (RPDs)
        - Remote MACPHY Devices (RMDs)
        - Remote MAC Cores (RMCs)
        - Remote OLTs (R-OLTs)
    - Virtualization
        - Virtualization of Control/Management Planes (vMgr)
        - Software Defined Networking (SDN)
        - Virtualization of Data Planes (vCore)
- Upstream (US) and Downstream (DS) Bandwidth (BW) Augmentation Variations
    - Full Duplex DOCSIS (FDX)
    - FDX Amps
    - Upstream Extended Spectrum DOCSIS (ESD) using 204-684 MHz Ultra-Splits and beyond
    - Downstream Extended Spectrum DOCSIS (ESD) using 1.8 GHz spectra and beyond
    - Static Soft Frequency Division Duplex (Static Soft-FDD)
    - Dynamic Soft Frequency Division Duplex (Dynamic Soft-FDD)
    - Active Taps
- Fiber Depth Variations
    - Node+0
    - Node+Non-Zero
    - Distributed Node Architectures (DNA)
    - Fiber-To-The-Last-Active (FTTLA)

- Fiber-To-The-Tap (FTTT)
- Fiber-To-The-Home (FTTH).

How do we (as an industry) make sense of all of these options? And how do we stay competitive in an ever-changing market-place? In coming years, Multiple System Operators (MSOs) will also be challenged by a set of HSD competitors offering new wireless-based 5G solutions and fiber-based (Passive Optical Network or PON) solutions. Some details on the competitor PON solutions are shown below in Figure 1. The rows shown in red are likely to be the near-term competitors with which HFC plants will need to contend. The rows shown in black are likely to be the longer-term competitors with which HFC plant augmentations will need to contend.

Type of OLT	Down-stream Capacity	Up-stream Capacity
GPON & Turbo-Mode EPON	**2.5 Gbps**	**1.25 Gbps**
XG-PON	**8.6 Gbps**	**2.4 Gbps**
Asym XGS-PON (low-cost) **Sym XGS-PON (high-cost)**	**8.6 Gbps** 8.6 Gbps	**2.4 Gbps** 8.6 Gbps
NG-PON2	8.6 Gbps	8.6 Gbps
10G EPON TDMA Downstream Dual-rate WDM Upstream Dual-rate TDMA	9.7 Gbps 10.7 Gbps	8.6 Gbps
10G EPON WDMA Downstream Dual-rate WDM Upstream Dual-rate WDMA	9.7 Gbps 10.7 Gbps	9.6 Gbps
10G EPON WDMA "Mixed Mode" Downstream Dual-rate WDM Upstream Dual-rate WDMA Mixed Mode	9.7 Gbps 10.7 Gbps	9.6 Gbps

Figure 1 – Competitor PON Solutions & Capabilities

The higher Bandwidth Capacities permitted by these new competitor offerings must be carefully considered by MSOs as they plan their HFC network evolutions and other technology evolutions for the next decade and beyond. MSOs must be able to easily evolve their network to compete, and according to some analysts and the Cable Industry's own 10G proponents, the Bandwidth Capacities of the future may require 10 Gbps (or higher) by 2030 (or sooner). Some also predict a need to support Symmetrical Services in the very near future (implying equal or close-to-equal Maximum Throughputs (Tmax's) on Upstream and Downstream Service Level Agreements (SLAs)- possible with 10 Gbps Upstream and Downstream SLAs needed in the 2030s). Low-latency transport will also become imperative to support gaming and Virtual Reality and autonomous vehicle navigation and various advanced mobile services. Supporting these features (and others) will likely require several phased evolutionary changes to the HFC network over the next ten to twenty years, with each MSO choosing a potentially different path (as shown in Figure 2).

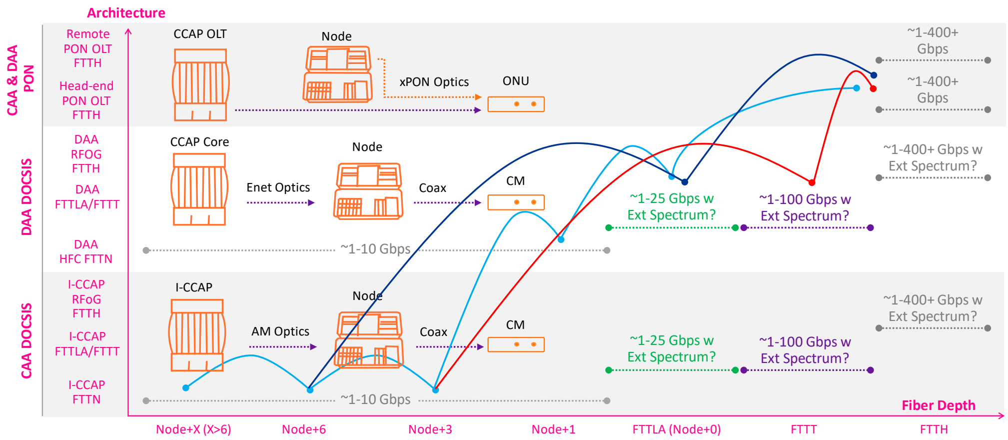

Figure 2 – Different Technology Paths MSOs May Utilize in the Future

Thus, it is clear that MSOs have arrived at an epoch in time where important decisions must be made to help the MSOs select their optimal paths. It is likely that different MSOs will have differing constraints, so there are likely to be various paths selected by different MSOs. However, it is probably beneficial for the industry to begin paring down the large, confusing list above. This would permit MSOs and vendors alike to focus on optimizing and cost-reducing the small subset of remaining solutions that will truly make the most positive impact on the cable industry going forward.

As MSOs make their HFC plant evolution decisions, they must consider their current constraints; but they must also consider the longer-term impact of their decisions on their future HFC network evolution path. Typically, Cable Modems (CMs) and Cable Modem Termination Systems (CMTSs) can be changed out and upgraded quite regularly as new technologies materialize (once every 5-7 years), but the general rule-of-thumb in the industry is that Outside Plant equipment (Nodes, Amplifiers, Taps, etc.) should remain in the field for 10-15 years or longer. As a result, Outside Plant changes deployed in 2029 may need to live in the field until 2044. For that reason, this paper will attempt to look out 25 years into the future to the year 2044- this will undoubtedly result in guestimates that are likely to be incorrect, but the hope is that this paper stimulates important industry-wide discussions on the evolution into that unclear future.

Thus, using reasonable estimates on a) future bandwidth growth, b) future technology challenges from competitor service providers, and c) possible future technologies permitted within the HFC plant, this paper will attempt to provide MSOs with a guide as they make the important decisions that will help them to migrate their HFC plants over the next 25 years.

Content

1. Overview of Bandwidth Trends and Attributes Driving the Future of HFC

In a very real sense, the Cable Industry is predominantly an industry focused on managing bandwidth delivery to and from subscribers. This is true for all services- High-Speed Data, Voice, and Video. As a result, predicting the Bandwidth Capacity trends for these future services is a difficult, but important task. Some key trends and predictions are illustrated in Figures 3 to 7.

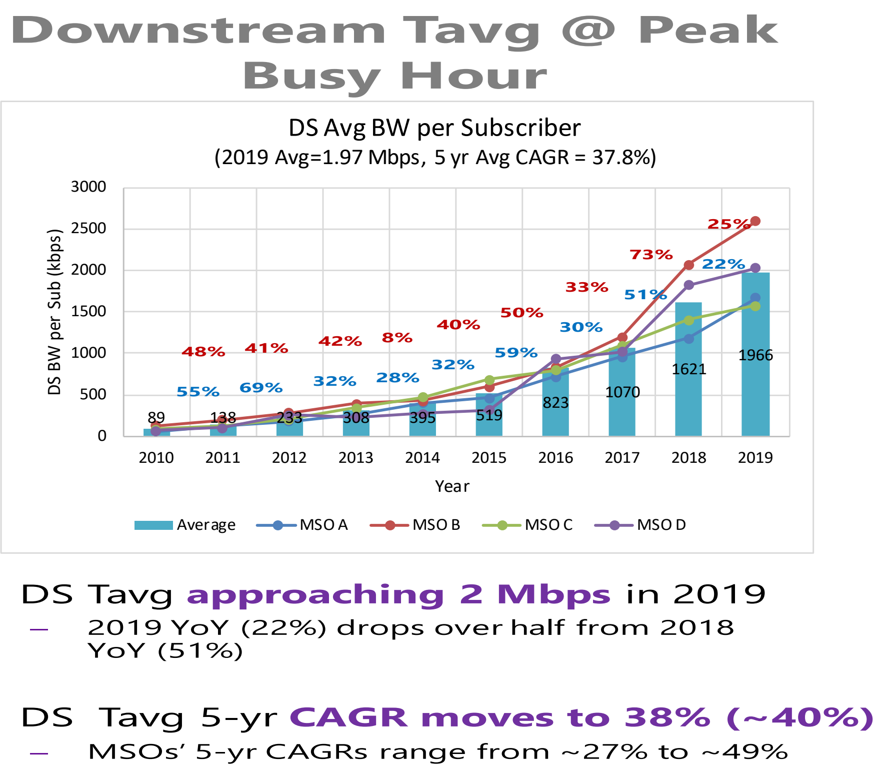

Figure 3 – Downstream Average Bandwidth Trends

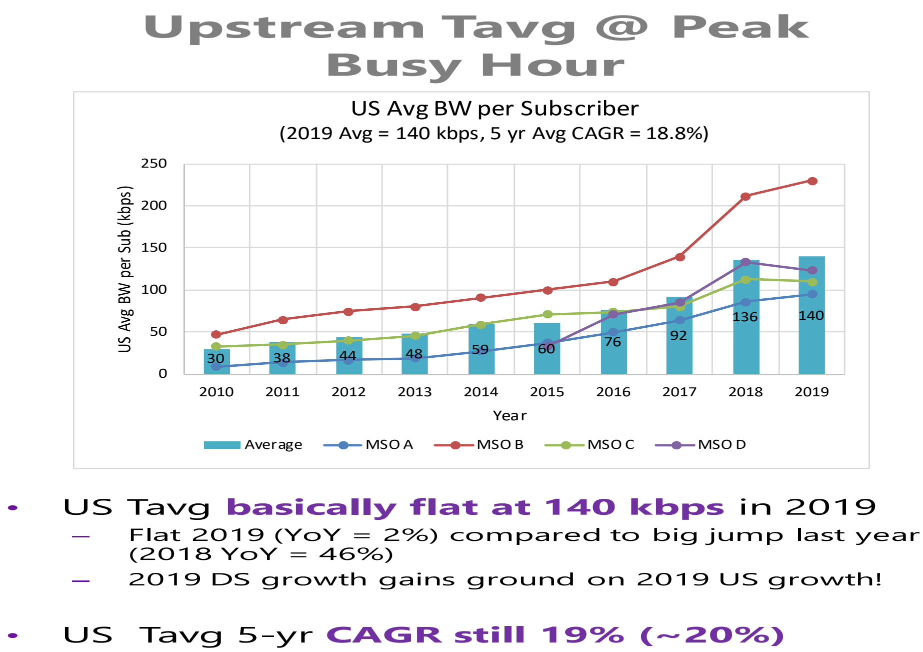

Figure 4 – Upstream Average Bandwidth Trends

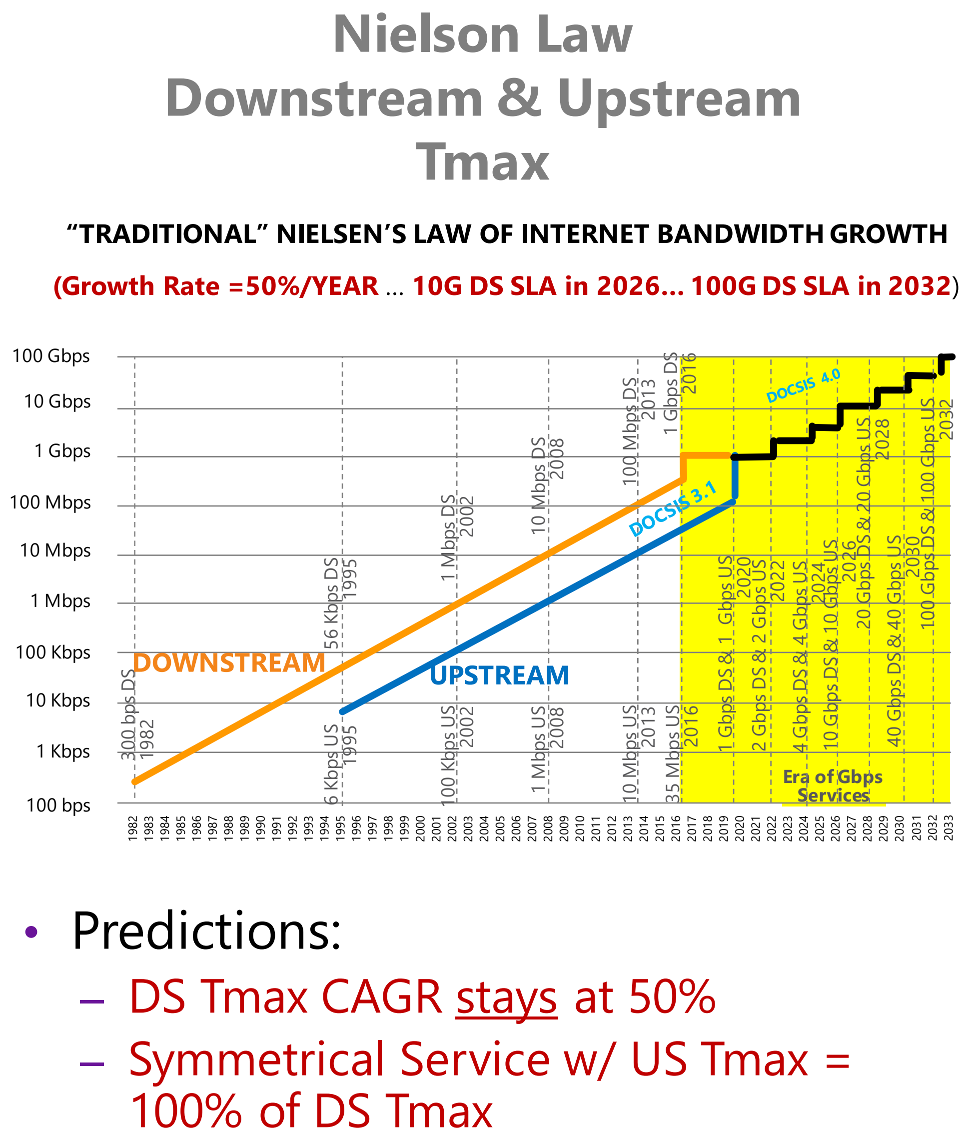

Figure 5 – Downstream & Upstream Maximum Bandwidth Trends (Nielson's Law)

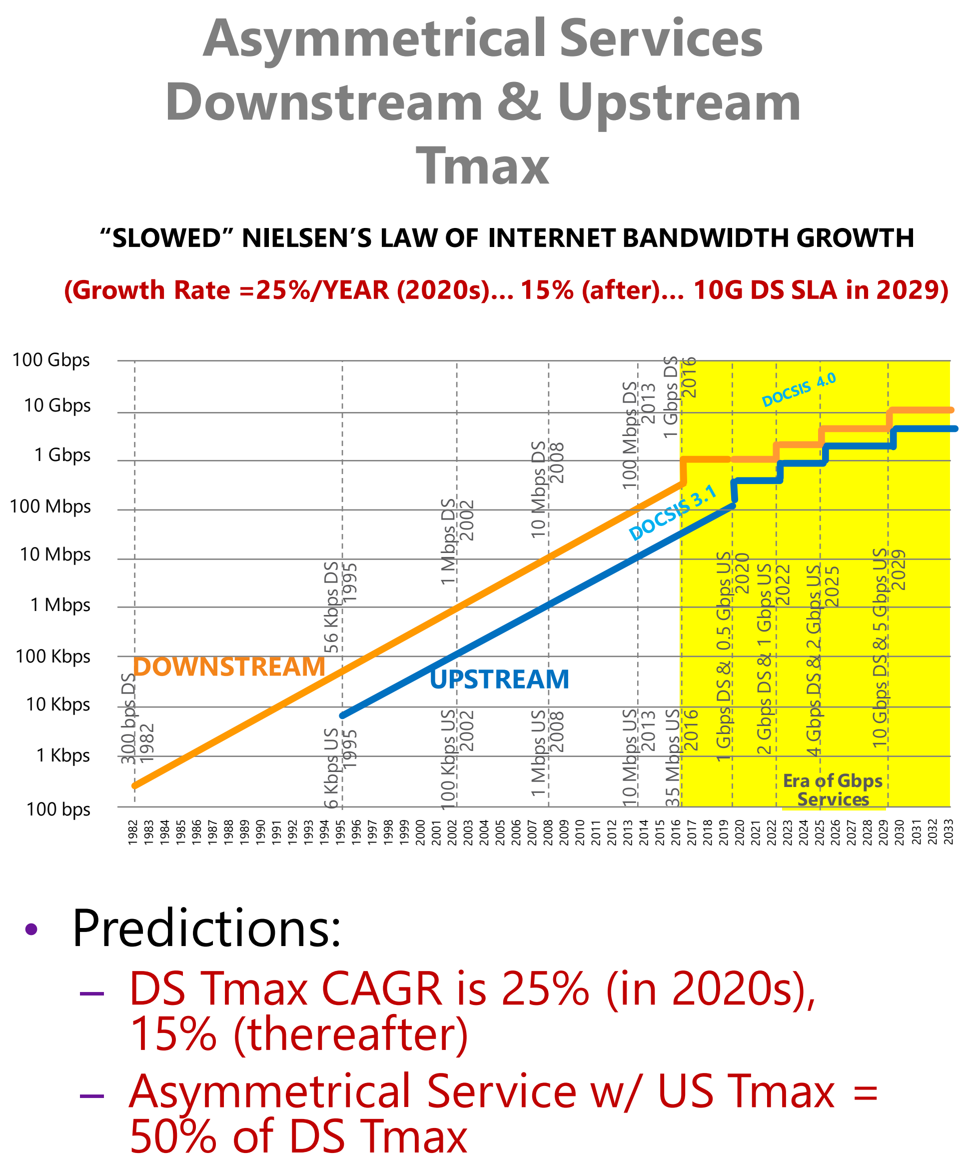

Figure 6 – Downstream & Upstream Maximum Bandwidth Trends ("Slowed" Nielson's Law for Asymmetrical Services)

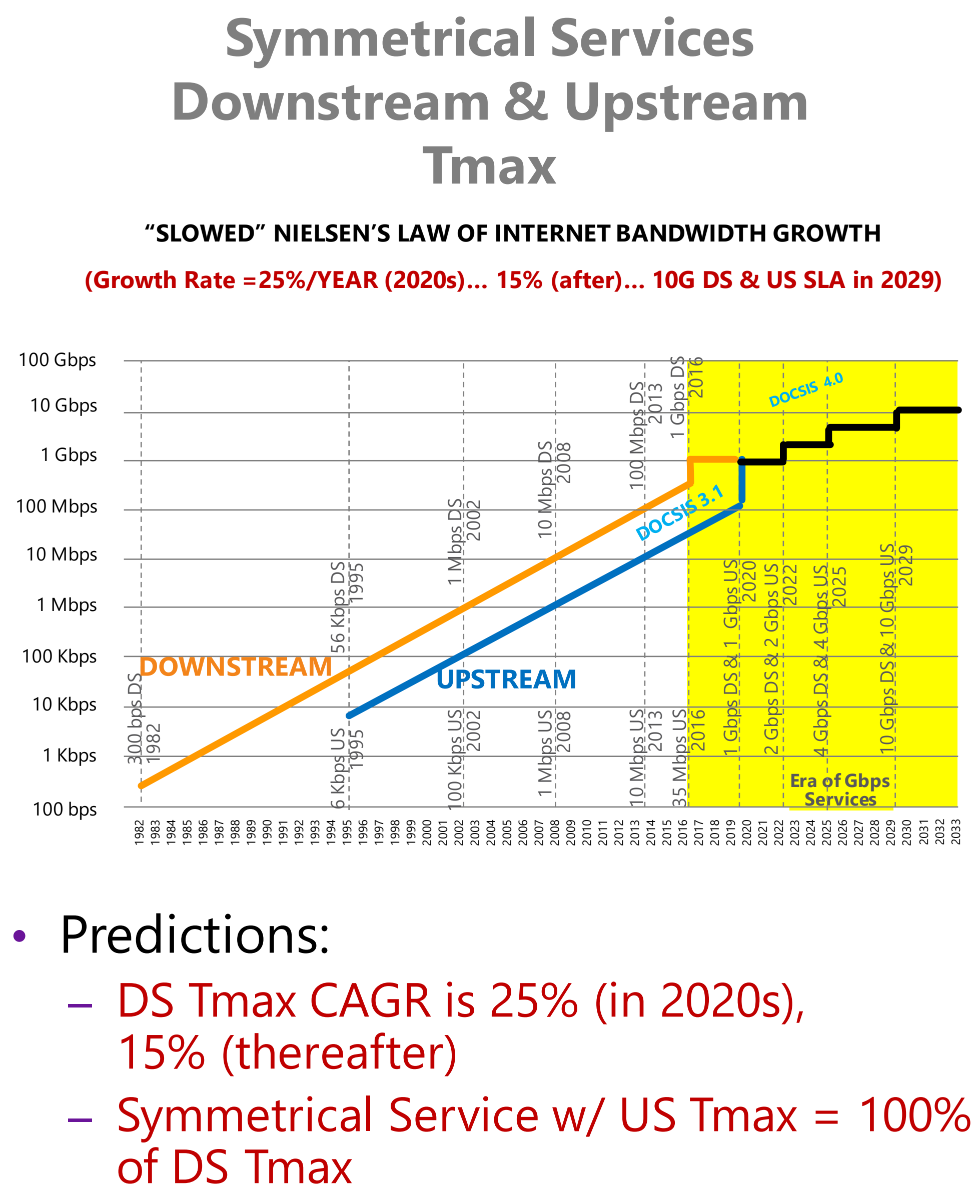

Figure 7 – Downstream & Upstream Maximum Bandwidth Trends ("Slowed" Nielson's Law for Symmetrical Services)

All of the above Figures hint at the coming challenges for the future HSD network. There will be higher Average Bandwidths and much higher Maximum Bandwidths that must be supported. In particular, the very challenging Maximum Bandwidths (which will soon exceed 1 Gbps) will likely become the dominant forcing function causing augmentation of the HFC network infrastructure time and time again over the next 2+ decades.

