Preparing For DOCSIS® 4.0 Upstream

A Technical Paper prepared for SCTE by

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1. Introduction

DOCSIS® 4.0 technology was created as a part of the 10G roadmap to increase capacity in both upstream (US) and downstream (DS). As we prepare to deploy this technology, the attention is rapidly shifting towards upstream, which was accelerated due to COVID-19. Last year, a noticeable jump in upstream utilization was realized by almost all multiple service operators (MSOs) worldwide, emphasizing the need for higher throughputs in the upstream. The shift to working remotely, learning from home, video conferencing and increased gaming activity demonstrated the need to increase bandwidth in the upstream to meet evolving consumer appetites.

Currently, many multiple system operators (MSOs) operate in 42, 65 or 85 MHz plant. The smaller bandwidth benefits the modems and amplifiers operating in the return spectrum. The same operators are planning on expanding the upstream spectrum bandwidth to 396 or 492 MHz in the near future, with 204 MHz as an intermediate step. Many operators are also planning on deploying DOCSIS 4.0 capable equipment in existing plant without re-spacing, which means there are a few key challenges to be considered.

In this paper, we will evaluate the DOCSIS 4.0 plant models by addressing these key challenges, including modem transmit capabilities, upstream amplifier performances and potential upstream performance expectations for various node and serving group architectures. The goal is to highlight the main areas that should be prioritized to ensure optimal DOCSIS 4.0 upstream performance in the access network.

Furthermore, this paper primarily aims to shed light on areas of the US that we need to focus on, along with providing new insights into performance of nodes and serving groups based on their characteristics and properties. The DOCSIS specifications define what can be expected from the cable modem (CM) and the cable modem termination system (CMTS). However, it does not specify what performance MSOs can expect in various plant architectures. This paper outlines the most important areas of focus for the optimal approach to deploying DOCSIS 4.0 technology in the US and sets expectations for performance in the access network.

2. Baselines and Assumptions

2.1. Distributed Access Architecture (DAA)

One of the main assumptions made in this paper is that DOCSIS 4.0 technology will be deployed in a DAA environment. There are many benefits to upgrading nodes to DAA that will not be discussed here, such as power savings in head-ends and hub-sites. In this paper the baseline assumption for required power levels and signal quality relies on DAA nodes being deployed as a part of DOCSIS 4.0 upgrades.

2.2. CM Transmit Capability

In order to find any potential shortfalls for the access network from the CM transmit channel set (TCS) back to the amplifier and DAA node port(s), the following table has been considered. In the DOCSIS 4.0 specification for modem transmit (Tx) power there are three different tilt options provided (8 dB, 10 dB and 12 dB). For the purpose of this paper only the 10 dB tilt option will be addressed.

Table 1 – DOCSIS 4.0 CM Tx /1.6 MHz

Upstream Centre Frequency	108 MHz	684 MHz	Spectral tilt (dB)
Upstream Reference Power Spectral Density (PSD) (dBmV/1.6MHz)	33	43	10

Converting the power levels above from 1.6 MHz reference power spectral density (PSD) to 6.4 MHz equivalent levels, the modem Tx power is shown below.

Table 2 – DOCSIS 4.0 CM Tx /6.4 MHz

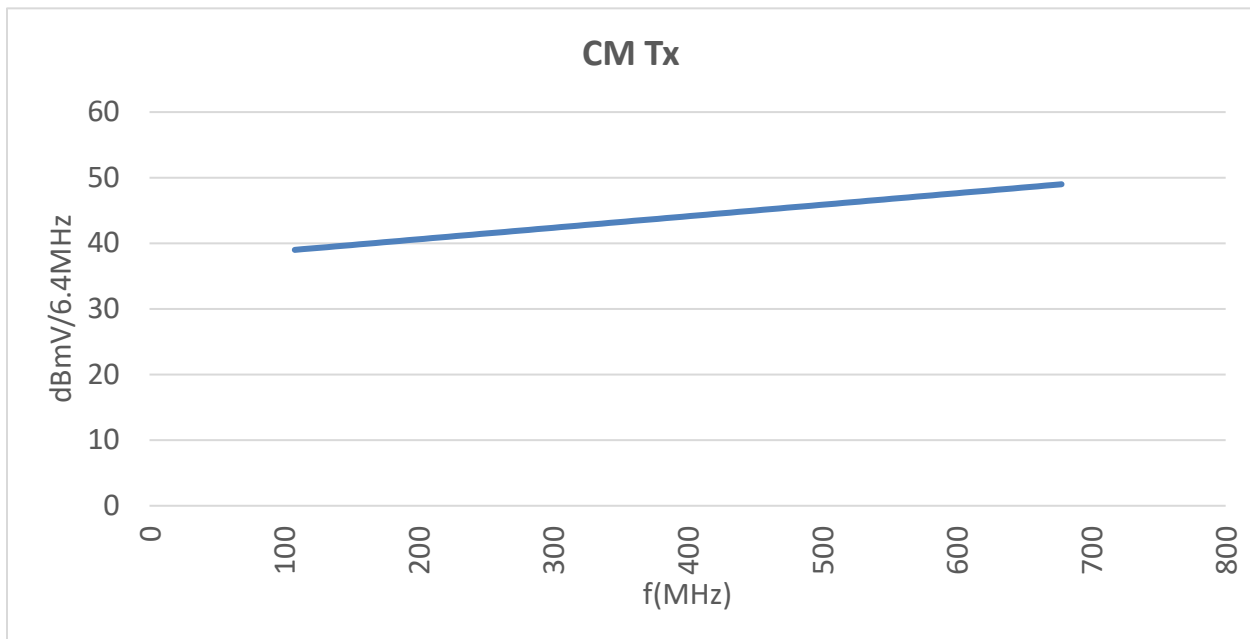| Upstream Centre Frequency	108 MHz	684 MHz	Spectral tilt (dB)
Upstream Reference PSD (dBmV/6.4MHz)	39	49	10

Table 2 has been illustrated in the graph below:

Figure 1 – DOCSIS 4.0 CM Tx Levels

2.3. CM Tx Modulation Error Rate (MER)

According to DOCSIS 4.0 CM PHY specifications, the following CM MER can be assumed:

Table 3 – DOCSIS 4.0 CM Tx MER

Grant	Tx MER
100% Grant (all OFDMA Mini Slots Used)	Each mini-slot MER ≥ 42 dB
Under-Grant Hold **Bandwidth (UGHB)**	Each mini-slot MER ≥ 47 dB

2.4. Modulation Order vs. Power and Carrier to noise

In order to have a baseline for achievable modulation orders throughout the plant in the US, Table 39 from the DOCSIS 4.0 PHY specification has been utilized. DOCSIS 4.0 PHY Table 39 outlines the performance that can be expected based on carrier to noise ratio (CNR) and power level received at the DAA node. Throughout this paper, power levels and CNR have been addressed to determine if one (or both) are limiting factors in performance.

The DOCSIS 4.0 PHY Table 39 does not account for the internal loss of the DAA node. For this reason, the required power levels for each modulation order have been increased by 3 dB to account for the additional insertion loss from the port of the amplifier to the remote-PHY-device (RPD) and/or remote-MAC/PHY-device (RMD) module, demonstrated in Table 4.

