MEASUREMENT-BASED EOL STOCHASTIC ANALYSIS AND DOCSIS 3.1 SPECTRAL GAIN

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Abstract

Achieving the promised DOCSIS 3.1 capacities is a function of the network architecture and its EoL performance. This paper analyzes the network End of Line (EoL) performance theoretically and stochastically based on location-aware real-world plant measurements. Computer simulations and laboratory experiments are also used to support the field measurements in characterizing the performance of different network segments (e.g., source, fiber links, coaxial cascades, and tap/drop/in-home network/modem) with an ultimate goal of identifying the network pieces that can potentially dominate the network EoL performance. The performance metrics of the network segments are then combined to yield an EoL performance range for multiple network architectures (e.g., centralized N+6/ N+3/ N+0 and distributed N+0/ N+3/ N+6 architectures). Finally, DOCSIS 3.1 spectral efficiency analysis is performed for the various network architectures given their EoL performance ranges.

1. INTRODUCTION

Traffic demand has been continuously grwoing over the past two decades triggering signifcant research efforts to find ways to augment the capacity of Hybrid Fiber Coax (HFC) networks [1] [2] [3] [4] [5] [6]. As MSOs prepare their networks for DOCSIS 3.1, they keep wondering about the potential capacity gain that can be obtained as they deploy DOCSIS 3.1 in their networks. While the question may sound simple, the answer can potentially change from one MSO to another as various MSOs could have different networks in terms of:

1. Architecture: fiber link length, number of wavelengths on the fiber link, number of amplifiers in cascade, coaxial cables length, etc.
2. Components performance, age, and supported spectral limits
3. Plant noise and interference
4. Subscribers' in-home network (IHN) architecture
5. MSO maintenance practices
6. Others

It is important to note that the network EoL performance depends on the above parameters. In particular, estimating the network capacity offered by DOCSIS 3.1 requires detailed study of the network in question, where the performance of different segments of the network (source, fiber portion, coaxial portion, in-home network, CM performance) are characterized using field measurements.

Previous analyses were performed to estimate the potential DOCSIS 3.1 capacity gain based on measurements collected from 20 Million CMs on Comcast network [7]. Since the number of data points is large, the theory of large numbers holds true such that the analysis would represent the potential average capacity gain across the whole network fairly well. The DS and US results of those analyses were slightly updated and are summarized in Table 1 and Table 2, respectively. Figure 1 and Fig. 2 are also included to show the DS and US DOCSIS 3.1 spectral efficiency analysis with MSO Signal to Noise Ratio (SNR) operating margin of 0 dB, respectively [7].

The analysis presented in this paper is a continuation of the study summarized above, where network-specific analysis is performed. In particular, instead of performing the analysis based on measurements collected via large number of CMs located in different regions with various network architectures, the goal of the analysis included in this article is to perform DOCSIS 3.1 spectral gain analysis for a network of a specific configurable architecture. The initial thought was to obtain a probability density function (pdf) that describes the SNR performance of each of the network portions (e.g., source, various fiber links, multiple coaxial cascades/topologies, in-home network) through characterization based on theory, computer simulations, and field measurements.

\Table 1. Average DOCSIS 3.1 DS spectral efficiency and percentage improvement over DOCSIS 3.0

MSO SNR Operating Margin (dB)	D3.1 DS Spectral Efficiency (bps/Hz)		% improvement over D3.0 in DS Direction	
	4K FFT	8K FFT	4K FFT	8K FFT
0	7.6106	8.212217	20%	30%
1	7.36889	7.951399	16%	26%
2	7.129489	7.693074	13%	22%
3	6.899551	7.44496	9%	18%
4	6.688912	7.217669	6%	14%

Table 2. Average DOCSIS 3.1 US spectral efficiency and percentage improvement over DOCSIS 3.0

MSO SNR Operating Margin (dB)	D3.1 US Spectral Efficiency (bps/Hz)		% improvement over D3.0 in US Direction	
	2K FFT	4K FFT	2K FFT	4K FFT
0	6.65631	7.047349	60%	70%
1	6.41872	6.795801	55%	64%
2	6.1879	6.551421	49%	58%
3	5.957387	6.307366	43%	52%
4	5.721412	6.057529	37%	45%

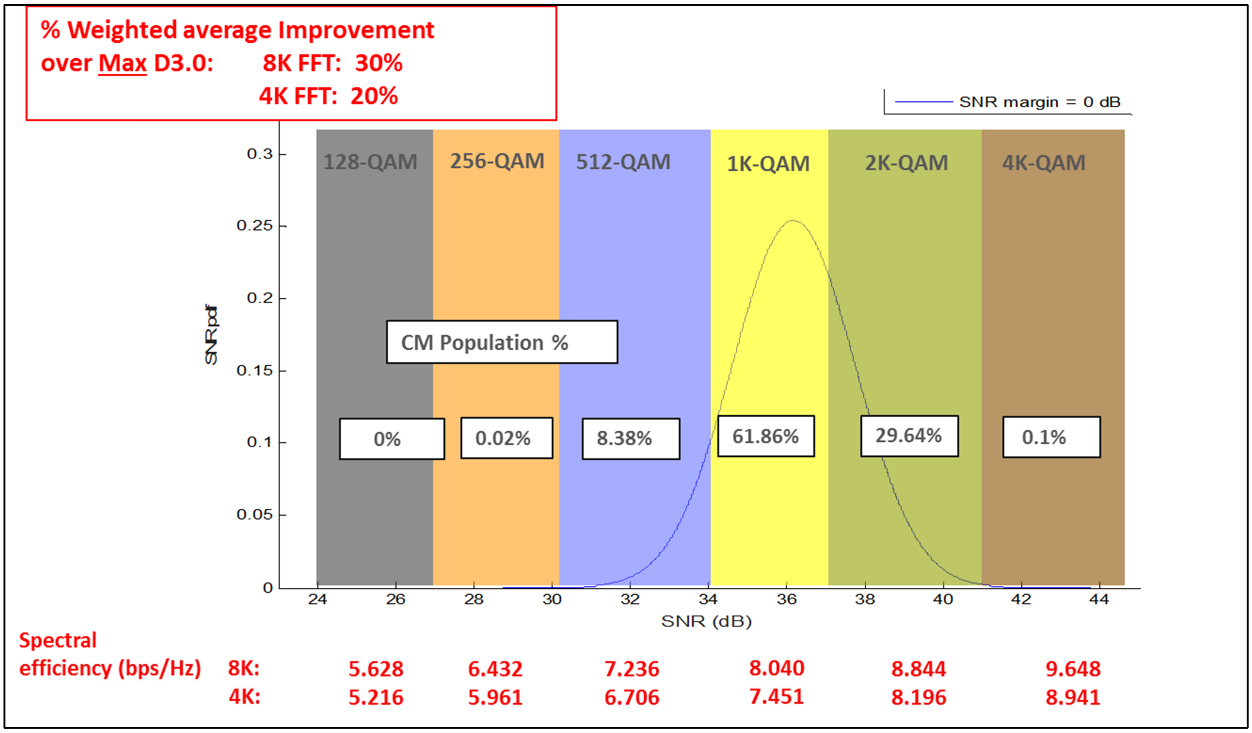

Figure 1. DOCSIS 3.1 Spectral efficiency analysis
with MSO SNR operating margin = 0 dB (DS Direction)