Predicting the future of bandwidth trends is always a challenging task, but it is particularly challenging when focusing on the Maximum Bandwidth (Tmax) trends across a 25-year horizon. These trends describe the Service Level Agreements (SLAs) that MSO Marketing departments are likely to roll out to subscribers on a year-by-year basis. Thus, these SLA trends are decided by a few select people within each MSO- not by the more-predictable traffic patterns of subscribers. The decisions to increase SLA levels is usually made for either competitive reasons or due to customer demand. In the past, Nielson's Law [NI98] was used to predict these SLA trends, and based on past observations from Nielson, the law assumed that a simple 50% Compound Annual Growth Rate (CAGR) could be applied to both the Upstream and Downstream Tmax values to predict future values. However, in this paper, the authors have decided to use a "Slowed" version of Nielson's Law (shown in Figures 6 and 7 above). The idea of "slowing down" the future CAGRs within Nielson's Law has been proposed by many MSOs and vendors for quite some time, because there are challenges in describing reasonable applications and technologies that would lead to 100 Gbps SLAs being offered by 2030 (which is the value predicted by direct application of Nielson's Law in its traditional form). The particular "Slowed" CAGRs shown in Figures 6 and 7 lead to ~10 Gbps SLAs showing up in the ~2029 time-frame. It is impossible to prove which CAGR predictions for the future are correct, but the "Slowed" CAGRs of Figures 6 and 7 will be utilized within this paper.

To quantify the requirements and the performance of these higher Bandwidth Capacity HFC networks, the authors have found it useful to define several attributes related to the HFC network. These attributes are defined below.

Number of Subscribers within a Service Group (Nsub): Within this paper, a Service Group group will be defined as neighboring subscribers who must share common Bandwidth Capacity on a coax or set of coaxes (assuming that the RF feeds to or from the set of coaxes are combined at a point in the HFC network). The number of subscribers within with a Service Group is sometimes given the label Nsub.

Downstream (DS) Maximum Throughput (Tmax): This attribute is the maximum Downstream bandwidth permitted for a subscriber within the best (highest bandwidth) Service Level Agreement (SLA). It is measured in Gbps and typically increases as time progresses. These increases occur due to market pressures. Based on recent traffic engineering studies outlined in [UL19], this paper will make the following assumption about these increases (unless otherwise specified).

- It is assumed that the DS Tmax value in the year 2020 will be 1 Gbps = 1000 Mbps.
- It is assumed that the DS Tmax values will experience a Compound Annual Growth Rate (CAGR) of 25% in the 2020's, 15% in the 2030's, and 15% in the 2040's. This mimics a gradual reduction that some MSOs and vendors have been expecting (since this CAGR is less than the 50% CAGRs predicted in the past by the Nielson Law [NI98]).
- It is assumed that the DS Tmax values will be "rounded-off" to values representing the following values: 1 Gbps, 2 Gbps, 4 Gbps, 10 Gbps, 20 Gbps, 40 Gbps, and 80 Gbps.
- It is assumed that by 2029, DS Tmax will therefore be 10 Gbps.
- It is assumed that by 2044, DS Tmax will therefore be 80 Gbps.

Upstream (US) Maximum Throughput (Tmax): This attribute is the maximum Upstream bandwidth permitted for a subscriber within the best (highest bandwidth) Service Level Agreement (SLA). It is measured in Gbps and typically increases as time progresses. These increases occur due to market pressures. Based on recent traffic engineering studies outlined in [UL19], this paper will make the following assumption about these increases (unless otherwise specified).

- MSO marketing teams appear to be bifurcating into two different groups:
    - Those who plan to offer **Asymmetrical Services** where the US Tmax = 50% of the DS Tmax.
    - Those who plan to offer **Symmetrical Services** where the US Tmax = the DS Tmax.
- For Asymmetrical Services, it is assumed that:

  - The US Tmax values will be "rounded-off" to values representing the following values: 0.5 Gbps, 1 Gbps, 2 Gbps, 5 Gbps, 10 Gbps, 20 Gbps, and 40 Gbps.
  - By 2029, US Tmax will therefore be 5 Gbps.
  - By 2044, DS Tmax will therefore be 40 Gbps.
- For Symmetrical Services, it is assumed that:
  - The US Tmax values will be "rounded-off" to values representing the following values: 1 Gbps, 2 Gbps, 4 Gbps, 10 Gbps, 20 Gbps, 40 Gbps, and 80 Gbps.
  - By 2029, US Tmax will therefore be 10 Gbps.
  - By 2044, DS Tmax will therefore be 80 Gbps.
- Offering Symmetrical Services will require more US Bandwidth Capacity than offering Asymmetrical Service.

Downstream (DS) Average Throughput (Tavg): This attribute is the average Downstream bandwidth consumed by a single typical subscriber within the busy-hour interval from (say) 9pm-10pm. It is measured in Mbps and typically increases as time progresses. These increases occur due to new Internat applications used by the subscriber. Based on recent traffic engineering studies outlined in [UL19], this paper will make the following assumption about these increases (unless otherwise specified).

- It is assumed that the DS Tavg value in the year 2020 will be 2.3 Mbps.
- It is assumed that the DS Tmax values will experience a Compound Annual Growth Rate (CAGR) of 39% in the 2020's, 29% in the 2030's, and 19% in the 2040's. This mimics a gradual reduction that has been witnessed in the past decade.
- It is assumed that by 2029, DS Tavg will therefore be 44.6 Mbps.
- It is assumed that by 2044, DS Tavg will therefore be 1356.7 Mbps. (Note: At this time, the authors cannot describe the Internet applications that would require this much bandwidth capacity. It can be conjectured that it may be related to holographic mutli-media experiences, but there is no proof of that at this time).

Upstream (US) Average Throughput (Tavg): This attribute is the average Upstream bandwidth generated by a single typical subscriber within the busy-hour interval from (say) 9pm-10pm. It is measured in Mbps and typically increases as time progresses. These increases occur due to new Internat applications used by the subscriber. Based on recent traffic engineering studies outlined in [UL19], this paper will make the following assumption about these increases (unless otherwise specified).

- It is assumed that the US Tavg value in the year 2020 will be 0.28 Mbps.
- It is assumed that the US Tmax values will experience a Compound Annual Growth Rate (CAGR) of 19% in the 2020's, 19% in the 2030's, and 19% in the 2040's. This mimics the relatively flat CAGR level that has been witnessed in the past decade.
- It is assumed that by 2029, US Tavg will therefore be 1.3 Mbps.
- It is assumed that by 2044, US Tavg will therefore be 18.2 Mbps.

Downstream (DS) Required BW Capacity per DS Service Group: This attribute is the Downstream Bandwidth Capacity required to support the subscribers sharing bandwidth within a Downstream Service Group during the busy-hour interval from (say) 9pm-10pm.

- It is assumed that for a Service Group (a group of neighboring subscribers sharing common Bandwidth Capacity) with the actual number of attached subscribers given by the value Nsub, then the average bandwidth consumed by the Service Group will be given by Nsub*Tavg.

- For a Service Group with a number of attached subscribers given by the value Nsub and with the maximum DS SLA bandwidth given by Tmax, it is assumed that the following formula accurately describes the amount of High-Speed Data (HSD) Bandwidth Capacity required to keep high Quality of Experience (QoE) levels [CL14]:

  Required DS HSD Bandwidth Capacity = Nsub*Tavg + 1.0*Tmax [Eq. 1]

  (Note: The second term provides head-room capacity for low-probability bandwidth bursts. Due to smaller Nsub values and much large Tmax values in the future, this second term is likely to dominate traffic engineering in the future).

- To simplify the analysis, it is assumed that there will be a constant amount of DS Bandwidth Capacity dedicated to video for all years in this study. That amount will be equal to 336 MHz of spectrum dedicted to SC-QAM Video transport. This could correspond to 56 Annex B 6 MHz channels or 42 Annex A 8 MHz channels. It is assumed that improved video compression techniques will permit more and more video content to be propagated over this spectrum as time progresses.

Upstream (US) Required BW Capacity per US Service Group: This attribute is the Upstream Bandwidth Capacity required to support the subscribers sharing bandwidth within a Upstream Service Group during the busy-hour interval from (say) 9pm-10pm.

- It is assumed that for a Service Group (a group of neighboring subscribers sharing common Bandwidth Capacity) with a number of attached subscribers given by the value Nsub, the average bandwidth consumed by the Service Group will be given by Nsub*Tavg.
- For a Service Group with a number of attached subscribers given by the value Nsub and with the maximum US SLA bandwidth given by Tmax, it is assumed that the following formula accurately describes the amount of High-Speed Data (HSD) Bandwidth Capacity required to keep high Quality of Experience (QoE) levels [CL14]:

  Required US HSD Bandwidth Capacity = Nsub*Tavg + 1.0*Tmax [Eq. 2]

  (Note: The second term provides head-room capacity for low-probability bandwidth bursts. Due to smaller Nsub values and much large Tmax values in the future, this second term is likely to dominate traffic engineering in the future).

Downstream (DS) HSD Utilization: This attribute is the Downstream HSD Utilization level, which describes the percentage of the total Required Bandwidth Capacity that is utilized by the Average Bandwidth levels. The formula is given by Utilization = (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax).

Upstream (US) HSD Utilization: This attribute is the Upstream HSD Utilization level, which describes the percentage of the total Required Bandwidth Capacity that is utilized by the Average Bandwidth levels. The formula is given by Utilization = (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax).

Fiber Depth: This attribute defines how deep the fiber has been routed into the HFC Network. It is usually described using the Node+X notation, where X specifies the maximum number of serialized amplifiers in a cascade within the coaxial portion of the HFC network. A Node with no amplifiers south of it exists in a Node+0 environment, and a Node with at least one amplifier south of it exists in a Node+Non-Zero environment. A longer coaxial run with X serialized amplifiers usually implies a shorter fiber run, and vice versa. If one assumes that a typical amplifier supports a coaxial length of (say) 1000 feet, then a typical Node+X system might have a maximum aggregated distance of ~(1000 feet)*(X+1) between the Fiber Node and the most distant subscriber on that coaxial run. The number of subscribers connected to a particular Fiber Node is closely related to the value of X. With each node-split (which reduces the number of subscribers per Fiber Node by roughly a factor of two), there is usually a corresponding reduction in the value of X (since less distance and less serialized amplifiers are usually needed to reach the smaller number of subscriber). Within this paper, we assume a typical MSO has a ~50% take-rate on their services. While different MSOs assume different numbers for these relationships, this paper will assume the following relationships exists between Fiber Depth and the number of Households Passed (HHP) and the number of subscribers:

Table 1 – Relationships between Fiber Depth, # of HHP, & # of Subs

Fiber Depth	# of HHP	# of Subs (Nsub)
Node+0	120	60
Node+1	240	120
Node+2	480	240
Node+3	800	400
Node+4	1200	600
Node+5	1600	800
Node+6	2000	1000

MSOs seem to have bifurcated into two groups. One group has a strong affinity to move to Node+0 as quickly as possible (in an effort to quickly move towards the expected end-game architecture with fiber going directly to the home). The other group has a strong affinity to stay away from Node+0 (in an effort to avoid the increased costs of fiber pulls and numerous Fiber Node deployments that are associated with Node+0 or FTTH). For example, one anonymous MSO has indicated that 71% of the Capex+Opex cost of moving from Node+3 to Node+0 is in the final Node+1 to Node+0 transition, and their annual budgets will not permit them to tackle that large expense for many years to come. As a result, they will opt to utilize Node+Non-Zero architectures (and wider spectral widths yielding higher BW Capacities) for as long as possible. This paper will study both the Node+0 and Node+Non-Zero approaches.

Top of US Bandwidth Range: This attribute (also known as the "split") defines how much of the coaxial spectrum is utilized for US transmissions. It is assumed that the US signals will occupy the spectrum from (say) 5 MHz to the Top of the US Bandwidth Range. Higher required US Bandwidth Capacities will typically require higher US Bandwidth Ranges. Depending on the required frequencies, higher US Bandwidth Ranges may require the development of new chipsets (ex: FPGAs, Hybrids) and new actives (ex: Nodes, Amplifiers, CMs), and new passives (ex: Taps).

Top of Downstream (DS) Bandwidth Range: This attribute defines how much of the coaxial spectrum is utilized for DS transmissions. It is assumed that the DS signals will occupy the spectrum from the Bottom of the DS Bandwidth Range to the Top of the DS Bandwidth Range. Higher required DS Bandwidth Capacities will typically require higher DS Bandwidth Ranges. The Bottom of the DS Bandwidth Range is determined by the particular technology used to combine US & DS signals (as will be described below). Depending on the required frequencies, higher DS Bandwidth Ranges may require the development of new chipsets (ex: FPGAs, Hybrids) and new actives (ex: Nodes, Amplifiers, CMs), and new passives (ex: Taps). It is assumed that the Outside Plant (OSP) network will be physically and electrically isolated from subscriber in-home network using portal-based gateways, so augmentation of most in-home passives should not be required.

Downstream (DS) Equipment Housing Bandwidth: This attribute is closely related to the Top of the DS Bandwith Range. However, this attribute recognizes two important facts:

1) Outside Plant Equipment (such as Nodes and Amplifiers) are typically expected to be deployed into the field and not replaced for many years (ex: 10-15 years or more).
2) If a piece of Outside Plant Equipment is to be deployed in a given year, it should probably include a housing design that can support the expected frequencies of its future life-span.

Thus, the DS Housing Bandwidth represents an attempt to group together several generations of frequency improvements that might be added (via modular plug-ins) into a piece of Outside Plant Equipment, and then it tries to ensure that at least the Housing for that equipment can support those multiple generations and all of the anticipated future frequencies prior to the Housing being replaced. The highest frequency that a particular generation of Housing is expected to support is the DS Housing Bandwidth (in MHz).

Upstream:Downstream (US:DS) Frequency Band Re-Use Ratio: A very important attribute is called the US:DS Frequency Band Re-Use. This attribute is measured as a frequency range and uses units of MHz. If a particular solution permits the US and DS frequency spectra to dynamically overlap during normal operation by (say) Z MHz, then that solution is said to have US:DS Frequency Band Re-Use of Z MHz, and Z would be a positive number. If the US and DS frequencies do not overlap but are contiguous, then the Re-Use value Z would be zero. If the US and DS frequencies do not overlap and actually have a frequency domain guard-band between them (for example, for diplex filter rolloffs), then the Re-Use value Z would be negative. In this latter case, a region of spectrum is excluded from being used and represents an undesirable "spectral penalty." Another related attribute is the US:DS Frequency Band Re-Use Ratio, which is defined to be the Re-Use value Z divided by the top of the useable spectral range. Positive US:DS Frequency Band Re-use Ratios with large absolute values are good because they indicate a lot of spectral overlap. Negative Re-use Ratios with large absolute values tend to be undesirable, because they indicate a lot of wasted spectrum.

2. Overview of Some Key Technology Candidates for Future Upstream/Downstream Bandwidth Augmentation

In the Introduction section above, several candidate technologies for the future were listed. Those technologies were sub-divided into several different categories depending on their focus. This has led the authors to visualize the evolution of the future within the four axes of the "4-dimensional" coordinate system shown in Figure 8. This visualization attempts to illustrate that changes will be taking place in at least four different areas, including changes in MAC/Management Placement, Upstream Bandwidth Augmentation, Downstream Bandwidth Augmentation, and Fiber Depth.

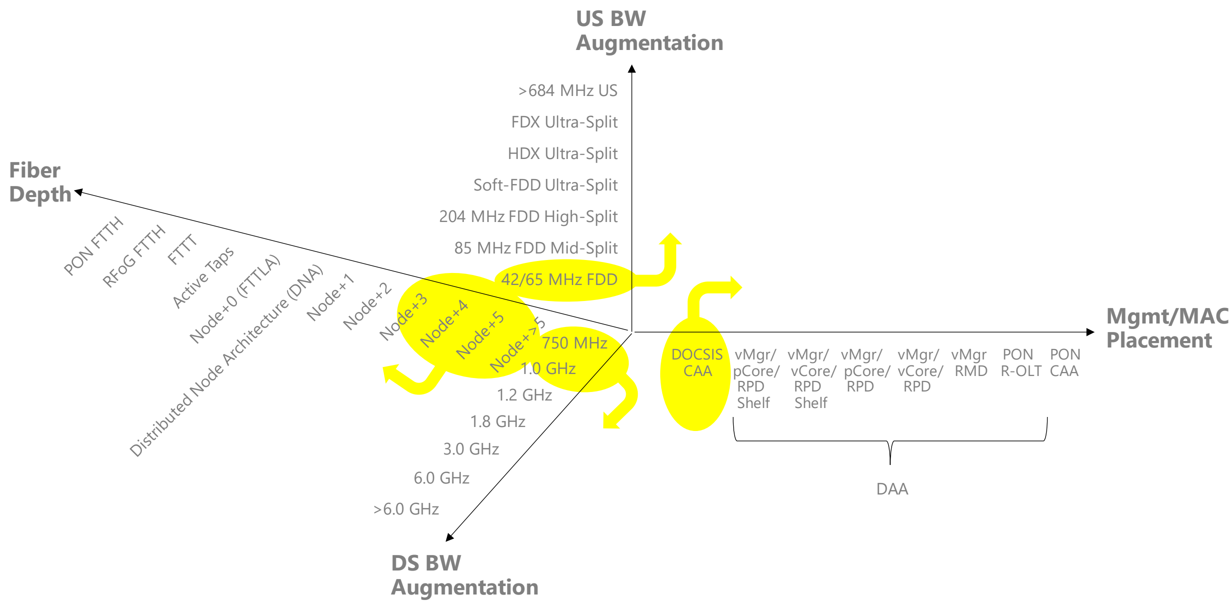

Figure 8 – Changes in Four Different Areas to Support Future Bandwidth Growth

The yellow regions in Figure 8 indicate roughly where many MSOs are currently at in this evolutionary process on all four axes. The yellow arrows indicate likely directions that the MSOs may choose to take as that move into the future and add more Bandwidth Capacity to their networks. It is likely that different MSOs will choose different hops on different axes at different times. Selecting when to take the "right hop on the right axis at the right time" requires a careful analysis of Bandwidth Capacity requirements (which will be done below).

Over the next 2+ decades, MSOs will be focused on determining ways to augment both Upstream and Downstream Bandwidth Capacities within their HFC networks (prior to transitioning to FTTH PON systems). There are many different technology improvements that can potentially offer this augmentation. MSOs will undoubtedly need to determine which technology to utilize, and they will also need to determine when to transition between different technologies to maximize their Bandwidth Capacity while minimizing their costs. This section will give a brief overview of some of the more promising technology improvements that may be considered in the future. At the end of each sub-section, an assessment of the "Likelihood of Success" for each technology is given. A more detailed analysis of many of these technology improvements (along with suggestions on how to improve their performance) is contained in [AL19].

2.1. Traditional-Full-Duplex DOCSIS (Traditional-FDX) for Upstream Augmentation

This well-known technology has been discussed by the Cable Industry for years, and the specification changes associated with Traditional-FDX recently were recently moved into the newly-created DOCSIS 4.0 specification. This exciting technology proposes to have Downstream and Upstream transmissions occurring in the same frequency band at the same time. In the specification, the overlapping frequency bands can be in any of the following ranges: 108-204 MHz, 108-300 MHz, 108-396 MHz, 108-492 MHz, or 108-684 MHz.

The Traditional-FDX capability offers a powerful and unique benefit that permits Upstream spectrum expansions to occur without causing commensurate reductions in Downstream spectrum widths. One of the key technology enablers leading to Traditional-FDX is the Echo Canceller functionality that is required to cancel high-power, reflected noise in both the Fiber Node's Upstream and the Cable Modem's (CM's) Downstream. Based on experiments and field trials in which the authors have been involved, it is clear that Traditional-FDX should work quite well in Node+0 environments. The basic concept is illustrated in Figure 9.

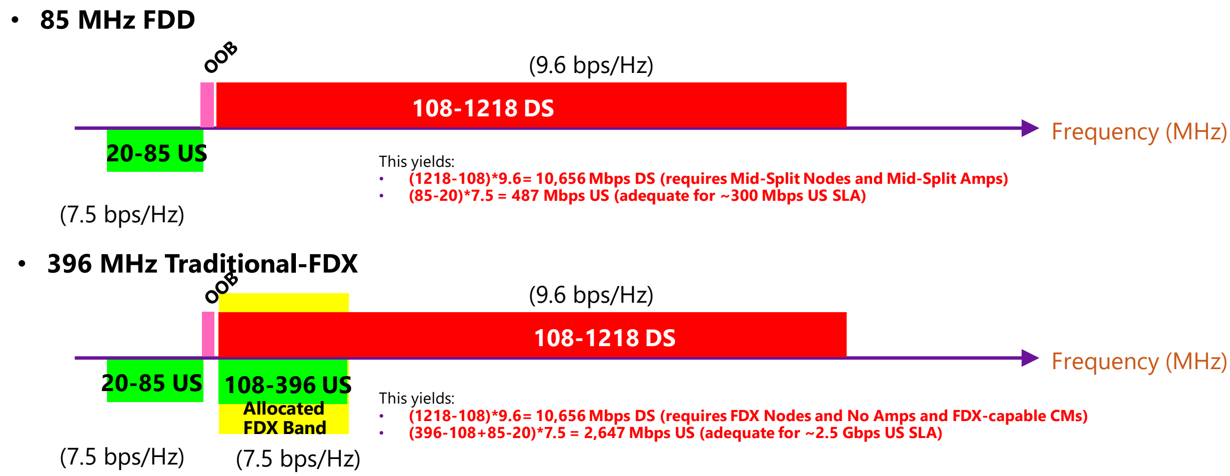

Figure 9 – Spectrum for 85 MHz FDD Mid-Split & 396 MHz Traditional-FDX (w/ First-Order Guestimates on Bandwidth Capacities)

Unfortunately, despite many design approaches and analyses, the ability of Traditional-FDX systems to perform in Node+Non-Zero environments (where there exists at least one amplifier south of the Fiber Node) is still questionable and under study. The key component enabling Traditional-FDX operation in a Node+Non-Zero environment is the FDX Amplifier. While FDX Amplifiers of various forms have been proposed and are possible to construct, all have resulted in Time Division Duplex (TDD)/Frequency Division Duplex (FDD) performance levels- not Traditional-FDX performance levels. For example, recent studies on noise amplification and Interference Group formation have shown that a particular issue may develop. In particular, the use of Echo Chancellation and Amplification techniques in FDX Amplifiers may suffer from an Interference Group Elongation problem (see Figure 10) that effectively makes each RF Leg a single large Interference Group operating in a TDD/FDD fashion. While still under study, this Interference Group Elongation problem may preclude Traditional-FDX solutions from operating well in any Node+Non-Zero environments, and it may require MSOs who plan to continue using Node+Non-Zero HFC plants to consider using some of the alternative techniques described in the sub-sections below.

