Using Profile Management to operationalize the roll-off region in DOCSIS 3.1 HFC networks

A Technical Paper prepared for SCTE by

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1. Introduction

As high split deployments begin to ramp up, demand for broadband services keeps driving the need for higher network capacities. Operators are required to do plant hardware reconfigurations and upgrades across their Hybrid-Fiber Coaxial (HFC) networks. Plant hardware reconfigurations and upgrades are expensive. This is why implementation of techniques and strategies that minimize physical changes in the HFC networks is crucial to allow cable operators to optimize their HFC networks for the long-term, and to remain competitive.

DOCSIS 3.1 introduced features that not only allow operators to increase network capacity through their HFC networks, but also to optimize downstream and upstream transmissions in a more granular manner to obtain better performance. One of those features is Orthogonal Frequency-Division Multiplexing (OFDM), which is associated with higher modulation orders (up to 4096-QAM) and can be deployed over existing HFC plants to significantly increase network capacities, while deferring the need for immediate RF spectrum expansions. However, higher modulation orders do require higher Modulation Error Ratio (MER) and distortion performance, and not every HFC network will support the highest orders ubiquitously. Flat OFDM profiles only support one order of modulation across the entire OFDM channel and can be deployed initially to take advantage of higher MER conditions in specific areas, but do not necessarily result in optimal transport capacity. This is especially the case when plant impairments in specific areas of the HFC spectrum force the use of lower modulation orders across every single OFDM sub-carrier. Optimizing bandwidth utilization and transport capacity requires a dynamic mechanism to track MER performance for every OFDM sub-carrier, identify HFC plant impairments, and assign the most efficient modulation orders to one or more OFDM sub-carriers for a given set of plant conditions.

The Profile Management Application (PMA) is a cost-effective, software-based implementation to address the demand for more network capacity through data collection, analysis, and efficient selection of OFDM profiles. The selected profiles for each OFDM channel can assign different modulation orders to groups of subcarriers within the channel, known as segments, based on plant conditions. PMA not only will prove to be a valuable tool in evolving the network, but also will help MSOs improve network efficiency by maximizing modulation rates to and from each modem in the network, enabling higher user throughput overall.

This paper will present the results of the practical application of PMA in an HFC plant. The primary focus will be on OFDM operation in HFC plant roll-off areas as a practical mechanism to gain additional network capacity by increasing the modulation order and bit loading capacity of individual subcarriers for those CMs reporting higher RxMER values. The paper will discuss first the observed roll-off characteristics between 1.0 GHz and 1.2 GHz for a representative HFC plant segment configured with a mix of 1.2 GHz amplifiers and 1.0 GHz passives, and the worsening conditions impacting this portion of the HFC spectrum as the number of cascaded 1.0 GHz passives increases. It will discuss next the maximum expected MER and modulation orders at various tap locations throughout the cascade, and how an initial optimization of OFDM parameters for operation in roll-off areas using only flat modulation profiles can deliver limited capacity gains prior to a PMA deployment. Finally, the paper outlines how a full PMA approach is used to correctly identify physical channel conditions as seen by individual customer modems, and how this data is used to dynamically select the most appropriate OFDM profiles for optimal roll-off operation of modems connected throughout the cascade. Expected overall capacity gains when applying a PMA approach that enables efficient operation of OFDM carriers in roll-off areas will be discussed.

2. HFC Lab Network Description

Testing was performed in a typical node-based HFC network segment designed with a remote fiber optical node feeding a cascade of RF amplifiers, taps, and express, distribution, and drop cables. Total cable footage was 4,800 feet of RG-11 cable.

As seen in Figure 1, the express cables, illustrated in green, connect the optical node to the first (amp 1) and second (amp 2) 1.2 GHz system amplifiers. These express actives are Mini-Bridger (MB) type radio frequency (RF) amplifiers, designed to overcome cable attenuation and passive losses over sections of the network where there are few splitters and directional taps. The distribution portion of the HFC network, represented in blue, includes a combination of two line extenders (amp 3 and amp 5) and one MB amplifier (amp 4) to boost the RF levels to provide adequate signal level to multiple taps. In between the distribution amplifiers there are 1.0 GHz passives including: directional couplers (DC), power inserters (PI) and taps.

The drop portion of the network consisted of a 100-foot span of RG-6 cable from the tap port to the input of a two-way splitter, and 50 feet of RG-6 cable from the output of the two-way splitter to the Cable Modem (CM) input.

For the worst case scenario at the farthest end of line, there are a total of 20 1.0 GHz passives between the optical node and the CMs connected to the last tap.

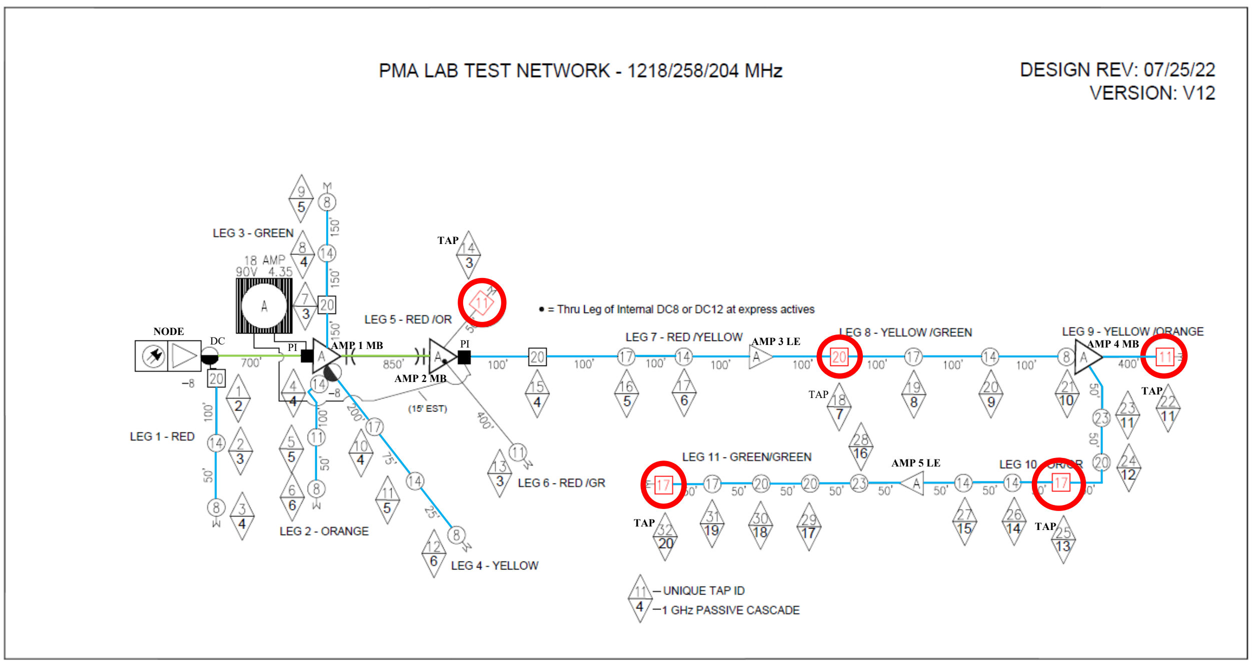

Figure 1. Typical HFC plant using 1.2 GHz actives and 1.0 GHz passives

The series of tests described below were performed using a high split Cable Modem Termination System (CMTS) that supports two downstream OFDM channels and two upstream OFDMA channels. Five sets of four different D3.1 CMs were connected to tap ports at five different tap locations, circled in red, across the network (Tap ID 14, 18, 22, 25 and 32). The 1.2 GHz actives in the test-bed were aligned to meet the designed RF output levels and tilt up to 1.2 GHz, but only loaded with a partial 1.0 GHz channel line-up. This ensured that after completing the alignment, the addition of a 192 MHz OFDM channel in the 1.0 to 1.2 GHz range, required for the first round of testing, would not affect amplifier performance.

3. Deploying OFDM in the Roll-Off Region

The advantages of OFDM operation over traditional Single Carrier Quadrature Amplitude Modulation (SC-QAM) channels have been widely documented. OFDM has allowed cable operators to increase downstream efficiency and to transmit data more robustly. OFDM transmits data over a combination of orthogonal narrowband sub-carriers. Each sub-carrier can have a different modulation order (bit loading) within the OFDM channel as determined by the different segments configured within a modulation profile. The number of segments that can be configured within a profile will vary by CMTS vendor.

The ability to configure multiple profiles allows the OFDM channel to operate higher modulation orders in parts of the spectrum with minimal impairments. Conversely, OFDM sub-carriers can operate with lower modulation orders or profiles that are more robust in the presence of impairments such as frequency roll-off in the 1.0 to 1.2 GHz range, which is introduced by the accumulated non-flat signature of cascaded 1.0 GHz passives.

