Leveraging DOCSIS® 4.0 CM Backward Compatibility on DOCSIS 3.1 Networks

For an Increase in Capacity and Downstream Speed Tiers

A Technical Paper prepared for SCTE by

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1. Introduction

Every generation of DOCSIS® technology includes requirements for backward compatibility with the previous generation to enable seamless transitions. With a DOCSIS 4.0 cable modems (CM), there is opportunity to further exploit the capabilities of a currently deployed DOCSIS 3.1 cable modem termination system (CMTS).

Specification work was completed clarifying the behavior of DOCSIS 4.0 CMs with DOCSIS 3.1 CMTSs. This paper examines these possibilities, it discusses how a DOCSIS 3.1 CMTS negotiates capabilities with a DOCSIS 4.0 CM, how a DOCSIS 4.0 CM, either FDD (frequency division duplex, (also known colloquially as Extended Spectrum DOCSIS), and FDX (full duplex) will operate with various diplex filters on the DOCSIS 3.1 network, and how a DOCSIS 4.0 CM can be used to increase capacity on an existing HFC network.

With recent product upgrades, a DOCSIS 3.1 CMTS can now support up to five (or more) OFDM channels; however, currently available DOCSIS 3.1 CMs only support two OFDM channels that have a peak downstream rate of about 5 Gbps. Operating a DOCSIS 4.0 CM on a DOCSIS 3.1 CMTS (with additional OFDM channels), can support a downstream peak capacity of up to 8.8 Gbps—a 75% increase relative to currently deployed DOCSIS 3.1 CMs. With higher capacities, operators can provide enhanced services and faster downstream speed tiers even before implementing DOCSIS 4.0 network topology changes and installing DOCSIS 4.0 CMTSs.

For DOCSIS 4.0 CMs to become operational, a DOCSIS 3.1 CMTS may need a software update. This update enables a DOCSIS 3.1 CMTS to gracefully interpret and negotiate DOCSIS 4.0 modem capabilities, thereby enabling DOCSIS 4.0 CMs to be operated on a DOCSIS 3.1 CMTS. This paper touches on other dependencies such as support by the CMTS for bigger certificate sizes, and bonding on more than two OFDM channels, support for OUDP testing and overlapping channels. We will also report on lab testing results that we plan to conduct.

1.1. History

From a historical perspective, DOCSIS 3.0 technology had several iterations of CM silicon, each supporting an increasing number of bonded single-carrier quadrature amplitude modulation (QAM) (SC-QAM) channels. The DOCSIS 3.1 specifications (which introduced orthogonal frequency division multiplexing (OFDM) technology) were designed the same way, mandating that a CM support a minimum of two OFDM channels (in addition to 32 SC-QAM channels) while allowing a CM to support more than two OFDM channels. Currently deployed DOCSIS 3.1 CMs, however, only support two OFDM channels in the downstream direction, and DOCSIS 3.1 CMs with additional OFDM channels are no longer anticipated, as the industry's energy and focus are now directed toward DOCSIS 4.0 CM designs.

In contrast, while early DOCSIS 3.1 CMTS solutions supported only two OFDM channels, updated designs now support up to five OFDM channels. The additional OFDM channels on these more capable DOCSIS 3.1 CMTSs can be used by a DOCSIS 4.0 CM to provide much higher downstream peak capacity. As cable operators enhance the available spectrum in their HFC networks—such as moving the upper band edge up to 1.0 GHz or 1.2 GHz—spectrum is opened to support those additional OFDM channels. (This outside plant work is typically combined with efforts to increase the upstream bandwidth by transitioning from a sub-split to either a mid-split or high-split HFC network.)

2. DOCSIS Evolution and Capabilities

2.1. DOCSIS 3.0 Technology

DOCSIS 3.0 Technology was introduced in 2006~2008 and included a new feature called channel bonding which led to a substantial increase in broadband capacity. Prior to the DOCSIS 3.0 specifications, modems used a single downstream QAM channel and a single upstream QAM channel.

Downstream Channel Bonding enabled functionality at a CM to receive data simultaneously on multiple receive channels. Downstream Channel Bonding refers to the ability (at the MAC layer) to schedule packets for a single service flow across those multiple channels. Upstream Channel Bonding enabled a CM to transmit simultaneously on multiple transmit channels. This allowed the CMTS to schedule the traffic for a single upstream service flow across those multiple channels.

Channel Bonding offers significant increases in the peak data rate that can be provided to a single CM, in both directions. Other enhancements in the upstream request-grant process like Continuous Concatenation and Fragmentation (CCF) also improved the efficiency of the upstream link.

DOCSIS 3.0 technology also introduced support for the Internet Protocol version 6 (IPv6). CMs can be provisioned with an IPv4 management address, an IPv6 management address, or both. Further, CMs can provide transparent IPv6 connectivity to devices behind the cable modem (CPEs), with full support for Quality of Service and filtering. DOCSIS 3.0 technology also introduced support for delivery of Source-Specific IP Multicast streams to CPEs.

DOCSIS 3.0 technology started off with minimum requirements of 4 Quadrature Amplitude Modulation (QAM) channels in the downstream and 4 QAM channels in the upstream. After starting with 4 QAM channels and enabling channel bonding, future iterations of DOCSIS 3.0 products, CMs and CMTS, enabled more channels in each direction. In the downstream the number of channels (bonded together) grew from 4 to 8 to 16 to 24 to 32 channels (32 channels provided the means for up to 192 MHz of downstream DOCSIS spectrum). In the upstream direction the number of channels grew from 4 to 8 SQAM upstream channels.

At that time most of the cable spectrum was used for video programming, and DOCSIS 3.0 technology ushered in a new era of dedicating more spectrum to broadband and the beginning of using less spectrum for the traditional video offering. This also led to the introduction of MPEG-4 video coding technology, however, the driver was to allocate more spectrum to broadband.

2.2. DOCSIS 3.1 Technology

DOCSIS 3.1 technology was introduced in 2013~2015 and added Orthogonal Frequency Division Multiplexing (OFDM) downstream signals and Orthogonal Frequency Division Multiple Access (OFDMA) upstream signals to achieve robust operation and provide more efficient use of the spectrum than previous DOCSIS versions. To reach the higher service tiers in the upstream direction, plant changes on the upstream/downstream spectrum split were also created. The DOCSIS 3.1technology allowed for a system to have options of several split configurations that can be chosen by an operator based on traffic demand, services offered and the capability of the cable plant. The upstream split options available were 42 MHz, 85 MHz, and 204 MHz of spectrum. In the downstream direction, HFC network spectrum was designed to start at 108 MHz or 258 MHz and extend up to 1.2 GHz of spectrum.

The OFDM downstream multicarrier system is composed of many subcarriers that have either 25 kHz or 50 kHz spacing. These subcarriers are grouped into independently configurable OFDM channels each occupying a spectrum of up to 192 MHz in the downstream, totaling 7680 25 kHz subcarriers or 3840 50 kHz subcarriers; of which up to 7600 (25 kHz) or 3800 (50 kHz) active subcarriers span 190 MHz of spectrum. The OFDMA upstream multicarrier system is also composed of either 25 kHz or 50 kHz subcarriers. In the upstream, the subcarriers are grouped into independently configurable OFDMA channels each of up to 95 MHz encompassed spectrum, totaling 3800 25 kHz spaced subcarriers or 1900 50 kHz spaced subcarriers or 1920 50 kHz spaced subcarriers. Many parameters of these channels can be independently configured thereby optimizing configuration based on channel conditions.

In DOCSIS 3.1, the OFDM/OFDMA technology allows different subcarriers to use different modulation orders. This is referred to as variable bit-loading on the channel. A downstream profile will define the modulation order (i.e., bit-loading) on each carrier. To account for varying downstream plant conditions across different devices, an operator can define multiple downstream profiles, where each profile can be tuned to account for specific plant conditions. By optimizing the downstream profiles, this will allow a downstream channel to be able to operate with lower SNR margin, potentially allowing a channel to operate at an overall higher throughput. For OFDMA Channels, a minislot is a set of symbols and subcarriers and different modulations across minislots are allowed. This enables IUCs that allow different modems to transmit with different modulations in the upstream.