Table 4 – Constellation vs. Power vs. CNR

Constellation	CNR (dB)	Set Point (dBmV/6.4 MHz)
QPSK	11.0	-1
8-QAM	14.0	-1
16-QAM	17.0	-1
32-QAM	20.0	-1
64-QAM	23.0	-1
128-QAM	26.0	3
256-QAM	29.0	3
512-QAM	32.5	3
1024-QAM	35.5	3
2048-QAM	39.0	10
4096-QAM	43.0	13

CNR in the table above is otherwise referred to as signal to noise ratio (SNR) or MER.

SNR and MER have been used interchangeably throughout this paper. In Section 2.10 carrier to composite noise (CCN) has also been used as a method to estimate SNR/MER.

Section 5 explores expected performance in various plant architectures.

2.5. Amplifier Noise Figures

In order to determine the capability and performance in a cascade line, the noise figure of the return path amplifiers should be specified. The table below demonstrates this.

Table 5 – Return Path Amplifier Noise Figure

Return Path (US) Amplifier NF	6 dB

2.6. DOCSIS 4.0 Plant Models

The following plant models were created as a part of the DOCSIS 4.0 project:

- Span Loss:
  - 750MHz:
    - Distribution: 27dB
  - 1GHz:
    - Typical Plant:
      - Distribution: 32dB
    - Stretched Plant:
      - Distribution: 35dB
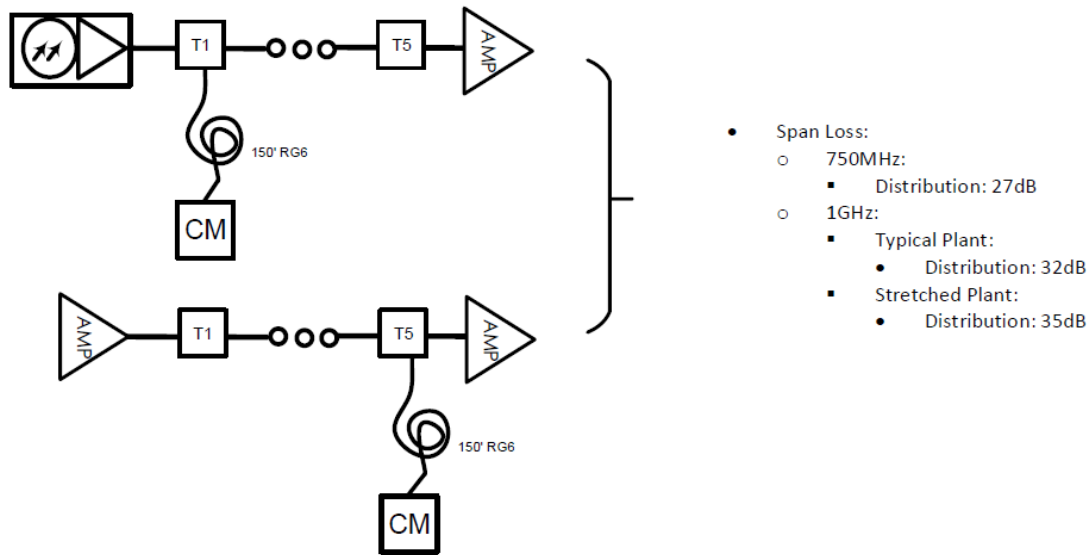
Figure 2 – DOCSIS Plant Models

In order to create a 'reasonable worst-case scenario' plant to analyze which essentially covers a higher percentile of the architectures MSOs might encounter in the outside plant (OSP), a distribution plant with 35 dB of span loss at 1 GHz has been considered. Refer to Section 3 for further details.

2.7. Noise

Designing a cascaded system for optimal CNR is always a top priority for an operator. One of the biggest contributors in network design is the receive (Rx) power at the amplifier, given that it is one of the primary drivers for achieving higher CNR throughout the distribution plant.

The minimum thermal noise power can be calculated using the following formula:

$$n_p = kTB$$

Where:

- n_p = noise power in watts
- k = Boltzmann's constant (1.34×10^{-23} joules/K)
- T = absolute temperature in K
- B = bandwidth of the measurement in Hz

The thermal noise in ~16.7 °c expressed in dBmV/6.4MHz is:

$$N_p = 57.1 \ dBmV$$

The conversion of bandwidth from 6 MHz to 6.4 MHz has been rounded up from 0.28 dB to 0.3 dB.

From the equations above, carrier to noise can be calculated using the following formula:

$$C/_N (dB) = \ C_i(dBmV) + 57.1 - NF(dB)$$

Where:
- C_i = input signal
- NF = noise figure of the amplifier

The equation above shows the significance of the Rx power versus noise figure of the amplifier, in network design.

The overall cascade C/N for amplifiers operating at different output levels can be derived from the following equation:

$$C/_{N_{total}} (dB) = \ -10log \left\{ 10^{\frac{-C/_{N1}}{10}} + \ 10^{\frac{-C/_{N2}}{10}} + \cdots + \ 10^{\frac{-C/_{Nn}}{10}} \right\}$$

Where, $C/_{N_x}$ is the carrier to noise of each amplifier calculated independently.

When cascading identical amplifiers operating at the same output level, the following approximation is typically used:

$$C/_{N_{total}} (dB) = \ C/_{N_x} - 10log_n$$

Where:
- $C/_{N_x}$ = the carrier to noise of a single amplifier
- n = the number of identical amplifiers in cascade

2.8. Distortion

Distortion products from an amplifier or cascade of amplifiers have historically been characterized by measuring second order (CSO) and composite triple beat (CTB) on analog carriers. These distortion products are harmonics of the primary signal. Today, however, MSOs primarily use digital carriers. Digital carriers' distortion products do not appear similar to those of analog carriers. Instead, they appear very similar to a raised noise floor. For this reason, composite intermodulation noise (CIN) is the best way to characterize the distortion performance of amplifiers today.

The rate of accumulation of CIN products is dependent on many factors but two primary factors in how fast CIN accumulates are the amount of total composite power (TCP) utilized in the gain chip and the output level. In this paper, it is assumed that CIN products will accumulate at a 10*log rate.

2.9. Carrier to Composite Noise (CCN)

In this paper, CCN has been used as the primary method of determining signal quality. Although SNR and MER can be measured using meters and measurement equipment, there are inconsistencies in these types of measurements, especially when using different measuring equipment [4]. Some of these are:

- Equalized vs. unequalized MER measurements
- Measuring device noise floor (NF)
- Input level to the measuring equipment
- Temperature

In order to remove these inconsistencies, this paper aims to calculate CCN as a more consistent representation of signal quality based on input power levels, carrier to thermal noise (CTN), and CIN from each equipment. The formula used for calculating CCN is outlined below:

$$CCN(dB) = -10log\left\{10^{\frac{-Starting\ CCN/SNR/MER}{10}} + 10^{\frac{-CTN_{Total}}{10}} + 10^{\frac{-CIN_{Total}}{10}}\right\}$$

3. Plant Model Created

Based on the assumptions made for DOCSIS 4.0 plant models in Section 2.7, the plant model below has been created as a 'reasonable worst-case scenario' for analysis. This plant model results in roughly 35 dB of span loss at 1 GHz, which can be considered 'stretched' for today's standards of deployment, as per Section 2.6. Consideration that the following plant model encompasses a higher percentage of the scenarios that one might encounter in the outside plant has been covered.

