Network Capacity Options on the Path to 10G

A Technical Paper prepared for SCTE by

Karthik Sundaresan
Distinguished Technologist
CableLabs
858 Coal Creek Cir, Louisville, CO, 80027
3036613895
k.sundaresan@cablelabs.com

Table of Contents

Title **Page Number**

List of Figures

Title **Page Number**

List of Tables

Title **Page Number**

1. Introduction

Hybrid fiber cable (HFC) or data over cable service interface specifications (DOCSIS) networks are the most widely deployed technology for delivering Internet data services to the consumers. Cable operators today have variety of choices in front of them, in terms of upgrading and evolving their HFC networks. The upgrade choices with the current DOCSIS 3.1 technology includes Mid-spilt, High Split and distributed access architecture (DAA) and extending the downstream to 1.2 Gigahertz (GHz). With DOCSIS 4.0 technology there are even more plant upgrade options, from Full Duplex DOCSIS to the four new Ultra High Split upstream options (up to 684 Megahertz (MHz)) and the Extended spectrum to 1.8 GHz for the downstream. For each of these scenarios, operators are interested in knowing what are the data capacities that the system can realize from each of these plant upgrades. Also, for a consumer service, what are the potential service tiers that could be realized within each of these technology options. This paper gives a detailed analysis on each of these scenarios and layout the possible spectrum options for an operator given the different types of plant conditions. Understanding these options is a very important tool in figuring out what services can be reliably deployed. The cost benefit analysis for each of these options will help answer various for tactical and strategic network planning questions.

1.1. DOCSIS Evolution

DOCSIS 3.1 uses orthogonal frequency-division multiplexing (OFDM) for downstream modulation. In the downstream direction, the cable system is assumed to have a pass band with a lower edge of either 54 MHz, 87.5 MHz, 108 MHz or 258 MHz, and an upper edge that is implementation-dependent but is typically in the range of 550 to 1002 MHz. Upper frequency edges extending to 1218 MHz, 1794 MHz and others are expected in the upcoming DOCSIS 4.0 technology deployments in the plant. Within that pass band, digital television signals in 6 MHz channels are assumed present on the standard, as well as other narrowband and wideband digital signals.

The cable modem (CM) supports a minimum of two independently configurable OFDM channels each occupying a spectrum of up to 192 MHz in the downstream. The demodulator in the CM supports receiving downstream transmissions up to at least 1.218 GHz and optionally support receiving downstream transmissions up to at least one or more of the following downstream upper band edges: 1.002 GHz, 1.218 GHz, 1.794 GHz.

1.2. Technology Evolution

Allocating more spectrum to broadband is a priority for cable operators. Initially all of the downstream spectrum was allocated for carrying video programming. Over the past ~25 years, the downstream has transitioned by migrating the spectrum from video to broadband. In addition to transitioning the existing spectrum to broadband, there are several scenarios where additional downstream spectrum can be added and used for broadband service. Analyzing downstream DOCSIS capacity is different than analyzing upstream DOCSIS capacity. For the initial evolution from DOCSIS 1.0 to 2.0 to 3.0, the upstream spectrum allocation was fairly straightforward because the spectrum was mostly unused and could be allocated to broadband. In the last many years, upstream has become the bottleneck for cable networks, and is now driven by shifts in user behavior and symmetrical competition. Ultimately this became the primary driver for today's capacity upgrades, be it mid-split or DOCSIS 4.0. Downstream spectrum is much wider than upstream spectrum, and it also carries video signals. The table below shows the evolution in the spectrum supported by a cable modem for each DOCSIS version.

Table 1 – CM Spectrum Support

DOCSIS Version	Downstream Spectrum (usable)	**Upstream Spectrum** (usable)
DOCSIS 1.0	6 MHz	6.4 MHz
DOCSIS 1.1	6 MHz	6.4 MHz
DOCSIS 2.0	6 MHz	6.4 MHz
DOCSIS 3.0	24 to 192 MHz	25.6 (to 51.2) MHz
DOCSIS 3.1	576 MHz	192 MHz
DOCSIS 4.0	1152 MHz	Frequency Division Duplex (FDD) CMs 272/ 368/ 464/ 656 MHz Full Duplex DOCSIS (FDX) CMs 272/ 464/ 656 MHz

As shown by Table above the trend has been for each DOCSIS version to require more downstream and upstream spectrum support on the modem. The DOCSIS 3.0 specifications was a seminal moment when channel bonding was introduced. Early DOCSIS 3.0 modems would support up to 24 MHz of downstream spectrum, and the last DOCSIS 3.0 modems supported up to 192 MHz of downstream spectrum (256 MHz of downstream spectrum if Annex A quadrature amplitude modulation (QAMs) were used).

1.3. Spectrum Evolution

The cable modem termination system (CMTS) has more variability—it can support the minimum requirements as described above or it can support additional DOCSIS spectrum when there is spectrum available in the cable plant. With the move to both more broadband and Internet Protocol television (IPTV), and a recent trend is for a CMTS to support more downstream spectrum than a modem.

About 20 years ago, cable plants were carrying analog television (TV) signals. In North America, this equated to allocating 6 MHz of spectrum, one Consumer Technology Association (CTA) channel, to carry one analog TV channel in the National Television System Committee (NTSC) format. A sub-split 750-MHz system can carry about 115 CTA channels (each 6 MHz) for a total of 690 MHz of downstream spectrum.

Digital video technology was already on the rise to pack more television programming into a single CTA channel. MPEG-2 encoding allowed a single 6-MHz CTA channel to carry up to 10 standard-definition NTSC or 3 high-definition NTSC channels. MPEG-4 encoding allowed up to 17 standard-definition and about 9 high-definition NTSC channels to be put into a single 6-MHz channel.

Today, the coaxial cable is assumed to carry around 300 MHz of video programming. The amount of spectrum allocated to video programming varies widely, and 300 MHz is chosen as a "nominal" number. There are numerous solutions that can raise or lower that number, including the use of MPEG-4 encoding, switched digital video, and migration to IPTV. This number is assumed to go down as video switches to IPTV solutions.

Before 2008, the DOCSIS 1.0, 1.1, and 2.0 systems used only one downstream channel, a 6-MHz CTA channel. Since 2009, the DOCSIS 3.0 deployments allowed more downstream spectrum to be used for broadband, starting with four DOCSIS downstream channels (24 MHz) and, eventually, products that supported up to 32 downstream channels (192 MHz). The rise of digital video coincided with the availability of DOCSIS 3.0 technology, all around 2008, and spectrum that previously carried analog TV channels could now be reclaimed to carry both digital TV and broadband. As the internet bandwidth consumption continued to rise, the need for additional spectrum for broadband became apparent. Around 2016, DOCSIS 3.1 technology was made available, resulting in the downstream needing additional spectrum for the new OFDM technology.

1.4. Modem peak speeds and service Tiers.

An old rule of thumb which multi system operators (MSOs) use is to offer a service tier which is about half of the CM's peak throughput capacity. (CM Capacity/Service Tier = 2/1) As service group bandwidth capacity increases with CMTSs providing more channels than the modem can handle, this ratio is slowly edging closer to the modem's peak capacity. We are now starting to see ratios of 1.5/1 or lower, as the higher network bandwidth capacity allows operators to take better advantage of the statistical multiplexing inherent in a medium like the DOCSIS network.

The throughput numbers described in this paper is peak broadband capacity per modem. As will be seen in the cases, the coaxial cable/CMTS can support more broadband capacity than a D3.1 CM or D4.0 CM can use, which can be used for load balancing and increasing service tiers. For purposes of this paper, the channel conditions are assumed to be good enough to get to the better/top modulation orders. All the capacity numbers are calculated as described in our previous paper [D3.1 Capacity]. Numbers will need to be adjusted if the actual channel conditions are lower than expected in certain deployments.

2. D3.1 Technology Options

This section talks about the various configurations which in operator can implement when deploying DOCSIS 3.1 technology and the capacities for each setting. An operator typically has one of the following types of networks in which they can deploy D3.1 technology. The first (and most common in the past), is a low split network with the upstream ranging from 5 to 42 MHz and the downstream ranging up to 750 or 860 MHz. The next is a mid-split network with the upstream ranging from 5 to 85 MHz and the downstream ranging up from 108MHz up to 1 GHz. The third is a high split network with the upstream ranging from 5 to 204 megahertz and the downstream ranging from 258Mhz to 1.2 GHz. Some operators may have networks with different combinations of the downstream with the upstream depending on when those plant upgrades were done.

