DEVICE TESTING AND EVALUATION OF PNM TEST OPERATIONS VIA SIGNAL ANALYSIS

A Technical Paper Prepared for SCTE/ISBE by

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Introduction

DOCSIS 3.1 offers new physical layer based on Orthogonal Frequency Division Multiplexing (OFDM) technology. OFDM is also the technology foundation of LTE, Wi-Fi, and MoCA. DOCSIS 3.1 PHY specifications improve spectral efficiency and provide robust techniques to combat impairments including micro-reflections and impulse noise, and also to increase spectral efficiency in Gaussian noise via low-density parity check (LDPC) coding.

DOCSIS 3.1 improves spectrum usage by dynamically optimizing the best modulation profile and pushing the capacity closer to the Shannon limit. New analysis techniques are also possible in DOCSIS 3.1 to monitor cable modems (CM) via new performance metrics and maintenance information provided. Software Defined Networks (SDN), such as the Profile Management Application (PMA) that is currently in development by Cable Labs, utilizes such metrics and is required to determine and develop processes to customize plant-specific modulation profiles or improve HFC network health.

DOCSIS 3.1 Proactive Network Maintenance (PNM) offers a diverse set of new test features to characterize quickly and accurately, the effects of the HFC on the OFDM channels to guarantee the highest throughput and reliability of service. These features were previously only available in equipment such as spectrum, vector, and network analyzers. Given the adaptive nature of DOCSIS 3.1 coupled with unpredictable HFC network impairments, accurate measurements using these new 3.1 PNM tools are essential to creating predictive modulation profile performance models. In particular, great insight into network health can be provided simply by using the DOCSIS 3.1 PNM feature Downstream Receive Modulation Error Ratio Per Subcarrier (RxMER) to determine OFDM signal fidelity at the CM tuner frontend.

This paper address the following hypotheses:

Is a DOCSIS 3.1 CM with enhanced PNM functionality indeed a viable alternative to lab-quality test equipment?

Can cable operators use DOCSIS 3.1 CMs' to determine how close the HFC can get to the upper bound Shannon Limit individually as well as collectively sampled?

These hypotheses will be shown to be true via evaluation of the accuracy of the CM DOCSIS 3.1 OFDM decode. The necessary test setup is provided, and an in-house software tool, OpenPNM is used, which is a software application that performs PNM data analysis specifically for this paper in assessing closeness to the Shannon Capacity Limit for each sub-carrier via the RxMER mean and standard deviation.

Acknowledgement

First, I want to thank David Urban, who has mentored and guided me for the last couple of years and encouraged me in writing this paper. Without his support and assistance, the cable modem vs. signal analyzer comparative analysis would not have been possible. Thanks also to Michael Pettit, who co-developed the OpenPNM application with me, specifically the graphical and user interface.

DOCSIS 3.1 Modulation Profiles

1. Downstream Modulation Profile

1.1. Profile Selection and Transition

DOCSIS 3.1 OFDM profiles provide a broad range of modulation choices that can be used to fine-tune the CMTS transmissions to get the best performance from current network conditions. The option for multiple modulation profiles provides lower orders of modulation for those CMs with lower SNR and higher order modulations for modems with higher SNR. Roughly 3 dB additional SNR is required to support the next higher order of modulation in quadrature amplitude modulation (QAM).

In practice, since 256-QAM is the most common single carrier QAM (SC-QAM) used for both DOCSIS and linear video, creating a new profile that matches to that scheme is not necessary. At 256-QAM an SNR of 27dB using Reed-Solomon (RS) forward error correction (FEC) coding is the lower limit. With DOCSIS OFDM subcarriers using 256-QAM, it is closer to 24dB SNR. The improvement of 3 dB is due to the additional coding gain provided by LDPC coding in DOCSIS 3.1. So while an SNR of 27 dB in DOCSIS 3.0 would mean using 256 QAM, in DOCSIS 3.1 27 dB SNR means we can assign subcarriers 512-QAM modulation, which is indeed closer to the Shannon Limit for that SNR.

1.2. Modulation Profiles

DOCSIS 3.1 specifies that the CM MUST support a minimum of four modulation profiles. The profiles are called Profiles A through D for convenience. Profile-A is specified to be the most robust, meaning it should work in any network condition, i.e., when the network is at its minimum health level or alternately when the minimum MER is provided by the network conditions. In the case of using 256-QAM for Profile-A, this is a logical choice since DOCSIS 3.0 and video SC-QAM are both currently running robustly at 256-QAM in today's networks.

However in DOCSIS 3.1, the CM MUST support constellations BPSK, QPSK, 16-, 256-, 512-, 1024-, 2048-, 4096-, optionally 8192- and 16384-QAM. Moreover, while we cannot test these directly i 3.0, we can measure the SNR and map it to these modulation orders for profile specifications n DOCSIS. Capturing SC-QAM SNR over a particular serving group (SG) will thus determine the best-starting profile. Using a well-publicized example of analysis by Dave Urban that gives the probability density function (PDF) of modem SNRs across the entire Comcast network, we can determine a case for a profile selection.

It should also be noted that the PDF represents 6 million modems over the Comcast footprint, and note that nearly identical results, within 1 dB of this PDF, have been observed by other cable operators and discussed in SCTE working groups. Hence this PDF represents a valid industry benchmark for current HFC network architectures, and is expected to further improve as fiber-deep, remote-PHY and other advanced architectures are deployed. Hence this PDF curve accurately reflects a typical, well-maintained cable network for the purpose of designing DOCSIS 3.1 profiles. For this paper and limited samples with DOCSIS 3.1 we are assuming the overall distribution and the SG distribution are expected to be similar.

The following tables are estimations based on optimistic radio frequency (RF) performance and a reasonable leverage of ranges yet provides a practical demonstration on developing profiles for a given SG.

Note that the profile designation assumes all subcarriers use the same order of modulation and coding parameters.

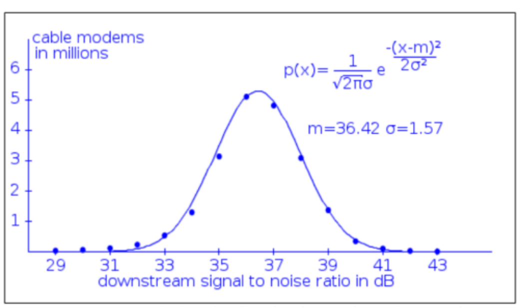


Figure 1 - Dave Urban Probability Density Function Graph

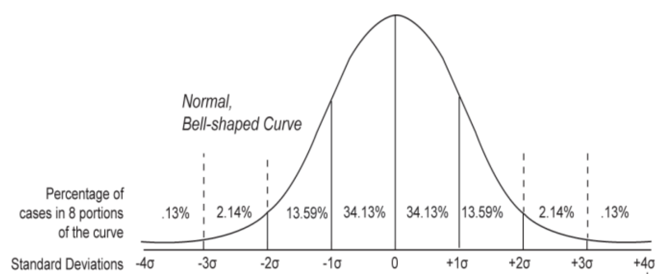


Figure 2 - Standard Deviation Gaussian Distribution Graph

M-QAM	MER_{Min} (dB) AWGN	Profile Transition Range	MER_{Range} (dB) Non-AWGN *	Profile Transition Range **
256	24.1	$25.6 \pm 1.5dB$	26 - 29	$27.5 \pm 1.5dB$
512	27.1	$28.6 \pm 1.5dB$	29 - 32	$30.5 \pm 1.5dB$
1024	30.1	$31.6 \pm 1.5dB$	32 - 35	$33.5 \pm 1.5dB$
2048	33.1	$34.6 \pm 1.5dB$	35 - 38	$36.5 \pm 1.5dB$
4096	36.1	$37.6 \pm 1.5dB$	38 - 41	$39.5 \pm 1.5dB$
8192	39.1	$40.6 \pm 1.5dB$	41 - 44	$42.5 \pm 1.5dB$
16384	42.1	$43.6 \pm 1.5dB$	44 - 47	$45.5 \pm 1.5dB$

Table 1 - AWGN vs. Non-AWGN Profile Transition

*Non-AWGN refers to non-ideal channels with impairments, higher margin for system variations, as well as fluctuations in the MER throughout the day/year from temperature/season and in particular random signal ingress of LTE interference. Examples of these non-ideal channel conditions are seen in Figure 8 through Figure 15.

***Profile Transition Range* provides a real-world estimation of the MER range supported by a particular modulation.

Sigma	Observe Population	σ Range (± 1.57 dB)	AWGN M-QAM Profile Fit**	Non-AWGN M-QAM Profile Fit***
+2σ = 39.56	~2.27%	37.99 – 41.13	4096	2048/4096
+σ = 37.99	~15.86%	36.42 – 39.56	4096	2048
m = 36.42	~49.99%	34.85 - 37.99	2048	1024
-σ = 34.85	~ 84.12%	33.28 – 34.92	2048	1024
-2σ = 33.28	~ 97.72%	31.71 – 34.85	1024	512
-3σ = 31.71	~ 99.86%	30.14 – 32.85	1024	512

Table 2 - AWGN vs. Non-AWGN Profile PDF Fit

In Table 2 each σ represent the next modulation midpoint. Since σ = 1.57 and a particular modulation has a swing of +/- 1.5dB this provides a close estimation to illustrate profile fitting.

** M-QAM selection relies on the lower bound MER sigma range

*** M-QAM selection relies on sigma

Profile Support by CM	M-QAM (AWGN)	M-QAM (Non-AWGN)
A - 512-QAM	100%	~99.86%
B - 1024-QAM	~99.86%	~84.13%
C - 2048-QAM	~84.13%	~15.86%
D - 4096-QAM	~15.86%	~2.27%

Table 3 - AWGN vs. Non-AWGN Profile Allocation per PDF

1.3. Conclusion

For a given DS serving group CM population:

- The higher the mean or average, the higher modulation can be supported.
- The smaller the overall standard deviation, the less number of profiles are needed to support a given serving group.
- The larger the overall standard deviation, suggest the need for multiple bit loading within a given profile and an increase of profiles within a serving group.

Depending on the spread and the mean, and starting with Profile-A at the highest percentage of coverage, the results do not automatically suggest that it should be at 256-QAM. Later in this paper, it is demonstrated that at a low enough RxMER @ 256-QAM, the SC-QAM signal fidelity reached a point where the RS codewords were not discernable by the Rx SC-QAM demodulators @ ~27 dB MER.

2. Modulation Profile Transition

One of the key features of DOCSIS 3.1 is the ability to customize profiles for a group of CMs with similar network impairments. An example of this would be in given SG CMs that are part of node would have similar impairments of a given MER mean given a modulation profile best suited, whereas CM's in another node would have dissimilar impairments with a lower MER mean and would be assign a given modulation profile.

Before registration, a CM only has one downstream profile, *Profile-A,* and one upstream profile available to it. After registration, the CMTS needs a way to test the physical layer performance of a given CM on a downstream so that it can determine which profiles can successfully be assigned to a given CM to maximize the channel capacity.

This part of the specification it reserves for the CMTS vendor implementation for differentiation. The CMTS sends an OFDM Downstream Profile Test Request (OPT-REQ) message for one of the following metrics, but may request other in multiple requests. The CMTS uses this method to help determine the maximum channel capacity profile:

- RxMER Statistics per Subcarrier
- RxMER per Subcarrier Threshold Comparison for Candidate Profile
- SNR Margin for Candidate Profile
- Codeword Statistics for Candidate Profile
- Codeword Threshold Comparison for Candidate Profile
- NCP Field statistics
- NCP CRC Threshold Comparison

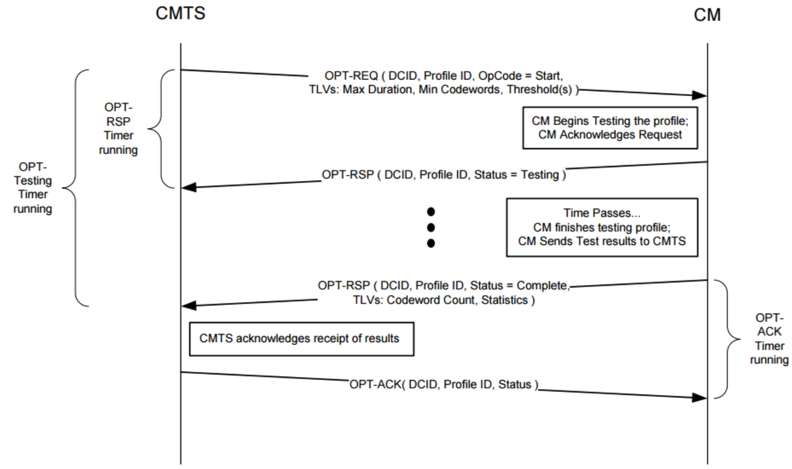


Figure 3 - Modulation Profile Transition Process [1]