The frequency response curve of 1.0 GHz passives beyond their defined passband has different peaks and valleys. The non-flat frequency response of a single 1.0 GHz passive in the 1.0 – 1.2 GHz range can be considered fixed, but it does vary in severity by manufacturer. The combination of poor return loss and higher insertion loss creates a non-flat roll-off signature that increases in severity as the number of 1.0 GHz passives increases. The cumulative effects of higher insertion loss and poor return loss in the 1.0 to 1.2 GHz range after four passives in cascade, using passives from two different vendors, are illustrated below in Figure 2 and Figure 3.

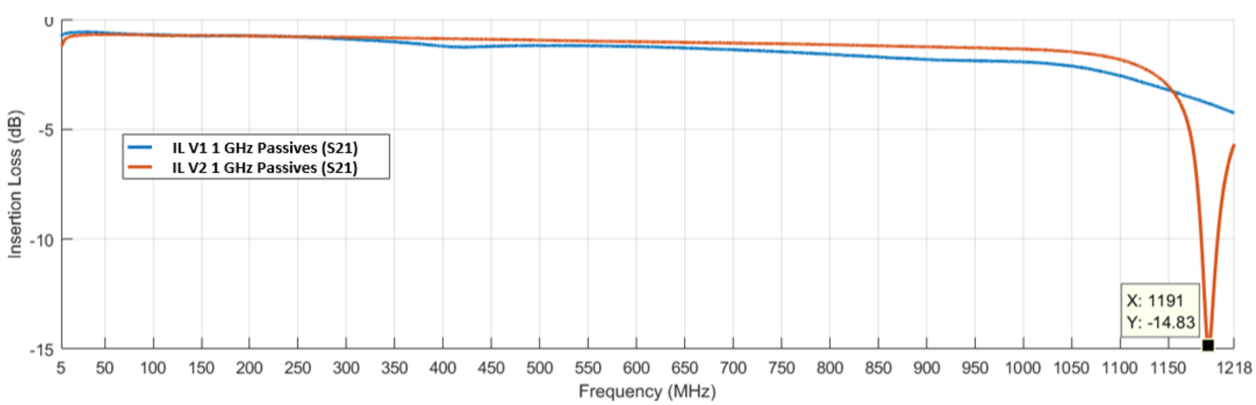

Figure 2. Cumulative Insertion Loss after four 1.0 GHz passives - two different vendors

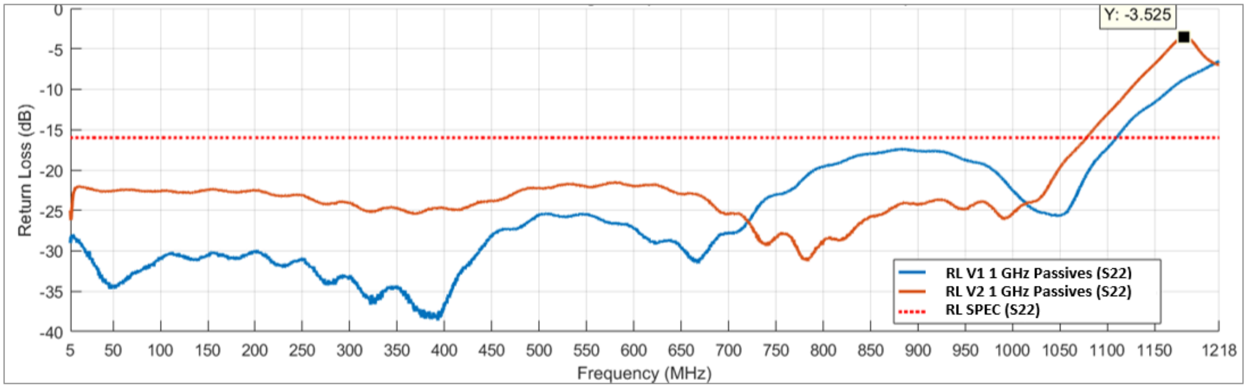

Figure 3. Cumulative Return Loss after four 1.0 GHz passives - two different vendors

As shown in Figure 4 the non-flat frequency response signature creates a roll-off that worsens as the number of 1.0 GHz passives increases. Eventually, the distortion of the OFDM carrier is such that CM operation may not be possible. RxMER data from individual CMs was no longer accessible after 11 passives, CMs stopped receiving data on the lowest modulation profile due to the amount of uncorrectable codeword errors. Ultimately CMs were unable to bond to the OFDM channel. As a result, the sequence of plots of the 192 MHz-wide OFDM channel across the five selected tap locations was obtained using a spectrum analyzer.

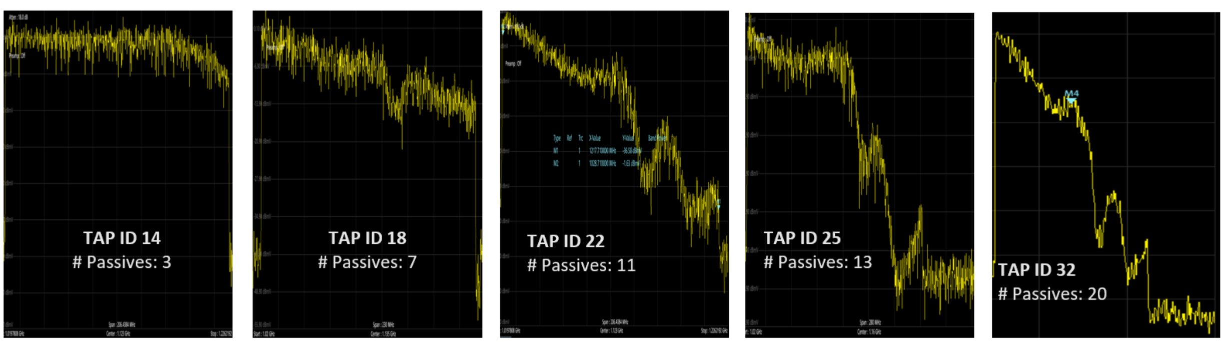

Figure 4. Roll-Off in the 1.0 – 1.2 GHz region at each of five selected tap locations across the network

Consequently, it is important to understand the overall impact of the roll-off on CM operation, and to select optimal OFDM parameters prior to enabling PMA in order to minimize issues such as those listed below and described in [PMA-D3.1-CL]:

- Profile flapping, which is defined as the process of a CM switching from a higher modulation profile to a lower modulation profile and back. It can be a result of the RxMER for the OFDM channel being marginal, falling slightly below the configured threshold for the CM to decode a certain modulation order. Therefore the CM starts to experience uncorrectable codeword errors on the assigned profile. The CM reacts by sending a CM-STATUS profile failure message to the CMTS, the CMTS response is to send data on a lower profile to the CM. If the RxMER increases over the configured threshold, then the CM will send a recovery CM-STATUS message to the CMTS, informing the CMTS that it can use a higher-modulation profile.
- Impaired channel operation due to loss of lock on the OFDM channel caused by high uncorrectable codeword errors on the assigned modulation profile. When loss of lock is

detected, the CM sends a loss-of-lock event message to the CMTS. The CMTS can either reprogram the OFDM channel or the profile.

- Partial channel mode occurs when, despite detecting lock loss, the OFDM channel is still partially functional for data reception, but uncorrectable codeword errors are high either in the PLC, NCP or profile A, and the CM tries to maintain use of the OFDM channel. When a CM enters partial channel mode the CMTS can either switch the CM to another profile on the OFDM channel or stop sending data on the reported profile.

HFC networks have different cascade depths that vary from node to node, as does the number of passives and type of passives that have been deployed throughout the years. Consequently the cumulative frequency response across different HFC plants will also vary. This is why it is important for MSOs to implement tools that help characterize and adjust to their network's performance. This ensures that subscriber quality of experience (QoE) is not impacted due to high volume packet loss and loss-of-lock events while operating an OFDM channel in the roll-off region. In addition, it is important to implement profiles with different modulation orders that account for the frequency response of the HFC plant to avoid significant network capacity reduction and/or intermittent connectivity issues caused by profile flapping. Further it will benefit MSOs to leverage extra network capacity by assigning a set of profiles based on the RxMER levels reported by different groups of CMs across different areas of the HFC spectrum.

Additional variables cable operators should consider when deploying and operating DOCSIS 3.1 (OFDM) channels in an HFC network with roll-off, due to the non-flat frequency response of 1.0 GHz passives in the 1.0 to 1.2 GHz range, are the configuration settings of the OFDM channel. A clear understanding of DOCSIS 3.1 configuration parameters is crucial to leverage stable CM operation of OFDM channels in the roll-off region. Parameters such as location of the OFDM channel, location of the PLC and NCP subcarriers within the channel and CM-STATUS messaging frequency can all affect the overall efficiency of the OFDM channel [PMA-D3.1-CL]. This impact will be discussed in more detail in the following sections.

