Cable Modem Transmit Headroom Resiliency Management

A Technical Paper prepared for SCTE by

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Table of Contents

List of Figures

List of Tables

Title **Page Number**

1. Introduction

Cable operators are extending the operating frequency range of their cable networks, including the upstream. Expanding the upstream operating bandwidth and adding more channels brings with it a variety of challenges, including an impact on cable modem (CM) upstream transmit power capability and headroom. In particular, the modem's available transmit power spectral density (PSD) is reduced because it must be spread over a wider radio frequency (RF) bandwidth. Cable operators face new challenges for managing upstream power in the cable network, because of a complicated system of transmitted RF power, dynamic range window (DRW), long loop automatic level control (ALC), pre-equalization settings, and channel bandwidth. If a CM's transmitted power is insufficient, then forward error correction (FEC) errors can result, and bit loading may need to be reduced. As well, modems can go into partial service, resulting in those modems being unable to achieve advertised upstream speeds.

Figure 1 illustrates the total composite power (TCP) distribution for a population of CMs transmitting only single carrier quadrature amplitude modulation (SC-QAM) channels in the upstream. The horizontal axis in this and the next figure is TCP in units of decibel millivolt (dBmV), increasing right-to-left.

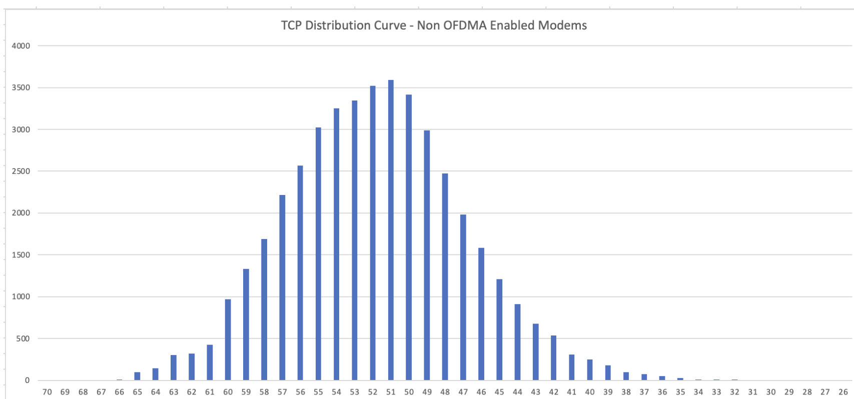


Figure 1 - TCP distribution curve for non-OFDMA enabled modems.

Figure 2 shows the TCP distribution for a population of CMs transmitting SC-QAM *and* orthogonal frequency division multiple access (OFDMA) signals. Note the shift of the curve to the left; why is this important? As the TCP increases, the transmit headroom can decrease because more modems are transmitting closer to their maximum capability.

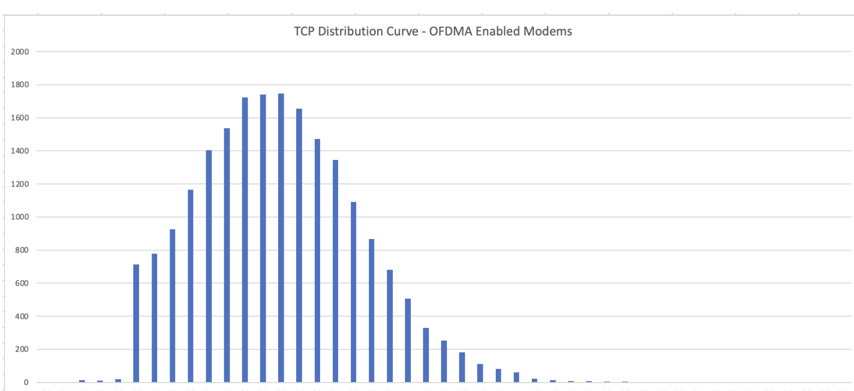


Figure 2 - TCP distribution curve for SC-QAM plus OFDMA-enable modems.

Therefore, it is incumbent upon cable operators to manage CM transmit power so that service quality is maintained. Understanding the impact of impairments in the spectrum and how they relate to the amount of transmit power "reserve" available to the CM, operators are able to not only grasp the urgency and prioritization of proactive repair in these cases, but also the impact on service, so they can manage this important resiliency mechanism.

This paper and its companion presentation discuss the latest understanding of the dynamic system that is the CM's upstream RF transmission operation and how it can impact service quality. Also included is guidance to create a spreadsheet for modeling available cable modem transmit headroom.

2. Cable Modem Upstream Transmit Power

Data-Over-Cable Service Interface Specifications (DOCSIS®) CM upstream transmitters are designed to accommodate a wide range of net attenuation[1] between each modem and the upstream burst receiver circuitry in a cable modem termination system (CMTS), converged cable access platform (CCAP), or remote PHY device (RPD). Net attenuation in this context includes the combination of all upstream active device gains and coaxial cable and passive device losses in the RF signal path. Further complicating net attenuation is the impact of ambient temperature changes on coaxial cable attenuation from day to night, season to season, and so forth.

2.1. Principal DOCSIS 3.1 Cable Modem Transmit Power Requirements

The minimum highest value of the total power output of the cable modem P_{max} is 65 dBmV, although higher values are allowed.

A CM is typically configured to transmit on a number of channels, but the number of channels and amount of spectrum in those channels varies from node to node and possibly even modem to modem. Upstream occupied bandwidth is defined in [D3.1PHY] as spectrum the modem may be required to transmit within its current upstream channel configurations. A number of "equivalent DOCSIS channels" is calculated from the occupied bandwidth (BW_{legacy} and BW_{OFDMA}), which is, informally, the number of 1.6 MHz "chunks" of spectrum that is configured for possible transmission by the modem. The total number of DOCSIS equivalent channels configured for a CM is denoted as N_{eq}.

The maximum PSD for the CM derives from when the maximum modem transmit power is used, and is a function of how much spectrum the modem may be required to transmit within its current configuration (that is, N_{eq}). In DOCSIS 3.1 the cable modem PSD is dealt with on a "per 1.6 MHz" basis, and is referred to as the equivalent channel power.

The maximum PSD for the CM, depending on its configured upstream occupied bandwidth, is its maximum equivalent channel power, and is denoted as $P_{1.6hi}$ in DOCSIS 3.1. $P_{1.6hi}$ is calculated as follows:

$$P_{1.6hi} = P_{max}[dBmV] - 10\log_{10}(N_{eq})$$

Each channel in the transmit channel set (TCS) is described by its reported power $P_{1.6r\_n}$, which is the channel power when it is fully granted, divided by the occupied bandwidth of the channel (in units of MHz), multiplied by 1.6. The result is called "the power per 1.6 MHz" of the channel.

[1] Net upstream attenuation is the combination of all gains and losses between a modem and the input to the CMTS. For instance, if a cable modem's upstream transmit level is +45 dBmV and the input to the CMTS is 0 dBmV, the net upstream attenuation is 45 dBmV – 0 dBmV = 45 dB.

2.2. Dynamic Range Window

The concept of DRW was introduced in [D3.0PHY] and carried over in later versions of DOCSIS (refer to Appendix B for more information about DRW). It could be stated that the primary purpose of DRW is to prevent the channel in the TCS with the lowest PSD from being "too far" below the channel with the highest PSD. This is important because the modem has a limited dynamic range capability.

The CMTS is expected to manage the modem's commanded transmit power levels and DRW. Regardless of a DRW violation, the CM has to attempt to comply with what the CMTS commands. Typically, a CMTS may drop from a CM's TCS a channel with a PSD that is too low. It is always possible that a CMTS might operate the high PSD channel at a lower transmit power or the low PSD channel at a higher transmit power to prevent DRW violation. This will result in those channels reaching the burst receiver at a lower or higher PSD than the set point (aka the burst receiver target PSD).

Much more detail is given about the DRW in Appendix B.

3. What is Cable Modem Transmit Headroom?

Generally speaking, a CM's upstream transmit headroom is the difference, in decibels, between that modem's maximum transmit power capability and its actual transmit power. But in DOCSIS the CM transmit headroom really has two different interpretations or definitions: 1) CM TCP headroom, and 2) what we call CM minimum channel (Min Ch) headroom. These two headroom values comprise two different figures-of-merit to characterize a CM's commanded channel power compared to its transmit power capability. Note: In a plant with tilt and two or more upstream channels, the Min Ch headroom will be the "stop" before the TCP headroom. Additionally, each channel of a CM has its own figure-of-merit in this regard: CM channel headroom. These figures-of-merit are explained in the following sections.[2]

3.1. Cable Modem Total Composite Power Headroom

The CM TCP headroom is the difference between the maximum total composite power *capability* of the CM, P_{max} in [D3.1PHY], and the total composite power currently commanded (called "reported power" in the DOCSIS specs) to the CM's TCS by the CMTS. In [D3.1PHY] the transmit power commanded to the n[th] channel is the product of the PSD commanded to the n[th] channel, $P_{1.6r\_n}$, and the occupied bandwidth of the n[th] channel divided by 1.6 MHz:[3]

$$Power\ in\ n^{th} channel\ (dBmV) = PWR_n$$

$$= P_{1.6r\_n}(dBmV) + 10log_{10}\left(BW_{legacy\ or\ OFDMA}(MHz)/1.6\ MHz\right).\ \{D3.1\}$$

$$= P_{r\_n}\ \ \{D3.0\}$$

The commanded TCP of the CM in both [D3.1PHY] and [D3.0PHY] is the sum of the commanded power of all of the channels:

[2] Several of the equations in this section include a bracketed term such as "{D3.1}" at the end of the equation. That bracketed term is not a mathematical operation; rather, it indicates the version of DOCSIS to which the equation applies.

[3] P_{r_n} is a well-defined term in the D3.0 spec, referring to the *reported* power for the n[th] channel. It is not a term explicitly used in the D3.1 spec. We use PWR_n in this paper as a generic term to denote the power in the channel for D3.0 or D3.1.

$$Commanded\ TCP\ (dBmV) = 10log_{10}\left(sum\ over\ all\ n\ of\ 10^{(PWR_n/10)}\right).\ \{D3.0\ and\ D3.1\}$$

For the DOCSIS 3.1 CM, the CM TCP headroom is given by:

$$CM\ TCP\ headroom\ (dB) = P_{max}(dBmV) - Commanded\ TCP\ (dBmV).\ \{D3.1\}$$

For DOCSIS 3.0 modems, the calculation of the Commanded TCP is straightforward when the constellations are 32-QAM or larger, so we will consider this case for an introductory explanation. The legacy TDMA channels are all commanded in terms of the channel power, where PWR_n is the commanded ("reported") power of the n^th channel, in units of dBmV.

The determination of the CM's TCP headroom capability in [D3.0PHY] can be complicated, unless we invoke the assumption of 32-QAM TDMA or larger constellation in all channels, which we will retain for now. The DOCSIS 3.0 CM TCP capability is 57 dBmV with these conditions, for any number of channels (one to four).[4] Thus, for DOCSIS 3.0, with 32-QAM or higher constellations with TDMA channels:

$$CM\ TCP\ headroom\ (dB) = 57\ dBmV - Commanded\ TCP(dBmV).\ \{D3.0, 32\text{-}QAM\ or\ larger\}$$

3.2. Cable Modem Minimum Channel Headroom

In addition to the CM TCP headroom, there is also the CM Min Ch headroom. The CM Min Ch headroom is important because it quantifies how much increase can occur in the channel with the largest PSD [D3.1PHY] or largest power, PWR_n [D3.0PHY] (with the assumption of 32-QAM or larger constellation using DOCSIS 3.0 technology).

In DOCSIS 3.1 the CM Min Ch headroom is the difference between the maximum PSD for the CM, which is $P_{1.6hi}$, and the largest PSD commanded in the TCS (largest value of $P_{1.6r\_n}$, over all N channels):

$$CM\ Min\ Ch\ headroom\ (dB) = P_{1.6hi}(dBmV) - max\left(P_{1.6r\_n}, over\ all\ N\ channels\right).\ \{D3.1\}$$

In DOCSIS 3.1 the CM Min Ch headroom is described by the term $P_{1.6load\_1}$, the loading of the highest loaded channel (see [D3.1PHY]):

$$CM\ Min\ Ch\ headroom\ (dB) = P_{1.6load\_1}.\ \{D3.1\}$$

In DOCSIS 3.0 the CM Min Ch headroom is described by the term P_{load_1}, the loading of the highest loaded channel (see [D3.0PHY]):

$$CM\ Min\ Ch\ headroom\ (dB) = P_{load\_1}.\ \{D3.0\}$$

In DOCSIS 3.0, since P_{load_1} equals P_{hi_1} minus P_{r_1}, and since for our simplifying assumption of TDMA with at least 32-QAM constellations, P_{hi_1} is 57 dBmV with one channel in the TCS, 54 dBmV with two channels in the TCS, and 51 dBmV with three (or four) channels in the TCS, we can also write:

$$CM\ Min\ Ch\ headroom\ (dB) = P_{hi\_1} - P_{r\_1}.\ \{D3.0, 32\text{-}QAM\ or\ larger\}$$

[4] P_{max} represents the CM's TCP capability in [D3.1PHY] but represents an individual channel power limit in [D3.0PHY]. There is not a term relating to TCP capability in [D3.0PHY], which is why we show how to calculate it in this paper.

Note that in both DOCSIS 3.0 and DOCSIS 3.1 each upstream channel of each CM can be described with its own figure-of-merit: CM Channel headroom. For DOCSIS 3.0 modems, the n^th channel's CM channel headroom is P_{load_n}, which also equals P_{hi_n} minus PWR_n. For DOCSIS 3.1 modems, the n^th channel's CM channel headroom is $P_{1.6hi}$ minus $P_{1.6r\_n}$.