2.1. Legacy Low Split with 750 MHz

Let's start with the legacy DOCSIS 3.0 plant with a low split for the upstream (42 MHz), and a 750 MHz plant for the downstream. The typical configuration used by MSOs has been 4 SC-QAM upstream channels and anywhere from 8 to 32 SC-QAM downstream channels. An operator would use 6.4 MHz channels upstream carriers and placing them directly adjacent to each other and using the modulation orders to 64 QAM for the upstream SC-QAM carriers.

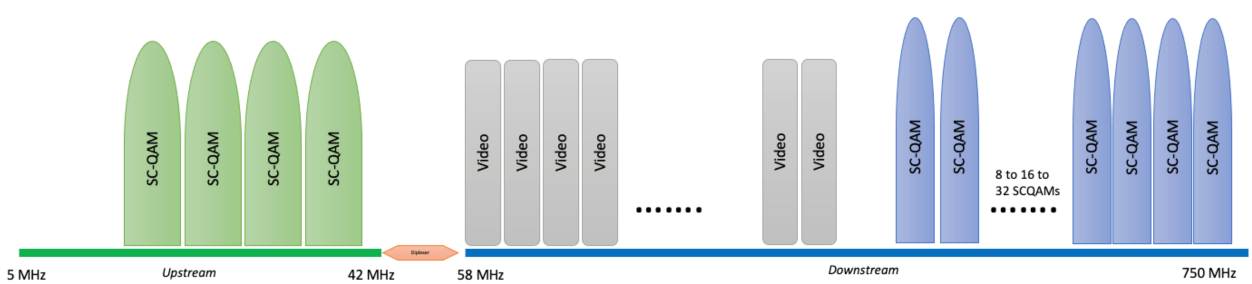

Figure 1 – Legacy D3.0 Plant

With four 6.4-MHz-wide channels operating at 64 QAM, the aggregate throughput of the CMs is about **106 Mbps**. With 32 x 6 MHz-wide channels operating at 256 QAM, the aggregate throughput of this CM on the downstream is about **1.2 Gbps**.

2.1.1. Legacy Low split with 750 MHz, Adding OFDM, Adding 5th SC-QAM

Here we stay on to the legacy low split plant with the upstream still at 42 MHz, and a 750 MHz plant for the downstream. The downstream has the 32 SC-QAM downstream channels and with the DOCSIS 3.1 technology being introduced, we now have a new additional 96 MHz OFDM channel deployed, typically at the higher band edge of the downstream spectrum.

As a final step for the upstream in a sub-split network, operators could try adding one or more additional upstream SC-QAM carriers, up high or down low, as shown in Figure. The paper [Bandwidth Growth] draws the conclusion that even adding 10% additional upstream capacity can help alleviate upstream congestion. Operators have been successful in adding new carriers, which is a testament to maintaining the plant more diligently over the last decade. So, in many operator networks, the upstream configuration now adds a 5th SC-QAM channel.

The number of homes passed has decreased, which lowers the effect of noise funneling at low frequencies, and cascades have shortened, which lessens the impact of group delay close to the diplex filter cutoff frequency. Operators have been successfully running narrow carriers (typically with lower order modulation) both down to 10 MHz and closer to the diplex filter.

With 5 x 6.4-MHz-wide channels operating at 64 QAM, the aggregate upstream throughput of the CMs is about **133 Mbps**. With 32 x 6 MHz-wide channels operating at 256 QAM, and an additional 96 MHz OFDM channel (at 4096 QAM) the aggregate throughput of this CM on the downstream is ~ **2.1 Gbps**.

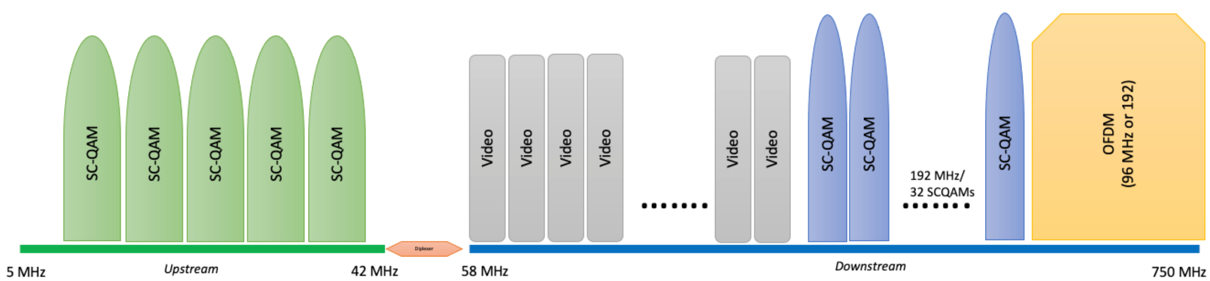

Figure 2 – D3.1 Deployment on a Low Split Plant

2.1.2. Legacy Low Split with 750 MHz, with OFDMA

Here we stay on the legacy low split plant with the upstream still at 42 MHz, and a 750 MHz plant for the downstream. For the upstream configuration, an operator could bring the number of SC-QAM upstream channels down to 1 and add a 25.6 MHZ orthogonal frequency-division multiple access (OFDMA) channel. While this may not be a realistic scenario, due to the number of D3.0 CMs that may need to be supported, this is an interesting thought exercise on the capacity increase on the upstream for a low split plant. The downstream stays at 32 SC-QAM downstream channels and the 96 OFDM channel.

With a 25.6 MHz OFDMA channel operating at the max of 2048 QAM, along with the 1 SC-QAM channel, the aggregate upstream throughput of the CMs is about **267 Mbps**. With 32 x 6 MHz-wide channels operating at 256 QAM, and an additional 96 MHz OFDM channel the aggregate throughput of this CM on the downstream is about **2.1 Gbps**.

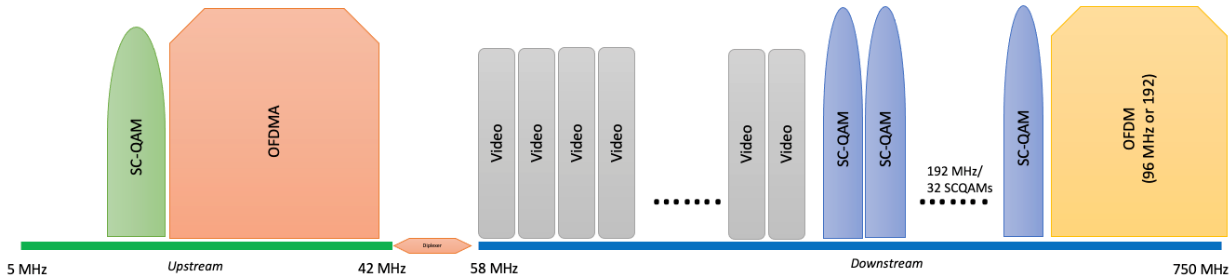

Figure 3 – D3.1 Deployment on a Low Split Plant w OFDMA

2.1.3. D3.1 Low Split Upstream and 860Hz Downstream

If the sub-split deployment cannot be changed and there are enough DOCSIS 3.1 modems on the network, operators can consider replacing SC-QAM channels with an OFDMA channel. OFDMA technology makes better use of spectrum because it can operate nominally at 1024 QAM, whereas an upstream SC-QAM channel is limited to 64 QAM.

In this scenario, the legacy low split plant stays with the upstream at 42 MHz, and an 860MHz plant for the downstream. For the upstream configuration, an operator could bring the number of SC-QAM upstream channels to 3 and add a 12.8 MHZ OFDMA channel. The downstream has at 32 SC-QAM downstream channels and two 192 MHz OFDM channel. (Leaving about 226 MHz for about 37 CTA/video channels)

With a 12.8 MHz OFDMA channel operating at the max of 2048 QAM, along with the 3 SC-QAM channels, the aggregate upstream throughput of the CMs is about **200 Mbps**. With 32 SC-QAM channels operating at 256 QAM, and an additional 2 x 192 MHz OFDM channel the aggregate throughput of this CM on the downstream is about **5 Gbps**.