Traditional-FDX solutions may therefore only be useable by MSOs who expend the effort and money to convert their current HFC networks into Node+0 networks. This may create a bifurcation of MSOs into two camps in the future; there may be the Node+0 camp using Traditional-FDX and the Node+Non-Zero camp using other alternative Upstream Bandwidth Augmentation technologies listed below. This paper will study proposals for both camps.

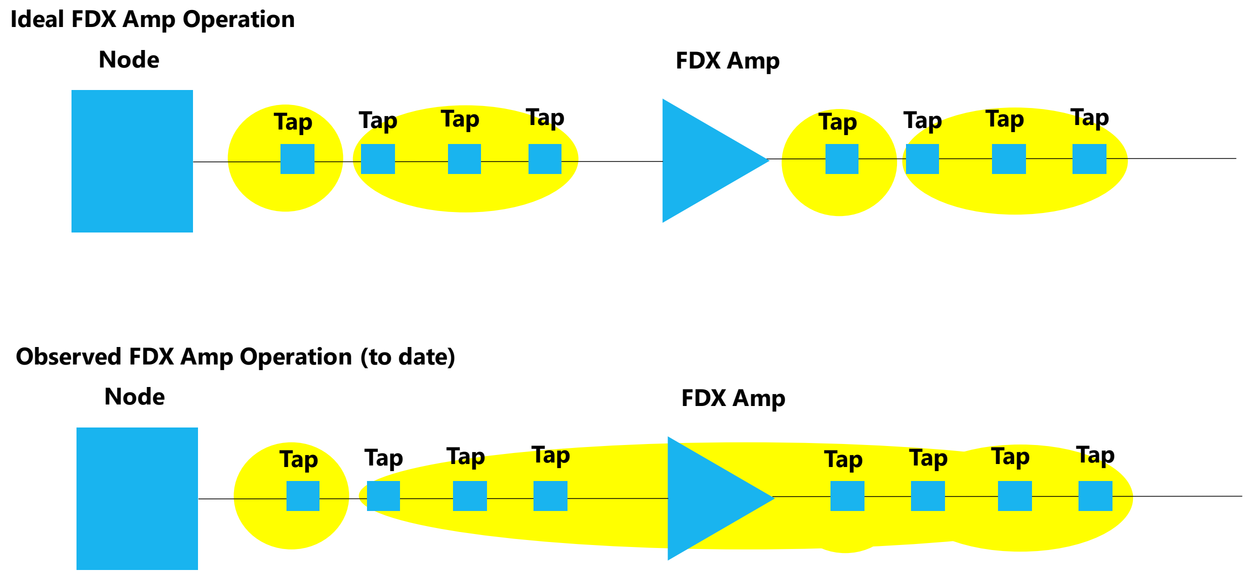

Figure 10 – Interference Group Elongation Problem That May Occur With FDX Amplifiers (Not A Problem For FDD High-Split or FDD Ultra-Split Approaches)

For the Node+0 MSO camp planning to use Traditional-FDX, several changes will be required. If the Interference Group Elongation problem remains, then splits to a Node+0 level will likely need to be made. In addition, CCAP Cores, Fiber Nodes, and CMs will all require changes; there will be changes in both the PHY and MAC layers of DOCSIS. The complexities of FDX Echo Cancellation functionality may also force the initial FDX offerings to occur in only RPHY environments and using 1 DSSG x 1 USSG Fiber Nodes, so the impact of these limitations must be analyzed when considering FDX for deployments in the early 2020's.

Likelihood of Success: High probability of success; much development is still required.

2.2. 204 MHz Frequency Division Duplex (FDD) High-Splits for Upstream Augmentation

This technology improvement can be utilized by the Node+Non-Zero camp of MSOs. It permits the MSOs to expand their HFC plant's Upstream spectrum from the current 42 or 55 or 65 MHz or 85 MHz spectral widths to a much larger 204 MHz spectral width- resulting in more Upstream Bandwidth Capacity that can be offered to subscribers. This technique proposes to keep things simple by continuing to use Frequency Division Duplex technologies that separate Upstream spectrum from Downstream spectrum- usually with a diplexer filter guard-band in between the disjoint Upstream and Downstream frequency ranges. This is illustrated in Figure 11.

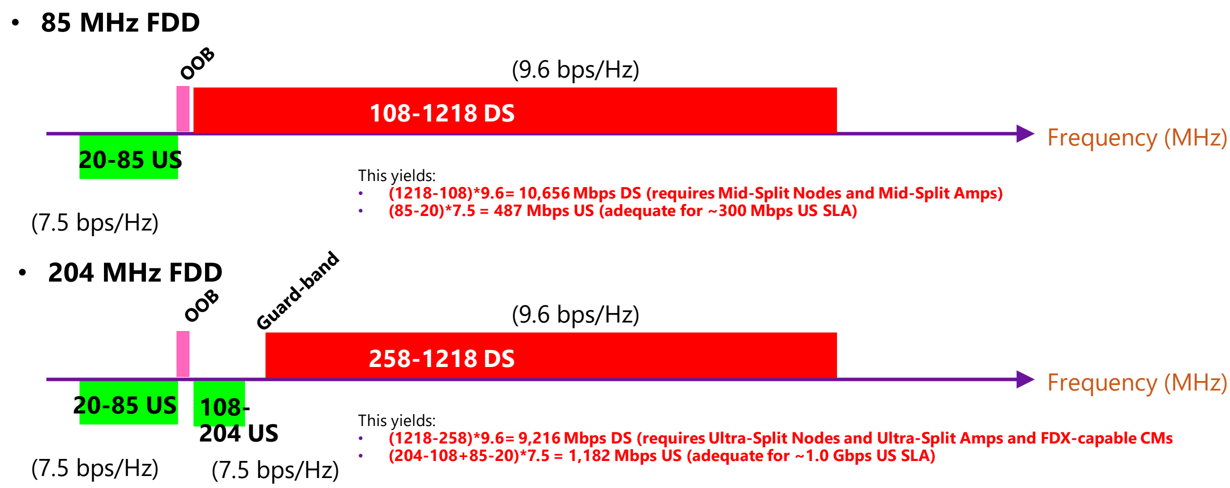

Figure 11 – Spectrum for 85 MHz FDD Mid-Split & 204 MHz FDD High-Split (w/ First-Order Guestimates on Bandwidth Capacities)

This transition to 204 MHz FDD High-Split operation typically requires changes to both the existing Nodes and the existing Amplifiers and some existing CMs (only in the high-end subscriber homes) on the HFC plant. Sometimes, plug-in modules may be made available for new diplex filters that can be utilized to simplify this upgrade path. The 204 MHz diplex filters would typically have a roll-off that permits the Downstream spectrum to pass at frequencies higher than ~258 MHz, so the resulting guard-band creates a diplex filter "spectral penalty" of ~(204-258) = -54 MHz; i.e.- ~54 MHz of spectrum is deemed to be unusable when this technology is deployed without any assistance from Guardband Reduction technologies (using Echo Cancellers or other techniques). As can be seen from the Figure, the move to a 204 MHz FDD High-Split solution also "steals" some of the DS Bandwidth Capacity (in red) and "donates" it to the US Bandwidth Capacity (in green). These effects may or may not represent an issue in the future, as will be described below.

One of the benefits of this FDD approach is that it works well in a Node+X (X>=0) environment without any complications to the Amplifiers (other than the use of a higher split). It does not require the use of Echo Cancellation techniques in the Amplifiers (as needed for Full Duplex DOCSIS solutions), and

One of the side issues that must be dealt with when 204 MHz FDD High-Split is utilized is the passing of Downstream Out-Of-Band (OOB) signals to some existing Set-Top Boxes. To support this OOB capability vendors are exploring the use of techniques such as the use of high-Q filter modules that can be added to existing or future Amplifiers that would permit these Downstream OOB signals to be passed through the Amplifier even though the Downstream OOB signals are in the Upstream portion of the spectrum.

Likelihood of Success: Very high probability of success; since this is actually DOCSIS 3.1, it is already available.

2.3. 204-684 MHz Frequency Division Duplex (FDD) Ultra-Splits for Upstream Augmentation

This technology improvement can also be utilized by the Node+Non-Zero camp of MSOs, and it provides them with similar Upstream Bandwidth augmentation benefits that may be experienced by the Node+0 camp who uses Traditional-FDX- however this FDD Ultra-Split technology also has a commensurate Downstream Bandwidth Capacity degradation that is experienced due to a “zero-sum game” effect).

The technology is very similar to the 204 MHz FDD High Split approach defined above. However, it recognizes that one could push the Upstream Split levels to frequencies well beyond the 204 MHz limit of the original DOCSIS 3.1 specification. In particular, with the expected arrival of FDX-capable Cable Modem (CM) chipsets in the next year or so, it seems clear that one could hypothesize the deployment of FDD Ultra-Splits at any of the Upstream frequencies that are supported by the coming FDX-capable CM chipsets. The resulting FDX-capable CMs would be used in a simple “non-FDX” operating mode, whereby Sounding and fast Resource Block Assignments and other features would not be needed for this simple FDD Ultra-Split operation. The resultant FDD Ultra-Split frequencies may therefore include:

- 204 MHz
- 300 MHz
- 396 MHz
- 492 MHz
- 684 MHz.

The FDD Ultra-Split technique proposes continued use of simple Frequency Division Duplex, separating Upstream spectrum from Downstream spectrum (usually with a diplexer-based frequency guard-band in between) and avoiding the forementioned FDX Interference Group Elongation problem. Unfortunately, the required guard-band with FDD Ultra-Split tends to grow in size with higher Split frequencies (ex: a 396 MHz Ultra-Split might require a 69 MHz guard-band ranging from 396 MHz to 465 MHz). As a result, there are studies under way that could potentially employ Echo Cancellation techniques to reduce or eliminate the need for this guard-band range. Cost and power issues are still being worked out in those studies.

As one might expect, the initiation of this FDD Ultra-Split operation typically requires changes to both the existing Fiber Nodes and the existing Amplifiers on the HFC plant. CMs will also need to be updated within high-end subscriber homes. For some MSOs, it also may require the addition of high-Q filters to support the passage of the Downstream OOB signals within the extended Upstream frequency band.

Like the FDD High-Split solution, the FDD Ultra-Split solution also “steals” Bandwidth Capacity from the DS; but it steals even more DS Bandwidth Capacity (in red) and “donates” it to the US Bandwidth Capacity (in green), as shown in Figure 12 and Table 2. As illustrated in Table 2, there is a clear zero-sum game trade-off; large increases in US Bandwidth Capacity will typically lead to large decreases in DS Bandwidth Capacity. Fixes for this problem may be available if the Cable Industry ultimately decides to support Extended Spectrum DOCSIS concepts (described below) for Downstream augmentation, using them in conjunction with the FDD Ultra-Split solution for the Upstream augmentation.

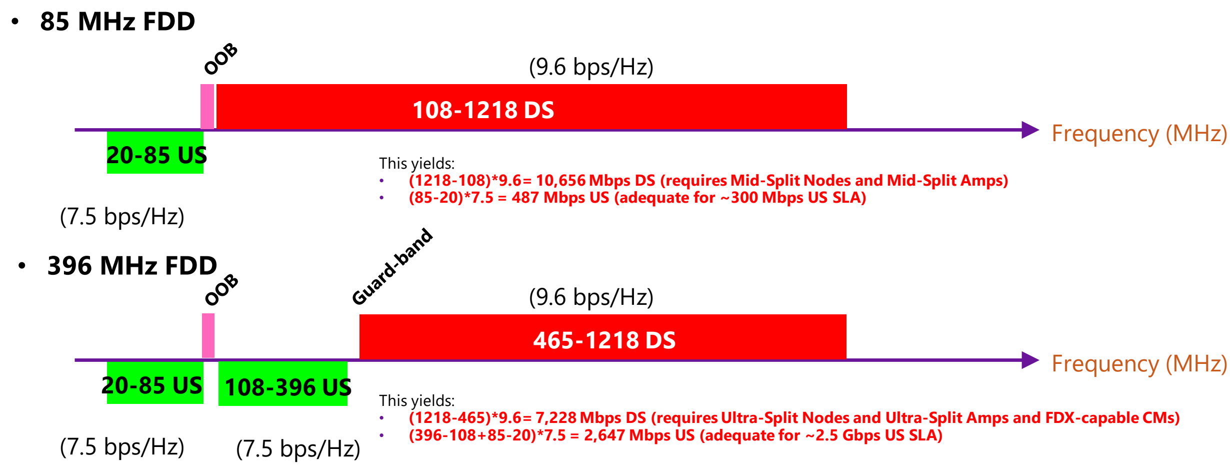

Figure 12 – Spectrum for 85 MHz FDD Mid-Split & 396 MHz FDD Ultra-Split (w/ First-Order Guestimates on Bandwidth Capacities)

Table 2 – US & DS BW Capacities for Various FDD Ultra-Split Frequency Bands Illustrating the Zero-Sum Game

Top of Ultra-Split FDD US Frequency Band (MHz)	Bottom of US Frequency Band (MHz)	Top of DS Frequency Band (MHz)	Bottom of DS Frequency Band (MHz)	US BW Capacity w/ 7.5 bps/Hz (Mbps)	DS BW Capacity w/ 9.6 bps/Hz (Mbps)	Unuseable Guard-Band #1 from 85-108 MHz (MHz)	Unuseable Guard-Band #2 at US:DS Split (MHz)	Total Unuseable Guard-Band (MHz)	US:DS Frequency Band Re-Use Ratio (%)
204	20	1218	258	1208	9216	23	54	77	-6%
300	20	1218	352	1928	8314	23	52	75	-6%
396	20	1218	465	2648	7229	23	69	92	-8%
492	20	1218	578	3368	6144	23	86	109	-9%
588	20	1218	690	4088	5069	23	102	125	-10%
684	20	1218	803	4808	3984	23	119	142	-12%

Because it does not require FDX Amplifiers with Echo Cancellation, FDD Ultra-Split operation does not suffer from the Interference Group Elongation issue. Thus, FDD Ultra-Split operation permits MSOs to continue to work within Node+Non-Zero environments, saving the MSOs the cost of Node+0 Node-Splits and Fiber Deep optical runs . The implications of these effects will be analyzed in more detail below.

Likelihood of Success: High probability of success; development is still required, but it is low risk development.

2.4. Static Soft-Full-Duplex DOCSIS (Static Soft-FDX) for Upstream and Downstream Bandwidth Augmentation

If a Node or Amplifier is designed to permit multiple Upstream Splits (as with Ultra-Split) or if a Node or Amplifier is designed to permit multiple Downstream Spectra (which may occur if/when Extended Spectrum DOCSIS is utilized in the future), then one must consider how those Split changes and/or Spectra changes will be initiated.

The simplest technique (which was oftentimes used in the past) was to simply require the physical swap-out of plug-in modules to modify the useable frequency band. This approach may be permissible in the future. However, this approach requires a truck roll to the Node or Amplifier being modified, which may be undesirable.

Soft-FDX is an improvement that could permit the MSO to use software configurability from the Head-end to change the Split or Spectra within the distant Node or Amplifier. The Soft-FDX technology requires the addition of a processor and (usually) a CM or receiver to each Amplifier, so the added cost on Amplifiers must be considered by MSOs before deploying this technology.

There are two variants of Soft-FDX; namely Static Soft-FDX and Dynamic Soft-FDX. The Static version is described in this section, and the Dynamic version is described in the next section. Static Soft-FDX is the variant that permits the FDD frequency range splits to be dynamically changed with a Command Line Interface configuration in the head-end. Thus, changes are assumed to occur somewhat infrequently, and the transitions between FDD frequency ranges do not necessarily need to occur very quickly. With Static Soft-FDX, the Upstream Bandwidth and Downstream Bandwidth cannot share the spectrum once the FDD frequency range has been set on a given RF Leg. However, it is possible (although improbable) that an MSO could set the split frequency to be different on different RF Legs, which could lead to some level of FDX operation at the Node Level (with overlapping US & DS operation at a single frequency).

An example of an application of Static Soft-FDX is illustrated in Figure 13, and an example of spectrum changes on a yearly basis is shown in Figure 14 (with time on the y-axis and frequency splits on the x-axis).

Likelihood of Success: High probability of success; development is still required.

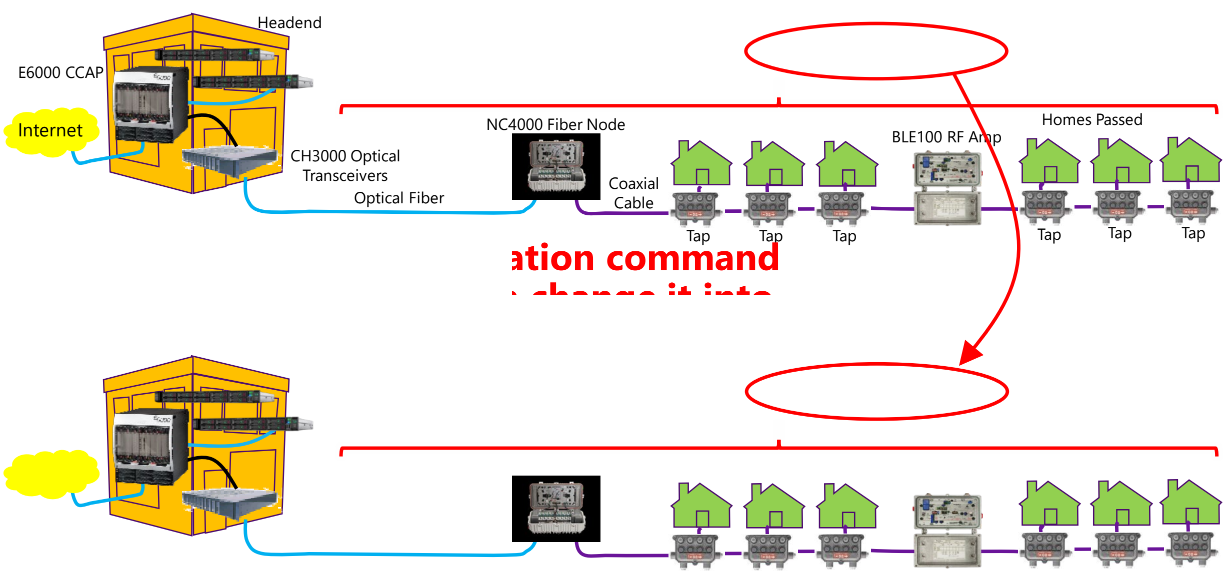

Figure 13 – Static Soft-FDX

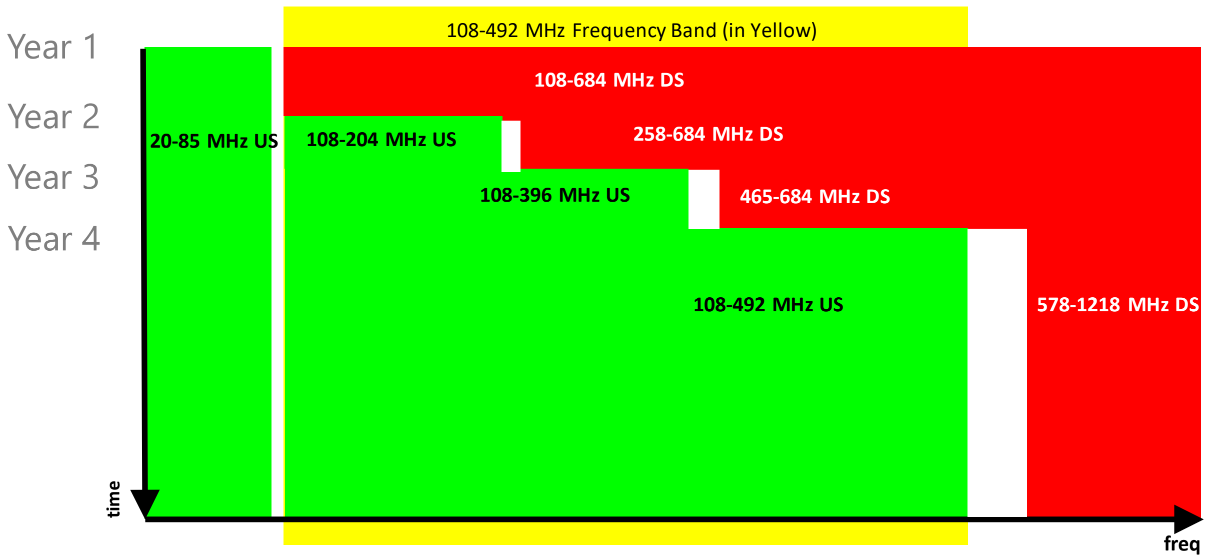

Figure 14 – Examples of Yearly Spectrum Changes using Static Soft-FDX

2.5. Dynamic Soft-Frequency-Division Duplex (Dynamic Soft-FDX) for Upstream and Downstream Bandwidth Augmentation

Dynamic Soft-FDX is an interesting solution that is half-way between Traditional-FDX and Static Soft-FDX. Like Traditional-FDX, it requires that the changes between different FDD frequency ranges occur frequently and rapidly. The FDD frequency changes within Dynamic Soft-FDX are not typically initiated by Command Line Interface commands (as they are with Static Soft-FDX), but they are instead initiated by the DOCSIS Media Access Control sub-system monitoring the Upstream and Downstream Bandwidth usage in real-time (as is done in Traditional-FDX). Thus, Dynamic Soft-FDX does not actually "steal" Bandwidth Capacity from the Downstream and permanently give it to the Upstream- instead it temporarily "borrows" Bandwidth Capacity from the Downstream and temporarily loans it to the Upstream before quickly returning it back to the Downstream (assuming Upstream bursts are less frequent than Downstream bursts).