3.3. DOCSIS 3.0 Example

According to [D3.0PHY], the maximum total transmit power that the CM can support, P_{max}, for a DOCSIS 3.0 modem transmitting four 64-QAM channels is 51 dBmV per channel (57 dBmV total power).[5] If the modem is transmitting 44 dBmV for each channel (50 dBmV total power), and P_{hi_n} for each channel is 51 dBmV, then the CM Min Ch headroom is 51 dBmV – 44 dBmV = 7 dB. In this example, the CM TCP headroom is the same as the CM Min Ch headroom, since from a total power perspective, 57 dBmV – 50 dBmV = 7 dB. See Figure 3.

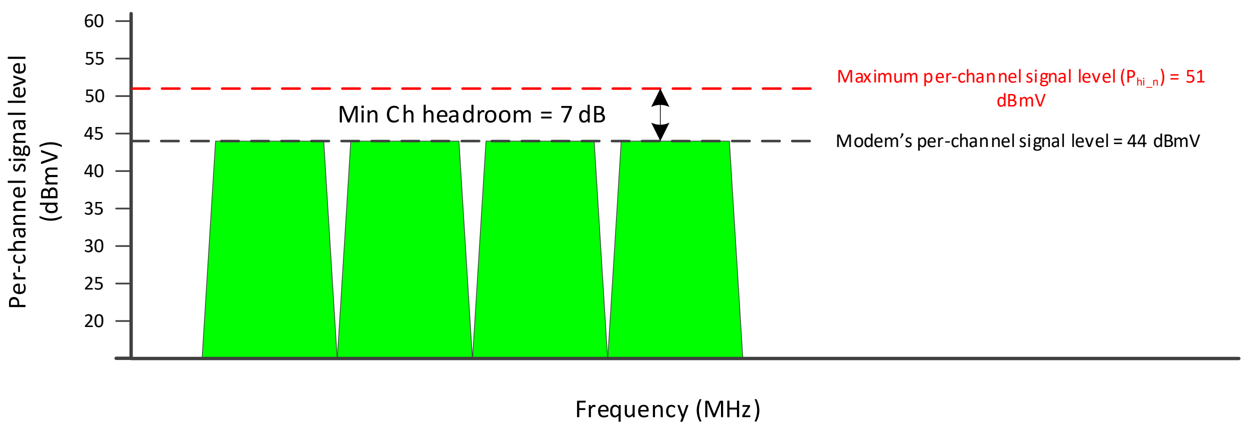


Figure 3 - Cable modem Min Ch headroom is 7 dB in this example.

If, however, that same modem is transmitting 51 dBmV per channel, so that PWR_n equals P_{hi_n} for each channel, the CM Min Ch headroom is 51 dBmV – 51 dBmV = 0 dB, and the CM TCP headroom is the same, 57 dBmV – 57 dBmV = 0 dB, as shown in Figure 4.

[5] Note that [D3.0PHY] supports higher per-channel transmit power for lower modulation orders such as QPSK, than what is shown in this example. For more information the reader is encouraged to review Section 6.2.19 of [D3.0PHY].

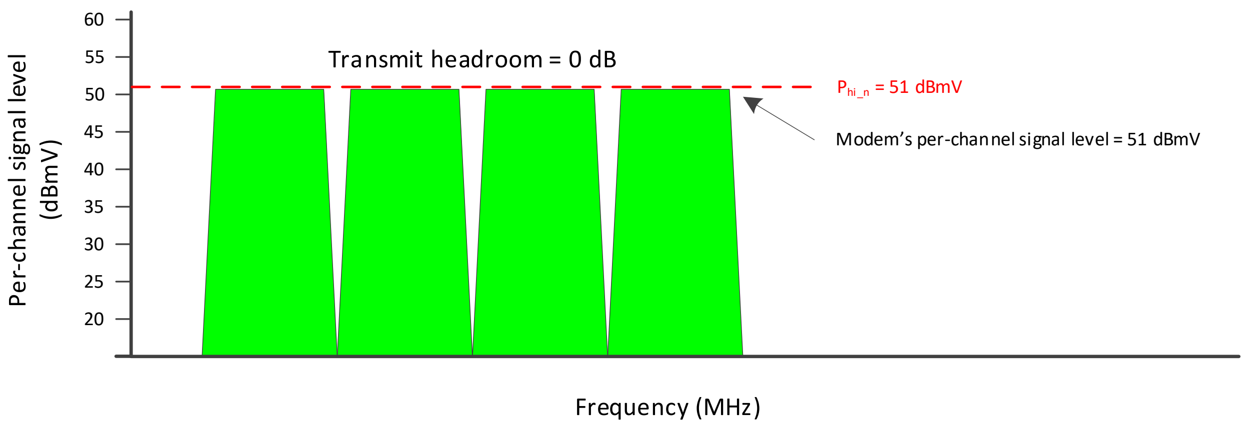


Figure 4 – Here, the modem's transmitted per-channel signal level is equal to the maximum per-channel signal level P_{hi_n}, resulting in 0 dB Min Ch transmit headroom.

For another example (refer to Figure 5), consider that the same modem is transmitting 44 dBmV on one channel, 41 dBmV on another channel, and 38 dBmV each on the third and fourth channels. In this case P_{r_1} equals 44 dBmV, and P_{hi_n} for each channel is 51 dBmV, so the CM Min Ch headroom is 51 dBmV – 44 dBmV = 7 dB.

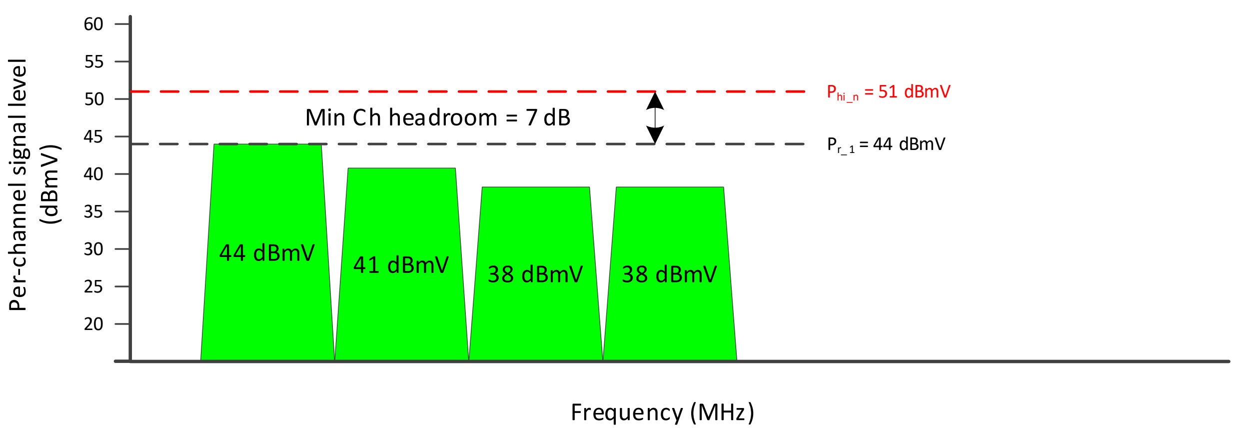


Figure 5 - In this example the Min Ch transmit headroom is 7 dB and the TCP headroom is 10 dB (see text).

The CM TCP for this uneven per-channel transmit power example is 47 dBmV. The CM TCP capability is still 57 dBmV, so the CM TCP headroom is 57 dBmV – 47 dBmV = 10 dB.

In this example the CM TCP headroom is larger than the CM Min Ch headroom, 10 dB compared to 7 dB. While the CM total transmit power can be increased by 10 dB according to the CM TCP headroom, there is the practical constraint to consider, especially if the channel already transmitting at 44 dBmV is a channel where additional power is desired. This channel can only increase its transmit power by 7 dB, the amount of the CM Min Ch headroom; however, if this channel is commanded to increase by 7 dB, the two lower powered channels will be 13 dB lower than this channel, and this will violate the conditions of the 12 dB range of the DRW for [D3.0PHY]. The second channel is now much more than 4 dB lower than the first channel, so if the channel power changes are implemented, the spurious emissions requirements will be significantly relaxed (see [D3.0PHY]). If the lower power channels are increased in power and arrive at the burst receiver above the target power for the channels, then the spurious emissions contributions budgeted are larger due to the increased channel power; and also, because they arrive higher than the target power, the spurious emissions from this CM for these channels are larger than intended in making the requirements. In a practical sense, if the channel with the largest power is a channel needing even more power, then the CM Min Ch headroom may be a more important consideration than the CM TCP headroom. But both must be managed.

3.4. DOCSIS 3.1 Example

As with DOCSIS 3.0 modems, an ideal case for DOCSIS 3.1 CMs is with all channels having the same PSD, $P_{1.6r\_n}$ the same for all n. In these cases, the CM TCP headroom and CM Min Ch headroom are the same. Whenever any $P_{1.6r\_n}$ is equal to $P_{1.6hi}$, then the CM Min Ch headroom will be 0 dB.

Now consider some further examples of CM transmit headroom for DOCSIS 3.1 modems.

In the first example, assume one SC-QAM channel of 1.6 MHz bandwidth and three 6.4 MHz-wide SC-QAM channels, and two OFDMA channels, with 16 MHz modulated spectrum (occupied bandwidth) and 40 MHz modulated spectrum; see Figure 6. The number of equivalent DOCSIS channels, N_{eq}, is 48. $P_{1.6hi}$ equals 48.2 dBmV. Let the PSD for the six channels be, respectively: 37 dBmV, 37 dBmV, 37 dBmV, 37 dBmV, 40 dBmV, and 43 dBmV.

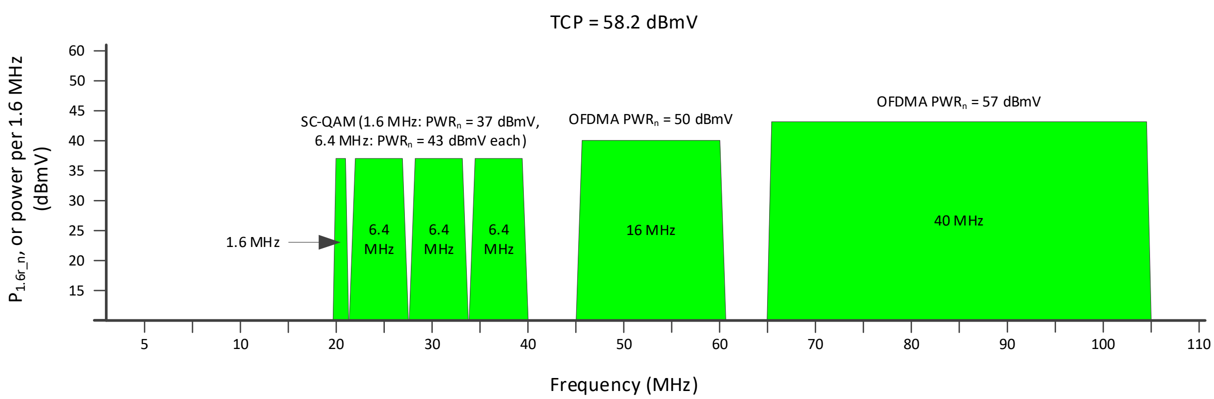


Figure 6 - The TCP headroom and Min Ch headroom in this example are 6.8 dB and 5.2 dB respectively; see text.

The powers for the six channels, PWR_n, are: 37.0 dBmV, 43.0 dBmV, 43.0 dBmV, 43.0 dBmV, 50.0 dBmV, and 57.0 dBmV. The TCP of the TCS sums to 58.2 dBmV.

The CM TCP headroom is P_{max} – 58.2 dBmV = 65 dBmV – 58.2 dBmV = 6.8 dB.

The CM Min Ch headroom is $P_{1.6hi}$, 48.2 dBmV, minus the largest $P_{1.6r\_n}$, 43.0 dBmV, which yields 5.2 dB.

The CM's TCP headroom and Min Ch headroom are fairly close, 6.8 dB compared to 5.2 dB.

For another more extreme example, illustrated in Figure 7, consider one SC-QAM channel of 1.6 MHz bandwidth and one SC-QAM channel of 6.4 MHz bandwidth, and two OFDMA channels, with 16 MHz modulated spectrum (occupied bandwidth) and 40 MHz modulated spectrum. The number of equivalent

DOCSIS channels, N_{eq}, is 40. $P_{1.6hi}$ equals 49.0 dBmV. Let the PSD for the six channels be, respectively: 46 dBmV, 40 dBmV, 36 dBmV, and 36 dBmV.

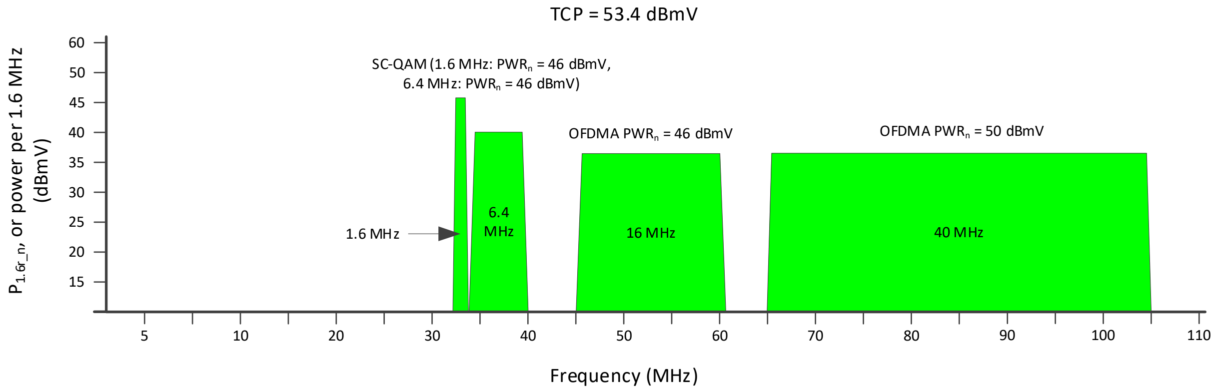


Figure 7 - The TCP headroom and Min Ch headroom in this example are 11.6 dB and 3.0 dB respectively; see text.