3.1. Baseline testing: characterizing roll-off and MER impact using flat profiles

A first round of baseline measurements was taken using a DOCSIS 3.1 field meter. A 192-MHz OFDM channel was configured using default OFDM settings as shown in Table 1. No attempt was made to optimize these setting as the primary objective was to identify the impact on RxMER due to the non-flat frequency response above 1.0 GHz when mixing 1.0 GHz passives and 1.2 GHz actives across the HFC network.

The first round of testing was performed using the default OFDM settings as shown in Table 1. These parameters were re-configured as shown later in Table 3 to optimize CM operation in the roll-off region pre-PMA implementation. The latter approach is discussed in more detail in section 4.

Table 1. Initial OFDM settings

OFDM SETTINGS	PARAMETER
OFDM Channel	996-1188 MHz
PLC location	1004 MHz
Primary capable	No
Pilot-scale-factor	48
NCP Profile	16-QAM Flat
Max-event-hold-off	20 minutes

As mentioned in [OFDM RxMER], RxMER plots per sub-carrier are a valuable tool to characterize impairments such as roll-off. CMs will report via SNMP MIBS different RxMER values based on tap location and RF spectrum conditions across the network. Therefore an imperative first step in our process was to measure and record RxMER values using a typical DOCSIS 3.1 field meter. Not only did these measurements, collected manually, help quantify and map the impact of plant roll-off across a full 192-MHz channel spectrum and at various points in the cascade, but they could also be used to validate the accuracy of CM reported RxMER values.

For the initial measurements, the test bed was configured as follows:

1. Channel loading: 4 SC-QAMs below 1.0 GHz and a 192 MHz OFDM starting at 1.0 GHz;
2. OFDM settings were as described in Table 1;
3. Four flat profiles were configured, each supporting a single modulation order for all subcarriers across the entire OFDM channel.

RxMER values at different tap locations through the HFC network were recorded to identify RF signal degradation from 1.0 to 1.2 GHz due to the non-flat frequency response of the 1.0 GHz passives. As expected, the overall result is increasingly degraded CM performance (RxMER) as the number of cascaded actives and passives increases. In practical terms, this means that while CMs closer to the node can support 4096-QAM modulation across all sub-carriers within the OFDM block, CMs that are progressively farther away can only support 4096-QAM order of modulation over an increasingly reduced set of sub-carriers within the same block.

Recorded RxMER values at increasingly deeper locations within the cascade can be grouped by frequency blocks of varying widths across the entire 192 MHz OFDM channel. Each colored block then represents the maximum reported RxMER value within that frequency block that can be maintained by the CMs at a given tap location. The colored frequency blocks for the last tap in the cascade would illustrate the maximum RxMER values that could be maintained by the farthest end-of-line CMs connected to that last tap.

As seen in Figure 5, the RxMER values reported by four different CMs across a 192 MHz channel at the third 1.0 GHz passive (Tap ID 14) in cascade is within tenths of a dB and it is enough to support 4096-QAM operation across the full OFDM channel.

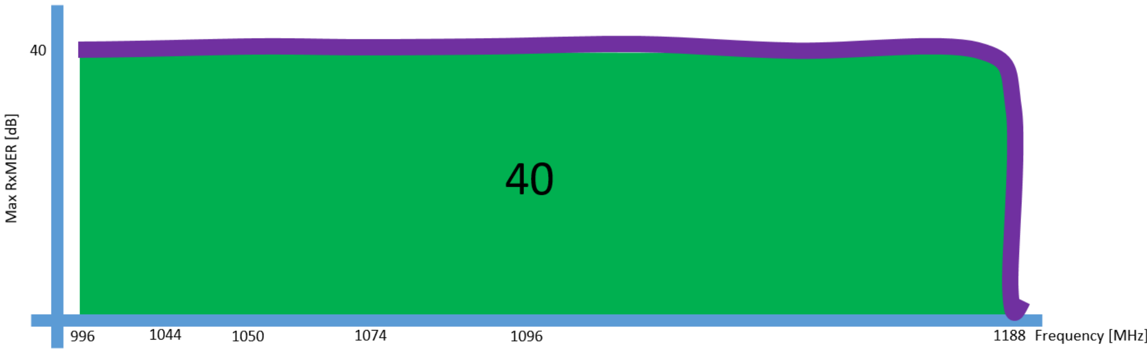

Figure 5. Reported CM RxMER levels across a 192 MHz OFDM after three 1.0 GHz passives

As seen in Figure 6, when the amount of 1.0 GHz passives in cascade is at seven, the roll-off region starts to affect a minor portion of the upper frequency edge of the 192 MHz OFDM channel. It was observed that CMs started to experience a few correctable codeword errors due to the lower RxMER values in the last 48 MHz of the OFDM channel, but the RxMER degradation of the affected sub-carries did not have a meaningful impact on overall performance. RxMER was enough to support the highest modulation profile (4096-QAM).

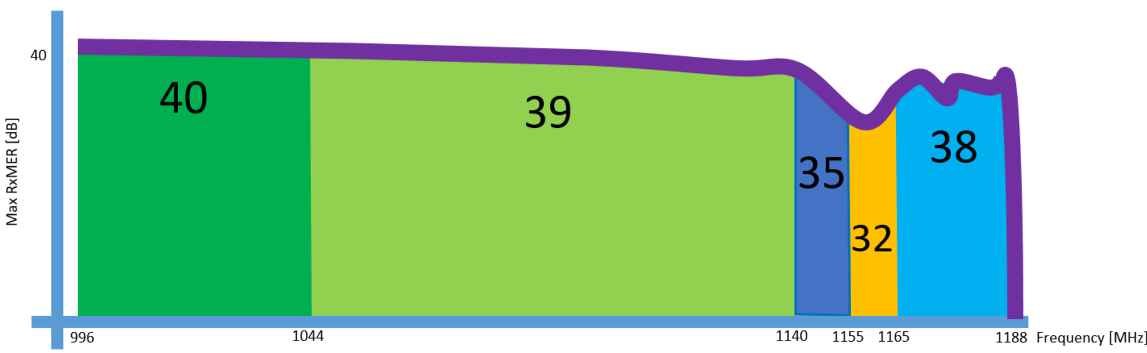

Figure 6. Reported CM RxMER levels across a 192 MHz OFDM after seven 1.0 GHz passives

Referring to Figure 7, as the 192 MHz OFDM carrier travels even deeper into the cascade and the number of 1.0 GHz passives increased to 11 (Tap ID 22), the first 48 MHz block within the OFDM channel remains capable of supporting a MER of 40 dB for all sub-carriers within that block. As the roll-off starts to affect a higher percentage of sub-carriers in the OFDM channel RxMER progressively drops to 38 dB for the next 76 MHz block, to 36 dB for the next 20 MHz block, to 30 dB and to 26 dB for the next two 10 MHz blocks respectively. Ultimately RxMER for the sub-carriers of the last 28 MHz portion of the 192 MHz OFDM channel sank to 18 dB. At this 11th tap, CMs were not able to bond to the OFDM channel and stopped receiving data on the lowest modulation profile due to the amount of uncorrectable codeword errors.

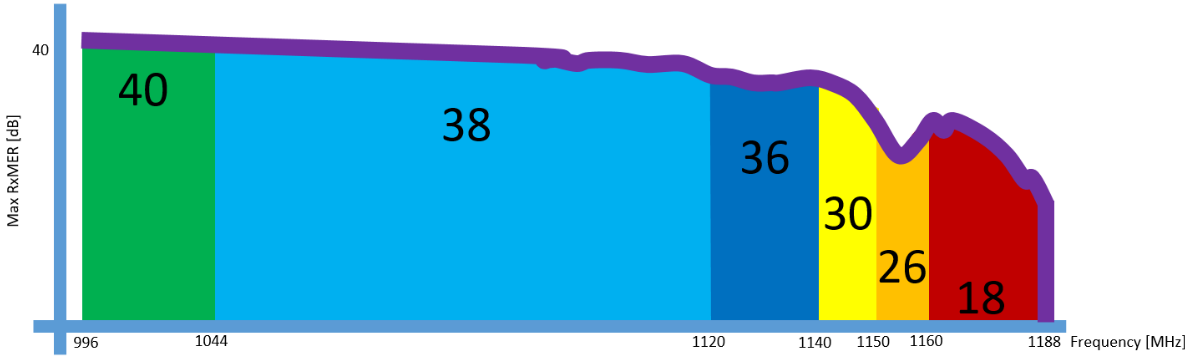

Figure 7. Reported CM RxMER levels across a 192 MHz OFDM after 11 1.0 GHz passives

At 13, 1.0 GHz passives (Tap ID 25) as visually illustrated in Figure 8, the first 48 MHz block within the OFDM channel remain capable of supporting an MER of 40 dB for all sub-carriers within that block, which should enable modulation orders of up to 4096-QAM . The second 26 MHz block was not significantly affected by the roll-off and can support an MER of 38 dB. However, as a higher number of sub-carriers are affected by the roll-off the MER values started to progressively drop to 32 dB and 30 dB for the third and fourth 40 MHz blocks. Eventually the fifth 10 MHz block can only support an MER of 20 dB and the last 28 MHz block of the OFDM channel can only support an MER of 13 dB across the entire network. As a result, none of the CMs were able to bond to the OFDM channel.