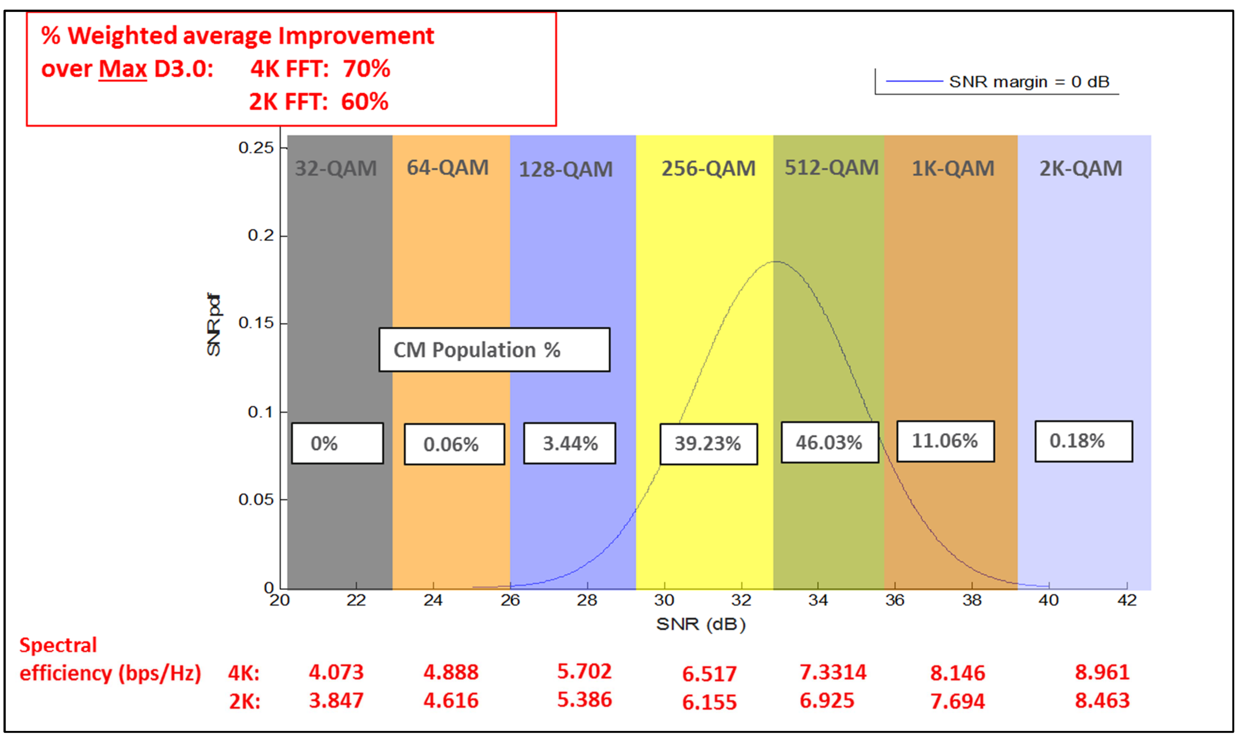

Figure 2. DOCSIS 3.1 Spectral efficiency analysis
with MSO SNR operating margin = 0 dB (US Direction)

The measurements that form the basis of the analysis presented this article were collected in collaboration with one of ARRIS' partner MSOs. What's unique about these collected measurements is that they are *location-aware* in the sense that the location of the CM reporting those measurements is known within the network topology. The analysis, which will be described later in this document, is not solely based on Modulation Error Ratio (MER) measurements but also takes Codeword Error Rate (CER) measurements into consideration due to the fact that MER measurements alone may not be sufficient to perform comprehensive analysis in some scenarios that will be explained later in the article. Other measurements (e.g., Tx power, Rx Power) were also collected to contribute to the analysis.

Performing an analysis on the collected field measurement revealed new facts manifesting a real-world twist to the above initial theoretical-oriented approach, where a network-specific pdf is generated based on convolving multiple pdfs. The results will show how the performance of multiple CMs on the same network (even at similar topology location) can be very different. In particular, the analysis of this paper will present scenarios where some portions of the network can actually dominate the whole network performance. Therefore, changing the network architecture (reducing the cascade length or moving to distributed architectures) does not necessarily add performance gain in those situations. In a nutshell, it will be shown that different CMs at similar locations in the same network can perceive the change in network architecture differently.

This paper is organized as follows. Section 2 describes the theoretical foundation for the analysis. Different cascade depths are characterized in section 3, where MER-based stochastic EoL performance analysis and potential D3.1 spectral efficiency gains analysis are presented. Section 4 shows the FEC analysis and relates that back to the MER-based analysis presented in Section 3. Different network segments are characterized and system EoL performance is generated for multiple architectures along with their corresponding DOCSIS 3.1 spectral efficiency gain in Section 5. Section 6 covers network optimization techniques that can be deployed to identify and resolve the performance limitations of HFC networks. Finally, Section 7 concludes the paper.

2. THEORITICAL FOUNDATION OF MER ANALYSIS

Assume that CNR_{EoL} represents the EoL Carrier to Noise Ratio (CNR) value (in dB) of a network that is composed of multiple segments (e.g., source, fiber, coax, tap/drop/In-home network/modem), as illustrated in Fig. 3. It can be shown that CNR_{EoL} is given by [8]

$$CNR_{EoL} = -10\log\left(10^{\frac{-CNR_S}{10}} + 10^{\frac{-CNR_F}{10}} + 10^{\frac{-CNR_C}{10}} + 10^{\frac{-CNR_{TDHM}}{10}}\right), \qquad (1)$$

Where CNR_s, CNR_F, CNR_C, and CNR_{TDHM} represent the CNR value, in dB, of the source, Fiber, Coax, and Tap/ Drop/ Home-Network/ Modem (TDHM) pieces, respectively.

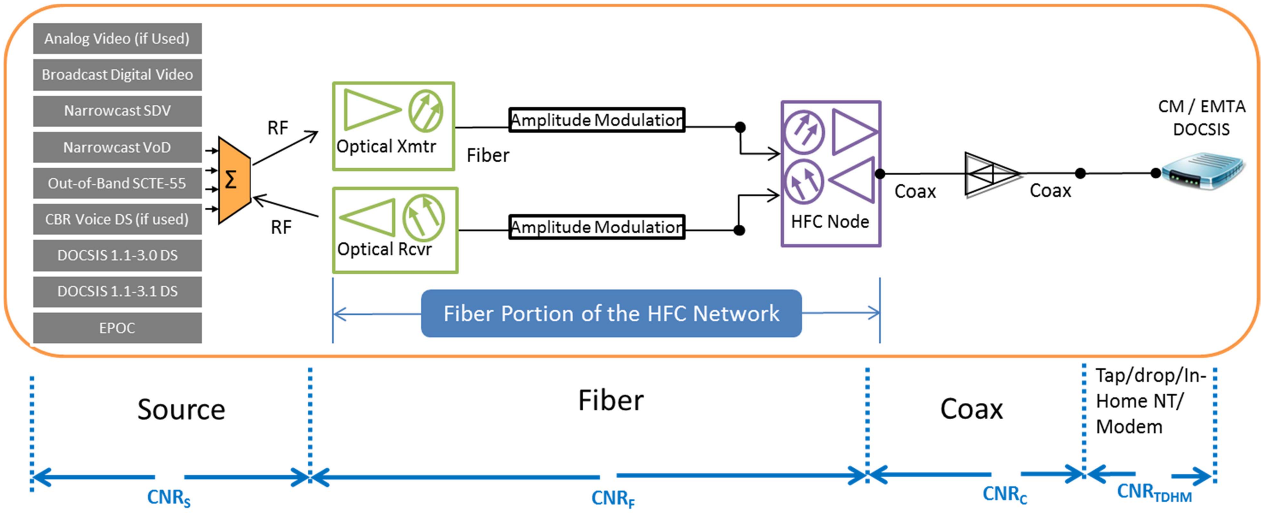

Figure 3. Different portions composing an HFC network

Since the focus of the article is to characterize different portions of the network efficiently, the article proposes a novel approach for estimating the CNR performance of different network portions solely based on the data measured at the CM. In particular, given the CNR values measured by CMs located in different places in the network, as shown in Fig. 4, the CNR of different portions of the network can be back-calculated using the following equations, which are derived from (1)

$$CNR_{optical} = -10\log\left(10^{\frac{-CNR_{node}}{10}} - 10^{\frac{-CNR_{source}}{10}}\right)$$

$$CNR_{RF1} = -10\log\left(10^{\frac{-CNR_{AMP1}}{10}} - 10^{\frac{-CNR_{node}}{10}}\right)$$

$$CNR_{TDHM2.1} = -10\log\left(10^{\frac{-CNR_{M2.1}}{10}} - 10^{\frac{-CNR_{AMP2}}{10}}\right), \quad (2)$$