3. PNM OFDM DS Receive Modulation Error Ratio (RxMER) and FEC Summary

3.1. DOCSIS 3.1 Downstream PNM Features

DOCSIS 3.1 Proactive Network Maintenance (PNM) features and capabilities in the CMTS and CM can be leveraged to enable significantly improved measurement and reporting of network conditions such that undesired impacts such as plant equipment and cable faults, interference from other systems and ingress can be detected and measured. With this information, a cable operator can make modifications necessary to improve conditions, adjust modulation profiles, and monitor network trends to detect when further network improvements are needed. The CMTS and CM contain test points which include essentially the basic functions of a spectrum analyzer (SA), vector signal analyzer (VSA), and a network analyzer (NA). The cable plant itself is considered the Device under Test (DUT) [2]. New PNM features and capabilities in DOCSIS 3.1 include:

- Symbol Capture
- Wideband Spectrum Analysis
- Noise Power Ratio (NPR) Measurement
- Channel Estimate Coefficients
- Constellation Display
- Receive Modulation Error Ratio (RxMER) Per Subcarrier
- Histogram

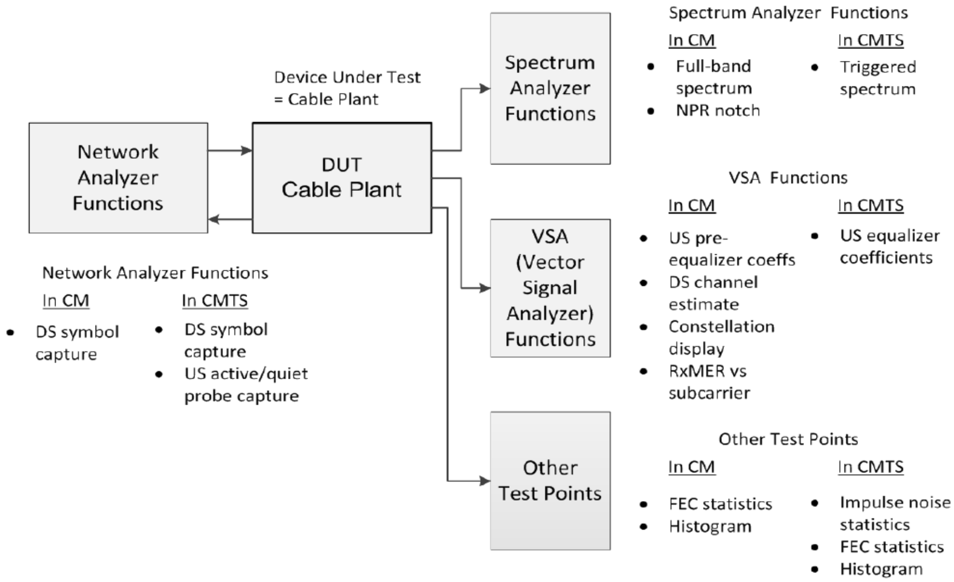


Figure 4 - PNM System Overview [2]

3.2. PNM Data Retrieval Call Flow

Below is a general interaction between the PNM server and cable modem for test set operation and the PNM file retrieval process is the same process used in the evaluation.

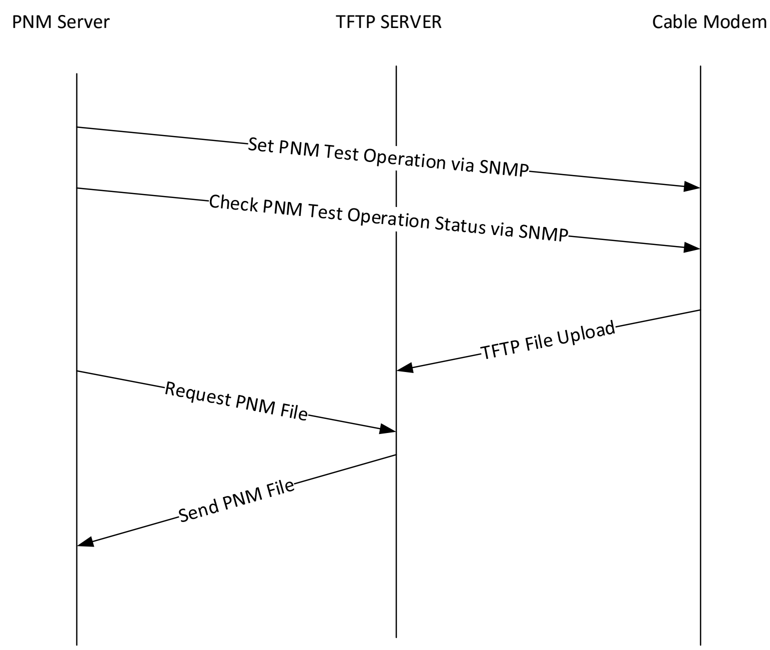


Figure 5 - PNM Server Process

3.3. RxMER Theory of Operation

DOCSIS 3.1 PNM provides measurements of the RxMER for each subcarrier, thereby allowing much more granular characterization of overall channel condition vs. frequency. The CM measures the RxMER using both continuous and scatter pilots and PLC preamble symbols, which are not as likely subject to symbol errors as data subcarriers would be. Each data subcarrier becomes a pilot every 128 symbol times. So at a minimum, it would take 128 symbol times to get all RxMER values.

The OFDM receiver's processing is similar to the SC-QAM receiver processing in many respects. At a high level, the demodulator must first estimate and remove frequency offset between the transmitting modulator and receiver's tuner. Likewise, a symbol timing clock offset must be determined and compensation made. Finally, the phase and amplitude variations of the channel impulse response must be removed through equalization. [1]

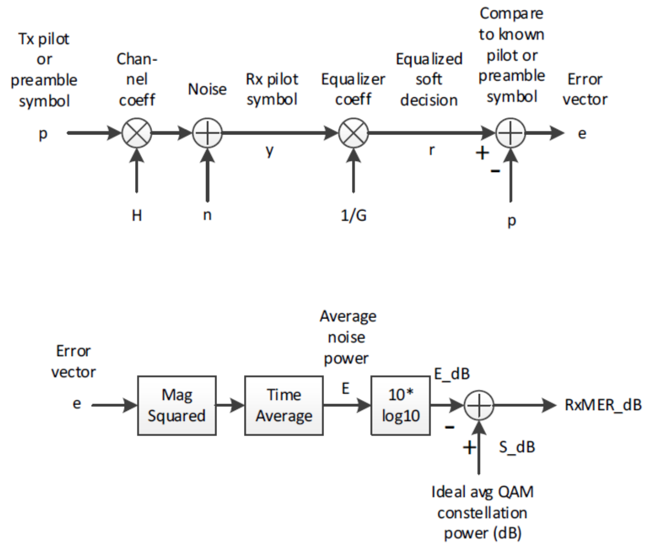


Figure 6 - RxMER DOCSIS Implementation Process [1]

The amount of error between the ideal (hard) received symbol and actual received (soft) symbol, the error vector, is sampled and averaged to compute an RMS error vector magnitude (EVM), from which the MER is determined.

The error vector in Figure 7 is the difference between the equalized pilot and PLC preamble received value (Soft Decision) and the known correct pilot value or preamble value (Hard Decision). [1]

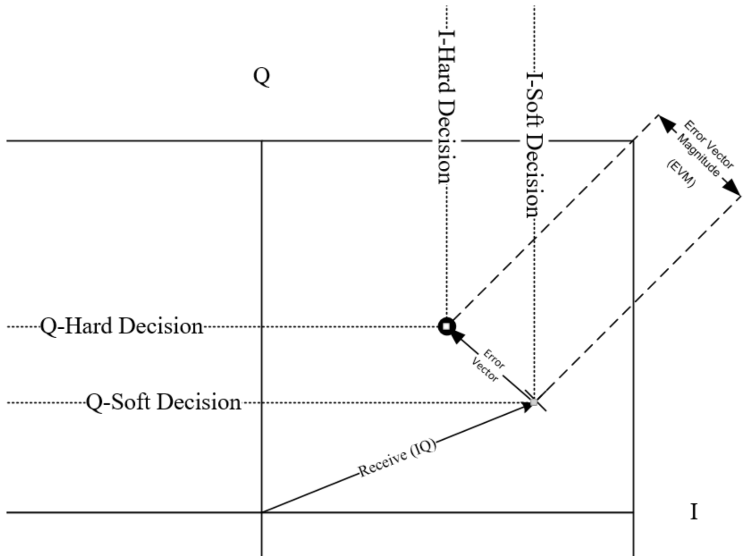


Figure 7 - Error Vector Diagram

The error vector is another transformation of the difference between the hard and soft symbol decisions. In appendix section, SNR vs. MER explains further the general determination of calculating MER without knowing the vector phase and amplitude error.

The RxMER is calculated per the as described in the DOCSIS 3.1 PHY specification [1]:

$$RxMER_{dB} = 10 * Log_{10}(EVM)$$

3.4. RxMER Analysis

MER is used as a proxy for the SNR to the extent an ideal or nearly ideal transmitter and receiver are used; this approximation is now considered generally valid, although in the past there were differences in different vendor's implementations of MER reporting. In the example used in this paper, the OpenPNM application plots the MER magnitude in dB versus subcarrier frequency in the graphical format. Variations in MER may be due to variation in the receive level or the ingress strength among the subcarriers, or a combination of both. In displaying the RxMER, the user can observe any ingress or network impairments. The following figures are captured samples from a DOCSIS 3.1 field trial conducted by Comcast.

A search criterion was used to search for CMs with a standard deviation greater than one with a skewness value less than -1 to detect sharp ingress.

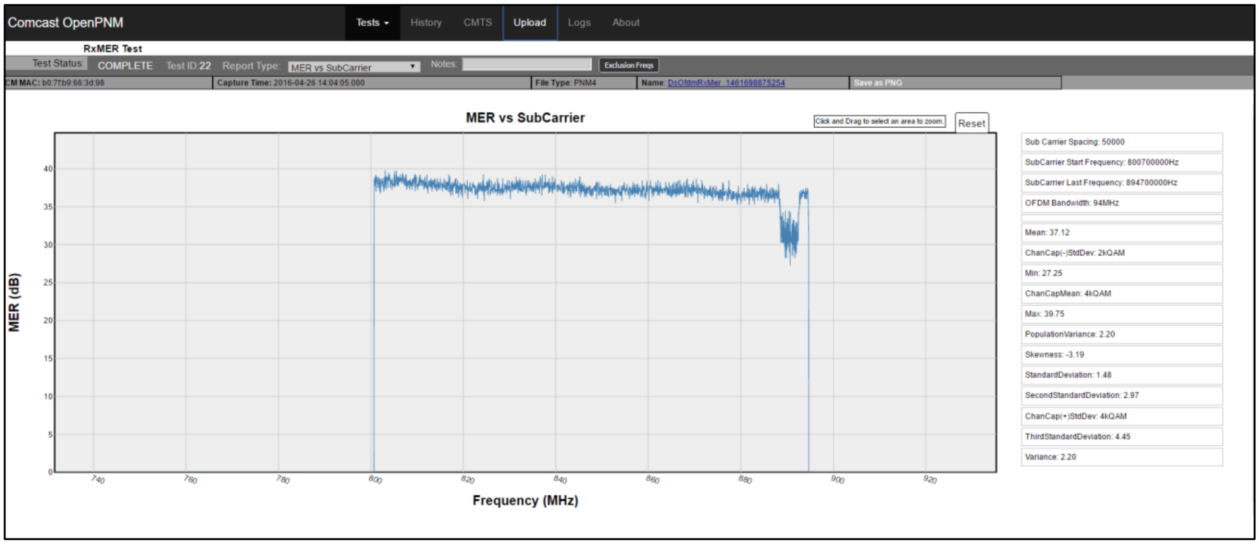


Figure 8 - RxMER Response - Signal Ingress

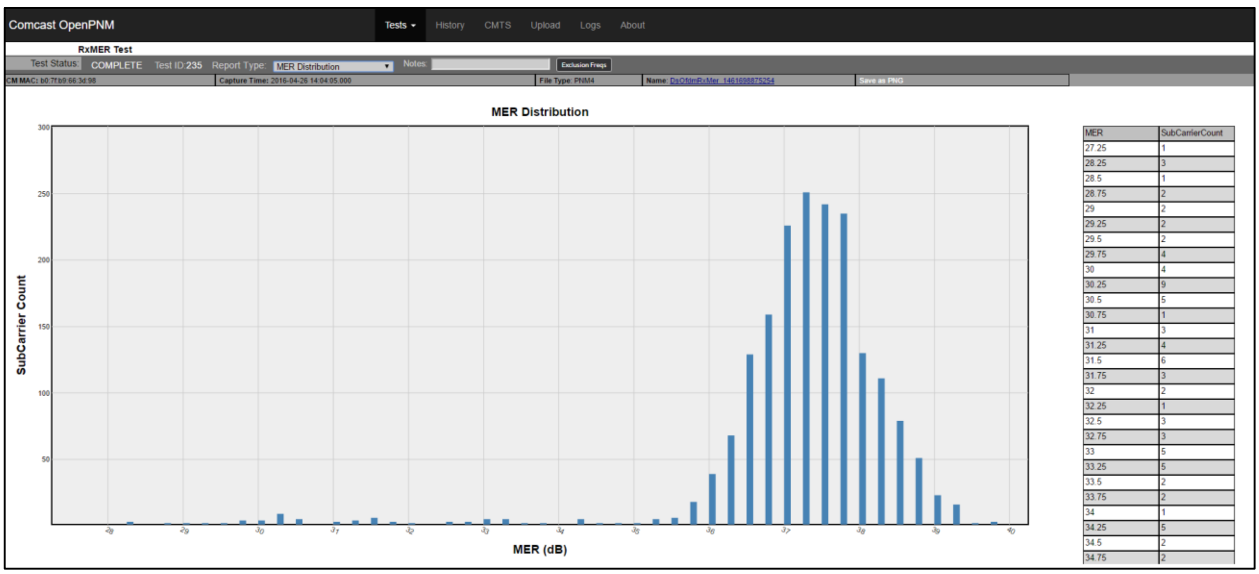


Figure 9 - MER Distribution indicating Skewness - Skewness < -1 or -3.19

Note that Figure 8 was obtained in Comcast's corporate offices, rather than in the field, which shows the power of the centralized monitoring provided by PNM technology. It is unknown how the signal ingress was introduced, but one can see the side statistics by using the standard deviation and skewness as key performance indicators (KPI). Using automation, CMs can be quickly screened for a potential problem.