Like Static Soft-FDX, Dynamic Soft-FDX relies on simple FDD operations to eliminate the need for the Echo Cancellation in Amplifiers. Thus, it will still work well in Node+Non-Zero environments.

A potential algorithm for Dynamic Soft-FDX might require continual monitoring of Upstream and Downstream bandwidth flows and provide for early recognition of Upstream Bandwidth bursts. Upon recognizing the start of an Upstream Bandwidth Burst, the system could change the frequency ranges on a second-by-second basis to temporarily provide more Upstream Bandwidth Capacity (and less Downtream Bandwidth Capacity) whenever required. An example of an application of Dynamic Soft-FDX is illustrated in Figure 15, and an example of spectrum changes on a second-by-second basis is shown in Figure 16 (with time on the y-axis and frequency splits on the x-axis).

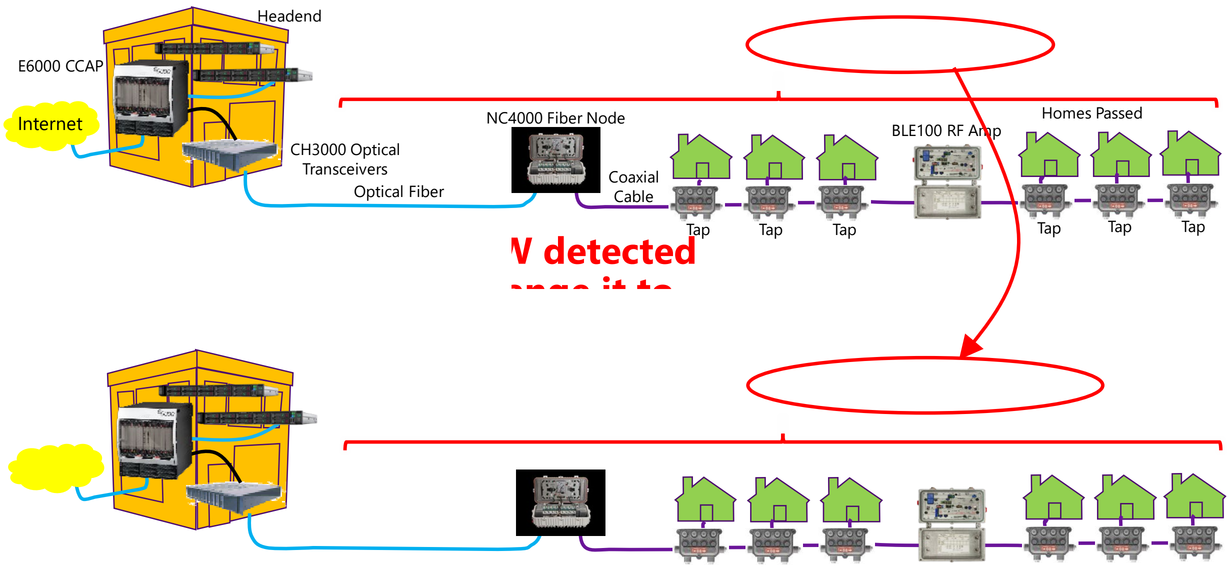

Figure 15 – Dynamic Soft-FDX

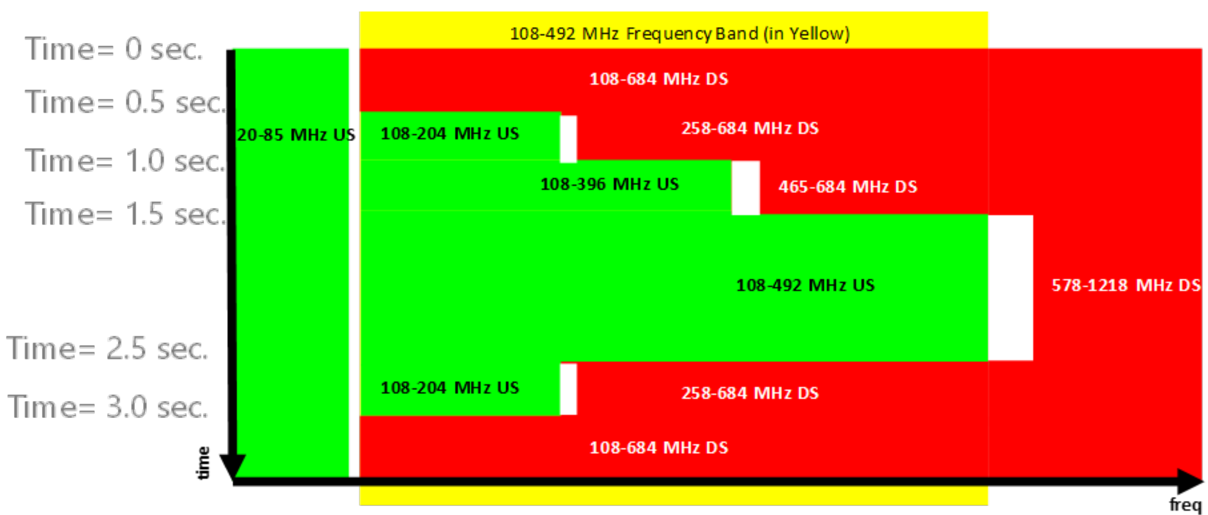

Figure 16 – Examples of Second-by-Second Spectrum Changes using Dynamic Soft-FDX

These rapid frequency range changes are quite similar to solutions that have been proposed for Traditional-FDX operation. In fact, Traditional-FDX must perform these functions within each Interference Group of a Service Group. In fact, the operation within a Traditional-FDX Interference Group could be identical to that which is shown in Figure 16.

However, the Dynamic Soft-FDX frequency range modifications would likely be managed at an RF Distribution Leg level (or perhaps at a Node level) instead of at the Interference Group level (as done for Traditional-FDX). Another way to look at this Dynamic Soft-FDX solution is to consider it to be a simplified Traditional-FDX solution where the Traditional-FDX Interference Group has been enlarged to cover an entire RF Distribution Leg (or perhaps the entire Service Group within a Node) instead of covering small subsets of FDX CMs on neighboring Taps that cause noise to one another. Thus, Dynamic Soft-FDX is indeed a form of FDX, which is apparent when one compares the Interference Groups in Figure 17 and Figure 18.

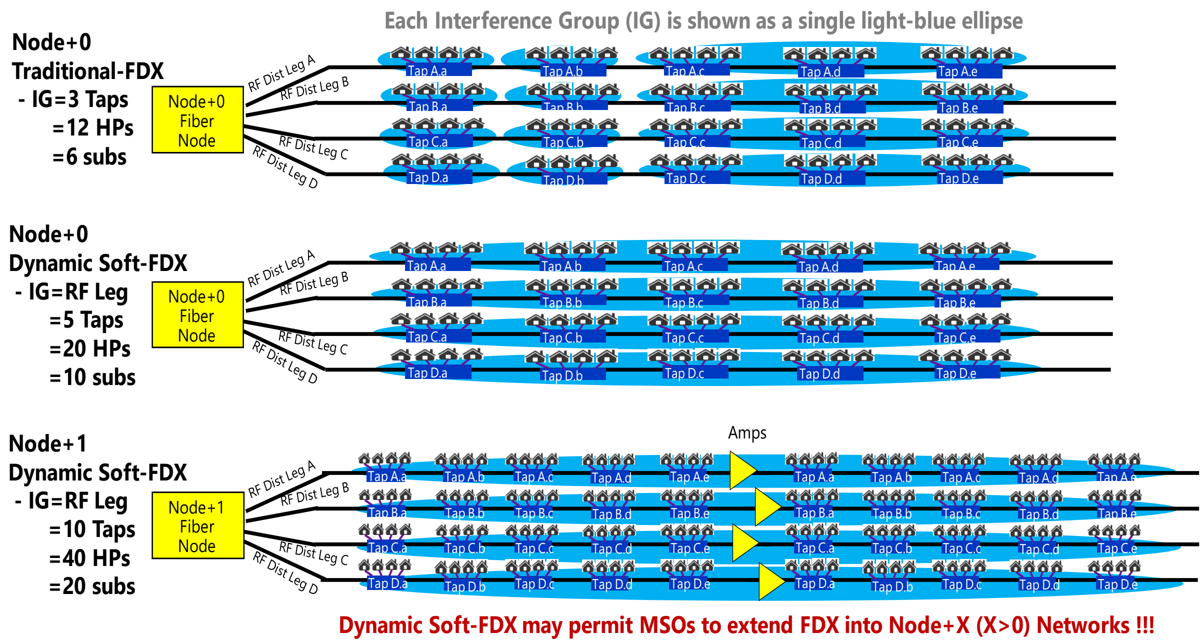

Figure 17 – Interference Groups in Traditional-FDX and RF Leg-based Dynamic Soft-FDX (for Node+0 and Node+1 Systems)

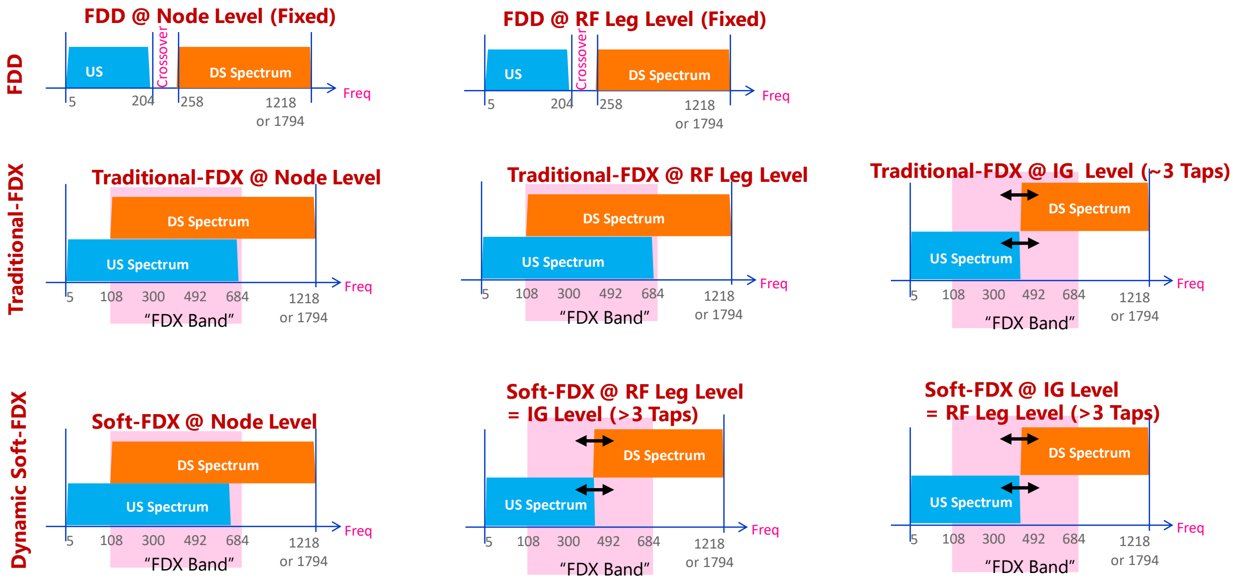

Figure 18 – FDX Operation vs Sliding FDD Operation at Various Levels of FDD Systems, Traditional-FDX Systems, & Dynamic Soft-FDX Systems

Dynamic Soft-FDX (operating with Interference Groups sized to be entire RF Legs) would still require Sounding algorithms, because each FDX CM must be mapped into the correct Interference Group (RF Leg). However, Sounding algorithms may be able to be simplified when operated at the RF Leg level. In addition, Dynamic Soft-FDX requires that the FDX Resource Block Assignments (RBAs) be changed on a regular basis (like Traditional-FDX), and the Fiber Nodes and Amplifiers and CMs must all support those RBA changes in a coordinated and synchronized fashion. These changes are ultimately managed by the DOCSIS Media Access Control sub-systems that continually monitor the dynamic changes in Upstream and Downstream traffic flows. However, the Dynamic Soft-FDX architecture has embraced large FDX Interference Groups (covering an entire RF Leg) as an acceptable construct. This permits Dynamic Soft-FDX to work well in Node+Non-Zero environments using simpler FDD-based Amplifier designs that do not require Echo Cancellation. The Amplifiers may just require low-cost switchable Filter Banks that could be added to existing Amplifiers already deployed in the field.

In the end, Dynamic Soft-FDX and Traditional-FDX are merely different variations of FDX solutions with different views on acceptable Interference Group sizes. Figure 19 illustrates a taxonomy of Upstream Augmentation solutions, and within that Figure, it can be seen that there are actually a continuum of FDX solutions that use different Interference Group (IG) sizes and different subsets of Resource Block Assignments (RBAs).

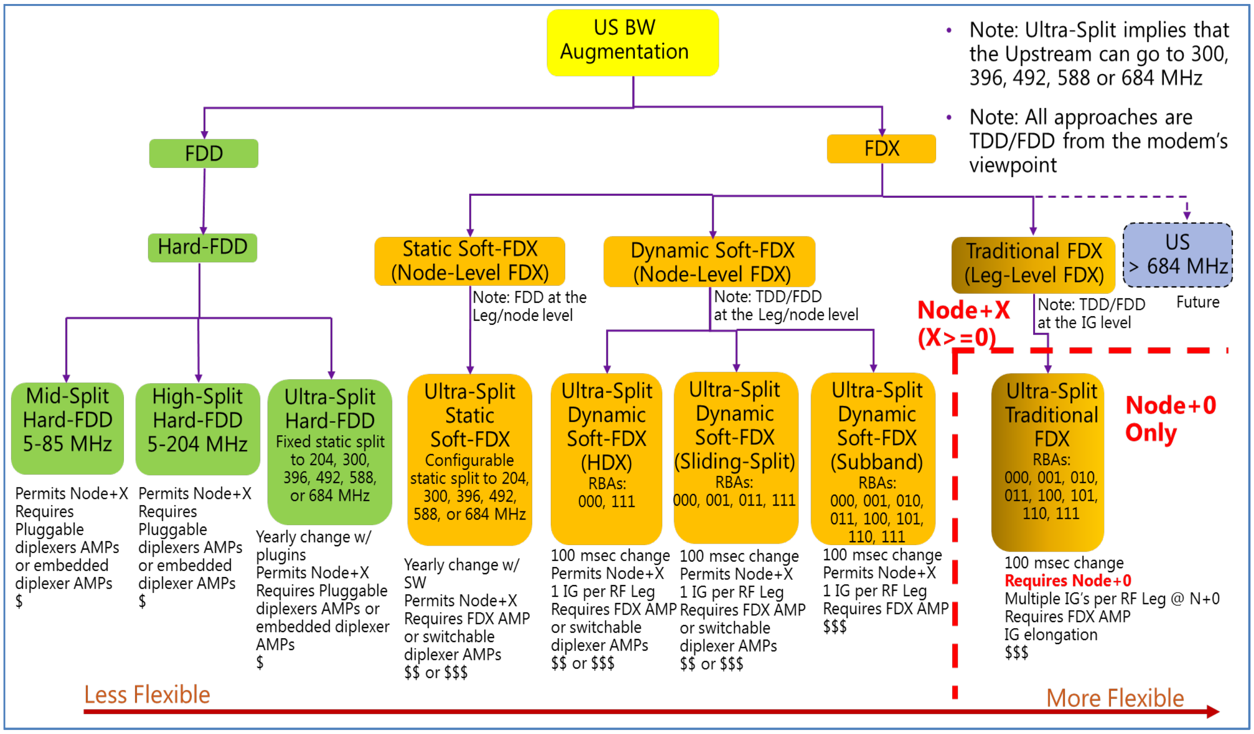

Figure 19 – Taxonomy of Upstream Augmentation Solutions with a Continuum of FDX Solutions (including Tradition-FDX and Dynamic Soft-FDX and Static Soft-FDX)

Dynamic Soft-FDX can (in some ways) be viewed as a "simplified version" of Traditional-FDX, with slightly larger Interference Groups and more subscribers sharing the FDD/TDD bandwidth. (Note: The same FDD/TDD operation exists inside of Interference Groups of Traditional-FDX). Therefore, Dynamic Soft-FDX should experience slightly lower QoE performance levels than FDX. However, Traffic Engineering studies performed by the authors to discover the magnitude of the QoE impacts resulting from changing the FDX Interference Group sizes from a small subset of CMs to a full RF Distribution leg (or even a full Service Group) have shown promising results.

As an example, the authors ran a convolution-based simulation (using predicted probability density functions of futuristic bandwidth usage based on high-sample-rate data collections from present-day, real-world HFC plants extended into the future). Many scenarios were simulated, but we will focus on just two of those scenarios to illustrate the point. The first is a Node+0 Traditional-FDX environment with 64 subscribers per Node and (worst-case) 8 subscribers per Interference Group. The second is a Node+1 Dynamic Soft-FDX environment with 128 subscribers per Node and 32 subscribers per Interference Group (which represents an entire RF Leg).

In both scenarios, we assume futuristic ~2024 numbers of DS Tmax_max=2000 Mbps and US Tmax_max = 2000 Mbps and DS Tavg=13.9 Mbps and US Tavg=0.57 Mbps. To create a challenging environment, the "Legacy DOCSIS DS Band" was assumed to carry sixteen 6 MHz 256QAM SC-QAM DOCSIS DS channels plus one 192 MHz OFDM channel (~2016 Mbps in total). The "Legacy DOCSIS US Band" was assumed to carry four 6.4 MHz 64QAM SC-QAM DOCSIS DS channels plus one 43-MHz OFDMA channel operating from 42 to 85 MHz (~422 Mbps on total). The simulation determined the amount of Bandwidth Capacity (in Mbps) required for the shared frequency range to ensure that the Quality of Experience (QoE) levels in 2024 would remain the same as they are today by ensuring that the probability of a bandwidth burst exceeding the capacity of the HFC plant is the same as it is today.

In those simulation results, the total shared FDX BW Capacity required for the 2024 time-frame using the Node+0 Traditional-FDX design (with 8-subscriber Interference Groups) was found to be 2015 Mbps, which (assuming a useable spectral efficiency of 7.5 bps/Hz) required an FDX Band running from ~108-377 MHz.

The total shared FDX BW Capacity required for the 2024 time-frame using the Node+1 Dynamic Soft-FDX design (with 32-subscriber RF Legs = 32-subscriber Interference Groups) was found to be 2164 Mbps, which (assuming a useable spectral efficiency of 7.5 bps/Hz) required an FDX Band running from ~108-397 MHz. (Note: The slight increase in Required Bandwidth Capacity is primarily due to the need to support more subscribers within the Node+1 Service Group).

Thus, both of these solutions come close to fitting nicely within the BW Capacity of a 108-396 MHz FDX Band system. This illustrates that Dynamic Soft-FDX works about as efficiently as Traditional-FDX.

Likelihood of Success: High probability of success; much development is still required.

2.6. Extended Spectrum DOCSIS (ESD) for Upstream and Downstream Bandwidth Augmentation

Extended Spectrum DOCSIS (ESD) is a proposal originally made by the authors at the CableLabs 2015 Summer Conference and again at the NCTA Shows in 2015 [CL15] and 2016 [CL16]. The simple idea proposes to extend the spectrum of DOCSIS 3.1 to Upstream ranges higher than 684 MHz and to Downstream ranges higher than 1218 MHz.

The keys to a successful implementation of this idea include:

1) Maintain a Total Composite Power output level from devices (Nodes, Amplifiers, CMs) at levels similar to those of today
2) Utilize the same tilted power spectral density (as utilized today) for all SC-QAM signals (ex: Video & pre-DOCSIS 3.1 signals) that are operating at the lower frequencies in the spectrum (which should preclude the need for any re-spacing of Amplifiers in the HFC plant)
3) Utilize DOCSIS 3.1 Orthogonal Frequency Division Multiplexing (OFDM) and Low Density Parity Check (LDPC) Forward Error Correction (FEC) for all signals in higher frequency ranges
4) Utilize a different power spectral density for the higher frequencies by applying a flat power spectral density in all of the OFDM regions at the high frequency range of the spectrum
5) Rely on the benefits of OFDM bit-loading to match the Quadrature Amplitude Modulation (QAM) levels to the particular Signal-to-Noise (SNR) ratios that will undoubtedly decrease at higher frequencies (due to increased attenuation levels at higher frequencies)
6) For legacy Set-top Boxes, use high-Q filters or other techniques to pass OOB Downstream video signals within the Upstream frequency range
7) Use a 2-port Gateway-style of CM at the portal into the home to electrically isolate the Outside Plant from the in-home network for any home receiving and processing the ESD signal (which is identical to a requirement for Traditional-FDX operation)

There are several variants of Upstream ESD spectral widths and Downstream ESD spectral widths that can be envisioned for the future. Table 3 illustrates some of these proposals. Spectral widths requiring greater than ~8 GHz will require a move to FTTT or FTTH systems. It is also clear that wider spectra usually will display a lower Spectral Efficiency (due to increased attenuation and lowered SNRs at the higher frequencies). The 396 MHz Upstream and 1218 MHz Downstream rows (shown with red numbers in the Table) are the likely configurations needed to compete with the 8.6 Gbps DS x 2.4 Gbps US of the near-term low-cost Asymmetric XGS-PON competitor shown in Figure 1. An augmentation to the 1218 MHz Upstream ESD row (shown with maroon numbers in the Table) is a likely configuration change needed to compete with the 8.6 Gbps DS x 8.6 Gbps US of the Symmetric XGS-PON competitor shown in Figure 1.