The DOCSIS 3.0 channels are referred to as single carrier QAM (SC-QAM) systems in contrast to the multicarrier DOCSIS 3.1 OFDM/OFDMA system.

DOCSIS 3.1 technology allowed the continued use of channel bonding between SC-QAM and OFDM/OFDMA channels. The result was an increase in the spectrum that could be allocated to broadband. DOCSIS 3.1 technology required support for a minimum of 32 SC-QAM channels and 2 OFDM channels in the downstream, and support or 8 SC-QAM channels and 2 OFDMA channels in the upstream. This provided the means for up to 576 MHz of downstream DOCSIS spectrum and now the move was away from legacy video technology and the pivot toward IPTV service.

2.3. DOCSIS 4.0 Technology

DOCSIS 4.0 technology is expected to be introduced in the 2024 timeframe and builds on the proven DOCSIS 3.1 OFDM and OFDMA technology, providing even more capacity. DOCSIS 4.0 technology leverages the existing DOCSIS3.1 Media Access Control (MAC) and Physical (PHY) layers. It includes backward compatibility for the existing PHY layers to enable a seamless migration to the new technology. DOCSIS 4.0 technology is enabled by two key modes of operation: frequency division duplex and full duplex modes of operation.

Full Duplex (FDX) DOCSIS technology is a new set of features that significantly increases upstream capacity and allows for the same spectrum to be used as downstream or upstream. FDX allows for simultaneous upstream and downstream transmission and reception within the same cable system spectrum. The FDX technology increases upstream capacity without significant loss of downstream capacity as compared to DOCSIS 3.1 technology. The FDX node transmits downstream and receives upstream at the same time on the same frequencies. FDX transmissions from node to modem and modem to node are overlapped both in time and frequency where new echo cancellation technology in the node allows this simultaneous bidirectional communication. While an FDX CMTS will simultaneously receive and transmit in the same FDX spectrum, FDX CMs can only receive or transmit at a time in the same FDX spectrum.

Frequency division duplex (FDD) DOCSIS technology is the traditional frequency division duplex mode of operation that has been operating for years and now supports significant increases in upstream and downstream capacity. FDD supports legacy high-split (204 MHz) and provides extended upstream splits up to 684 MHz in an operational band plan which is referred to as ultra-high split (UHS). There are 4 new UHS options available including 300 MHz, 396 MHz, 492 MHz, or 684 MHz for the upstream upper band edge. FDD also increases the downstream bandwidth by extending the DOCSIS downstream upper band edge to 1794 MHz of spectrum.

DOCSIS 4.0 technology will provide a means for up to 1,536 MHz of downstream spectrum, almost tripling what was available with DOCSIS 3.1 technology. DOCSIS 4.0 technology envisions all services being provided over broadband and in fact, some operators are already moving in this direction.

2.4. DOCSIS 3.1 and DOCSIS 4.0 Device Channel Capabilities and Peak Speeds

DOCSIS 3.1 technology and DOCSIS 4.0 technology are very similar. DOCSIS 3.1 specifications laid the groundwork for including OFDM and OFDMA technology. DOCSIS 4.0 technology provides methods to get more of these channels on the coaxial cable network to provide even higher speeds.

Table 1 – DOCSIS Equipment minimum channel capabilities

DOCSIS Version	Device Type	Downstream OFDM Channels	Upstream OFDMA channels
DOCSIS 3.1	CM	2	2
	CMTS	2	2
DOCSIS 4.0	CM	5	7
	CMTS	6	8

Table 1 presents the minimum number of downstream OFDM channels supported on DOCSIS-compliant equipment. As noted above, currently deployed DOCSIS 3.1 CMs support two downstream OFDM channels, whereas several upgraded DOCSIS 3.1 CMTSs now support more than two OFDM channels. A DOCSIS 4.0 CM supports at least five downstream OFDM channels. A DOCSIS 4.0 CMTS will support 6 OFDM downstream channels.

Also on a related note, the upstream OFDMA channel capability for CMs increases from 2 (for DOCSIS 3.1 CMs) to 7 (for DOCSIS 4.0 CMs) and on the CMTS side increases from 2 to 8. The focus of this paper is increased capacity on DOCSIS 3.1 networks, so the increase in upstream channels is not as useful on a DOCSIS 3.1 network, given 2 OFDMA channels are enough to cover a mid-split or high-split plant.

Table 2 – CM Peak Downstream Capacities with enhanced DOCSIS 3.1 CMTS

CMTS	Number of downstream channels on Service Group		Spectrum allocated to DOCSIS Downstream (MHz)	CM	Capacity of Service group/ Peak Downstream Speeds at CM
	OFDM	SCQAM			
D3.1	2	32	576	D3.1	5.0 Gbps
D3.1	3	32	768	D4.0	6.9 Gbps
D3.1	4	32	960	D4.0	8.8 Gbps
D3.1	5	0	960	D4.0	9.5 Gbps

Table 2 shows how device capabilities relate to capacity of the downstream with a mixture of DOCSIS 3.1 and DOCSIS 4.0 CMs operating on a DOCSIS 3.1 CMTS. These speeds indicate the downstream capacity of the plant and also equate to the peak downstream speeds possible at a CM, assuming the bandwidth is not shared with any other CMs on the plant. The speeds in Table 2, are 'goodput' speeds available for the user data traffic, i.e., after considering the DOCSIS overhead (including FEC, MAC management and other PHY layer overhead). For an understanding of how to calculate speeds on a OFDM and OFDMA channel and DOCSIS 3.1 or 4.0 networks please refer to [D31 Capacity], [10G Capacity]. The speeds in Table 2 are not the product speeds or service tiers, that an MSO would offer, this is the total capacity of the plant, typically operators offer speed tiers well within the capacity of the network or the peak speed enabled by a CM. See [Capacity Model] for further analysis on network capacity planning. Some of the scenarios in lab testing that achieved some of these speeds are described in Section 4.2.

In the current baseline scenario, a DOCSIS 3.1 CM supports a peak of up to 5 Gbps downstream speed (using both OFDM and SC-QAM channels). In the past, D3.1 CMTS supported only two OFDM channels in a MAC domain. These CMTS are typically deployed in a mix of sub-split, mid-split (more prevalent) and high-split spectrum plans, with the downstream extending up to 1.2 GHz , all of which are the design parameters for a DOCSIS 3.1 network. A DOCSIS 4.0 network on the other hand increases the upstream by enabling ultra-high-split spectrum for the upstream and extending the downstream , or enabling full duplex operations, see section 2.3 and 2.5.

Now recently, there have been new product upgrades to existing DOCSIS 3.1 CMTS for use on the existing DOCSIS 3.1 Networks. DOCSIS 3.1 CMTSs have added support for additional OFDM channels in the downstream, within the same MAC domain. This upgraded DOCSIS 3.1 CMTS can support 3, or 4 or 5 OFDM channels in the downstream. To clarify, this is not a DOCSIS 4.0 CMTS and it doesn't understand the any new MAC management messages from DOCSIS 4.0 technology, neither does it support any of the new DOCSIS 4.0 features such as ultra-high splits, extended downstream, or full duplex operations.

A DOCSIS 4.0 CM which supports five OFDM channels can make use of these new OFDM channels on a DOCSIS 3.1 CMTS and a DOCSIS 3.1 network. A DOCSIS 3.1 CMTS that supports four OFDM channels paired with a DOCSIS 4.0 CM can achieve up to 8.8 Gbps downstream speed. Also keep in mind that to enable these additional OFDM channels, an operator does need to plan their spectrum assignment to various services and may need to take away bandwidth from say QAM video to enable spectrum for data. A DOCSIS 3.1 CMTS that supports five OFDM channels paired with a DOCSIS 4.0 CM can achieve up to 9.5 Gbps downstream speed. In this case all the bandwidth on the plant is allocated to DOCSIS spectrum, meaning there is no spectrum for QAM video , assumption here is video services have moved to be delivered over IP.