Figure 9 shows the distribution of the subcarrier count per MER. The skewness is observed with a shift of the MER count to the right. Further examples of Skewness vs. Non-Skewness are shown in Figure 12, Figure 14 and Figure 16.

For completion, Figure 10 of a AWGN MER Distribution is provided for comparison.

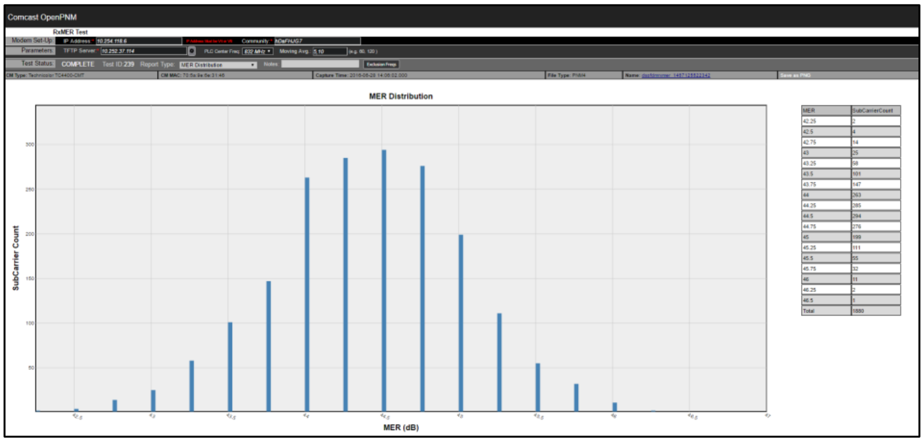


Figure 10 - MER Distribution of an AWGN Channel

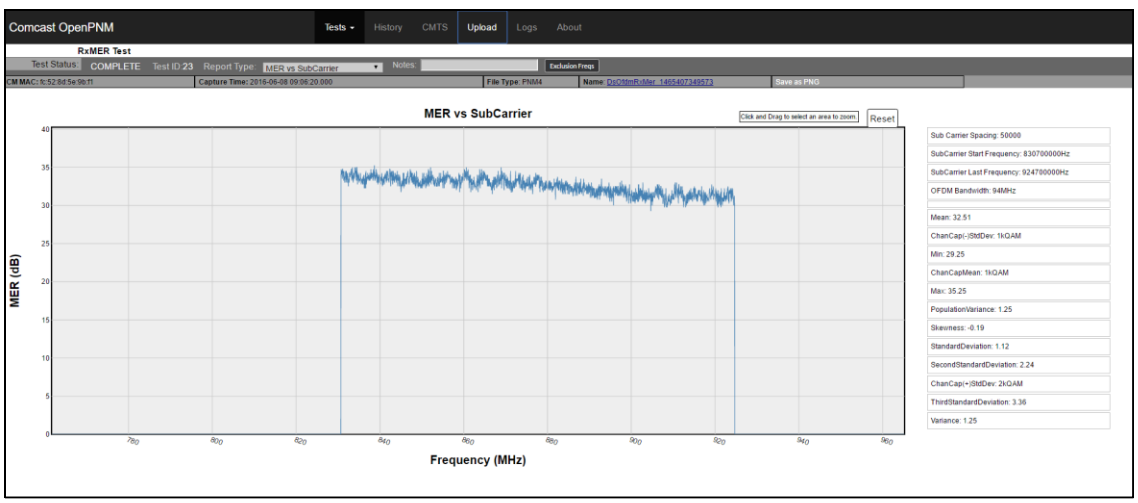


Figure 11 - RxMER Response – Oscillation

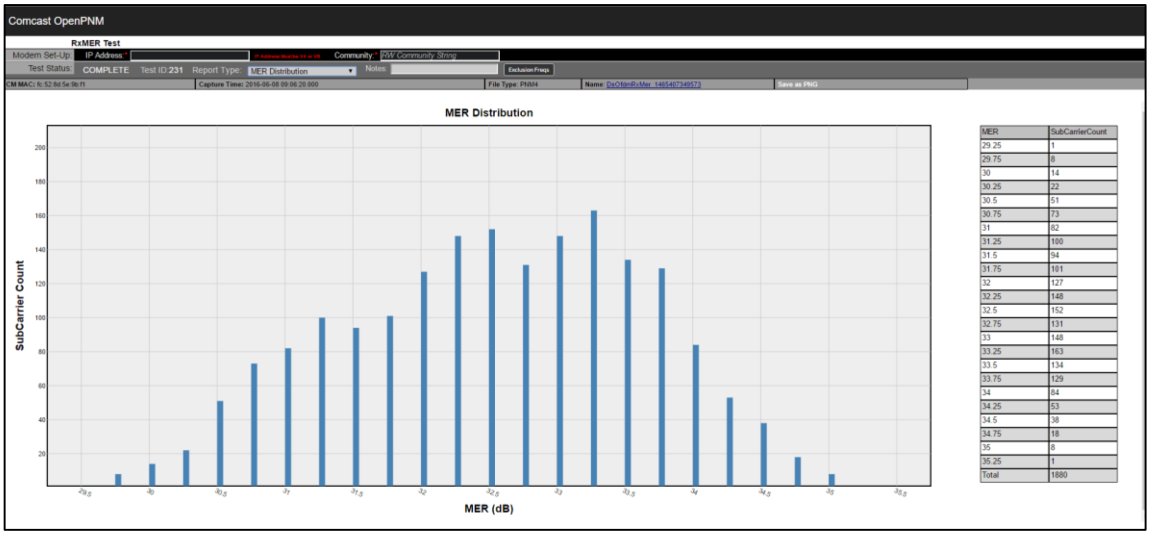


Figure 12 - MER Subcarrier Distribution - Oscillation – Skewness < -1 or -0.19

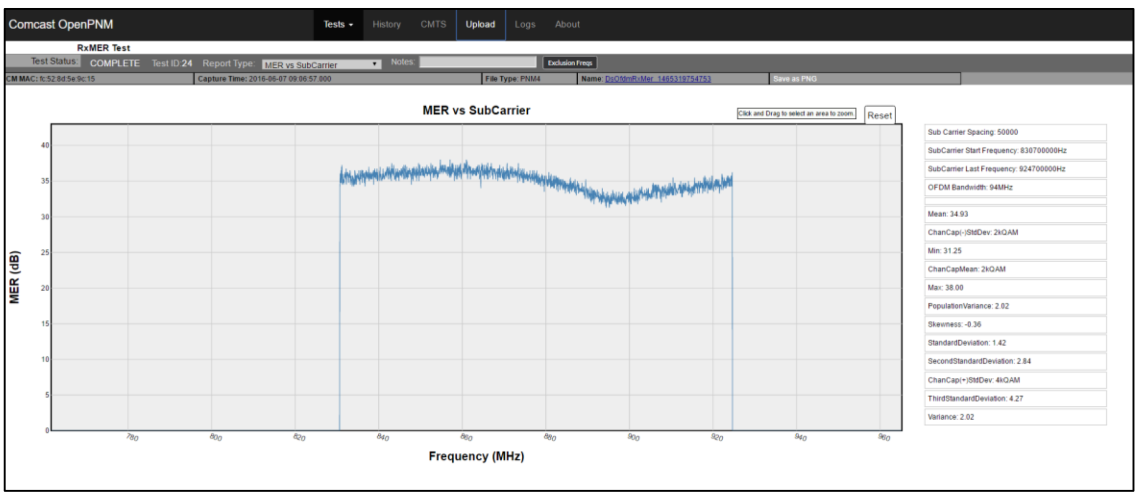


Figure 13 - RxMER Response – HUM Like

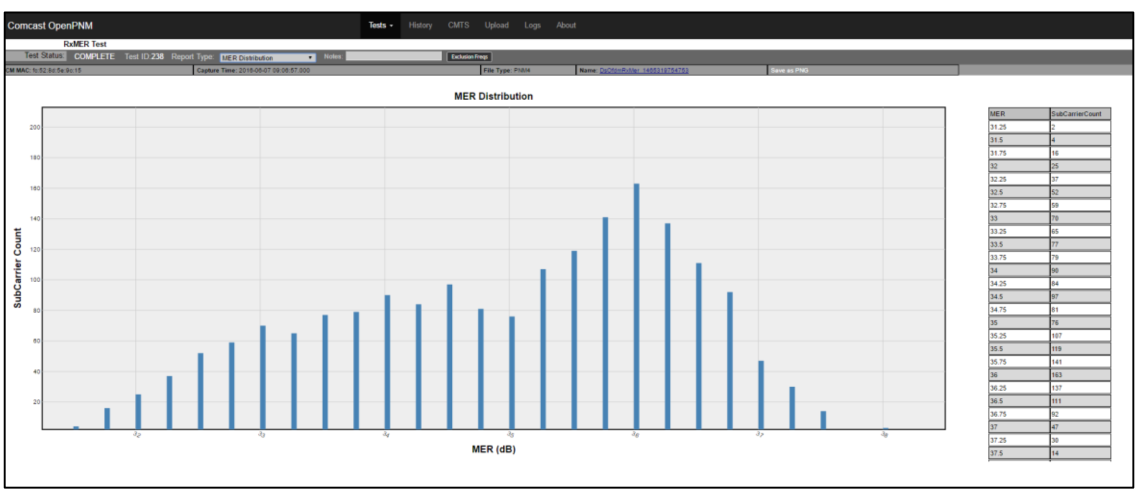


Figure 14 - MER Distribution - HUM Like - Skewness > -1 or -0.36

Figure 11 and Figure 13 are captured from a DOCSIS 3.1 field trial and indicate a type of oscillation. Both are showing a skewness of > -1, and a severity of MER response swing of a standard deviation of greater than 1 dB.