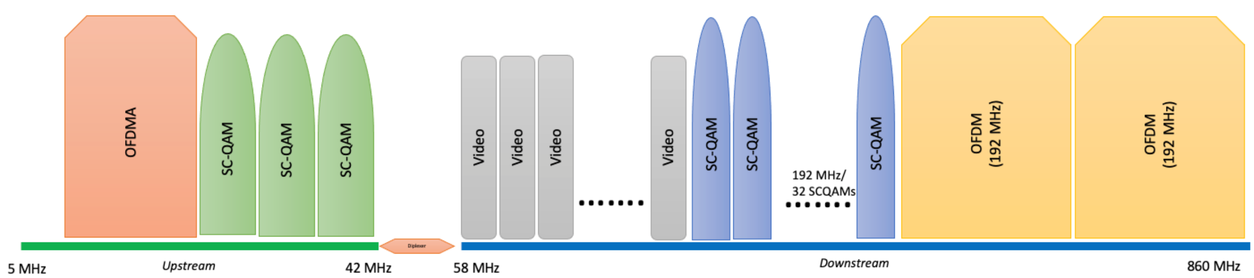

Figure 4 – D3.1 Deployment on a Low Split Plant and 860 MHz

When there is a higher percentage of DOCSIS 3.0 modems on the network, as those modems cannot use the DOCSIS 3.1 spectrum, it may make sense to replace the second OFDM channel with 32 SC-QAM channels. When there is a higher percentage of DOCSIS 3.1 modems on the network, the 2 OFDM channels will provide more OFDM capacity for those modems to use. Because this case has more spectrum allocated to DOCSIS 3.1 technology, the aggregate throughput is 5 Gbps.

2.2. D3.1 Mid-Split

A mid-split HFC network has a return path of up to 85 MHz, or two times the spectrum of a sub-split network. With a mid-split, the forward path begins around 108 MHz; therefore, set top box (STB) based video services should be able to be maintained because the forward data channel can be up to 130 MHz. The additional upstream spectrum provided by a mid-split network can provide about 500 Mbps of capacity. Per the [PHYv4.0] specifications upstream SNR must increase from 22 dB for 64 QAM to 35 dB for 1024 QAM. An upgrade to mid-split offers the MSO an opportunity to access cleaner upstream spectrum to achieve this improvement. The SC-QAM channels depicted here may need to operate below 64 QAM if the mid-split upgrade does not also improve upstream SNR at the lowest frequencies. The downstream extends to a 1GHz plant but allows the same number of channels tunable by the CM as in the above scenarios. With 32 SC-QAM channels operating at 256 QAM, and an additional 2 x 192 MHz OFDM channel the aggregate throughput of these CMs on the downstream is about **5 Gbps**.

2.2.1. Start with SC-QAMs

In terms of additional upstream spectrum, a mid-split can be configured in several ways. As shown in the figure, a mid-split can fit 10 traditional upstream SC-QAM carriers of 6.4-MHz width (for a total of 64 MHz of upstream spectrum allocated to broadband).

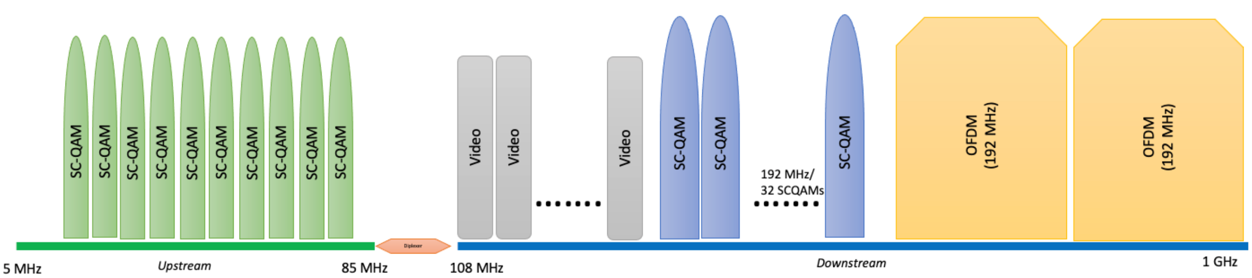

Figure 5 – D3.1 Deployment on a Mid-Split Plant

This configuration can yield up to **265 Mbps** of aggregate upstream capacity. Note that DOCSIS technology allows SC-QAM to be modulated up to 256 QAM and no higher. That is, with SC-QAM, 512 QAM and 1024 QAM are not available. However, the newer DOCSIS 3.1 technology does allow higher order QAM modulation.

2.2.2. Add an OFDMA Channel

Figure shows another configuration of the traditional 4 upstream SC-QAM channels along with a 49.5 MHz OFDMA running at 2048 QAM up to 85 MHz.

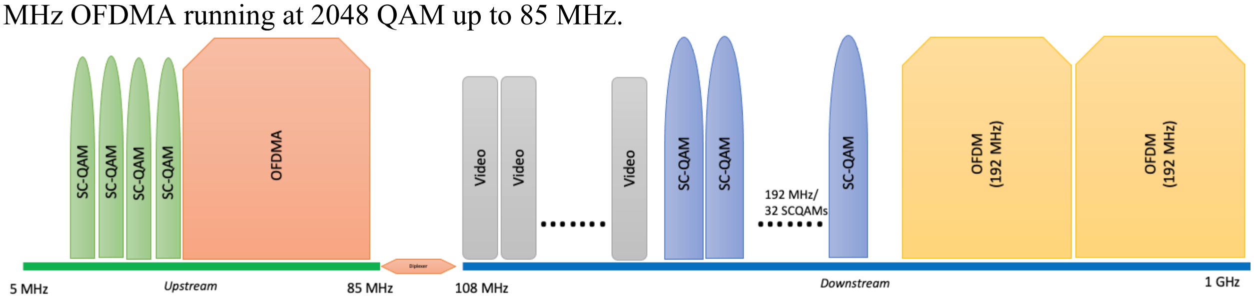

Figure 6 – D3.1 Deployment on a Mid-Split Plant with SC-QAM and OFDMA Channels

This configuration can yield up to **572 Mbps** of aggregate upstream capacity and an increase of ~300 Mbps using the same spectrum because the OFDMA carrier can operate at a higher order of QAM modulation than single-carrier QAMs.

2.2.3. Replace with OFDMA

The next step for an operator could be to use 75 MHz of OFDMA, which can offer **708 Mbps** of upstream capacity, an increase of ~443 Mbps using the same spectrum. It may be necessary, however, to retain a single SC-QAM upstream channel for DOCSIS 3.0 modems.

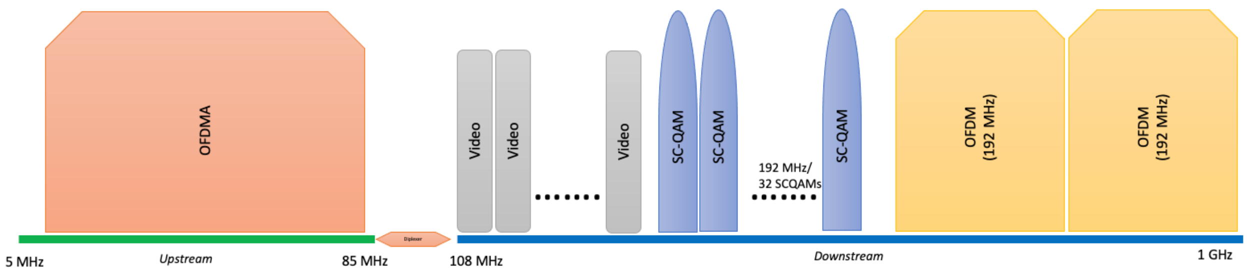

Figure 7 – D3.1 Deployment on a Mid-Split Plant with OFDMA Channel

2.3. D3.1 High Split Deployments

A high-split HFC network has a return path of up to 204 MHz, or more than 4 times the spectrum of a sub-split network. With a high-split, the forward path begins around 258 MHz, so STB-based video services cannot be maintained because the forward data channel can only be moved as high as 130 MHz, as described in the SCTE-55 standards. However, the additional upstream spectrum provided by a high-split network can provide more than 1.8 Gbps of capacity.

An interesting observation is that a high-split 1.2-GHz system supports about the same amount of downstream spectrum as a sub-split 1-GHz system (12 MHz more downstream spectrum). The benefit of the high-split system is the additional upstream broadband capacity, though this additional 12 MHz of downstream spectrum can be used in a downstream OFDM channel. As a result, the approximate downstream throughputs for the 1.2-GHz system are only slightly higher than the subsplit 1-GHz system.

Though this system supports up to 1.2 GHz, many older CPE only support a lower top frequency. For example, early DOCSIS 3.0 modems were required to support only up to 870 MHz, though later DOCSIS 3.0 modems supported up to 1002 MHz. Similarly, different models of video CPE will also have different top ends. These constraints on CPE should be considered while laying out services on the coaxial cable.

2.3.1. SC-QAM and OFDMA

In the High-split plant, the upstream spectrum is up to 204 MHz, and a 1218 MHz plant for the downstream. The downstream configuration still remains about the same and can have 32 SC-QAM downstream channels and 2 x 192 MHz OFDM channels.