Figure 3 – Analyzed Plant Mode – 35 dB Span Loss

As demonstrated above, a 26 dB tap value has been considered for an ultra-high-split (396 and 492 MHz) scenario and a 23 dB tap has been considered for a high-split scenario, both of which are analyzed further in this paper.

4. Analysis

4.1. Upstream Spectrum Bandwidth

Further to Section 2.11, in order to accurately set a baseline for the input power to the return path amplifier, the noise-power ratio (NPR) of the amplifiers must be studied. Due to lack of availability of NPR data at the time of writing, the following assumption has been made:

$$P_i(new) = P_i(legacy) - 10 * \log\left(\frac{new\ BW}{legacy\ BW}\right)$$

Where:

- $P_i(new)$ = the new input power /6.4 MHz into the return path amplifier
- $P_i(legacy)$ = the current input power /6.4 MHz into the return path amplifier

An assumption has been made that the current input level to the return path amplifiers in an 85 MHz plant is 16 dBmV/6.4MHz. In this case the following table can be calculated using the formula above.

Table 6 – Return Path Expected Levels for US Splits

Return Path BW	Input Power to Return Path Amp. (dBmV/6.4MHz)
85 MHz	16
204 MHz	12
396 MHz	9
492 MHz	8

Historically MSOs have tried keep CM Tx levels as high as possible to keep carrier-to-ingress-noise as high as possible, but at the same time may have exhausted the transmit capability of the CM TCS. With that said, reducing Rx power levels into the return path amplifiers should not be a significant concern, assuming that regular plant maintenance and plant hardening practices are carried out.

Moreover, high transmit levels out of the modem can potentially increase the risk for interference between adjacent homes, as demonstrated in Section 4.3.

4.2. CM TCS's

DOCSIS 4.0 CMs will have two TCS's, one of which is capable of transmitting up to 204 MHz and the other from 108 MHz up to 684 MHz. It should be noted that there is an overlap region between the two TCS frequency bands.

The overlap region between the two TCS's can be used to the operator's advantage for near-term high-split deployment and long-term ultra-high-split deployment. MSOs have always tried to keep CM Tx levels as high as possible, both for achieving high SNRs and high carrier-to-ingress-noise. As discussed in the previous section, although the input to the return path amplifier has to be reduced by roughly 4 dB when expanding the return spectrum from 85 MHz to 204 MHz, that does not necessarily mean that modem transmit levels have to be reduced.

Amplifiers have the ability to pad the signal prior to the return (and forward) path amplifiers. Additionally, many MSOs condition their taps in the distribution line to 'force' CMs to transmit with high levels, increasing their source SNR/MER. In other words, CM transmit power, source (CM) MER and input to the return path amplifier chips have to be balanced by the MSO. Therefore, MSOs should try to optimize the amount of TCP available in the CM TCS without leaving 'unused power', which can help increase the CM Tx MER.
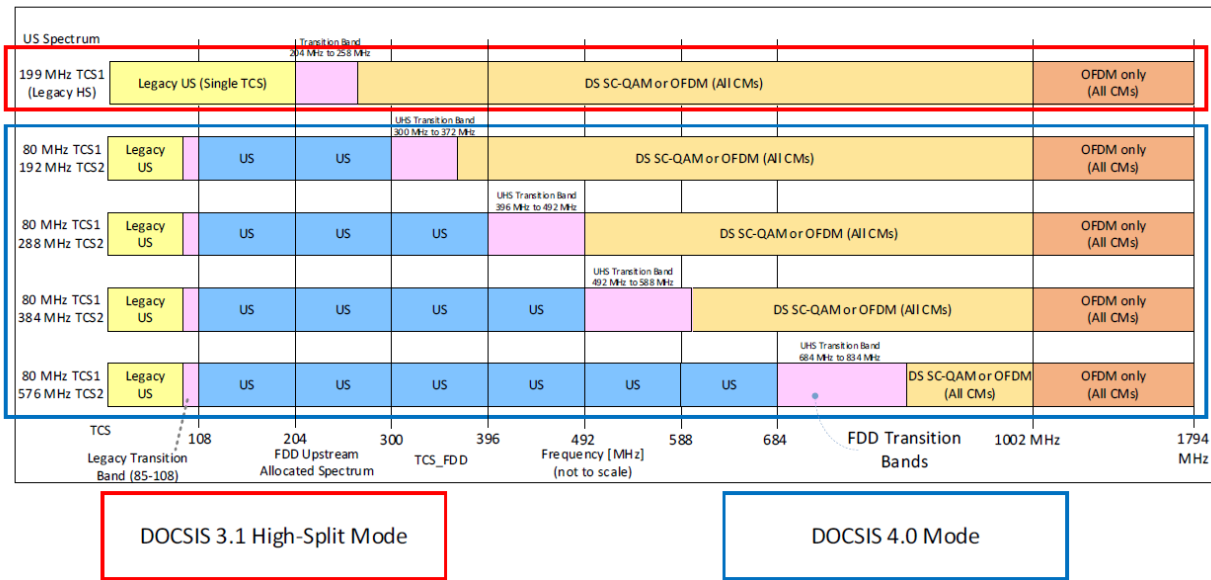
Figure 4 – Configurable FDD Upstream Allocated Spectrum Bandwidths

4.3. 204MHz Analysis

Based on the plant model discussed in Section 3, the following loss values can be calculated from the CM at the end of a 150' RG6 drop, installed as a point of entry device (PoE) to the amplifier or node port:

Table 7 – Plant Model Loss Values

Loss from each CM to Amp Port:					
Freq. (MHz)	Tap 1 (23)	Tap 2 (23)	Tap 3 (17)	Tap 4 (14)	Tap 5 (11)
5	23.87	22.39	20.91	19.83	19.55
30	24.77	23.78	22.79	22.20	22.40
50	25.29	24.54	23.80	23.45	23.90
83	25.93	25.48	25.03	24.98	25.71
108	26.34	26.07	25.82	25.95	26.87
150	26.91	26.96	27.03	27.47	28.70
204	27.54	27.96	28.38	29.19	30.76

Referring to Table 6, although the input to the 204 MHz return path amplifier needs to be reduced by 4 dB, the receive levels at the port of the amplifier is kept at 16 dBmV/6.4 MHz to determine if the CM has enough power to transmit to the amplifier port in this plant model. This is shown in Table 8.

Table 8 – CM Tx Levels to Amplifier or Node Port

CM Tx/6.4MHz to Port – 16 dBmV/6.4MHz Rx Level					
Freq. (MHz)	Tap 1 (23)	Tap 2 (23)	Tap 3 (17)	Tap 4 (14)	Tap 5 (11)
5	39.87	38.39	36.91	35.83	35.55
30	40.77	39.78	38.79	38.20	38.40
50	41.29	40.54	39.80	39.45	39.90
83	41.93	41.48	41.03	40.98	41.71
108	42.34	42.07	41.82	41.95	42.87
150	42.91	42.96	43.03	43.47	44.70
204	43.54	43.96	44.38	45.19	46.76

Knowing that the TCS is capable of 65 dBmV of TCP means that the modem can transmit 50 dBmV/6.4 MHz from 5 MHz to 204 MHz. As can be seen in the table above, the transmit levels are well below the TCP limit of the CM TCS. This can help the operator keep CM transmit levels 'consistent' with mid-split levels.