Where $CNR_{optical}$, CNR_{RF1}, $CNR_{TDHM2.1}$ are the CNR values, in dB, as follows

- $CNR_{optical}$ is the CNR of the optical link,
- CNR_{RF1} is the CNR of the RF segment between node and AMP1 outputs
- $CNR_{TDHM2.1}$ is the CNR of the tap/ drop/ home-network segment that connects to Modem M2.1.

Additionally, $CNR_{M2.1}$ is the CNR measured at the input of CM M2.1 and CNR_{source}, CNR_{node}, CNR_{AMP1}, CNR_{AMP2} are the CNR values, in dB, at the output of the source, node, AMP1, and AMP2, respectively. Note that while CNR_{node}, CNR_{AMP1}, and CNR_{AMP2} in Fig. 4 could be measured in the field, it is not practical to do that. Therefore, the analysis avoids the need to measure those values in the field by introducing a novel methodology to estimate those values based on measurements collected by CMs at their corresponding locations. In particular, at any given place in the cascade, it can be safely assumed that the quality of the signal in the distribution network is equal to or better than the best signal quality observed at any modem within that section of the cascade. For example, the CNR value at the output of AMP 1, CNR_{AMP1}, can be safely assumed to be equal or higher than the CNR values measured by CMs M1.1 and M1.2. Moreover, CNR_{AMP1} has to be higher than or equal to CNR_{AMP2}. Given that CNR_{node}, CNR_{amp1}, and CNR_{amp2} can be estimated via the approach described above, the performance of different portions of the network can be approximated using (2). That is, it will be possible to calculate $CNR_{optical}$, CNR_{RF1}, CNR_{RF2}, CNR_{RF3}, $CNR_{TDHMx.x}$, etc.

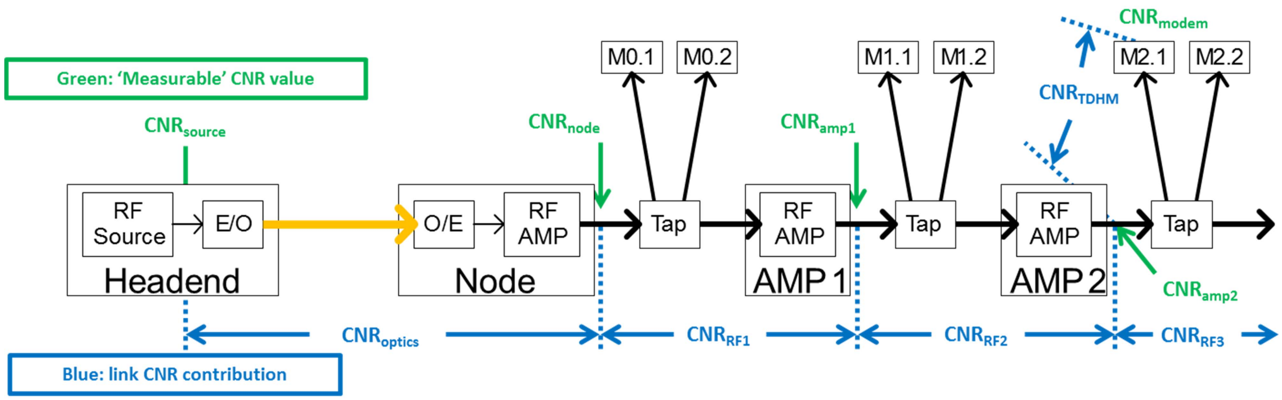

Figure 4. Estimating the performance of different portions of the network based on CM's CNR measurements

3. MER STOCHASTIC ANALYSIS & POTENTIAL DOCSIS 3.1 SPECTRAL EFFICIENCY

The MER analysis presented in this section is based on the concepts introduced in the previous section with field measurements collected from CMs of given locations. It is important to indicate that the analysis assumes that the measurements reported by the CM represent true MER values (i.e., not estimates of the channel CNR), which is true for most CMs. A sample set of collected measurements for a service node X1, where a fiber node is followed by 6 amplifiers in cascade (i.e., N+6) is shown in Table 3 with corresponding MER pdfs shown in Fig. 5. The X1 service group contained more than 500 customers. Note that the number of channels included in each row of Table 3 does not represent the number of unique channels servicing CMs in that segment but rather represents the absolute sum of all channels on all CMs in that segment (i.e., a channel can be counted multiple times). In particular, the total number of channels is equal to the number of measurements obtained by CMs in that segment because each CM provides a single measurement per channel and therefore one channel can correspond to multiple measurements each sourced from a different CM.

Observing the pdfs in Fig. 5, it is noted that there is large variations in MER values for CMs located at any cascade depth. The analysis in this section will try to study these curves and identify the sources of MER variations. For instance, MER measurements across different channel frequencies were collected as displayed in Table 4, where the results show that while the frequency of the channels whose MER were collected do contribute to the MER variation, those variations are minor and do not explain the range of MER variations shown in the pdfs.

Table 3. Reported MER measurements of CMs located in different cascade depths within service Node X1 (N+6 network)

N+x	Number of Channels	Number of Modems	Average MER (dB)	MER Stdev (dB)	Max MER (dB)	Min MER (dB)
0	45	10	37.66	0.46	38.7	36.8
1	181	35	37.88	1.13	42.1	30.1
2	546	124	37.48	1.08	41	31.8
3	507	104	37.59	1.36	42	30.5
4	708	143	37.41	0.90	41.6	34.2
5	179	37	37.12	0.61	38.8	33
6	401	81	37.09	1.25	41.4	33.7