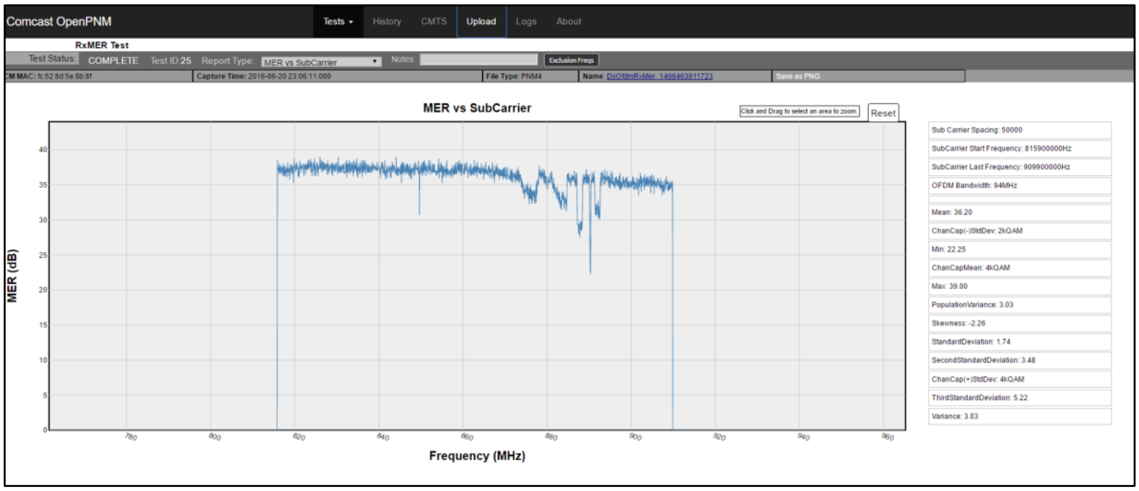


Figure 15 - Multiple Signal Ingress

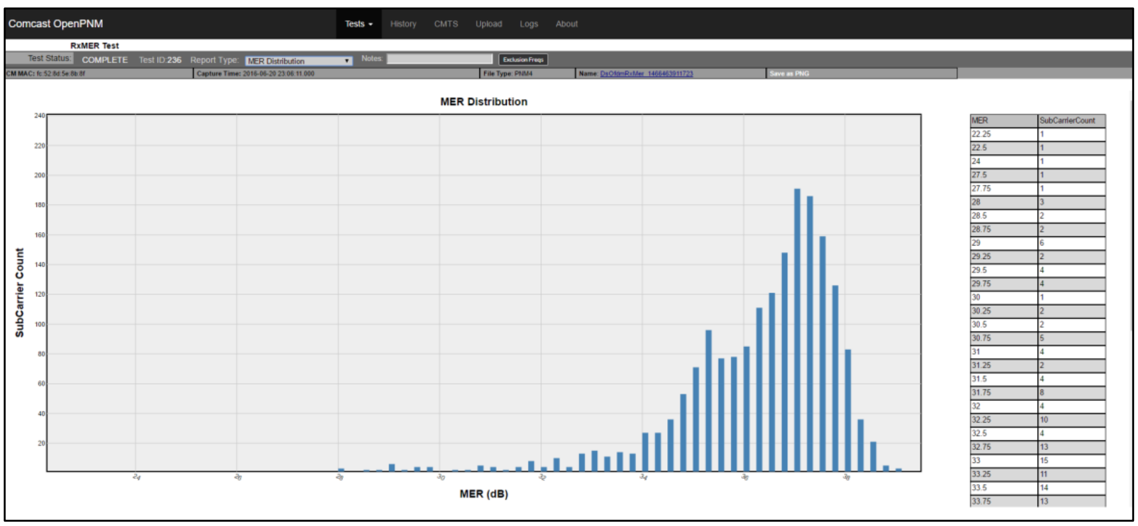


Figure 16 - MER Distribution – Skewness < -1 or -2.26

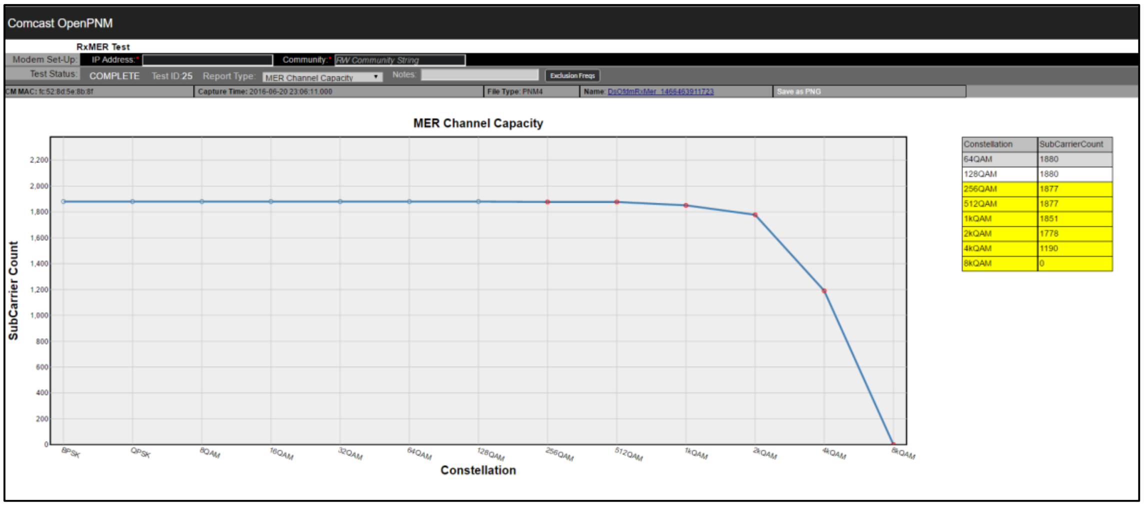


Figure 17 - MER per subcarrier Channel Capacity

Figure 15 and Figure 17 shows the per-subcarrier channel capacity performance from an MER point-of-view. Each subcarrier is evaluated against the required minimum MER for bit-per-symbol (b/sym) or equivalent the order of modulation, M-QAM. Although the MER response shows multiple signals ingressing that are causing a reduction of MER for a subset of subcarriers, as is seen in Figure 17 the impact is limited to a reduction from 4K-QAM to 2K-QAM, which equates from 12 b/sym to 11 b/sym. This gives a throughput reduction of about 8.5% if the CM is demoted to a lesser modulation profile.

3.5. FEC Summary

In LDPC monitoring, a larger number of iterations is an indication of a reduction of signal quality. Due the implementation of LDPC the number of iterations outside of “one iteration” it is not a good metric to measure signal or product performance. A series of codeword error rate measurements on a per-profile basis over a set period is a better metric of signal and product performance. [2]

3.6. FEC Summary Retrieval Methods and Metrics

DOCSIS 3.1 uses three metrics to report the FEC status, and there are two ways to obtain these metrics:

1. SNMP will give an overall count over time, but is somewhat limited if the SNMP queries are done with large interval since the counter is a 64 bits and run the risk of roll-over.

2. PNM FEC Summary provides two summary types:

- 10 minutes duration recording codeword data every second for a total of 600 measurements.

- 24-hour duration recording codeword data every 60 seconds for a total of 1440 measurements.

In both cases, data is summarized by OFDM channel and Profile including the Next Codeword Point (NCP).

OFDM FEC Metrics by Profile	
Total Codewords	Total number of codewords
Corrected Codewords	The number of codewords measured on this profile that failed pre-decoding LDPC syndrome check and passed BCH decoding
Uncorrectable Codewords	The number of codewords measured on this profile that failed BCH decoding

Table 4 - OFDM FEC Metrics by Profile [2]

4. Validating the Sensitivity of the CM RxMER via Signal Analysis

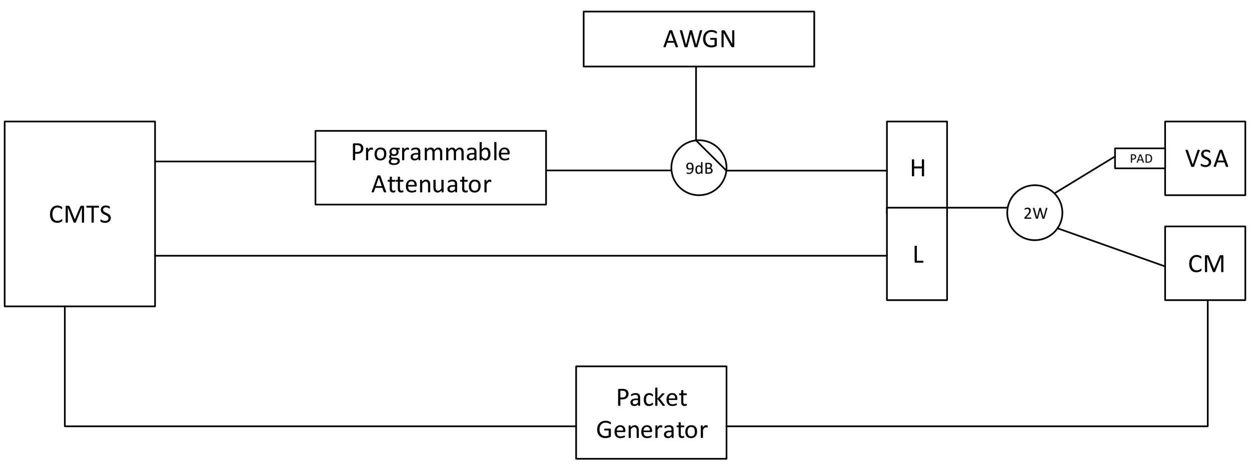
4.1. Test Scenario

This test is to compare the CM's ability to measure the MER accurately at the receiver front end versus a lab quality signal analyzer. The signal analyzer was configured to perform spectrum, vector, and DOCSIS OFDM analysis. If PNM based metrics are to be used moving forward for critical plant repairs and improvements, this evaluation is essential to determine the performance and assessment of the OFDM signal fidelity from the perspective of the CM. Furthermore, RxMER analysis via PNM file transfer is performed and compared to the signal analysis against controlled network impairments.

Note: At the time of testing, the acquisition of RxMER data was not averaged, which may result in a lower than expected channel capacity response.

4.2. Configuration

The test configuration is depicted as follows:



CMTS OFDM Configuration			
OFDM 96MHz (BW) (Tests 1 – 6)		**OFDM 96MHz (BW) (Tests 7 – 11)**	
Start Frequency*	786 MHz	**Start Frequency**	786 MHz
Stop Frequency*	882 MHz	**Stop Frequency**	882 MHz
PLC**	832 MHz	**PLC**	832 MHz
Profile A	4096QAM	**Profile A**	1024QAM
Cyclic Prefix	1024 Samples	**Cyclic Prefix**	1024 Samples
Roll-Off	256 Samples	**Roll-Off**	256 Samples
Single Carrier QAM		**Single Carrier QAM**	
Center Frequency	663 MHz	**Center Frequency**	663 MHz

Table 5 - CMTS OFDM Test Configuration based

*CMTS OFDM frequency selection is based on current field trial deployment configuration.

4.3. Table Column Definition

PROFILE

Due to dynamic modulation profile, only one modulation profile, Profile-A will be used to prevent transition between profiles. This evaluation will include 4096-QAM and 1024-QAM modulation profiles.

Vector Signal Analyzer (VSA) MER

The VSA uses DOCSIS decoding software to demodulate and evaluate OFDM modulation profiles, BER, LDPC/BCH FEC decode statistics and MER.

PNM RxMER

The RxMER is measured by using the DOCSIS PNM file retrieval method. A Standard Deviation is performed on all RxMER points to compute the mean and standard deviation of RxMER.

SNR

SNR is measured via spectrum analysis by calculating the following measurements:

$$\boldsymbol{SNR_{Relative} \cong (OFDM_{ChannelPower} - AWGN_{ChannelPower}) + 5.72_{Min/Max\ Pad}}$$

IP Data Throughput (THRUPUT)

100 concurrent state-full HTTP sessions were generated during the test using an IXIA IxLoad measured in Mbps.

LDPC CODE ITERATION (LCI)

LCI reports the number of iterations required to find a codeword as indicated by the VSA LDPC decoder. The number of iterations needed to obtain a codeword is a good indication of signal robustness. If less than five iterations are required to obtain a valid codeword, then the signal is well above the threshold. When the number of iterations go above 10, the SNR is usually only a few dB from the point where LDPC decoder will not resolve codewords.

Note that the VSA was unable to decode LDPC when the modulation was set to 1K-QAM. Therefore the number of LDPC iterations to obtain a codeword could not be measured for 1K-QAM.

4.4. Test Results

TEST	PROFILE-A	VSA MER (dB)	PNM RxMER (dB)	SNR (dB)	THRUPUT (Mbps)	LDPC CODE ITERATION
1	4KQAM	46.0	43.2	46	773	1
2	4KQAM	38.0	37.9	38	773	2
3	4KQAM	37.1	37.2	37	773	12
4*	4KQAM	36.7	36.4	36	773	15
5**	4KQAM	36.4	35.6	35	340	20
6	4KQAM	36.18	-	34	-	ALL ERRORS
7	1KQAM	35.0	34.2	35	651	-
8	1KQAM	33.2	33.2	34	651	-
9	1KQAM	32.4	31.3	33	651	-
10*	1KQAM	30.71	30.3	30	651	-
11	1KQAM	-	-	29	-	ALL ERRORS

Table 6 - Sensitivity of the CM RxMER via Signal Analysis Summary Results

PROFILE-A*	MINIMUM MER	VSA	(MM-V) DELTA	PNM	(MM-P) DELTA
4KQAM	36.1 dB	36.7 dB	.6 dB	36.4 dB	.3 dB
1KQAM	30.1 dB	30.7 dB	.6 dB	30.3 dB	.4 dB

Table 7 - Sensitivity of the CM RxMER via Signal Analysis Results

Table 7 summarizes the collected data from Table 6. The two data point used test 4 @ 4096-QAM and test 10 @ 1024-QAM because there was no degradation of IP throughput. When you calculate the delta for both VSA and PNM there is 0.2 – 0.3 difference between the samples.

4.5. Conclusion

The results of the above test is verified that accuracy of the CM ability to compute all subcarriers' RxMER and using the average or mean RxMER, the results were within 0.3 dB of a lab quality vector analyzer.

