Maximizing Upstream Spectral Efficiency

Tier Based Bonding Groups: Bonding Groups That Make Sense

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1. Introduction

The Data-Over-Cable Service Interface Specifications (DOCSIS®) 4.0 specifications drastically increase upstream capacity by expanding the upstream spectrum by more than eightfold to as high as 684 MHz and increase the number of supported orthogonal frequency division multiple access (OFDMA) channels to a minimum of seven; this is a significant improvement in comparison to DOCSIS 3.1 that supported up to 204 MHz in high-split and two OFDMA channels.

In addition to the above factors, increased upstream pathloss when operating at higher upstream frequencies while maintaining the same maximum modem transmit power from the DOCSIS 3.1 PHY specification could potentially result in a lower received power spectral density (PSD) at the remote physical-layer device (RPD) burst receiver. This, in turn, translates to lower modulation orders and reduced spectral efficiency.

In this paper, we introduce the concept of tier based bonding group (TBBG): an approach to improving the upstream received PSD and associated increased receive modulation error ratio (RxMER) by managing the bonding group assignments relative to the offered service tiers, thereby increasing the spectral efficiency of the upstream channels.

Simulation and experimental results are presented showing more than 6 decibels (dB) of gain in the PSD and RxMER.

2. Upstream in DOCSIS Networks

2.1. Upstream Enhancements in DOCSIS 4.0

DOCSIS 4.0 introduces support for multiple gigabits per second (Gbps) symmetric services by extending both the upstream and downstream supported capacities through a significant increase in the number of supported downstream and upstream OFDM/OFDMA channels in comparison to DOCSIS 3.1 as shown in Table 1 [1]:

Table 1 – CM/CMTS Capability Comparisons

	CM Supported Channels		CMTS Supported Channels	
	DOCSIS 3.1	DOCSIS 4.0	DOCSIS 3.1	DOCSIS 4.0
Downstream Channels	2 OFDM 32 SC-QAM	5 OFDM 32 SC-QAM	2 OFDM 32 SC-QAM	6 OFDM 32 SC-QAM
Upstream Channels	2 OFDMA 8 SC-QAM	7 OFDMA 4 SC-QAM	2 OFDMA 8 SC-QAM	8 OFDMA 4 SC-QAM

To support the additional downstream and upstream OFDM/OFDMA channels, DOCSIS 4.0 introduces an updated spectrum plan which extends the upstream spectrum to as high as 684 MHz and allows overlapping of the upstream and downstream channels in the 108 MHz to 684 MHz band for full duplex (FDX) DOCSIS or extends the downstream spectrum up to 1.8 GHz for frequency division duplexing (FDD).[1] The extension of the upstream band up to 684 MHz represents an 8× increase in the available upstream spectrum in comparison to a mid-split (5 MHz to 85 MHz) DOCSIS 3.1 system.

FDX DOCSIS 4.0 enables efficient spectrum utilization by supporting concurrent operation of the upstream and downstream channels in the same band (108 MHz to 684 MHz) as shown in Figure 1, while maintaining traditional upstream operation in the legacy part of the upstream band and maintaining backward compatibility with DOCSIS 3.0 and DOCSIS 3.1 devices [1].

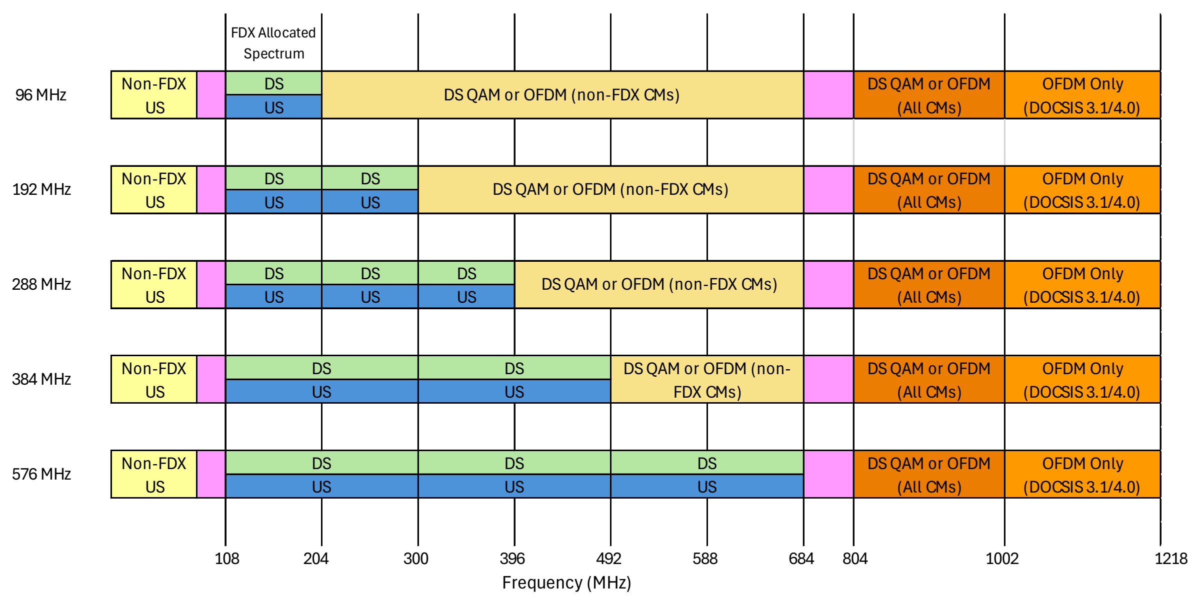

Figure 1 – FDX Sub-Band Options

[1] Formally known as DOCSIS 4.0 frequency division duplexing in the DOCSIS 4.0 specifications, this is also informally called extended spectrum DOCSIS (ESD).

2.2. Upstream Transmit Power in DOCSIS 4.0

DOCSIS 3.1 supports an upstream total composite power (TCP) of 65 dBmV. Despite an 8× increase in the upstream spectrum, the TCP in DOCSIS 4.0 remains fixed at 65 dBmV, the same value that was mandated in the DOCSIS 3.1 PHY Specification [1].

Additionally, the DOCSIS 4.0 specifications define a set of rules governing the operation of the upstream TCP across both the FDX and legacy bands; summarized in the following [1]:

- An FDX cable modem (CM) MUST be capable of transmitting a TCP of 65 dBmV.
- An FDX CM MUST be capable of transmitting a total average output power of 64.5 dBmV in the FDX band.
- An FDX CM MAY be capable of transmitting a total average output power greater than 64.5 dBmV in the FDX Band.
- The FDX CM MUST be capable of transmitting a total average output power of 55 dBmV in the legacy US band when operating in FDX mode.

Similar requirements also apply for DOCSIS 4.0 FDD systems; for the sake of brevity, we will limit the discussion here to FDX DOCSIS 4.0, keeping in mind that the same concepts also apply to DOCSIS 4.0 FDD.

To maximize upstream capacity and efficiency, upstream transmit power management in FDX DOCSIS needs to consider several factors when determining the optimum upstream transmit power:

- A high upstream received signal level in the FDX band is desired at the RPD to optimize the performance of the echo canceller at the receiver, maximize the RxMER of the upstream signal, and support higher bit loading in the upstream.
- At the same time, maximizing the upstream transmit power in the FDX band can potentially limit the available power for the upstream transmissions in the legacy band, and thus reducing the achievable bit loading in the upstream.
- Finally, a high upstream transmit power level at the CM can potentially increase the CM-to-CM interference across transmission groups, which in turn can potentially increase interference at adjacent CMs and thus reduce the downstream RxMER and achievable bit loading in the downstream.

2.3. Upstream Performance in DOCSIS 3.1 Networks

To better evaluate how to manage the upstream transmit power for DOCSIS 4.0 devices, it is important to find the baseline of the upstream performance of DOCSIS 3.1 devices in today’s networks. In this section, we summarize the upstream performance of DOCSIS 3.1 devices operating in mid-split on the Xfinity network.