In the upstream spectrum, an operator can retain the 4 SC-QAM channels for DOCSIS 3.0 (and earlier) CMs and then expand the first OFDMA channel up to 108 MHz. Now the operator can add a second

OFDMA channel to the mix. This second OFDMA channel will start from 108 MHz and span up to 204 MHz.

This configuration can yield up to **1764 Mbps** of aggregate upstream capacity. With 32 SC-QAM channels operating at 256 QAM, and the 2 x 192 MHz OFDM channel the aggregate throughput of this CM on the downstream is about **5 Gbps**.

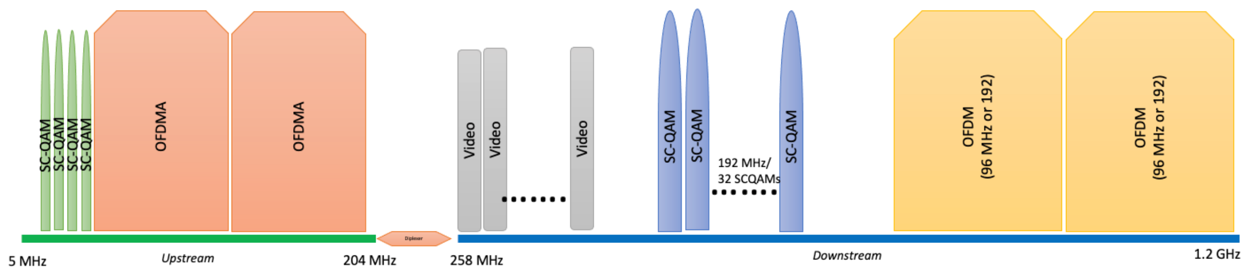

Figure 8 – D3.1 Deployment on a High-Split Plant with SCQAM & OFDMA Channels

2.3.2. Full OFDMA

In the scenario where there are no more D3.0 CMs in the plant, an operator can remove the 4 SC-QAM channels for DOCSIS 3.0 (and earlier) CMs and then expand the OFDMA channels to span from 12 MHz to 204 MHz.

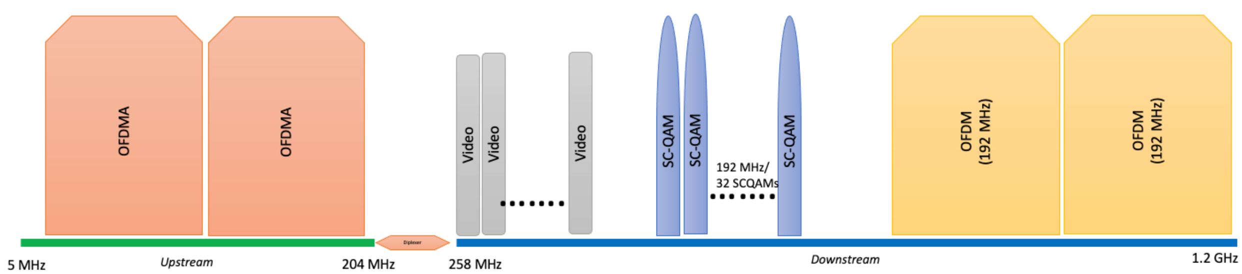

Figure 9 – D3.1 Deployment on a High-Split Plant with Full OFDMA Channels

This configuration can yield up to **1988 Mbps** of aggregate upstream capacity. With 32 SC-QAM channels operating at 256 QAM, and the 2 x 192 MHz OFDM channel the aggregate throughput of this CM on the downstream remains at about **5 Gbps**. If the Operator can free up more downstream bandwidth, the CMTS can source more downstream channels, but a D3.1 CM can only use the 32 SC-QAM and 2 OFDM channels worth of bandwidth, but these additional channels will allow an operator to load balance the different CMs on the network better across the available DOCSIS channels.

3. DOCSIS 4.0 ESD/FDX Technology Options

The DOCSIS 4.0 specifications builds upon the previous generations of DOCSIS specifications. It includes backward compatibility for the existing physical (PHY) layers in order to enable a seamless migration to the new technology. The DOCSIS 4.0 specifications introduces Full Duplex (FDX) DOCSIS PHY layer technology as an expansion of the OFDM/A PHY layer introduced in the DOCSIS 3.1 specification to increase upstream capacity without significant loss of downstream capacity within the same available spectrum. The DOCSIS 4.0 specification also builds upon DOCSIS 3.1 OFDM and OFDMA technology with an extended Frequency Division Duplex (FDD)

DOCSIS alternative. DOCSIS 4.0 FDD supports legacy high-split and also provides extended upstream splits up to 684 MHz in an operational band plan which is referred to as Ultra-high Split (UHS). DOCSIS 4.0 FDD also introduces expansion of usable downstream spectrum up to 1794 MHz (Extended spectrum DOCSIS). Both the FDX and FDD DOCSIS 4.0 alternatives based on the OFDM/A PHY carry the cable networks into the 10G space.

3.1. D4.0 ESD/FDD Technology Options

The 1.8-GHz systems are intended for DOCSIS 4.0 equipment where the CMTS is specifically designed to place more broadband spectrum on the coax, both upstream and downstream. However, these systems need to be backward compatible with DOCSIS 3.1, DOCSIS 3.0, and perhaps DOCSIS 2.0 modems. The DOCSIS 4.0 specification builds upon DOCSIS 3.1 OFDM and OFDMA technology with an extended frequency division duplex (FDD) DOCSIS alternative. DOCSIS 4.0 FDD supports both mid-split and high-split and provides extended upstream splits up to 300/396/492/684 MHz in an operational band plan referred to as ultra-high split (UHS).

DOCSIS 4.0 FDD also introduces the expansion of usable downstream spectrum up to 1794 MHz to support higher upstream splits. An FDD CM supports at least two or more of the following upstream upper band edges: 204 MHz; 300 MHz; 396 MHz; 492 MHz; and/or 684 MHz. The FDD CM supports a minimum of 5 independently configurable OFDM channels each occupying a spectrum of up to 192 MHz in the downstream, while the FDD node/CMTS supports 6 OFDM channels

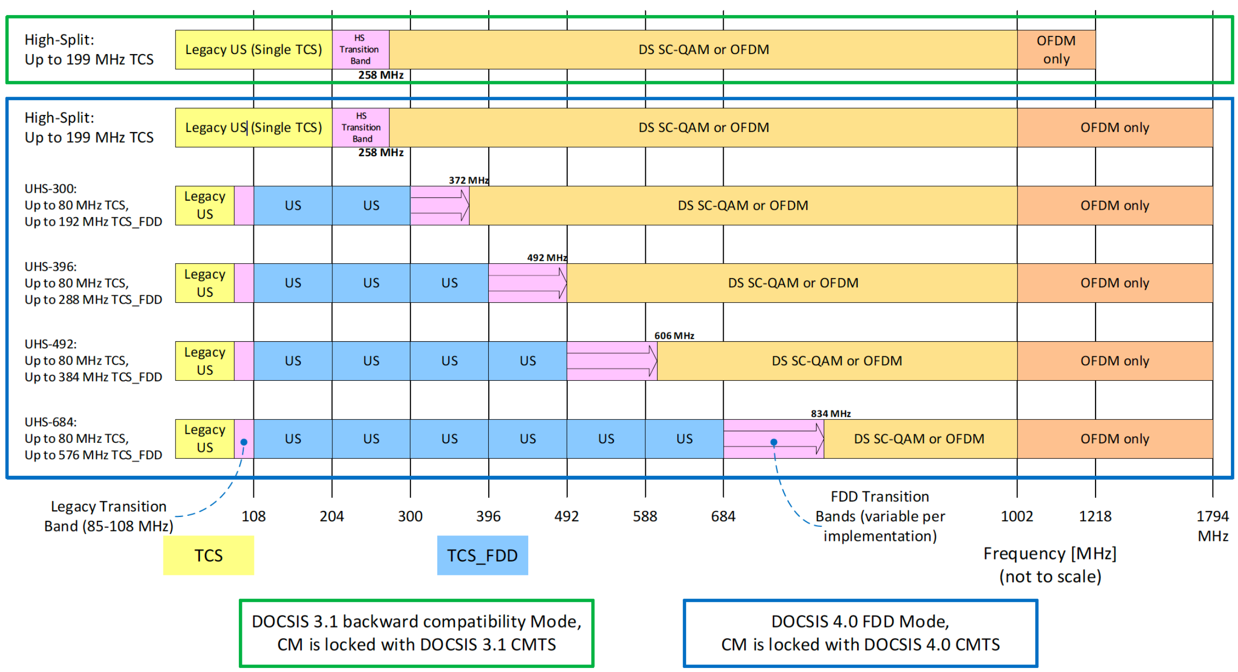

Figure 10 – D4.0 FDD Spectrum Options

Figure Source: [PHYv4.0] spec

3.1.1. D3.1 High Split with D4.0 CM

In the High split plant, the upstream spectrum is up until at 204 MHz, and the downstream up to 1218 Mhz. The downstream configuration can have 32-SC-QAM downstream channels and since the D4.0

CMs can support it, up to 4 x 192 MHz OFDM channels. In the upstream spectrum, an operator can retain the legacy 4 SC-QAM upstream channels and can have 2 OFDMA channels (70 and 96 MHz each)

This configuration can yield up to **1764 Mbps** of aggregate upstream capacity. The 32 SC-QAMs and the 4 x 192 MHz OFDM channel the aggregate throughput of this CM on the downstream is about **8.8 Gbps**.