Test 4, 5 and 10 are represented in Figure 18 through Figure 26 using the OpenPNM software application. It illustrates for test four Figure 20 that although only ~68% of the subcarriers support 4096-QAM

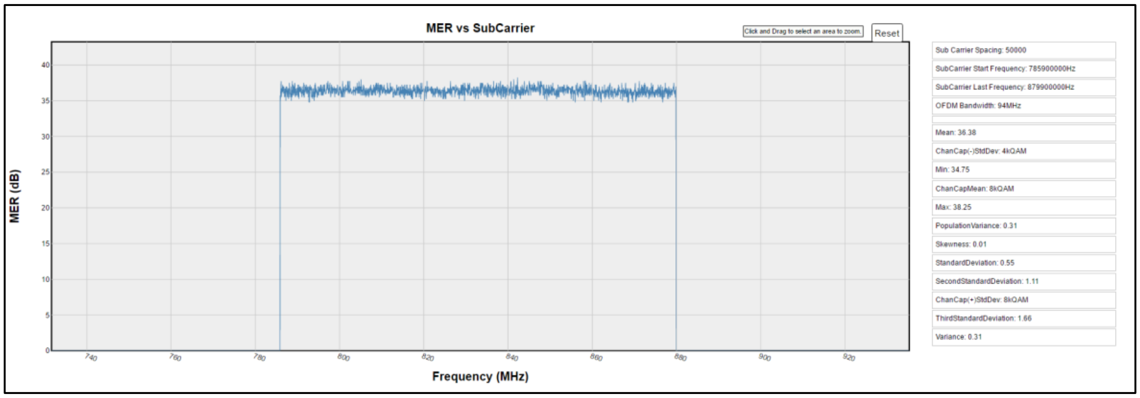


Figure 18 – Test 4 MER vs. Frequency - 4K-QAM CM Rx Sensitivity

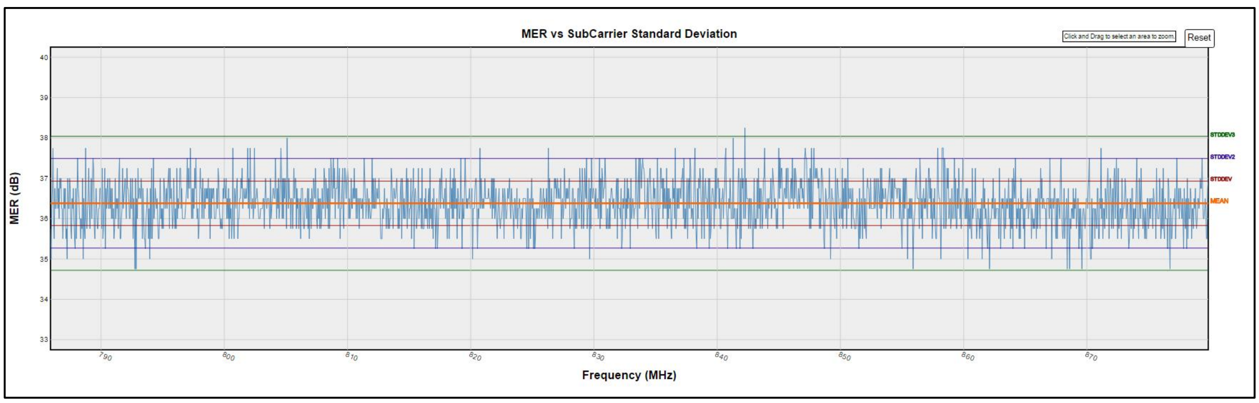


Figure 19 - Test 4 MER Standard Derivation - 4K-QAM CM Rx Sensitivity

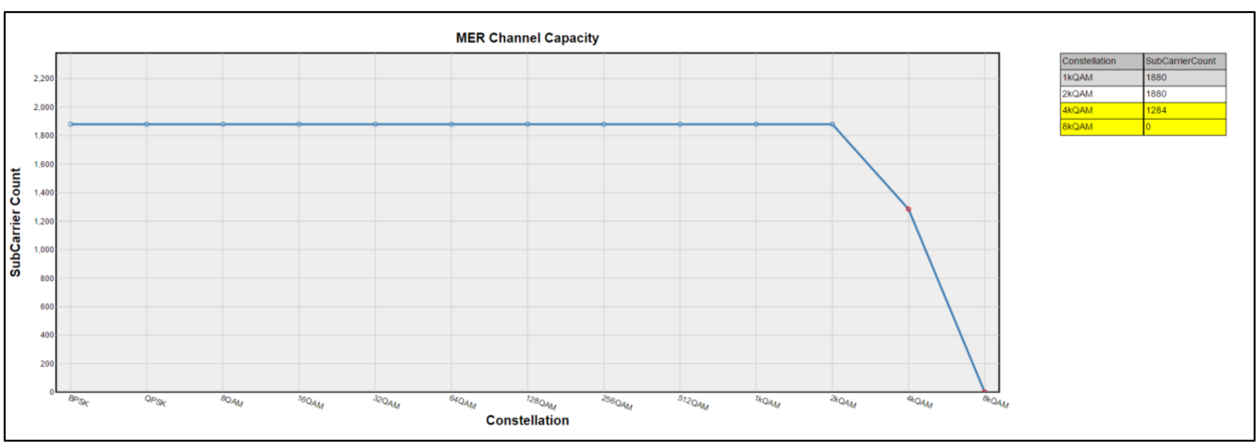


Figure 20 - Test 4 Min MER per Subcarrier Chan Capacity - 4K-QAM CM Rx Sensitivity

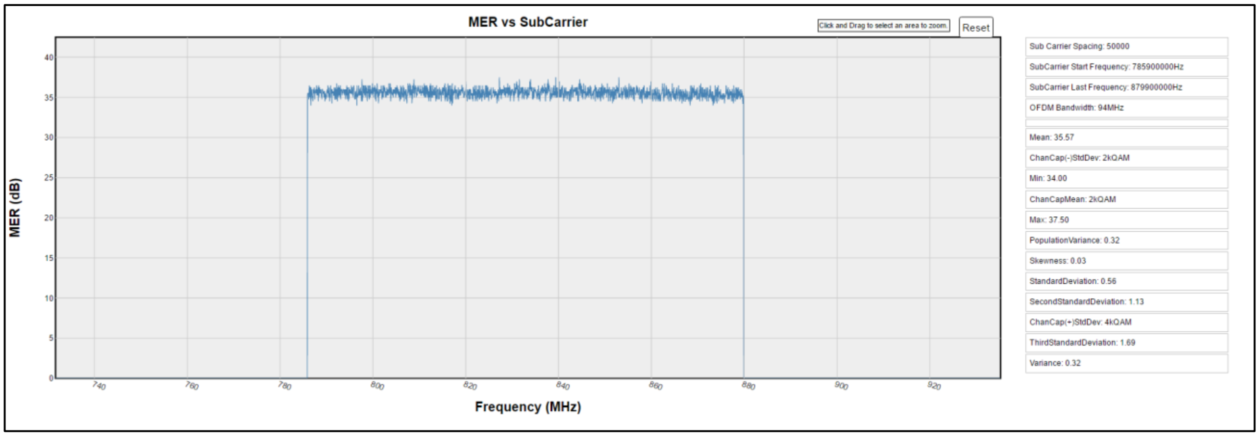


Figure 21 - Test 5 MER vs Frequency - 4K-QAM CM Rx Sensitivity @ 35.57dB MER

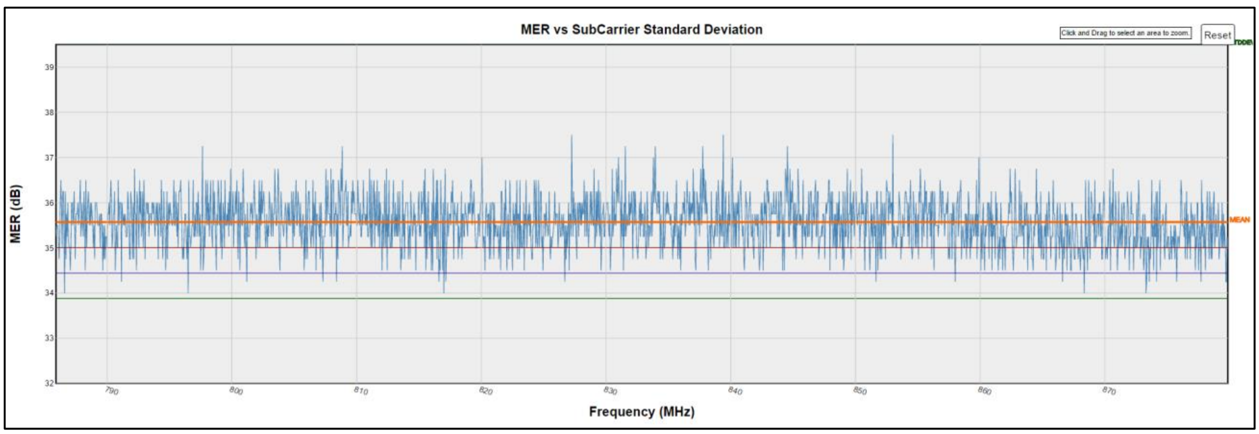


Figure 22 - Test 5 MER Standard Derivation - 4K-QAM CM Rx Sensitivity @ 35.57dB MER

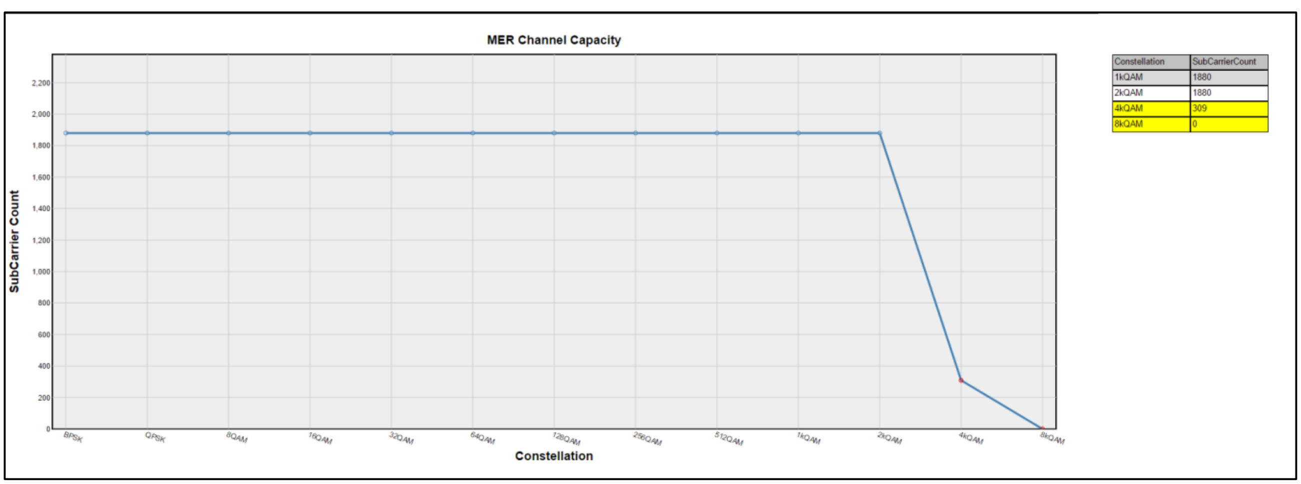


Figure 23 - Test 5 Min MER per SC Chan Capacity - 4K-QAM CM Rx Sensitivity @ 35.57dB MER

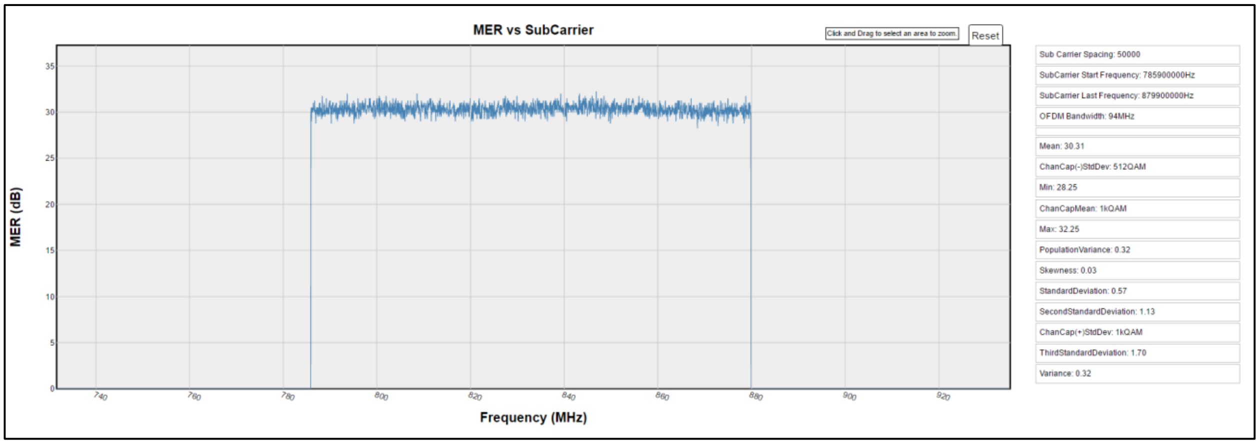


Figure 24 - Test 10 MER vs Frequency - 1K-QAM CM Rx Sensitivity @ 30.31dB MER

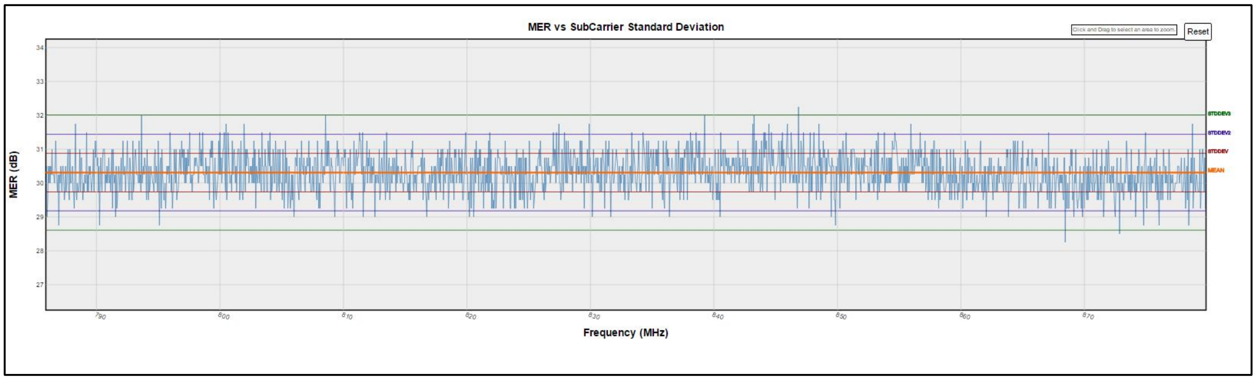


Figure 25 - Test 10 MER Standard Derivation - 1K-QAM CM Rx Sensitivity @ 30.31dB MER

