# DOCSIS 3.1 and Migration Options for Operators

A Technical Paper prepared for the Society of Cable Telecommunications Engineers
By

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# Overview

This paper investigates the methods and challenges an operator is faced with when considering an introduction of DOCSIS 3.1 into their network. It discusses the infrastructure and subscriber network changes that may be needed to implement different splits into the frequency spectrum for upstream and downstream bands, and offers a strategy for migration based on the goals and constraints different network topologies present.

## EVOLUTION OF DOCSIS

CableLabs introduced DOCSIS in 1997 and over the past 17 years, it has evolved to increase capacity, quality of service and security for end users. Table 1 below provides a quick summary of these changes and the version of DOCSIS that introduced them. Since it's inception, DOCSIS has improved throughput in both up and downstream directions allowing compelling services like IP Video delivery and higher data service tiers. Security improvements have allowed cable operators to ensure the secure transmission of user data over the cable infrastructure, with more robust encryption and authentication methods.

| **Version** | **Bandwidth** | | **Security** | **QoS** |
|---|---|---|---|---|
| | **Downstream** | **Upstream** | | |
| **DOCSIS 1.0** | 256-QAM<br>38 Mbps/ch | 16-QAM<br>10.24 Mbps/ch | BPI<br>Basic; no device authentication | Best effort<br>No parametric QoS |
| **DOCSIS 1.1** | Same as DOCSIS 1.0 | Same as DOCSIS 1.0 | BPI+<br>Expanded security<br>Device Authentication | Service flows<br>Parametric QoS |
| **DOCSIS 2.0** | Same as DOCSIS 1.0 | 64-QAM<br>ATDMA/S-CDMA<br>30.86 Mbps/ch | Same as DOCSIS 1.1 | Same as DOCSIS 1.1 |
| **DOCSIS 3.0** | 256-QAM<br>38 Mbps/ch<br>Channel bonding up to 32 channels<br>108 to 1002 MHz | 64-QAM<br>ATDMA/S-CDMA<br>30.86 Mbps/ch<br>Channel bonding up to 8 channels<br>5 to 42 MHz | BPI+<br>Early Authentication and Encryption<br>128-bit AES | Queue-depth based Requests<br>Adaptive Queue Management<br>Removal of PHS |
| **DOCSIS 3.1** | SC-QAM support per DOCSIS 3.0 | SC-QAM support per DOCSIS 3.0 | New PKI Scheme<br>Dual Root | Hierarchical QoS |

| | | | | |
|---|---|---|---|---|
| | OFDM<br>192 MHz/ch (max)<br>Minimum of 2 channels<br>Upper band edge of 1.794 GHz | OFDMA<br>96 MHz/ch (max)<br>Minimum of 2 channels<br>Upper band edge of 204 MHz | Certificate Structure<br>Longer Keys | |

**Table 1: DOCSIS Evolution**

Changes within DOCSIS rarely involve substantial changes to an operator's infrastructure, and typically involve a simple upgrade or replacement of the CMTS and its components in order to be implemented. Backward compatibility has always been a core tenet of DOCSIS, and has supported coexistence of legacy DOCSIS devices with their newer generation cousins. DOCSIS 3.0 introduced an increase in the upstream spectrum split to 85 MHz and also allowed the cable modem to transmit at higher power for SC-QAM (Single-Carrier Quadrature Amplitude Modulation) channels (bonded and non-bonded modes of operation). This presented challenges for cable operators in how to introduce these features as the changes force modifications to active plant equipment as well as requiring that the services traditionally transmitted in those frequencies (like TV channels 2-4) to be moved to accommodate the new upstream spectrum. DOCSIS 3.1 has expanded this upstream split further to a maximum of 204 MHz. These enhanced spectrum areas come with special challenges for implementation which are described later in this document.

## DOCSIS 3.1 PHY CHANGES

The most notable improvements are at the PHY level where DOCSIS 3.1 specifies the use of Orthogonal Frequency Division Multiplexing (OFDM) in the downstream and Orthogonal Frequency Division Multiple Access (OFDMA) in the upstream. DOCSIS 3.1 CMTSs are required to support 1024-QAM on upstream OFDMA channels, while DOCSIS 3.1 CMs are required to support higher QAM settings of 2048-QAM and 4096-QAM. DOCSIS 3.1 has also expanded the frequency spectrum for both the upstream and downstream. A DOCSIS 3.1 CMTS is required to support 1 GHz, and should support 1.212 GHz and may support as high as 1.788 GHz. The DOCSIS 3.1 CM is required to support downstream band edges of 1.212 GHz and may support the upper band edge of 1.788 GHz. Figure1 shows the DOCSIS 1.x/2.0 frequency spectrum vs. the DOCSIS 3.1 spectrum. Note the conflict that exists, as this will be discussed later when we analyze the challenges with migration to support a DOCSIS 3.1 network.