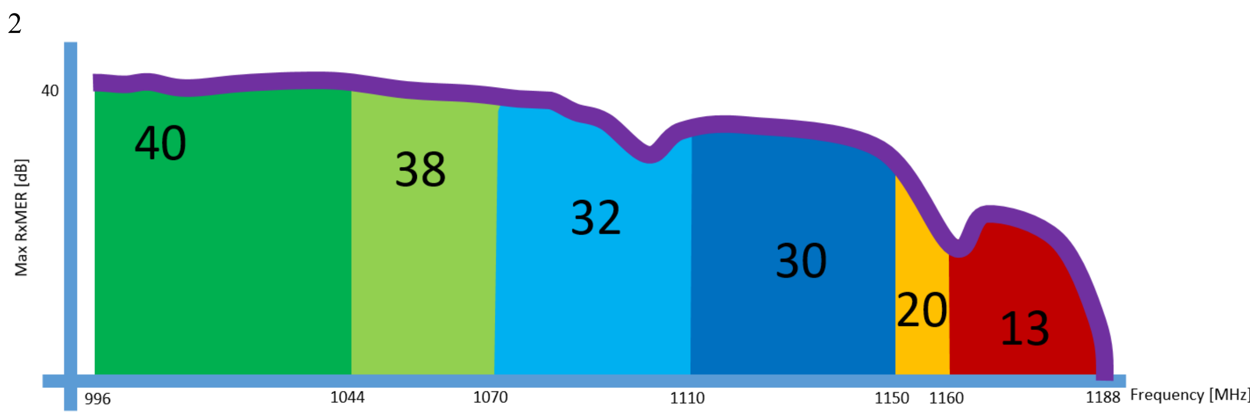

Figure 8. Reported CM RxMER levels across a 192 MHz OFDM after 13 1.0 GHz passives

At 20, 1.0 GHz passives in cascade at the EOL tap (Tap ID 32), Figure 9 shows only the first 24 MHz block still able to support a MER of 39 dB, but the severity of the roll-off significantly reduced the usable bandwidth of the OFDM channel. As a result the MER values decreased at a higher rate, reducing to 37 dB for the next 24 MHz then to 33 dB and 27 dB for the next 6 and 10 MHz blocks respectively. After MER values sank rapidly to 17 dB for the next 10 MHz block. Ultimately the MER for the last 118 MHz started to drop below 10 dB.

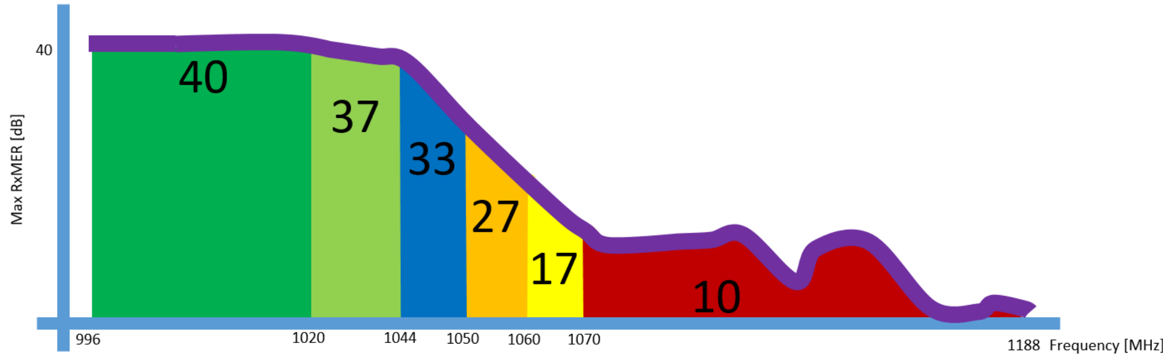

Figure 9. RxMER values across a 192 MHz OFDM after 20 1.0 GHz passives

This distribution of MER values across frequency blocks within a 192 MHz OFDM channel across different tap locations begins to uncover the value of a PMA approach. Without PMA, only flat modulation profiles are possible across the RF spectrum. Referencing Figure 5 through Figure 9, a flat modulation profile based on 4096-QAM operation that leverages the MER value distribution of Figure 5 can only be used by those few CMs closer to the node (Tap labeled 14). Likewise at seven passives in cascade (Tap labeled 18), 4096-QAM could be supported even though some sub-carriers started to be affected by the roll-off as shown on Figure 6. However CMs at the farthest end of line and reporting a distribution of MER values similar to that shown in Figure 9 reported a maximum RxMER that is considerably below the threshold for 4096-QAM. These CMs failed to operate with a flat 4096-QAM profile even though the subcarriers in the first 48 MHz block within the OFDM channel would support it.

3.2. Understanding CM operation in the roll-off

There are different ways for a CMTS to check the CM performance on a downstream OFDM channel. In the case of this paper, the CMTS sends an OFDM Downstream Profile Test Request (OPT-REQ). The OPT-REQ is used to test the CM ability to receive the specified OFDM profile and query the CM RxMER statistics. The CMTS uses the data from the OFDM Downstream Profile Test Response (OPT-RSP) to decide which OFDM profile is better for the CM at the time of collection. After this, the CM can still fail any available OFDM profile for other reasons such as the ones mentioned on [MULPIv3.1].

3.2.1. Results for CM performance when the OFDM channel width is varied

The objective of this test was to determine the tap location and RxMER threshold at which CM would start downgrading OFDM profiles. In addition, a throughput test was performed at the selected tap locations to quantify the additional throughput obtained above 1.0 GHz when using OFDM channels of varying width. All CMs were monitored as the roll-off severity increased across the test plant.

1. Channel loading: 4 SC-QAMs below 1.0 GHz and a 48 MHz wide OFDM starting at 1.0 GHz;
2. The same four flat profiles from the previous section were configured across the entire OFDM channel;
3. Tap location, profile, and the value of RxMER were recorded;
4. Throughput measurements were taken;
5. The OFDM bandwidth was increased in 6 MHz steps from 48 MHz to 192 MHz, and steps 3 & 4 were repeated.

As the OFDM bandwidth increased, CMs at tap locations further from the node were not able to achieve stable operation on the reported profile when the reported RxMER was between the threshold values showed in Table 2.

Table 2. Configured Flat MER Profile Thresholds

MODULATION RATE (QAM)	FLAT MER [dB] PROFILE THRESHOLDS
64	20.5
128	23.5
256	31
512	29.5
1024	33
2048	36
4096	38

For instance, when the RxMER was slightly below or above a configured RxMER threshold value (Table 2), as the upper end of the OFDM channel increased to about 1145 MHz, at 11 1.0 GHz passives in cascade (tap 22), all four CMs locked to the OFDM channel but CMs started to experience uncorrectable codeword errors. When CMs experienced enough codeword errors, the CMs sent a CM-STATUS message to the CMTS to communicate a profile failure on profile 2048-QAM due to the amount of uncorrectable codeword errors in the profile. The CM was reporting an RxMER slightly below 36 dB, which is the configured threshold for profile 2048-QAM. It was observed that CMs took a long time to drop to the next profile. After analyzing the CM's debug log it was found that the CM-STATUS message was not sent in a timely manner. The CMTS default setting for the max-event-hold-off was set to twenty minutes. See Table 1. This parameter was lowered to five minutes to allow the CMs with a marginal RxMER to switch to a lower profile faster.

Similarly, for the four CMs located farther from the node 13 passives into the cascade (tap 25), as the OFDM bandwidth increased beyond 1110 MHz some CMs reported RxMER below the 1024-QAM threshold. Other CMs were able to operate on 1024-QAM with some correctable errors, but when the upper end of the OFDM channel was increased up to 1150 MHz CMs were not able to bond to the OFDM channel due to the amount of uncorrectable codeword errors reported on the 1024-QAM profile. When the OFDM bandwidth was increased in 6 MHz steps between 1110 to 1150 MHz, CMs began to experience profile flapping between profiles 2048-QAM and 1024-QAM.

At 20, 1.0 GHz passives in cascade (tap 32) the cumulative effect of the 1.0 GHz passives worsened, and with a 48 MHz-wide OFDM channel some CMs started to experience uncorrectable codeword errors. These CMs notified the CMTS of a profile failure on 4096-QAM due to the RxMER being below the 38 dB MER configured threshold. This behavior was not as expected because we predicted that CMs connected at 20 1.0 GHz passives in cascade would work with a 48 MHz OFDM channel on the highest modulation profile as shown in Figure 9. In addition, when the OFDM channel width was increased beyond 66 MHz, all CMs went into partial channel mode or partial service mode due to high FEC errors in the used profile (1024-QAM) but continued trying to use the OFDM channel. These CMs sent a CM-STATUS message to inform the CMTS of a loss-of-lock event. Some CMs were able to fall back to the lowest modulation profile 256-QAM, but due to the amount of uncorrectable errors were not able to lock to the OFDM channel.