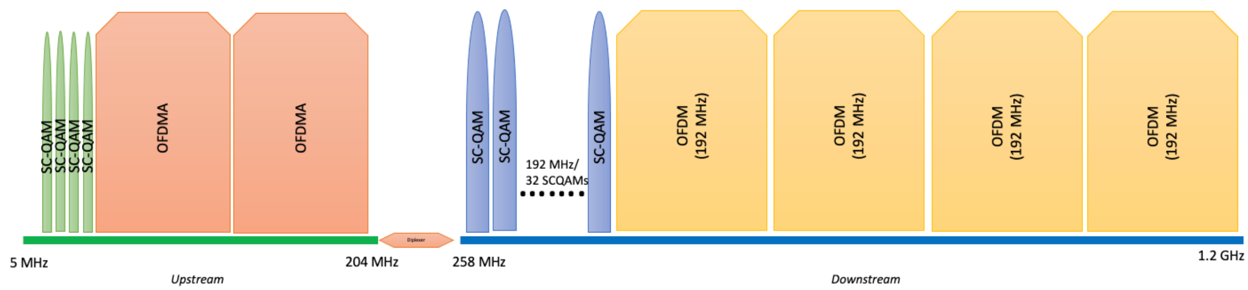

Figure 11 – D4.0 FDD CM on a High Split Network

3.1.2. D4.0 FDD 300 MHz Split

In the UHS-300 plant the upstream spectrum is up until at 300 MHz, and downstream extends up to 1794 Mhz. The downstream configuration can have 32 SC-QAM downstream channels and now 5 x 192 MHz OFDM channels. In the upstream spectrum, an operator can simply have 2 OFDMA channels from 108 to 300 MHz and one 75MHz OFDMA below 85 MHz. At this scenario and onwards, we are assuming the SC-QAM Channels are no longer needed, if they are the upstream numbers will need to be adjusted slightly lower, as seen in previous examples.

This configuration can yield up to **2696 Mbps** of aggregate upstream capacity. With 32 SC-QAM channels operating at 256 QAM, and the 5 x 192 MHz OFDM channel the aggregate throughput of this CM on the downstream is about **10.7 Gbps**.

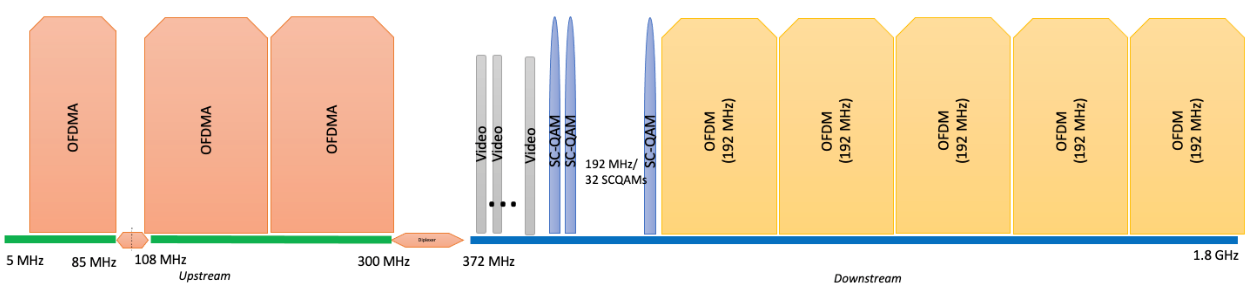

Figure 12 – D4.0 FDD CM on UHS-300 MHz Split Plant

3.1.3. D4.0 FDD 396 MHz Split

In the UHS-396 plant, the upstream spectrum is up until at 396 MHz, and downstream starts at 492 and extends up to 1794 Mhz. This makes a total of 1302 MHz of downstream spectrum, and the figure shows 1152 MHz for downstream DOCSIS channels. The downstream configuration can have 32 SC-QAM downstream channels and 5 x 192 MHz OFDM channels. In the upstream spectrum, an operator can simply have 3 OFDMA channels from 108 to 396 MHz and one 75MHz OFDMA below 85 MHz.

This configuration can yield up to **3690 Mbps** of aggregate upstream capacity. With 32 SC-QAM channels operating at 256 QAM, and the 5 x 192 MHz OFDM channel the aggregate throughput of this CM on the downstream is about **10.7 Gbps**.

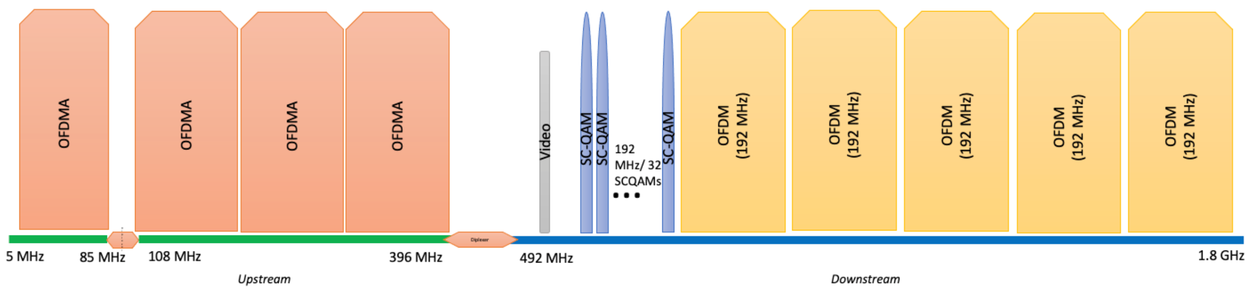

Figure 13 – D4.0 FDD CM on UHS-396 MHz Split Plant

3.1.4. *D4.0 FDD 492 MHz Split*

In the UHS-492 plant the upstream spectrum is up until at 492 MHz, and downstream starts at 606 and extends up to 1794 Mhz. This makes a total of 1188 MHz of downstream spectrum, and the figure shows 1152 MHz for downstream DOCSIS channels. The downstream configuration can have 32 SC-QAM downstream channels and 5 x 192 MHz OFDM channels. In the upstream spectrum, an operator can simply have 4 OFDMA channels from 108 to 492 MHz and one 75MHz OFDMA below 85 MHz.

This configuration can yield up to **4684 Mbps** of aggregate upstream capacity. With 32 SC-QAM channels and the 5 x 192 MHz OFDM channel the aggregate throughput of this CM on the downstream is about **10.7 Gbps**.

This is an interesting case; in case an operator decides to keep video services and D3.0 CMs. With the downstream starting at 606 MHz, and if an operator decides to keep some amount of video spectrum, the DOCSIS 3.0 spectrum needs to be below 870 MHz (The top end for some early DOCSIS 3.0 modems). Also, no DOCSIS 3.0 modem is specified to use spectrum above 1002 MHz; hence, the DOCSIS 3.0 spectrum ends at 1002 MHz. Further, because video CPE possibly cannot tune above 1002 MHz either, the spectrum below 1002 MHz would need to be allocated such that both the video CPE and the DOCSIS 3.0 and earlier modems can best utilize the downstream according to service plans.