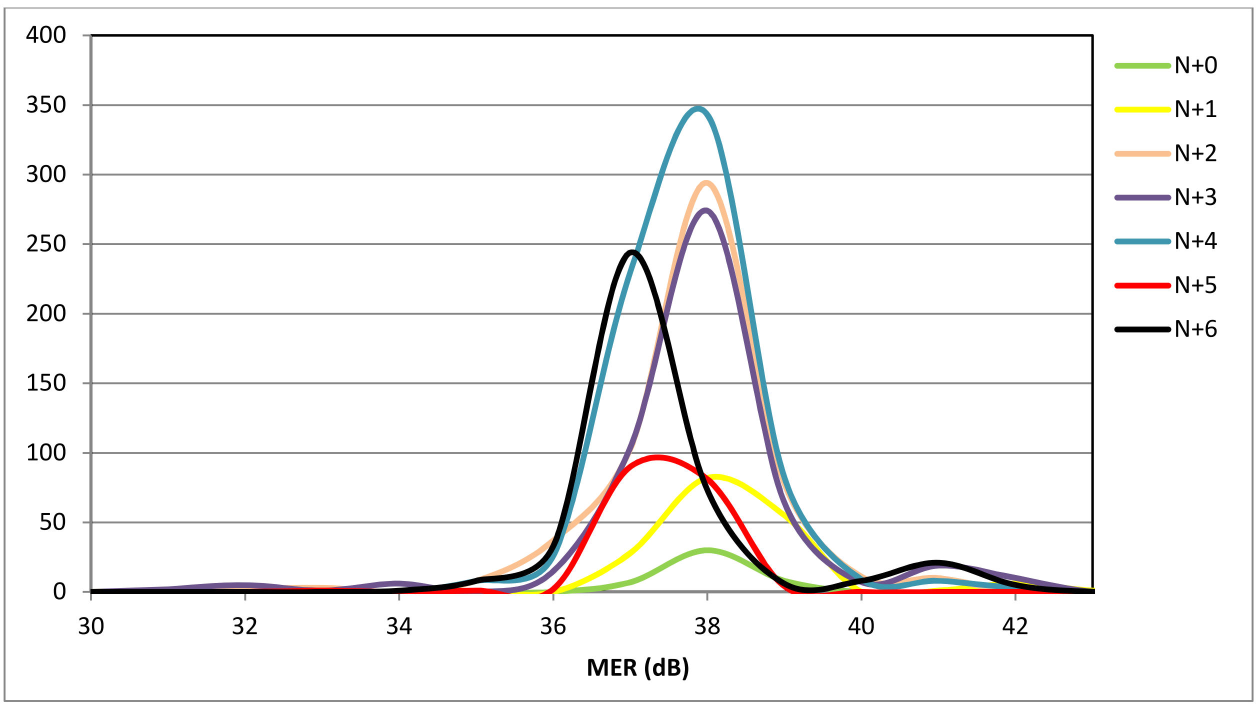

Figure 5. Distributions of MER values of a collection of CMs located in different cascade depths in Node X1 service group (N+6 network)

Table 4. Reported MER measurements vs channels frequencies

Channel Frequency (MHz)	Number of Channels	Average MER (dB)
603	361	37.44
615	363	37.24
609	351	37.32
627	341	37.31
621	325	37.11
633	333	37.19
639	339	37.10
645	348	36.94

Investigating the MER distributions shown in Fig. 5 brings up an interesting observation. The pdfs of MER values reported by CMs located at N+0/N+1/N+2/N+3/N+4 are similar. Moreover, there is only a slight shift for the pdfs corresponding to CMs at N+5/N+6 locations. One would naturally presume that deeper cascades will be manifested with a clear shift in the pdf as the location changes. To understand the underlying causes of the observed network behavior, more detailed MER analysis is performed. First, given that most of the pdfs looked similar; one potential reason for this situation could be that the optical link is limiting the performance (i.e., the bottle neck). Therefore, in order to verify or defy this assumption, the CNR value at the output of the optical link needs to be estimated using the MER values measured by the CMs.

However, before performing detailed CNR analysis for the optical link, it is worth noticing that CMs measure MER values that are calculated at the slicer. Those MER measurements include the modem's 'noise' contributions to the signal as it is received, demodulated, and decoded. Multiple CMs were characterized and it was found that the MER value reported by the CM tends to be close to the CNR value measured at the input of the CM when the CNR value is moderate (< 40 dB), where the background noise from the plan dominates the performance. On the other hand, when CNR values are high (> 40 dB), then the reported MER values will tend to be few dBs below CNR measured at the input of the CM mainly because the CM will be the dominant source noise contributions in this case. Several CMs were characterized to find an approximate mapping between the channel CNR value measured at the input of the CM and the CM's reported MER value so that comprehensive CNR analysis can be performed based on the available CMs MER values. For example, the maximum MER value of 41.4 dB as listed in Table 3 would correspond to a channel CNR of 43.2 dB. The rest of the analysis in this section is based on channel CNR values which correspond to the modems' measured MER values.

Given the CMs' measured MER values and the MER-CNR mapping, it is now possible to calculate the CNR value at the output of the fiber link (i.e., at the output of the fiber node) as originally intended. Recall that a CM located after the 6^{th} amplifier reported an MER value of 41.4 dB, which is equivalent to a CNR value of 43.2 dB at the input of that CM. Therefore, it is reasonable to assume that the CNR value at the output of the last amplifier (6^{th} amplifier) is at least 43.2 dB. Based on field experience, it is assumed that the CNR performance of the RF amplifier can range between 53 dB and 58 dB. Therefore, the CNR at the output of the fiber node considering the N+6 architecture of the network under investigation must be at least equal to the following

$$CNR_{node} = -10*\log(10^{(-43.2/10)}-(6*10^{(-53/10)})) = 47.5 \text{ dB} \quad \text{(Maximum)}$$

$$CNR_{node} = -10*\log(10^{(-43.2/10)}-(6*10^{(-55.5/10)})) = 45.1 \text{ dB} \quad \text{(Nominal)}$$

$$CNR_{node} = -10*\log(10^{(-43.2/10)}-(6*10^{(-58/10)})) = 44.2 \text{ dB} \quad \text{(Minimum)}$$

The above CNR_{node} values suggest that the performance of the optical link is comparable to the quality of the signal source and therefore it is concluded that the fiber link is not the performance limiter in this particular case. This can be observed in Fig. 6, which shows the above CNR_{node} values and the distribution of CNR values of node X1 on the same graph using a linear scale. Given that the fiber link and the 6-amplifier cascade are not the source of the performance limitation, it is very likely that the cause of performance degradation causing overlapping pdfs with wide MER measurement variations is an issue related to one or combination of the following: tap, drop, home network, or modem (TDHM).

Detailed CNR analysis is performed to verify that the one or combination of TDHM is the likely cause of performance degradation in this case. In particular, the minimum/average/maximum MER values reported by the CMs were identified for each cascade section as shown in Fig. 7. Note that while the figure shows reported MER values, the analysis was performed using CNR levels. Figure 7 shows that the MER value at the output of the 6th amplifier (AMP6) must be at least 41.4 dB because that value was reported by multiple CMs in that section of the cascade. The MER at the output of AMP5 must be at least 41.4 dB which is equal to the minimum MER at the output of AMP 6. Note that the CMs in the cascade section following AMP5 reported a maximum MER value of 38.8 dB. Since the MER value at the output of AMP6 (i.e., 41.4 dB) is larger than the maximum MER value reported by any CM in the cascade following AMP5 (38.8 dB), then the former was used to indicate the minimum MER value observed at the output of AMP5.

In a nutshell, the minimum MER value at the output of any amplifier (say AMPx) is equal to the maximum of 1) MER value at the output of the next amplifier (i.e., AMPx+1) and 2) the maximum reported MER value in the cascade section following AMPx. Following the same logic, the MER value at the output of amplifiers AMP4, AMP3, AMP2, and AMP1 must be at least 41.6 dB, 42 dB, 42 dB, and 42 dB, respectively. Similarly, the MER value at the output of the fiber node must be at least 42 dB. Note that while Fig. 7 and the description above use MER values, the actual analysis was performed using CNR values.