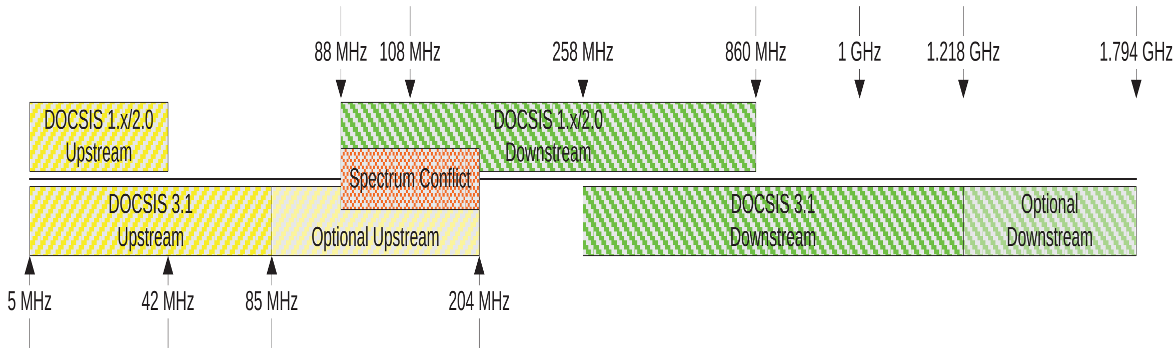


**Figure 1: Frequency Spectrum of DOCSIS 1.x/2.0 vs. DOCSIS 3.1**

Table 2 offers a comparison of how OFDMA increases the throughput versus the pre-DOCSIS 3.1 SC-QAM channels in the same bandwidth.

| Spectrum | DOCSIS 3.0 | Capacity | DOCSIS 3.1 | Capacity |
|---|---|---|---|---|
| **5 to 42 MHz** | SC-QAM<br>6.4 MHz @ 64-QAM<br>Five channels | 153 Mbps | OFDMA<br>4096-QAM (CM)<br>1024-QAM (CMTS)<br>1480 subcarriers | 325.8 Mbps with 1024 QAM |
| **42 to 85 MHz** | SC-QAM<br>6.4 MHz @ 64-QAM<br>Six channels | 184 Mbps | OFDMA<br>1024-QAM<br>1720 subcarriers | 325.8 Mbps |
| **5 to 85 MHz** | SC-QAM<br>6.4 MHz @ 64-QAM<br>12 channels | 368.6 Mbps | OFDMA<br>1024-QAM<br>3200 subcarriers | 651.7 Mbps |
| **5 to 204 MHz** | N/A | N/A | OFDMA<br>1024-QAM<br>7960 subcarriers<br>(2 96 MHz OFDMA channels) | 1.56 Gbps |

**Table 2: Maximum Theoretical Throughput, Upstream**

DOCSIS 3.1 effectively achieves about a 2.5x increase in upstream throughput by using OFDMA technology in the upstream. However, in order to support a mixed environment of pre-DOCSIS 3.1 devices, DOCSIS networks will still be required to offer legacy 3.0 upstream channels for some time.

This is where a more efficient use of the spectrum is beneficial to the operators. OFDM technology allows an operator to provide the same number of services in a much smaller bandwidth in the downstream. This becomes the key strategy to defining a migration plan to DOCSIS 3.1; compressing downstream channel offerings in a tighter bandwidth to free additional spectrum for upstream expansion.

When looking at the migration to DOCSIS 3.1, operators have many choices in how to implement the new DOCSIS architecture. It is beneficial to look at these deployment alternatives separately in the Downstream and Upstream directions as the work required in each case is different.

## Downstream Deployments

One of the main drivers for the DOCSIS 3.1 OFDM channels is increased efficiency on the downstream spectrum. This is achieved in several ways. First, the higher modulation orders of the subcarriers in the OFDM channel allow the CMTS to get more bits per second per Hertz[1]. The term "bits per second per hertz" or bps/Hz refers to the ability to pass data traffic over a given frequency and is often used to define spectral efficiency. In this paper we will use the term bps/Hz and bits per second per hertz interchangeably. The more bits per second per hertz a carrier can transfer, the higher the data rate that can be achieved. To illustrate this, using DOCSIS 3.0 downstream channels, it would take 26 downstream channels to offer a 1 Gbps service. With DOCSIS 3.1, the CMTS and CM only need to manage a single, 192 MHz OFDM channel which reduces the amount of signaling overhead needed to register and operate the CM. DOCSIS 3.1 also allows the operator to define exclusion bands for spectrum issues that are present within the OFDM channel. In DOCSIS 3.0, if a given 6 MHz channel had issues like ingress, the CMTS would not be able to use that channel. With DOCSIS 3.1, the cable operator can define an exclusion bands to work around the trouble spot and thus reclaim some spectrum that was previously unusable.

One of the important things to note is that DOCSIS 3.1 downstream channels can be implemented with minimal upgrades to the downstream plant. Many cable operator's serving groups are served with 750 MHz, or increasingly 870 MHz plant. If the cable operator can clear a portion (as little as 24 MHz) of downstream spectrum a DOCSIS 3.1 ODFM channel can be established.