DOCSIS 3.1 supports OFDMA transmissions in the upstream band, with required support for modulation orders up to 1024-quadrature amplitude modulation (QAM) and optional support for 2048-QAM and 4096-QAM. In comparison to DOCSIS 3.0, this is approximately a 67% increase in upstream spectral efficiency for 1024-QAM, and a 100% increase for 4096-QAM.

The use of OFDMA has been very effective in maximizing the upstream spectral efficiency and the upstream capacity overall.

For example, in the Xfinity network operating in mid-split, 77.2% of the upstream OFDMA traffic uses 4096-QAM, and 92.6% of the traffic uses 2048-QAM and above as shown in Figure 2.

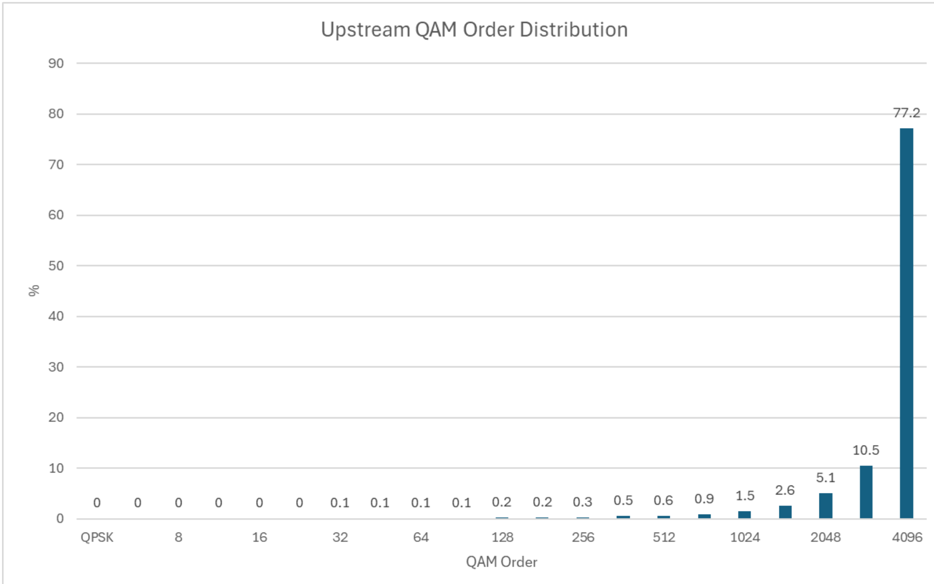

Figure 2 – OFDMA Traffic Distribution Across Modulation Orders

The upstream QAM order distribution results in an upstream spectral efficiency of approximately 11.43 bits per second (bps) per hertz (Hz), reflecting a 90% increase in upstream spectral efficiency in comparison to legacy DOCSIS 3.0 single carrier quadrature amplitude modulation (SC-QAM) channels.

Additionally, it is also important to consider the upstream TCP of the CMs in the network. The upstream transmit power distribution for the CMs in the network is detailed in Figure 3.

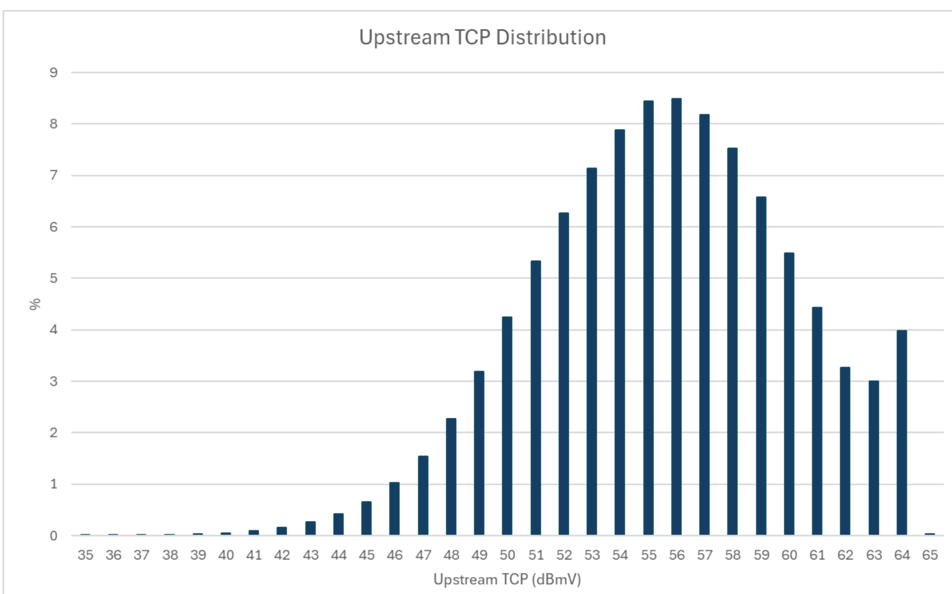

Figure 3 – Upstream Transmission TCP Distribution

As shown in Figure 3, the median TCP of the DOCSIS 3.1 CMs in the upstream is approximately 55 dBmV.

2.4. Impact of DOCSIS 4.0 Upstream Power Limitations on Upstream Performance

As discussed previously, it is desired to maximize the upstream received signal in the FDX band at the RPD receiver in order to maximize the upstream capacity. At the same time, it is also desired to maintain the current received signal level and performance of the legacy upstream band in order maximize the overall upstream capacity and reduce the possibility of impacting the performance of the DOCSIS 3.1 devices.

2.4.1. Impact of DOCSIS 4.0 Upstream Power Limitations on FDX Upstream Band

Currently, the maximum TCP of DOCSIS 4.0 devices is 65 dBmV, which is shared across the upstream FDX and legacy bands. Upstream TCP in the mid-split band exceeding 55 dBmV would require operation in the upstream FDX band at TCP less than 64.5 dBmV.

As shown in Figure 3, approximately 50% of the DOCSIS 3.1 devices operate with an upstream transmit power exceeding 55 dBmV. To maintain the performance of the mid-split upstream band, this would require a reduction in the available power in the FDX band, as shown in Figure 4.

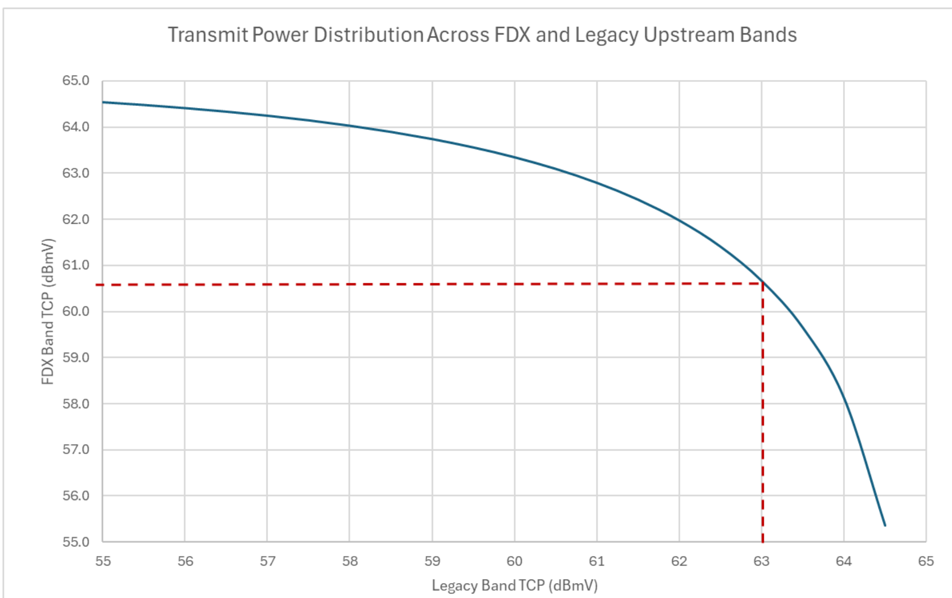

Figure 4 – Transmit Power Distribution Across FDX and Mid-Split Upstream Bands

For example, maintaining a 63 dBmV upstream TCP in the mid-split band requires a reduction of 3.8 dB of TCP in the FDX band to 60.7 dBmV.