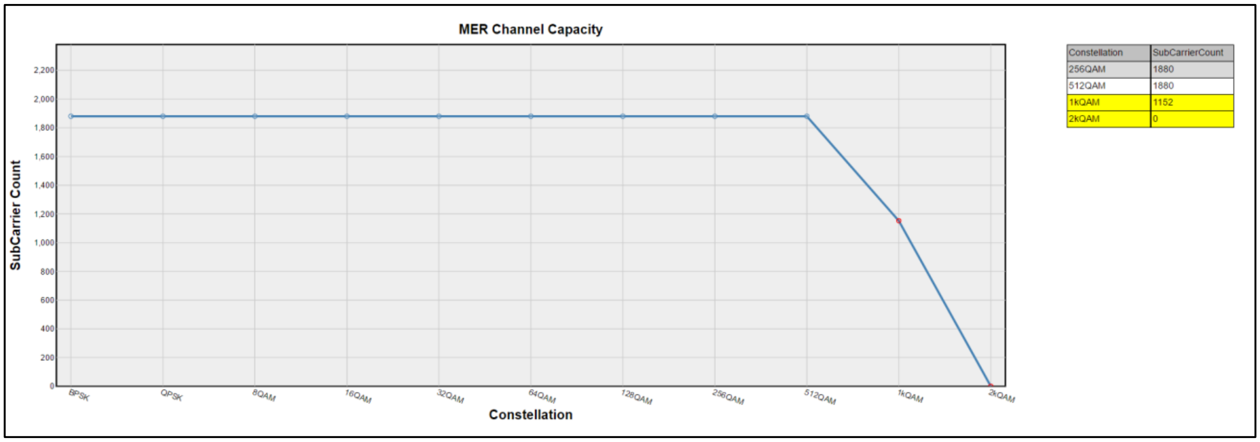


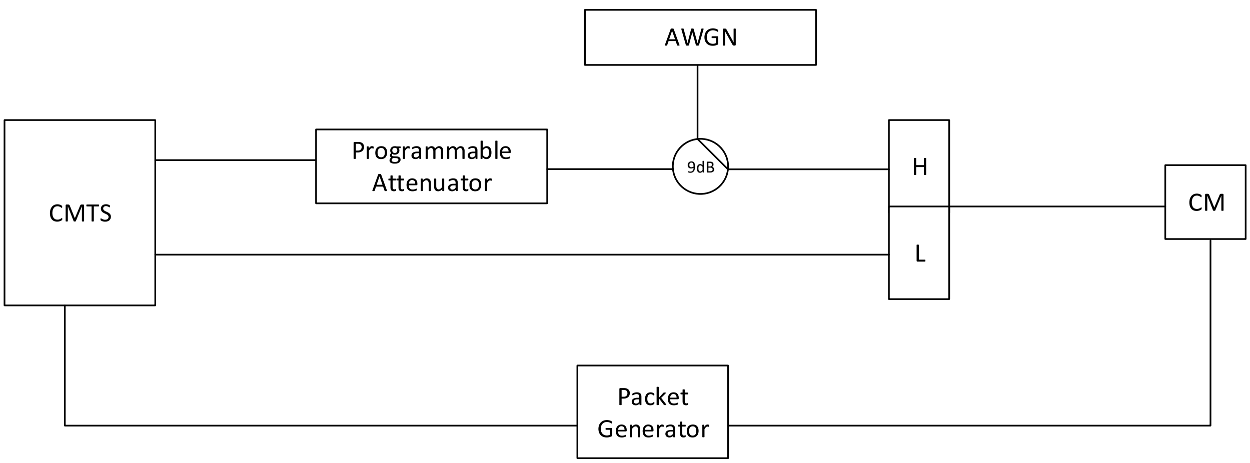
Figure 26 - Test 10 Min MER per SC Chan Capacity - 1K-QAM CM Rx Sensitivity @ 30.31dB MER

5. OFDM Modulation Profile Transition

5.1. Test Scenario

This test is to verify the demotion of OFDM profiles via an AWGN channel. At the time of this test, only three profiles were used due to that fact that not all D3.1 features were supported on the test hardware.

5.2. Configuration



CMTS OFDM Configuration	
OFDM 96MHz (BW)	
Start Frequency	786 MHz
Stop Frequency	882 MHz
PLC	832 MHz
Profile A	256-QAM
Profile B	1024-QAM
Profile C	4096-QAM
Cyclic Prefix	1024 Samples
Roll-Off	256 Samples
24 x Single Carrier QAM	
Center Frequency	597 - 735 MHz

5.3. Table Column Definition

PROFILE

This value is the highest profile assign to the CM reported by the CMTS

PNM RxMER

The RxMER is measured by using the DOCSIS PNM file retrieval method. A Standard Deviation is performed on all RxMER points to compute the mean and deviation.

AWGN

The dB value is the attenuation value relative to 0 dB over the frequency range 100Hz – 1GHz.

IP Data Throughput (THRUPUT)

100 concurrent state-full HTTP sessions were generated using the IXIA IxLoad measured in Mbps.

5.4. Test Results

TEST	PROFILE QAM**	PNM RxMER (dB)	AWGN (dB)	THRUPUT (Mbps)
1	4068	40.7	-	910
2	1024	37.36	37.0	910
3	1024	35.44	34.0	910
4	1024	31.50	31.0	910
5	1024	32.4	30.0	910
6	1024	31.54	29.0	910
7	1024	30.66	28.0	910
8	256	29.78	27.0	910
9*	256	24.99	22.0	492
10	256	24.39	21.5	492
11	256	24.28	21.3	492
12	256	24.12	21.1	492
13	256	-	-	-

Table 8 - OFDM Modulation Profile Transition 4096-QAM – 256-QAM Test Results

* During test nine the SC-QAMs @ 256-QAM using a RS FEC was unable to correct codewords. Only the DS-OFDM was passing IP traffic at this point.

** *Profile QAM* is the highest profile by the CMTS

TEST	PROFILE QAM	PNM RxMER (dB)	AWGN (dB)	THRUPUT (Mbps)
1	4068	40.24	40	910
2	4068	39.13	38	910
3	4068	38.40	37	910
4	4068	37.72	36	910
5*	1024	36.88	35	910

Table 9 - OFDM Modulation Profile Transition 4096-QAM Re-Test

The above table is a retest of the previous test due to an expected transition from 4096-QAM to 1024-QAM. This test used smaller increase of AWGN to determine the profile transition threshold.

*Test 5 throughput did not change because the total available BW is > 1Gbps due to the additional 24 SC-QAM.

5.5. Conclusion

This test verified the CM /CMTS interaction in demoting the CM to a lower profile was successful. In Table 8 test 7 the reported MER, before demoting to 256-QAM, is 30.66dB @ 1024-QAM. The calculated minimum MER for 1024-QAM is 30.1dB, which is relatively close to Shannon Limit < 1dB. In Table 9 test 4 the reported MER before demoting to 1024-QAM is 37.72dB. The calculated minimum MER is 36.1dB. This is a delta of 1.62dB.

This test demonstrated the demotion from 4096-QAM to 1024-QAM does not change within a fraction of a dB of Shannon limit as demonstrated in *Validating the Sensitivity of the CM RxMER via Signal Analysis.* This is due to the CMTS vendor decision-making implementation on when to move a CM from one profile to another which is defined in the DOCSIS 3.1 specification. The options for the CMTS to determine the threshold metrics are described in Section 2.

Conclusion

The promise of DOCSIS 3.1 has finally arrived with not just a significant improvement of spectral efficiency, but significantly enhanced and expanded tools embedded in the CM and CMTS that allow a cable operator to perform downstream signal analysis far beyond what is available today with DOCSIS 3.0 PNM. Even when only using RxMER we can project modulations profiles for a given serving group. We can also determine from a CM population that are experiencing signal ingress that have heretofore been hidden from spectrum analysis, and develop custom modulation profiles using the RxMER discrete values with a resolution of 25 kHz.

The two hypotheses of this paper were shown to be correct:

- Is a DOCSIS 3.1 CM with enhanced PNM functionality indeed a viable alternative to lab-quality test equipment?

  In section 4 we explored the sensitivity of the CM RF tuner ability to take precise MER measurements against a high-quality VSA. To be fair, the functions and features of a VSA are far more advanced than the capabilities of a CM. In practice the MER is measured after the demodulator and include quantization and thermal noise error, one would expect a lower sensitivity of signal measurement. A VSA uses high-quality, low noise amplifier (LNA) and possibly higher resolution analog to digital converters (ADC). But even with this clear distinction, the CM RxMER analysis was within a fraction of a dB of the VSA and the calculated Shannon Limit for the given modulation profile.

- Can cable operators use DOCSIS 3.1 CMs to determine how close the HFC can get to the upper bound of the Shannon Limit both individually as well as collectively sampled?

  In both section 4 and 5, the test scenarios pushed the limit of the CM in discerning the OFDM in an AWGN channel environment. In *Validating the Sensitivity of the CM RxMER via Signal Analysis*, it was demonstrated the CM reached within a fraction of a dB of Shannon Limit using the RxMER in the PNM toolkit. This calculation is the average of the RxMER of the subcarriers. This test establishes in a non-dynamic environment that the CM has the capability to determine the range between the modem sensitivity and Shannon Upper Limit.

  In the test scenario, *OFDM Modulation Profile Transition* the CM is in a dynamic environment where the CMTS makes the decision on which modulation profile to which the CM is assigned based on HFC conditions. Testing shows that the CM can be more than a 1 dB away from Shannon's Limit due to what the CM is reporting back as errors and the CMTS decision-making algorithms. These algorithms are vendor specific and may have little or no customization options for the cable operator to change.

The CMTS decision algorithms are based on the same PNM test options that OpenPNM can access. Cable operators in the future will have the ability to control the CM profile assignments using Profile Manager Application (PMA) that is currently being developed by CableLabs.

In conclusion, obtaining good statistical analysis is predicated on the CM's ability to measure MER accurately. However, if at some point in the future, DOCSIS 3.1 CMs are seen as a commodity with a similar push to drive the cost down below that required to support accurate parameter measurement. Compromises may be made for example to the tuner front end discrete electronics. It is up to the cable operator to repeat this procedure and test the MER accuracy with each code version and new product. In this paper, we have demonstrated with the first generation DOCSIS 3.1 devices, that DOCSIS 3.1 CMs and CMTSs have the ability now to do a precise MER measurement equivalent of a quality lab analyzer and reach data rates within 1 dB of the Shannon Limit.

Appendix A

DOCSIS 3.1 Fundamentals and Definitions

In this appendix, a review of some fundamentals of signal processing and signal impairments that relate to the tests in this paper are given, along with some examples of how variables can be accessed in DOCSIS 3.1. Field trial examples are incorporated to reveal the significate importance of PNM RxMER in contributing to the detection of signal ingress and performance impact. Techniques used to measure, evaluate and decision options in creating and selecting an OFDM downstream profile and the impact on the OFDM signal over an AWGN channel in a lab setting will be presented. In addition, real-world field studies will supplement the lab results.

.