Plant upgrades to the active plant equipment are also a consideration. In plants that have had upgrades in the past several years, it may be possible to augment these active plant components with drop-in upgrades that will help the operator achieve 1 GHz operation. Once these upgrades have taken place, the cable operator can likely

[1] Ayham Al-Banna et. al., "The Spectral Efficiency of DOCSIS® 3.1 Systems", SCTE-ET 2014, September 2014.

incorporate at least 1 full width OFDM downstream channel in the freshly available spectrum.

The next migration step might be to continue the upgrades to operate at 1.2 GHz or higher. This operation is a bit more involved than the easy drop-in method to bring 750/870 MHz plant up to 1 GHz. Studies using current generation technologies show that to get to 1.2 GHz operation in the actives on the plant will require significantly more power in the node to produce the proper signal levels across the entire band[2]. This is due to the tilted output levels in the outside plant. Some studies report that the additional 200 MHz contains more power than the entire original 54-1002 MHz spectrum.

Node splits are also an effective way to help gain additional capacity. While these splits do not offer more in the way of actual spectrum, they do offer a significant bonus in helping shrink the number of homes passed per node. When strategically implemented in the serving areas, these node splits have the effect of augmenting and making more bandwidth available to a smaller number of homes, improving everyone's connectivity.

Two challenges exist in the subscriber home when evaluating the expansion of the downstream spectrum above 1 GHz. First, many of the passive taps and splitters used within a home are typically rated at 1 GHz (possibly less). An upgrade of these may be required to accommodate these increases. Second, MoCA technology is becoming more prevalent within subscriber homes as well, which operates in the same spectrum as DOCSIS 3.1 expanded downstream, and once again, can result in contention if the DOCSIS network is carried into the home far enough. While it is possible to take advantage of this technology by terminating the DOCSIS 3.1 signal at the point of entry to the home, it still requires a substantial reconfiguration and potential replacement of the household's devices.

## Deploying DOCSIS 3.1 Upstream

We now turn the attention to enhancements to DOCSIS 3.1 for upstream OFDMA channels. The DOCSIS 3.1 specification offers several different steps for upstream spectrum increase – 65 MHz, 85 MHz, 117 MHz and 204 MHz. These enhancements have the most potential to be disruptive for active plant equipment and will require work to support by the cable operator. It is also important to note, DOCSIS 3.1 has a provision for the coexistence of legacy 3.0 upstream channels (called Single Carrier – QAM or SC-QAM) and OFDMA in the same spectrum. This means that, DOCSIS 3.1

[2] Dean Stoneback et.al, "Making Rational HFC Upstream Migration Decisions in the Midst of Chaos", 2012

OFDMA upstream channels can be deployed using existing 5-42 splits with support from the CMTS to help manage the transmissions of both channel types. .

As Migration strategies go, we can once again employ the node-split as a technique for operators to use while the planning and infrastructure changes to move to the newer and higher upstream splits are implemented. As discussed for the downstream expansion, these splits can be very effective for a time and allow the cable operator to manage the current splits for the short term. However, to achieve the true benefits of DOCSIS 3.1 and get the best possible spectrum efficiency in the upstream, the upstream frequency splits must change to the new 85, 117, or 204 MHz frequencies. It is these expansions that will drive the costs that operators will bear for the delivery of this service.

Cable operators thus have two distinct paths to use for upstream spectrum expansion; node splits to continue to use the 5-42 MHz with legacy DOCSIS 3.0 upstreams and one OFDMA DOCSIS 3.1 channel or upgrade active plant equipment to 85 MHz or greater operation.

The following section will detail some of the impacts that may be seen by cable operators as they work to enable this spectrum for upstream channels.

## Active Plant Impacts

For active plant elements in the HFC network, several impacts have been identified that need to be considered or directly addressed as cable operators look to these new upstream split values. One such impact is that the upstream gain that is currently supported may need to increase to support the increased cable loss and Customer Premise Equipment (CPE) transmit levels. Today, these values are typically in the 18-26 dB range. These values may need to be increased by as much as 3 to 7 dB to support 85/204 MHz diplex filter split to account for the additional tilt that is present at the higher frequencies. The HFC network design may also need to account for the introduction of new upstream thermal level compensation circuitry to compensate for increased cable loss/change over temperature in this new spectrum area. Another potential impact may be that the faceplates for taps may need to be replaced to support lower CPE transmit levels. An alternative to this might be to reduce amplifier/node input level which may impact CNR/NPR performance on each leg of the HFC network. These tap faceplate changes may impact more taps when the splits are raised to 204 MHz – some studies have predicted that this could be as much as 90% change-out versus approximately 12% for 85 MHz operation.

When considering the impact of the upstream frequency expansion and active DOCSIS upstream channels in this space, the cable operator needs to consider impacts to several key areas. Amplifier noise funneling is one area where there may be impacts.

With wider return spectrum frequencies, the possibility of funneling noise from a larger portion of the spectrum comes into play. It is also worth noting that with the increased frequency span for DOCSIS 3.1 upstream channels, bands like the FM band and some analog channels may be impacted when they occupy the same frequency.