The analysis proceeds further in effort to estimate specific values for CNR at the output of the amplifiers instead of estimating lower limits as was shown in Fig. 7. In particular, the CNR is back-calculated based on the CNR value at the output of the next amplifier assuming an average amplifier performance of 55.5 dB. That is, the CNR at the output of AMP5 is back-calculated using the CNR at the output of AMP6 (43.2 dB) assuming AMP6 performance of 55.5 dB as follows

$$CNR_{AMP5\text{-back-calculated}} = -10*\log(10^{(-43.2/10)}-(10^{(-55.5/10)})) = 43.5 \text{ dB}$$

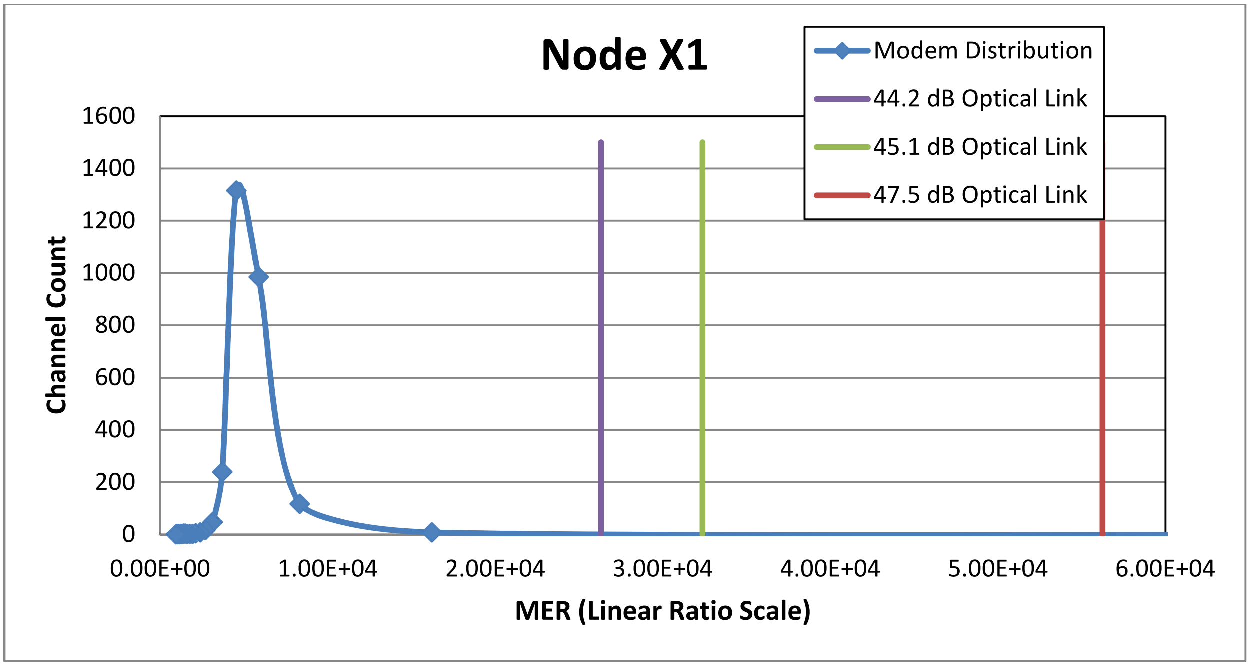

Figure 6. Node X1 CNR distribution and optical links CNR values showing that the optical link is not likely the source of performance degradation in Node X1

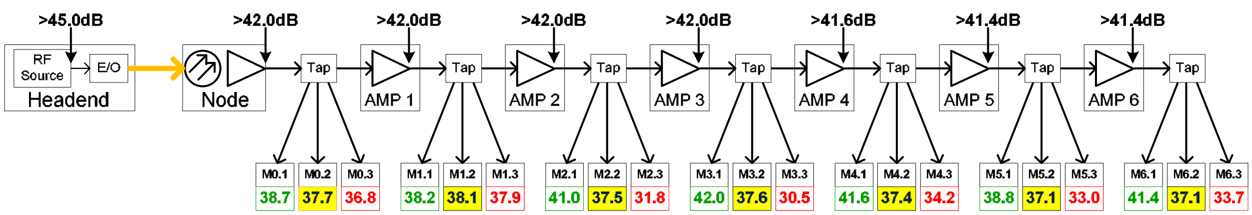

Figure 7. Minimum/Average/Maximum reported MER values by CMs in different cascade sections

The final estimated CNR value at the output of AMP5 is the maximum of two values, where the first value is the back-calculated CNR value above and the second value is the CNR that is equivalent to the maximum measured MER in the cascade section following AMP5 (i.e., CNR=MER = 38.8 dB). Therefore, the CNR at the output of AMP5 is estimated to be max(43.5, 38.8) = 43.5 dB. The CNR values at the output of the other amplifiers/node are calculated sequentially as summarized in Table 5.

Note that the CNR values at the output of different amplifiers within the cascade, which are estimated in Table 5, represent the achievable performance delivered to the tap within that cascade section. Therefore, comparing the CNR value at the input of the CM with that which is estimated at the amplifier/node output (i.e., delivered to the tap) can characterize the performance of the piece(s) between those two end points.

Specifically, comparing the tap CNR values with the average and minimum CNR values reported by CMs in corresponding locations, as summarized in Table 6, can show that at each point in the cascade:

- There is 9.3 dB - 15.1 dB difference in CNR between the worst CM and the amplifier/node serving that modem
- There is 6.1 dB - 8.4 dB difference in CNR between an average CM and the amplifier/node serving that modem

The above results suggest that, for significant number of modems in this service group, the link performance is dominated by one or combination of the following network pieces: tap, drop, in-home network, and the modem (TDHM).

It is critical to realize that these CMs whose link performance is dominated by one or a combination of the TDHM pieces will not likely perceive a large benefit of plant upgrade where N+0 and/or distributed architectures are implemented as a strategy to enhance the performance and increase the network capacity. In order to put this in perspective, DOCSIS 3.1 spectral efficiency analysis was performed for CMs with highest, average, and minimum performance using the assumptions listed in Table 7. In this spectral efficiency analysis, Additive White Gaussian Noise (AWGN) is assumed, the spectral efficiency is calculated for several SNR Gaussian distributions with the following mean values (dB): 30.5, 34, 37, 41, 45, and 49 as shown in Fig. 8. The analysis assumed a Gaussian SNR distribution with 1.18 dB standard deviation to match the MER field measurements. This analysis, depicted in Fig. 9, was performed in a similar way to that provided in [7], which also assumed that the average SNR was reduced by 0.25 dB to compensate for pilot boosting. DOCSIS 3.1 CMs are assumed to be robust to phase noise such that the optional QAM16K modulation order can be supported. The summary of the analysis is shown in Fig. 10.