1. Additive-White Gaussian Noise

Additive-White Gaussian Noise (AWGN) is the commonly used to simulate background noise of a channel, thus called the AWGN channel. It is the basic communication channel model and used as a standard channel model. The transmitted signal gets disturbed by a simple additive white Gaussian noise process. [3]

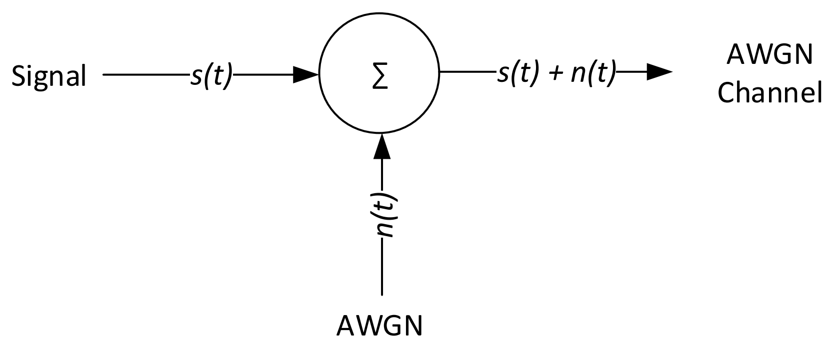


Figure 27 - Signal Insertion into an AWGN Channel

2. SNR vs. MER

The signal-to-noise ratio called (SNR) or S/N, defined as the ratio of signal power to the noise power corrupting the signal. SNR is determining signal quality. A high SNR guarantees clear signal acquisitions with little distortions and artifacts caused by noise. The higher the SNR, the better the signal stands out, the better the quality of the signals, and the achieving the desired results. In a digital system, noise is expressed using SNR.

$$SNR = \frac{E_s}{N_0} = \frac{Energy\ per\ symbol}{Noise\ Power\ Spectral\ Density}$$

$$\frac{E_b}{N_0} = \frac{Energy\ per\ bit}{Noise\ Power\ Spectral\ Density}$$

$$\frac{E_b}{N_0} = \frac{E_s}{pN_0} \rightarrow \frac{E_b}{N_0} * Log_2(M) \ = SNR$$

$$p = bit\ rate\ in \frac{\frac{bits}{second}}{Hz}\ to\ normailze\ SNR$$

$$M = M_{ary}QAM$$

$$SNR_{dB} = 10 * Log_{10}(SNR)$$

SNR is used to describe a signal BEFORE demodulation, MER or RxMER is used to describe the same signal AFTER demodulation. In the equation, the MER numerator represents the signal without distortion. Ideal IQ power over the difference between the receive IQ ideal component with the receive IQ components. This difference is analogous to SNR, but including quantization and thermal noise during the demodulation process.

$$RxMER_{dB} = 10 * Log_{10}\left[\frac{\sum_{j=1}^{N}\left(\tilde{I}_j^2 + \tilde{Q}_j^{\ 2}\right)}{\sum_{j=1}^{N}[(I_j - \tilde{I}_j)^2 + (Q_j - \tilde{Q}_j)^2]}\right]$$

$\tilde{I} = Ideal\ Inphase\ of\ Symbol$ (Hard Decision)

$\tilde{Q} = Ideal\ Quadrature\ of\ Symbol$ (Hard Decision)

$I = Recieve\ Inphase\ of\ Symbol\ (Soft\ Decision)$

$Q = Recieve\ Quadrature\ of\ Symbol\ (Soft\ Decision)$

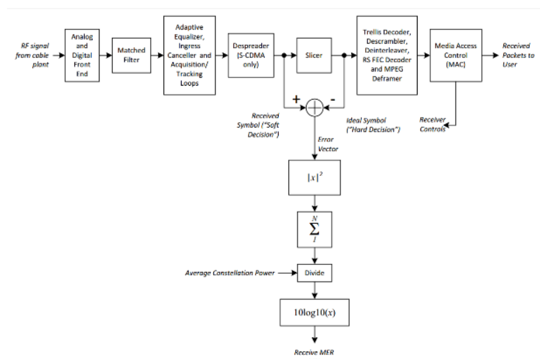


Figure 28 - System Overview of obtaining MER

The RxMER evaluates the demodulated complex baseband constellation symbols and measures their quality; this is performed before and after the slicer. The slicer is the element in the demodulator that is responsible for deciding which symbol was transmitted. The RxMER measurement gives the near "bottom line" status of the communications link because it is these demodulated symbols that go on to produce correct bits, or bit errors, at the receiver output after processing by the forward error correction (FEC) decoder.

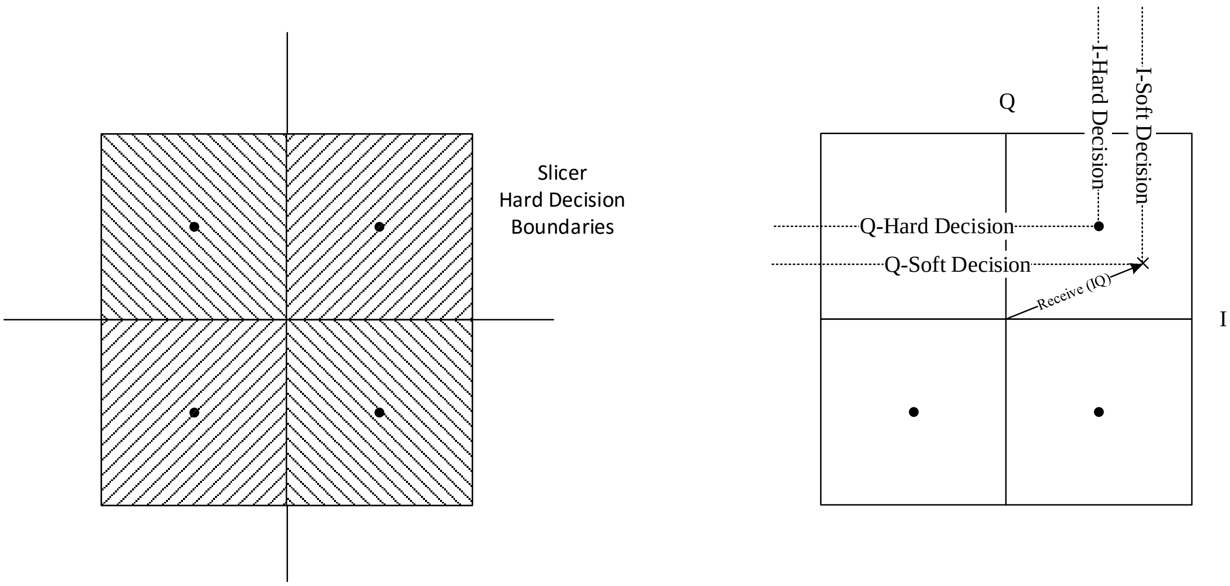


Figure 29 - Slicer Decision Boundaries and Hard/Soft Decision Determinations

3. Coding Gain and Noise Immunity Techniques

Channel Coding is the process to defeat channel noise. Digital communication aims to maximize the transmission bit rate, minimize the probability of bit error, minimize the required carrier-to-noise ratio (CNR) and while minimizing the necessary system complexity. Coding gain is the reduction in the SNR that is required to provide sufficiently low bit error rate (BER), compared to the SNR necessary for the desired BER without coding. When determining coding gain care must be taken to normalize for spectral efficiency.

The Shannon-Hartley Capacity law presents a theoretical limit for the transmission rate of data from a transmitter of given power, over a channel with a given bandwidth while operating in a particular noise environment. To find this maximum channel capacity, noise immunity techniques are needed to approach the capacity limit. [4] Further description of Shannon-Hartley is explained later in this paper.

To improve the clearing of any errors that might occur, the forward error correction (FEC) for DOCSIS 3.1 consists of a combination of the low-density parity check (LDPC) and Bose-Chaudhuri-Hocquenghem (BCH) code.

3.1. LDPC

Most OFDM subcarriers may be detected without errors, the overall bit error rate (BER) is dominated by a subset subcarriers that have a low SNR. FEC coding is essential to compensate the underperforming subcarriers due to signal fidelity. LDPC codes were proposed by Gallager in 1962, which had been forgotten until 1994 due to the computation complexly needed to perform this operation. LDPC performance is very close to the Shannon limit, and it is routinely being approached within 1dB with the help of LDPC coding.

LDPC is an iterative block code method that iteratively reduces the number of faulty bits. LDPC is based upon a message passing algorithm where probabilities are passed between check nodes and variable nodes. Variable nodes represent the probability of each bit in a codeword. Check nodes represent the parity checks used to determine if a codeword has been found. Messages are passed until a codeword is found.

A clean signal will take fewer iterations to find a codeword. A noisy signal may take many iterations to find a codeword. If the SNR is too low, no amount of iterations will find a codeword. The transition between the point at which the received and corrected signal is error free and the point at which the signal can no longer be reconstructed is very narrow.

As with any FEC, there is a limit to the number of errors that can be corrected per packet; this is no different with LDPC. The more time allotted to the LDPC algorithm increases the number of iterations, thereby increasing the number of errors that can be corrected. The LDPC algorithm stops as soon as all errors are corrected. The number of iterations required to correct all errors provides a method to assess the signal quality. It must be noted that the number of iterations is dependent on the implementation, and therefore, values measured for different receivers cannot be compared to one another.

3.2. BCH

BCH (Bose-Chaudhuri-Hocquenghem) Codes form a large class of multiple random error-correcting codes. They were first discovered by A. Hocquenghem in 1959 and independently by R. C. Bose and D. K. Ray-Chaudhuri in 1960. BCH codes are cyclic codes. [5] BCH is capable of correcting any residual errors arising as a result of the LDPC principle. BCH FEC is considering "clean up" after LDPC errors that cannot be corrected.

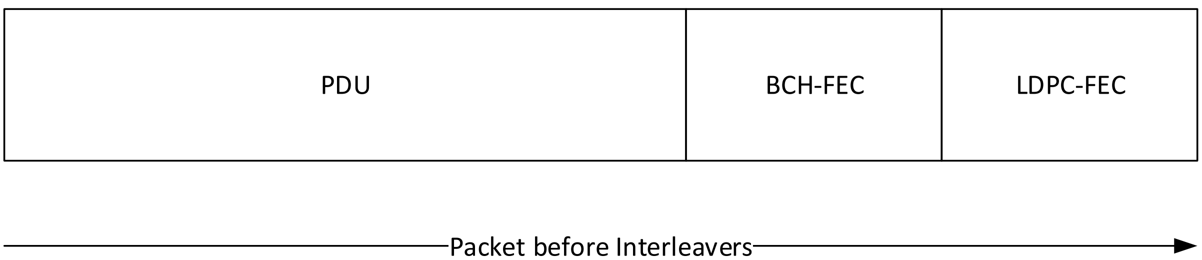


Figure 30 - Data Packet with BCH and LDPC Headers

In Figure 30 illustrates the concept of inner (LDPC) and outer (BCH) concatenated FEC technique

3.3. Interleaver

Interleaving, in general, is an attempt to spread the errors out in the bit-stream that is presented to the error correction decoder. When decoders experience a high number of errors, the decoder is unable to correct all the bit errors, then a burst of uncorrected errors occurs.

In the following tables, there are seven code words, at the start of each code word there is an FEC prefix that will fix any bit errors after the codeword is reconstructed.

FEC(F) + Code Word(xxxx) = Fxxxx

No Interleaving	
Error Free Code Words	FaaaaFbbbbFccccFddddFeeeeFffffFgggg
Transmission With a Burst Error	FaaaaFbbbbFccc_____dFeeeeFffffFgggg

Table 10 – No Interleaving of Codewords

In the above example, codeword 'c' has an error of 25%, but since the FEC is preserve, codeword 'c' can be repaired. Codeword 'd' suffered an error of 75% along with its FEC that codeword would be drop.

With Interleaving	
Error Free Code Words	FaaaaFbbbbFccccFddddFeeeeFffffFgggg
Interleaved	FabcdFefgaFbcdefgaFbcdeFfgabFcdFefg
Transmission With a Burst Error	FabcdFefgaFbcd____FbcdeFfgabFcdFefg
Received Code Words After Reconstruction	Faa_aFbbbbFccccFddddFe_eeFf_ffFg_gg
Reconstructed Code Words	Faa(a)aFbbbbFccccFddddFe(e)eeFf(f)ffFg(g)gg

Table 11 – Interleaving Codewords

In the example above where the same burst energy wiped out only 25% of four code words: a,e,f,g. Since there is only a 25% error of the affected code words, and the FEC is not affected, each of the code words can be reconstructed and maintain 100% error free result.

DOCSIS 3.1 uses two kinds of interleaver: frequency and time. Time interleaving (TI) needs long time delay for achieving good performance for long burst noise durations. On the other hand, frequency interleaving (FI) does not require a delay. Thus, in OFDM systems, FI is more favored to TI.

3.3.1. Frequency Interleaver

The frequency interleaving works along the frequency dimension. The FI changes the frequency locations of individual OFDM subcarriers; there are no latency effects, except for the data store and read latency. The aim of frequency interleaving is to disperse ingress. An example of this would be an LTE burst carrier that affects some consecutive subcarriers over the entire OFDM symbol. [6]

Frequency interleaving distributes the burst affected subcarriers over some LDPC code words. FI also increases resistance to frequency-selective channel conditions such as fading. When a segment of the channel bandwidth fades, frequency interleaving safeguards against bit errors because segments of the codewords would be distributed among non-adjacent and would spread out in the bit-stream rather than being concentrated.