Hypothetical Bandwidth Capacities for each of these systems is shown in the Table, but it should be understood that the equipment to support the higher capacity solutions does not yet exist. As a result, the authors were forced to utilize their best guestimates on the potential performance levels and frequency responses of futuristic, yet-to-be-designed equipment such as Nodes and Amplifiers and Taps and CMs. These performance levels were extrapolations from current designs. Thus, they may or may not be accurate, and the indicated results may or may not be achievable. The actual performance levels will not be known until final designs are completed. However, the performance levels within the Table will be utilized in the analysis below.

Table 3 – Examples of Extended Spectrum DOCSIS Variants & their Predicted Perfomance Levels (Zero-Order Models)

Spectrum Type	Top of Spectrum (MHz)	Bottom of Spectrum (MHz)	Assumed Size of Guard-band Region (85-108?) within the Spectral Range (MHz)	Total Useable Spectral Range (MHz)	Assumed Spectral Efficiency in Node+X System (bps/Hz)	Possible BW Capacity in Node+X System (Mbps)	Assumed Spectral Efficiency in Node+X System w/ Active Taps (bps/Hz)	Possible BW Capacity in Node+X System w/ Active Taps to increase spectral efficency at high frequencies (Mbps)	Assumed Spectral Efficiency in FTTT System (bps/Hz)	Possible BW Capacity in FTTT System (Mbps)
Downstream:										
1218 MHz Downstream	1218	108	0	1110	9.6	10656	9.6	10656	9.6	10656
1794 MHz Downstream ESD	1794	108	0	1686	9.3	15680	9.3	15680	9.6	16186
3000 MHz Downstream ESD	3000	108	0	2892	7.1	20533	8	23136	9.6	27763
6000 MHz Downstream ESD	6000	108	0	5892	3.2	18854	8	47136	9.6	56563
12000 MHz Downstream ESD	12000	108	0	11892	NA	Not supported w/ TEM propagation on Hard-line	NA	Not supported w/ TEM propagation on Hard-line	9.4	111785
Upstream:										
42 MHz Upstream	42	20	0	22	7.5	165	7.5	165	7.5	165
65 MHz Upstream	65	20	0	45	7.5	338	7.5	338	7.5	338
85 MHz Upstream	85	20	0	65	7.5	488	7.5	488	7.5	488
204 MHz Upstream	204	20	23	161	7.5	1208	7.5	1208	7.5	1208
300 MHz Upstream	300	20	23	257	7.5	1928	7.5	1928	7.5	1928
396 MHz Upstream	396	20	23	353	7.5	2648	7.5	2648	7.5	2648
492 MHz Upstream	492	20	23	449	7.5	3368	7.5	3368	7.5	3368
588 MHz Upstream	588	20	23	545	7.5	4088	7.5	4088	7.5	4088
684 MHz Upstream	684	20	23	641	7.5	4808	7.5	4808	7.5	4808
1218 MHz Upstream ESD	1218	20	23	1175	7.5	8813	7.5	8813	7.5	8813
1794 MHz Upstream ESD	1794	20	23	1751	6.9	12082	7.5	13133	7.5	13133
3000 MHz Upstream ESD	3000	20	23	2957	4.2	12419	7.5	22178	7.5	22178
6000 MHz Upstream ESD	6000	20	23	5957	1.8	10723	7.5	44678	7.5	44678
12000 MHz Upstream ESD	12000	20	23	11957	NA	Not supported w/ TEM propagation on Hard-line	NA	Not supported w/ TEM propagation on Hard-line	6.5	77721

The basic idea behind ESD is to maintain the Total Composite Power output levels emitted from Nodes and Amplifiers and CMs to be at levels which are similar to those which exists today. To illustrate the concept, an example 3000 MHz (3 GHz) system will be described. For the analyses below, the authors assumed 69.5 dBmV as a typical Total Composite Power level for the Nodes and Amplifers. As described above, the flattening of the Power Spectral Density at higher frequencies will be utilized along with OFDM bit-loading. The resulting Power Spectral Density and Total Composite Power level (integrated across the frequency band) is shown in Figure 19. The resulting Bit-Loading and Throughput is shown in Figure 20.

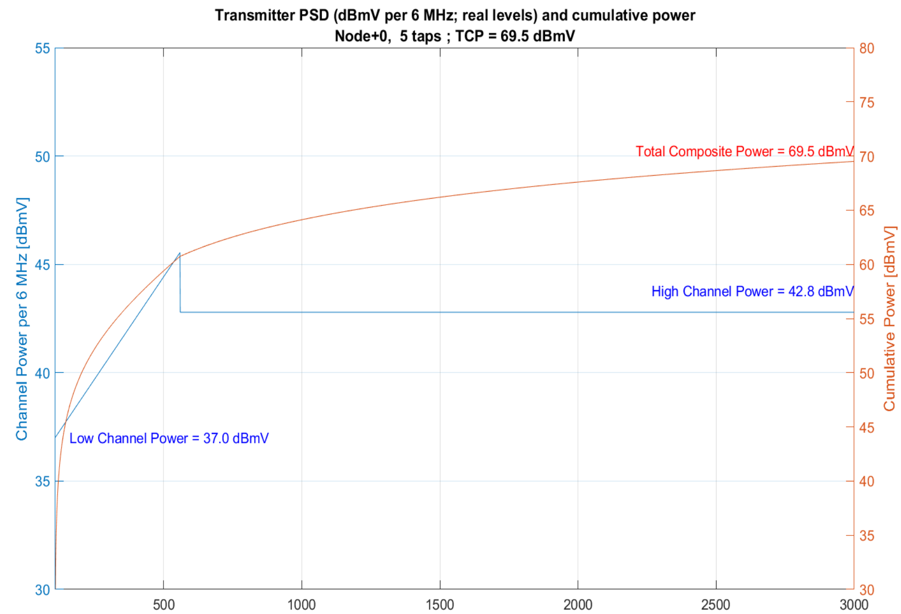

Figure 20 – Launch Power Spectral Density and Total Composite Power for a 3 GHz Extended Spectrum DOCSIS System

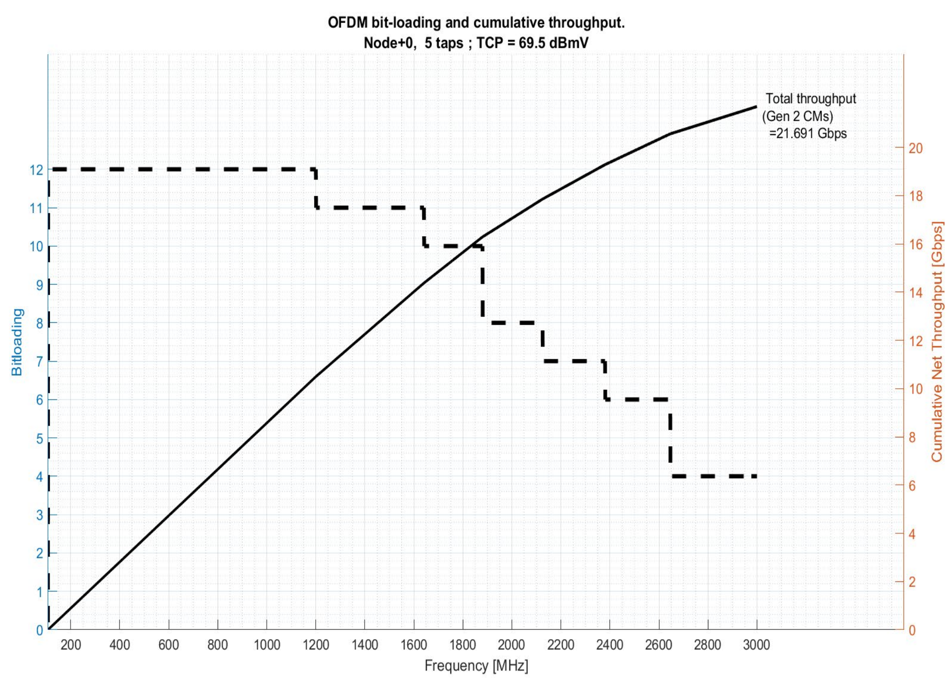

Figure 21 – OFDM Bit-loading & Corresponding Throughput for a 3 GHz Extended Spectrum DOCSIS Node+0 System

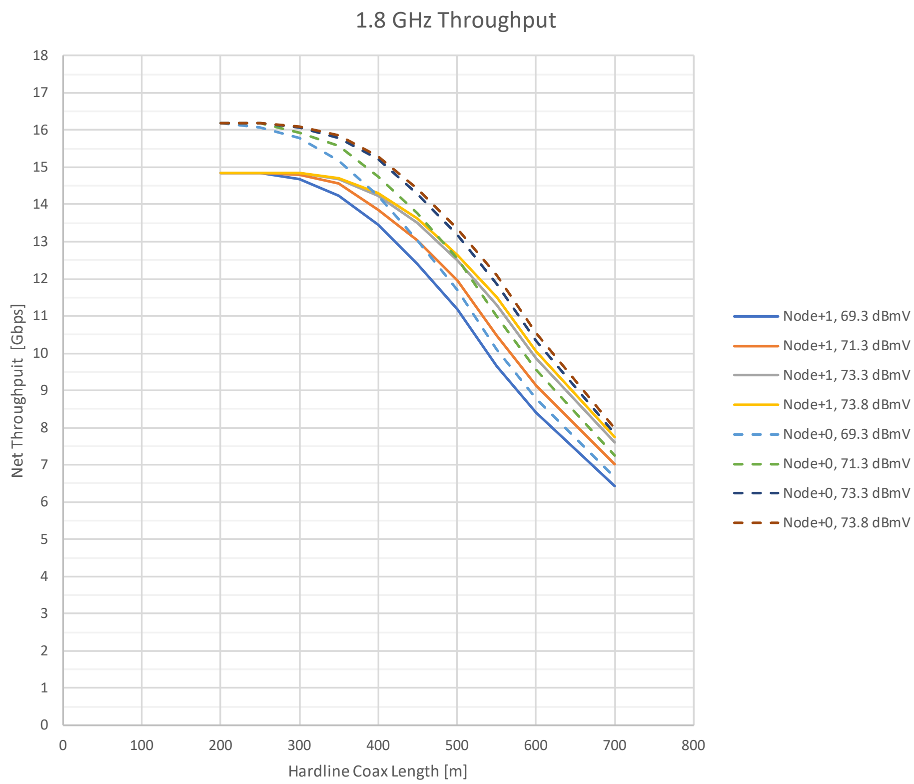

Figure 22 – Predicted 1.8 GHz Bandwidth Capacities as a Function of Amp-to-Amp Hard-line Coaxial Length and Amplifier Output Power Levels and Cascade Lengths

Figure 21 shows interesting predictions on Bandwidth Capacity changes as a function of Amp-to-Amp Hard-line coaxial length, Amplifier output levels, and cascade lengths for a 1.8 GHz solution. All of this data illustrates that the ESD concept does have a reasonable chance of working. In addition, Traditiona-FDX or Dynamic Soft-FDX or Static Soft-FDX techniques could all be used to operate within the Upstream ESD spectral ranges and the Downstream ESD spectral ranges described above.

Likelihood of Success: Medium probability of success; much development is still required and Nodes and Amplifiers and Taps and CMs that support these higher frequencies are still being researched.

2.7. Distributed Node Architectures and Active Taps for Futuristic Upstream and Downstream Bandwidth Augmentation

In the more distant future, two other advanced technologies may be considered for Bandwidth Capacity augmentation. They are Distributed Node Architectures and Active Taps. These technologies will also be considered in the analysis below, so they will be briefly described.

The Distributed Node Architectures (DNA) [MU16] concept propose a novel idea to use fiber feeds emanating south-bound from a Primary Fiber Node instead of coaxial outputs. The Primary Fiber Node might be a standard Fiber Node or a DAA Fiber Node. These south-bound fiber feeds can then be routed with low loss to other Optical-to-Electrical converter elements (typically at the previous sites of Amplifiers). These Optical-to-Electrical converter elements would be similar to low-cost RF over Glass (RFoG) ONUs, but they would typically reside in Outside Plant housings (such as Amplifier or Tap housings) and their output RF power levels on the south-bound coax would be capable of driving many homes connected to the south-bound coax. The DNA solution offers several potential benefits. First, it could greatly increase the area served and the number of subscribers served by the Primary Fiber Node, and this could help reduce the Cost per HHP for the deployments of the Primary Fiber Nodes. Secondly, it could provide a technique that permits future network evolutions such as the deployment of Fiber-To-The-Tap (FTTT) technologies. In these futuristic instantiations, the Primary Fiber Node could be a DAA Node supporting (for example) 24 Service Groups. The South-bound fiber feeds could employ Wavelength Division Multiplexing (WDM) techniques to deliver unique signals to each of 24 Taps subtending from the Primary Fiber Node. Each Tap would then receive a unique signal from the fiber feed and convert that unique signal into an RF signal that is then split and amplified and fed to the four or eight drop coaxes to each home. Using short ~150 foot drop coaxes from the Taps (as the only coaxial runs in the system), a previous study showed that very high bandwidth capacities exceeding 100 Gbps could be delivered via DOCSIS to the homes in these DNA FTTT environments. [CL15] [CL16]

The Active Tap concept is another futuristic idea that can help increase Bandwidth Capacity to subscribers. It places small bidirectional amplifiers in all or some of the Taps within the coaxial run. The amplification of the Downstream and Upstream RF signals in the upper frequency ranges can help to increase Signal-to-Noise ratios and ensure that Extended Spectrum DOCSIS systems can operate without having to resort to low bit-loading levels in the upper frequency range. This approach can help to increase the average Spectral Efficiency and the total Bandwidth Capacity of the system, as illustrated in the blue column of Table 3.

Likelihood of Success: Medium probability of success; much development is still required and most of these concepts are still being researched.

3. Analysis of Migration Paths for Different Architectures

With growing competitive threats and growing Bandwidth Capacity requirements, MSOs are planning to make HFC plant changes as the industry enters the 2020 decade. With the large array of technologies (outlined in the previous section) promising a myriad of solutions for their use in the future, many MSOs are asking important questions about which technologies to utilize and when to utilize them. In addition, different constraints are forcing MSOs to consider differing paths that are quite divergent.

Analyzing the many different plans that have been considered by MSOs in the past few years is not possible within a single paper. As a result, this paper will only select a subset of the many MSO architectural paths that are currently being considered- paths with very divergent approaches will be included to contrast the attributes of the different solutions. While only a few paths will be included, it is nevertheless hoped that the small number of MSO architectures analyzed within this paper will give some hints on the pros and cons of the different paths for the Cable Industry in the future.

Eighteen different architectures will be analyzed. The architectures can be divided into two different groupings based on the Upstream to Downstream Bandwidth ratio attribute. Some MSOs plan to offer their subscribers Asymmetric SLAs (with Upstream Tmax = ~50% of Downstream Tmax), while other

MSOs plan to offer their subscribers Symmetric SLAs (with Upstream Tmax = Downstream Tmax). Nine of the architectures will use Asymmetric SLAs, and nine of the architectures will use Symmetric SLAs.

The nine architectures (labeled 1 through 9) in both of the sets will each have a unique set of attributes that have been considered by MSOs. The attributes of the nine architectures are outlined below.

- **Architecture 1 (Traditional-FDX)**: A Traditional-FDX solution is assumed with overlapping Upstream and Downstream frequency ranges. The Downstream Tmax experiences a 25% CAGR in the 2020's, a 15% CAGR in the 2030's, and a 15% CAGR in the 2040's. The Downstream Tavg experiences a 39% CAGR in the 2020's, a 29% CAGR in the 2030's, and a 19% CAGR in the 2040's. The Upstream Tavg experiences a 19% CAGR for all time. 2-Service Group Nodes are used until 2028, and then 4-Service Group Nodes are used until FTTT solutions are required. The MSO is assumed to begin with 1.2 GHz Node+0 operation in 2020, and then the MSO attempts to stay with 1.2 GHz Node+0 and ESD until Bandwidth Capacity requirements force a transition to ESD spectra Architecture 1a supports Asymmetric SLAs, and Architecture 1b supports Symmetric SLAs.
- **Architecture 2 (Static Soft-FDX Base-line w/ 1.2 GHz Affinity)**: A "base-line" Static Soft-FDX solution is assumed with non-overlapping Upstream and Downstream frequency ranges and a guard-band between those frequency ranges. The Downstream Tmax experiences a 25% CAGR in the 2020's, a 15% CAGR in the 2030's, and a 15% CAGR in the 2040's. The Downstream Tavg experiences a 39% CAGR in the 2020's, a 29% CAGR in the 2030's, and a 19% CAGR in the 2040's. The Upstream Tavg experiences a 19% CAGR for all time. 2-Service Group Nodes are used until 2028, and then 4-Service Group Nodes are used until FTTT solutions are required. The MSO is assumed to start with 1.2 GHz Node+3 operation in 2020, and then the MSO moves to Node+2 and Node+1 when required (avoiding ESD as long as possible and avoiding the costs of Node+0); this continues until Bandwidth Capacity requirements force a transition to ESD spectra The MSO is assumed to try to keep 1.2 GHz operation for as long as possible, giving preference to Node-splits over ESD operation during this time. Architecture 2a supports Asymmetric SLAs, and Architecture 2b supports Symmetric SLAs.
- **Architecture 3 (Static Soft-FDX w/ Node+3 Affinity)**: A Static Soft-FDX solution is assumed with non-overlapping Upstream and Downstream frequency ranges and a guard-band between those frequency ranges. The Downstream Tmax experiences a 25% CAGR in the 2020's, a 15% CAGR in the 2030's, and a 15% CAGR in the 2040's. The Downstream Tavg experiences a 39% CAGR in the 2020's, a 29% CAGR in the 2030's, and a 19% CAGR in the 2040's. The Upstream Tavg experiences a 19% CAGR for all time. 2-Service Group Nodes are used until 2028, and then 4-Service Group Nodes are used until FTTT solutions are required. The MSO is assumed to start with 1.2 GHz Node+3 operation in 2020. This continues until Bandwidth Capacity requirements force a transition to ESD spectra. The MSO is assumed to try to keep Node+3 operation for as long as possible, giving preference to ESD operation over Node-splits during this time. Architecture 3a supports Asymmetric SLAs, and Architecture 3b supports Symmetric SLAs.
- **Architecture 4 (Static Soft-FDX w/ 15% DS Tmax CAGR)**: A Static Soft-FDX solution similar to the "base-line" is assumed with non-overlapping Upstream and Downstream frequency ranges and a guard-band between those frequency ranges, but the Downstream Tmax experiences a 15% CAGR in the 2020's (instead of 25%), a 15% CAGR in the 2030's, and a 15% CAGR in the 2040's. The Downstream Tavg experiences a 39% CAGR in the 2020's, a 29% CAGR in the 2030's, and a 19% CAGR in the 2040's. The Upstream Tavg experiences a 19% CAGR for all time. 2-Service Group Nodes are used until 2028, and then 4-Service Group Nodes are used until FTTT solutions are required. The MSO is assumed to start with 1.2 GHz Node+3 operation in 2020, and then the MSO moves to Node+2 and Node+1 when required (avoiding the costs of Node+0); this continues until Bandwidth Capacity requirements force a transition to ESD spectra.

The MSO is assumed to try to keep 1.2 GHz operation for as long as possible, giving preference to Node-splits over ESD operation during this time. Architecture 4a supports Asymmetric SLAs, and Architecture 4b supports Symmetric SLAs.

- **Architecture 5 (Static Soft-FDX w/ Reduced US Tmax)**: A Static Soft-FDX solution similar to the "base-line" is assumed with non-overlapping Upstream and Downstream frequency ranges and a guard-band between those frequency ranges. The Downstream Tmax experiences a 25% CAGR in the 2020's, a 15% CAGR in the 2030's, and a 15% CAGR in the 2040's. The Upstream Tmax is slightly reduced from the "base-line". The Downstream Tavg experiences a 39% CAGR in the 2020's, a 29% CAGR in the 2030's, and a 19% CAGR in the 2040's. The Upstream Tavg experiences a 19% CAGR for all time. 2-Service Group Nodes are used until 2028, and then 4-Service Group Nodes are used until FTTT solutions are required. The MSO is assumed to start with 1.2 GHz Node+3 operation in 2020, and then the MSO moves to Node+2 and Node+1 when required (avoiding the costs of Node+0); this continues until Bandwidth Capacity requirements force a transition to ESD spectra. The MSO is assumed to try to keep 1.2 GHz operation for as long as possible, giving preference to Node-splits over ESD operation during this time. Architecture 5a supports Asymmetric SLAs, and Architecture 5b supports Symmetric SLAs.
- **Architecture 6 (Static Soft-FDX w/ Selective Subscriber Migration)**: A Static Soft-FDX solution similar to the "base-line" is assumed with non-overlapping Upstream and Downstream frequency ranges and a guard-band between those frequency ranges. The Downstream Tmax experiences a 25% CAGR in the 2020's, a 15% CAGR in the 2030's, and a 15% CAGR in the 2040's, but the subscribers with the top tier SLA are assumed to always be moved to an alternative infrastructure, yielding Tmax's that are ½ of their normal values in the "base-line." The Downstream Tavg experiences a 39% CAGR in the 2020's, a 29% CAGR in the 2030's, and a 19% CAGR in the 2040's. The Upstream Tavg experiences a 19% CAGR for all time. 2-Service Group Nodes are used until 2028, and then 4-Service Group Nodes are used until FTTT solutions are required. The MSO is assumed to start with 1.2 GHz Node+3 operation in 2020, and then the MSO moves to Node+2 and Node+1 when required (avoiding the costs of Node+0); this continues until Bandwidth Capacity requirements force a transition to ESD spectra. The MSO is assumed to try to keep 1.2 GHz operation for as long as possible, giving preference to Node-splits over ESD operation during this time. Architecture 6a supports Asymmetric SLAs, and Architecture 6b supports Symmetric SLAs.
- **Architecture 7 (Static Soft-FDX w/ Guard-band Elimination)**: A Static Soft-FDX solution similar to the "base-line" is assumed with non-overlapping Upstream and Downstream frequency ranges, but no guard-band between those frequency ranges. The Downstream Tmax experiences a 25% CAGR in the 2020's, a 15% CAGR in the 2030's, and a 15% CAGR in the 2040's. The Downstream Tavg experiences a 39% CAGR in the 2020's, a 29% CAGR in the 2030's, and a 19% CAGR in the 2040's. The Upstream Tavg experiences a 19% CAGR for all time. 2-Service Group Nodes are used until 2028, and then 4-Service Group Nodes are used until FTTT solutions are required. The MSO is assumed to start with 1.2 GHz Node+3 operation in 2020, and then the MSO moves to Node+2 and Node+1 when required (avoiding the costs of Node+0); this continues until Bandwidth Capacity requirements force a transition to ESD spectra. The MSO is assumed to try to keep 1.2 GHz operation for as long as possible, giving preference to Node-splits over ESD operation during this time. Architecture 7a supports Asymmetric SLAs, and Architecture 7b supports Symmetric SLAs.
- **Architecture 8 (Dynamic Soft-FDX Base-line)**: A "base-line" Dynamic Soft-FDX solution is assumed with non-overlapping Upstream and Downstream frequency ranges within each RF Leg (but overlapping Upstream and Downstream frequency ranges within a Node) and a guard-band between those frequency ranges. Upstream and Downstream bandwidth monitoring that can rapidly change the split in any RF Leg is also assumed. The Downstream Tmax experiences a

25% CAGR in the 2020's, a 15% CAGR in the 2030's, and a 15% CAGR in the 2040's. The Downstream Tavg experiences a 39% CAGR in the 2020's, a 29% CAGR in the 2030's, and a 19% CAGR in the 2040's. The Upstream Tavg experiences a 19% CAGR for all time. 2-Service Group Nodes are used until 2028, and then 4-Service Group Nodes are used until FTTT solutions are required. The MSO is assumed to start with 1.2 GHz Node+3 operation in 2020, and then the MSO moves to Node+2 and Node+1 when required (avoiding the costs of Node+0); this continues until Bandwidth Capacity requirements force a transition to ESD spectra. The MSO is assumed to try to keep 1.2 GHz operation for as long as possible, giving preference to Node-splits over ESD operation during this time. Architecture 8a supports Asymmetric SLAs, and Architecture 8b supports Symmetric SLAs.