Return path amplifiers can also be impacted with the larger frequency spans. The diplex filters associated with these devices in some case may need to be replaced to account for the wider spectrum. These changes, along with the need to account for equalizer and thermal losses, make managing the performance of the return plant amplifiers important when choosing to move to the higher splits for DOCSIS 3.1.

Finally, the performance of the upstream optics may need to be reviewed and updated to help support the higher frequency splits. These items include the ability to support higher bandwidth optical link budgets. The Operator may need to employ multi-wavelength configurations to help manage the traffic load at the active node. These decisions could lead the operator into an accelerated assessment of Analog FP/DFB or employing digital return path optics.

The expansion past 42 MHz in North America will entail several activities. The first of which is to move any current content and channel definitions for Broadcast TV and be very vigilant about signal leakage in the spectrum between 42 and 204 MHz. Some of the services that already occupy this space include the following:

| Frequency Range | Service |
|---|---|
| 50-54 MHz | Amateur Radio |
| 54-72 MHz | Broadcast TV Channels 2-4 |
| 75 MHz | Aeronautical |
| 76-88 MHz | Broadcast TV Channels 5-6 |
| 88-108 MHz | FM Radio Band |
| 108-137 MHz | Aeronautical band |
| 130 MHz | Legacy STB OOB (SCTE 55) |
| 174-216 MHz | Broadcast Channels 7-13 |

**Table 3: Services and Frequencies 42-216 MHz**

To truly realize the full impact of OFDMA channels that are the full 96 MHz, the upstream splits need to increase past the current 45 MHz.

In addition to HFC network impacts, an increase to 85 MHz has impacts when dealing with the customer infrastructure. This is due to the number of devices existing in a subscriber's home that were designed based on early SCTE 40 guidelines. These guidelines specified "Maximum Individual Carrier Amplitude" of +20 dBmv above 54Mhz. DOCSIS 3.0 and 3.1 modems are allowed to transmit as high as 57dBmv which cause some issues with many front ends on STBs and early TVs. If a DOCSIS 3.1 device is transmitting on the upstream in the 42 to 85 MHz range, a STB will see this upstream transmission as downstream and erroneously make AGC adjustments because these upstream transmissions are forwarded through existing splitters and hit the front end of the STB. These transmissions are considered as interfering carriers which then activate the AGC adjustments. If these signals are more than 15dB above the video signal, these STBs will have trouble rendering video channels in a reliable way.

In Figure 2, a typical home is depicted that contains a cable modem, legacy STBs, and a connected TV. We will use this figure to provide insight into some of the issues that may be seen in the home when there are DOCSIS devices transmitting above 54 MHz.

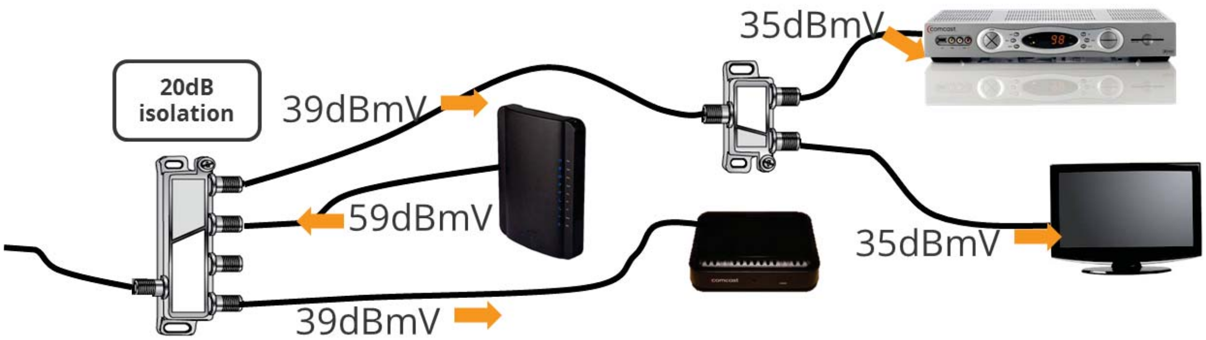


Figure 2: Representative Home Topology

In our diagram, this home has two legacy STBs, a cable modem and a connected TV. The initial 4 way splitter offers 20dB of port to port isolation. Note that the CM is transmitting at 59dBmv. Inside the home, these signals then are able to cross to adjacent ports on the splitter which only has a 20dB of isolation. The resulting carriers are then carried to either a second splitter or a second STB where that signal then hits the front end of the device.

There are two solutions to consider that address this problem. The least costly alternative would be to place a notch filter at the inputs to any legacy devices operating in accordance with a 5 to 42 MHz upstream. The location of these notch filters can be seen with the colored arrows in the figure.

A second mitigation technique would be to place a 2-way splitter in front of the 4 way and place the cable modem on that.  The second leg then could have a single notch filter installed on the link between the 2-way and the 4-way in the home which would then protect the devices.  This results in an additional 3-4dB of attenuation, but greatly simplifies the installation needed. This home topology is shown in Figure 3 below.