The powers for the six channels, PWR_n, are: 46.0 dBmV, 46.0 dBmV, 46.0 dBmV, and 50.0 dBmV. The TCP of the TCS sums to 53.4 dBmV.

The CM TCP headroom is P_{max} – 53.4 dBmV = 11.6 dB.

The CM Min Ch headroom is $P_{1.6hi}$, 49.0 dBmV, minus the largest $P_{1.6r\_n}$, 46.0 dBmV, which yields 3.0 dB.

The CM's TCP headroom and Min Ch headroom are very different in this example, 11.6 dB compared to 3.0 dB. This is attributable to the 1.6 MHz-wide SC-QAM channel having a relatively high PSD, much higher than the other three channels, and very close (within 3 dB) to the max PSD allowed with the given TCS occupied bandwidth, but also, the channel is only a small portion of the TCS occupied bandwidth. This leaves little room to increase this channel PSD. However, since the other channels have much larger bandwidth, their total channel power is significantly larger than with the 1.6 MHz SC-QAM channel.

Note that the fidelity requirements (both the spurious emissions and the TxMER, in [D3.1PHY]) are significantly relaxed compared to when all channels have the same $P_{1.6r\_n}$. The spurious emissions and TxMER requirements are relaxed by almost 10 dB in this example, due to the channels with the majority of the occupied bandwidth (the OFDMA channels) having their $P_{1.6r\_n}$ at 10 dB lower than the channel with the highest PSD.

If there is a need to raise the PSD of the 1.6 MHz-wide SC-QAM channel further, more than 3 dB, there is not enough CM Min Ch headroom to provide that increase. However, there is ample CM TCP headroom available. And already the fidelity requirements are significantly relaxed with the relatively large-bandwidth OFDMA channels operating at much lower PSD than the narrow-bandwidth SC-QAM channel. Also, raising the PSD of the 1.6 MHz-wide SC-QAM channel by 3 dB will violate the 12 dB DRW limit, if the OFDMA channels' PSD is not increased. Due to the large amount of CM TCP headroom available, and the large relaxation in fidelity requirements already occurring in the example, it may be preferred to not increase the 1.6 MHz SC-QAM channel power, and let it arrive below the receiver target PSD, or perhaps even drop the channel entirely from the TCS. The latter will result in tightened fidelity requirements, and minimal reduction in occupied bandwidth in the TCS.

4. Factors That Can Affect Transmit Headroom

At first glance it may seem that understanding and managing CM transmit headroom is fairly straightforward. If the net attenuation between a modem and CMTS changes, the CMTS will command the modem to adjust its transmit power as needed. If only it were that easy! Cable modem transmit headroom is affected by a complicated combination of factors including transmitted RF power, DRW, long loop automatic level control (ALC), pre-equalization settings, and channel bandwidth.

4.1. Transmitted RF power

4.1.1. Total Composite Power

As stated in Sections 2.1 and 3.1, [D3.1PHY] specifies P_{max} for the TCS. The TCP headroom is the difference between the TCP and P_{max}. If TCP in the TCS exceeds P_{max} supported by the CM, the modem does not have enough power to maintain such transmission. In this case the CM may be forced to drop one or more of the channels and fall back to partial service, so TCP is within the supported range. The headroom indicates how much reserve is available in the current TCP.

4.1.2. Cable Modem Termination System Set Point

The configured CMTS target set point[6] has a direct impact on the TCP of the CM's TCS. Configuring the CMTS target set point to a lower or higher level effectively decreases or increases the TCP of the CM's TCS, which in turn increases or decreases the effective CM headroom.

4.1.3. Transmit Channel Set Occupied Bandwidth

Assuming a CM is not already transmitting at its maximum capability, increasing the TCS occupied bandwidth also increases the TCS's TCP (see Figure 1 and Figure 2). Consider the following example. The TCS initially comprises four 6.4 MHz-wide SC-QAM channels (64-QAM) transmitting with $P_{1.6}$ = 32.75 dBmV, 32.75 dBmV, 34.75 dBmV, and 35.75 dBmV respectively. The power per 6.4 MHz-wide channel (PWR_n) = 38.77 dBmV, 38.77 dBmV, 40.77 dBmV, and 41.77 dBmV. As part of plant expansion, a new 52 MHz-wide OFDMA channel is added to the TCS. This channel transmits with $P_{1.6}$ = 33 dBmV. Table 1 shows the before and after headroom performance:

6 The target set point is the configured upstream receive signal level at the CMTS or CCAP. This parameter was called commanded nominal receive power in [D3.0PHY] and earlier.

Table 1 - Before and after headroom performance.

Channel	Channel width	Initial TCS Occupied Bandwidth: 25.6 MHz		New TCS Occupied Bandwidth: 77.6 MHz	
		$P_{1.6}$, dBmV	Headroom, dB	$P_{1.6}$, dBmV	Headroom, dB
1	6.4 MHz	32.75	20.21	32.75	15.35
2	6.4 MHz	32.75	20.21	32.75	15.35
3	6.4 MHz	34.75	18.21	34.75	13.35
4	6.4 MHz	35.75	17.21	35.75	12.35
5	52 MHz			33.00	15.10
Summary					
N_{eq}		16		49	
TCP, dBmV		46.24		50.29	
$P_{1.6hi}$**, dBmV**		52.96		48.10	
TCP Headroom, dB		18.76		14.71	
Min Ch Headroom, dB		17.21		12.35	

Table Summary:

- Bandwidth increased by 3.03 times, or logarithmically, $10\log_{10}(77.6 \text{ MHz}/25.6 \text{ MHz}) = 4.82$ dB
- TCP headroom degradation: 18.76 dB – 14.71 dB = 4.05 dB
- Min Ch headroom degradation: 17.21 dB – 12.35 dB = 4.86 dB

The bandwidth expansion (logarithmic) is 4.82 dB, and the degradation in Min Ch headroom is 4.86 dB. The two values are very close, and would be the same except for the quantization involved in using the ceiling function when computing N_{eq}.

See Section 4.5.1 for an additional illustrated example of occupied bandwidth expansion.

4.2. Dynamic Range Window

As mentioned in Section 2.2 and Appendix B, one of the factors that limits CM transmission power is DRW. DRW does not affect headroom directly as it limits the difference between the least and most loaded channels, and the headroom for the most loaded channel stays the same. If the DRW is violated, the fidelity requirements for the TCS may be compromised and eventually most loaded channel(s) will be dropped from the TCS, forcing the CM to partial service. The resulting partial TCS may have different (better) headroom for the remaining channels. But because the resulting TCS is impacted, directly comparing their headroom is incorrect.

4.3. Long Loop Automatic Level Control

The content in this section is excerpted and adapted from [LLALC], and is used with permission of the author.

A surprising amount of behind-the-scenes interaction occurs between DOCSIS cable modems and the CMTS (or CCAP or RPD). One important process is called station maintenance, during which the received upstream channels are evaluated by the CMTS's burst receiver. The burst receiver looks at the received signal level, the channel's center frequency, its timing, and other parameters. If any of those are out of tolerance, the CMTS will command the affected modem to adjust its transmitted signal as needed.

In particular, the received upstream signal level is supposed to match the CMTS's target set point, which has a default value of 0 dBmV in most CMTSs (that value is user configurable). If the received upstream signal level doesn't match the target set point, the CMTS instructs the modem via a ranging response (RNG-RSP) message to adjust its upstream transmit power as needed so the received signal level at the CMTS is correct. This upstream signal level management is called long loop ALC.

Anything that causes the net upstream attenuation between modems and the CMTS to change will result in the CMTS telling the affected modems to change their upstream transmit power accordingly. Examples include coaxial cable attenuation changes over temperature, installation of components in the drop that add loss (e.g., replacing a two-way splitter with a four-way splitter), changing padding in the headend or hub site upstream combiner, and so on.

4.3.1. Additional Loss in Return Path

Consider a scenario in which a subscriber has only high-speed Internet service. Figure 8 shows what the typical upstream signal levels might be. The downstream RF input to the modem is +3 dBmV, the modem's upstream transmit power is +43 dBmV, and that upstream channel's RF level at the input to the tap (after drop cable loss) is +41 dBmV. By the time the channel reaches the node, it's +15 dBmV. Assume that this configuration gives the desired 0 dBmV at the CMTS upstream port.

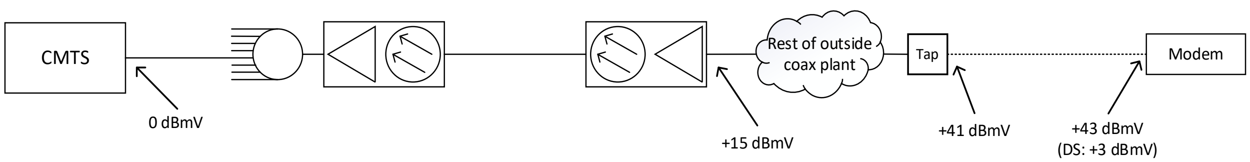


Figure 8 - Baseline upstream signal level scenario for Internet-only subscriber. Here the net upstream attenuation between the modem and CMTS is 43 dB.

Now assume the same subscriber decides to have three set-top boxes connected along with the existing CM. An installer is dispatched to the subscriber premises to install the additional outlets, cabling, and four-way splitter. What happens to the upstream channels with the additional 7 dB of loss from the splitter? As illustrated in Figure 9, for a brief amount of time the modem's upstream signal level is reduced by 7 dB, giving +34 dBmV at the tap, +8 dBmV at the node, and –7 dBmV at the CMTS upstream port. The modem's transmit level is still at its original +45 dBmV, but the downstream input to that modem has dropped by 7 dB from +3 dBmV to –4 dBmV.

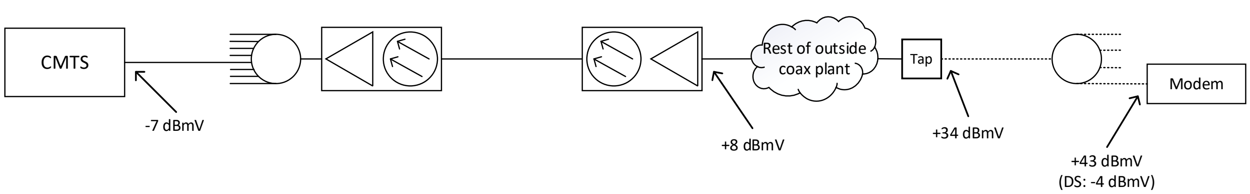


Figure 9 - The newly-installed four-way splitter adds 7 dB of attenuation to the drop, which reduces downstream and upstream levels. Note that the input to the CMTS is now –7 dBmV instead of the desired 0 dBmV. The net upstream attenuation between the modem and CMTS has increased to 50 dB.

The station maintenance process measures the lower RF input to the CMTS, and commands the modem via a RNG-RSP message to increase its transmit power by 7 dB (see Figure 10). Now the modem's upstream transmit level is +50 dBmV. Note that the input to the tap is back to the original +41 dBmV, the node input is +15 dBmV, and the CMTS input is 0 dBmV. The downstream level at the modem input is still 7 dB lower than its original value, though.

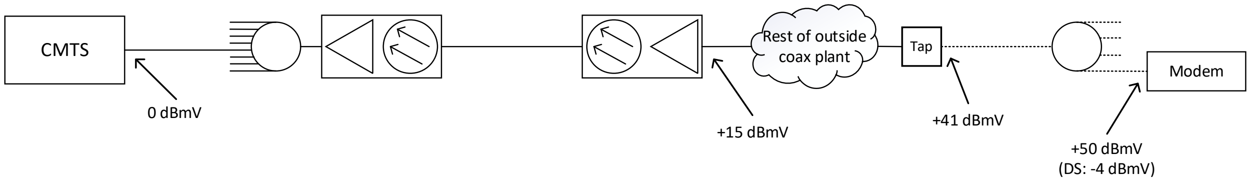


Figure 10 - The station maintenance process commands the modem to increase its upstream transmit level by 7 dB to overcome the 7 dB attenuation of the newly-installed splitter. The net upstream attenuation between the modem and CMTS remains at 50 dB.

4.3.2. Coaxial Cable Attenuation Versus Temperature

Coaxial cable attenuation in decibels changes about 1% for every 10 °F ambient temperature change. As the temperature increases, cable attenuation increases; as the temperature decreases, cable attenuation decreases. Both downstream and upstream RF signal levels are affected by temperature-related cable attenuation variations.

Long loop ALC can help to compensate for temperature-related coax attenuation changes in the upstream. For instance, assume 100 feet of overhead Series 6 drop cable at the subscriber premises, 1500 feet of overhead 0.500 inch diameter hardline feeder cable between the tap and the node, and a worst-case seasonal temperature variation from –10 °F to +105 °F. Table 2 and Table 3 summarize the upstream attenuation versus temperature at 5 MHz, 55 MHz, and 85 MHz.[7]

[7] The values in the tables were calculated using published 0.500 coax attenuation specifications of 0.16 dB/100 feet at 5 MHz, 0.55 dB/100 feet at 55 MHz, and 0.69 dB/100 feet at 85 MHz; and published Series 6 coax attenuation specifications of 0.58 dB/100 feet at 5 MHz, 1.60 dB/100 feet at 55 MHz, and 1.97 dB/100 feet at 85 MHz. All published attenuation values are at a reference temperature of 68 °F. See section 20.3.4. in [SCTEMath] for the equation used to calculate attenuation at other temperatures.