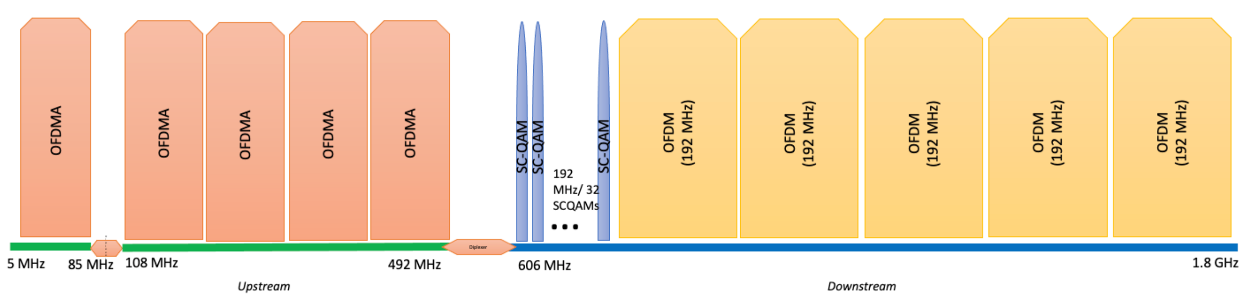

Figure 14 – D4.0 FDD CM on UHS-492 MHz Plant

3.1.5. D4.0 FDD 684 MHz Split

In the UHS-684 plant the upstream spectrum is up until at 684 MHz, and downstream starts at 834 MHz and extends up to 1794 Mhz. This makes a total of 960 MHz of downstream spectrum The downstream configuration can simply have 5 x 192 MHz OFDM channels. In the upstream spectrum, an operator can simply have 6 OFDMA channels from 108 to 684 MHz and one 75MHz OFDMA below 85 MHz.

This configuration can yield up to **6672 Mbps** of aggregate upstream capacity. the 5 x 192 MHz OFDM channel the aggregate throughput of this CM on the downstream is about **9.5 Gbps**.

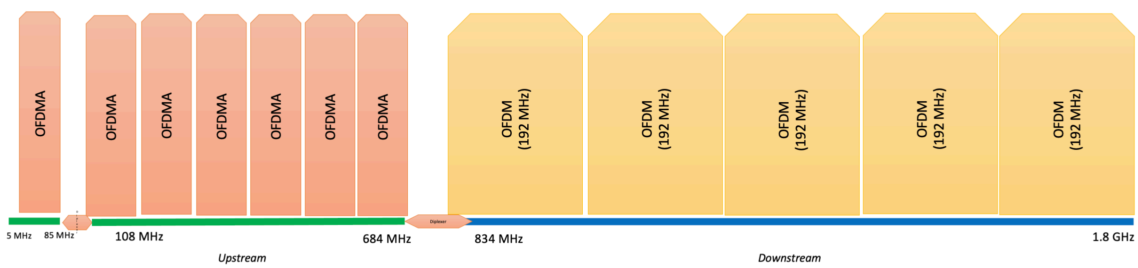

Figure 15 – D4.0 FDD CM on UHS-684 MHz Plant

3.2. D4.0 FDX Technology Options

DOCSIS 4.0 FDX functionality significantly increases upstream capacity by using the spectrum currently used for downstream transmission for simultaneous upstream and downstream communications via full duplex communications. The FDX Allocated Spectrum is subdivided into FDX sub-bands each with a single FDX Downstream Channel and the associated FDX Upstream Channel(s) that can be assigned to modems according to system requirements. In the full FDX spectrum, the 3 resource blocks (each 192 MHz wide) will fit 6 FDX OFDMA upstream channels and 3 FDX OFDM downstream channels. The FDX node will simultaneously transmit and receive data on these channels with the Echo cancellation technology while the FDX CM either receives or transmits within a channel in a given sub-band. The CMTS assignment of FDX channels within the FDX band for Full Duplex DOCSIS operation can be done incrementally over time as a transition strategy, from existing DOCSIS networks to Full Duplex DOCSIS networks, as FDX-capable CMTSs and modems become available. The figure below shows the FDX allocated spectrum within the cable plant.

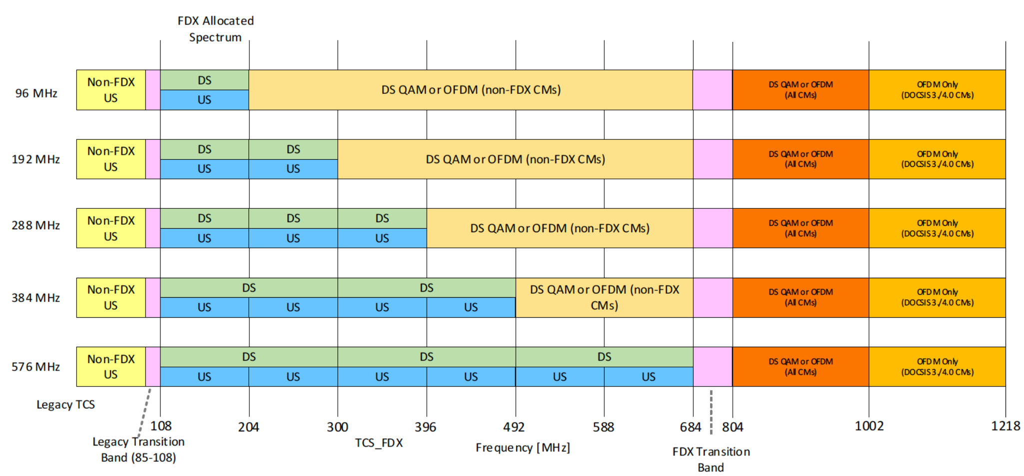

Figure 16 – FDX Allocated Spectrum

3.2.1. D4.0 FDX 1.0 GHz with SCQAMs or OFDM

In the initial FDX scenario, in a FDX plant the upstream-only spectrum is up until 85 MHz, and the downstream-only spectrum is from 804 MHz to a1002 MHz plant, and the FDX-Spectrum (simultaneous Upstream and Downstream) is from 108 MHz to 684 MHz. Staying at 1GHz downstream plant is a realistic initial scenario as it helps with not replacing all the taps at the start to 1.2 GHz.

In the spectrum between 684 and 804 is the as this is in the FDX transition band, to prevent any interference between the FDX bands and the downstream only region. An operator could choose to deploy video QAM channels here, and these channels can be used by other devices (STBs), but this spectrum cannot be used by the FDX CM itself

As regards a FDX CM's data capacity, in this type of a FDX plant, an operator can choose one of two options: to retain in the downstream-only spectrum (804 to 1002 MHz region) the 32 SC-QAMs or deploy a single 192 MHz OFDM channel and a single SC-QAM channel. In the upstream-only spectrum (5-85MHz), an operator can retain the 4 SC-QAM channels for DOCSIS 3.0 (and earlier) CMs or and cover the rest of the spectrum below 85 MHz with an OFDMA channel.

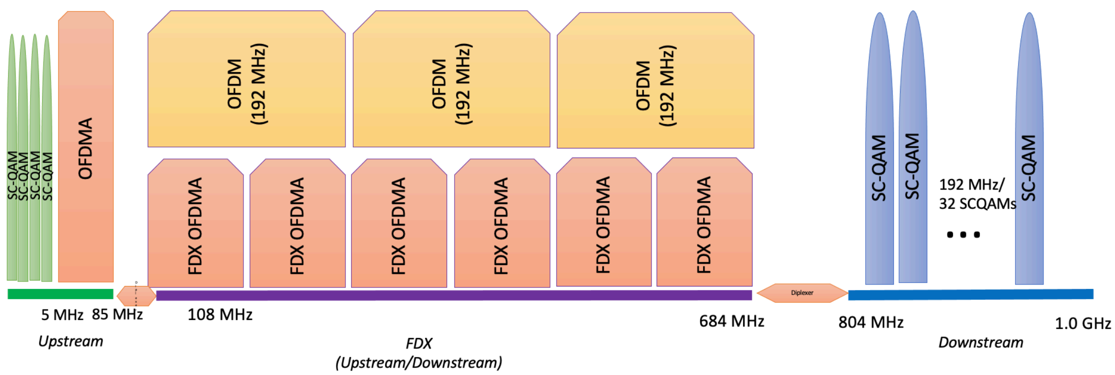

Figure 17 – D4.0 FDX (1.0 GHz) Channel Allocations with SCQAMs

In the FDX spectrum, the 3 resource blocks (each 192 MHz wide) will fit 6 FDX OFDMA upstream channels and 3 FDX OFDM downstream channels.

This configuration can yield up to **6537 Mbps** of peak aggregate upstream capacity. The peak aggregate throughput of this CM on the downstream, is **6937** Mbps, if the 32 SCQAM option is chosen and **7666** Mbps, if the 1 OFDM + 1 SC-QAM channel option is chosen.