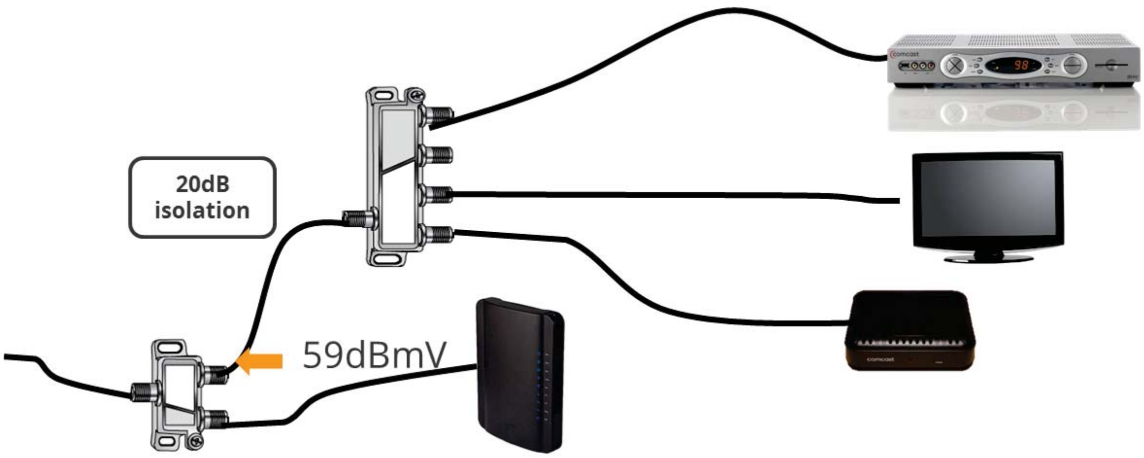


Figure 3: Alternate Home Topology

Adding these notch filters in this way also  addresses the neighboring households as well, however, all homes serviced by the node would need to install these filters regardless of using DOCSIS 3.1 devices or not to prevent issues caused by cable modems operating with upstream channels above 42 Mhz. Another much more costly solution involves the replacement of any legacy QAM devices in the home with devices that accommodate a 5 to 85 MHz upstream spectrum split. This would need to occur for all homes on a given node that has been upgraded to run upstream channels at greater than 42 Mhz.

Another mitigation strategy has been emerging recently that also shows promise.  This strategy employs a DOCSIS gateway with dual RF ports to be used as the point of entry into the home network.  In this scenario, a cable is home run to the gateway and connected to the DOCSIS gateway. No other devices are on the same drop from the tap.  The second port is then connected to the existing home coaxial network.  In the DOCSIS gateway, a downstream switchable band pass filter can be employed to provide the isolation needed for the in-home MoCA services as well as keeping the new DOCSIS 3.1 downstream frequencies above 1Ghz off of the home RF or coaxial network. QAM based video carriers can be passed through from port 1 to port 2 so that legacy QAM STBs can continue to function. On the upstream side, all the DOCSIS upstream transmissions are kept on the first RF port which prevents any issues with legacy device front ends. These devices are likely to have some additional costs due to the addition filters, but offer significant upside for isolation management of both outside and inside networks. This topology is shown in Figure 4 below.

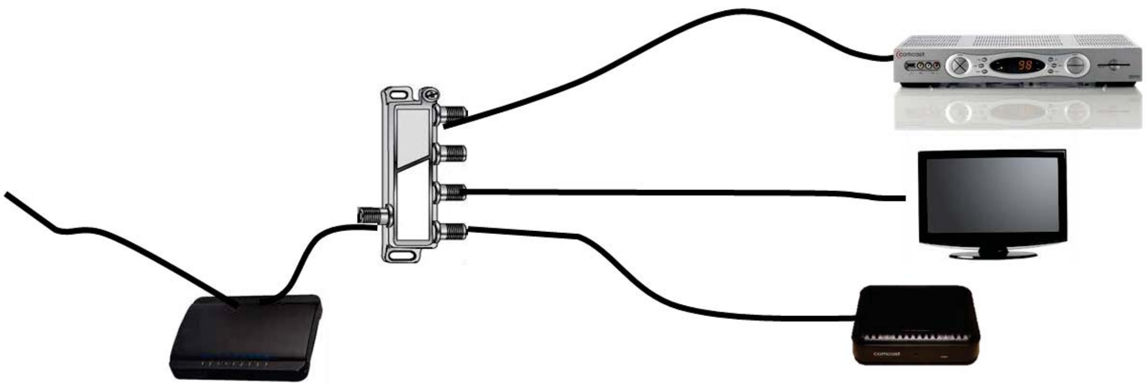

Figure 4: DOCSIS Gateway as a Point of Entry

Finally, the Operator needs to pay attention to older generation STBs that are not DSG and which use an OOD control channel. These control channels are used for several important STB functions such as:

- Configuration and Entitlements
- IPPV Purchase Collection and Polling
- Add and Delete Set tops from the System
- Channel Line-up and Guide Data
- Code updates

The OOB frequencies that have been defined are 72.75, 75.25, 92.25, 98.25, 103.75, 104.20, 107.25, 107.40, 110.25, and 116.25, MHz. There are several ways in which these OOB channels can be accommodated when DOCSIS upstream channels are configured above 42 MHz. The first method would be to move the STBs from a frequency under 103 MHz to above 103 MHz. Many STBs can accomplish this task with modifications to the running configuration on the boxes. A second method might be to replace these older generation STBs with DSG STBs. In this case, the OOD services are done using IP and not RF so there are no issues with configuring upstream channels in the spectrum. The final mitigation method can be to define DOCSIS 3.1 upstream channel exclusions for the carriers that are employed for these older generation STBs.