- **Architecture 9 (Static Soft-FDX w/ Active Taps)**: A Static Soft-FDX solution similar to the "base-line" is assumed with non-overlapping Upstream and Downstream frequency ranges and a guard-band between those frequency ranges, but Active Taps are included in the path of the coax to improve Singal-to-Noise ratios and Spectral Efficiencies at higher frequencies. The Downstream Tmax experiences a 25% CAGR in the 2020's, a 15% CAGR in the 2030's, and a 15% CAGR in the 2040's. The Downstream Tavg experiences a 39% CAGR in the 2020's, a 29% CAGR in the 2030's, and a 19% CAGR in the 2040's. The Upstream Tavg experiences a 19% CAGR for all time. 2-Service Group Nodes are used until 2028, and then 4-Service Group Nodes are used until FTTT solutions are required. The MSO is assumed to start with 1.2 GHz Node+3 operation in 2020, and then the MSO moves to Node+2 and Node+1 when required (avoiding the costs of Node+0); this continues until Bandwidth Capacity requirements force a transition to ESD spectra. The MSO is assumed to try to keep 1.2 GHz operation for as long as possible, giving preference to Node-splits over ESD operation during this time. Architecture 2a supports Asymmetric SLAs, and Architecture 2b supports Symmetric SLAs.

The authors attempted to predict the yearly decisions that might be made by an MSO working with each of the nine Architectures and for both Asymmetric SLAs (in Figures 22-30) and Symmetric SLAs (in Figures 31-39), and the resulting changes and migration paths (for the 25 years from 2020 to 2044) for all eighteen of the resulting Architectures are displayed in Figures 22-39 below. The orange region gives a description of the HFC Plant, the yellow region describes the Upstream Bandwidth requirements, and the green section describes the Downstream Bandwidth requirements.

While the Figures display only even-numbered years (for brevity), many important decisions needed to be made on a yearly basis within the predictive analysis of each of the Figures. The need for change within each year of each Figure was predominantly driven by expected yearly increases in US Tavg, US Tmax, DS Tavg, and DS Tmax. The questions answered within each year of each Figure included:

1) What is the year's US Tavg & US Tmax & DS Tavg & DS Tmax & Nsub value?
2) What is the Required Upstream HSD Bandwidth Capacity given by Nsub*Tavg+1.0*Tmax?
3) What is the Required Downstream HSD Bandwidth Capacity given by Nsub*Tavg+1.0*Tmax?
4) Should a Node-split or a move to FTTT or a move to Selective Subscriber Migration be performed?
5) What is the year's new US Tavg & US Tmax & DS Tavg & DS Tmax & Nsub value?
6) What is the new Required Upstream HSD Bandwidth Capacity given by Nsub*Tavg+1.0*Tmax?
7) What is the new Required Downstream HSD Bandwidth Capacity given by Nsub*Tavg+1.0*Tmax?
8) Should the Bottom & Top of the US DOCSIS Spectrum be moved to increase US Capacity?
9) What SNR levels and bit-loading levels and US Spectral Efficiency can be supported in the resulting US DOCSIS Spectrum (assuming launch power levels are fixed)?

10) Does that US DOCSIS Spectrum and US Spectral Efficiency support the Required Upstream HSD Bandwidth Capacity requirement?
11) If not, return to step (8)
12) Should the Bottom & Top of the DS DOCSIS Spectrum be moved to increase DS Capacity?
13) What SNR levels and bit-loading levels and DS Spectral Efficiency can be supported in the resulting DS DOCSIS Spectrum (assuming launch power levels are fixed)?
14) Does that DS DOCSIS Spectrum and DS Spectral Efficiency support the Required Downstream HSD Bandwidth Capacity requirement?
15) If not, return to step (12)
16) Is the solution acceptable?
17) If not, return to step (4)

The results of all of these decisions made on a yearly basis are illustrated in the Migration Paths within each of the Figures below. It should be understood that these particular Migration Paths are not being define as "the best" Migration Paths. With so many decisions to be made on a yearly basis, it is clear that different MSOs will likely make different decisions leading to many different and desirable Migration Paths. As a result, the Migration Paths depicted below should only be used as examples to guide our analysis. Other equally valid Migration Paths are also possible.

FDX Asymmetric Tmax (US = 50% of DS) with 0 Guardbands (EC)	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	4	24	24	24	24	24
Fiber Depth	Node+0	Node+0	Node+0	Node+0	Node+0	Node+0	Node+0	Node+0	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	120	120	120	120	120	120	120	120	120	120	120	120	120
Nsub in Service Group	30	30	30	30	30	15	15	15	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	417	417	417	417	417	417	417	417	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
US Tmax_max (Mbps)	500	1000	1000	2000	2000	5000	5000	5000	10000	10000	20000	20000	40000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	508	1012	1017	2024	2034	5024	5034	5048	10018	10026	20036	20051	40073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	1.65%	1.18%	1.66%	1.18%	1.66%	0.48%	0.67%	0.95%	0.18%	0.26%	0.18%	0.26%	0.18%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	73	140	141	275	276	675	676	678	1341	1342	2677	2679	5348
Top of US Band (MHz)	85	204	204	300	300	684	684	684	1794	1794	3000	3000	6000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1069	2133	2258	4498	4962	10862	11435	12387	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	6.45%	6.25%	11.41%	11.06%	19.38%	7.94%	12.55%	19.27%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	5	5	5	5	5	5	5	5	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.6	9.6	9.3	9.3	9.3	9.6	9.6	9.6	9.6	9.4
US:DS Frequency Band Re-Use BW (MHz)… Positive = Re-Use & Negative = Guard-band	-23	96	96	192	192	576	576	576	1686	1686	2892	2892	5892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-2%	8%	8%	16%	16%	32%	32%	32%	56%	56%	48%	48%	49%
Bottom of DS DOCSIS Spectrum (MHz)	108	108	108	108	108	108	108	108	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	555	666	679	913	961	1612	1674	1776	2638	2711	4893	5010	9532
Tap BW (MHz)	1218	1218	1218	1218	1218	1794	1794	1794	3000	3000	6000	6000	12000

Figure 23 – Migration Path for Architecture 1a (Traditional-FDX- Asymmetric SLA)

Static SoftFDD Asymmetric Tmax (US = 50% of DS) with 1 Guardband	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	4	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+2	Node+1	Node+1	Node+1	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	480	240	240	240	240	120	120	120	120	120
Nsub in Service Group	200	200	200	120	60	30	30	30	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	105	209	209	209	209	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
US Tmax_max (Mbps)	500	1000	1000	2000	2000	5000	5000	5000	10000	10000	20000	20000	40000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	556	1079	1112	2095	2068	5048	5068	5096	10018	10026	20036	20051	40073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	10.07%	7.35%	10.10%	4.55%	3.27%	0.95%	1.34%	1.88%	0.18%	0.26%	0.18%	0.26%	0.18%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	79	149	153	284	281	678	681	684	1341	1342	2677	2679	5348
Top of US Band (MHz)	85	204	204	300	300	684	684	684	1794	1794	3000	3000	6000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	2889	3717	5991	5923	11724	12869	14775	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	30.77%	46.20%	33.23%	32.47%	14.71%	22.29%	32.32%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	1	1	1	1	1	1	1	1	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.6	9.6	7.1	7.1	7.1	9.6	9.6	9.6	9.6	9.4
US:DS Frequency Band Re-Use BW (MHz)… Positive = Re-Use & Negative = Guard-band	-15	-36	-36	-53	-53	-120	-120	-120	1686	1686	2892	2892	5892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-1%	-3%	-3%	-4%	-4%	-4%	-4%	-4%	56%	56%	48%	48%	49%
Bottom of DS DOCSIS Spectrum (MHz)	100	240	240	353	353	804	804	804	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	588	877	963	1313	1305	2791	2952	3221	2638	2711	4893	5010	9532
Tap BW (MHz)	1218	1218	1218	1218	1218	3000	3000	3000	3000	3000	6000	6000	12000

Figure 24 – Migration Path for Architecture 2a (Static Soft-FDX Baseline w/ 1.2 GHz Affinity- Asymmetric SLA)

Static SoftFDD Asymmetric Tmax (US = 50% of DS) with 1 Guardband	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	4	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+3	Node+3	Node+3	Node+2	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	800	800	800	480	240	120	120	120	120	120
Nsub in Service Group	200	200	200	200	200	100	60	30	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	63	63	63	105	209	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
US Tmax_max (Mbps)	500	1000	1000	2000	2000	5000	5000	5000	10000	10000	20000	20000	40000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	556	1079	1112	2159	2225	5159	5135	5096	10018	10026	20036	20051	40073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	10.07%	7.35%	10.10%	7.37%	10.12%	3.09%	2.64%	1.88%	0.18%	0.26%	0.18%	0.26%	0.18%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	79	149	153	293	302	693	690	684	1341	1342	2677	2679	5348
Top of US Band (MHz)	85	204	204	300	300	684	684	684	1794	1794	3000	3000	6000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	2889	3717	7318	10410	15747	15738	14775	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	30.77%	46.20%	45.34%	61.58%	36.50%	36.46%	32.32%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	1	1	1	1	1	1	1	1	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.3	9.3	7.1	3.2	3.2	9.6	9.6	9.6	9.6	9.4
US:DS Frequency Band Re-Use BW (MHz)… Positive = Re-Use & Negative = Guard-band	-15	-36	-36	-53	-53	-120	-120	-120	1686	1686	2892	2892	5892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-1%	-3%	-3%	-3%	-3%	-4%	-2%	-2%	56%	56%	48%	48%	49%
Bottom of DS DOCSIS Spectrum (MHz)	100	240	240	353	353	804	804	804	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	588	877	963	1475	1808	3358	6058	5757	2638	2711	4893	5010	9532
Tap BW (MHz)	1218	1218	1218	1794	1794	3000	6000	6000	3000	3000	6000	6000	12000

Figure 25 – Migration Path for Architecture 3a (Static Soft-FDX w/ Node+3 Affinity - Asymmetric SLA)

Static SoftFDD Asymmetric Tmax (US = 50% of DS) with 1 Guardband	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	4	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+3	Node+1	Node+1	Node+1	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	800	240	240	240	240	120	120	120	120	120
Nsub in Service Group	200	200	200	200	60	30	30	30	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	63	209	209	209	209	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
US Tmax_max (Mbps)	500	500	1000	1000	2000	2000	2000	5000	5000	5000	10000	10000	10000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	556	579	1112	1159	2068	2048	2068	5096	5018	5026	10036	10051	10073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	10.07%	13.69%	10.10%	13.72%	3.27%	2.34%	3.28%	1.88%	0.36%	0.51%	0.36%	0.51%	0.72%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	79	82	153	160	281	278	281	684	674	675	1343	1345	1348
Top of US Band (MHz)	85	85	204	204	300	300	300	684	684	684	1794	1794	1794
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 15% in 2020s, 15% in 2030s, 15% in 2040s	1000	1323	1749	2313	3059	4046	5350	7076	9358	12375	16367	21645	28625
"Rounded-off" DS Tmax_max (Mbps)	1000	1000	2000	2000	4000	4000	4000	10000	10000	10000	20000	20000	20000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	1889	3717	5318	5923	5724	6869	14775	11059	11763	22706	23832	25427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	47.06%	46.20%	62.39%	32.47%	30.12%	41.77%	32.32%	9.58%	14.99%	11.92%	16.08%	21.34%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	1	1	1	1	1	1	1	1	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.6	9.6	9.6	9.3	7.1	9.6	9.6	9.6	9.6	9.6
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	-15	-15	-36	-36	-53	-53	-53	-120	576	576	1686	1686	1686
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-1%	-1%	-3%	-3%	-4%	-4%	-3%	-4%	32%	32%	56%	56%	56%
Bottom of DS DOCSIS Spectrum (MHz)	100	100	240	240	353	353	353	804	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	588	633	963	1130	1305	1285	1427	3221	1596	1669	2809	2927	3093
Tap BW (MHz)	1218	1218	1218	1218	1218	1218	1794	3000	1794	1794	3000	3000	3000

Figure 26 – Migration Path for Architecture 4a (Static Soft-FDX w/ 15% DS Tmax CAGR-Asymmetric SLA)

Static SoftFDD Asymmetric Tmax (US = 40% of DS) with 1 Guardband	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	4	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+2	Node+1	Node+1	Node+1	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	480	240	240	240	240	120	120	120	120	120
Nsub in Service Group	200	200	200	120	60	30	30	30	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	105	209	209	209	209	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
US Tmax_max (Mbps)	400	800	800	1600	1600	4000	4000	4000	8000	8000	16000	16000	32000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	456	879	912	1695	1668	4048	4068	4096	8018	8026	16036	16051	32073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	12.28%	9.02%	12.31%	5.63%	4.05%	1.18%	1.67%	2.34%	0.23%	0.32%	0.23%	0.32%	0.23%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	66	122	127	231	227	545	547	551	1074	1075	2143	2145	4281
Top of US Band (MHz)	85	204	204	204	204	492	492	492	1794	1794	3000	3000	6000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	2889	3717	5991	5923	11724	12869	14775	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	30.77%	46.20%	33.23%	32.47%	14.71%	22.29%	32.32%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	1	1	1	1	1	1	1	1	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.6	9.6	7.1	7.1	7.1	9.6	9.6	9.6	9.6	9.4
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	-15	-36	-36	-36	-36	-86	-86	-86	1686	1686	2892	2892	5892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-1%	-3%	-3%	-3%	-3%	-3%	-3%	-3%	56%	56%	48%	48%	49%
Bottom of DS DOCSIS Spectrum (MHz)	100	240	240	240	240	578	578	578	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	588	877	963	1200	1193	2565	2727	2995	2638	2711	4893	5010	9532
Tap BW (MHz)	1218	1218	1218	1218	1218	3000	3000	3000	3000	3000	6000	6000	12000

Figure 27 – Migration Path for Architecture 5a (Static Soft-FDX w/ Reduced US Tmax-Asymmetric SLA)

Static SoftFDD Asymmetric Tmax (US = 50% of DS) with 1 Guardband & Sel Sub Mig	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	4	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+3	Node+1	Node+1	Node+1	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	800	240	240	240	240	120	120	120	120	120
Nsub in Service Group	200	200	200	200	60	30	30	30	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	63	209	209	209	209	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
US Tmax_max (Mbps)	500	500	500	1000	1000	2000	2000	5000	5000	5000	10000	10000	20000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	556	579	612	1159	1068	2048	2068	5096	5018	5026	10036	10051	20073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	10.07%	13.69%	18.34%	13.72%	6.33%	2.34%	3.28%	1.88%	0.36%	0.51%	0.36%	0.51%	0.36%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	79	82	87	160	147	278	281	684	674	675	1343	1345	2681
Top of US Band (MHz)	85	85	85	204	204	300	300	684	684	684	1794	1794	3000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	500	781	1221	1907	2980	4284	5666	7493	9909	13105	17332	22921	30313
"Rounded-off" DS Tmax_max (Mbps)	1000	1000	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	1889	2717	5318	3923	5724	6869	14775	11059	11763	22706	23832	45427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	47.06%	63.20%	62.39%	49.02%	30.12%	41.77%	32.32%	9.58%	14.99%	11.92%	16.08%	11.95%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	1	1	1	1	1	1	1	1	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.6	9.6	9.6	9.3	7.1	9.6	9.6	9.6	9.6	9.6
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	-15	-15	-15	-36	-36	-53	-53	-120	576	576	1686	1686	2892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-1%	-1%	-1%	-3%	-3%	-4%	-3%	-4%	32%	32%	56%	56%	48%
Bottom of DS DOCSIS Spectrum (MHz)	100	100	100	240	240	353	353	804	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	588	633	719	1130	984	1285	1427	3221	1596	1669	2809	2927	5176
Tap BW (MHz)	1218	1218	1218	1218	1218	1218	1794	3000	1794	1794	3000	3000	6000

Figure 28 – Migration Path for Architecture 6a (Static Soft-FDX w/ Selective Subscriber Migration- Asymmetric SLA)

Static SoftFDD Asymmetric Tmax (US = 50% of DS) with 0 Guardbands (EC)	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	4	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+3	Node+1	Node+1	Node+1	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	800	240	240	240	240	120	120	120	120	120
Nsub in Service Group	200	200	200	200	60	30	30	30	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	63	209	209	209	209	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
US Tmax_max (Mbps)	500	1000	1000	2000	2000	5000	5000	5000	10000	10000	20000	20000	40000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	556	1079	1112	2159	2068	5048	5068	5096	10018	10026	20036	20051	40073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	10.07%	7.35%	10.10%	7.37%	3.27%	0.95%	1.34%	1.88%	0.18%	0.26%	0.18%	0.26%	0.18%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	79	149	153	293	281	678	681	684	1341	1342	2677	2679	5348
Top of US Band (MHz)	85	204	204	300	300	684	684	684	1794	1794	3000	3000	6000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	2889	3717	7318	5923	11724	12869	14775	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	30.77%	46.20%	45.34%	32.47%	14.71%	22.29%	32.32%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	2	2	2	2	2	2	2	2	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.6	9.6	7.1	7.1	7.1	9.6	9.6	9.6	9.6	9.4
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	0	0	0	0	0	0	0	0	1686	1686	2892	2892	5892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	0%	0%	0%	0%	0%	0%	0%	0%	56%	56%	48%	48%	49%
Bottom of DS DOCSIS Spectrum (MHz)	85	204	204	300	300	684	684	684	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	573	841	927	1398	1253	2671	2833	3101	2638	2711	4893	5010	9532
Tap BW (MHz)	1218	1218	1218	1218	1218	3000	3000	3000	3000	3000	6000	6000	12000

Figure 29 – Migration Path for Architecture 7a (Static Soft-FDX w/ Guard-band Elimination- Asymmetric SLA)

Dynamic SoftFDD Asymmetric Tmax (US = 50% of DS) with 1 Guardband	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	4	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+3	Node+2	Node+2	Node+2	Node+2	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	800	480	480	480	480	120	120	120	120	120
Nsub in Service Group	200	200	200	200	120	60	60	60	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	63	105	105	105	105	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
US Tmax_max (Mbps)	500	1000	1000	2000	2000	5000	5000	5000	10000	10000	20000	20000	40000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	556	1079	1112	2159	2135	5096	5135	5192	10018	10026	20036	20051	40073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	10.07%	7.35%	10.10%	7.37%	6.33%	1.88%	2.64%	3.70%	0.18%	0.26%	0.18%	0.26%	0.18%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	79	149	153	293	290	684	690	697	1341	1342	2677	2679	5348
Top of US Band (MHz)	85	204	204	300	300	684	684	684	1794	1794	3000	3000	6000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	2889	3717	7318	7846	13448	15738	19549	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	30.77%	46.20%	45.34%	49.02%	25.64%	36.46%	48.85%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	3	3	3	3	3	3	3	3	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.6	9.6	9.3	7.1	7.1	9.6	9.6	9.6	9.6	9.6
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-b	-23	96	96	192	192	576	576	576	1686	1686	2892	2892	5892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-2%	8%	8%	16%	16%	32%	19%	19%	56%	56%	48%	48%	49%
Bottom of DS DOCSIS Spectrum (MHz)	108	108	108	108	108	108	108	108	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	596	781	867	1259	1314	2010	2780	3317	2952	3025	5418	5535	10393
Tap BW (MHz)	1218	1218	1218	1218	1218	1794	3000	3000	3000	3000	6000	6000	12000

Figure 30 – Migration Path for Architecture 8a (Dynamic Soft-FDX Baseline- Asymmetric SLA)