During this test, the main observation was that only CMs closer to the node (less or equal than seven passives deep, tap 18) were able to operate using a full 192 MHz OFDM channel, and did not experience uncorrectable codeword errors because the severity of the roll-off was not affecting as many sub-carriers in the OFDM channel. As shown in Figure 10, all four CMs connected to the third and the seventh 1.0 GHz passive (tap 14 and tap 18 in Figure 1) reported a similar RxMER of approximately 40 dB. The CMTS sent traffic on the highest modulation profile and the overall throughput was not impacted. Due to the CM operational issues just described, CM RxMER data was not measured at 11, 13 and 20 passives in cascade.

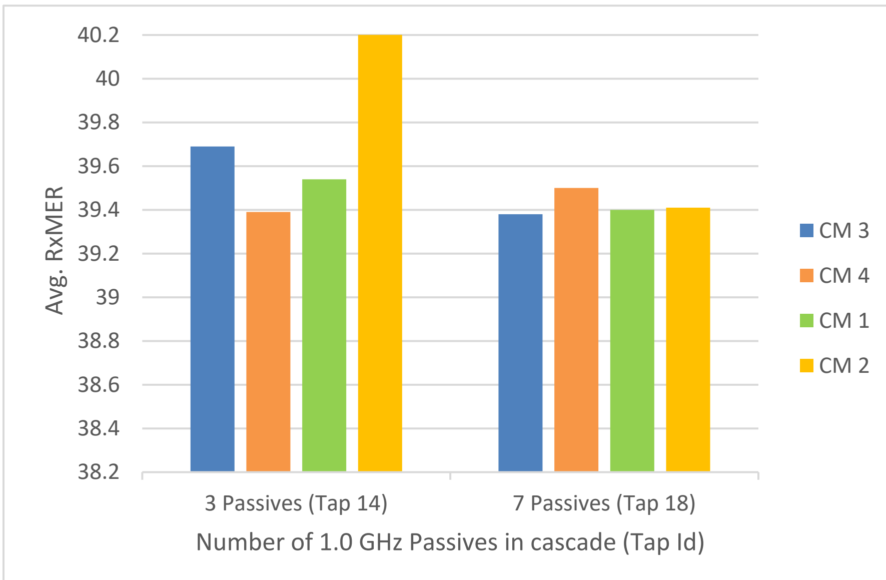

Figure 10. D3.1 Avg. RxMER values per CM at three & seven 1.0 GHz passives for a 192 MHz OFDM channel

4. Optimizing OFDM Performance for Roll-off Operation

It can be seen from section 3 that it is crucial to revise certain OFDM configuration parameters before PMA implementation in the roll-off region to ensure stable operation. The OFDM settings mentioned previously in Table 1 were optimized in Table 3. Optimized settings can help minimize Partial Channel Mode, impaired OFDM channel, and profile flapping events similar to those reported in this paper. Optimization will also help ensure that a CM is assigned the most appropriate modulation profile for specific plant conditions such as severe roll-off.

Table 3. Optimized OFDM Settings

OFDM Setting	Optimized Parameter
OFDM Channel	996-1188 MHz
PLC Location	1004 MHz
Pilot-scale-factor	120
NCP Profile	16-QAM from 996 to 1100 MHz and 0 QAM from 1100 MHz to 1188 MHz.
Max-event-hold-off	5 minutes

After analyzing the flat OFDM profile configuration and CM behavior it was determined that NCP-profile should be dynamically adjusted based on the roll-off characteristics of the plant. Also the pilot scale factor was set to the highest value (120). As described in [PMA-D3.1-CL] the CMTS defines modulated sub-carriers with a particular modulation pattern as pilots in the downstream. All the CMs in the system know this to allow interoperability. The pilot scale factor increases the amount of continuous pilots that occur at fixed frequencies in every symbol, as shown in the following formula:

$$Number\ of\ Continuous\ Pilots = \min\left[\max\left(8, ceil\left(M * \left(\frac{F_{max} - F_{min}}{192^6}\right)\right)\right), 120\right]$$

The value of M is the pilot scale factor in the equation and can be adjusted at the CMTS between ($120 \geq M \geq 48$). The pilot factor was adjusted from $M = 48$, which results on a total of 56 pilots (48 + 8 PLC pilots) for a 192 MHz channel to $M = 120$, which equals to 128 pilots (120 + 8 PLC pilots) for 192 MHz to improve OFDM downstream channel estimation.

4.1. Pre-PMA implementation baseline

The objective of this test was to establish a new baseline after adjusting OFDM settings to ensure the maximum amount of CMs were able to use the OFDM channel in the roll-off region across the entire HFC network pre-PMA implementation:

1. Channel loading: 4 SC-QAMs below 1.0 GHz and a 192 MHz OFDM at 1.0 GHz;
2. The following 4 profiles were configured across a 192 MHz OFDM channel:
    a. Profile 0: 256-QAM from 996 MHz to 1050 MHz and 0 bit loading from 1050 MHz to 1188 MHz
    b. Profile 1: 256-QAM flat
    c. Profile 2: 1024-QAM flat
    d. Profile 3: 4096-QAM flat
3. OFDM was configured as described in Table 3;
4. RxMER at different tap locations throughout the HFC network was recorded to identify RF signal degradation from 1.0 to 1.2 GHz due to the non-flat frequency response of the 1.0 GHz passives.

As seen in Figure 11, after adjusting OFDM settings to the values in Table 3, CMs were able to operate in the roll-off region with a 192 MHz OFDM beyond tap 18 (seven 1.0 GHz passives in cascade). Consequently, all CMs located at 11 (tap 22) and 13 (tap 25) passives in cascade were able to bond to the OFDM channel after initialization based on the configured CMTS MER thresholds in Table 2. At the end of line (EOL) tap 32 only CM 3 was able to bond to the OFDM channel. CM 1, CM 2 and CM 4 were not able to bond to the OFDM.

Figure 11 quantifies the positive impact the changes made in the OFDM settings had in CM operation throughout the network. Most CMs were able to successfully bond to a 192 MHz channel after the changes, and only two CMs did not report RxMER at the EOL tap. The root cause for the failure to bond for these two CMs is still under investigation.

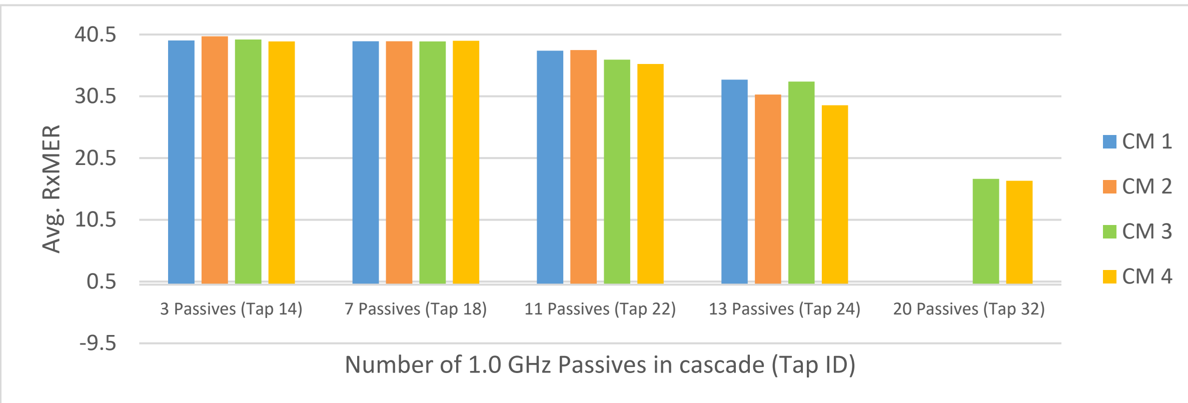

Figure 11.D3.1 Avg. RxMER values per CM at 3,7,11,13 & 20 passives for 192 MHz OFDM channel

At three (tap 14) 1.0 GHz passives in cascade, the average (mean of all supported sub-carriers) RxMER value of CM 1, represented in blue in Figure 11, was obtained from the expanded RxMER plot per sub-carrier shown in Figure 12. Correspondingly, the RxMER of CM 3 located at 20 (tap 32) 1.0 GHz passives, represented in green in Figure 11, was calculated from the RxMER plot per sub-carrier illustrated in Figure 13.