## Possible Strategies for Increasing Upstream Spectrum to 85 MHz and Beyond

While there are many different strategies and tools that can be employed, there is no one solution for every situation.

The first strategy could be to employ analog channel reclamation by using DTAs or Switched Digital Video (SDV) to help move the needed downstream VHF video channel content out of the spectrum between 42 MHz and 85/117/204 MHz.

The next step might be to perform the upgrade to at least 85 MHz on active plant equipment. This strategy allows the cable operator to address new OFDM and well as legacy DOCSIS 3.0 modems and allow these devices to operate in as yet unused spectrum allowing additional gains for both populations of modems. This strategy also capitalizes on the DOCSIS 3.1 capability to run OFDMA and legacy DOCSIS 3.0 upstreams in the same spectrum.

A possible next step would be to reclaim legacy STBs with from service groups. The older generations of STBs use a return path for interactive services like Pay Per View and Video on Demand which is located at 130 MHz. This effort is aided in large part by the use of newer generation of STBs and video gateway products that are in deployment today in several operators' networks which use an IP based return path over DOCSIS upstream channels. Once this set of devices has been removed from the plant, the cable operator is then able to increase the usage of the upstream spectrum to at least 117MHz so that a full 96 MHz OFDMA channel can be deployed and offer in excess of 500 Mbps upstream in a single channel.

Another strategy might be to continue to perform node splits on existing nodes. This strategy may allow the cable operator to hold off upgrades of the current HFC plant to supporting 85 MHz or higher upstream frequencies.

# USE CASES

In this section we will investigate a pair of use cases that illustrate potential ways that an Operator can deploy DOCSIS 3.1 technologies to provide a 1 Gbps down and 100 Mbps upstream service. This is one target that is often described by cable operators as a logical early deployment target for DOCSIS 3.1 equipment.

In order to understand some of the terminology used in the following use case, it is important to understand some of the mechanics and configuration of the new DOCSIS 3.1 channels. ODFM and OFDMA channels use subcarriers that are spaced at regular intervals across the channel. In order to process those subcarriers, the CMTS and CM respectively use a fast Fourier transform for sampling the upstream or downstream frequency. In the downstream direction, a 4K and 8K FFT sampling rate is supported in the DOCSIS 3.1 specifications. In the upstream direction a 2K and 4K FFT are mandated. In general, a larger FFT size will lead to higher numbers of subcarriers being supported in the channel which allows for higher data capacities and greater spectral efficiencies.

OFDMA channels are interleaved in both time and frequency and use a similar minislot transmission method as we used in previous versions of DOCSIS. There are different in DOCSIS 3.1 in that a minislot contains pilot subcarriers (which help keep the receiver locked with the transmitter and data subcarriers (these carry the data).

DOCSIS 3.1 OFDMA channels can coexist in the same frequency spectrum as any pre-DOCSIS 3.1 upstream channel. To accomplish this, the CMTS creates transmission opportunities on and OFDMA channel while at the same time assigning the same time slots on the single carrier QAMs to a null SID which ensures that no transmissions from those upstream channel can be made. Likewise, when a single carrier QAM channel is scheduled to transmit, those tile slots are not available to the OFDMA channel.

In this section we also make use of the concept of Spectral Efficiency. The term spectral efficiency is a method that allows one to calculate the number of bit per second per Hertz or the amount of data that can be transferred over a given frequency span. Using these Spectral Efficiency values, we can calculate the channel capacity of different sized upstream and downstream OFDM channels as well as SC-QAM channels.

In order to calculate the channel capacity portions in this section, we have used the following assumptions based on the information in the paper “The Spectral Efficiency of DOCSIS® 3.1 Systems”[3]. This paper provides a number of spectral efficiency values that can be used in the following equation to calculate the channel capacity of a given OFDM or OFDMA channel.

$$\textbf{\textit{channel capacity}} = \textbf{\textit{spectral eff.}} * \textbf{\textit{channel BW}}$$

For downstream channels, the paper indicates that for an OFDM channel with an 8K FFT and an SNR operating Margin of 0dB, we can expect a spectral efficiency of 8.1996 bits/second/Hertz, while a 4K FFT size yields a spectral efficiency of 7.5989 bits/second/Hertz. Using these values in the equation above, a 192 MHz OFDM channel can achieve a downstream data rate of 1.5 Gbps with an 8K FFT and a 1.46 Gbps rate with a 4K FFT.

[3] Ayham Al-Banna et. al., “The Spectral Efficiency of DOCSIS® 3.1 Systems”, SCTE-ET 2014, September 2014.