This is only true if the MSO is operating in 204 MHz return plant. If the return path spectrum is expanded to any frequency higher than 204 MHz, the first TCS will be limited to 108 MHz.

Another item to note is that the modem can in fact transmit with an 'up-tilt' (Table 9). This will be used in Section 4.4 for evaluating adjacent channel interference (ACI).

It can also be seen that we are now operating closer to the CM dynamic range window (DRW). Although many operators will not deploy any carriers below 15 MHz due to noise concerns, the modem can still transmit with up-tilt, as high as ~9 dB of tilt. This can cause concerns with the DRW of the CM, given that the current CMs have a maximum DRW of 12 dB.

4.4. Near Term Risk Analysis

In [3], a method for estimating the level of risk for ACI is outlined. Figure 5 demonstrates this method. It can be seen that with higher modem transmit levels—up to 204 MHz and beyond—the potential for energy leakage between adjacent tap ports increases. This additional energy in the adjacent home, assumed to be a 'legacy' mid-split home, can interfere with set top boxes (STB) and CMs. When the delta between the interferer and the downstream received signal for the legacy device goes above a certain threshold, depending on the front-end design of each device, it can cause degraded service.
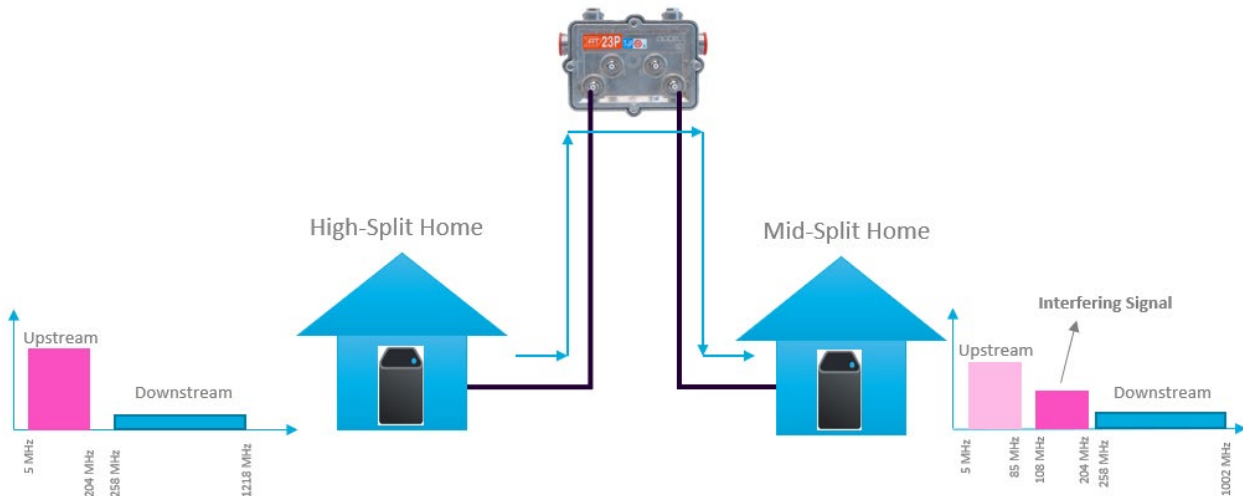
Figure 5 – Adjacent Home Interference – 204 MHz

A few modifications have been made to the methodology used in Dr. Prodan's paper to better outline the level of risk when an operator moves to high-split and ultra-high-split.

Prior to the analysis, the following should be noted:

- Based on Table 9 (below), the CM can transmit with 3 dB higher power per measured BW.
  - This has been determined by averaging the transmit levels from Table 9 from 85 MHz to 204 MHz.
- Tx levels close to 85 MHz have been gathered from the mid-split capable modems in the field.
- Rx levels close to 258 MHz have been gathered from the mid-split capable modems in the field.
- The high-split and mid-split devices are installed behind two-way splitters.

With that in mind, the following formulas can be used to evaluate the level of risk:

$$P_{loss} = (tap\ port\ to\ port\ isolation) + 2 * (drop\ cable\ attenuation + in\ home\ splitter\ loss)$$

$$Adjacent\ Channel\ Interferene\ (ACI) = CM\ Tx\ Level + 3(dB) - P_{loss}$$

$$Carrier\ to\ Adjacent\ Channel\ Interference\ Ratio\ (CACIR) = CM\ Rx\ Level - ACI$$

Along with the assumptions above, let us also assume that the tap port-to-port isolations can be any of the following:

- 20 dB
- 25 dB
- 30 dB

Table 9 outlines the assumed loss values for this analysis.

Table 9 – Averaged Loss Values

Loss Value Table	Drop (100' RG6)	Splitter	Port-to-Port Iso
	4 dB	3.5 dB	20, 25, 30 dB
	(Averaged from 108 – 204MHz)	(2-way splitter insertion loss)	

Tap port-to-port isolations are dependent on the frequency in which they are measured, along with the internal splitting formation of the tap ports. The values in the table above are assumed to be averaged across the spectrum.

Based on these numbers, the following figure was produced by sorting the calculated carrier to adjacent channel interference ratio (CACIR) value for each modem in an ascending order:
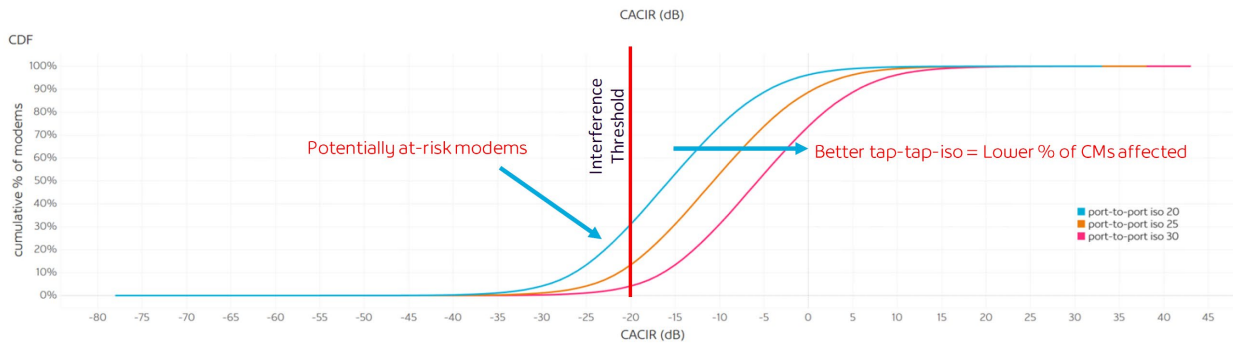

Figure 6 – CACIR Cumulitive Density Function

As seen in the figure above, the tap-to-tap isolation values of 20-, 25- or 30-dB result in vastly different levels of risks for interference in the field.

The CACIR threshold of -20 dB is set as a baseline for this study. Various devices in the field, including CMs with different front ends, can change this threshold and by extension the level of risk.