Table 5. Estimating the CNR value at the output of different amplifiers within the HFC cascade

Parameter	Note	N+6	N+5	N+4	N+3	N+2	N+1	Node (N+0)
Number of Modems		81	37	143	104	124	35	10
Estimated Modem CNR (dB)	Max	43.2	38.8	43.7	44.8	42.3	45.1	38.7
back-calculated Node/AMP output CNR (dB)			43.5	43.7	44.0	45.2	45.6	46.1
Estimated Node/AMP output CNR (MAX[,]) (dB)		43.2	43.5	43.7	44.8	45.2	45.6	46.1

Table 6. Comparing average and minimum CM CNR values
with serving amplifier/node CNR value

Parameter	Note	N+6	N+5	N+4	N+3	N+2	N+1	Node (N+0)
Estimated Node/AMP output CNR (MAX[,]) (dB)		43.2	43.5	43.7	44.8	45.2	45.6	46.1
Estimated Modem CNR (dB)	Mean	37.1	37.1	37.4	37.6	37.5	37.9	37.7
CNR Delta from Node/Amp (dB)	Mean	6.1	6.4	6.3	7.2	7.7	7.7	8.4
Estimated Modem CNR (dB)	Min	33.7	33	34.2	30.5	30.5	30.1	36.8
CNR Delta from Node/Amp (dB)	Min	9.5	10.5	9.5	14.3	14.7	15.5	9.3

Table 7. DOCSIS 3.1 parameters assumed for the spectral efficiency analysis

Parameter	Assumption Value
Channel size	*Synchronous* 192 MHz with 190 MHz active spectrum
Subcarrier spacing	25 kHz
FFT size	8K (8192)
FFT duration	40 usec
Subcarriers in 192 MHz	7680
Active subcarriers in 190 MHz	7600
Guard band (2MHz total)	80 subcarriers
Continuous Pilots	88
Scattered pilots	60
PLC subcarriers	16
CP duration	2.5 usec
NCP subcarriers	48
Effective FEC code rate	0.8785

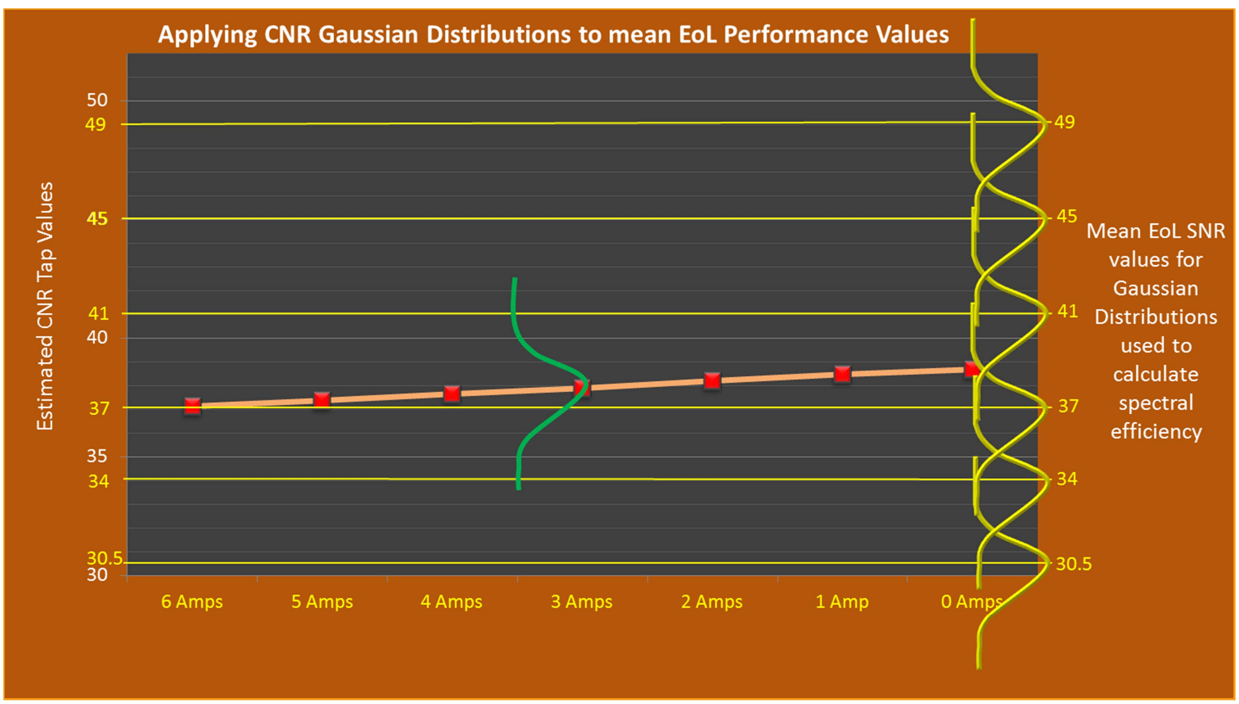

Figure 8. Calculation of DOCSIS 3.1 spectral efficiency for different CNR values: Gaussian CNR distributions are assumed with 1.18 dB standard deviation. Analysis was performed for several mean values: 30.5, 34, 37, 41, 45, and 49 dB

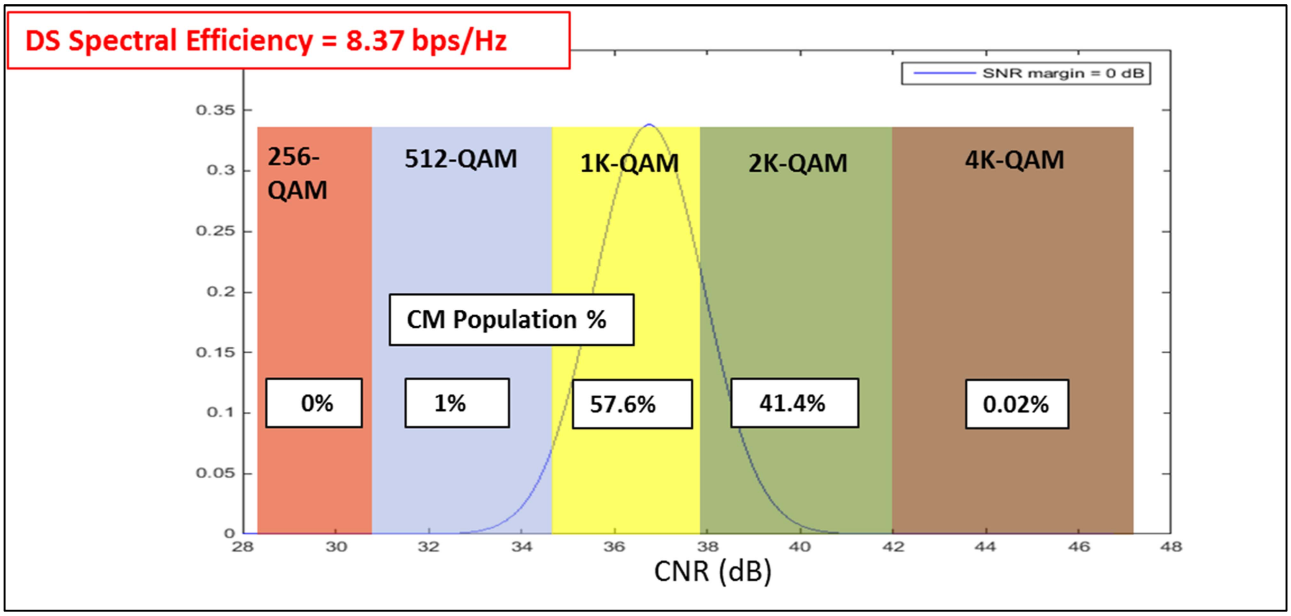

Figure 9. DOCSIS 3.1 DS spectral efficiency analysis for Gaussian CNR distribution with mean value of 37 dB and 1.18 dB standard deviation (with 0.25 dB pilot boosting compensation). Net spectral efficiency is 8.37 bps/Hz for mean SNR of 37 dB