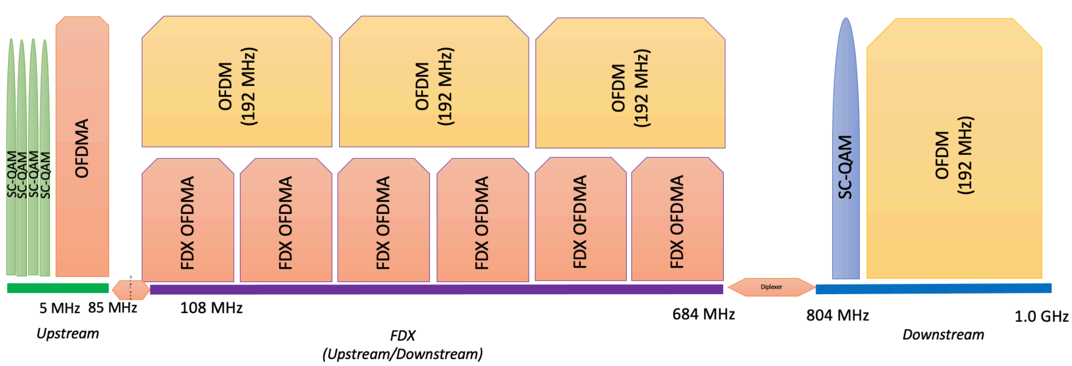

Figure 18 – D4.0 FDX (1.0 GHz) Channel Allocations with an OFDM

3.2.2. D4.0 FDX 1.2 GHz with SCQAMs

In the initial FDX scenario, in a FDX plant the upstream-only spectrum is up until 85 MHz, and the downstream-only spectrum is from 804 MHz to 1218 MHz plant, and the FDX-Spectrum (simultaneous Upstream and Downstream) is from 108 MHz to 684 MHz.

In this type of a FDX plant, an operator can choose to retain in the downstream-only spectrum (804 to 1218 MHz region), the 32 SC-QAMS and then deploy a 192 MHz OFDM channel and a second smaller 30 MHz OFDM channel. In the upstream-only spectrum (5-85MHz), an operator can retain the 4 SC-QAM channels for DOCSIS 3.0 (and earlier) CMs or and cover the rest of the spectrum below 85 MHz with an OFDMA channel.

The FDX spectrum, will fit 6 FDX OFDMA upstream channels and 3 FDX OFDM downstream channels.

This configuration can yield up to **6537 Mbps** of peak aggregate upstream capacity and **9141 Mbps** of the peak aggregate throughput of this CM on the downstream.

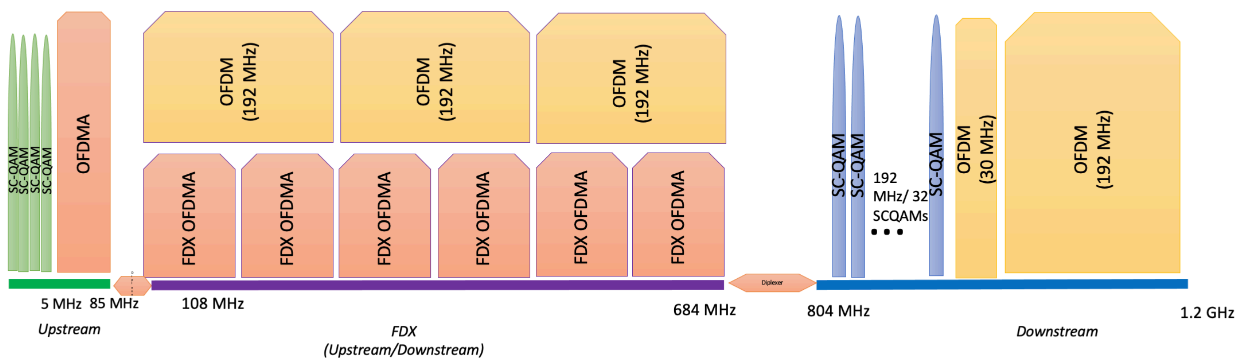

Figure 19 – D4.0 FDX 1.2 GHz Channel Allocations with SCQAMs and OFDM

3.2.1. D4.0 FDX 1.2 GHz with OFDMA and 2 OFDMs

Building on the FDX plant as described above, now the operator can remove the 4 SC-QAM channels for DOCSIS 3.0 (or earlier) CMs and expand the OFDMA channel to cover the spectrum below 85 MHz. Similarly for the downstream an operator could reduce the 32 SC-QAM channels to 4 and add an OFDM channel for more efficiency, for a total of 2 OFDM channels. The FDX band remains the same with 6 x 96MHz OFDMA upstream channels and 3 x 192 MHz OFDM downstream channels

This configuration can yield up to **6672 Mbps** of peak aggregate upstream capacity. The peak aggregate throughput of this CM on the downstream is about **9687 Mbps.**

One additional use case to consider would be FDX in a N+x configuration. While spectrum plans will likely remain quite similar, if we assume a lower RxMER (say 3-4 dB) or one modulation order lower for the FDX channels, the peak capacity will adjust lower to 6144 Mbps on the upstream and 9144 Mbps. Depending on the performance from the FDX amplifiers the modulation orders possible on the OFDM/A channels will change and the capacity calculation will also vary.

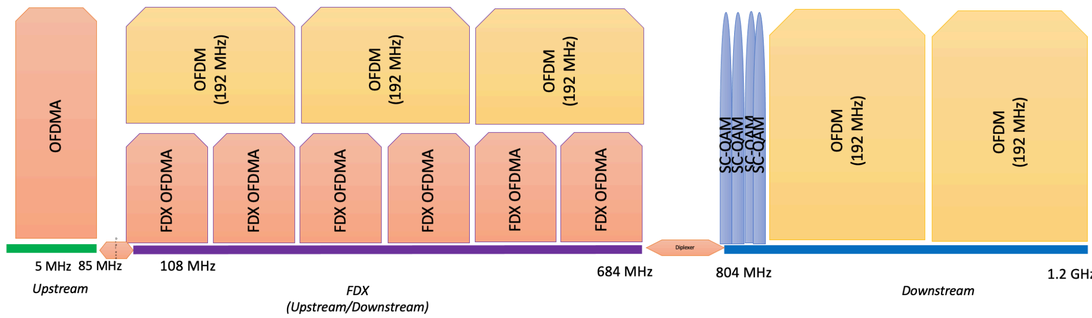

Figure 20 – D4.0 FDX Channel Allocations with OFDM/A and 2 OFDMs

3.3. Comparison to FTTP/PON Technology Options

Most FTTH networks are based on passive optical network architectures, simply as it is usually the lowest cost way to design a FTTH network. Many operators are deploying passive optical networks (PON) in many of their market segments

Per *[Broadband Pie],* one operator's investigations and analysis has concluded that the overall cost of deploying FTTP to their residential footprint would be about 5 to 6 times the cost of rolling out DOCSIS 4.0 with DAA.

3.3.1. 10 G EPON

10G Ethernet PON (EPON) is the current and widely available generation of EPON technology, although the Nx25G EPON specifications have also recently been published. This technology is defined by Institute of Electrical and Electronics Engineers (IEEE) 802.3 standard and offers asymmetrical (10/1Gbps) and symmetrical (10/10 Gbps) rates for downstream and upstream.

The peak user throughput to an optical network unit (ONU) is around 8.6 Gbps upstream and 8.65 Gbps downstream

3.3.1. XGS PON

XGS-PON the current and widely available generation of gigabit PON (GPON) technology, although the 50G higher speed PON (G.HSP) specifications are now available. XGSPON is defined by the ITU-T G.9807.1. standard and offers asymmetrical (10/1Gbps) and symmetrical (10/10 Gbps) rates for downstream and upstream.

The peak user throughput to an ONU is around 8.55 Gbps upstream and 8.6 Gbps downstream

4. Conclusion

The table below offers a summary of the scenarios that we reviewed in this paper. It documents the number of downstream/upstream channels and the theoretical (best conditions) peak capacity that would be obtained in each of those configurations. (Do keep in mind that changing the underlying assumptions e.g., channel conditions, number of channels, spectrum allocated will change the numbers appropriately.)