The actual speeds achieved will depend on the specific OFDM channel parameters and the signal to noise ratio of the fiber node or plant. When the channel parameters are tuned for robust operation, the speed could be different. In initial lab tests we proved out 8.8 Gbps speeds in a lab network tests, on a simple coax network, see notes in section below.

2.5. Transition from DOCSIS 3.1 Networks to DOCSIS 4.0 Networks

DOCSIS 3.1 technology was straight-forward to introduce onto the existing HFC network. Initially, spectrum had to be cleared for the first downstream OFDM channel and it was possible to get started with half of an OFDM channel, 96 MHz, instead of a full 192 MHz of spectrum. And the upstream was initially not changed and many operators in North America remained at the usual sub-split (42 MHz) configuration. Over time many operators made the upstream transition to mid-split (85 MHz) and some to high-split (204 MHz) configuration and introduced OFDMA channels in that new upstream spectrum.

DOCSIS 4.0 technology can be more fully utilized with the evolution of the HFC network. The existing coaxial plant can carry the additional DOCSIS 4.0 spectrum once the actives and passives on the network need to be changed to enable all the spectrum capabilities. This equipment is available, and some operators have already begun evolving the network to support DOCSIS 4.0 technology.

The HFC network evolution will provide more spectrum on the coaxial cable that will be allocated to broadband. This new spectrum will be used with OFDM and OFDMA technology, which will rapidly become the new normal for providing broadband service, as compared to the SC-QAM technology which had been used through DOCSIS 3.0 technology. OFDM and OFDMA channels bring in new operational and PNM activities which operators are quickly getting familiar with. DOCSIS 4.0 FDD technology will be based on the access network upgrades for existing actives and passives up to 1.8 GHz along with a choice of diplex ultra-high split configurations. DOCSIS 4.0 FDX technology will be based on upgrades to introduce new Echo Cancellation functions into the RPHY nodes and amplifier platforms.

A DOCSIS 4.0 network uses a Distributed Access Architecture (DAA) which provides better end-of-line performance as compared to a traditional integrated headend CMTS. See [10G Playbook] for further details. The DAA technologies place part of the CMTS in the fiber node and are known as either Remote MACPHY or Remote PHY technology, see CableLabs specifications for both. DOCSIS 4.0 technology will need an upgrade in the network to migrate to 1.8 GHz DOCSIS 4.0 FDD DAA nodes or DOCSIS 4.0 FDX nodes (with Echo cancellation)

DOCSIS 4.0 technology drives additional changes including the method for signal leakage detection, legacy video services, CableCARD™ technology, and other technologies that are beyond the scope of this paper. While the DOCSIS 4.0 network upgrades are ongoing, updating the current DOCSIS 3.1 CMTS, Section 2.6, enables operators to seed the network with DOCSIS 4.0 CMs.

2.6. Updating the DOCSIS 3.1 CMTS

The DOCSIS 3.1 specifications introduced OFDM and OFDMA technology to the DOCSIS ecosystem. The DOCSIS 4.0 specifications added support for more OFDMA and OFDMA channels, and so the DOCSIS 4.0 CM can support five OFDM channels as compared to a DOCSIS 3.1 CM supporting two OFDM channels, see Table 1.

2.6.1. Additional OFDM channels with channel bonding

DOCSIS 3.1 CMTS equipment was originally designed to provide two OFDM channels on each service group, to match the DOCSIS 3.1 CM. With the advent of DOCSIS 4.0 CMs, it is possible to modify the DOCSIS 3.1 CMTS to provide more than two OFDM channels per service group, even up to five OFDM channels per service group. Generally, this can be done without new CMTS equipment; however, check with the CMTS supplier if this new operation impacts the number of service groups that can be served with this increased number of OFDM channels.

The DOCSIS 3.1 CMTS will also need to bond the additional OFDM channels with the existing downstream OFDM channels and the SC-QAM channels, thereby providing the additional downstream capacity for the DOCSIS 4.0 CMs. The CMTSs already supports different bonding groups, which will continue to be needed, to allow DOCSIS 3.0 , 3.1 and the new 4.0 CMs to operate seamlessly.

With the addition of up to 5 OFDM channels on the downstream, there are now new options for a DOCSIS 3.1 CM, specifically which two OFDM channels to use. Hence the DOCSIS 3.1 CMTS may want to introduce both downstream bonding groups for DOCSIS 3.1 CMs and a method for downstream load balancing for DOCSIS 3.1 CMs. A DOCSIS 4.0 CM will use all the OFDM channels available, however, a DOCSIS 3.1 CM can only use two of the OFDM channels and there should be a method to get the DOCSIS 3.1 CMs on certain OFDM channels.

On the upstream, the DOCSIS 3.1 CMTS already supports mid-split or high-split configuration, and this includes the two OFDMA channels available per service group. Based on the available spectrum for upstream in a high split plant, DOCSIS 4.0 CMs should be able to use all the upstream spectrum without adding any more OFDMA channels per service group on the CMTS. That is, the DOCSIS 3.1 CMTS supports two OFDMA channels per service group and will continue to support those two OFDMA channels in a high-split configuration when DOCSIS 4.0 CMs are introduced. A DOCSIS 4.0 CM is required to operate on a high-split network.

2.6.2. Support DOCSIS 4.0 CM registration

2.6.2.1. CM Capabilities

Backwards compatibility for CMs and CMTSs has been a long time goal of DOCSIS protocol design and specification. The DOCSIS 3.1 CMTS needs to gracefully interpret and negotiate DOCSIS 4.0 modem capabilities, thereby enabling DOCSIS 4.0 CMs to operate on a DOCSIS 3.1 CMTS, albeit only with the DOCSIS 3.1 features.

Though a DOCSIS 3.1 CMTS should have supported the newer DOCSIS 4.0 CMs to come online and operate as DOCSIS 3.1 CMs, as per the DOCSIS specifications, the reality of DOCSIS 3.1 CMTS software implementations was that these CMs were initially unable to register. This was about a year ago, and since then the quick software fixes to DOCSIS 3.1 CMTSs already enable the recognition of the DOCSIS 4.0 CMs and bring them online. DOCSIS 4.0 CMs are backward compatible with DOCSIS 3.1 CMTS in an interoperable fashion. A DOCSIS 3.1 CMTS negotiates the best possible service offering for a DOCSIS 4.0 CM, considering several factors, including the number of OFDM channels, diplex filter, etc., supported by the CM.

Operators need to ensure that their DOCSIS 3.1 CMTS has the appropriate software updates to recognize and register DOCSIS 4.0 CMs on the DOCSIS 3.1 network. Registration of DOCSIS 4.0 CMs on DOCSIS 3.1 CMTSs has now been proven in the lab in the latest CableLabs DOCSIS 4.0 Interoperability events.

2.6.2.2. Larger Auth-Req

There are other dependencies such as support by the CMTS for bigger certificate sizes. A DOCSIS 3.1 CMTS needs to allow support for DOCSIS 4.0-style CM certificate and the associated larger Auth-REQ (authorization) message for BPI+ V1. Without this support, an operator cannot turn on BPI+ security when running a DOCSIS 4.0 CM on a DOCSIS 3.1 CMTS. A DOCSIS 3.1 CMTS is not required to support BPI+ V2 though does need to support the new DOCSIS 4.0 device certificate and the associated larger Auth-REQ message; both features have been proven in the latest CableLabs DOCSIS 4.0 Interoperability events.

2.6.3. Other Features

There are other features that would be nice to have on a DOCSIS 3.1 CMTS, but not necessary to bring up DOCSIS 4.0 CMs on the CMTS. OUDP Testing (OFDMA Upstream Data Profile) is a part of the DOCSIS 3.1 technology with CM vendors including support for it. In high-split networks, OUDP used as a signal to detect RF signal leakage. The DOCSIS 3.1 CMTS will need to support a mechanism to trigger the CMTS to command high-split CMs to transmit OUDP bursts to enable RF leakage testing.