For the downstream channels, the following tables show some probable OFDM Channel Configurations and their corresponding channel capacities.

| Channel width | Spectral Efficiency in bps/Hz | Channel Capacity in bps |
|---|---|---|
| 192 | 8.1996 | 1,574,323,200 |
| 96 | 8.1996 | 787,161,600 |
| 48 | 8.1996 | 393,580,800 |
| 24 | 8.1996 | 196,790,400 |

**Table 4: Downstream OFDM Channel Capacities**

| Channel width | Spectral Efficiency in bps/Hz | Channel Capacity in bps |
|---|---|---|
| 192 | 7.5989 | 1,458,988,800 |
| 96 | 7.5989 | 729,494,400 |
| 48 | 7.5989 | 364,747,200 |
| 24 | 7.5989 | 182,373,600 |

**Table 5: Downstream OFDM Channel Capacities**

In a similar fashion, upstream OFDMA channel capacities can be calculated as well. For upstream channels, the paper indicates that for an OFDMA channel with a 4K FFT and an SNR operating Margin of 0dB, we can expect a spectral efficiency of 8.146 bits/second/Hertz, while a 2K FFT size yields a spectral efficiency of 7.694 bits/second/Hertz when the upstream is configured for 1024-QAM . Using these values in the equation above, a 96MHz OFDMA channel can achieve an upstream data rate of 782 Mbps with an 4K FFT and a 738.6 Mbps rate with a 2K FFT.

| Channel width | Spectral Efficiency in bps/Hz | Channel Capacity in bps |
|---|---|---|
| 96 | 8.146 | 782,016,000 |
| 48 | 8.146 | 391,008,000 |
| 40 | 8.146 | 325,840,000 |
| 24 | 8.146 | 195,504,000 |
| 6.4 | 8.146 | 52,134,400 |

**Table 6: Downstream OFDM Channel Capacities 1024-QAM**

| Channel width | Spectral Efficiency in bps/Hz | Channel Capacity in bps |
|---|---|---|
| 96 | 7.694 | 738,624,000 |
| 48 | 7.694 | 369,312,000 |
| 32 | 7.694 | 246,208,000 |
| 24 | 7.694 | 184,656,000 |
| 10 | 7.694 | 76,940,000 |

**Table 7: Downstream OFDM Channel Capacities 1024-QAM**

As noted earlier, it is possible for DOCSIS 3.1 OFDMA and legacy DOCSIS 3.0 upstream channels to occupy the same frequency spectrum. In these cases, each of the channels is impacted by the utilization of each type of channel. For instance, if we had two DOCSIS 3.0 ATDMA channels that were both 6.4 MHz wide and 40 % utilized and a single OFDM channel that was 10 MHz wide completely overlapped by the ATDMA channels, the OFDMA channel would only have access to a maximum of 60% of its capacity. This case is illustrated by the following diagram,

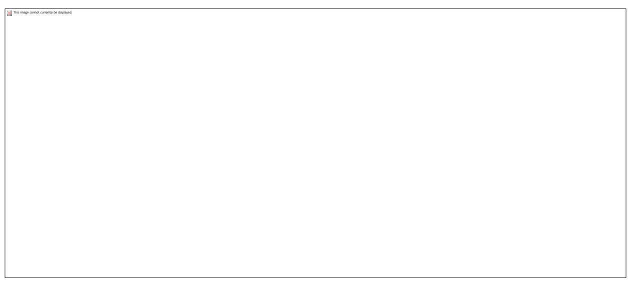

Figure 5: OFDMA Overlapping Case 1

OFDMA channel capacity in this case is calculated as

$$\boldsymbol{channel\ capacity} \\ = \boldsymbol{OFDMA\_spectral\ eff.} * \boldsymbol{OFDMA\_channel\ BW} * \boldsymbol{OFDMA\_utliization}$$

Another overlapping case exists where the OFDMA channel is larger than the SC-QAM channels. In this case, we can calculate the channel capacity as the capacity of the overlapped part of the ODFMA channel plus the capacity of the non-overlapped portion of the OFDMA channel. This scenario is represented in Figure 6 below.

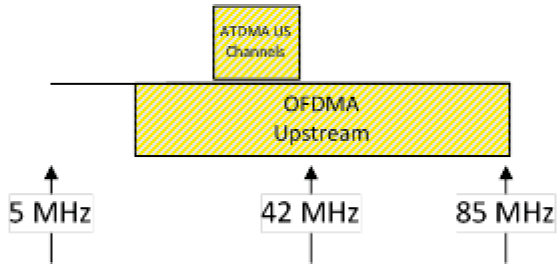


Figure 6: OFDMA Overlapping Case 1

The channel capacity calculation for this case is:

$$\boldsymbol{Capacity = OFDMA\ \ Capacitynon - overlapped + OFDMA\_Capacity\_overlapped}$$

Where capacity mixed is calculated as:

$$\boldsymbol{channel\ capacity = OFDMAspectral\ eff.* \ OFDMA\_channel\ BW\_overlapped * OFDMA\_utliization}$$