3.3.2. Time Interleaver

The time interleaving is a convolutional interleaver that operates in the time dimension on individual subcarriers of a sequence of OFDM symbols. The TI does not change the frequency location of any OFDM subcarrier. A burst event can reduce the SNR of all the subcarriers of one or two consecutive OFDM symbols. The purpose of the TI is to disperse these burst-affected OFDM subcarriers between M successive OFDM symbols, where M is the interleaver depth. This dispersion distributes the burst-affected subcarriers uniformly over some LDPC code words.

Time interleaving ensures that bits that are originally close together in the bit-stream are transmitted far apart in time, thus mitigating against long duration impulse noise. [7]

3.4. Grey Code

Grey Code (GC) is a binary numeral system where two successive values differ in only one binary bit. When designing a constellation map GC is part of the design. Mainly when assigning bits to a symbol, adjacent codeword should only have a small difference from each other. In other words, the constellation points that are close together differ in as few bits as possible. Gray code improves coding in case of an incorrect slicing so only one bit will be errored.

Binary	Grey Code
0000 <- Start	0000 <- Start
0001 <- 1 Bit Change	0001 <- 1 Bit Change
0010 <- 2 Bit Change	0011 <- 1 Bit Change
0011 <- 1 Bit Change	0010 <- 1 Bit Change
0100 <- 3 Bit Change	0110 <- 1 Bit Change

Table 12 - Natural Binary Sequence vs. Grey Code Sequence

3.5. Cyclic Prefix and Micro-reflections

The Cyclic Prefix (CP) is the repetition or a copy of part of the signal of a symbol period that is append at the end of the symbol. CP needed to combat HFC multipath or micro-reflection. Micro-reflections are reflections or echoes of signal that bounce back and forth between cable segments ends that contain splitters or connections that are processing analog signals. This reflection or echo overlaps a small part of the next symbol and causes an impairment called Inter-symbol Interference (ISI).

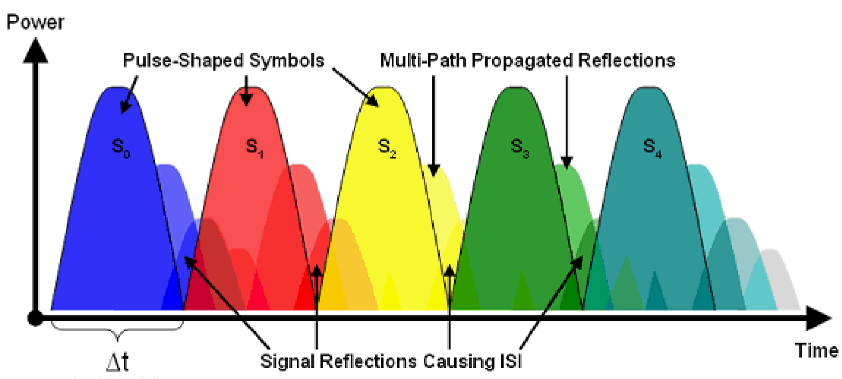


Figure 31 - ISI Inter-symbol Interference [8]

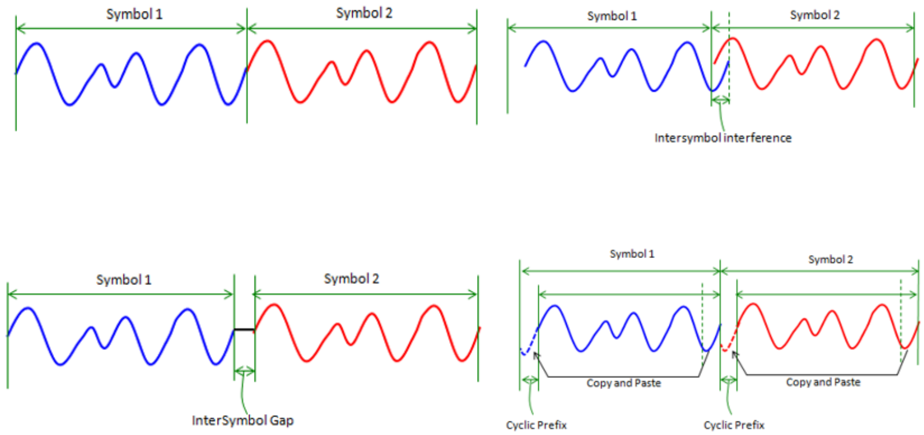


Figure 32 - Cyclic Prefix Example [9]

A weakness of the CP is that it increases the symbol duration and will have an adverse impact on data throughput.

Using Figure 33 example of a micro-reflection, we can calculate an appropriate CP.

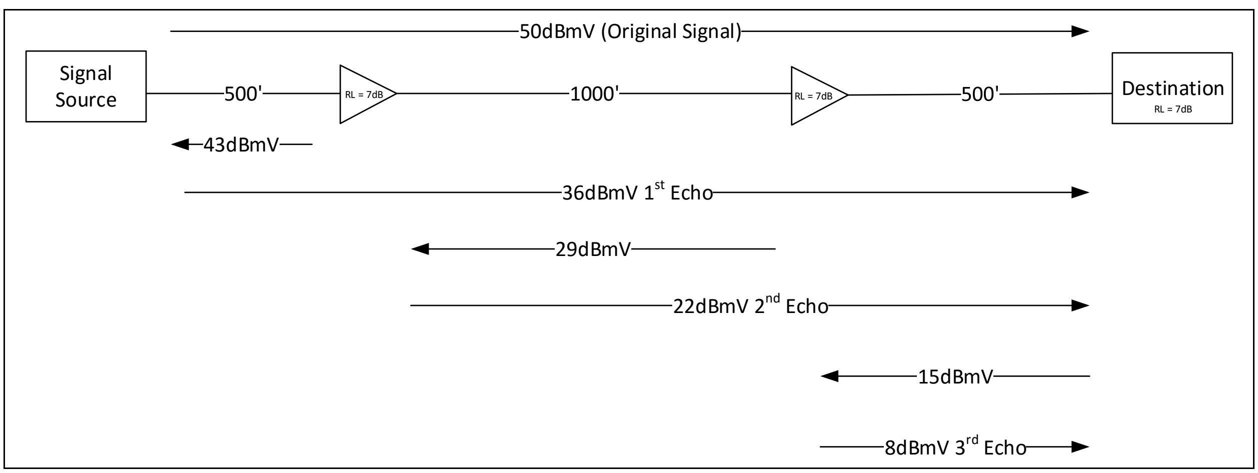


Figure 33 - Three Echo Micro-reflection Example

$1\ Foot \cong 1\ ns\ (10^{-9})$ of signal propagation delay. Taking the first echo to calculate a total echo delay

$$Delay_{FirstEcho} = (Distance) * (RoundTrip) * (Propagation\ \ Delay)$$

$$2000 * 2 * 10^{-9} = 4us$$

Cyclic Prefix Options	Delay	CP	Symbol Period
0.9375us	4 us	5 us	$@50\ KHz = 25us$ $@25\ KHz = 45us$
1.25 us			
2.5 us			
3.75 us			
5 us			

Table 13 - Cyclic Prefix Lookup Table

Using the lookup table in Table 13, select the appropriate CP.

$$CP_{Selection} > Delay_{FirstEcho}$$

$$5us > 4us$$

To calculate the performance impact:

$$SymbolPeriod = \frac{1}{SubcarrierBW}$$

$$SymbolDuration = SymbolPeriod + CP_{Selection}$$

$$25us = 20us + 5us\ @\ 50KHz$$

$$45us = 40us + 5us\ @\ 25KHz$$

$$Net\ Performace\ = \frac{1}{SymbolDuration} * Log_2(M)$$

$$Performace = \frac{1}{Symbol\ Period} * Log_2(M)$$

M = modulation scheme i.e. 256-QAM

$$Efficiency_{PerSubcarrier} = \frac{Net\ Performace}{Performace} * 100$$

Calculations base on 4096-QAM				
Symbol Period	**Performance**	**With CP**	**Net Performance**	**Efficiency**
25 KHz = 40 us	300 kbps	5 us	266.7 kbps	89%
		2.5us	282.4 kbps	94%
50 KHz = 20 us	600 kbps	5 us	480 kbps	80%
		2.5 us	533.3 kbps	89%

Table 14 - CP Subcarrier Efficiency @ 4096-QAM

In Table 14 determine the extended CP duration; it would be more efficient to use a 25 KHz subcarrier spacing as oppose to 50 KHz spacing.

3.6. Summary

The combined effect of interleaving and channel coding takes advantage of the frequency diversity provided by the wideband nature of the transmitted signal. [4]

Because of the increase robustness of the channel due to improvement in code gain and interleaving, the OFDM channel can handle noise and common path interference that would otherwise create an undesirable effect in the previous version of DOCSIS single-carrier QAM (SC-QAM) channels. If any portion of the SC-QAM faces interference from a foreign signaled the entire channels unusable.

More efficient error correction by replacing the Reed-Solomon algorithm used in DOCSIS today by more modern and more efficient low-density parity check algorithm. This enhancement alone provides an increase in performance of about 3 dB which is express in two ways. The same bits per second per hertz is achieve with 3 dB less SNR were almost two orders of magnitude increase by bits-per-second (bps) can be reached by the same SNR.

LDPC/BCH improve code gain allow cable operators to leverage higher-order modulations where prior it was not obtainable. Before DOCSIS 3.1 256-QAM was the highest used modulation, but now operators can select with 512-QAM, 4096-QAM and as high as 16384-QAM.

4. Channel Capacity Estimation Using Shannon Capacity Limit

4.1. Shannon Capacity Theorem

Claude Shannon regarded as the father of the Information Age; he formulated the notion of channel capacity in 1948. Within several decades, mathematicians and engineers had developed methods to communicate reliably at data rates within 1% of the *Shannon limit*. [10]

$$C = B * Log_2\left(1 + \frac{S}{N}\right)$$

$C = Channel\ Capacity$

$B = Bandwidth\ of\ the\ transmission$

$\frac{S}{N} = Signal\ to\ noise\ ratio, not\ represented\ in\ dB$

$Log_2\left(1 + \frac{S}{N}\right) = \ bits\ per\ \sec per\ hertz\ that\ can\ be\ transmitted\ in\ a\ noisy\ channel$

Calculate the minimum number of bits per sec per Hz with a given SNR_{dB}:

$$bpsHz = floor\left[Log_2\left(1 + 10^{SNR_{dB}/_{10}}\right)\right]$$

To calculate the minimum SNR_{dB}:

$$SNR_{dB} = 10 * Log_{10}(2^{bpHz} - 1)$$

or

$$SNR_{dB} = 10 * Log_{10}(Log_2(M) - 1)$$

M = modulation scheme i.e. 256-QAM

This simple equation is the foundation of digital communications to determine the amount of information that can transmit within a noisy channel.

Abbreviations

AWGN	Additive-White Gaussian Noise
BER	Bit Error Rate
BCH	Bose-Chaudhuri-Hocquenghem
bps	bits per second
bpsym	bits per symbol
BPSK	Bi-Phase Shift Keying
CP	Cyclic Prefix
CNR	Carrier-to-Noise Ratio
CM	Cable Modem
CMTS	Cable Modem Termination System
CRC	Cyclic Redundancy Check
dB	decibel
DOCSIS	Data Over Cable System Interface Specification
D3.1	DOCSIS 3.1
DUT	Device Under Test
EVM	Error Vector Magnitude
FEC	Forward Error Correction
FI	Frequency Interleaver
HFC	Hybrid fiber-coax
HTTP	Hyper Text Transfer Protocol
Hz	Hertz
IQ	Inphase Quadrant
ISI	Inter-symbol Interference
Kbps	Kilobits per second
KPI	Key Performance Indicator
LCI	LDPC Code Iteration
LDPC	low-density parity check
LTE	Long Term Evolution
OPT-REQ	OFDM Downstream Profile Test Request
OFDM	Orthogonal Frequency-Division Multiplexing
PDF	Probability Density Function
PDU	Payload Data Unit
PLC	Physical Link Channel
PNM	Proactive Network Maintenance
PMA	Profile Management Application
MER	Modulation Error Ratio
NA	Network Analyzer
NCP	Next Codeword Point
NPR	Noise Power Ratio
RF	Radio Frequency
RxMER	Receive Modulation Error Ratio

SA	Spectrum Analyzer
SCTE	Society of Cable Telecommunications Engineers
SC-QAM	Single Carrier Quadrature Amplitude Modulation
SDN	Software Defined Network
SG	Serving Group
SNR	Signal-To-Noise Ratio
SNMP	Simple Network Management Protocol
TI	Time Interleaver
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
VSA	Vector Signal Analyzer

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