Overlapping OFDMA channels (OOC) is a CMTS feature that allows operators to create a logical upstream channel that overlaps a physical one. The CMTS essentially creates logical channels such that it looks like there are two OFDMA channels: a “base” channel and an “overlap” channel. This can then be used to support mid-split CMs on a high-split CMTS without capacity loss. DOCSIS3.1 mid-split CM cannot use a partial OFDMA channel, if say a channel goes above the 85 MHz in the spectrum. Without OOC, operators will have to discard at least 23 MHz of upstream spectrum (between 85 to 108 MHz) when operating in a high split plant (204 MHz). A DOCSIS 4.0 FDX CM when booting on a DOCSIS 3.1 CMTS will boot as a mid-split CM and so the benefits extend to those CMs in the plant as well.

3. Cable Modem Registration

DOCSIS systems follow a common registration process where the CM reports capabilities that are negotiated with the CMTS, with the CMTS deciding how a CM uses the network (based on operator policy). Figure 1 shows a simplified registration process where the CM presents its capabilities to the CMTS, the CMTS decides which services and channels that CM can have access, and then provides a service configuration back to the CM.

During registration, a DOCSIS 4.0 CM must identify its version as “DOCSIS 4.0” to the CMTS. This will allow operators to both track DOCSIS 4.0 CMs on their networks and have their DOCSIS 3.1 CMTS enforce policy regarding how those DOCSIS 4.0 CMs become operational on the DOCSIS 3.1 network. As described in Section 2.6.2, a DOCSIS CMTS may need a software fix to recognize the DOCSIS 4.0 CMs correctly.

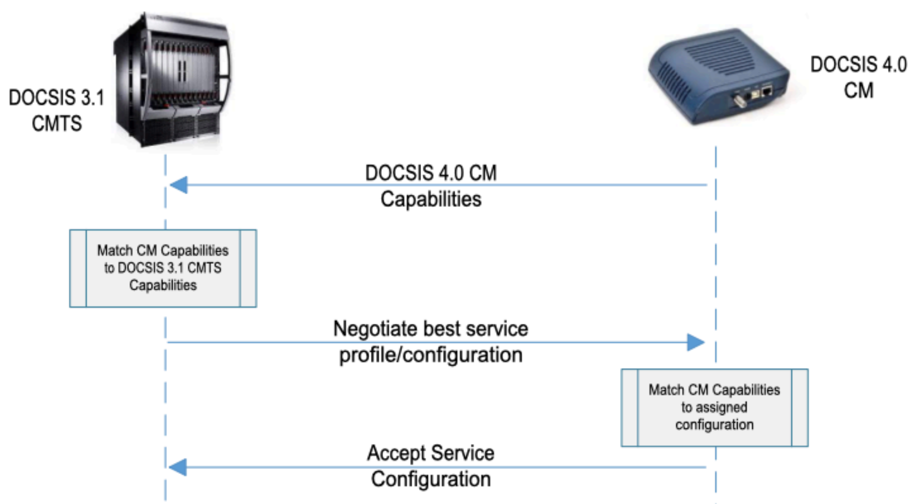

Figure 1 – Simplified DOCSIS 4.0 CM Registration

3.1. DOCSIS 4.0 CM Capabilities

Every CM reports its capabilities to the CMTS. Table 3 shows the relevant DOCSIS 4.0 CM capabilities, such as the new ultra-high-split DOCSIS 4.0 diplex filters and lists the new values that the DOCSIS 4.0 CM will indicate for some of the legacy DOCSIS 3.1 CM capabilities.

Table 3 – DOCSIS 4.0 CM Capabilities

Description	Capability Sub-TLV	CM Capability	D4.0 FDX CM	D4.0 FDD CM
Version	5.2	DOCSIS Version	v4.0	v4.0
Channel Support	5.49	OFDM Multiple Receive Channel Support	5	5
	5.50	OFDMA Multiple Transmit Channel Support	7	7
Legacy Band Edge Support	5.62	Diplexer Upstream Upper Band Edge Options	85	204
	5.60	Diplexer Downstream Lower Band Edge Options	108	258
	5.61	Diplexer Downstream Upper Band Edge Options	1218	1794
New D4.0 Capabilities	5.63	Adv. Band Plan Capability	FDX	FDD
	5.84	Adv. Diplexer Upstream Upper Band Edge Options List	-	204/300/396/492/684
	5.82	Adv. Diplexer Downstream Lower Band Edge Options List	-	258/372/492/606/834
	5.83	Adv. Diplexer Downstream Upper Band Edge Options List	-	1794

A DOCSIS 3.1 CMTS needs to support parsing of these new values from the legacy CM capability TLVs (Type/Length/Value) and to gracefully ignore the new DOCSIS 4.0 capabilities that it does not support. Based on the capabilities indicated by the CM for the diplexer band edges (TLVs 5.60, 5.61, 5.62) and matching them to the configuration of the DOCSIS 3.1 network (see description of MDD , Section 3.2), the CMTS will allocate appropriate channels to the CM.

In a DOCSIS system, the modem is required to report its capabilities to the CMTS. It is then the role of the CMTS to decide how to allow that modem to come online. Hence, a DOCSIS 3.1 CMTS needs to be upgraded to understand and gracefully handle the values in the capabilities of a DOCSIS 4.0 CM, at least for the relevant DOCSIS 3.1 CM capabilities.

3.2. Registration on a DOCSIS 3.1 CMTS and CMTS Band Edge Capabilities

A significant factor in the process of a DOCSIS 4.0 CM registering on a DOCSIS 3.1 CMTS relates to the various upstream and downstream bands that can be used (along with the associated diplex filter settings) and is different for each type of DOCSIS 4.0 CM.

The MAC Domain Descriptor (MDD) message is used to convey various DOCSIS system settings from the CMTS to all CMs. The MDD Diplexer Band Edge Sub-TLV (21) indicates the diplexer upstream and downstream band edges to which the HFC network is configured. The Table 4 shows the values of this TLV on different HFC networks.

Table 4 – DOCSIS 3.1 CMTS MDD Diplexer Band Edge Value

MDD Sub-TLV	CMTS MDD Sub-TLV Name	D3.1 Sub-Split	D3.1 Mid-Split	D3.1 High-Split
17	CMTS DOCSIS Version	v3.1	v3.1	v3.1
21.1	Diplexer Upstream Upper Band Edge	42	85	204
21.2	Diplexer Downstream Lower Band Edge	108	108	258
21.3	Diplexer Downstream Upper Band Edge	1218	1218	1218

DOCSIS 3.1 CMs can have various diplex filters and DOCSIS 4.0 CMs support additional diplex filters. A CMTS will consider the combinations of CM diplex filters and allocate the right channels to each CM.

Upon detecting the broadcast MDD message and the band edge settings, a DOCSIS 3.1 CM and a DOCSIS 4.0 CM will reset its diplex filter to best match the MDD message, and then the CM will reboot and attempt to register with the CMTS. Below are some of the rules that describe the expected behavior.

- The CM sets its diplexer upstream upper band edge to the highest upstream frequency that it supports within the range reported in the Diplexer Upstream Upper Band Edge MDD sub-TLV.
    - If the supported CM diplexer upstream upper band edge frequencies are greater than the range reported in the MDD message, the CM sets its diplexer upstream upper band edge to the lowest upstream frequency that it supports.
- The CM sets its diplexer downstream lower band edge to the lowest downstream frequency that it supports within the range reported in the Diplexer Downstream Lower Band Edge MDD sub-TLV.
    - If the supported CM diplexer downstream lower band edge frequencies are less than the range reported in the MDD message, the CM sets its diplexer downstream lower band edge to the highest downstream frequency that it supports.
- The CM sets its diplexer downstream upper band edge to the highest downstream frequency that it supports within the range reported in the Diplexer Downstream Upper Band Edge MDD sub-TLV.
    - If the supported CM diplexer downstream upper band edge frequencies are greater than range reported in the MDD message, the CM sets its diplexer downstream upper band edge to the lowest downstream frequency that it supports.