2.4.2. Impact of DOCSIS 4.0 Upstream Power Limitations on Legacy Upstream Band

To maximize the upstream performance in the FDX band, it is beneficial for the CMs to be able to operate at 64.5 dBmV. This requires limiting the TCP in the upstream legacy band to 55 dBmV.

With 50% of the devices operating at a TCP exceeding 55 dBmV in the mid-split upstream band, limiting their upstream TCP to 55 dBmV correlates to reduction in upstream PSD which translates to a reduction in spectral efficiency in the mid-split band as shown in Figure 4.

Using the same sample of devices as in Figure 2 but limiting the maximum TCP to 55 dBmV, only 37.7% of the upstream OFDMA traffic uses 4096-QAM, and only 70.8% of the traffic uses 2048-QAM and above. This is in contrast to 77.2% and 92.6% respectively when the maximum TCP was 65 dBmV. See Table 2 and Figure 5.

Table 2 – QAM Order Distribution with 55 dBmV limit on TCP in Mid-Split Upstream Band

	Max TCP 65 dBmV	Max TCP 55 dBmV
4096-QAM	77.2%	37.7%
2048-QAM and above	92.6%	70.8%

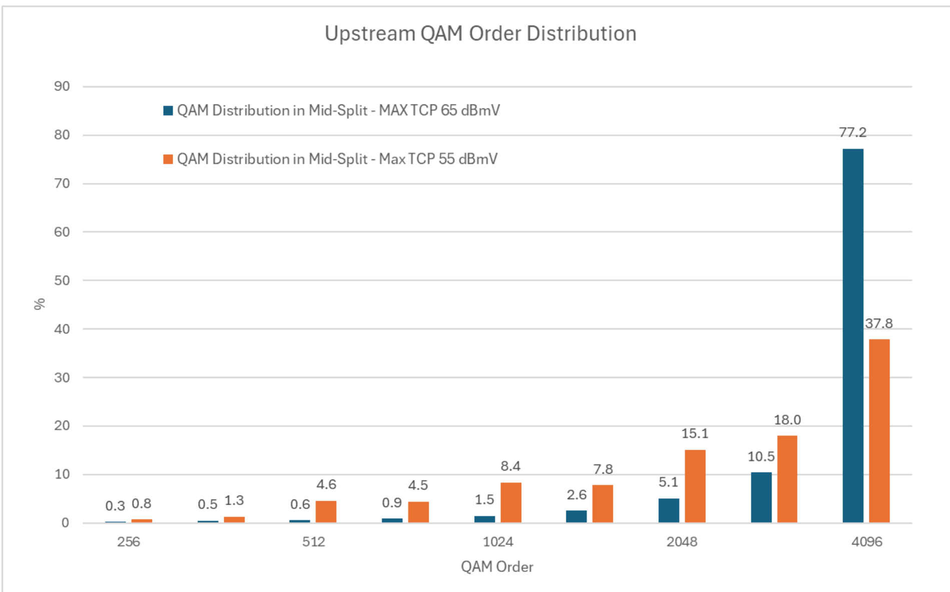

Figure 5 – Impact of Upstream TCP on QAM Order Distribution

3. Tier Based Bonding Groups

In this section, we introduce a new approach to managing bonding groups that enables more flexibility in managing power allocation across upstream bands, in addition to managing interference across the hybrid fiber/coax (HFC) network. The TBBG takes a more deliberate approach in building and selecting bonding groups based on the provisioned service tiers being delivered on the network, which provides significant benefits in managing upstream TCP of the device.

3.1. Upstream Bonding Groups

Upstream bonding groups refer to the aggregation of multiple upstream channels, which creates a single large pipe for traffic transfer, in turn increasing the upstream capacity available to the CM. In addition to increasing upstream capacity, bonding groups enable load balancing across multiple channels, thus reducing the possibility of channel congestion and providing additional reliability through channel redundancy, as the CM is not dependent on a single channel for communication.

Typically, bonding groups are formed to maximize the capacity available to the CM. For example, in the upstream a DOCSIS 3.1 CM supports eight SC-QAM and two OFDMA channels. If the cable modem termination system (CMTS) is configured for six upstream SC-QAM channels and one OFDMA channel, then the CM will be assigned a bonding group composed of six SC-QAM and one OFDMA channel regardless of the capacity requirements of the CM.

During the ranging process, the upstream TCP is ranged across all channels in the upstream bonding group (also referred to as transmit channel set or TCS) and set the power adjustments such that the upstream signal at the RPD is received at the correct level, and that the TCP does not exceed the maximum available TCP to the CM (65 dBmV for DOCSIS 3.1 devices).

3.2. Upstream Tier Based Bonding Groups

DOCSIS 4.0 introduces an 8× increase in the available upstream spectrum in comparison to a mid-split DOCSIS 3.1 system, while at the same time the upstream TCP available to the CM remains the same at 65 dBmV.

Comparing the maximum upstream PSD between DOCSIS 3.1 and DOCSIS 4.0, the maximum PSD in a DOCSIS 3.1 device is approximately 47 dBmV/1.6 MHz; while for a DOCSIS 4.0 device with the upstream band operating up to 684 MHz, this would be 38 dBmV/1.6 MHz in the mid-split band, and 39 dBmV/1.6 MHz in the FDX band (assuming no tilt in the upstream transmit PSD in both cases for simplification).

The limitations on the available upstream TCP for DOCSIS 4.0 CMs translate to approximately 9 dB loss in upstream maximum PSD in DOCSIS 4.0 devices in comparison to a DOCSIS 3.1 device.

With upstream TBBGs, upstream DOCSIS 4.0 bonding groups are formed based on the service tier the CM is subscribed to, thus not needing the CM to bond across all the upstream channels available to it. This can be achieved via dynamic bonding change (DBC) messaging to add only a subset of the FDX band channels to a modem's TCS once DOCSIS 3.1 registration has completed.

For example, in a DOCSIS 4.0 network where the upstream band extends from 108 MHz to 684 MHz as shown in Figure 6, a device that is subscribed to a 3 Gbps symmetric service would have a bonding group comprised of the channels in the mid-split band, in addition to the first two sub-bands in the FDX band; a CM with a service tier of 1 Gbps symmetric service tier could potentially have a bonding group comprised of the legacy band and the last sub-band (492 MHz to 684 MHz) in the FDX band.

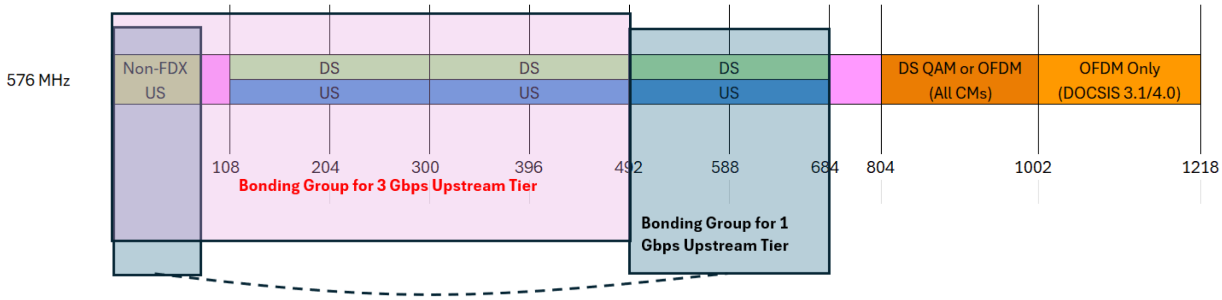

Figure 6 – Tier Based Bonding Groups Example

Configuring the bonding groups to align with the device service tier has a direct impact on the available upstream power to be allocated to the upstream channels in the bonding group, and potentially increasing the received PSD and RxMER at the RPD.

3.2.1. Upstream Transmit Power Gains

Intelligent selection for the number of upstream channels in a modem's TCS enables flexibility in how power can be allocated across the FDX band and the legacy upstream band.