Table 2 - Attenuation versus temperature for 1500 feet of 0.500 inch hardline cable.

	–10 °F	68 °F	+105 °F	Maximum variation over temperature
5 MHz	2.19 dB	2.4 dB	2.5 dB	0.31 dB
55 MHz	7.54 dB	8.25 dB	8.59 dB	1.05 dB
85 MHz	9.46 dB	10.35 dB	10.77 dB	1.31 dB

Table 3 - Attenuation versus temperature for 100 feet of Series 6 drop cable.

	–10 °F	68 °F	+105 °F	Maximum variation over temperature
5 MHz	0.53 dB	0.58 dB	0.60 dB	0.07 dB
55 MHz	1.46 dB	1.60 dB	1.67 dB	0.21 dB
85 MHz	1.80 dB	1.97 dB	2.05 dB	0.25 dB

To account for the combined temperature related attenuation changes in the 100 feet of Series 6 drop cable and 1500 feet of 0.500 inch diameter feeder cable, the modem's transmit power would vary up to 1.56 dB (at 85 MHz) from –10 °F to +105 °F.

4.4. Upstream Pre-Equalization

Upstream pre-equalization is used to compensate for non-flat frequency response in the channel caused by an impairment between the modem and the burst receiver. For instance, if a frequency response impairment in the network causes a suckout in the upstream channel, the pre-equalization process "pre-distorts" the modem's transmitted signal to have essentially the opposite frequency response of the channel impairment. Ideally, the pre-equalized channel will be received with a flat frequency response at the CMTS's burst receiver.

It is important to note that pre-equalization is normalized so that it will not change the CM transmit power. The CM transmit power remains as commanded. After application of a non-flat pre-equalization, generally the receive power at the burst receiver is reduced because more power was shifted into the parts of the channel with the greatest insertion loss. The overall effect is that the CM needs more transmit power to satisfy the target PSD at the receiver. The target PSD for the receiver is termed the "set point" in [D3.1PHY].

Figure 11 provides an example of an OFDMA channel frequency response which is flat and provides 45 dB of insertion loss between the CM transmitter and the upstream burst receiver. The example OFDMA channel has 240 subcarriers covering 12 MHz, and in the healthy channel each subcarrier is transmitted with approximately 30 dBmV and received at approximately –15 dBmV. These values correspond to 45 dBmV per 1.6 MHz and 0 dBmV per 1.6 MHz respectively. Figure 11 then also shows an example impairment which begins impacting the channel, with 6 dB peak-to-peak ripple, 4.45 dB additional insertion loss, and a 20 dB suckout covering 2 MHz of the channel.

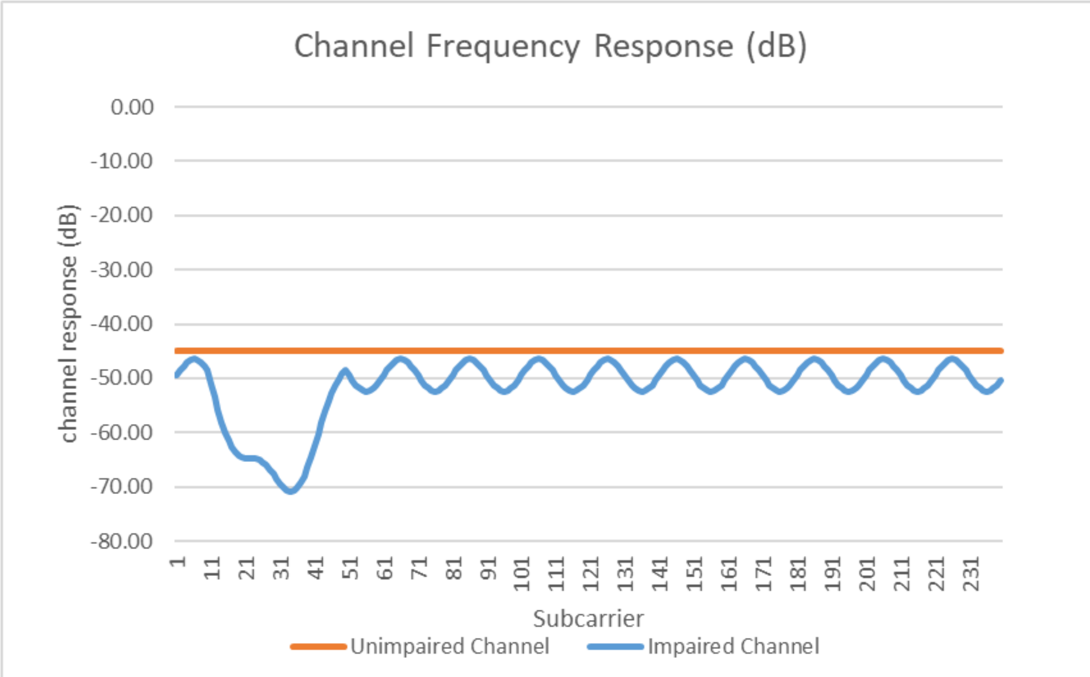


Figure 11 - Channel frequency response before and after onset of an impairment.

Figure 12 shows the power per subcarrier received at the burst receiver before the impairment occurs, which is about –15 dBmV per subcarrier. Figure 12 also shows the received power at the burst receiver after the suckout has occurred, which varies from about –16 dBmV per subcarrier at a maximum to below –40 dBmV per subcarrier in the deepest part of the suckout. Figure 12 also shows the average of the received power per subcarrier, in the dotted line; this average power per subcarrier after the impairment is 4.6 dB lower than the received power per subcarrier before the impairment. Figure 12 also shows the resulting received power per subcarrier after the first ranging which occurred after the impairment impacted the channel. After the first ranging the received subcarriers are now the same power (flat) across the channel at the receiver again, by virtue of the pre-equalization. The first ranging also called for an increase of the CM transmit power by 4.6 dB to compensate for the insertion loss, based on the received average power per subcarrier being 4.6 dB low after the impairment. The average of the power per subcarrier after the impairment onset includes the effect of the power diminished in the relatively small percentage of the channel impacted by the large suckout. While the suckout is large, it covers less than 20% of the channel. It can also be seen in Figure 12 that after the first ranging following the impairment onset the subcarriers are all received at the same power as a result of the pre-equalization; however, it can also be seen that the “per subcarrier” received power is now reduced from –15 dBmV per subcarrier with the healthy channel, to about –24 dBmV per subcarrier. More precisely, the subcarriers are 8.8 dB lower after the first ranging following the impairment onset.

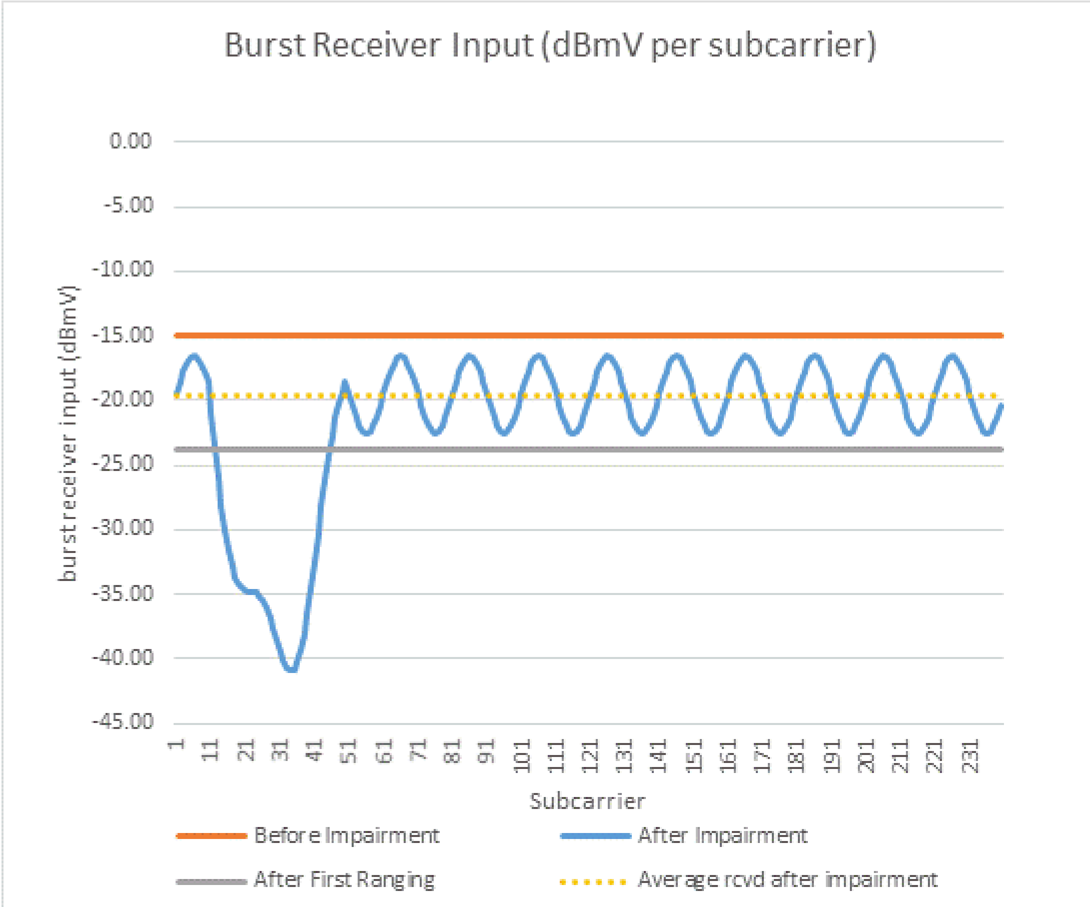


Figure 12 - Burst receiver input power per subcarrier, a) before onset of an impairment; b) after the impairment impacts the channel but prior to a ranging, where about 5 dB of loss occurs across most of the channel and up to 25 dB loss in the suckout; c) the average power per subcarrier after the impairment occurs; and d) after the first ranging response, which increases the transmit power by 4.6 dB and equalizes the channel with pre-equalization.

Figure 13 illustrates why the burst receiver input is reduced by almost 9 dB after the first ranging following the onset of the impairment. Figure 13 shows the normalized pre-equalization vector (normalized to unity power). It can be seen that the normalized pre-equalization vector varies from about –12 dB to +12.5 dB, with most of the channel having the value hovering around –10 dB and only a few MHz in the suckout-impacted region hovering around 10 dB. Since the averaging is performed with linear power, and not the decibel values, the small amount of spectrum with 10 dB pre-equalization is drawing so much power that the transmit power outside the suckout is suppressed by almost 10 dB. Figure 13 shows the power transmitted per subcarrier prior to the onset of the impairment, and also the power per subcarrier transmitted after the first ranging, which included the 4.6 dB commanded increase in transmit power (mentioned in discussion of Figure 12) and the pre-equalization shaping. The average power per subcarrier after the first ranging is indicated in Figure 13 with the dotted line, showing that it is 4.6 dB higher than the (flat) power per subcarrier transmitted prior to the impairment. The pre-equalization at the CM is pushing down the transmit power per subcarrier in most of the channel, causing the power at the burst receiver to be reduced from prior to the impairment onset, even with the commanded power increase to the CM of 4.6 dB. The average PSD of the CM transmission after the first ranging is increased from the initial (flat) transmitted PSD solely because of the 4.6 dB command to increase the CM transmit power, where the pre-equalization is not impacting the CM transmit power. Another 8.8 dB of increased transmit power is needed in a second ranging response, as illustrated in Figure 12, to bring the power per subcarrier back up to the desired amount, –15 dBmV, which is 0 dBmV per 1.6 MHz.

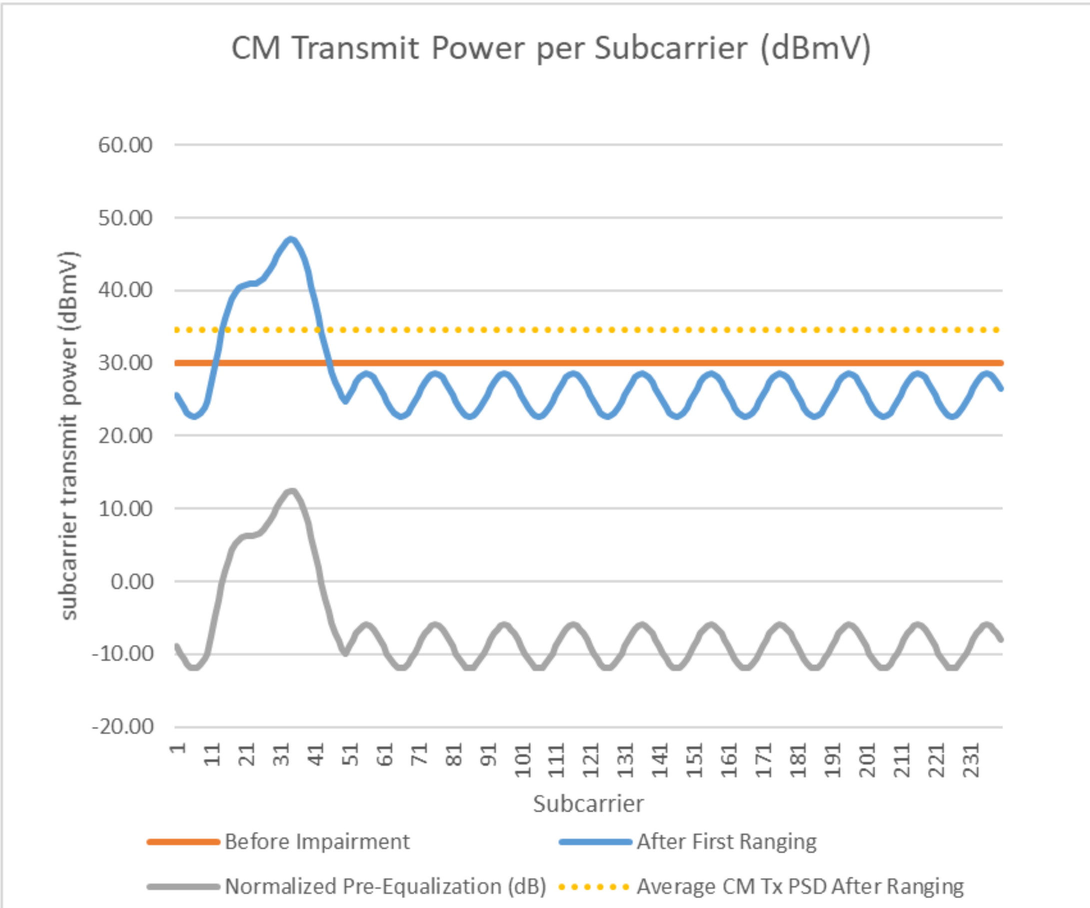


Figure 13 - The cable modem transmit power per subcarrier a) prior to the onset of the impairment; and b) after the first ranging response following the onset of the impairment, with the average power per subcarrier indicated by the dotted line. Also shown is the normalized pre-equalization of the first ranging response, seen to vary from about –12 dB to about 12.5 dB, with most of the channel pre-equalization hovering around –10 dB.