For a DOCSIS 4.0 CM, as shown in Table 3, the legacy band edge support CM capabilities, describing the diplexer band edges have one set of values for the DOCSIS 4.0 FDD CM (204-258MHz) , and one set of values for the DOCSIS 4.0 FDX CM (85-108MHz). So, per the MDD message diplexer setting rules above, these DOCSIS 4.0 CMs will always use these diplexer values and boot up with those diplexer settings.

As a related note, if a CMTS calculates that any of the supported CM diplexer band edge frequencies (as indicated by the CM capabilities) are outside the frequency range reported in the Diplexer Band Edge MDD TLV, the CMTS can allow or disallow the CM to register depending on operator policy. [MULPIv3.1]

3.3. DOCSIS 4.0 FDD CM on a D3.1 CMTS

A DOCSIS 4.0 FDD CM is required to support at least two diplex filters, including both high-split and one of the new ultra-high splits. Thus, on a DOCSIS 3.1 network, the FDD CM will use a high-split diplex filter because that is the filter that most closely aligns with the capabilities of a DOCSIS 3.1 network. An FDD CM can also operate using its high-split diplex filter on any of the following: a sub-, European-, mid-, or high-split DOCSIS 3.1 network.

For a high-split DOCSIS 3.1 network, the downstream begins at 258 MHz. With its high-split diplexer an FDD CM can only use downstream channels above 258 MHz in the spectrum. If the DOCSIS 3.1 CMTS supports more than two OFDM channels, this DOCSIS 4.0 CM can take advantage of these channels both for more capacity and higher speeds. On the upstream, an FDD CM will get the most upstream speeds out of a high-split network. A sample spectrum plan of a DOCSIS 3.1 high-split CMTS is shown in Figure 2.

A DOCSIS 4.0 FDD CM will reconfigure its diplexer, from one of the Ultra High splits that it supports and will use the 204-258 MHz diplexer when it boots up on a DOCSIS 3.1 network.

On a DOCSIS 3.1 high-split network, with the channel configuration as shown in Figure 2, the main difference between the DOCSIS 3.1 high-split CM and the DOCSIS 4.0 FDD CM is that the DOCSIS 4.0 CM can use the additional 2 OFDM channels to enable higher bandwidth service tiers.

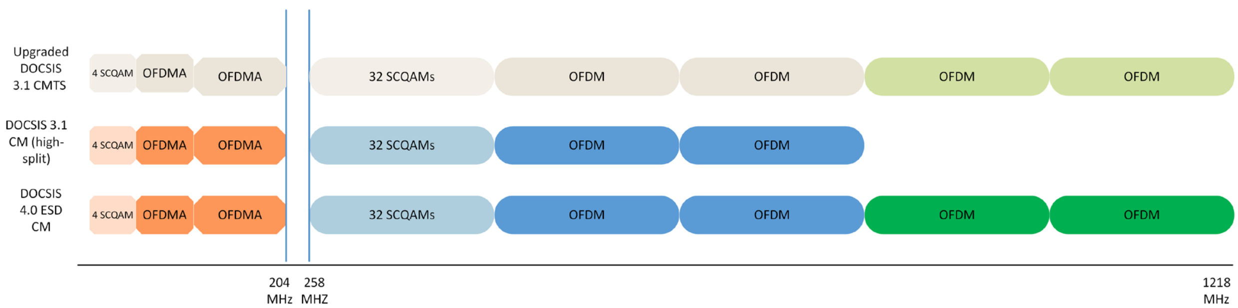

Figure 2 - D4.0 FDD CM, D3.1 CM w High-Split DiplexFilter, on High-Split D3.1 CMTS

The FDD CM can also operate on a sub- or mid-split HFC network and use the available upstream channels, with the caveat that because that FDD CM will still be using a high-split diplex filter, so it can only use DOCSIS downstream channels above 258 MHz in the spectrum. This is shown in Figure 3.

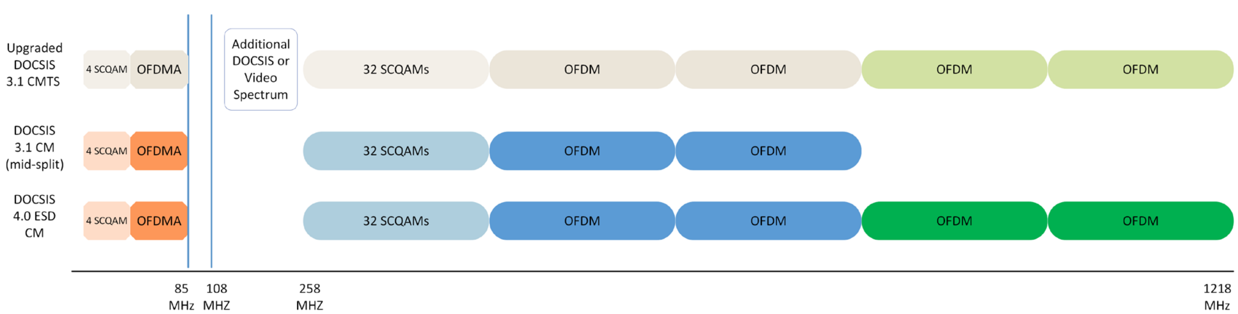

Figure 3 - D4.0 FDD CM, D3.1 CM w Mid-Split Diplex Filter, on Mid-split D3.1 CMTS

3.4. DOCSIS 4.0 FDX CM on a D3.1 CMTS

A DOCSIS 4.0 FDX CM is required to support two modes of operation; one in FDX mode and the other as a mid-split CM. Thus, on a DOCSIS 3.1 network, the FDX CM will use a mid-split diplex filter as that is the filter that most closely aligns with the capabilities of a DOCSIS 3.1 network. An FDX CM can also operate using its mid-split diplex filter on any of the following: a sub-, European-, mid-, or high-split DOCSIS 3.1 network.

A DOCSIS 3.1 CMTS does not support FDX technology. On a DOCSIS 3.1 network, a DOCSIS 4.0 FDX CM is expected to come online as a mid-split CM with no transition band from 684 MHz to 804

MHz in the spectrum. Figure 4 shows that an FDX CM will register as mid-split and use upstream spectrum up to 85 MHz and downstream spectrum starting at 108 MHz up to the limit of where the HFC network is operated.

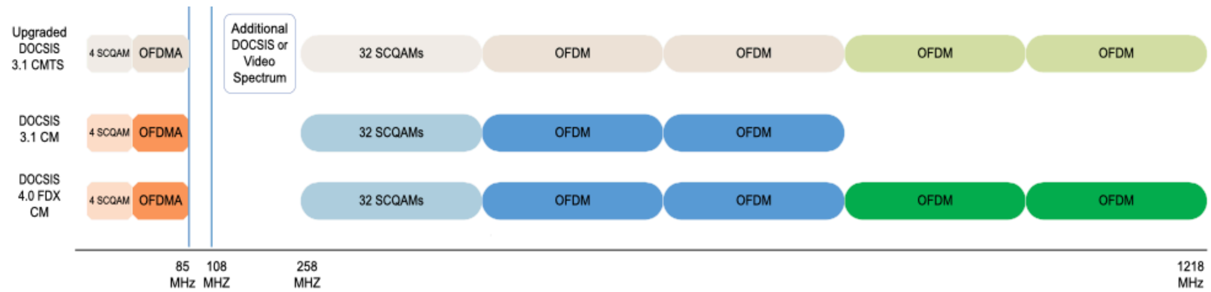

Figure 4 - D4.0 FDX CM, D3.1 CM w Mid-Split Diplex Filter, on a Mid-split D3.1 CMTS

An FDX CM can be deployed on any DOCSIS 3.1 network and is best suited for a mid-split network. For a mid-split DOCSIS 3.1 network, the downstream begins at 108 MHz in the spectrum. With its mid-split diplexer an FDX CM can use downstream channels above 108 MHz in the spectrum. If the DOCSIS 3.1 CMTS supports more than two OFDM channels, this DOCSIS 4.0 CM can take advantage of these channels both for more capacity and higher speeds. On the upstream, this DOCSIS 4.0 FDX CM will be able to use all the upstream capacity in the mid-split network as also shown in Figure 4.