DOCSIS 4.0 defines a reference upstream PSD for DOCSIS 4.0 devices which is defined as a line in dBmV (per 1.6 MHz) for the y-axis and linear frequency in the x-axis, and passes through the points 33.0 dBmV in 1.6 MHz centered at 108.8 MHz and 43.0 dBmV centered at 683.2 MHz as shown in Figure 7; this equates to a total power of 64.5 dBmV in the FDX band [1].

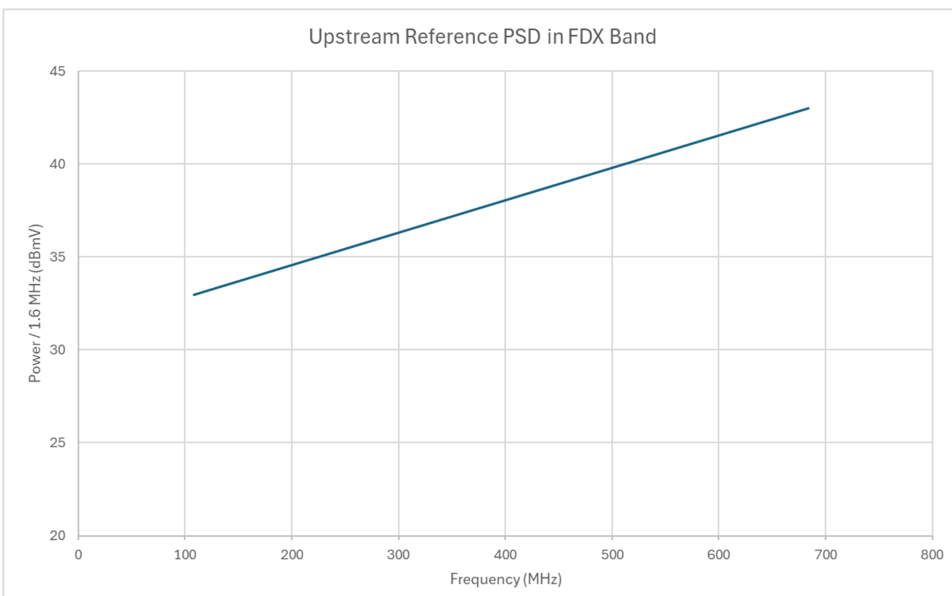

Figure 7 – Upstream Reference PSD in FDX Band

Table 3 provides an example for the TCP based on the TCSs in the FDX spectrum configuration of 576 MHz (108 MHz to 684 MHz) shown in Figure 6.

Table 3 – Impact of Transmit Channel Set Bandwidth on TCP

FDX Spectrum TCS Bandwidth						
192 MHz				**384 MHz**		
TCS in FDX spectrum	TCP	dB Savings rel/ 576 MHz		TCS in FDX spectrum	TCP	dB Savings rel/ 576 MHz
108 MHZ to 300 MHz	55.6	8.9		108 MHz to 492 MHz	60.6	3.9
300 MHZ to 492 MHz	58.9	5.6		108 to 300 & 492 MHz to 684 MHz	63.1	1.4
492 MHz to 684 MHz	62.3	2.2		300 MHz to 684 MHz	63.9	0.8

For example, if a CM that has a 1 Gbps service tier has a TCS in the FDX band comprising the three sub-bands shown in Figure 6 in addition to the legacy mid-split channel, then its maximum TCP would align with the reference PSD shown in Figure 7, and it would be limited to a maximum TCP of 55 dBmV in the mid-split band and 64.5 dBmV across the FDX band.

With TBBGs implemented and the device's TCS comprising the middle sub-band (300 MHz to 492 MHz) in addition to the mid-split band, then the total TCP for the CM would be 60.4 dBmV (assuming a TCP of 55 dBmV in the mid-split band), leaving 4.6 dB of TCP headroom below P_{max}.

This provides flexibility for the CM to transmit at higher levels in either or both bands. For example, the CM can transmit at a TCP of 61 dBmV in the mid-split band and a TCP of 62.8 dBmV in the second FDX sub band (300 MHz to 492 MHz) for a total of 65 dBmV. NOTE: There are restrictions on how far away from the reference PSD ($P_{ref\text{-}FDX}$) a modem is allowed to transmit before fidelity and performance requirement adherence is no longer applicable.

To achieve the same transmit levels without using TBBGs would require the CM to support an upstream TCP of 68.4 dBmV. We call this value as the virtual TCP for the CM.

The virtual TCP is defined as *the TCP required for the CM to support to achieve the same TCP in the bonded spectrum of interest if the CM were bonded across 576 MHz of FDX spectrum (570 MHz of modulated spectrum) and the legacy upstream band.*

3.2.2. Upstream Spectral Efficiency Gains

Enabling CMs to transmit at higher levels in the reduced TCS under TBBG operation allows driving higher spectral efficiencies, overcoming excessive path loss, and maximizing system capacity without exceeding the devices' maximum TCP of 65 dBmV.

Revisiting the previous example where the CMs were transmitting at the reference PSD in the FDX band, but this time leveraging TBBGs, allows the CM to transmit at higher levels than 55 dBmV in the mid-split band. Figure 8 shows the simulation results using the same sample of devices as in Figure 2 when implementing TBBGs.

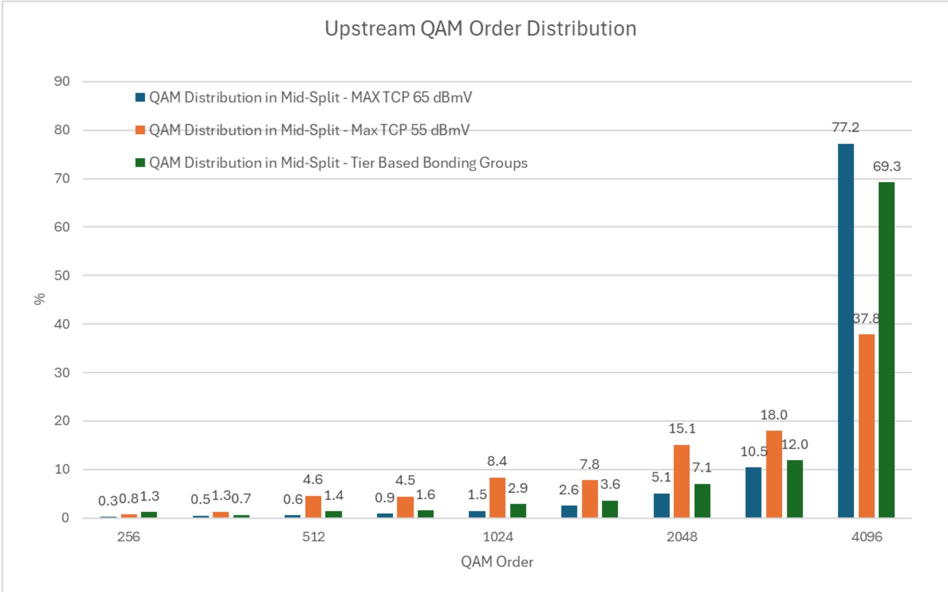

Figure 8 – Impact of Tier Based Bonding Groups on QAM Order Distribution

When using TBBGs, 69.3% of upstream OFDMA traffic uses 4096-QAM, and 88.4% of the traffic uses 2048-QAM and above. Table 4 summarizes the results for the three scenarios.

Table 4 – QAM Order Distribution Gains Due to Tier Based Bonding Groups

	Max TCP 65 dBmV	Max TCP 55 dBmV	Tier Based Bonding
4096-QAM	77.2%	37.7%	69.3%
2048-QAM and above	92.6%	70.8%	88.4%

As shown in the simulation results above, TBBGs provides an effective way to optimize the available TCP at the CM and enhance the upstream spectral efficiency and the overall system performance, without the need to drive higher upstream TCP requirements at the CM.