And capacity of the non-overlapped channel as

$$\boldsymbol{channel\ capacity\ = OFDMA\_spectral\ eff.* \ OFDMA\_channel\ BW\_nooverlapped}$$

## Use Case 1

In this Use Case, the operator wishes to use existing HFC plant splits of 42 MHz. The cable operator has an 860 MHz maximum downstream band edge and has not yet deployed a 1 GHz downstream. The cable operator has 48 MHz of downstream spectrum that has been reclaimed and will be used for an OFDM downstream channel. The cable operator also has 16 SC-QAM channels in every serving group for a total DOCSIS downstream capacity of 608 Mbps. DOCSIS 3.1 has specified that a DOCSIS 3.1 cable modem can utilize bonding groups that contain both SC-QAM and OFDM downstream channels. In this use case, we will assume that the operator has configured such a bonding group which would then yield a downstream capacity of about 940 Mbps.

On the upstream side, the cable operator has four (4) 6.4 MHz wide, 64-QAM channels deployed today between 25 and 42 MHz. for their DOCSIS 2.0 and 3.0 modem populations. The cable operator can then deploy one (1) or more OFDMA upstream channels in the 10-42 MHz space. One method might be to establish a channel with no overlap with current US channels between 5 and 25 MHz. In this case, the ODFMA channel would have a capacity of 162.9 Mbps when using 4 2 K FFT and 1024-QAM configuration. With a 2 K FFT and a channel width of 20 MHz, the operator can expect to get about 153.8 Mbps.

The cable operator could also deploy an ODFMA channel from 5-45MHz (a 40 MHz channel width) which would overlap the current 4 ATDMA channels. For the sake of the calculations, let's assume that the 4 ATDMA channels are all 50% loaded leaving 50% of the time open for DOCSIS 3.1 OFDMA operation. This means that the 1024 QAM OFDAM capacity in the non-overlapped spectrum is (14.4 * 8.146) or 117.3 Mbps and the OFDMA capacity in the overlapped spectrum is (25.6*8.146*.5) or 104.2 Mbps. In this case, the cable operator would still be able to support an aggregate of 221.5 Mbps in a bonded configuration for DOCSIS 3.1 modems.

## Use Case 2

In this Use Case, the cable operator has chosen to upgrade the downstream plant from 860 MHz in the first use case to 1 GHz. The cable operator now has access to the 48 MHz from the earlier use case as well as the 142 MHz gained from the upgrade to 1 GHz. The cable operator can now deploy a full OFDM downstream channel which provides a 1.5 Gbps capacity downstream in addition to the currently deployed 16 SC-QAMs. With channel bonding, this service group has 2.1 Gbps of downstream capacity to offer subscribers.

On the upstream side, the operator makes the jump to an 85 MHz return path. In this case, the cable operator has several choices for the deployment of both SC-QAM and OFDMA channels, but chooses to create an OFDMA channel that runs from 5-85 (80 MHz channel OFDMA 1024 QAM, 4K FFT) and completely encompasses the 4 current ATDMA channels. In this case the upstream capacity is raised to 547.3 Mbps from the earlier 221.5 Mbps.

A second alternative would be to create a 40 MHz OFDMA channel that sits above the 5-42 MHz DOCSIS 3.0 upstreams with no overlaps in channel frequencies. In this case, the operator would have 106 Mbps from the 4 DOCSIS 3.0 upstream channels and 325.8 Mbps from the 40 MHz OFDMA channel for a total bonded capacity of 431.8 Mbps

## SUMMARY

As you can see, the introduction of DOCSIS 3.1 to an operator's network is easily achieved and possible with very little, if any, plant modifications. While many people believe that a cable operator must upgrade their HFC plant to deploy DOCSIS 3.1 channels, we have shown that it is entirely possible to implement these new channel types on an existing plant with existing diplex filter splits. DOCSIS 3.1 requirements allow for flexibility in managing the frequency spectrum to accommodate adoption rates of new and existing customers. The expansion of the DOCSIS 3.1 network is merely a function of cost analysis and determining the solution that works best for the operator. As more and more of the network transitions to DOCSIS 3.1, a continual conversion of SC-QAM channels to OFDM/OFDMA technology can occur, which can result in a 30% reduction in bandwidth utilization and gives the cable operator the means to realize a 1 Gbps upstream and 10+ Gbps downstream service, providing their customers with a user experience capable of supporting technologies in years to come.

# Bibliography

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# Abbreviations & Acronyms

| Abbreviation | Description |
|---|---|
| ATDMA | Advanced Time Division Multiple Access |
| bps/Hz | Bits per second per Hertz |
| CM | Cable Modem |
| CMTS | Cable Modem Termination System |
| CPE | Customer Premise Equipment |
| DTA | Digital Terminal Adapter |
| FFT | fast Fourier transform |
| Gbps | Gigabits per Second |
| Mbps | Megabits per Second |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OFDMA | Orthogonal Frequency Division Multiple Access |
| OOB | Out Of Band |
| SDV | Switched Digital Video |

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