4.5. Ultra High-split Analysis

To determine shortfalls in the upstream with regards to the modem transmit power, it is assumed that all of the modems in the analyzed plant model are transmitting with their maximum capability (see Figure 1). Note that the focus of this analysis is on ultra-high-split TCS in the DOCSIS 4.0 CM. Refer to Section 4.2 for further information.

Figure 7 on Receive Power /6.4 MHz at the node and amplifier ports was created based on the required levels in Table 6, along with CM Tx capabilities and the assumed plant model, in Sections 2.2 and 3 respectively.
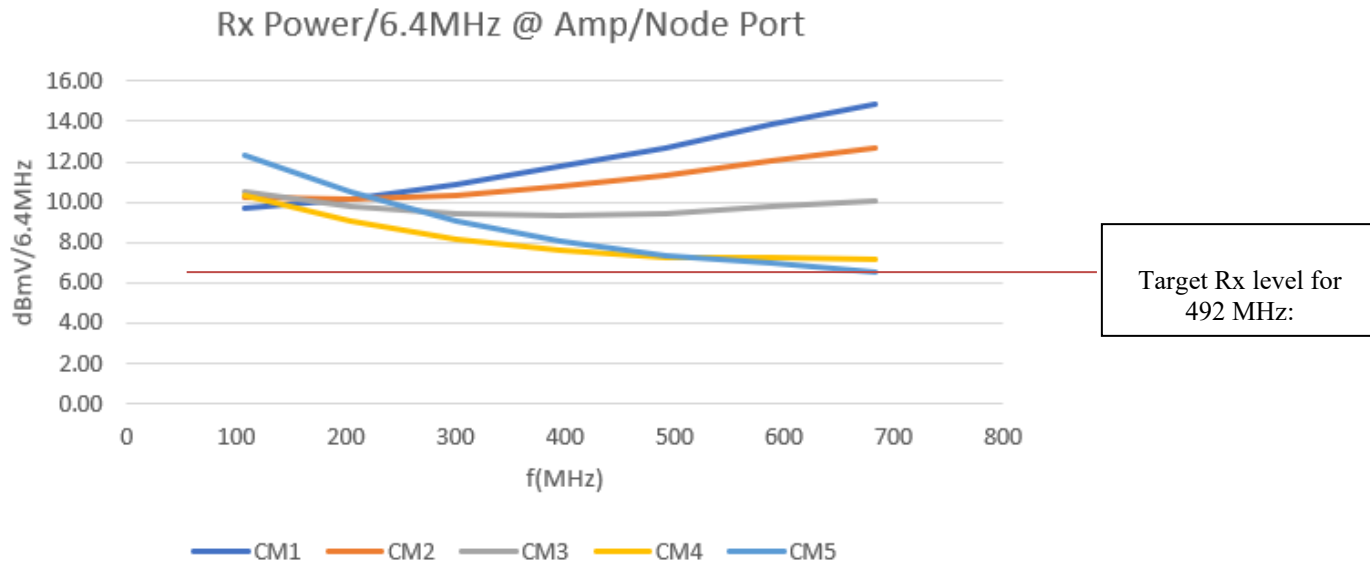
Figure 7 – Receive Power /6.4 MHz at Node and Amplifier Port

It can be observed that the modems installed at the end of the drop from Taps 1-3 have plenty of headroom in comparison to the target levels assumed at the port. It can also be seen that 'lower' receive levels at the amplifier port are only a concern for higher frequencies in modems that are in lower value taps (farther away from the node and amplifiers).

Figure 7 shows that frequency allocations (frequency stacking) appear to be an appealing approach for CMs. Essentially, although the DOCSIS 4.0 CMs will bond to all the Orthogonal Frequency Division Multiple Access (OFDMA) channels available in the spectrum, the CMs that are closer to the node/amplifier can use higher frequencies more efficiently given the 'headroom' available to them. Consequently, CMs that are farther away from the node and amplifiers can use lower portions of the spectrum.

As data usage patterns today outline, CMs will rarely use all the channels that they have bonded to. They will only do so in instances when large files are being uploaded or a speed test is being performed. For a majority of the usage cases, frequency stacking seems to be an appealing option for MSOs to optimize their return path, assuming the CMs do not do this automatically.

4.5.1. Splitter Added to the Plant Model

In this section the effect of additional flat losses such as splitters in the mainline will be discussed. When designing the plant, all additional insertion losses must be taken into account. This means that if a two-way splitter was to be added to the plant model, the 5 dB additional insertion loss must be deducted from the overall span loss, equaling to 30 dB of overall loss. As a result, the total span length of the original plant model could be reduced by roughly 200 feet. Figure 8 demonstrates this concept.
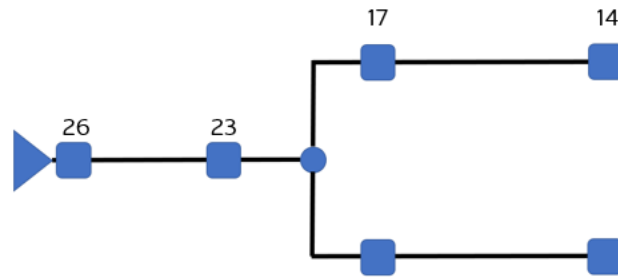
Figure 8 – Plant Model with Added Two-Way Splitter

Based on the new plant model, the receive levels at the port can be revised, as illustrated in Figure 9.
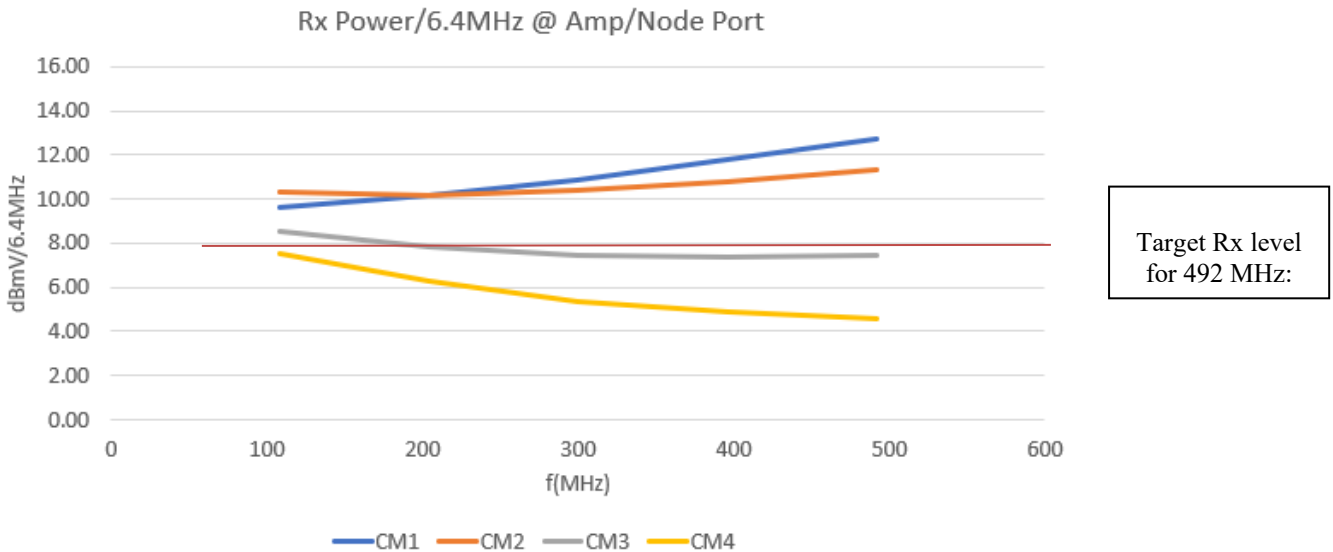