If the CM is already transmitting near or at its maximum transmit PSD prior to when the impairment occurs, the desired increase of 8.8 dB for the CM transmissions noted in the example above (in the second ranging response), may not be possible for the CM. The initial commanded increase of 4.6 dB may not even be achievable, partly or completely. The DOCSIS 3.0 and 3.1 specifications anticipate such occurrences and provide a) requirements[8] for the burst receiver to operate with a minimum dynamic range about its target PSD, thus providing operation when channels reach the burst receiver at a lower PSD than

[8] From [D3.1PHY], Section 7.4.14.1, "REQ25088 The CMTS Upstream demodulator MUST operate within its defined performance specifications with received bursts within the ranges defined in Table 17 - Upstream Channel Demodulator Input Power Characteristics of the set power." Table 17 shows a range about the Set Point of –9 dB up to +3 dB for constellations 256-QAM and lower. For the higher constellation densities of 512-QAM to 4096-QAM the required supported dynamic range is –3 dB to +3 dB.

the target; and b) requirements allowing different upstream bit loading profiles, allowing the CMTS to make grants to the CM with lower bit loading to accommodate a lower SNR. (With lower input channel PSD to the burst receiver, the SNR at the input of the burst receiver due to the upstream noise present at the receiver input will be lower, too, which might require a lower bit loading in data grants than if the transmissions were able to reach the receiver at the target PSD.)

A mathematical treatment of how the normalization process of the pre-equalization maintains the CM's transmit power for the channel is included in the appendix.

4.5. Transmit Channel Set Occupied Bandwidth (Power Spectral Density Versus RF Bandwidth)

Cable modem transmit power is a limited resource in the connection between each modem and the CMTS. A CM is limited in the amount of power it can transmit across all channels, and the power is fairly allocated across the channels; essentially, the maximum power that a modem can transmit is divided among the various channels, which includes SC-QAM (both TDMA and S-CDMA) and OFDMA channels. This allocation of transmit power determines the requirements for the dynamic range window.

As cable operators migrate from sub-split band plans to mid-split or high-split band plans, additional spectrum becomes available to carry more upstream channels (see [SPLIT] for more information about cable network band plans). Those additional upstream channels support greater data capacity. One potential constraint to manage is the impact of the newly added channels to a modem's transmitted total power.

Recall from Section 2.1, in DOCSIS 3.1 the maximum PSD for the CM depends on its configured upstream occupied bandwidth, and is denoted as $P_{1.6hi}$ in DOCSIS 3.1. $P_{1.6hi}$ is calculated as:

$$P_{1.6hi} = P_{max}[dBmV] - 10\log_{10}(N_{eq})$$

In DOCSIS 3.1 the CM Min Ch headroom is the difference between the maximum PSD for the CM, which is $P_{1.6hi}$, and the largest PSD commanded in the TCS (largest value of $P_{1.6r\_n}$, over all N channels):

$$CM\ Min\ Ch\ headroom\ (dB) = P_{1.6hi}(dBmV) - max(P_{1.6r\_n}, over\ all\ N\ channels).\ \{D3.1\}$$

If the TCS is commanded an increase in its occupied bandwidth by an amount corresponding to N_{eq_added} (additional "chunks" of 1.6 MHz bandwidth), this will reduce $P_{1.6hi}$ by

$$P_{1.6hi}\ decrease(dB) = 10log_{10}[(N_{eq} + N_{eq\_added})/N_{eq}]$$

$$= 10log_{10}[1 + (N_{eq\_added}/N_{eq})]$$

If the Min Ch headroom is smaller than $P_{1.6hi}$ *decrease (dB)*, that is,

$$CM\ Min\ Ch\ headroom\ (dB) < 10log_{10}[1 + (N_{eq\_added}/N_{eq})]$$

then either a) you cannot add all of the desired new occupied bandwidth, or b) the highest PSD channel(s) will have to have its (or their) transmit power(s) per 1.6 MHz decreased.

Thus, the reader may be interested in knowing how much occupied bandwidth can be added maintaining the existing channel powers; solving some algebra shows that

$$N_{eq\_additional\_possible} = \left(\left[10^{(CM\ Min\ Ch\ headroom\ dB/10)}\right] - 1\right) * N_{eq}$$

Of course, alternatively, the PSD of the highest loaded channel could be lowered instead, to allow the addition of more new occupied bandwidth. The same principles apply with DOCSIS 3.0.

4.5.1. Example: Adding Channels to the Transmit Channel Set

Consider the example shown in Figure 14, which illustrates four upstream 6.4 MHz-wide SC-QAM channels. Assume the power per 6.4 MHz channel is 46.02 dBmV (or 40 dBmV per 1.6 MHz). The total power of the four SC-QAM channels is $P_{total(SC\text{-}QAM)} = 46.02\ dBmV + 10log_{10}(4) = 52.04\ dBmV$. In this example N_{eq} = 16 and $P_{1.6hi}$ = 52.96 dBmV, and CM Min Ch headroom is 12.96 dB. The additional bandwidth that can be added to the TCS based on the current CM Min Ch headroom is

$$N_{eq\_additinal\_possible} = \left(\left[10^{(CM\ Min\ Ch\ headroom\ dB/10)}\right] - 1\right) * N_{eq} = 64$$

That is, 64 * 1.6 MHz = 102.4 MHz.

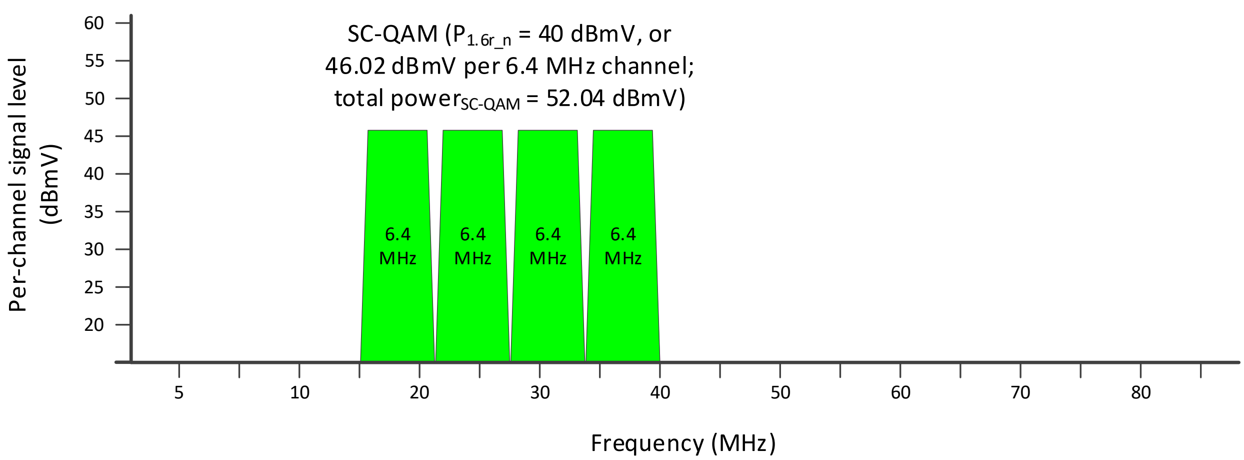


Figure 14 - The total power of four 6.4 MHz-wide SC-QAM channels in this figure, each with a per-channel signal level of 46.02 dBmV, is 52.04 dBmV.

Next, consider a scenario in which a 25.6 MHz-wide OFDMA channel (N_{eq_added} = 16) is added to the upstream spectrum along with the original four 6.4 MHz-wide SC-QAM channels, as shown in Figure 15. Assume for this example the OFDMA's power is 40 dBmV per 1.6 MHz. The total power of the OFDMA channel is $P_{total(OFDMA)} = 40\ dBmV + 10log_{10}(16) = 52.04\ dBmV$. When the total power of the four SC-QAM channels and the total power of the OFDMA channel are added together (logarithmically), the combined total power has doubled and now is

$$P_{total(SC\text{-}QAM+OFDMA)} = 10log_{10}\left[10^{(52.04/10)} + 10^{(52.04/10)}\right] = 55.05\ dBmV$$

The new $P_{1.6hi}$ is 49.95 dBmV, and the new CM Min Ch headroom is 9.95 dB.

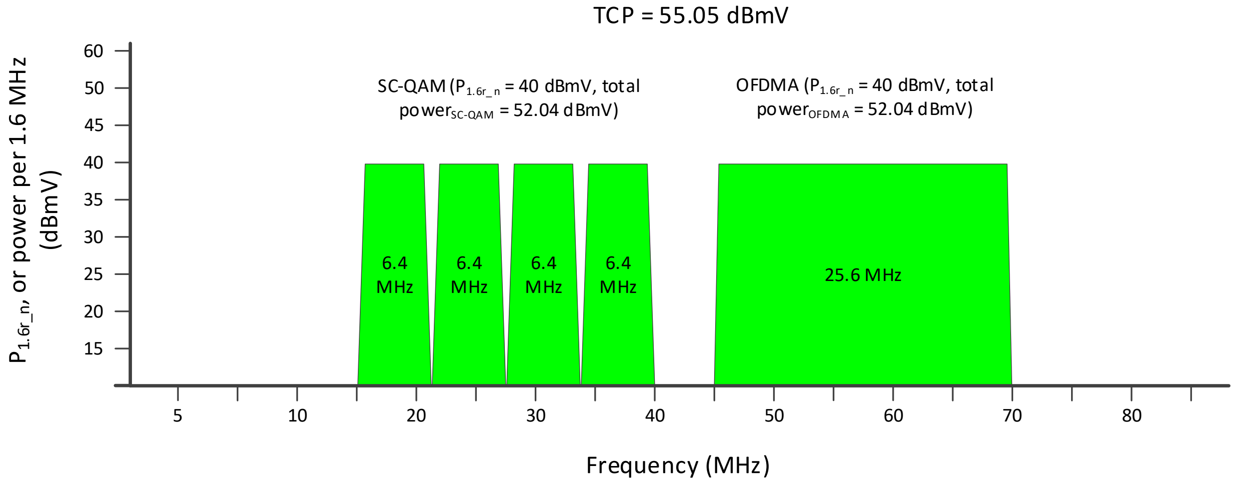


Figure 15 - In this example a 25.6 MHz-wide OFDMA channel has been added to the upstream spectrum.

Table 4 summarizes the before and after headroom performance for the examples in this section.

Table 4 - Before and after headroom performance.

Channel	Channel width	Initial TCS Occupied Bandwidth: 25.6 MHz		New TCS Occupied Bandwidth: 51.2 MHz	
		$P_{1.6}$, dBmV	Headroom, dB	$P_{1.6}$, dBmV	Headroom, dB
1	6.4 MHz	40.00	12.96	40	9.95
2	6.4 MHz	40.00	12.96	40	9.95
3	6.4 MHz	40.00	12.96	40	9.95
4	6.4 MHz	40.00	12.96	40	9.95
5	25.6 MHz			40	9.95
Summary					
N_{eq}		16		32	
TCP, dBmV		52.04		55.05	
$P_{1.6hi}$, **dBmV**		52.96		49.95	
TCP Headroom, dB		12.96		9.95	
Min Ch Headroom, dB		12.96		9.95	

Table Summary:

- Bandwidth increased by two times, or logarithmically, $10\log_{10}$(51.2 MHz/25.6 MHz) = 3.01 dB
- TCP headroom degradation: 12.96 dB – 9.95 dB = 3.01 dB
- Min Ch headroom degradation: 12.96 dB – 9.95 dB = 3.01 dB

The bandwidth expansion (logarithmic) is 3.01 dB, and the degradation in Min Ch headroom is 3.01 dB. The two values are the same.

As the size of a CM's TCS increases to take advantage of the expanded upstream spectrum, the total combined power of those transmitted channels increases. If the modem was already transmitting at or near its maximum power with a smaller channel load, it may not be able to support the transmit power requirements of added channels.

5. Management of Modem Transmit Power in Cable Network Operation

The previous sections discuss the interaction of spectrum bandwidth and transmit power headroom, and the impact and conditions associated with adding more upstream occupied bandwidth to a CM. The impact of adding a channel could be much greater in the presence of impairments. Knowing the actual transmit power that a modem is using before adding a new upstream channel (or channels) is therefore important to measure, and is useful when estimating the impact to the transmit power of adding a channel to the system. All of this emphasizes the importance of properly managing CM transmit headroom.