3.2.3. Load Balancing for Tier Based Bonding Groups

With TBBGs, one needs to make sure that the creation and assignment of a TBBG does not create high disparity in the utilization of the upstream channel in the FDX band. For example, if all TBBGs prioritized the use of the first sub-band as part of the TCS, then the first sub-band would have high utilization relative to the remaining sub bands.

To effectively recommend and assign bonding groups based on service tier offerings and optimized utilization distribution across FDX channels, we utilize the cloud-based external load balancer discussed in another SCTE 2024 paper: "Optimizing Spectrum Efficiency with Cloud-Based Load Balancing"[2].

The external load balancer is a virtual network function (VNF) that migrates the load balancing functionality of the CMTS to a software application running in the cloud with more capable and sophisticated algorithms and policy configuration support. It can consume additional information for making bonding group recommendations and assignments. In the use case of TBBG, to simplify the system an additional preprocessing step provides information and policy configurations for TBBG optimizations to be accounted for by the external load balancer.

There are few requirements for this optimization:

- The assigned bonding group must be able to provide the capacity required for reaching the maximum provisioned rates (including over-provisioned amounts). This ensures that all users are served with promised bandwidth while performing this optimization.
- The bonding group capacity must be calculated with the estimated bit-loadings across its channels.
    - We define these bit-loadings as "conditional" bit-loadings since the same CM may be able to use different modulation orders depending on the number of FDX channels it bonds to and the RxMER gain that can result from TCP savings on different bonding groups.
    - The estimated bonding group bit-loadings should not only consider the TCP savings under different bonding group sizes, but also different path loss factors across the spectrum from 108 MHz to 684 MHz.
- The aggregated channel utilizations must be considered such that:
    - The projected CM utilization added to the bonding group's channel set, weighing in the bit-loading variations, is correctly accounted for.

These requirements drive the design and implementation for TBBG to integrate with our external load balancer. As shown in Figure 9, a preprocessing step takes the FDX CM's provisioned rates and policy configurations into account to specify mappings between each FDX CM and its usable FDX bonding groups along with its estimated mean bit-loadings on different bonding groups. The external load balancer then consumes this information as exclusion rules for bonding groups and ratios for utilization impact projection when assigning a CM to a certain bonding group.

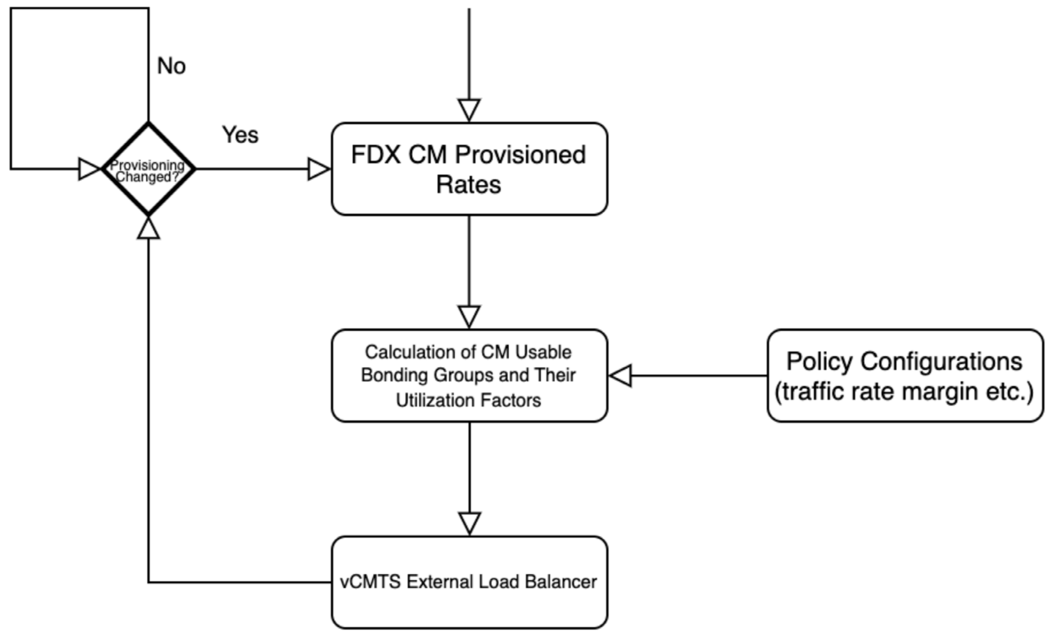

Figure 9 – Integration with the External Load Balancer

To experiment with the design of the TBBG, we developed a simple simulation with a graphical user interface (GUI) to examine and interactively visualize the concepts behind TBBG, as shown in Figure 10. With this simulation, different combinations of inputs can be tested. Based on the requirements discussed earlier, we supply baseline bit-loadings for each FDX upstream OFDMA channel, the conditional bit-loading gains for a CM when it is assigned a certain bonding group, existing aggregated utilization on each channel (calculated during load balancing calculation's iterations before allocating the CM under consideration), and the CM's provisioned rate as user input to the simulation. Based on the number of configured FDX channels, the simulation automatically calculates possible FDX bonding groups, and incorporates the given data to calculate "usable" bonding groups (as marked by green checkmarks in the lower part of Figure 10), the recommended bonding group to be assigned – prioritized by the bonding group size (the smaller the better) and the total available capacity (the higher the better) for a CM on the bonding group.

In the example shown in Figure 10, the recommended bonding group for the CM under the given condition covers 108 MHz to 492 MHz (384 MHz bandwidth) because its conditional bonding capacity is greater than the requirement (2.2 Gbps), its number of channels is less than the largest bonding group with six FDX OFDMA channels, and its available capacity is higher than another 384 MHz bonding group covering 300 MHz to 684 MHz at the load balancing optimization time. This is the sequence of logic where a bonding group is selected for an FDX CM during one iteration of the external load balancer's algorithm.

Bonding Group	Bandwidth	Capacity	Capacity + D3.1	Used	Available	Available + D3.1	Cond. Bonding Capacity	Usable	Assigned	Cond. Bit-Loading Gains
108 - 300 MHz	192.00 MHz	1620.00 Mbps	2095.80 Mbps	685.80 Mbps	934.20 Mbps	1410.00 Mbps	1987.80 Mbps	✗		0, -1.5
300 - 492 MHz	192.00 MHz	1476.00 Mbps	1951.80 Mbps	963.72 Mbps	512.28 Mbps	988.08 Mbps	1843.80 Mbps	✗		0, -1.5
492 - 684 MHz	192.00 MHz	1346.40 Mbps	1822.20 Mbps	719.06 Mbps	627.34 Mbps	1103.14 Mbps	1714.20 Mbps	✗		0, -1.5
108 - 492 MHz	384.00 MHz	3096.00 Mbps	3571.80 Mbps	1649.52 Mbps	1446.48 Mbps	1922.28 Mbps	3024.60 Mbps	✓	✓	0, -1.5, -2.5, -3.6
300 - 684 MHz	384.00 MHz	2822.40 Mbps	3298.20 Mbps	1682.78 Mbps	1139.62 Mbps	1615.42 Mbps	2751.00 Mbps	✓		0, -1.5, -2.5, -3.6
108 - 684 MHz	576.00 MHz	4442.40 Mbps	4918.20 Mbps	2368.58 Mbps	2073.82 Mbps	2549.62 Mbps	3802.20 Mbps	✓		0, -1.5, -2.5, -3.6, -3.9, -4.0

Figure 10 – Simulation Application: FDX Bonding Group Playground

Figure 11 illustrates another experiment (with the same 2.2 Gbps upstream capacity requirement) where the utilization allocated to the first four FDX OFDMA channels increased. In this example, the algorithm picked a bonding group covering 300 MHz to 684 MHz because its available capacity became higher than the first four-channel bonding group after the utilization condition change.