Target Rx level for 492 MHz:

Figure 9 – Receive Power /6.4 MHz at Node and Amplifier Port

It can be observed that the upstream signals from CMs behind the mainline two-way splitter are received with less power than the target level of 8 dBmV/6.4 MHz for 492 MHz of return bandwidth (BW), based on Table 7. This may seem concerning at first but knowing that many MSOs will not be utilizing the entire 684 MHz of return BW, the CM can theoretically allocate the unused TCP from the higher portion of the spectrum to lower parts. For the purpose of this example, an assumption has been made that a maximum return BW of 492 MHz has been planned as a part of DOCSIS 4.0 upgrades. With most of the TCP concentrated at the higher frequencies, the CM can theoretically 'raise' the original transmit power by roughly 4 dB. However, in order to avoid concerns with spurious emissions, this paper assumes that the modem has 3 dB of additional power per channel, shown in the figure below.
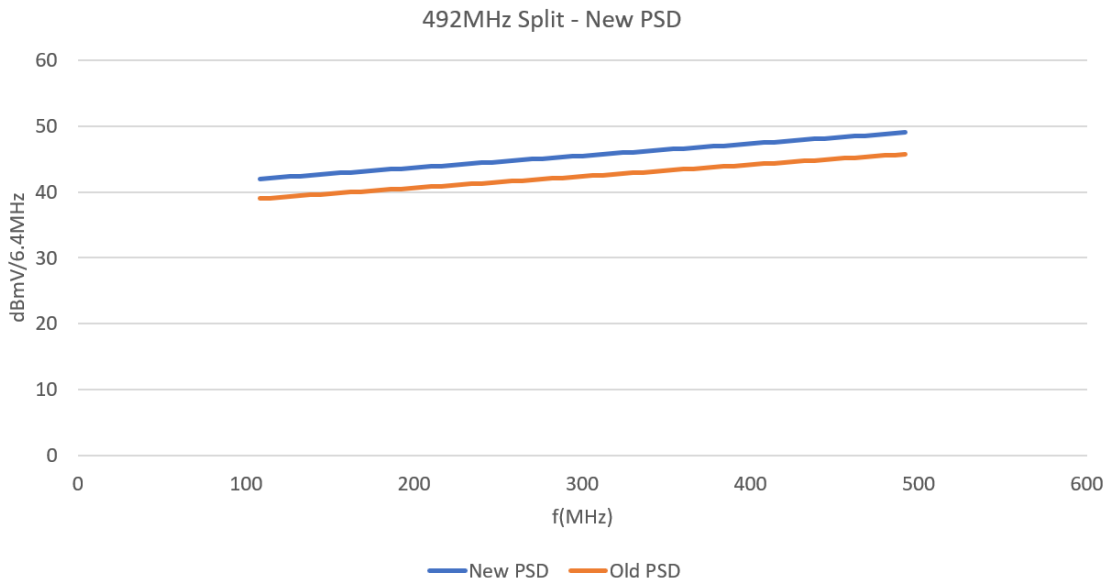
492MHz Split - New PSD

Figure 10 – CM Tx Level with 3 dB Boost for 492 MHz Split

Applying the new CM PSD to the same plant model, the following receive levels can be expected at the port of the node and amplifiers:

Rx Power/6.4MHz @ Amp/Node Port
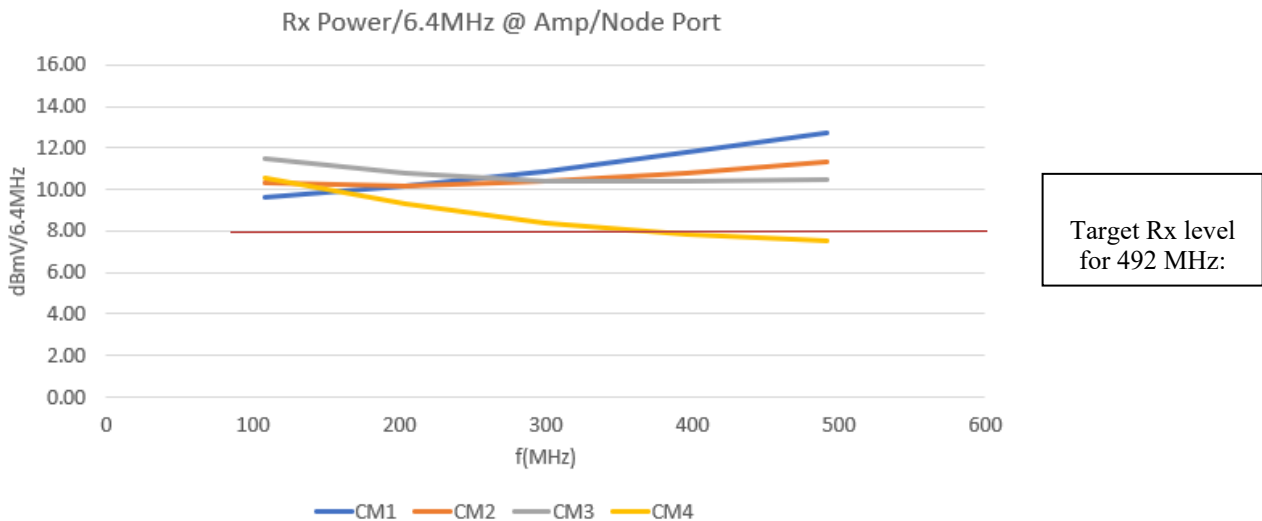
Target Rx level for 492 MHz:

Figure 11 – Receive Power /6.4 MHz at Node and Amplifier Port

The raised CM PSD and increased power levels from the CM can increase the risk for ACI. Close examination of this option in various plant models and scenarios prior to deployment is encouraged.

It should be noted that receiving below the rated level for each upstream split (outlined in Table 7) will not always result in a noticeable MER degradation. CCN and MER are highly dependent on the source MER and the NF of each amplifier in the return path, along with the cumulative noise and distortion products from each amplifier. This will be explored more in Section 5 of this paper.

4.5.2. Flat Losses – The Limiting Factor

One of the most significant results from the studies done in Section 4.5, and particularly in Section 4.5.1 when a two-way splitter was added to the plant model, is that high flat losses appear to be the most limiting factor in the upstream.

The plant model analyzed was 35 dB of span loss at 1 GHz, which can be considered quite 'stretched' for today's OSP span losses. It was observed that CMs in the plant model at the end of 150 feet of RG6 cable should be able to make it back to the amplifier and node ports, approximately within the range of 396 or 492 MHz, which are being considered by many MSOs. In other words, coaxial loss is something that has been taken into consideration in the CM design with the ultra-high-split TCS.