As explained in Section 4.5, as operators add channels to address increasing demand, added upstream occupied bandwidth will result in a reduction of $P_{1.6hi}$ (with DOCSIS 3.1 as the example), which may mean some modems cannot participate in the expansion if they do not have enough available transmit power to use the additional channels. These CMs will not be able to provide higher data rates reliably as a result. When this occurs, proactive network maintenance (PNM) may be required to allow these modems to use the new channels.

When transitioning a network to a higher band split, legacy sub-split components – especially those with diplex filters, equalizers, etc. – may affect transmission in mid-split or high-split frequencies. More power may be required from impacted modems as a result, which further limits the power available to add occupied bandwidth to the TCS.

Adding channels is not the only reason to manage the CM transmit power limits. A modem will be commanded to adjust its transmit power levels periodically to address changes in the network's transmission capabilities due to temperature changes (see Section 4.3.2), and the appearance of impairments which often change over time as well. Plant or drop problems will affect signal transmission, and require more power from the modem to try to compensate. A CM that is already close to its transmission limits is likely to exhaust its transmit power budget on occasion due to natural changes in the network. When the CM has insufficient power headroom to transmit at the necessary signal level (to reach the burst receiver at the target PSD), it can potentially benefit from a lower modulation order for some or all channels, otherwise service may be impacted. Calculating CM transmit power compared to the upper limit of its capability (the CM transmit power headroom, P_{load_1} and $P_{1.6load\_1}$, in DOCSIS 3.0 and 3.1 respectively), as shown in Section 3.2, is therefore a useful tool for PNM.

The CM's transmit power headroom is one of the figures-of-merit describing a CM's operating margin.

5.1. Ways to Manage Cable Modem Transmit Headroom

When managing CM transmit power headroom, the cause of any issues impacting that headroom must first be considered. If the plant was properly designed and built, degradation may be the main factor to address. But in addition, changes to the network to accommodate evolution, such as converting to a gateway architecture at the subscriber premises, or migrating to higher band splits, can lead to a mix of plant conditions that can affect modem transmit headroom.

If impairments are present and they are causing excessive net attenuation between the modem and CMTS, then long loop ALC (see Section 4.3) will compensate with higher modem transmit power and thus may exhaust the transmit headroom for some CMs in the system. PNM should be conducted first in this case. Poor drop conditions, including water in the cable, or other damage and degradation, can lead to higher CM transmit levels to compensate. Likewise, unused splitters and other passives at the subscriber premises can contribute to the problem, and should be removed if not needed. Improperly installed drop components such as backwards splitters should be fixed. In the distribution network, correct alignment of amplifiers and nodes is critical to ensuring proper modem transmit headroom.

In an otherwise unimpaired plant, adding capacity or changing band splits can lead to the need to address CM transmit headroom. Legacy sub-split components in a mid- or high-split network should be removed or replaced. In older network designs it was common to use high-value taps (29 dB and even 32 dB!) at the outputs of actives, which cause modems connected to those taps to transmit at higher levels. Modern HFC networks often use 26 dB or lower value taps at active device outputs, but some of the older higher value taps may have been missed during upgrades and rebuilds. Those high value taps should be replaced with correct values.

Any distribution components that have integrated sub-split filtering need to be replaced or upgraded with the correct filtering when moving to a mid- or high-split architecture. This includes in-line and drop equalizers (and so-called step or reverse attenuators), and drop amplifiers. By removing or replacing equipment intended for a previous architecture and ensuring correct tap values, the pressure on CM transmission levels can be eased, and thus managed to relieve headroom.

Some newer network architectures take advantage of conditioned taps,[9] which can help to narrow the window of modem transmit levels, further helping with modem transmit headroom. See Figure 16 for an example of a mid-split feeder design using conditioned taps.

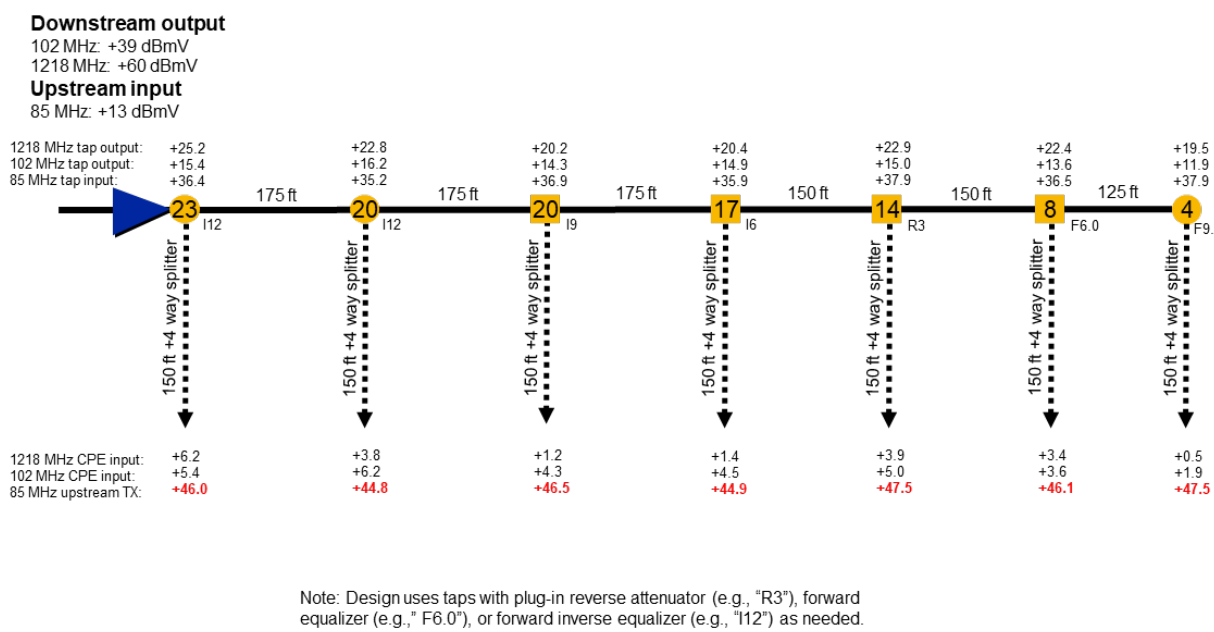


Figure 16 - Example mid-split distribution design using conditioned taps

At the headend/hub CMTS or R-PHY node, operators can optimize the configured target set point. As well, headend or hub upstream combining and splitting (and use of external padding at the CMTS upstream ports) should be evaluated and modified if necessary to ensure the overall net attenuation between the modem and CMTS isn’t excessive.

[9] Conditioned taps use plug-in pads or equalizers to fine tune downstream and upstream losses in the tap, allowing the modem transmit window to be narrowed and upstream levels optimized.

A balanced system provides the most dynamic range for the CMs to transmit at lower levels overall so that all CMs have some transmit power headroom for resiliency. If a system is designed so that one or a few CMs are already transmitting at high levels without impairments, then there is less headroom for these CMs to use for resiliency.

5.2. Headroom Management Knobs

There are three "knobs" to manage transmit headroom:

- Reduce CMTS upstream receive set point
- Reduce the TCS occupied bandwidth
- Fix net attenuation problems (see Section 5.1)

The next section includes guidance to create a spreadsheet that can be used as a tool for better understanding the impact of the three transmit headroom management knobs.

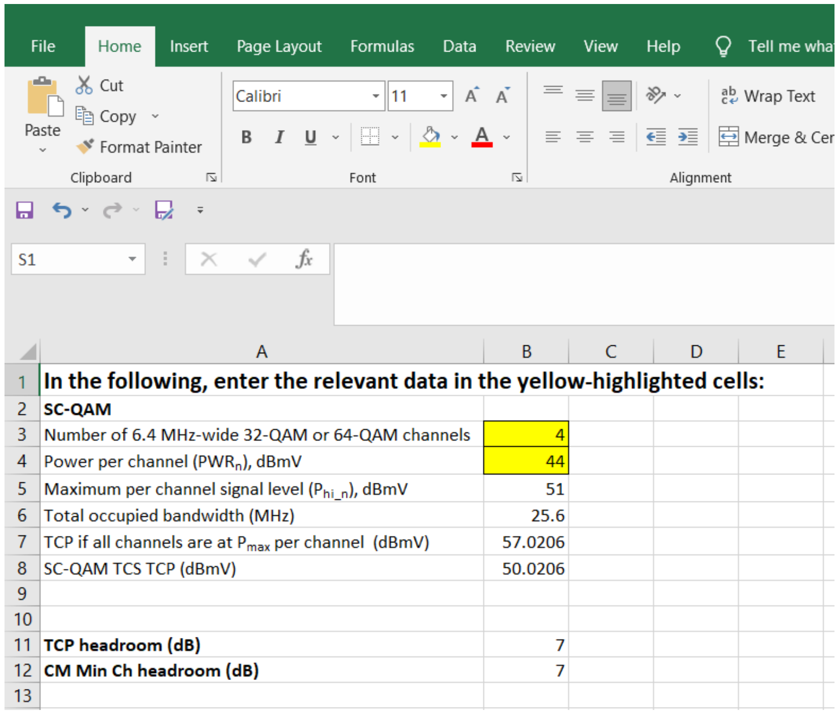
6. Create Your Own Spreadsheet

This section includes guidance to create a spreadsheet for calculating and modeling available CM transmit headroom.

6.1. Simple Headroom Calculation for DOCSIS 3.0

Figure 17 shows an example of a simple spreadsheet to calculate a DOCSIS 3.0 CM's TCP headroom and Min Ch headroom. The user enters data in the yellow-highlighted cells. That data includes the number of SC-QAM channels (four shown), and power per channel in dBmV (44 dBmV shown). The assumptions in this simple example are that the SC-QAM channels are either 32-QAM or 64-QAM, are all 6.4 MHz wide, and have the same per-channel transmit power.

The spreadsheet calculates total occupied bandwidth (25.6 MHz shown); the maximum per channel signal level P_{max} per the DOCSIS 3.0 specification (51 dBmV shown); the TCP if all channels are at P_{max} per channel (57.02 dBmV shown); and the TCS's TCP (50.02 dBmV shown). The example spreadsheet's final output in cell B11 is the CM's TCP headroom (7 dB shown), and in cell B12 the Min Ch headroom (7 dB shown). Note that TCP headroom and Min Ch headroom are equal because all four channels have the same PWR_n.



	A	B	C	D	E
1	**In the following, enter the relevant data in the yellow-highlighted cells:**				
2	**SC-QAM**				
3	Number of 6.4 MHz-wide 32-QAM or 64-QAM channels	4			
4	Power per channel (PWR_n), dBmV	44			
5	Maximum per channel signal level (P_{hi_n}), dBmV	51			
6	Total occupied bandwidth (MHz)	25.6			
7	TCP if all channels are at P_{max} per channel (dBmV)	57.0206			
8	SC-QAM TCS TCP (dBmV)	50.0206			
9					
10					
11	**TCP headroom (dB)**	7			
12	**CM Min Ch headroom (dB)**	7			
13					

Figure 17 - Simple spreadsheet to calculate DOCSIS 3.0 cable modem TCP headroom and Min Ch headroom.

Table 5 summarizes the formulas for various cells in the spreadsheet in Figure 17.

Table 5 - Formulas for spreadsheet in Figure 17.

Cell	Formula
B5	=57-3*CEILING(LOG(B3,2),1)
B6	=B3*6.4
B7	=B5+(10*(LOG(B3)))
B8	=B4+(10*(LOG(B3)))
B11	=B7-B8
B12	=B5-B4

6.2. Mixed Channels Headroom Calculation for DOCSIS 3.1

The next example, shown in Figure 18, is a spreadsheet that can handle up to six SC-QAM channels and two OFDMA channels. As before the user enters data in the yellow-highlighted cells.

The spreadsheet calculates a variety of parameters. Examples include channel TX headroom (row 14); channel RX difference from the CMTS set point (row 15); adjusted channel TX headroom (row 16); TCS TCP headroom (cell B24); combined TCS RX difference from the CMTS set point (cell B25); adjusted TCS TCP headroom (cell B26); $P_{1.6hi}$ (cell B30); $P_{1.6r\_1}$ (cell B31); Min Ch headroom (cell B32); worst RX channel difference from the CMTS set point (cell B33); worst adjusted Min Ch headroom (cell B34); and effective DRW (cell B36). This particular spreadsheet was customized with conditional formatting to color certain cells with respect to pre-defined thresholds (beyond the scope of this paper).