Bonding Group	Bandwidth	Capacity	Capacity + D3.1	Used	Available	Available + D3.1	Cond. Bonding Capacity	Usable	Assigned	Cond. Bit-Loading Gains
108 - 300 MHz	192.00 MHz	1620.00 Mbps	2095.80 Mbps	1140.12 Mbps	479.88 Mbps	955.68 Mbps	1987.80 Mbps	✗		0, -1.5
300 - 492 MHz	192.00 MHz	1476.00 Mbps	1951.80 Mbps	1100.16 Mbps	375.84 Mbps	851.64 Mbps	1843.80 Mbps	✗		0, -1.5
492 - 684 MHz	192.00 MHz	1346.40 Mbps	1822.20 Mbps	719.06 Mbps	627.34 Mbps	1103.14 Mbps	1714.20 Mbps	✗		0, -1.5
108 - 492 MHz	384.00 MHz	3096.00 Mbps	3571.80 Mbps	2240.28 Mbps	855.72 Mbps	1331.52 Mbps	3024.60 Mbps	✓		0, -1.5, -2.5, -3.6
300 - 684 MHz	384.00 MHz	2822.40 Mbps	3298.20 Mbps	1819.22 Mbps	1003.18 Mbps	1478.98 Mbps	2751.00 Mbps	✓	✓	0, -1.5, -2.5, -3.6
108 - 684 MHz	576.00 MHz	4442.40 Mbps	4918.20 Mbps	2959.34 Mbps	1483.06 Mbps	1958.86 Mbps	3802.20 Mbps	✓		0, -1.5, -2.5, -3.6, -3.9, -4.0

Figure 11 – Simulation Application: Increased Utilization on the First Four FDX OFDMA Channels

The virtual cable modem termination system (vCMTS) external load balancer provides unmatched flexibility and extensibility that were never provided before by the traditional integrated cable modem termination system (I-CMTS) platforms, allowing us to approach a simple and modular system design from the beginning of the development and giving us confidence and convenience for integration and incremental implementations of this new feature.

3.2.4. *Other Applications for Tier Based Bonding Groups*

In this paper, we focus on the upstream TCP optimization using TBBG for maximizing the upstream capacity in the mid-split band for a DOCSIS 4.0 device. TBBG can also provide several other benefits such as optimizing the upstream capacity in the 108 MHz to 684 MHz upstream band, and an effective way for managing and reducing neighbor-to-neighbor interference and reducing impact to legacy downstream DOCSIS channels or video channels.

4. Initial Laboratory Proof-of-Concept Testing

Testing was conducted in a laboratory environment to gauge the impact of attempting to maintain TCP levels while reducing the number of channels in the FDX band extended transmit channel set.

4.1. Method of Test

FDX-capable cable modems were configured with a TCS including four 6.4 MHz ATDMA, one 44.4 MHz L-OFDMA, and six 94.4 MHz FDX-OFDMA channels. Upstream traffic was run continuously at 1.5 Gbps through the modem under test as it tended to stabilize RxMER and power level measurements as opposed to the idle state.

Return path loss in the physical plant was balanced to achieve TCP levels approaching 55 dBmV for total legacy band power, and 64.5 dBmV in the extended band, as shown in Figure 12:

	As Reported From Genome Cable Modem Query			From PHYv4.0			As Reported in CM Console		From UCD								
Channel Id	Pr_n (DOCSIS 3.0 reporting)	P1.6r_n (DOCSIS 3.1 reporting)	P1.6r_n-FDX	Pref (Reference Power)	P1.6r_n (Delta from Reference Power)	Plimit	CmdPwr	CmdPwr Ext	Number of Excluded Subcarriers	Unused Subcarriers	Occupied Bandwidth (MHz)	Number of Minislots	N_{eq}	$N_{eq\text{-}FDX}$	PWR_n Power in n^{th} channel (dBmV)	TCP (dBmV)	
1	43.00						37.00				6.4		1		43		
2	43.30						37.25				6.4		1		43.3		
3	43.30						37.25				6.4		1		43.3		
4	43.50						37.50				6.4		1		43.5		
41		38.50					38.50		2320	0	44.4	111	27.75		52.932630		
																54.495618	Total CM legacy output power
50			34.75	33.75	1.00	1.50		34.50	352	0	93.6	234		58.5	52.421559		55 dBmV minimum support required
51			38.50	35.5	3.00	1.50		38.25	320	0	94.4	236		59	56.208520		
52			38.25	37.25	1.00	1.50		38.25	320	0	94.4	236		59	55.958520		
53			39.50	38.75	0.75	1.00		39.50	320	0	94.4	236		59	57.208520		
54			38.75	40.5	-1.75	1.00		38.75	320	0	94.4	236		59	56.458520		
55			40.25	42.25	-2.00	1.00		40.25	320	0	94.4	236		59	57.958520		
																64.116014	Total CM extended output power
																	64.5 dBmV minimum support required
																64.565854	TCP
																	65 dBmV minimum support required

Figure 12 – Initial Upstream Channel Transmit Power Levels

A baseline RxMER measurement, shown in Figure 13, was taken at these transmit levels:

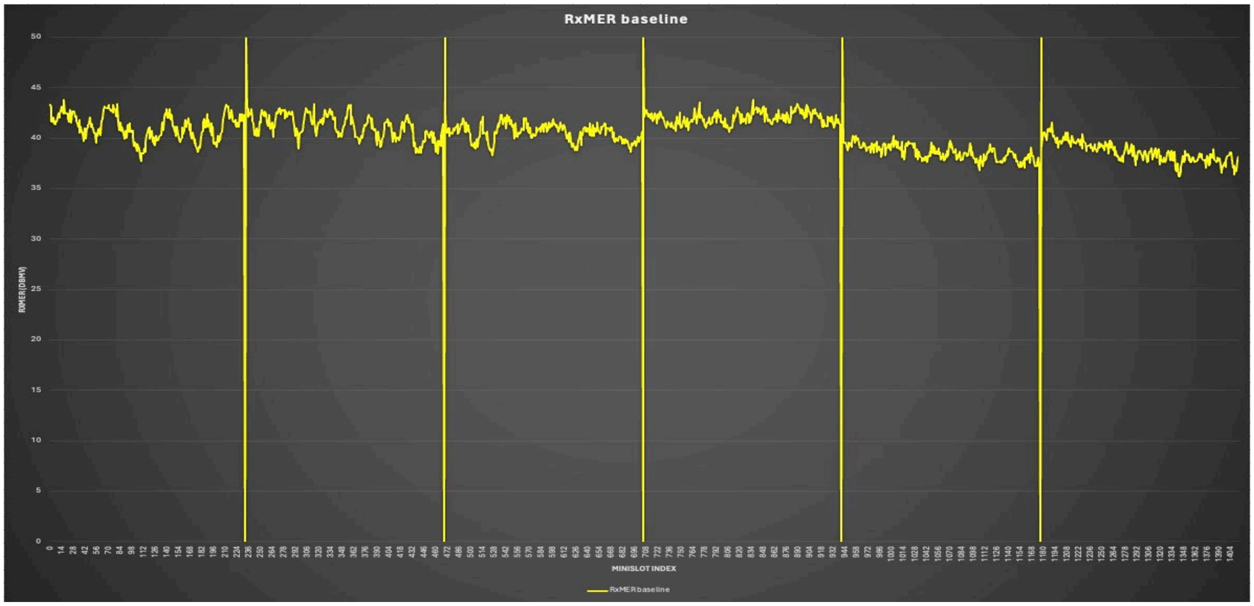

Figure 13 – Baseline RxMER Measurement Across the FDX Band OFDMA Channels

The two OFDMA channels in the upper sub-band were put in “admin down” state, and the modem under test then moved from the 11 upstream channel TCS and bonded to the nine upstream channel bonding group. A drop in TCP of 2 dB was observed, as shown in Figure 14:

	As Reported From Genome Cable Modem Query			From PHYv4.0			As Reported in CM Console		From UCD								
Channel Id	Pr_n (DOCSIS 3.0 reporting)	P1.6r_n (DOCSIS 3.1 reporting)	P1.6r_n-FDX	Pref (Reference Power)	P1.6r_n (Delta from Reference Power)	Plimit	CmdPwr	CmdPwr Ext	Number of Excluded Subcarriers	Unused Subcarriers	Occupied Bandwidth (MHz)	Number of Minislots	N_{eq}	$N_{eq\text{-}FDX}$	PWR_n Power in n^{th} channel (dBmV)	TCP (dBmV)	
1	43.00						37.00				6.4		1		43		
2	43.30						37.25				6.4		1		43.3		
3	43.30						37.25				6.4		1		43.3		
4	43.50						37.50				6.4		1		43.5		
41		38.50					38.50		2320	0	44.4	111	27.75		52.932630		
																54.495618	Total CM legacy output power
50			36.50	33.75	2.75	1.50		36.50	352	0	93.6	234		58.5	54.171559		55 dBmV minimum support required
51			38.25	35.5	2.75	1.50		38.00	320	0	94.4	236		59	55.958520		
52			38.25	37.25	1.00	1.50		38.25	320	0	94.4	236		59	55.958520		
53			38.75	38.75	0.00	1.00		38.75	320	0	94.4	236		59	56.458520		
54			0.00	40.5	-40.50	1.00			320	0	94.4	236		59			
55			0.00	42.25	-42.25	1.00			320	0	94.4	236		59			
																61.738839	Total CM extended output power
																	64.5 dBmV minimum support required
																62.489412	TCP
																	65 dBmV minimum support required

Figure 14 – Upstream Transmit Power Levels for the Nine Channel Bonding Group

The power-adjust value for the remaining bonded channels was increased by 3 dB. The modem was able to transmit at up to 5.75 dB above the reference PSD, however a limit of 3.5 dB was more often observed. After boosting the commanded receive level set point, TCP was close to the previous full band levels, summarized in Figure 15:

	As Reported From Genome Cable Modem Query			From PHYv4.0			As Reported in CM Console		From UCD								
Channel Id	Pr_n (DOCSIS 3.0 reporting)	P1.6r_n (DOCSIS 3.1 reporting)	P1.6r_n-FDX	Pref (Reference Power)	P1.6r_n (Delta from Reference Power)	Plimit	CmdPwr	CmdPwr Ext	Number of Excluded Subcarriers	Unused Subcarriers	Occupied Bandwidth (MHz)	Number of Minislots	N_{eq}	$N_{eq\text{-}FDX}$	PWR_n Power in n^{th} channel (dBmV)	TCP (dBmV)	
1	43.00						37.00				6.4		1		43		
2	43.30						37.25				6.4		1		43.3		
3	43.50						37.50				6.4		1		43.5		
4	43.80						37.75				6.4		1		43.8		
41		38.50					38.50		2320	0	44.4	111	27.75		52.932630		
																54.535671	Total CM legacy output power
50			37.50	33.75	3.75	1.50		37.50	352	0	93.6	234		58.5	55.171559		55 dBmV minimum support required
51			41.25	35.5	5.75	1.50		40.75	320	0	94.4	236		59	58.958520		
52			40.25	37.25	3.00	1.50		40.25	320	0	94.4	236		59	57.958520		
53			41.25	38.75	2.50	1.00		41.25	320	0	94.4	236		59	58.958520		
54			0.00	40.5	-40.50	1.00			320	0	94.4	236		59			
55			0.00	42.25	-42.25	1.00			320	0	94.4	236		59			
																64.026889	Total CM extended output power
																	64.5 dBmV minimum support required
																64.489612	TCP
																	65 dBmV minimum support required

Figure 15 – Power Levels After +3 dB Power-Adjust Value Setting Applied

An increase in RxMER in Channels 50, 51, and 52 was observed, with a decrease in Channel 53, illustrated in Figure 16:

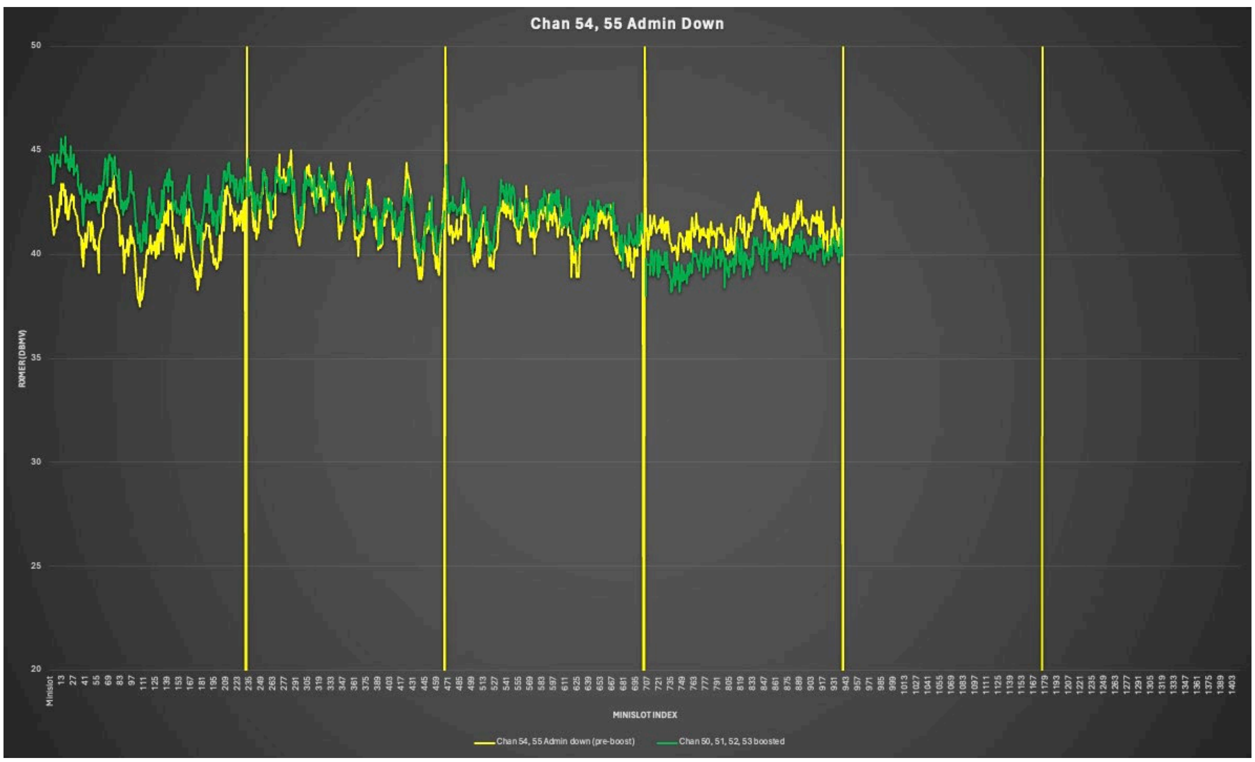

Figure 16 – RxMER Measurement After +3 dB Power-Adjust Setting

A closer view of Channel 50 in this case shows that at 62.5 dBmV TCP levels the channel is capable of supporting an IUC profile comprised of 1024/2048-QAM modulated minislots, as shown in Figure 17:

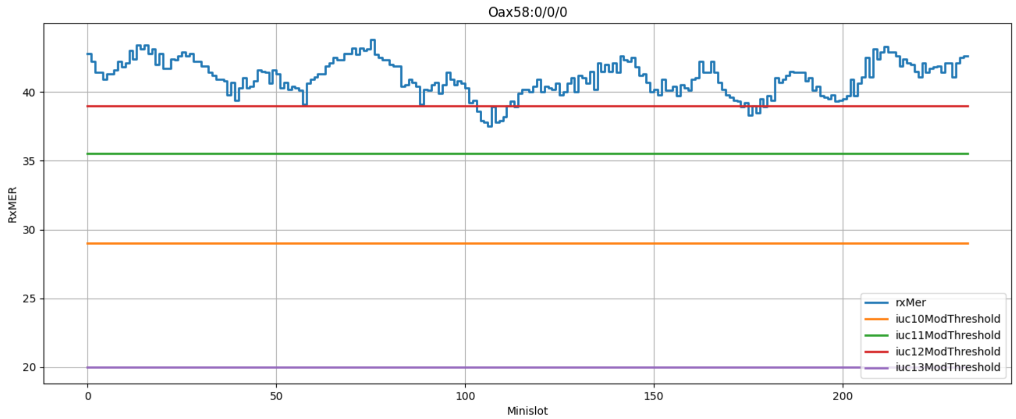

Figure 17 – Channel 50 RxMER Capable of 1024/2048-QAM @ 62.5 dBmV TCP

After adjusting the power-adjust levels to reach 64.5 dBmV TCP, the channel is now able to support an IUC profile using 2048/4096-QAM, illustrated in Figure 18:

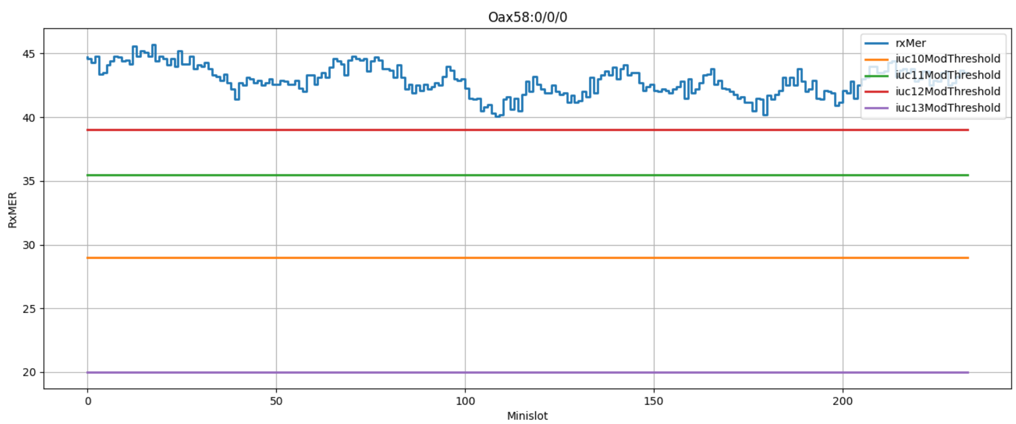

Figure 18 – Channel 50 RxMER Now Capable of 2048/4096 QAM @ 64.5 dBmV TCP

This process was repeated by shutting down the middle sub-band – leaving only the lower sub-band active – allowing the modem to bond the remaining channels, that is, Channels 50 and 51 in the FDX band. In this configuration, the modem was unable to be commanded to transmit more than 3.25 dB above the reference level. This increased TCP from 59.89 dBmV to 60.06 dBmV resulting in minimal impact (see Figure 19).

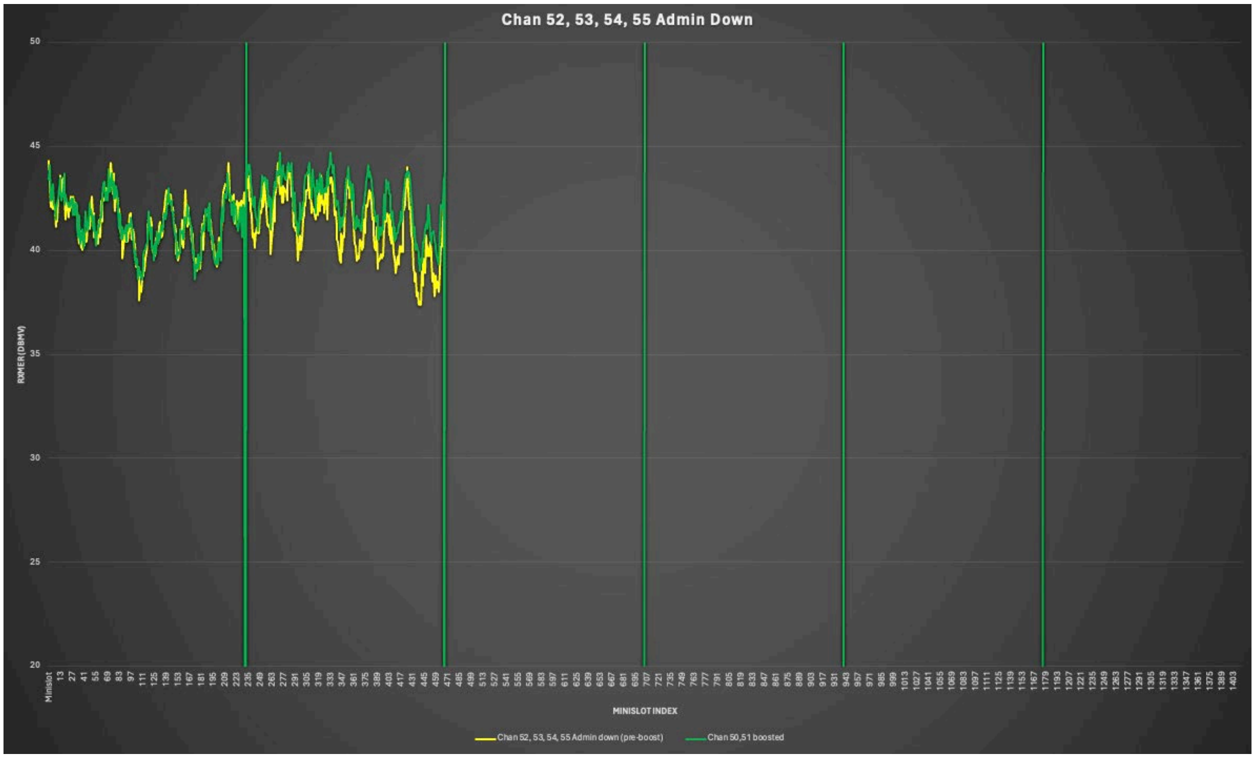

Figure 19 – Slight Improvement in Lower Sub-band RxMER

This result indicates that some potential changes such as relaxing PSD reference adherence or tweaking RPD burst receiver parameters may yield better US physical layer performance, especially in fiber-deep RF environments.

5. Conclusion

TBBG provides an effective way to maximize the upstream spectral efficiency without driving any new requirements on the TCP capabilities of the CM. Leveraging TBBG enables the CM to deliver upstream signal levels commensurate with devices that have significantly higher TCP capabilities.

Our simulation results show how leveraging TBBG enables DOCSIS 4.0 devices to transmit at the maximum PSD in the upstream FDX band (which would limit the TCP to 55 dBmV in the legacy band without TBBG) and to maintain nearly the same performance in the mid-split band. This approach is applicable to both FDX and FDD deployments, driving improved spectral efficiency for DOCSIS 4.0 networks.

Abbreviations

CM	cable modem
CMTS	cable modem termination system
dB	decibel
dBmV	decibel millivolt
DOCSIS	Data-Over-Cable Service Interface Specifications
ESD	extended spectrum DOCSIS
FDD	frequency division duplexing
FDX	full duplex [DOCSIS]
Gbps	gigabits per second
GUI	graphical user interface
HFC	hybrid fiber/coax
Hz	hertz
I-CMTS	integrated cable modem termination system
Mbps	megabits per second
OFDMA	orthogonal frequency division multiple access
PSD	power spectral density
QAM	quadrature amplitude modulation
RPD	remote physical layer device
RxMER	receive modulation error ratio
SCTE	Society of Cable Telecommunications Engineers
SC-QAM	single carrier quadrature amplitude modulation
TBBG	tier based bonding group
TCP	total composite power
vCMTS	virtual cable modem termination system
VNF	virtual network function

Bibliography & References

1. *DOCSIS 4.0 Physical Layer Specification*, CM-SP-PHYv4.0-I06-221019.

2. *Optimizing Spectrum Efficiency with Cloud-Based Load Balancing*, J. Zhu, D. Li, A. Skvirsky, Q. Zang, D. Wang, B. Hamzeh, D. Rice, and M. Niv, TechExpo24 Fall Technical Forum technical paper.