Flat losses can be somewhat challenging to overcome, especially in the upstream. Flat losses, as the name suggests, affect the entire spectrum in the same way, meaning that it cannot be overcome by tilt. It should be noted that this analysis was undertaken with only a two-way splitter. There are other types of OSP equipment currently deployed by MSOs that have much higher amounts of flat loss across the spectrum, namely, couplers and multi-dwelling-unit (MDU) style indoor splitters. The additional flat loss can cause concerns due to the modem having to transmit at close to maximum across the entire spectrum for the carriers to be received at the target level. This can potentially cause the CM to go into partial service mode due to insufficient Tx power. The overall upstream performance will be discussed further in Section 5.

5. Signal Quality and Noise Funneling

In order to quantify performance in the network both signal quality and power must be taken into consideration. Thus far, this paper has analyzed signal power in the plant models created for DOCSIS 4.0 networks. We discussed how the CM is able to overcome coaxial loss due to its increased TCP, output power level and tilt in the upstream. However, that does not indicate the signal quality that can be expected in the upstream. In this section, we analyze the possible upstream MER and outline limiting factors.

SNR and MER modeling in the upstream can be quite challenging due to the funneling effect. To define it broadly, noise funneling is the summation of all the unwanted noise and distortions in the return path. There can be many different sources of noise funneling, such as impulse noise, ingress noise and common path distortion (CPD). Generally, it is accepted that if the plant is free of physical impairments such as cuts in cable or unterminated taps, the funneling effects from the sources mentioned above can be minimized, if not resolved. For this paper, we focus instead on the amplifiers in the field and how they contribute to thermal noise (CTN) and distortion (CIN) accumulations in the upstream.

DOCSIS 4.0 technology is designed to be deployed in a cascaded environment. Although the number of amplifiers in cascade (series) is one of the most important factors in the downstream, for upstream, as it currently stands today, it is the total number of amplifiers. As an example, an N+6 plant with no splitters can have up to 24 amplifiers, assuming four outputs from the node. This number can increase dramatically with the addition of splitters in the topology.

In reality MSOs will deploy different amplifier types for their gain capabilities and the number of output ports, such as multi-port amplifiers and line extenders. However, this will not have a significant impact on overall performance, as will be demonstrated further in this section. In this paper, all amplifiers are assumed to be identical with the same NF mentioned in Section 2.5.

In order to quantify performance and determine the most important factor, the following has been assumed:

- Amplifier NF: 6 dB
- Amplifier CIN: 56 dB
- Input level to each amplifier in the return path: 6 dB flat across the spectrum
- Number of ports utilized in the node: 4
- CTN: All amplifiers on either the entire node or each leg that would contribute to signal degradation
- CIN: Only the amplifiers in series on each leg of the node that would contribute to signal degradation

Following the assumptions above, we need to consider the number of amplifiers that exist both in series and in total. On the one hand, the total number of amplifiers is what is considered for the cumulative effect of thermal noise funneling from each individual amplifier in the node, assuming that each leg of the node cannot be isolated and they all funnel into a single port in the return. The amplifiers in series, on the other hand, would be contributing to total CIN in each leg of the node along with the total CTN, assuming that port of the node has been isolated. Utilizing the formulas outline in Sections 2.8, 2.9 and 2.10, Tables 10 and 11 can be calculated.

Table 10 – Upstream Peformance – All Ports Funneled

Total Number of Amplifiers	CTN	CIN	Source MER (38 dB)	Source MER (40 dB)	Source MER (47 dB)
16	45.36	49.98	37.04	38.56	42.28
32	42.35	48.22	36.35	37.61	40.3
44	40.97	47.55	35.92	37.04	39.3
56	39.92	46.97	35.52	36.54	38.48
68	39.07	46.00	35.12	36.04	37.73

Table 11 – Upstream Performance – Single Amplifier Leg

Total Amps in Series	CTN	CIN	Source MER (38 dB)	Source MER (40 dB)	Source MER (47 dB)
4	51.38	49.98	37.55	39.31	44.29
6	48.37	48.22	37.26	38.87	43.05
7	46.99	47.55	37.08	38.61	42.4
8	45.94	46.97	36.9	38.37	41.84
10	45.1	46.00	36.68	38.07	41.19

To better compare the results, the MER values for each table have been plotted in Figures 12 and 13.
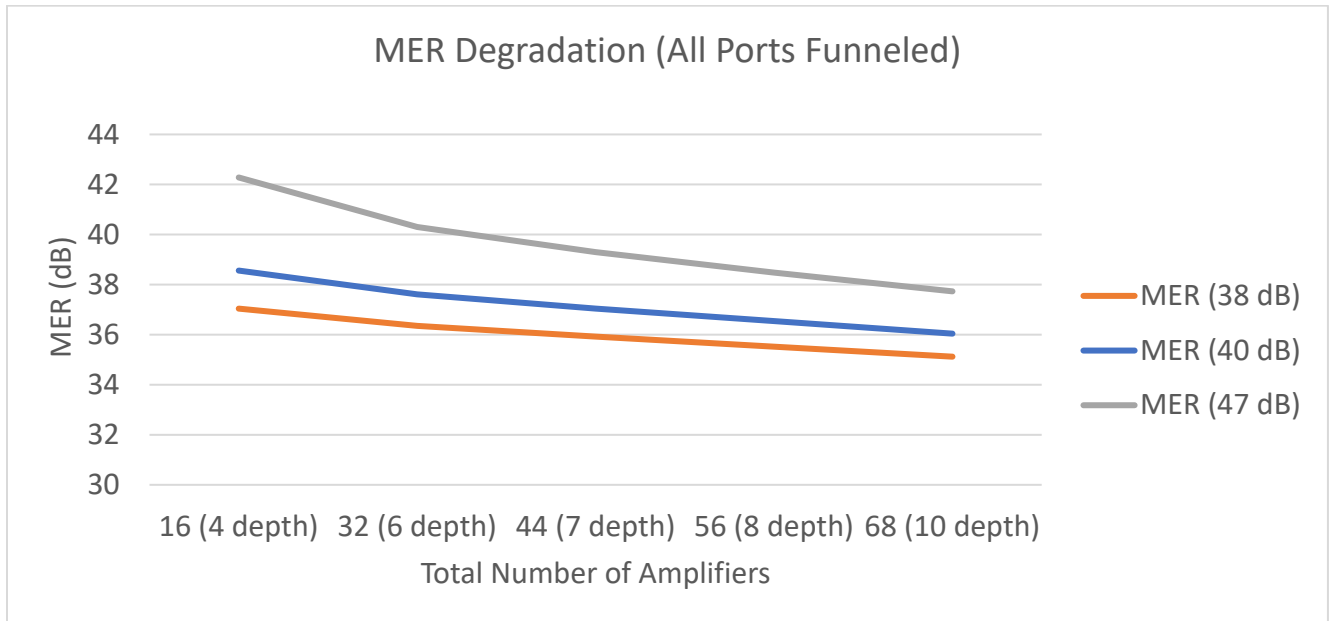
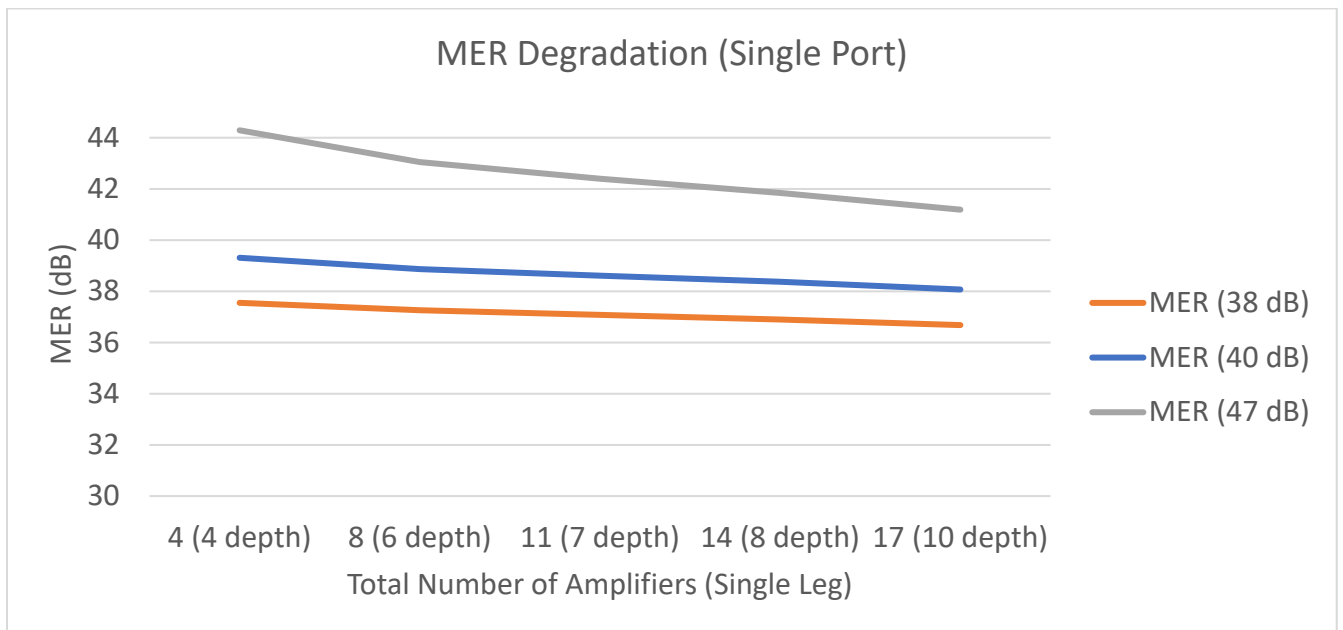**Figure 12 – MER vs. Total Number of Amplifiers – All Ports Funneled**