	A	B	C	D	E	F	G	H	I
1	**Transmit Channel Set (TCS)**	**Legacy Channel 1**	**Legacy Channel 2**	**Legacy Channel 3**	**Legacy Channel 4**	**Legacy Channel 5**	**Legacy Channel 6**	**OFDMA Channel 1**	**OFDMA Channel 2**
2	Channel Center Frequency (MHz)	16.4	22.8	29.2	35.6			64	
3	Channel Width (MHz)	6.4	6.4	6.4	6.4	-	-	42.000	-
4	Bandwidth in which power is measured (MHz)	6.4	6.4	6.4	6.4	-	-	1.6	-
5	Reported Modem Transmit Power (dBmV)	44.0	47.0	53.0	53.0	-	-	47.0	-
6	Actual Receive Power at CMTS (dBmV)	0.0	0.0	-1.0	0.0	0.0	0.0	0.0	0.0
7	CMTS's Set Point Receive Power (dBmV)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8									
9	**Per channel report**	**Legacy Channel 1**	**Legacy Channel 2**	**Legacy Channel 3**	**Legacy Channel 4**	**Legacy Channel 5**	**Legacy Channel 6**	**OFDMA Channel 1**	**OFDMA Channel 2**
10	Linear Transmit Power	25118.86432	50118.72336	199526.2315	199526.2315	0	0	1315616.488	0
11	Channel N_{eq_n}	4	4	4	4	-	-	27	-
12	Channel TX Power, (dBmV)	44.00	47.00	53.00	53.00	-	-	61.19	-
13	Channel Power Spectral Density $P_{1.6r\_n}$ (dBmV)	37.98	40.98	46.98	46.98	-	-	47.00	-
14	Channel TX Headroom (dB)	**10.69**	**7.69**	**1.69**	**1.69**	**0.00**	**0.00**	**1.67**	**0.00**
15	Channel RX Difference from CMTS Set Point (dB)	0.0	0	-1	0	0	0	0	0
16	Adjusted Channel TX Headroom (dB)	10.69	7.69	0.69	1.69	0.00	0.00	1.67	0.00
17									
18									
19	**TCS report**	**Whole TCS**	**Legacy (SC-QAM)**	**OFDMA**					
20	N_{eq} (number of 1.6 MHz equiv)	43	16	27					
21	Occupied US Spectrum (MHz)	67.600	25.6	42					
22	TCP (dBmV)	62.53	56.76	61.19					
23	P_{max} (dBmV)	65.00							
24	TCS TCP Headroom (dB)	2.47							
25	Combined TCS RX Difference from CMTS Set Point (dB)	-0.09							
26	Adjusted TCS TCP Headroom (dB)	2.38							
27									
28	**Worst channel report**		**Identified channel**						
29			**Description**	**Center Frequency**					
30	$P_{1.6hi}$ (dBmV)	48.67							
31	$P_{1.6r\_1}$ (dBmV)	47.00	OFDMA Channel 1	64					
32	Min Ch Headroom (dB)	1.67	OFDMA Channel 1	64					
33	Worst RX Channel Difference from CMTS Set Point (dB)	-1.00	Legacy Channel 3	29.2					
34	Worst Adjusted Min Ch Headroom (dB)	0.69	Legacy Channel 3	29.2					
35									
36	**Effective DRW**	9.02							
37									

Figure 18 - Another example spreadsheet for calculating modem transmit headroom.

Table 6 summarizes some of the formulas for various cells in the spreadsheet in Figure 18. (The formulas in rows 10-16 of columns C-I are similar to those in cells 10-16 of column B. For example, the formula in cell C10 is =10^(C13/10)*C3/1.6 and so on.

An online tool for calculating CM transmit headroom is available at https://promptlink.com/tools/headroomcalc3.1

Table 6 - Formulas for spreadsheet in Figure 18.

Cell	Formula
B10	=10^(B13/10)*B3/1.6
B11	=CEILING(B3/1.6,1)
B12	=IF(B3>0,B5-10*LOG(B4/B3),"-")
B13	=IF(B3>0, B5-(10*LOG(CEILING(B4/1.6,1))),0)
B14	=IF(B3>0,B30-B13,0)
B15	=B6-B7
B16	=B14+B15
B20	=CEILING(B21/1.6,1)
B21	=SUM(B3:I3)
B22	=10*LOG(SUM(B10:I10))
B24	=B23-B22
B25	=SUMPRODUCT(B15:I15,B3:I3)/B21
B26	=B24+B25
B30	=B23-10*LOG(B20)
B31	=MAX(B13:I13)
B32	=B30-B31
B33	=MINIFS(B15:I15,B3:I3,">0")
B34	=MINIFS(B16:I16,B3:I3,">0")
B36	=MAXIFS(B13:I13,B3:I3,">0")-MINIFS(B13:I13,B3:I3,">0")

7. Additional Work Underway

As cable operators deploy DOCSIS 3.1 OFDMA in the upstream RF spectrum, better understanding of the CM's TCS performance is needed to ensure reliable service. While this paper's in-depth analysis of CM transmit headroom is useful to provide additional insight for deploying, activating, and maintaining additional occupied bandwidth, there is more work to be done. For instance, the CableLabs PNM Working Group is looking at additional improvements to the existing PNM measurements:

- **OFDMA in-channel frequency response** – Consistent with the definition of ICFR carried over from DOCSIS 3.1 PNM but adding additional context to how the information is used, having significantly higher frequency resolution.
- **OFDMA channel tilt** – Used to quantify important plant setup, filter performance and response impairments.
- **OFDMA channel tilt residual** – Important to distinguish impairment magnitude when separating the effects of tilt, which are often unrelated.
- **Frequency amplitude ripple periodicity** – Provides improved distance accuracy when measuring the length of echo cavities caused by impedance mismatches.
- **Frequency response signature matching** – Determining frequency response commonalities to provide localization, which is useful in the troubleshooting process.

8. Conclusion

At first glance CM transmit headroom seems relatively simple: generally speaking, it is the difference, in dB, between a modem's maximum transmit power capability and its actual transmit power. But as discussed in this paper, CM transmit headroom is more complicated and really has two different interpretations or definitions: 1) CM TCP headroom, and 2) what we call CM Min Ch headroom. These two headroom values comprise two different figures-of-merit to characterize a CM's commanded channel power compared to its transmit power capability. Additionally, each channel of a CM has its own figure-of-merit in this regard: CM channel headroom.

CM transmit headroom is related to a combination of transmitted RF power, DRW, long loop ALC, pre-equalization settings, CMTS receive power set point, and channel bandwidth. All of these factors are even more important as operators migrate to an expanded upstream spectrum, and increase the occupied bandwidth of transmitted signals to support greater data rates. Insufficient CM transmit headroom is a good indication that service quality could be impacted, making it all the more important that operators properly understand and manage CM transmit power.

Appendix A

9. What is Power Spectral Density?

9.1. Power and Power Spectral Density

The terms "power" and "power spectral density" are used throughout this paper, but what do those terms mean? First, we need to understand what the power of a channel is. RF power refers to the amount of energy carried by the channel (its signal level) – more specifically, power is the rate at which work is done, or energy per unit of time. 1 watt of power is equal to 1 volt causing a current of 1 ampere. Note: While the watt is the International System of Units (SI) unit of power, the cable industry uses dBmV (or decibel microvolt, dBμV, in some parts of the world), which is an expression of power in terms of voltage. If we plot the spectrum of the channel (i.e., plot the PSD), power can be represented as the complete area under the PSD covered by the channel over its occupied bandwidth.

From a high-level perspective, power spectral density "describes how power of a signal … is distributed over frequency." PSD is commonly expressed in units of power over bandwidth, typically (but not always) as power per hertz (Hz).[10] For more information see [TPPSD]

Assuming the power of a channel is distributed evenly across its occupied bandwidth (i.e., its relative amplitude is uniform across the spectrum), then PSD can be calculated as:

$$PSD_{[dBmV/Hz]} = Power_{[dBmV]} - 10log_{10}\left(Bandwidth_{[Hz]}\right)$$

Note: The examples in this appendix focus on SC-QAM channels, but the concepts are the same for OFDM, OFDMA, and other RF signal types. What matters is channel power, occupied bandwidth and PSD, and the relationship between them.

Consider an example in which a single 1.6 MHz-wide SQ-QAM channel is being transmitted with a digital channel power of 45 dBmV. The PSD of that channel can be calculated as:

$$PSD_{[dBmV/Hz]} = 45\ dBmV - 10log_{10}(1.6 * 10^6[Hz]) = -17.04\ dBmV/Hz$$

Another way to look at PSD in this example is that each hertz of the 1.6 MHz-wide SC-QAM channel's occupied bandwidth carries –17.04 dBmV of power.

For the next two examples, assume that we have four SC-QAM channels of different bandwidths: two at 1.6 MHz, and one each at 3.2 MHz and 6.4 MHz.

For the first example (see Figure 19) the four channels are transmitted with the same PSD = –17.04 dBmV/Hz. All the channels will have the same relative PSD, as illustrated in the figure. But the power of each channel varies depending on its occupied bandwidth. The power of each 1.6 MHz-wide channel is 45 dBmV. The 3.2 MHz-wide channel has the same amount of power as *two* 1.6 MHz-wide channels together ($3.2\ MHz = 2 * 1.6\ MHz$), so its power is twice as much ($10 * log_{10}(2) =$ 3.01 dB more) as a single 1.6 MHz-wide channel: $45\ dBmV + 10log_{10}(2) = 48.01\ dBmV$. The 6.4 MHz-wide SC-QAM channel has four times the power (or 6.02 dB more) of one 1.6 MHz-wide channel ($6.4\ MHz = 4 * 1.6\ MHz$), so its power is $45\ dBmV + 10log_{10}(4) = 51.02\ dBmV$.

[10] $P_{1.6hi}$ and similar spec terms in [D3.1PHY] have units of power (dBmV) and are not literally a PSD, but represent power measured in a 1.6 MHz bandwidth and function in the specification much like a PSD "per 1.6 MHz."

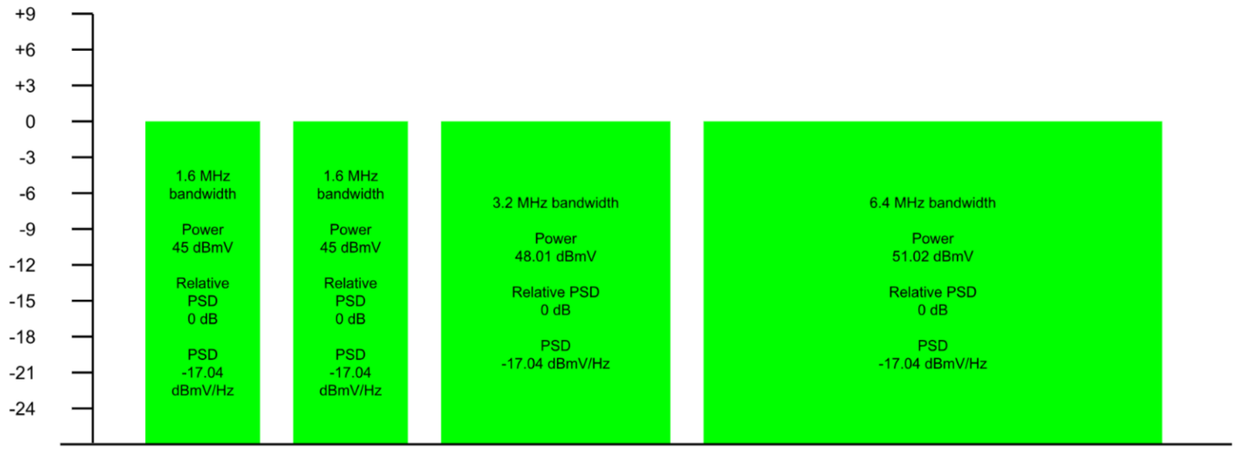


Figure 19 - Example showing four SC-QAM channels with different bandwidths but identical PSD.

For the next example (see Figure 19) the four channels are transmitted with identical power, each at 45 dBmV. There are no changes compared to the previous examples for the 1.6 MHz-wide channels, so they maintain the same power and PSD as before. However, for the twice-as-wide 3.2 MHz-bandwidth channel, in order to maintain the same power the PSD needs to be *decreased* by a factor of two (by $10log_{10}(2) = 3.01$ dB) and will be

$$PSD = -17.04\ dBmV/Hz - 10log_{10}(2) = -20.05\ dBmV/Hz$$

For the four-times-as-wide 6.4 MHz bandwidth channel, the PSD needs to be reduced even further, by $10log_{10}(4) = 6.02$ dB:

$$PSD = -17.04\ dBmV/Hz - 10log_{10}(4) = -23.06\ dBmV/Hz$$

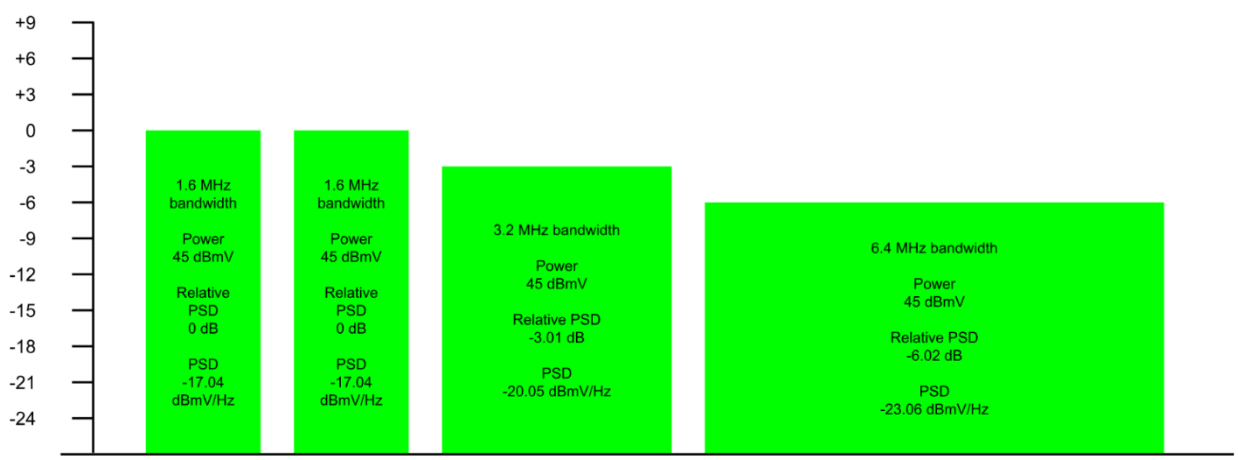


Figure 20 - Example showing four SC-QAM channels with different bandwidths but identical per-channel power.