As shown in Figure 5, the FDX CM will become operational on any DOCSIS 3.1 network, including sub-split or high-split networks, and will only be able to use the OFDMA channels that are below 85 MHz and the OFDM channels that are above 108 MHz in the spectrum.

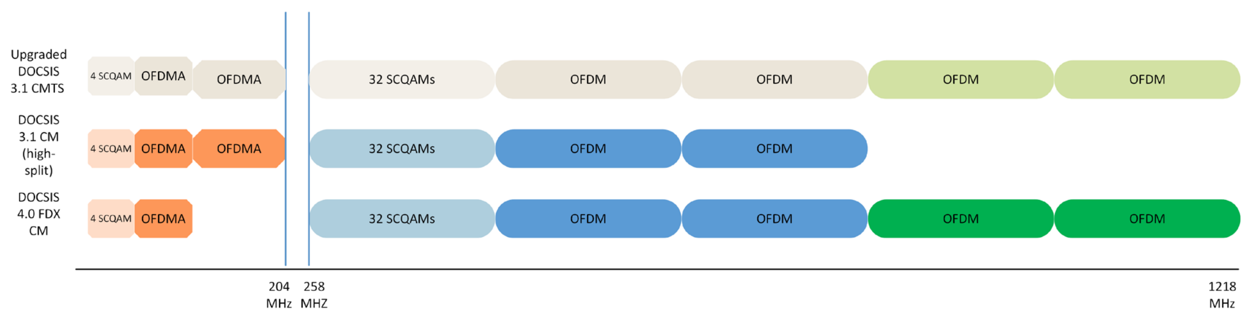

Figure 5 - D4.0 FDX CM, D3.1 CM w High-Split Diplex Filter, on High-Split D3.1 CMTS

4. Results from Lab Testing

CableLabs did quite a bit of lab work with the latest DOCSIS equipment this year. This included DOCSIS CMTS setup and bring up of DOCSIS 4.0 CMs. The results in this section are for a DOCSIS 3.1 CMTS with the cable spectrum filled with only DOCSIS channels. There are no video QAMs or other signals on the coaxial cable. This work was done in a lab with passive coaxial cable, that is, no amplifiers.

The speeds listed below are measured throughputs for the downstream and upstream channels. The downstream capacity exceeds that of a single DOCSIS 3.1 CM, hence, multiple high-split DOCSIS 3.1 CMs would be needed to utilize this capacity. In the case of a DOCSIS 4.0 CM, it can utilize all the capacity described in this section.

4.1. Equipment

CableLabs has been working with high-split DOCSIS 3.1 CMTS equipment from multiple suppliers and in multiple form-factors.

Our lab network included the following CMTS setups:

- Integrated CMTS
- Integrated CMTS acting as a CCAP-Core hosting a Remote PHY Device (RPD)
- Virtual CCAP-Core hosting an RPD
- Remote MACPHY Device (RMD)

All these CMTS equipment are the latest generation (hardware and software) of equipment that can support a high-split network where the return path runs up to 204 MHz and the forward path runs from 258 MHz to 1218 MHz for a total of 960 MHz downstream spectrum which can all be filled with DOCSIS channels.

This is way more downstream than was available in either 750 MHz or 860 MHz networks and even more downstream spectrum than is available on a sub-split 1 GHz plant. And now, all this spectrum can be allocated to DOCSIS services with the latest generation of DOCSIS 3.1 CMTS.

For example, that downstream 960 MHz can be filled with downstream channels in a few ways:

- 32 x 6-MHz SC-QAM channels (total of 192 MHz) and 4 x 192 MHz OFDM channels (total of 768 MHz). The use of downstream SC-QAM channels allows DOCSIS 3.0 CMs to operate.
- 5 x 192 MHz-OFDM channels. With no SC-QAM channels, this network setup only supports DOCSIS 3.1 CMs and DOCSIS 4.0 CMs.

The latest generation DOCSIS 3.1 CMTS (with support for an increased number of OFDM channels) paired with DOCSIS 4.0 CMs will provide a useful increase in speed and capacity. DOCSIS 3.1 and earlier CMs can still be supported on the same network.

4.2. Speeds obtained with D3.1 CMTS and D4.0 CMs

4.2.1. Downstream 32 SC-QAM + 4 OFDM channels

The first network that we built had a DOCSIS 3.1 downstream spectrum that spans from 258 MHz to 1218 MHz, with 32 SC-QAM channels, each 6 MHz for a total of 192 MHz, and 4 OFDM channels, each 192 MHz wide. These channels fill 960 MHz from 258 MHz to 1218 MHz in the spectrum. Figure 6 shows a spectrum capture of the SC-QAM channels from 258 MHz to 450 MHz, and the spectrum from 450 MHz to 1218 MHz being occupied by 4 OFDM channels.

A DOCSIS 4.0 CM can successfully register on this system and use all the downstream channels. Both the DOCSIS 4.0 CMs (both FDD and FDX) can successfully register on the system and were able to use the 4 OFDM channels along with the 32 SC-QAMs. This DOCSIS 4.0 CM was successfully able to receive traffic which the CMTS had bonded on the downstream across all of the SC-QAM and OFDM channels.

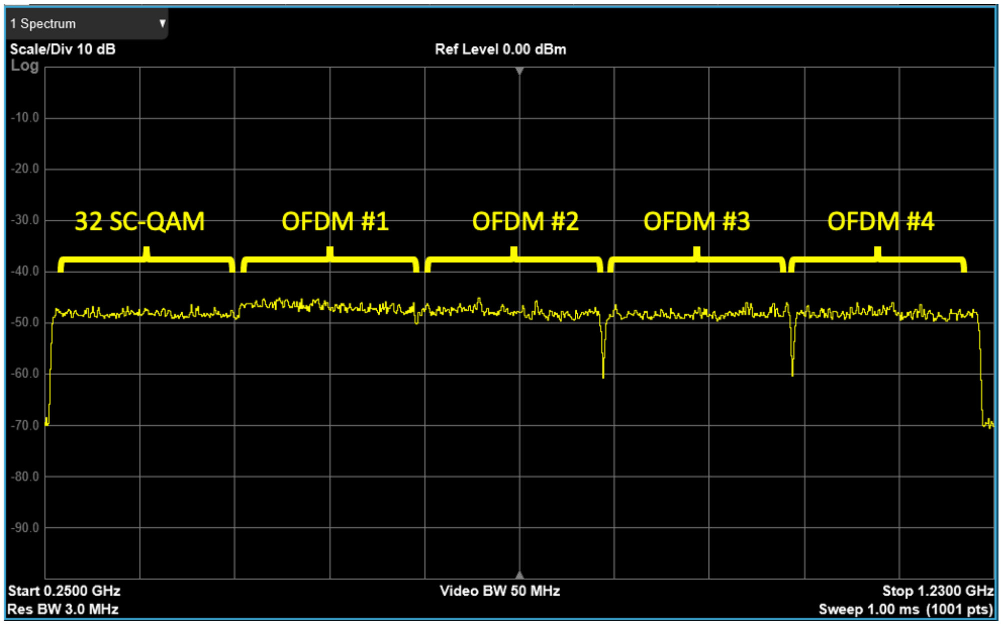

Figure 6 – Downstream with 32 SC-QAM and 4 OFDM Channels

Figure 7 shows a close-up of the first seven SC-QAM channels from 258 MHz to 300 MHz, illustrating that each is 6 MHz wide.