Table 2 – Summary of Peak Speeds on the Path to 10G

Plant Config	Technology	DS Channels			US Channels				Theoretical Peak Capacity	
		SC QAM DS	DS-192-OFDM	FDX DS-192	SCQAM US	OFDMA-US-75	OFDMA-US-96	FDX US-96	Max DS Mbps	Max US Mbps
42 split / 750 MHz	D3.0	32			4				1216	106
42 split/ 860 MHz	D3.1	32	0.5		5	0	0		2170	133
42 split/ 860 MHz	D3.1	32	0.5		1	0.34	0		2170	267
42 split/ 860 MHz	D3.1	32	2		3	0.17	0		5030	200
85 split/ 1.2 GHz	D3.1	32	2		10	0	0		5030	265
85 split/ 1.2 GHz	D3.1	32	2		4	0.66	0		5030	572
85 split/ 1.2 GHz	D3.1	32	2		0	1	0		5030	708
204 split/ 1.2 GHz	D3.1	32	2		4	0.938	1		5030	1764
204 split/ 1.2 GHz	D3.1	32	2		0	0	2		5030	1988
204 split/ 1.2 GHz	D4.0 ESD	32	4		4	0.938	1		8844	1764
300 split/ 1.8 GHz	D4.0 ESD	32	5			1	2		10751	2696
396 split/ 1.8 GHz	D4.0 ESD	32	5			1	3		10751	3690
492 split/ 1.8 GHz	D4.0 ESD	32	5			1	4		10751	4684
684 split/ 1.8 GHz	D4.0 ESD	0	5			1	6		9535	6672
FDX/1.0 GHz	D4.0 FDX	32	0	3	4	0.66		6	6937	6537
FDX/1.0 GHz	D4.0 FDX	1	1	3	4	0.66		6	7666	6537
FDX/1.2 GHz	D4.0 FDX	32	1.15	3	4	0.66		6	9141	6537
FDX/1.2 GHz	D4.0 FDX	4	2	3	0	1		6	9687	6672
PON	10GEPON								8700	8650
PON	XGSPON								8660	8600

The figures below summarize the information in the table above in a graph, to get a feel for the differences in technology. The first figure shows the various downstream and upstream peak capacities, while the second figure shows the amount of actual usable spectrum (upstream versus downstream versus FDX) at the CM based on the number of channels in each of these configurations.

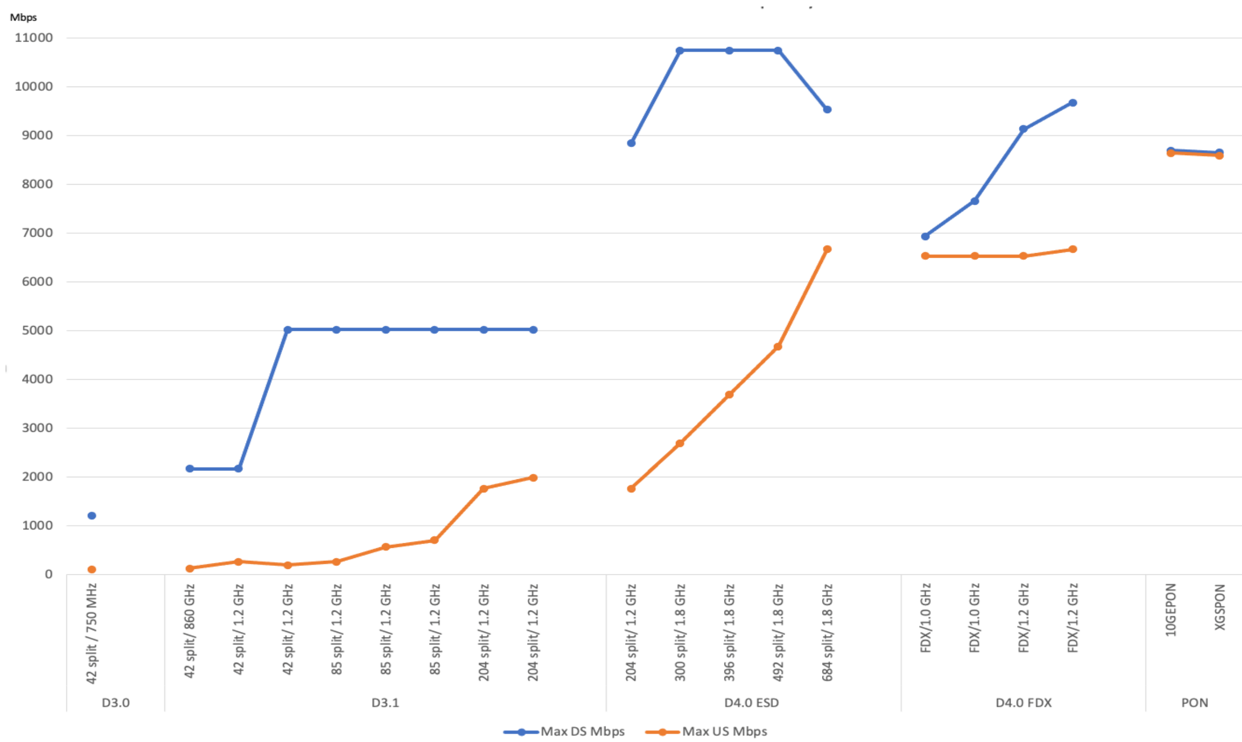

Figure 21 – DOCSIS CM DS/US capacity across technologies

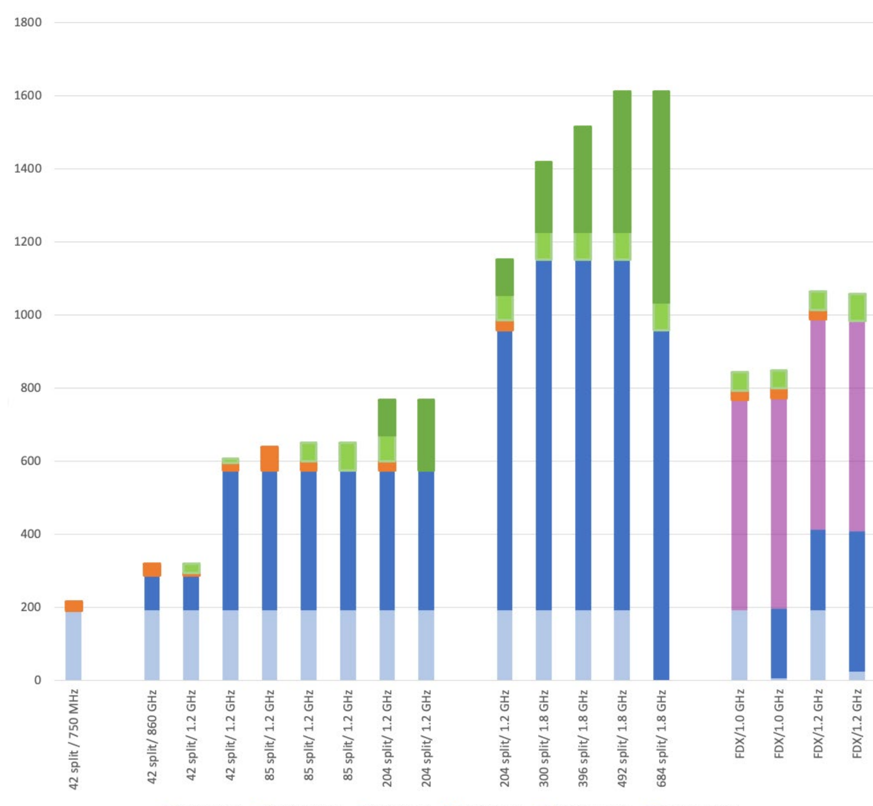

Figure 22 – DOCSIS CM DS/US Usable spectrum usage

As seen in the table/figures above and in the example scenarios in this paper cable operators have many useful and cost-effective choices to increase the service speeds to their customers. Both DOCSIS 3.1 and DOCSIS 4.0 technologies give the operators plenty of options in both the upstream and downstream network design. The speeds provided by these technologies are more than capable to meet the competitive pressures in each of their respective markets. D3.1 can provide up to 5 Gbps downstream and almost 2 Gbps upstream peak speeds, ultimately enabling high service tier speeds to the customers. D4.0 FDD and FDX technologies take those peak downstream speeds to the 10 Gbps level and 6.6 Gbps in the upstream. This paper walks through the various channel planning scenarios that operator would need to go through to figure out which of these options they choose in each of their markets for scale, reliability, and cost for the benefit of speeds offered.

Abbreviations

CM	cable modem
CMTS	cable modem termination system
CTA	consumer technology association
DAA	distributed access architecture
DOCSIS	data over cable service interface specifications
EPON	ethernet PON
FDD	frequency division duplex
FDX	full duplex DOCSIS
GHz	gigahertz
HFC	hybrid fiber coax
IEEE	Institute of Electrical and Electronics Engineers
IPTV	internet protocol television
Mbps	megabits per second
MHz	megahertz
MSO	multiple system operator
NTSC	National Television System Committee
OFDM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multiple access
ONU	optical network unit
PHY	physical
PON	passive optical network
QAM	quadrature amplitude modulation
SC-QAM	single carrier QAM
SCTE	Society of Cable Telecommunications Engineers
STB	set top box
TV	television
UHS	ultra-high split

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