Appendix B

10. Dynamic Range Window

From DOCSIS 3.0 onwards, cable modems started supporting multiple upstream and downstream channels, which were logically bonded to provide higher data rates than were available with the single-channel operation in DOCSIS 1.0, 1.1, and 2.0 technology. To accommodate multiple upstream channels, new upstream power control parameters were introduced. When a CM is using multiple upstream channels, typically the power spectral density varies from channel-to-channel. This is because generally the upstream receiver operates to control the PSD to be flat at its input, and the frequency response of the plant from most CMs back to the receiver is typically not perfectly flat. Some channels generally transmit with a larger average PSD than others, even from the same modem.

When a cable modem is using multiple upstream channels, typically the PSD varies from channel-to-channel. This is because generally the upstream receiver operates to control the PSD to be flat at its input, and the frequency response of the plant from most CMs back to the receiver is typically not perfectly flat. Some channels generally transmit with a larger average PSD than others, even from the same CM. To accommodate multiple upstream channels a DRW is defined. The DRW in DOCSIS 3.0 defines a 12 dB range of transmit power levels for the cable modem. It is expected that the CMTS will maintain each of the upstream channels in the CM's TCS within the CM's DRW. The cable modem learns the TCS from the CMTS during registration. The CMTS manages the DRW for the modem, ensuring that the cable modem is not ranged at a value that would result in a violation of the DRW. If the CMTS commands the modem to use a transmit power level, that would result in a violation of the DRW; the modem performs the commanded adjustment and indicates an error to the CMTS (the modem must obey the CMTS all the time). The DRW is controlled by the CMTS and communicated to the CM in the ranging or in the registration (TCS) or the dynamic bonding change (DBC) message. Occasionally the plant conditions cause the modem to go out of the DRW, which eventually result in the CM dropping the channel and indicating partial service to the CMTS. Partial service impacts subscribers' upstream speed.

The new parameters introduced from DOCSIS 3.0 are $P_{load\_min\_set}$, and P_{load_n} (e.g., P_{load_1}, P_{load_2}, etc.). The top of the DRW is defined as $P_{load\_min\_set}$ and is expressed as some number of dB below P_{hi} for each channel. The P_{hi} for each channel depends on the multiplexing technology – for instance, time division multiple access (TDMA), commonly known as A-TDMA in DOCSIS 2.0 and later – and the modulation order (e.g., 16-QAM, 64-QAM, etc.) for the channel as well as the total number of active channels. The P_{hi} is defined in the PHY specification.

The parameter $P_{load\_min\_set}$ is commanded to the modem by the CMTS and sets in place the restriction on P_{load_n} that $P_{load\_min\_set} \leq P_{load\_n} \leq P_{load\_min\_set} + 12$ dB, for all channels in the TCS.

Since $P_{load\_n} = P_{hi\_n} - P_{r\_n}$, the value of $P_{load\_min\_set}$ places the limit on P_{r_n} for each channel. The P_{r_n} provides the transmission power level, as an offset from the reference channel that the modem is to use on the new channel such that transmissions arrive at the CMTS at the desired power.[11]

$$\left(P_{hi\_n} - P_{load\_min\_set}\right) \geq P_{r\_n} \geq \left(P_{hi\_n} - P_{load\_\min\ \_set} - 12\ dB\right)$$

For each channel in the TCS, the range of P_{r_n} for that channel is restricted to operating over a window of 12 dB by the value commanded by the CMTS. This is the DRW for the modem for the n^{th} channel.

[11] PWR_n is used in other parts of this paper to denote P_{r_n} in [PHY3.0] and $P_{1.6r\_n}$ in [PHY3.1].

For example, with 64-QAM TDMA the maximum power level allowed is 57 dBmV, 54 dBmV, and 51 dBmV for one, two, and three (or four) channels, respectively, in the TCS. A “fully loaded” 64-QAM TDMA SC-QAM channel with one channel in the TCS would be transmitted at 57 dBmV while a “fully loaded” 64-QAM SC-QAM channel with three channels in the TCS would be transmitted at 51 dBmV. A 64-QAM TDMA SC-QAM which is “underloaded” by 15 dB would transmit at 57 dBmV – 15 dB = 42 dBmV with one channel in the TCS, and a 64-QAM TDMA SC-QAM channel which is “underloaded” by 15 dB would transmit at 51 dBmV – 15 dB = 36 dBmV with three channels in the TCS. The parameter P_{load_n} is used to convey the amount by which the n^{th} channel is underloaded. Thus, in the case of the single channel in the TCS, with 42 dBmV for the 64-QAM TDMA SC-QAM channel’s transmit level, the channel is underloaded by 15 dB, therefore, P_{load_1} = 15 dB. Similarly, in the case of three channels in the TCS, with three 64-QAM TDMA SC-QAM channels transmitted at 41 dBmV, 38 dBmV, and 36 dBmV, we have P_{load_1} = 10 dB, P_{load_2} = 13 dB, and P_{load_3} = 15 dB, where P_{load_1} corresponds to the channel with the lowest value of P_{load}, or equivalently, the highest or more full loading. The concept of “loading,” and the values of P_{load_n}, are only indirectly tied to the absolute transmit power, with the absolute transmit power equaling the maximum transmit power (for the modulation and number of channels in the TCS) minus P_{load_n} for the n^{th} channel.

Consider a modem that has a TCS with three 6.4 MHz wide 64-QAM TDMA upstream SC-QAM channels. The theoretical capacity is 3 * 5.12 megasymbols per second * 6 bits per symbol = 92.16 Mbps.

If that modem lost one of its SC-QAM channels due to a DRW violation, then it would operate using two TDMA SC-QAM channels, result in lower upstream capacity: 2 * 5.12 megasymbols per second * 6 bits per symbol = 61.44 Mbps.

Appendix C

11. Why Pre-Equalization Does Not Impact Transmit Power, When All is Working as Intended

This appendix describes the "basics" of the operation of the CM transmit power in the DOCSIS long loop automatic level control of a DOCSIS HFC network (see [LLALC] for more information on long loop ALC). The specified details of updating the CM transmit power are presented in the first section (the [D3.1PHY] details for OFDMA are shown for illustration). In the second section it is shown that the normalization of the pre-equalization (Pre-Eq) coefficients provides that the CM transmit power is not altered by the pre-equalization. The third section of this appendix is a reproduction of the definitions of terms for upstream transmit power control in [D3.1PHY].

In an OFDMA channel in [D3.1PHY], some upstream subcarriers may be excluded, but all other subcarriers in the channel are active subcarriers, and are used in probes from a CM in that channel. This appendix defines a set of pre-equalization coefficients *for all active subcarriers* for a given CM as "the pre-equalization vector" for the CM. Similarly, when writing "the Pre-Eq coefficients," it is intended to mean the set of coefficients for the CM, for *all* the active subcarriers of the channel.

11.1. Cable Modem Transmit Power Adjustment in DOCSIS PHYv3.1

The CM determines its target transmit power per channel $P_{1.6t\_n}$, as follows, for each channel which is active. Define for each active channel, for example, upstream channel n:

$P_{1.6c\_n}$ = commanded power for channel n. (TLV-17 in RNG-RSP)

$P_{1.6r\_n}$ = reported power level (dBmV) of the CM for channel n.

$P_{1.6hi} = P_{max}$ dBmV $- 10\log_{10}(N_{eq})$

The CM updates its reported power per channel in each channel by the following steps:

$$\Delta P = P_{1.6c\_n} - P_{1.6r\_n}$$

$$P_{1.6r\_n,new} = P_{1.6r\_n,previous} + \Delta P$$

Add power level adjustment (for each channel) to reported power level for each channel. Written another way, to avoid recursion but to clarify the assignment of value (as in programming),

$$P_{1.6r\_n} := P_{1.6r\_n} + \Delta P$$

Now, we introduce the pre-equalization portion. For OFDMA, the CM then transmits each data subcarrier with the target power:

$$P_{t\_sc\_i} = P_{1.6r\_n} - P_{1.6delta\_n} + Pre\text{-}Eq_i - 10 * \log_{10}(number\ of\ subcarriers\ in\ 1.6\ MHz\{32\ or\ 64\})$$

where Pre-Eq$_i$ is the magnitude of the ith subcarrier pre-equalizer coefficient (dB), and $P_{1.6delta\_n}$ equals 0 dB for non-boosted channels, 0.5 dB for boosted channels with 25 kHz subcarrier spacing, and 1 dB for boosted channels with 50 kHz subcarrier spacing.

11.2. The Pre-Equalization Vector is Normalized to Unity Power and Application of Pre-Equalization Does Not Alter the Cable Modem Transmit Power

In this section we illustrate the normalization of the Pre-Eq vector which is required to be performed in the CM, and we illustrate how as a result of the normalization the CM transmit power is not impacted by the application of the Pre-Eq vector.

Let's (for here) call the i^{th} coefficient of the normalized Pre-Eq vector as:

$$pe_i = I_i + jQ_i$$

We can then let:

$P_{pre\text{-}eq\_i}$ = power of i^{th} Pre-Eq coefficient, but in linear power rather than dB,

$$P_{\text{pre-eq}_i} = \text{power of the } i^{th} \text{ Pre-Eq coefficient, but in linear power rather than dB}$$

so:

$$P_{\text{pre-eq}_i} = |pe_i|^2 = I_i * I_i + Q_i * Q_i$$

Recall we had *Pre-Eq_i* as the power of the i^{th} pre-eq vector expressed in units of dB:

$$\begin{aligned}\text{Pre-Eq}_i[dB] &= 10 * \log_{10}(|pe_i|^2) \\ &= 10 * \log_{10}(I_i * I_i + Q_i * Q_i)\end{aligned}$$

And thus,

$$\text{Pre-Eq}_i[\text{dB}] = 10 * \log_{10} P_{\text{Pre-Eq}_i}$$

And also note, due to the normalization of the Pre-Eq coefficients, the following condition is ALWAYS satisfied (presuming spec-compliant operation of the CM):

-With the number of active (that is, non-excluded) subcarriers in the OFDMA channel being N,

-Sum of $\{P_{pre\text{-}eq\_i} / N\}$ over all non-excluded subcarriers is 1.

Consider a pre-equalization vector which is not yet normalized, $P_{pre\text{-}eq\_unnormalized\_i}$:

Total_Pre-Eq_Power_unnormalized = Sum of $\{P_{pre\text{-}eq\_unnormalized\_i}\}$ over all active (non-excluded) subcarriers

Then to NORMALIZE the Pre-Eq coefficients to unity power, they should be divided by a scaling factor:

$$\text{Scaling\_Factor} = \sqrt{\text{Total\_Pre-Eq\_Power\_unnormalized}}$$

So that the scaled pre-equalization normalized values are computed as:

$$pe_{normalized\_i} = pe_i = \frac{pe_{unnormalized\_i}}{\text{Scaling\_Factor}}$$

$$= \frac{\left(I_{unnormalized\_i} + jQ_{unnormalized\_i}\right)}{\text{Scaling\_Factor}}$$

$$= (I_i + jQ_i)$$

With the above notation, we can formally walk through the calculations applying the pre-equalization coefficient values to each subcarrier, collect terms, and mathematically show that the CM transmit power after application of normalized pre-equalization values does not alter the CM transmit power.

We desire to add up the impact of *Pre-Eq*$_i$ (dB) over all non-excluded subcarriers (N), which we do in linear power.

$$10^{P_{t\_sc\_i}/10} = \frac{10^{P_{1.6r\_n}/10} * P_{\text{Pre-Eq}_i}}{\left(N * 10^{P_{1.6delta\_n}/10}\right)}$$

And so, to sum over the non-excluded subcarriers, we have

$$\sum_{i=1}^{N} 10^{P_{t\_sc\_i}/10} = \sum_{i=1}^{N} \frac{10^{P_{1.6r\_n}/10} * P_{\text{pre-eq}_i}}{(N * 10^{P_{1.6delta\_n}/10})}$$

$$\sum_{i=1}^{N} 10^{P_{t\_sc\_i}/10} = \frac{10^{P_{1.6r\_n}/10}}{10^{P_{1.6delta\_n}/10}} \sum_{i=1}^{N} \frac{P_{\text{pre-eq}_i}}{N}$$

$$\sum_{i=1}^{N} 10^{P_{t\_sc\_i}/10} = \frac{10^{P_{1.6r\_n}/10}}{10^{P_{1.6delta\_n}/10}}$$

Where the last step is because the sum of $\{P_{pre\text{-}eqi} / \mathrm{N}\}$ over all non-excluded subcarriers is 1. So,

$$P_{t\_sc} = P_{1.6r\_n} - P_{1.6delta\_n}$$

Thus, the pre-equalization coefficients have no impact on the channel power!

Note: Many of the definitions of the terms used in this analysis are discussed in this paper, and are also included in Section 7.4.12.3.1 of [D3.1PHY].

Abbreviations

ALC	automatic level control
CCAP	converged cable access platform
CM	cable modem
CMTS	cable modem termination system
dB	decibel
DBC	dynamic bonding change
dBmV	decibel millivolt
DOCSIS	Data-Over-Cable Service Interface Specifications
DRW	dynamic range window
e.g.	exempli gratia (for example)
°F	degree Fahrenheit
FEC	forward error correction
HFC	hybrid fiber/coax
Hz	hertz
i.e.	id est (that is)
kHz	kilohertz
MHz	megahertz
Min Ch	minimum channel [headroom]
OFDMA	orthogonal frequency division multiple access
PHY	physical layer
PMA	profile management application
PNM	proactive network maintenance
PSD	power spectral density
QAM	quadrature amplitude modulation
RF	radio frequency
RNG-REQ	ranging request
RNG-RSP	ranging response
RPD	remote PHY device
S-CDMA	synchronous code division multiple access
SC-QAM	single carrier quadrature amplitude modulation
SCTE	Society of Cable Telecommunications Engineers
TCP	total composite power
TCS	transmit channel set
TDMA	time division multiple access

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