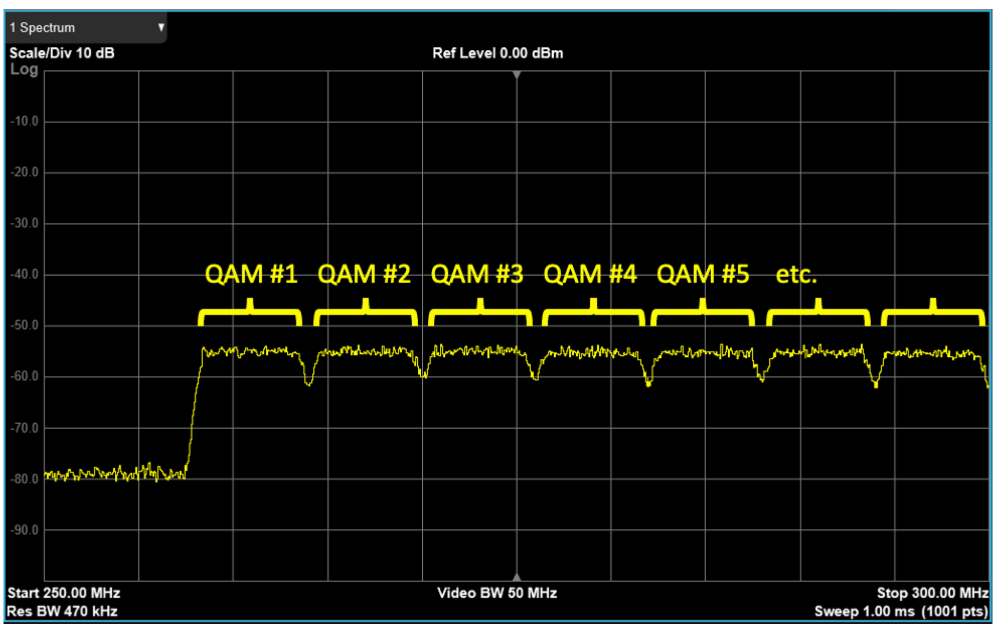

Figure 7 – Close-up of First Seven QAM Channels

Each downstream 6 MHz SC-QAM channel, using a modulation of 256 QAM, supports about 35 Mbps of throughput; hence, 32 of these channels provides about 1.1 Gbps of throughput. In Europe, a similar setup would use 8 MHz SC-QAM channels and 24 channels would fit within that 192 MHz of spectrum.

A 192 MHz OFDM channel (as configured here) can support approximately 1.76 Gbps of throughput and theoretically up to 1.9 Gbps under the best conditions. In the lab, these OFDM channels were set up for throughput which can vary with different choices of cyclic prefix and other OFDM parameters. Add this all up, and this configuration provides ~ 8.1 Gbps of capacity downstream. This speed was achieved using a traffic generator sending traffic from the NSI of the CMTS to the CPE side of the DOCSIS 4.0 CM. This was achieved on multiple CMTS setups, including one test CMTS platform. Theoretically, with different OFDM parameters the rates could go up to 8.5 Gbps, see [D31 capacity], [10G Capacity].

4.2.2. Downstream of 5 OFDM Channels

The next cable network that we built had a DOCSIS 3.1 downstream spectrum that spans from 258 MHz to 1218 MHz, with simply 5 OFDM channels, each 192 MHz wide. These channels fill 960 MHz from 258 MHz to 1218 MHz in the spectrum. Figure 8 shows a spectrum capture of the spectrum from 258 MHz to 1218 MHz being occupied by 5 OFDM channels.

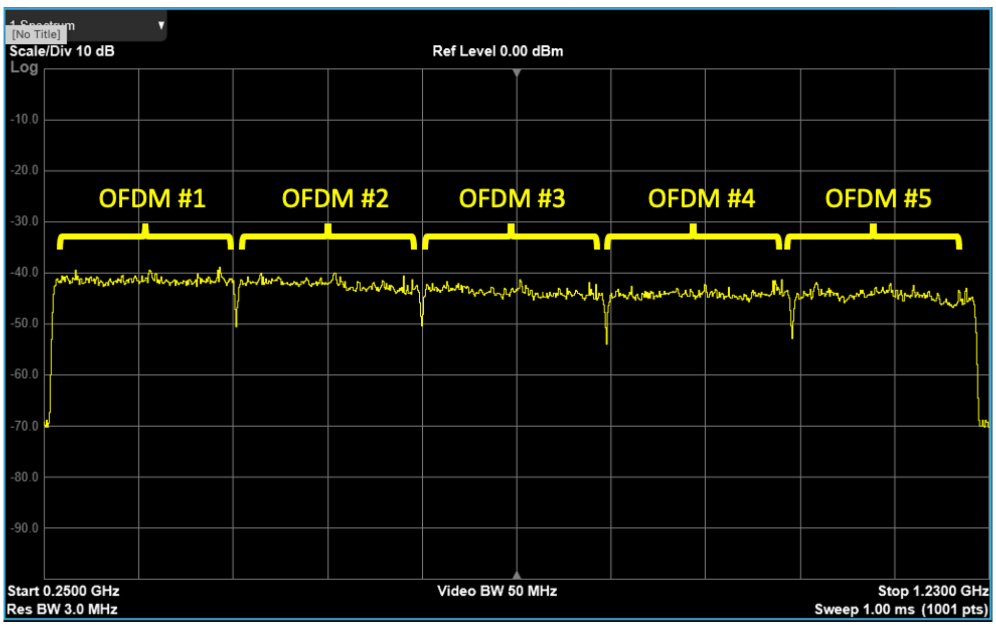

Figure 8 – Downstream with 5 OFDM Channels

A 192 MHz OFDM channel can support up to ~1.76 Gbps of throughput, and five of these channels provides about 8.8 Gbps of capacity on the downstream. This speed was achieved using a traffic generator sending traffic from the NSI of the CMTS to the CPE side of the DOCSIS 4.0 CM. The DOCSIS 4.0 CM was able to bond across all 5 OFDM channels. Not all CMTS setups supported this configuration, but the proof of concept was achieved at least on one CMTS setup.

A 192 MHz OFDM channel can theoretically support up to 1.9 Gbps under the best conditions and configuration (this would amount to 9.5 Gbps), see [D31 capacity] and [10G Capacity]. It is possible in the lab to tweak the channel settings to achieve upwards of 8.8 Gbps. In the lab, the current effort has not been able to attain 9+ Gbps although this will be a part of future testing and refining the channel parameters. The lab is an easier environment than an outside plant and with real-world settings, a real network should support peak speeds in the range of 8.5-9.5 Gbps in many deployments.

Downstream SC-QAM channels are required for DOCSIS 3.0 and earlier CMs; hence, only DOCSIS 3.1 CMs and DOCSIS 4.0 CMs would work on this system since there are no downstream SC-QAMs. An operator could choose to include fewer than 32 SC-QAMs and then do a partial fifth OFDM channel and get a total downstream capacity over 8 Gbps while still supporting DOCSIS 3.0 and earlier CMs.

4.2.3. Upstream with 2 OFDMA Channels

The next cable network that we built had a DOCSIS 3.1 upstream spectrum that spans from 12 MHz to 204 MHz, with simply 2 OFDMA channels, each 96 MHz wide. This enables us to reach the maximum upstream speeds possible on a DOCSIS 3.1 upstream plant. Only DOCSIS 3.1 and DOCSIS 4.0 CMs would operate on this plant as DOCSIS 3.0 CMs and earlier CMs need upstream SC-QAM channels.

The two OFDMA channels, each 96 MHz wide, span from 12 MHz to 108 MHz, and 108 MHz to 204 MHz, respectively. This is clearly an increase from a traditional DOCSIS upstream (sub-split) of 4 SC-QAM channels that provide about 25.6 MHz of DOCSIS spectrum. The DOCSIS 4.0 CMs we tested successfully registered in this setup.