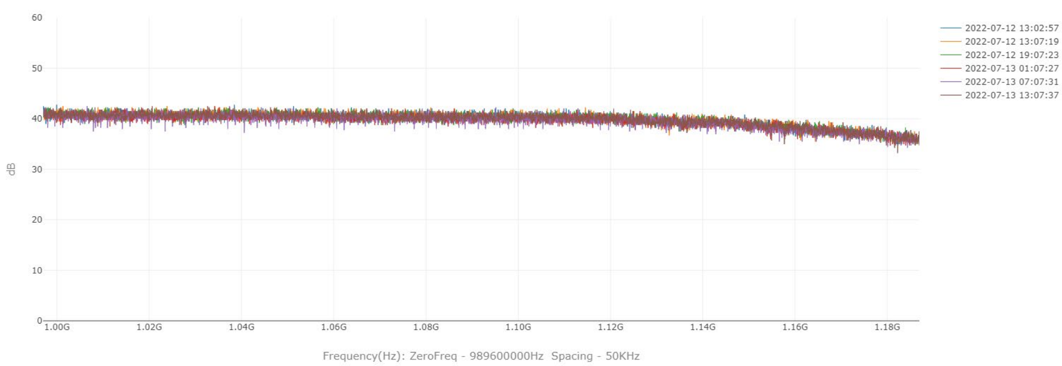

Figure 12. RxMER per sub-carrier for CM 1 located at three 1.0 GHz passives

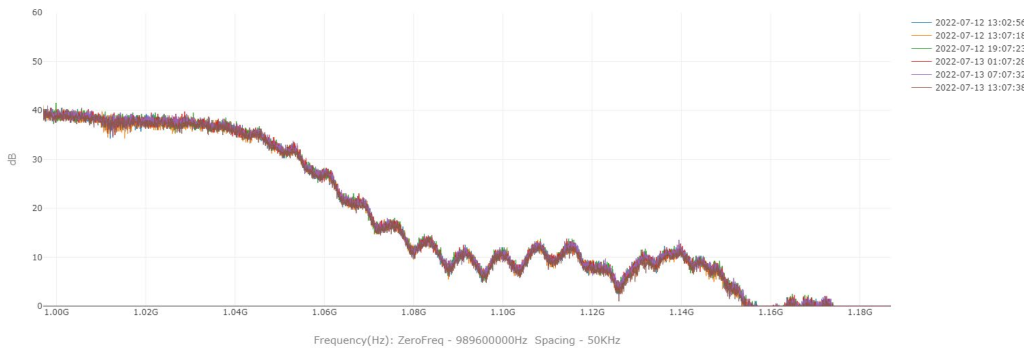

Figure 13. RxMER per sub-carrier for CM 3 located at 20 1.0 GHz passives

At three (tap 14) and seven (tap 18) 1.0 GHz passives in cascade all CMs reported an average RxMER close to 40 dB allowing the CMs to use all profiles and operate with the highest profile and the highest modulation order (4096-QAM) as shown in Figure 14 and Figure 15.

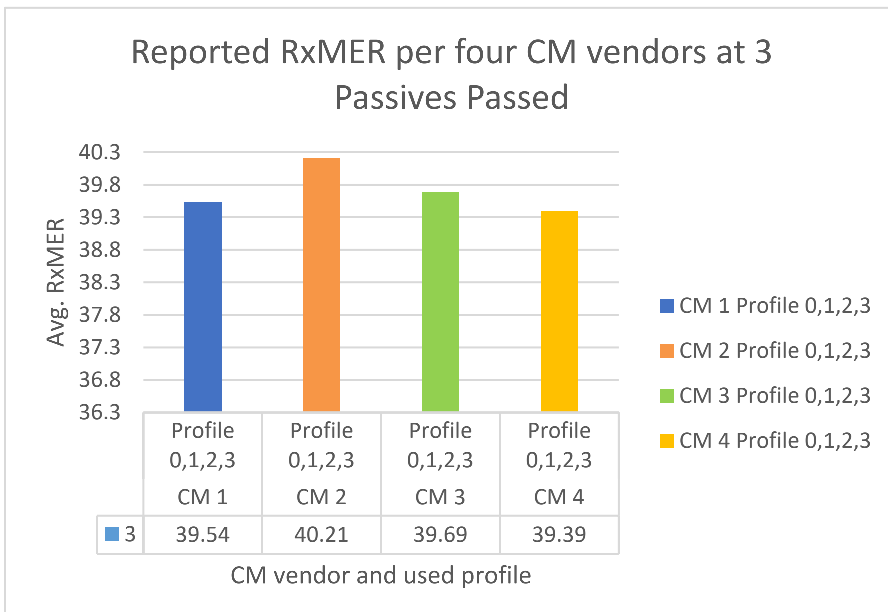

Figure 14. Reported RxMER per four CM vendors and used profiles after three 1.0 GHz passives

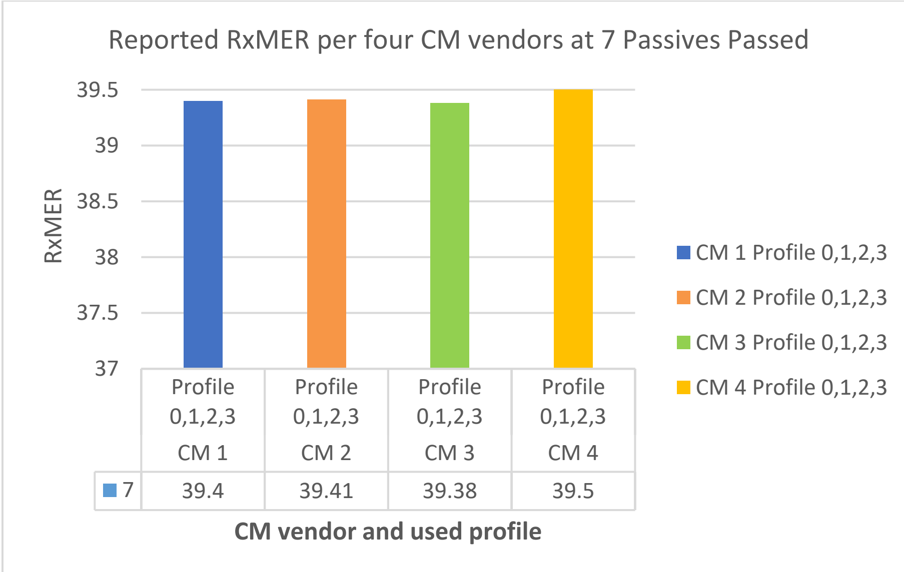

Figure 15. Reported RxMER per four CM vendors and used profiles after seven 1.0 GHz passives

After configuring 0 bit loading on the NCP-profile in the severe roll-off region, the ability of CMs to bond to the OFDM channel was greatly improved. For the Pre-PMA baseline, as seen in Figure 16 all CMs located at 11 (tap 22) 1.0 GHz passives were able to bond to the OFDM. An interesting observation during this test was that different D3.1 CMs reported slightly different RxMER values. CM 3 and CM 4 stopped receiving data on the highest profile three due to uncorrectable codeword errors. The CMTS responded to the CM-STATUS message by downgrading the profile to a lower profile in this case profile 2.

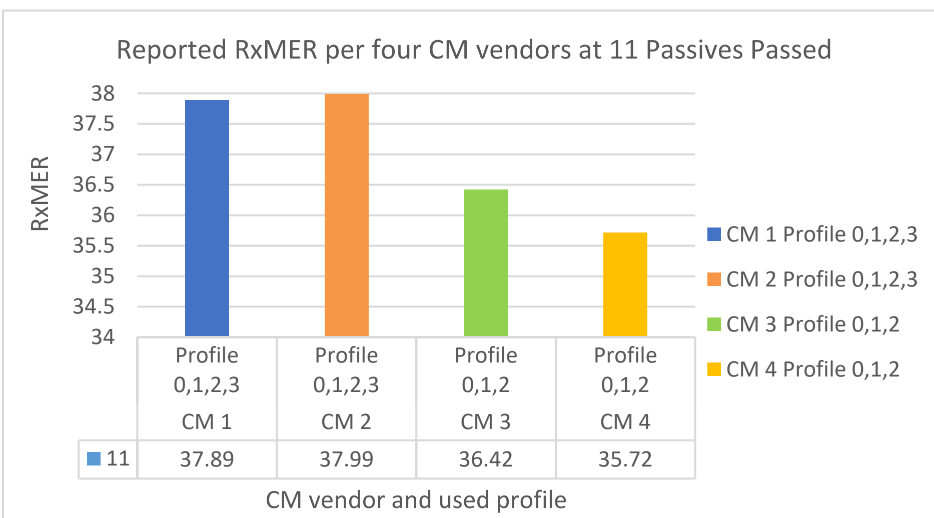

Figure 16. Reported RxMER per four CM vendors and used profiles at 11 1.0 GHz passives

Even though the cumulative effect of the non-flat frequency response of the 1.0 GHz passives was worse at 13 1.0 GHz passives, all CMs still bonded to the OFDM channel. However, higher differences in the reported RxMER values from all four CMs were observed. CM 1 and CM 3 were able to receive data on profile one, but CM 2 and CM 4 were able to only use profile zero due to the amount of uncorrectable errors on profile 1. See Figure 17. The differences in reported RxMER values among CM manufacturers have not yet been explained at the time of this writing. Further testing needs to be performed to research possible causes.