Static SoftFDD Asymmetric Tmax (US = 50% of DS) with 1 Guardband	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	4	4	4	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+2	Node+1	Node+1	Node+1	Node+1	Node+1	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	480	240	240	240	240	240	240	120	120	120
Nsub in Service Group	200	200	200	120	60	30	30	30	30	30	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	105	209	209	209	209	209	209	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
US Tmax_max (Mbps)	500	1000	1000	2000	2000	5000	5000	5000	10000	10000	20000	20000	40000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	556	1079	1112	2095	2068	5048	5068	5096	10136	10192	20036	20051	40073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	10.07%	7.35%	10.10%	4.55%	3.27%	0.95%	1.34%	1.88%	1.34%	1.89%	0.18%	0.26%	0.18%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	79	149	153	284	281	678	681	684	1356	1364	2677	2679	5348
Top of US Band (MHz)	85	204	204	300	300	684	684	684	1794	1794	3000	3000	6000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	2889	3717	5991	5923	11724	12869	14775	27945	33222	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	30.77%	46.20%	33.23%	32.47%	14.71%	22.29%	32.32%	28.43%	39.80%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	1	1	1	1	1	1	1	1	1	1	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.6	9.6	8.0	8.0	8.0	8.0	8.0	9.6	9.6	9.4
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	-15	-36	-36	-53	-53	-120	-120	-120	-314	-314	2892	2892	5892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-1%	-3%	-3%	-4%	-4%	-4%	-4%	-4%	-5%	-5%	48%	48%	49%
Bottom of DS DOCSIS Spectrum (MHz)	100	240	240	353	353	804	804	804	2108	2108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	588	877	963	1313	1305	2605	2748	2987	5937	6597	4893	5010	9532
Tap BW (MHz)	1218	1218	1218	1218	1218	3000	3000	3000	6000	6000	6000	6000	12000

Figure 31 – Migration Path for Architecture 9a (Static Soft-FDX w/ Active Taps- Asymmetric SLA)

FDX Symmetric Tmax (US = DS) with 0 Guardbands (EC)	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	4	24	24	24	24	24
Fiber Depth	Node+0	Node+0	Node+0	Node+0	Node+0	Node+0	Node+0	Node+0	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	120	120	120	120	120	120	120	120	120	120	120	120	120
Nsub in Service Group	30	30	30	30	30	15	15	15	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	417	417	417	417	417	417	417	417	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
US Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	1008	2012	2017	4024	4034	10024	10034	10048	20018	20026	40036	40051	80073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	0.83%	0.59%	0.84%	0.59%	0.84%	0.24%	0.34%	0.48%	0.09%	0.13%	0.09%	0.13%	0.09%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	6.9	6.9	6.9	7.5	7.5	7.5	7.5	6.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	139	273	274	542	543	1458	1459	1461	2674	2675	5343	5345	12324
Top of US Band (MHz)	204	300	300	492	492	1794	1794	1794	3000	3000	6000	6000	12000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1069	2133	2258	4498	4962	10862	11435	12387	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	6.45%	6.25%	11.41%	11.06%	19.38%	7.94%	12.55%	19.27%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	5	5	5	5	5	5	5	5	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.6	9.6	9.3	9.3	9.3	9.6	9.6	9.6	9.6	9.4
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	96	192	192	384	384	1686	1686	1686	2892	2892	5892	5892	11892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	8%	16%	16%	32%	32%	94%	94%	94%	96%	96%	98%	98%	99%
Bottom of DS DOCSIS Spectrum (MHz)	108	108	108	108	108	108	108	108	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	555	666	679	913	961	1612	1674	1776	2638	2711	4893	5010	9532
Tap BW (MHz)	1218	1218	1218	1218	1218	1794	1794	1794	3000	3000	6000	6000	12000

Figure 32 – Migration Path for Architecture 1b (Traditional-FDX- Symmetric SLA)

Static SoftFDD Symmetric Tmax (US = DS) with 1 Guardband	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	24	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+2	Node+2	Node+2	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	480	480	480	240	120	120	120	120	120	120
Nsub in Service Group	200	200	200	120	120	60	30	4	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	105	105	105	209	417	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
US Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	1056	2079	2112	4095	4135	10096	10068	10013	20018	20026	40036	40051	80073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	5.30%	3.81%	5.32%	2.33%	3.27%	0.95%	0.67%	0.13%	0.09%	0.13%	0.09%	0.13%	0.09%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	6.9	6.9	7.5	7.5	7.5	7.5	7.5	6.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	6
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	146	282	287	551	556	1468	1464	1340	2674	2675	5343	5345	12324
Top of US Band (MHz)	204	300	300	492	492	1794	1794	1794	3000	3000	6000	6000	12000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	2889	3717	5991	7846	13448	12869	10637	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	30.77%	46.20%	33.23%	49.02%	25.64%	22.29%	5.99%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	1	1	1	1	1	1	1	5	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.3	9.3	3.2	3.2	9.6	9.6	9.6	9.6	9.6	9.4
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	-36	-53	-53	-86	-86	-314	-314	1686	2892	2892	5892	5892	11892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-3%	-4%	-4%	-5%	-5%	-5%	-5%	94%	96%	96%	98%	98%	99%
Bottom of DS DOCSIS Spectrum (MHz)	240	353	353	578	578	2108	2108	108	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	728	989	1076	1558	1758	6647	6466	1552	2638	2711	4893	5010	9532
Tap BW (MHz)	1218	1218	1218	1794	1794	6000	6000	1794	3000	3000	6000	6000	12000

Figure 33 – Migration Path for Architecture 2b (Static Soft-FDX Baseline w/ 1.2 GHz Affinity- Symmetric SLA)

Static SoftFDD Asymmetric Tmax (US = DS) with 1 Guardband	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	24	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+3	Node+3	Node+2	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	800	800	480	240	120	120	120	120	120	120
Nsub in Service Group	200	200	200	200	200	60	30	4	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	63	63	105	209	417	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
US Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	1056	2079	2112	4159	4225	10096	10068	10013	20018	20026	40036	40051	80073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	5.30%	3.81%	5.32%	3.82%	5.33%	0.95%	0.67%	0.13%	0.09%	0.13%	0.09%	0.13%	0.09%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	6.9	6.9	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	146	282	287	560	568	1468	1464	1340	2674	2675	5343	5345	10681
Top of US Band (MHz)	204	300	300	492	684	1794	1794	1794	3000	3000	6000	6000	12000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	2889	3717	7318	10410	13448	12869	10637	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	30.77%	46.20%	45.34%	61.58%	25.64%	22.29%	5.99%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	1	1	1	1	1	1	1	5	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.3	7.1	3.2	3.2	9.6	9.6	9.6	9.6	9.6	9.4
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	-36	-53	-53	-86	-120	-314	-314	1686	2892	2892	5892	5892	11892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-3%	-4%	-4%	-5%	-4%	-5%	-5%	94%	96%	96%	98%	98%	99%
Bottom of DS DOCSIS Spectrum (MHz)	240	353	353	578	804	2108	2108	108	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	728	989	1076	1701	2606	6647	6466	1552	2638	2711	4893	5010	9532
Tap BW (MHz)	1218	1218	1218	1794	3000	6000	6000	1794	3000	3000	6000	6000	12000

Figure 34 – Migration Path for Architecture 3b (Static Soft-FDX w/ Node+3 Affinity - Symmetric SLA)

Static SoftFDD Symmetric Tmax (US = DS) with 1 Guardband	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	24	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+3	Node+1	Node+1	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	800	240	240	240	120	120	120	120	120	120
Nsub in Service Group	200	200	200	200	60	30	30	4	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	63	209	209	209	417	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
US Tmax_max (Mbps)	1000	1000	2000	2000	4000	4000	4000	10000	10000	10000	20000	20000	20000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	1056	1079	2112	2159	4068	4048	4068	10013	10018	10026	20036	20051	20073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	5.30%	7.35%	5.32%	7.37%	1.66%	1.18%	1.67%	0.13%	0.18%	0.26%	0.18%	0.26%	0.36%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	146	149	287	293	547	545	547	1340	1341	1342	2677	2679	2681
Top of US Band (MHz)	204	204	300	300	492	492	492	1794	1794	1794	3000	3000	3000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 15% in 2020s, 15% in 2030s, 15% in 2040s	1000	1323	1749	2313	3059	4046	5350	7076	9358	12375	16367	21645	28625
"Rounded-off" DS Tmax_max (Mbps)	1000	1000	2000	2000	4000	4000	4000	10000	10000	10000	20000	20000	20000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	1889	3717	5318	5923	5724	6869	10637	11059	11763	22706	23832	25427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	47.06%	46.20%	62.39%	32.47%	30.12%	41.77%	5.99%	9.58%	14.99%	11.92%	16.08%	21.34%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	1	1	1	1	1	1	1	5	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.6	9.6	9.6	9.3	9.6	9.6	9.6	9.6	9.6	9.6
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	-36	-36	-53	-53	-86	-86	-86	1686	1686	1686	2892	2892	2892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-3%	-3%	-4%	-4%	-5%	-5%	-5%	94%	94%	94%	96%	96%	96%
Bottom of DS DOCSIS Spectrum (MHz)	240	240	353	353	578	578	578	108	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	728	772	1076	1242	1531	1510	1653	1552	1596	1669	2809	2927	3093
Tap BW (MHz)	1218	1218	1218	1218	1794	1794	1794	1794	1794	1794	3000	3000	3000

Figure 35 – Migration Path for Architecture 4b (Static Soft-FDX w/ 15% DS Tmax CAGR-Symmetric SLA)

Static SoftFDD ~Symmetric Tmax (US = 90% of DS) with 1 Guardband	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	24	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+2	Node+1	Node+1	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	480	240	240	240	120	120	120	120	120	120
Nsub in Service Group	200	200	200	120	60	30	30	4	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	105	209	209	209	417	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
US Tmax_max (Mbps)	900	1800	1800	3600	3600	9000	9000	9000	18000	18000	36000	36000	72000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	956	1879	1912	3695	3668	9048	9068	9013	18018	18026	36036	36051	72073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	5.86%	4.22%	5.87%	2.58%	1.84%	0.53%	0.75%	0.14%	0.10%	0.14%	0.10%	0.14%	0.10%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	6.9	6.9	7.5	7.5	7.5	7.5	7.5	6.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	132	256	260	498	494	1316	1319	1207	2407	2408	4810	4812	11093
Top of US Band (MHz)	204	300	300	492	492	1794	1794	1794	3000	3000	6000	6000	12000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	2889	3717	5991	5923	11724	12869	10637	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	30.77%	46.20%	33.23%	32.47%	14.71%	22.29%	5.99%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	1	1	1	1	1	1	1	5	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.3	9.3	3.2	3.2	9.6	9.6	9.6	9.6	9.6	9.4
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	-36	-53	-53	-86	-86	-314	-314	1686	2892	2892	5892	5892	11892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-3%	-4%	-4%	-5%	-5%	-5%	-5%	94%	96%	96%	98%	98%	99%
Bottom of DS DOCSIS Spectrum (MHz)	240	353	353	578	578	2108	2108	108	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	728	989	1076	1558	1551	6108	6466	1552	2638	2711	4893	5010	9532
Tap BW (MHz)	1218	1218	1218	1794	1794	6000	6000	1794	3000	3000	6000	6000	12000

Figure 36 – Migration Path for Architecture 5b (Static Soft-FDX w/ Reduced US Tmax-Symmetric SLA)

Static SoftFDD Symmetric Tmax (US = DS) with 1 Guardband & Sel Sub Mig	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	24	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+3	Node+1	Node+1	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	800	240	240	240	120	120	120	120	120	120
Nsub in Service Group	200	200	200	200	60	30	30	4	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	63	209	209	209	417	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
US Tmax_max (Mbps)	1000	1000	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	1056	1079	1112	2159	2068	4048	4068	10013	10018	10026	20036	20051	40073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	5.30%	7.35%	10.10%	7.37%	3.27%	1.18%	1.67%	0.13%	0.18%	0.26%	0.18%	0.26%	0.18%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	146	149	153	293	281	545	547	1340	1341	1342	2677	2679	5348
Top of US Band (MHz)	204	204	204	300	300	492	492	1794	1794	1794	3000	3000	6000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	500	781	1221	1907	2980	4284	5666	7493	9909	13105	17332	22921	30313
"Rounded-off" DS Tmax_max (Mbps)	1000	1000	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	1889	2717	5318	3923	5724	6869	10637	11059	11763	22706	23832	45427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	47.06%	63.20%	62.39%	49.02%	30.12%	41.77%	5.99%	9.58%	14.99%	11.92%	16.08%	11.95%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	1	1	1	1	1	1	1	5	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.6	9.6	9.3	9.3	9.6	9.6	9.6	9.6	9.6	9.6
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	-36	-36	-36	-53	-53	-86	-86	1686	1686	1686	2892	2892	5892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	-3%	-3%	-3%	-4%	-4%	-5%	-5%	94%	94%	94%	96%	96%	98%
Bottom of DS DOCSIS Spectrum (MHz)	240	240	240	353	353	578	578	108	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	728	772	859	1242	1097	1530	1653	1552	1596	1669	2809	2927	5176
Tap BW (MHz)	1218	1218	1218	1218	1218	1794	1794	1794	1794	1794	3000	3000	6000

Figure 37 – Migration Path for Architecture 6b (Static Soft-FDX w/ Selective Subscriber Migration- Symmetric SLA)

Static SoftFDD Symmetric Tmax (US = DS) with 0 Guardbands (EC)	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	4	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+1	Node+1	Node+1	Node+1	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	240	240	240	240	240	120	120	120	120	120
Nsub in Service Group	200	200	200	60	60	30	30	30	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	209	209	209	209	209	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
US Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	1056	2079	2112	4048	4068	10048	10068	10096	20018	20026	40036	40051	80073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	5.30%	3.81%	5.32%	1.18%	1.66%	0.48%	0.67%	0.95%	0.09%	0.13%	0.09%	0.13%	0.09%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	146	282	287	545	547	1345	1347	1351	2674	2675	5343	5345	10681
Top of US Band (MHz)	204	300	300	492	492	1794	1794	1794	3000	3000	6000	6000	12000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	2889	3717	4995	5923	11724	12869	14775	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	30.77%	46.20%	19.93%	32.47%	14.71%	22.29%	32.32%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	2	2	2	2	2	2	2	2	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.3	9.6	7.1	7.1	7.1	9.6	9.6	9.6	9.6	9.4
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	0	0	0	0	0	0	0	0	2892	2892	5892	5892	11892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	0%	0%	0%	0%	0%	0%	0%	0%	96%	96%	98%	98%	99%
Bottom of DS DOCSIS Spectrum (MHz)	204	300	300	492	492	1794	1794	1794	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	692	937	1023	1365	1445	3781	3943	4211	2638	2711	4893	5010	9532
Tap BW (MHz)	1218	1218	1218	1218	1794	6000	6000	6000	3000	3000	6000	6000	12000

Figure 38 – Migration Path for Architecture 7b (Static Soft-FDX w/ Guard-band Elimination- Symmetric SLA)

Dynamic SoftFDD Symmetric Tmax (US = DS) with 1 Guardband	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	24	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+3	Node+2	Node+2	Node+2	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	800	480	480	480	120	120	120	120	120	120
Nsub in Service Group	200	200	200	200	120	60	60	4	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	63	105	105	105	417	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
US Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	1056	2079	2112	4159	4135	10096	10135	10013	20018	20026	40036	40051	80073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	5.30%	3.81%	5.32%	3.82%	3.27%	0.95%	1.34%	0.13%	0.09%	0.13%	0.09%	0.13%	0.09%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	6.9	6.9	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	146	282	287	560	556	1468	1474	1340	2674	2675	5343	5345	10681
Top of US Band (MHz)	204	300	300	492	492	1794	1794	1794	3000	3000	6000	6000	12000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	2889	3717	7318	7846	13448	15738	10637	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	30.77%	46.20%	45.34%	49.02%	25.64%	36.46%	5.99%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	3	3	3	3	3	3	3	5	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.6	9.6	7.1	7.1	9.6	9.6	9.6	9.6	9.6	9.6
US:DS Frequency Band Re-Use BW (MHz)... Positive = Re-Use & Negative = Guard-band	96	192	192	384	384	1686	1686	1686	2892	2892	5892	5892	11892
Re-Use Ratio (Re-Use BW/Top of Spectrum)	8%	16%	16%	32%	32%	56%	56%	94%	96%	96%	98%	98%	99%
Bottom of DS DOCSIS Spectrum (MHz)	108	108	108	108	108	108	108	108	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	632	797	884	1292	1347	2652	2975	1866	3163	3236	5943	6060	11443
Tap BW (MHz)	1218	1218	1218	1218	1218	3000	3000	1794	3000	3000	6000	6000	12000

Figure 39 – Migration Path for Architecture 8b (Dynamic Soft-FDX Baseline- Symmetric SLA)

Static SoftFDD Symmetric Tmax (US = DS) with 1 Guardband	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044
Node Type (# SGs/Node)	2	2	2	2	2	4	4	4	24	24	24	24	24
Fiber Depth	Node+3	Node+3	Node+3	Node+2	Node+1	Node+1	Node+1	Node+1	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap	Fiber2Tap
# Homes Passed in Node	800	800	800	480	240	240	240	240	120	120	120	120	120
Nsub in Service Group	200	200	200	120	60	30	30	30	4	4	4	4	4
# Nodes to Support a 50,000 HHP Market	63	63	63	105	209	209	209	209	417	417	417	417	417
US Tavg (Mbps) w/ 19% CAGR	0.3	0.4	0.6	0.8	1.1	1.6	2.3	3.2	4.5	6.4	9.1	12.9	18.2
US_Tmax_max:DS_Tmax_max Ratio	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
US Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd US HSD BW Capacity w/ K=1.0 (Mbps)	1056	2079	2112	4095	4068	10048	10068	10096	20018	20026	40036	40051	80073
US HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	5.30%	3.81%	5.32%	2.33%	1.66%	0.48%	0.67%	0.95%	0.09%	0.13%	0.09%	0.13%	0.09%
US Spectral Efficiency (bps/Hz)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Bottom of US DOCSIS Spectrum (MHz)	5	5	5	5	5	5	5	5	5	5	5	5	5
Top of US DOCSIS Spectrum w/ 7.5 bps/Hz (MHz)	146	282	287	551	547	1345	1347	1351	2674	2675	5343	5345	10681
Top of US Band (MHz)	204	300	300	492	492	1794	1794	1794	3000	3000	6000	6000	12000
DS Tavg (Mbps) w/ CAGR of 39% in 2020s, 29% in 2030s, 19% in 2040s	2.3	4.4	8.6	16.6	32.1	57.5	95.6	159.2	264.8	440.7	676.6	958.1	1356.7
Natural DS Tmax_max (Mbps) w/ CAGR 25% in 2020s, 15% in 2030s, 15% in 2040s	1000	1563	2441	3815	5960	8568	11331	14986	19819	26210	34663	45842	60626
"Rounded-off" DS Tmax_max (Mbps)	1000	2000	2000	4000	4000	10000	10000	10000	20000	20000	40000	40000	80000
Req'd DS HSD BW Capacity w/ K=1.0 (Mbps)	1460	2889	3717	5991	5923	11724	12869	14775	21059	21763	42706	43832	85427
DS HSD Utilization (Nsub*Tavg)/(Nsub*Tavg+1.0*Tmax)	31.51%	30.77%	46.20%	33.23%	32.47%	14.71%	22.29%	32.32%	5.03%	8.10%	6.34%	8.74%	6.35%
1=Stat_FDD_GB 2=Stat_FDD_EC 3=Dyn_FDD_GB 4=Dyn_FDD_EC 5=FDX?	1	1	1	1	1	1	1	1	5	5	5	5	5
DS Spectral Efficiency (bps/Hz)	9.6	9.6	9.6	9.3	9.3	8.0	8.0	8.0	9.6	9.6	9.6	9.6	9.4
US:DS Frequency Band Re-Use (MHz)... Positive = Re-Use & Negative = Guard-band	-36	-53	-53	-86	-86	-314	-314	-314	2892	2892	5892	5892	11892
Re-Use Ratio (Re-Use/Top of Spectrum)	-3%	-4%	-4%	-5%	-5%	-5%	-5%	-5%	96%	96%	98%	98%	99%
Bottom of DS DOCSIS Spectrum (MHz)	240	353	353	578	578	2108	2108	2108	108	108	108	108	108
Top of DS DOCSIS Spectrum w/ 9.0 bps/Hz + 56 Annex B Video QAMs (MHz)	728	989	1076	1558	1551	3909	4053	4291	2638	2711	4893	5010	9532
Tap BW (MHz)	1218	1218	1218	1794	1794	6000	6000	6000	3000	3000	6000	6000	12000

Figure 40 – Migration Path for Architecture 9b (Static Soft-FDX w/ Active Taps-Symmetric SLA)

Conclusions

After constructing the eighteen Migration Paths within the previous section and after studying the general trends, several observations and conclusions could be developed.

With such a large amount of data available to the authors in the various Migration Paths above, some analytics tools that filtered out un-interesting years were developed to help pull insights from the data. Some of the outputs from those tools are illustrated in Figures 40-57 (Asymmetric SLAs in Figures 40-48, and Symmetric SLAs in Figures 49-57). Only the important years with "Big Changes" are high-lighted for each of the eighteen Architectures.