Figure 13 – MER vs. Total Number of Amplifiers – Single Amplifier Leg

When considering Tables 11 and 12, as well as Figures 12 and 13, a few interesting observations can be made. First and foremost, it can be observed that higher starting MERs such as 47 dB are more subject to degradation when exposed to noise and distortions. Figure 13 demonstrates that even with the addition of four amplifiers a ~3 dB MER reduction is realized. This reduction is then somewhat 'flattened' with further additions to noise and distortion products.

The most interesting observation from the figures above is that the 'starting MER' is arguably the most important factor in achieving higher orders of modulation. As an example, let's focus on a source MER of

40 dB as per Figure 12. There is only ~2.5 dB of additional MER reduction when the total number of amplifiers is increased from 16 to 68. Expanding on that further, focusing on the 38 dB MER graph in Figure 12, it can be seen that by reducing the number of amplifiers from 56 to 32 by performing a node split, the MER is increased by roughly1 dB. Alternatively, if the starting MER was increased by 2 dB to 40 dB, the same results can be achieved. Conversely, the total number of amplifiers or reduction of the cascade depth does not yield substantial MER increases in the upstream.

Lastly, it can be observed that isolating each leg of the node will yield more noticeable increases in MER for higher MER values. This is also true for reducing the total number of amplifiers.

It is very important to note that the results above do not tell the whole story of why it is important to be able to isolate each leg of the node from one another. Although this will have a direct positive impact on upstream performance, it also isolates noise from other sources (ingress noise) to one leg of the node. Additionally, node splits have many other benefits such as reducing the number of customers sharing the same data pipe and pushing fibre deeper into the HFC networks. These benefits are extremely important but have not been quantified in this paper.

6. Conclusion

DOCSIS 4.0 technology has been developed to enable HFC networks to provide multi-gigabit services. In this paper, a reasonable worst-case scenario plant was analyzed to estimate the capability of current HFC networks, with no amplifier re-spacing. It should be noted that the 35 dB span loss model was considered a 'stretched' plant by many MSOs during the development of DOCSIS 4.0 sets of specifications and plant models.

This study observed that achieving higher orders of modulation such as 1024 QAM is possible for the majority of cases. The only areas of concern for legacy plant design are areas where high flat losses are incurred in the upstream, namely due to splitters and couplers. This is only an issue in 'stretched' plant areas where there is already a higher amount of insertion loss from the modems installed at the end of drops and the end of line taps. How a modem can overcome the higher insertion loss with higher transmit powers was also discussed, assuming the operator does not utilize the entire 684 MHz band capability of the CM in the upstream. This should be balanced in conjunction with neighbour interference, since higher transmit levels from the CM can lead to additional neighbour interference cases between DOCSIS 4.0 devices and 'legacy' devices. MSOs will have to balance many moving parts, especially CM transmit powers, in order to optimize performance in the upstream to achieve higher source MER and high carrier-to-ingress noise ratio.

MSOs should optimize the TCP and power available in the modem to ensure sufficiently high transmit powers for higher transmit MER. This can assist with achieving higher orders of modulation in the upstream, along with a higher carrier to interference noise ratio. We also noted that funneling and the total number of amplifiers play a part in the overall signal quality in the upstream. Further, isolating each leg of the node from one another in the upstream results in a better overall signal quality. It can also help with isolating ingress noise to a particular leg, rather than it funneling to all ports in the return path. Finally, the source MER from the CM is one of the most—if not *the* most—important factor in the overall signal quality in the upstream. This can help MSOs prioritize efforts for increasing upstream capacity in the most efficient manner.

Abbreviations

ACI	adjacent channel interference
CACIR	carrier to adjacent channel interference ratio
CCN	carrier to composite noise ratio
C/N	carrier to noise ratio
CIN	carrier to intermodulation noise
CINR	carrier to interface noise ratio
CM	cable modem
CMTS	cable modem termination system
CNR	carrier to noise ratio
CPD	common path distortion
CSO	composite second order distortion
CTB	composite triple beat distortion
CTN	carrier to thermal noise
DAA	distributed access architecture
dB	decibels
dBmV	decibels relative to one millivolt
DAA	distributed access architecture
DRW	dynamic range window
DOCSIS	data over cable service interface specification
DS	downstream
ESD	extended spectrum DOCSIS
GHz	gigahertz
HFC	hybrid fibre-coax
ISBE	International Society of Broadband Experts
MER	modulation error ratio
MHz	megahertz
MSO	multiple service operator
NF	noise figure
NPR	noise power ratio
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OSP	outside plant
PoE	point of entry
PSD	power spectral density
QAM	quadrature amplitude modulation
RF	radio frequency
Rx	receive
SCTE	Society of Cable Telecommunications Engineers
SNR	signal to noise ratio
STB	set top box
TCS	transmit channel set
TCP	total composite power
Tx	transmit
UGHB	under grant hold bandwidth
US	upstream

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