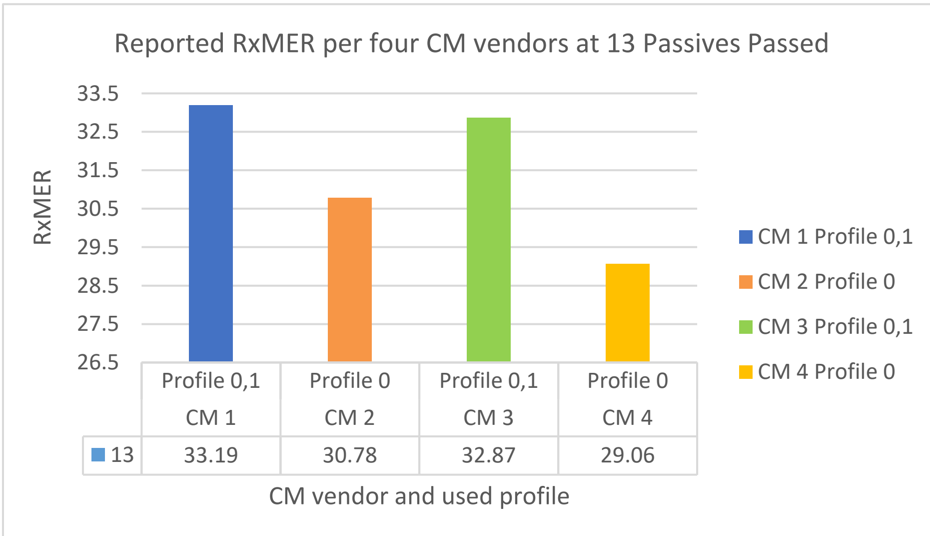

Figure 17. Reported RxMER per four CM vendors and used profiles at 13 1.0 GHz passives

As the non-flat frequency response of the 1.0 GHz passives accumulated the severity of the roll-off worsened. As a result CM 1, CM 2 and CM 4 located at tap 32, after 20 1.0 GHz passives, were not able to use any of the configured profiles. See Figure 18. However CM 3 was able to receive data on profile 0, a major observation is that it appears that certain D3.1 CM manufacturers do not report RxMER values if the channel is in Partial Service/Channel Mode. This can potentially be of concern for a PMA implementation since profile generation is based on CM RxMER reported data.

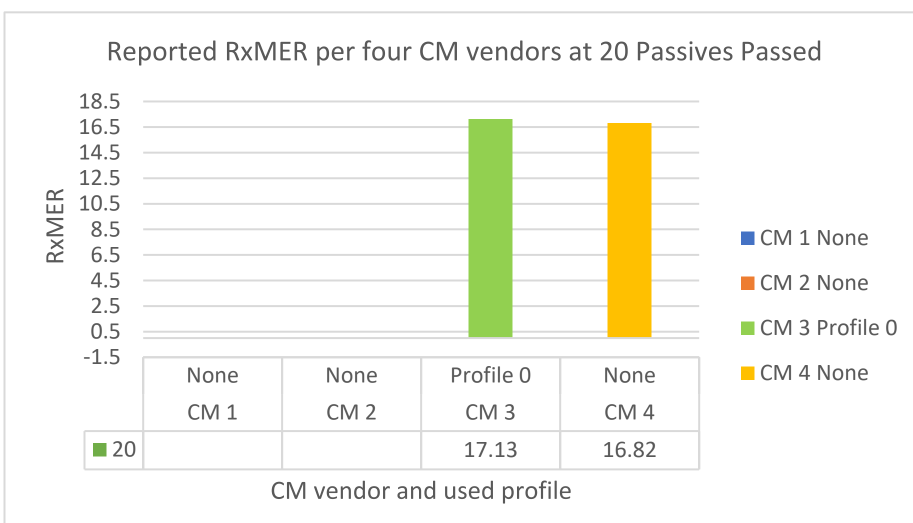

Figure 18. Reported RxMER per four CM vendors and used profile at 20 1.0 GHz passives

In summary, as shown in Figure 19, some CM manufacturers were able to achieve a maximum throughput of approximately 1.569 Gbps after up to 11 passives in cascade, while other CMs were able to achieve a maximum throughput of 1.343 Gbps at 11 passives. With optimized OFDM settings more CMs were able to operate with higher flat modulation profiles at the same tap location in the network compared to typical OFDM settings. At the cascade EOL, at 20 1.0 GHz passives in cascade only one CM was able to operate on profile 0 while the other CM were impaired on the OFDM channel.

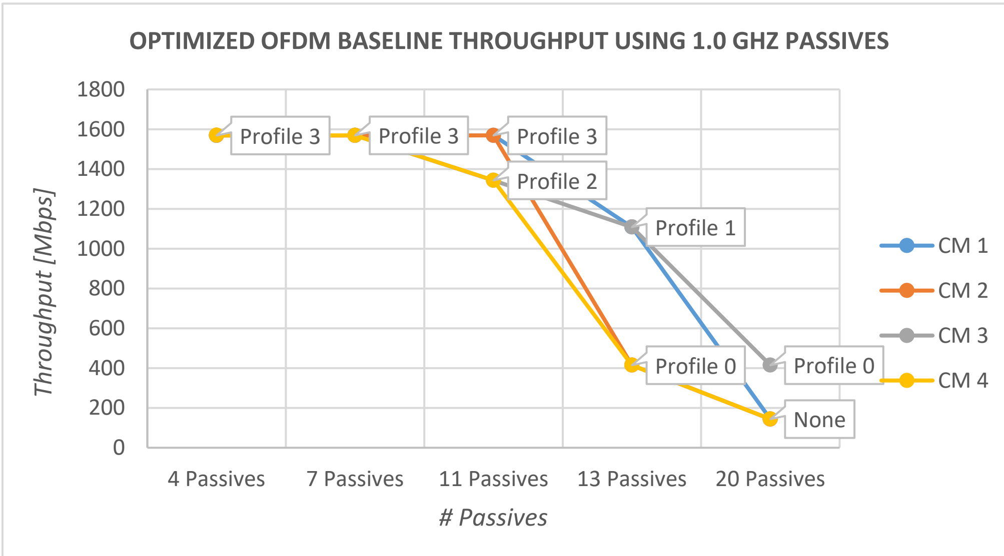

Figure 19. Typical Throughput of OFDM at 1.0 GHz for Full Coverage of All Taps

5. PMA vs No-PMA

PMA alone does not allow operation in the roll-off region, particularly for CMs further away from the node that are severely affected by the cascading effect of the non-flat response of the 1.0 GHz passives. We must use a combination of optimized OFDM settings to get as many CMs online as possible before PMA is implemented.

CM performance testing has proven that CMs can operate modulation orders with MER thresholds below the specified D3.1 MER thresholds [MULPIv3.1]. Hence the thresholds used in the PMA engine to generate the variable modulation profiles were lowered and were less conservative compared to the MER thresholds used during the baseline testing described in section 3.2. As a result, more CMs were able to operate in higher order modulations at the selected tap locations. The lowered MER thresholds are listed in Table 4.

Table 4. PMA engine MER profile thresholds

MODULATION RATE (QAM)	PMA MER [dB] THRESHOLDS
64	19
128	22
256	25
512	28
1024	31
2048	34
4096	37

Figure 20 illustraes the four modulation profiles used during the Pre-PMA baseline testing performed in section 4.1. Profile 0 is deliberately non-flat because, as seen in Figure 9, the severity of the roll-off is such that 256-QAM can only be supported up to 1050 MHz. Since profile 0 must be usable by all CMs, zero-bit loading was configured for the rest of the subcarriers in the OFDM channnel.

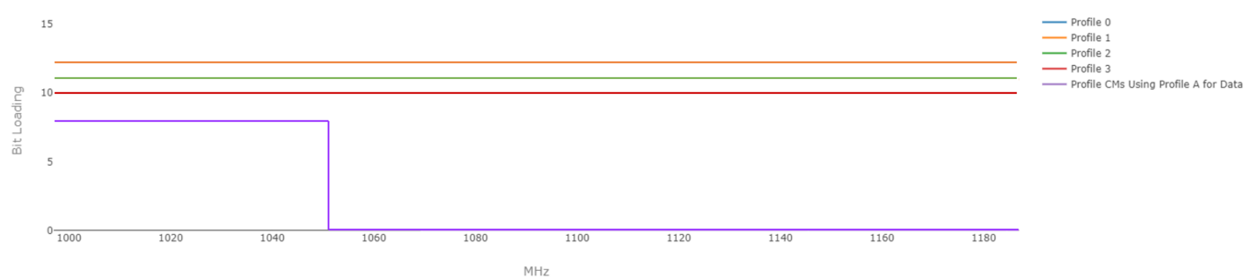

Figure 20. Pre-PMA Baseline 4 profiles

Figure 21 shows the four variable modulation profiles generated using the modified CableLabs PMA tool based on the reported RxMER data from 18 out of 20 CMs connected to the five tap locations mentioned previously in Figure 1. The MER thresholds used to generate the four variable modulation profiles in Figure 21 are listed in Table 4. These profiles were converted to CMTS commands and applied to the CMTS.