1a) FDX Asymmetric Tmax (US = 50% of DS) with 0 Guardbands (EC)	2020	2022	2025	2029	2035	2039	2044
US:DS Transmission Technology	FDX						
Life-span of US:DS Transmission Technology	25						
Fiber Depth	Node+0				Fiber2Tap		
Life-span of Fiber Depth (Years)	15				10		
US BW Transitions (MHz)	85	204	300	684	1794	3000	6000
DS BW Transitions (MHz)	1218			1794	3000	6000	12000
Snapped DS Housing Transitions (MHz)	1218			6000			12000
Life-span of Housing (Years)	9			15			1

Figure 41 – "Big Changes" for Architecture 1a (Traditional-FDX- Asymmetric SLA)

2a) Static SoftFDD Asymmetric Tmax (US = 50% of DS) with 1 Guardband	2020	2022	2025	2026	2028	2029	2035	2039	2044
US:DS Transmission Technology	St FDD_GB						FDX		
Life-span of US:DS Transmission Technology	15						10		
Fiber Depth	Node+3			Node+2	Node+1		Fiber2Tap		
Life-span of Fiber Depth (Years)	6			2	7		10		
US BW Transitions (MHz)	85	204	300			684	1794	3000	6000
DS BW Transitions (MHz)	1218					3000		6000	12000
Snapped DS Housing Transitions (MHz)	1218					6000			12000
Life-span of Housing (Years)	9					15			1

Figure 42 – "Big Changes" for Architecture 2a (Static Soft-FDX Baseline w/ 1.2 GHz Affinity- Asymmetric SLA)

3a) Static SoftFDD Asymmetric Tmax (US = 50% of DS) with 1 Guardband	2020	2022	2025	2026	2029	2031	2032	2034	2035	2039	2044
US:DS Transmission Technology	St FDD_GB								FDX		
Life-span of US:DS Transmission Technology	15								10		
Fiber Depth	Node+3						Node+2	Node+1	Fiber2Tap		
Life-span of Fiber Depth (Years)	12						2	1	10		
US BW Transitions (MHz)	85	204	300		684				1794	3000	6000
DS BW Transitions (MHz)	1218			1794	3000	6000			3000	6000	12000
Snapped DS Housing Transitions (MHz)	1218			6000							12000
Life-span of Housing (Years)	6			18							1

Figure 43 – "Big Changes" for Architecture 3a (Static Soft-FDX w/ Node+3 Affinity - Asymmetric SLA)

4a) Static SoftFDD Asymmetric Tmax (US = 50% of DS) with 1 Guardband	2020	2023	2028	2032	2033	2036	2040
US:DS Transmission Technology	St FDD_GB					FDX	
Life-span of US:DS Transmission Technology	16					9	
Fiber Depth	Node+3		Node+1			Fiber2Tap	
Life-span of Fiber Depth (Years)	8		8			9	
US BW Transitions (MHz)	85	204	300		684		1794
DS BW Transitions (MHz)	1218			1794	3000	1794	3000
Snapped DS Housing Transitions (MHz)	1218			3000			
Life-span of Housing (Years)	12			13			

Figure 44 – "Big Changes" for Architecture 4a (Static Soft-FDX w/ 15% DS Tmax CAGR- Asymmetric SLA)

5a) Static SoftFDD Asymmetric Tmax (US = 40% of DS) with 1 Guardband	2020	2022	2025	2026	2028	2029	2035	2039	2044
US:DS Transmission Technology	St FDD_GB						FDX		
Life-span of US:DS Transmission Technology	15						10		
Fiber Depth	Node+3			Node+2	Node+1		Fiber2Tap		
Life-span of Fiber Depth (Years)	6			2	7		10		
US BW Transitions (MHz)	85	204	300	204		492	1794	3000	6000
DS BW Transitions (MHz)	1218					3000		6000	12000
Snapped DS Housing Transitions (MHz)	1218					6000			12000
Life-span of Housing (Years)	9					15			1

Figure 45 – "Big Changes" for Architecture 5a (Static Soft-FDX w/ Reduced US Tmax- Asymmetric SLA)

6a) Static SoftFDD Asymmetric Tmax (US = 50% of DS) with 1 Guardband & Sel Sub Mig	2020	2025	2028	2029	2032	2033	2036	2039	2044
US:DS Transmission Technology	St FDD_GB						FDX		
Life-span of US:DS Transmission Technology	16						9		
Fiber Depth	Node+3		Node+1				Fiber2Tap		
Life-span of Fiber Depth (Years)	8		8				9		
US BW Transitions (MHz)	85	204		300		684		1794	3000
DS BW Transitions (MHz)	1218				1794	3000	1794	3000	6000
Snapped DS Housing Transitions (MHz)	1218				3000				6000
Life-span of Housing (Years)	12				12				1

Figure 46 – "Big Changes" for Architecture 6a (Static Soft-FDX w/ Selective Subscriber Migration- Asymmetric SLA)

7a) Static SoftFDD Asymmetric Tmax (US = 50% of DS) with 0 Guardbands (EC)	2020	2022	2025	2027	2029	2035	2039	2044
US:DS Transmission Technology	St FDD_EC					FDX		
Life-span of US:DS Transmission Technology	15					10		
Fiber Depth	Node+3			Node+1		Fiber2Tap		
Life-span of Fiber Depth (Years)	7			8		10		
US BW Transitions (MHz)	85	204	300		684	1794	3000	6000
DS BW Transitions (MHz)	1218				3000		6000	12000
Snapped DS Housing Transitions (MHz)	1218				6000			12000
Life-span of Housing (Years)	9				15			1

Figure 47 – "Big Changes" for Architecture 7a (Static Soft-FDX w/ Guard-band Elimination- Asymmetric SLA)

8a) Dynamic SoftFDD Asymmetric Tmax (US = 50% of DS) with 1 Guardband	2020	2022	2025	2028	2029	2031	2035	2039	2044
US:DS Transmission Technology	Dyn FDD_GB						FDX		
Life-span of US:DS Transmission Technology	15						10		
Fiber Depth	Node+3			Node+2			Fiber2Tap		
Life-span of Fiber Depth (Years)	8			7			10		
US BW Transitions (MHz)	85	204	300		684		1794	3000	6000
DS BW Transitions (MHz)	1218				1794	3000		6000	12000
Snapped DS Housing Transitions (MHz)	1218				6000				12000
Life-span of Housing (Years)	9				15				1

Figure 48 – "Big Changes" for Architecture 8a (Dynamic Soft-FDX Baseline- Asymmetric SLA)

9a) Static SoftFDD Asymmetric Tmax (US = 50% of DS) with 1 Guardband & Active Taps	2020	2022	2025	2028	2029	2035	2039	2044
US:DS Transmission Technology	St FDD_GB						FDX	
Life-span of US:DS Transmission Technology	19						6	
Fiber Depth	Node+3		Node+2	Node+1			Fiber2Tap	
Life-span of Fiber Depth (Years)	5		3	11			6	
US BW Transitions (MHz)	85	204	300		684	1794	3000	6000
DS BW Transitions (MHz)	1218				3000	6000		12000
Snapped DS Housing Transitions (MHz)	1218				6000			12000
Life-span of Housing (Years)	9				15			1

Figure 49 – "Big Changes" for Architecture 9a (Static Soft-FDX w/ Active Taps- Asymmetric SLA)

1b) FDX Symmetric Tmax (US = DS) with 0 Guardbands (EC)	2020	2022	2025	2029	2035	2039	2044
US:DS Transmission Technology	FDX						
Life-span of US:DS Transmission Technology	25						
Fiber Depth	Node+0				Fiber2Tap		
Life-span of Fiber Depth (Years)	15				10		
US BW Transitions (MHz)	204	300	492	1794	3000	6000	12000
DS BW Transitions (MHz)	1218			1794	3000	6000	12000
Snapped DS Housing Transitions (MHz)	1218			6000			12000
Life-span of Housing (Years)	9			15			1

Figure 50 – "Big Changes" for Architecture 1b (Traditional FDX- Symmetric SLA)

2b) Static SoftFDD Symmetric Tmax (US = DS) with 1 Guardband	2020	2022	2025	2029	2031	2034	2035	2039	2044
US:DS Transmission Technology	St FDD_GB					FDX			
Life-span of US:DS Transmission Technology	14					11			
Fiber Depth	Node+3		Node+2		Node+1	Fiber2Tap			
Life-span of Fiber Depth (Years)	5		6		3	11			
US BW Transitions (MHz)	204	300	492	1794			3000	6000	12000
DS BW Transitions (MHz)	1218		1794	6000		1794	3000	6000	12000
Snapped DS Housing Transitions (MHz)	1218		6000						12000
Life-span of Housing (Years)	5		19						1

Figure 51 – "Big Changes" for Architecture 2b (Static Soft-FDX Baseline w/ 1.2 GHz Affinity- Symmetric SLA)

3b) Static SoftFDD Asymmetric Tmax (US = DS) with 1 Guardband	2020	2022	2025	2028	2029	2031	2034	2035	2039	2044
US:DS Transmission Technology	St FDD_GB						FDX			
Life-span of US:DS Transmission Technology	14						11			
Fiber Depth	Node+3				Node+2	Node+1	Fiber2Tap			
Life-span of Fiber Depth (Years)	9				2	3	11			
US BW Transitions (MHz)	204	300	492	684	1794			3000	6000	12000
DS BW Transitions (MHz)	1218		1794	3000	6000		1794	3000	6000	12000
Snapped DS Housing Transitions (MHz)	1218		6000							12000
Life-span of Housing (Years)	5		19							1

Figure 52 – "Big Changes" for Architecture 3b (Static Soft-FDX w/ Node+3 Affinity - Symmetric SLA)

4b) Static SoftFDD Symmetric Tmax (US = DS) with 1 Guardband	2020	2023	2028	2033	2040
US:DS Transmission Technology	St FDD_GB			FDX	
Life-span of US:DS Transmission Technology	13			12	
Fiber Depth	Node+3		Node+1	Fiber2Tap	
Life-span of Fiber Depth (Years)	8		5	12	
US BW Transitions (MHz)	204	300	492	1794	3000
DS BW Transitions (MHz)	1218		1794		3000
Snapped DS Housing Transitions (MHz)	1218		3000		
Life-span of Housing (Years)	8		17		

Figure 53 – "Big Changes" for Architecture 4b (Static Soft-FDX w/ 15% DS Tmax CAGR- Symmetric SLA)

5b) Static SoftFDD ~Symmetric Tmax (US = 90% of DS) with 1 Guardband	2020	2022	2025	2028	2029	2034	2035	2039	2044
US:DS Transmission Technology	St FDD_GB					FDX			
Life-span of US:DS Transmission Technology	14					11			
Fiber Depth	Node+3		Node+2	Node+1		Fiber2Tap			
Life-span of Fiber Depth (Years)	5		3	6		11			
US BW Transitions (MHz)	204	300	492		1794		3000	6000	12000
DS BW Transitions (MHz)	1218		1794		6000	1794	3000	6000	12000
Snapped DS Housing Transitions (MHz)	1218		6000						12000
Life-span of Housing (Years)	5		19						1

Figure 54 – "Big Changes" for Architecture 5b (Static Soft-FDX w/ Reduced US Tmax-Symmetric SLA)

6b) Static SoftFDD Symmetric Tmax (US = DS) with 1 Guardband & Sel Sub Mig	2020	2025	2028	2029	2033	2039	2044
US:DS Transmission Technology	St FDD_GB				FDX		
Life-span of US:DS Transmission Technology	13				12		
Fiber Depth	Node+3		Node+1		Fiber2Tap		
Life-span of Fiber Depth (Years)	8		5		12		
US BW Transitions (MHz)	204	300		492	1794	3000	6000
DS BW Transitions (MHz)	1218			1794		3000	6000
Snapped DS Housing Transitions (MHz)	1218			3000			6000
Life-span of Housing (Years)	9			15			1

Figure 55 – "Big Changes" for Architecture 6b (Static Soft-FDX w/ Selective Subscriber Migration- Symmetric SLA)

7b) Static SoftFDD Symmetric Tmax (US = DS) with 0 Guardbands (EC)	2020	2022	2025	2028	2029	2035	2039	2044
US:DS Transmission Technology	St FDD_EC					FDX		
Life-span of US:DS Transmission Technology	15					10		
Fiber Depth	Node+3		Node+1			Fiber2Tap		
Life-span of Fiber Depth (Years)	5		10			10		
US BW Transitions (MHz)	204	300	492		1794	3000	6000	12000
DS BW Transitions (MHz)	1218			1794	6000	3000	6000	12000
Snapped DS Housing Transitions (MHz)	1218			6000				12000
Life-span of Housing (Years)	8			16				1

Figure 56 – "Big Changes" for Architecture 7b (Static Soft-FDX w/ Guard-band Elimination- Symmetric SLA)

8b) Dynamic SoftFDD Symmetric Tmax (US = DS) with 1 Guardband	2020	2022	2025	2027	2029	2034	2035	2039	2044
US:DS Transmission Technology	Dyn FDD_GB					FDX			
Life-span of US:DS Transmission Technology	14					11			
Fiber Depth	Node+3			Node+2		Fiber2Tap			
Life-span of Fiber Depth (Years)	7			7		11			
US BW Transitions (MHz)	204	300	492		1794		3000	6000	12000
DS BW Transitions (MHz)	1218				3000	1794	3000	6000	12000
Snapped DS Housing Transitions (MHz)	1218				6000				12000
Life-span of Housing (Years)	9				15				1

Figure 57 – "Big Changes" for Architecture 8b (Dynamic Soft-FDX Baseline- Symmetric SLA)

9b) Static SoftFDD Symmetric Tmax (US = DS) with 1 Guardband & Active Taps	2020	2022	2025	2028	2029	2035	2039	2044
US:DS Transmission Technology	St FDD_GB					FDX		
Life-span of US:DS Transmission Technology	15					10		
Fiber Depth	Node+3		Node+2	Node+1		Fiber2Tap		
Life-span of Fiber Depth (Years)	5		3	7		10		
US BW Transitions (MHz)	204	300	492		1794	3000	6000	12000
DS BW Transitions (MHz)	1218		1794		6000	3000	6000	12000
Snapped DS Housing Transitions (MHz)	1218		6000					12000
Life-span of Housing (Years)	5		19					1

Figure 58 – “Big Changes” for Architecture 9b (Static Soft-FDX w/ Active Taps-Symmetric SLA)

Several key observations can be deduced from the results and are outlined below. These observations assume that the listed assumptions for each Architecture remain valid until the future 2044 time-frame and that the required technologies can be developed within the required time-frames.

- Node+Non-Zero and Node+0 Life-spans:
    - FDX solutions can support the MSO Bandwidth Capacity requirements using traditional Node+0 HFC networks until the ~2035 time-frame (requiring FTTT or FTTH solutions after that time-frame)
    - Static Soft-FDX solutions can support the MSO Bandwidth Capacity requirements using traditional Node+Non-Zero HFC networks until the ~2034-2035 time-frame (requiring FTTT or FTTH solutions after that time-frame)
    - Dynamic Soft-FDX solutions can support the MSO Bandwidth Capacity requirements using traditional Node+Non-Zero HFC networks until the ~2034-2035 time-frame (requiring FTTT or FTTH solutions after that time-frame)
    - FTTT or FTTH solutions are probably not required until the mid-2030 time-frame; greater Tmax CAGRs will cause the transition to FTTT or FTTH to occur sooner; smaller Tmax CAGRs will cause the transition to FTTT or FTTH to occur later; some MSOs may opt to move to FTTH sooner than required
    - Active Taps can extend the life-span of the Node+X HFC solutions and delay the deployment of FTTT/FTTH solutions by 1-4 years (depending on traffic statistics)

- Frequency Requirements:
    - Frequency Band changes are closely correlated to Tmax changes
    - For all Architectures (excluding the 15% Tmax CAGR & Selective Subscriber Migration solutions), Ultra-Split US frequencies (300+ MHz) will be required by 2025
    - For all Architectures (excluding the 15% Tmax CAGR & Selective Subscriber Migration solutions), Extended Spectrum DOCSIS frequencies (1794, 3000, 6000, and 12000 MHz) will be required at various times for both the US & DS
    - For Traditional-FDX Architectures, Asymmetric SLAs permit 1218 MHz DS operation until 2029, and Symmetric SLAs also permit 1218 MHz DS operation until 2029 (the benefit of overlapped DS & US spectra)
    - For Static Soft-FDX Baseline Architectures, Asymmetric SLAs permit 1218 MHz DS operation until 2029, but Symmetric SLAs end the life-span of 1218 MHz DS operation by as early 2025
    - For Dynamic Soft-FDX Architectures, Asymmetric SLAs permit 1218 MHz DS operation until 2029, and Symmetric SLAs also permit 1218 MHz DS operation until 2029 (the benefit of overlapped DS & US spectra)

  - A 15% Tmax CAGR in the 2020's (instead of a 25% Tmax CAGR) permits 1218 MHz DS operation to work for ~3 extra years (2032 for Asymmetric SLAs and 2028 for Symmetric SLAs)
  - Selective Subscriber Migration (eliminating the highest Tmax values) permits 1218 MHz DS operation to work for ~3-4 extra years (2032 for Asymmetric SLAs and 2029 for Symmetric SLAs)
  - Guard-band Elimination can extend the life-span of 1218 MHz DS operation by 0-3 years (depending on traffic statistics)
  - Staying in a Node+3 Architecture (and avoiding transitions to Node+2 or Node+1 or Node+0) forces the HFC network to transition to Ultra-Split US Extended Spectrum DOCSIS DS frequencies much more rapidly

- Other Interesting Findings:
  - Dynamic Soft-FDX keeps the total Node counts lower for the longest period of time (due to later required Node-splits)
  - Static Soft-FDX keeps the total Node counts lower for a medium period of time
  - Traditional-FDX keeps the total Node counts lower for the shortest period of time (due to earlier required Node-splits)
  - For Static Soft-FDX, the percentage of total DS spectrum that is unuseable Guard-band spectrum is quite small (<= 5% of the total) due to the fact that large Guard-bands are only needed when Extended Spectrum DOCSIS DSs are used
  - DS HSD Utilization levels are always less than or equal to 65%
  - US HSD Utilization levels are always less than 18%

Future work will continue to analyze the various network Architectures described above (plus other new ideas). However, these initial results and observations indicate that MSOs should be able to find one or more solutions that permit them to operate on Node+Non-Zero HFC networks or Node+0 HFC networks deep into the future. If the assumptions above are valid, then transitions to FTTT or FTTH architectures could be delayed until the mid-2030's if the Cable Industry decides to embrace Ulta-Split US and Extended Spectrum DOCSIS US and Extended Spectrum DOCSIS DS frequency ranges (and if their associated technologies can be developed).

For most MSOs, an important decision will likely need to be made between following a Node+0 Migration Path or following a Node+Non-Zero Migration Path. Both are fine paths, but the resulting investments and required technologies and upgrade steps on the two paths are quite different. The two paths do share some key technologies along the way; for example, both paths can make use of FDX-capable CMs, using them in slightly different operating modes. And both paths can make use of Extended Spectrum DOCSIS capabilities to support the extremely high Tmax values of the future. But the Node+0 Migration Path is focused on the use of Traditional-FDX, whereas the Node+Non-Zero Migration Path is focused on the use of either Static Soft-FDX or Dynamic Soft-FDX. The underlying goal behind the Node+Non-Zero approach is to delay the need to move to Node+0 and delay the associated costs.

As described above, Dynamic Soft-FDX is an interesting blend between the simplicity of Static Soft-FDX and the bandwidth savings (due to overlapped US & DS spectral) of Traditional-FDX; it is a simplified form of FDX that has the same benefits of re-using over-lapping frequency ranges for both Upstream and Downstream transmissions, but it does not require Echo Cancellation (which permits it to work in a Node+Non-Zero environment with Amplifiers). Thus, both Traditional-FDX and Dynamic Soft-FDX offer similarly efficiencies, but Traditional-FDX may require a Node+0 environment whereas Dynamic Soft-FDX may permit operation within a Node+Non-Zero environment.

It should be clearly stated and understood that many of the advanced technologies described in this forward-looking paper do not yet exist, and their ultimate performance levels are still conjecture. This includes Traditional-FDX, Static Soft-FDX, Dynamic Soft-FDX, Ultra-Split Upstreams, Extended Spectrum DOCSIS Upstreams, Extended Spectrum DOCSIS Downstreams, Active Taps, FTTT, and Distributed Node Architectures. Active research is still on-going in all of these key technology areas. If road-blocks are encountered that preclude some of the technologies, then MSO's may need to move towards FTTT or FTTH solutions sooner than predicted within this paper.

In the opinion of the authors, all three of the different Architectures (Static Soft-FDX, Dynamic Soft-FDX, and Traditional-FDX) will likely find applications in the future evolution of the MSO's HFC plant. However, since it is the "new kid" on the block with some very interesting attributes, the authors recommend that many Node+Non-Zero MSOs should at least consider the benefits of Dynamic Soft-FDX architectures (using ESD) as a way to greatly extend the life-span of their Node+Non-Zero HFC plants while maintaining simpler Amplifier solutions. Later upgrades to Node+0 Traditional-FDX architectures and/or Active Tap solutions and/or DNA-based FTTT solutions and/or FTTH solutions may make sense as subsequent steps.

Abbreviations

bps	bits per second
BW	bandwidth
CAGR	Compound Annual Growth Rate
CM	Cable Modem
CMTS	Cable Modem Termination System
CPE	Customer Premise Equipment
DAA	Distributed Access Architecture
dB	decibel
dBmV	decibel (relative to a millivolt)
DNA	Distributed Node Architecture
DOCSIS	Data Over Cable System Interface Specification
DS	Downstream
ESD	Extended Spectrum DOCSIS
FDD	Frequency Division Duplex
FDX	Full Duplex DOCSIS
FEC	Forward Error Correction
FPGA	Field Programmable Gate Array
FTTH	Fiber-To-The-Home
FTTLA	Fiber-To-The-Last-Active
FTTN	Fiber-To-The-Node
FTTT	Fiber-To-The-Tap
HDX	Half Duplex
HFC	Hybrid Fiber-coax
HHP	Households Passed
HSD	High Speed Data
Hz	hertz
IG	Interference Group
ISBE	International Society of Broadband Experts
K	K value (describing the QoE Coefficient)
LDPC	Low Density Parity Check
MAC	Media Access Control
MSO	Multiple System Operator
Nsub	Number of subscribers
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OOB	Out Of Band
OSP	Outside Plant
pCore	Physical Core
PHY	Physical Layer
PON	Passive Optical Network
PSD	Power Spectral Density
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
RBA	Resource Block Assignment
RFoG	RF over Glass
RMC	Remote MAC Core

RMD	Remote MACPHY Device
R-OLT	Remote Optical Line Termination
RPD	Remote PHY Device
RxD	Remote MACPHY Device or Remote PHY Device
SC-QAM	Single Carrier- Quadrature Amplitude Modulation
SCTE	Society of Cable Telecommunications Engineers
SDN	Software Defined Network
SG	Service Group
SLA	Service Level Agreement
SNR	Signal-to-Noise Ratio
sub	subscriber
TCP	Total Composite Power
TDD	Time Division Duplex
Tavg	Average Throughput
Tmax	Maximum Throughput
US	Upstream
vCore	Virtualized Core
W	watt
WDM	Wavelength Division Multiplexing

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