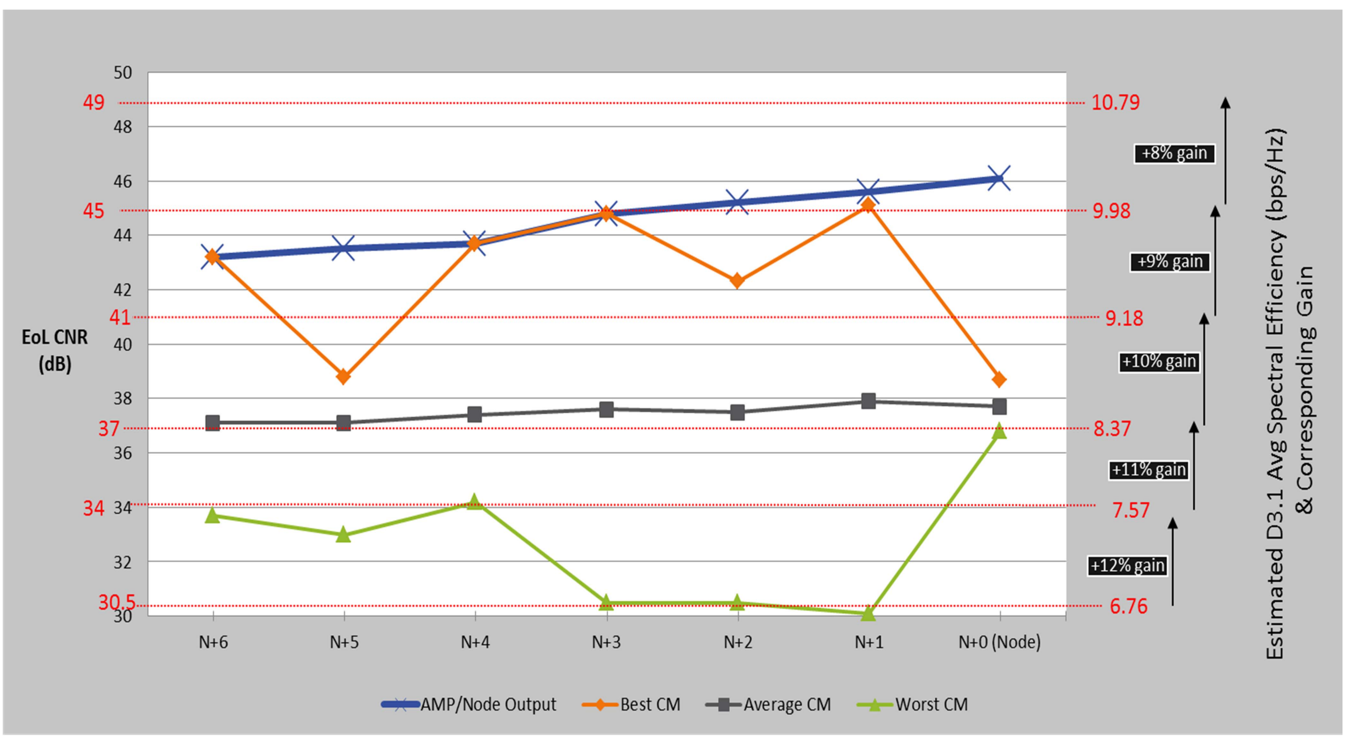

Figure 10. Spectral Efficiency for CMs with worst/average/best CNR performance based on EoL CNR values corresponding to MER values collected from CMs in service node X1 (N+6 network)

It can be noted from Fig. 10 that the lowest performing CMs gain very little benefit as the architecture is upgraded to smaller cascades or distributed architecture. In fact, the performance drops in some cases! Average performing CMs in this service group achieve marginal benefit while the best performing CMs get to their best capacity potential as plant upgrades are implemented. Moreover, it is critical to observe that subscribers located in the same cascade section can see very different performance due to differences in the performance of the TDHM pieces that correspond to their link. Observe that all CMs at the N+0 location performed similarly suggesting that they have comparable drop/tap performance.

To verify the above results, a laboratory experiment was created with an N+3 network as shown in Fig. 11. The network had 4 amplifiers, 62 modems, 93 active channels and represented 15 km of fiber and over 5,700 feet of coaxial cable. The CNR values that correspond to the collected MER measurements from the CMs are summarized in Table 8, where it can be observed that CNR variations throughout the network are minimal and the CNR does not increase significantly as the cascade depth decreases. This is especially true when the cascade (i.e., rigid cable) part of the HFC does not dominate the performance, which is true for most real-world networks.

Tracing back to the field measurements, many service groups were investigated and few sample results are included here (e.g., service nodes X2, X3, and X4). Some nodes showed similar performance to node X1's performance, where one or combination of the TDHM pieces dominated the performance. For example, the node X2 with summary measurements listed in Fig. 12, Table 9, and Table 10, show that the performance for large percentage of CMs in this service group is dominated by the one or combination of the TDHM pieces. Specifically, the pdf's are overlapping and the tables show that at each point of the cascade:

- There is 5.3 dB - 10.1 dB difference in CNR between the worst CM and the amplifier/node serving that modem
- There is 2.7 dB - 9.4 dB difference in CNR between an average CM and the amplifier/node serving that modem

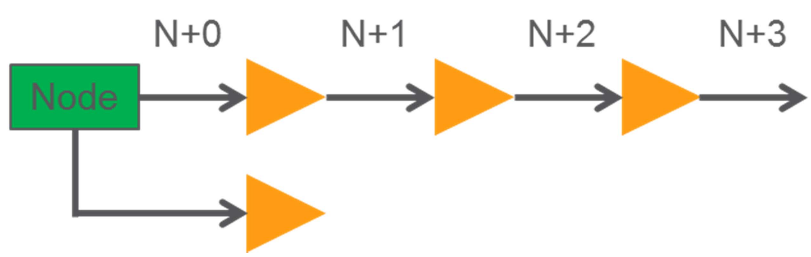

Figure 11. Laboratory experiment to investigate CNR vs. Cascade length

Table 8. CNR values measured at CMs located at different cascade depths in network shown in Fig. 11

N+x	Number of Channels	Average CNR (dB)	CNR Stdev (dB)	Min CNR (dB)	Max CNR (dB)
0	17	44.5	0.63	43.40	45.40
1	36	44.1	0.81	41.10	45.40
2	21	44.3	0.49	43.20	45.30
3	19	43.7	0.57	42.50	44.60

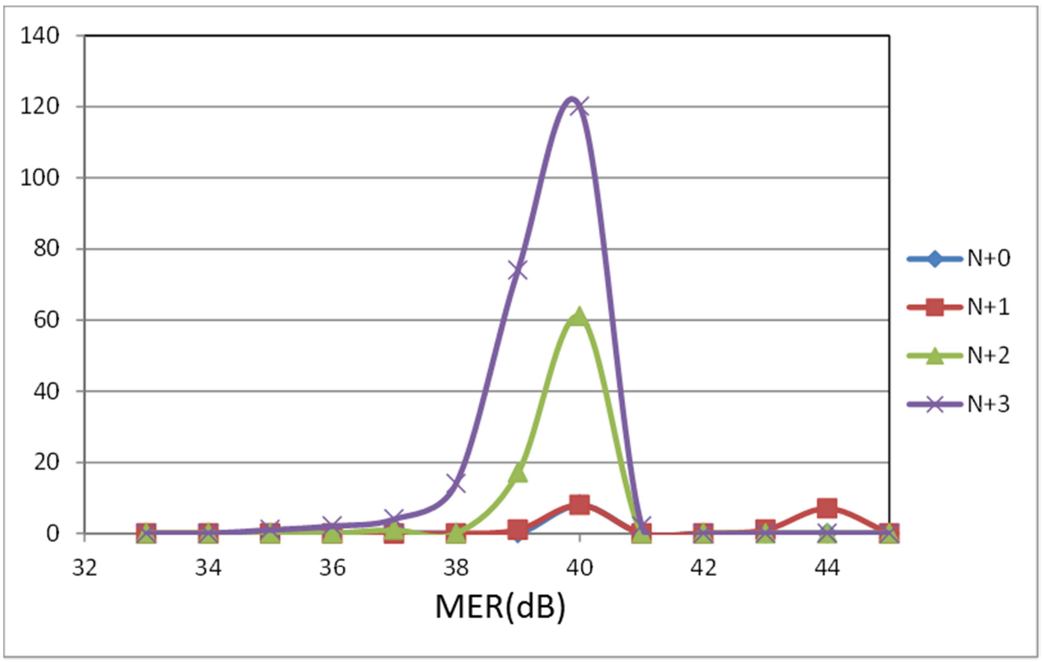

Figure 12. Pdf of MER values collected from CMs in service Group X2 (N+3 network)