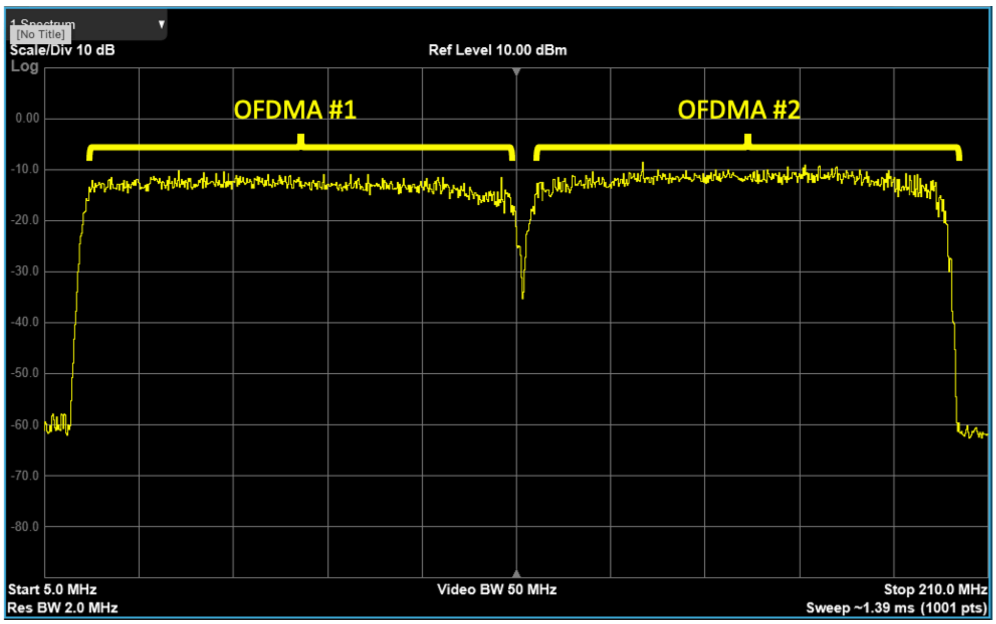

Figure 9 – Upstream with 2 OFDMA Channels

A 96 MHz OFDM channel can support around 0.8 Gbps (800 Mbps) of throughput on many cable plants. Theoretically one could tweak the parameters further to get a bit more throughput. In the lab, these OFDMA channels were set up for throughput which can vary with different choices of cyclic prefix and other OFDMA parameters. Two of these channels provided 1.6 Gbps of capacity upstream. This speed was achieved using a traffic generator sending traffic from CPE side of the DOCSIS 4.0 CM to the NSI of the CMTS. This is like speeds we obtain with DOCSIS 3.1 high-split CMs on a high-split CMTS.

4.2.4. Fastest DOCSIS 3.1 Configuration

The fastest DOCSIS 3.1 channel configuration is obtained with all OFDM and OFDMA channels. Specifically on a high-split upstream with two OFDMA channels and 960 MHz downstream with five OFDM channels. This configuration/setup provided up to 1.6 Gbps upstream and 8.8 Gbps downstream (and potentially up to 9.5 Gbps). We successfully got DOCSIS 4.0 CMs to register in this configuration as well with a high-split CMTS configuration but did not get a chance to run traffic throughput tests. This spectrum plan is quite interesting with only 7 OFDM/A channels and no SC-QAMs in the upstream or downstream. Also there cannot be any traditional video service on the network (no available spectrum), and only IPTV service can be supported on such a plant.

4.2.5. Speeds including DOCSIS 3.0 and Earlier Modems

A real-world requirement for most operators is to support DOCSIS 3.0 and earlier CMs, which still live on the plant. To support this, SC-QAM channels would need to be added in both the upstream and downstream. For a given amount of spectrum, a SC-QAM is less spectrally efficient, i.e., provides less speed than using that spectrum for OFDM.

Typically, in the downstream up to thirty-two SC-QAMs would be included although fewer are possible, depending on how many DOCSIS 3.0 CMs are on the plant and the speed tiers that need to be supported. Regardless, a downstream of 8 Gbps or better can still be achieved. In the upstream, typically 25.6 MHz is reserved for four upstream SC-QAMs and then the lower OFDMA channel would run from about 40 MHz to 108 MHz (assuming the FM band is used). This combination of channels would provide up to 1.5 Gbps.

Hence a DOCSIS configuration to support DOCSIS 3.0 and earlier CMs as well as DOCSIS 3.1 and DOCSIS 4.0 CMs, the system can still provide about 8 Gbps in the downstream and about 1.5 Gbps in the upstream.

5. Conclusions

With recent product upgrades, a DOCSIS 3.1 CMTS can now support four or even five OFDM channels on the same cable plant. This is still a DOCSIS 3.1 CMTS operating on a DOCSIS 3.1 sub/mid/high-split network. Currently available DOCSIS 3.1 CMs only support two OFDM channels that, along with 32 SC-QAMs, have a peak downstream rate of about 5 Gbps.

The new DOCSIS 4.0 CM can use those additional downstream OFDM channels on the DOCSIS 3.1 CMTS, yielding a total capacity and peak downstream rate of up to 8.8 Gbps with 4 OFDM channels + 32 SC-QAMs, and potentially up to 9.5 Gbps with 5 OFDM channels. These increases network capacities can enable operators to offer faster downstream speed tiers than they could with just DOCSIS 3.1 CMs.

DOCSIS specifications have always been designed with backwards compatibility in mind. DOCSIS 4.0 CMs can become operational on a DOCSIS 3.1 CMTS. (Software bugs which prevented this last year have been fixed in CMTS implementations). With these fixes and upgrades to bond more than 2 OFDM channels, DOCSIS 3.1 CMTS can now interpret and negotiate DOCSIS 4.0 modem capabilities and register these CMs on the network allowing them to use the additional downstream capacity.

DOCSIS 4.0 CMs can operate seamlessly on a DOCSIS 3.1 CMTS. In the testing of various CMTS configurations (Integrated, RPHY, RMACPHY, etc.), we successfully brought up DOCSIS 4.0 CMs to register on multiple D3.1 CMTS. These CMs with support for 5 OFDM channels can use the additional CMTS downstream channels and bond data traffic across all of them to prove the ~8.8 to 9.5 Gbps peak downstream data rates.

Enabling DOCSIS 4.0 CMs on the DOCSIS 3.1 network today provides operators with a cost-effective means of providing enhanced services during the transition to DOCSIS 4.0 technology. As seen in lab testing with the example scenarios in this paper, cable operators have many useful and cost-effective methods to increase the service speeds to their customers.

The combination of DOCSIS 3.1 CMTS and DOCSIS 4.0 CM technologies give operators plenty of options in both the upstream and downstream network design. The speeds provided by this combination of technologies will be able to stand up to market pressures until the full network evolution for the DOCSIS 4.0 network are complete over the next many years. A DOCSIS 3.1 CMTS can now provide up to 9.5 Gbps of downstream capacity and almost 1.7 Gbps upstream capacity, enabling high service tier speeds to the customers. D4.0 FDD and FDX CMs can seamlessly make use of this upgraded capability in the DOCSIS 3.1 network.

Abbreviations

BPI +	Baseline Privacy Interface Plus
BPKM	Baseline Privacy Key Management
CM	cable modem
CMTS	cable modem termination system
DAA	distributed access architecture
DOCSIS	data over cable service interface specification
ESD	extended spectrum DOCSIS 4.0 technology
FDD	frequency division duplex
FEC	Forward Error Correction (code)
FDX	full duplex DOCSIS 4.0 technology
FM	frequency modulation
Gbps	gigabits per second
GHz	gigahertz
HFC	hybrid fiber-coax
IPTV	Internet protocol television
MAC	media access control
MACPHY	media access control (MAC) and physical (PHY) layers
MDD	MAC domain descriptor
MHz	megahertz
MPEG	motion pictures experts group
OFDM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multiple access
OOC	overlapping OFDMA channels
PHY	physical layer
PNM	proactive network maintenance
QAM	quadrature amplitude modulation
RMD	Remote MACPHY device
RPD	Remote PHY device
SC-QAM	single carrier quadrature amplitude modulation
SCTE	Society of Cable Telecommunications Engineers
TLV	type/length/value

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