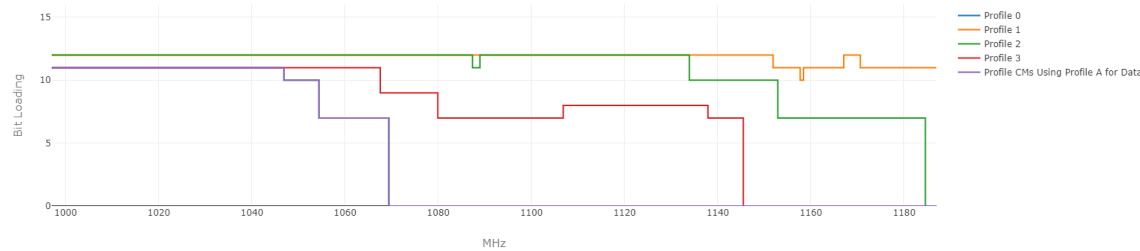

Figure 21. CableLabs PMA tool – Four variable modulation profiles

PMA allowed us to create custom-made profiles consisting of segments of different modulation orders based on plant conditions over the frequency range of the OFDM channel. In the case of impairments such as roll-off, the profiles are adjusted to follow the non-flat frequency response of the 1.0 GHz devices. As a result most CMs were able to bond to a 192 MHz OFDM channel.

Figure 22 contrasts the difference in overall throughput by applying four flat modulation profiles (Figure 20) vs. the four variable modulation profiles obtained from the PMA tool (Figure 21). By using the four variable modulation profiles generated by the modified CableLabs PMA engine, some CMs were able to operate at higher speeds across the network than when using flat profiles. For instance, as shown in Figure 22, at 11 passives there was a 4% increase in average throughput across four CMs. At 20 1.0 GHz passives, there was a 35% increase in average throughput.

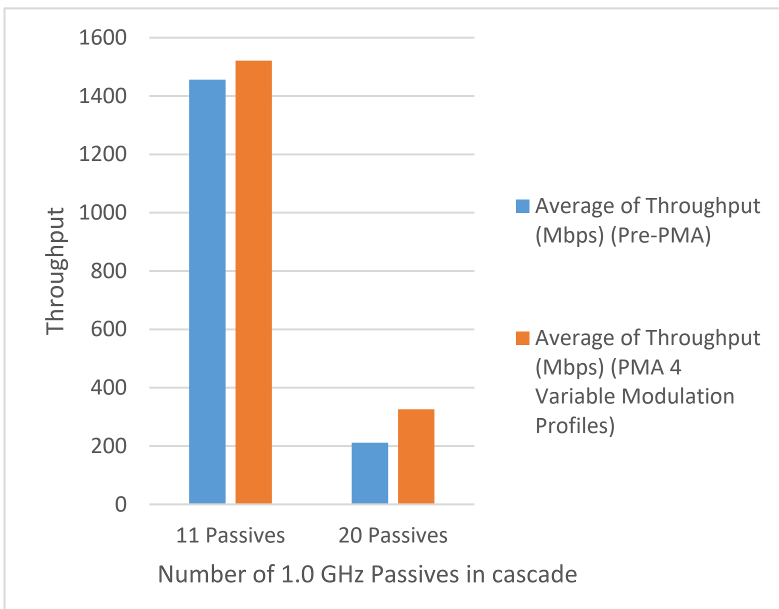

Figure 22. Baseline vs PMA overall throughput

There is a close correlation between the mean RxMER reported by the five four-CM groups at five tap locations across the HFC network and the results previously presented in sections 3 and 4. As the cumulative effect of the non-flat frequency of the 1.0 GHz passives worsens, an increasing number of sub-carriers in the OFDM channel are affected and mean RxMER decreases creating five distinct clusters that correspond to the five selected tap locations in the HFC network as shown in Figure 23. The RxMER data reported by the four CMs located at tap 14 (three 1.0 GHz passives), circled in yellow, resembles the mean RxMER values of Figure 14. Similarly, the average RxMER values circled in lilac, correspond to the average RxMER values reported by the four CMs located at tap 32 (20 1.0 GHz passives in cascade) and illustrated in Figure 18.

Figure 23. Median vs Standard Deviation for CM across the HFC plant

PMA is a valuable tool that generates customize profiles with different modulations (segments) based on impairments CMs experience across different HFC networks. PMA not only helps MSOs increase the reliability of their networks, but it can leverage the operation of an OFDM channel in HFC networks with severe roll-off. PMA implementation provides extra network capacity that can be used to alleviate traffic during peak hours. Further testing will be performed to continuously implement the benefits that PMA can provide.

6. Conclusions

- When operating in the roll-off region, there will be significant differences between the average reported RxMER values across the HFC network at different tap locations. As the number of 1.0 GHz passives increased, the severity of the roll-off increased, and usable modulation orders decrease due to the lower RxMER values. This was expected since the non-flat frequency response of the taps worsened as the number of passives in cascade increases.

- The amount of uncorrectable codeword errors on the OFDM channel operating in the roll-off region increased as the severity of the roll-off affected a higher number of sub-carries across the network. As a result, CMs farther from the node started experiencing loss of lock to the OFDM channel. This was alleviated by changing OFDM configuration parameters such as NCP-profile and pilot-scale-factor, allowing more modems to be online at the EOL tap. It also helped some modems to use higher modulation profiles across the network. This also reinforces the need for optimization of OFDM parameters prior to PMA deployments.

- When using flat profiles, the non-flat frequency response of legacy 1.0 GHz passives in the 1.0 to 1.2 GHz range creates challenges as a result of profile flapping and partial service for D3.1 CM operating in the roll-off. Uncorrectable codeword errors were recorded for the OFDM channel as the severity of the roll-off increased across the network.

- The severity of the frequency response (peaks and dips) will vary by tap manufacturer, and will worsen as the number of passives in a cascade increases. As a result, successful reception of an OFDM channel will be limited to a maximum cascade depth depending on deployed passive manufacturer. Since cascade depth varies from node to node, as does the number of passives and the nature of the induced roll-off, attempting to create custom OFDM modulation profiles manually can be time consuming and yield unpredictable results. A PMA approach will greatly simplify operation in the roll-off regions.

- PMA provides operators the ability to implement proactive and adaptive network operations in a network with inevitable impairments such as roll-off. The benefits include reduced trouble calls, a higher throughput, and the ability to scale and deploy incrementally. However, should an operator decide to operate OFDM in roll-off regions, the OFDM carrier should be configured/optimized first to ensure the highest possible performance prior to PMA implementation. Once optimal performance is achieved pre-PMA, higher and stable capacity gains can be obtained through the implementation of a fully automated PMA solution.

- When using PMA, CMs were ranked by RxMER quality, they naturally fell into clusters or groups that closely aligned with the tap locations selected and the severity of the experienced impairment, as shown in Figure 23. This natural clustering helps ensure that the set of profiles created by the PMA tool are optimized and targeted to the specific degree of impairment severity as seen by the CMs across the HFC network.

- Cable modems experienced the effect of the roll-off differently across the network. The impact of the roll-off region on cable modem operations was observed as a degradation of the RxMER values of the sub-carriers operating in the roll-off region. But by configuring the profiles generated by the PMA engine, the CMTS assigns customized profiles based on the type of collected RxMER per groups of cable modems, thus minimizing transmission errors on the network and maximizing the overall network capacity with up to a 35% gain at EOL tap compared to a non-PMA solution.

- The maximum throughput of approximately 1.569 Gbps over the OFDM and SC-QAM channel combination used for this testing was not achieved consistently, unless the CM is in close proximity to the node and within a limited number of passives in cascade (depends on the profile signature of the passive) and the CM manufacturer.

- Higher network capacity gains may be possible if the number of modulation profiles increases beyond four. Additional testing is planned to explore the overall network capacity gains in the near future with six and eight dynamic modulation profiles.

Abbreviations

CM	Cable Modem
Gbps	Giga bits per second
FEC	forward error correction
HS	high split
MHz	Mega-Hertz
PMA	Profile Management Application
SCTE	Society of Cable Telecommunications Engineers
RxMER	Received Modulation Error Ratio

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[OFDM RxMER] Characterizing Network Problems Using DOCSIS 3.1 OFDM RxMER Per Sub-carrier Data.

[D3.1 PMA-CC] DOCSIS 3.1 Profile Management Application

[BL-PMA] Making the Most of Your HFC Network, Bit by Bit

[Full-Scale-PMA] Full Scale Deployment of PMA