Table 9. Summary of CNR values corresponding to MER values collected from CMs in service Group X2 (N+3 network)

N+x	# CMs	# Ch	CNR (dB)			
			Min	Avg	Max	σ
0	1	8	39.3	39.55	39.8	0.27
1	3	17	38.1	41.26	43.9	2.22
2	16	79	36.8	39.31	40.0	0.55
3	35	217	34.7	38.92	40.8	0.77

Table 10. Summary of CNR Analysis for service Group X2 (N+3 network)

Parameter	Note	N+3	N+2	N+1	Node (N+0)
Number of Modems		35	16	3	1
Estimated Modem CNR (dB)	Max	41.9	40.5	48.2	40.1
Back-calculated Node/AMP output CNR (dB)			42.1	42.3	49.1
Estimated Node/AMP output CNR (MAX[,]) (dB)		41.9	42.1	48.2	49.1
Estimated Modem CNR (dB)	Mean	38.9	39.4	42.9	39.7
CNR Delta from Node/Amp (dB)	Mean	3.0	2.7	5.3	9.4
Estimated Modem CNR (dB)	Min	34.7	36.8	38.1	39.4
CNR Delta from Node/Amp (dB)	Min	7.2	5.3	10.1	9.7

Several other service groups showed different behavior than node X1's performance, where the performance was either not completely dominated by the TDHM pieces or the performance was very good throughout the whole node. For instance, node X3 with measurements shown in Fig. 13 and with an analysis summarized in Table 11 indicates that while part of the performance is dominated by one or combination of the TDHM pieces, other factors affecting the performance are not far behind. This can be concluded from the analysis summary, where at each point in the cascade.

- There is 2.1 dB – 6.3 dB difference in CNR between the worst CM and the amplifier/node serving that modem
- There is 1.3 dB – 3.3 dB difference in CNR between an average CM and the amplifier/node serving that modem

Another service group example where the node performance was different from node X1's performance is node X4 with measurements summarized in Table 12, Table 13, Fig. 14, and Fig. 15. Observe that the analysis summary shows that the performance for the majority of CMs in this service group is very good, where *only* the lowest performing CMs are dominated by one or combination of the TDHM pieces. This is because at any point in the cascade

- There is 1.7 dB – 6.9 dB difference in CNR between the worst CM and the amplifier/node serving that modem
- There is 1.1 dB – 1.8 dB difference in CNR between an average modem and the amplifier/node serving that modem

The above observations suggest that the majority of the CMs are *not* dominated by the TDHM pieces. The degradation of about 2 dB at most is contributed to other factors like the shortage in the RF power levels where the low RF levels tend to limit the CNR levels as shown on the left side of Fig. 15.

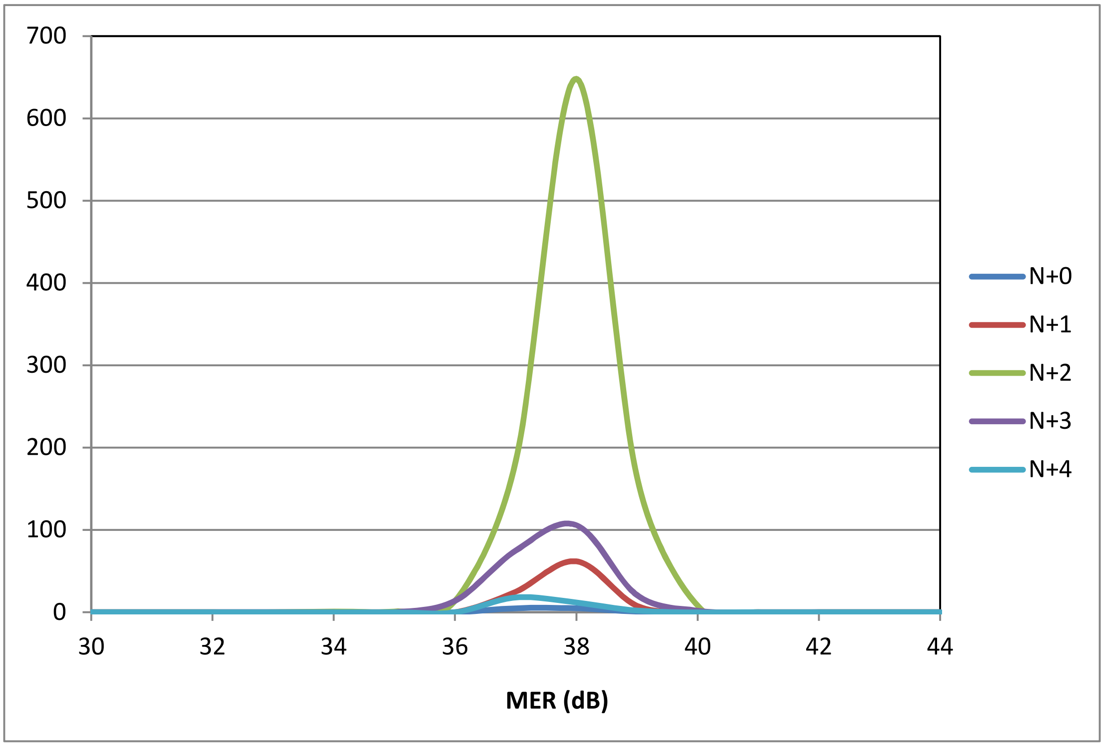

Figure 13. Pdf of MER values collected from CMs in service Group X3 (N+4 network)

Table 11. Summary of CNR Analysis for service Group X3 (N+4 network)

Parameter	Note	N+4	N+3	N+2	N+1	Node (N+0)
Number of Modems		8	38	201	18	3
Estimated Modem CNR (dB)	Max	38.4	39.5	40.3	38.2	38.1
back-calculated Node/AMP output CNR (dB)			38.5	38.7	40.4	40.6
Estimated Node/AMP output CNR (MAX[,]) (dB)		38.4	38.6	40.3	40.4	40.6
Estimated Modem CNR (dB)	Mean	37.1	37.3	37.6	37.5	37.3
CNR Delta from Node/Amp (dB)	Mean	1.3	1.3	2.7	2.9	3.3
Estimated Modem CNR (dB)	Min	36.3	35.4	34	36.3	36.6
CNR Delta from Node/Amp (dB)	Min	2.1	3.2	6.3	4.1	4.0

Table 12. Summary of CNR values corresponding to MER values collected from CMs in service Group X4 (N+3 network)

N+x	# CMs	# Ch	SNR (dB)				RF Power (dBmV)			
			Min	Avg	Max	σ	Min	Avg	Max	σ
0	5	40	37.3	37.9	38.2	0.2	-1.5	4.7	15.5	5.8
1	4	18	35.0	37.1	38.8	1.0	1.1	3.2	6.0	1.2
2	44	226	32.9	37.1	38.8	0.8	-9.9	-1.5	12.1	5.4
3	41	208	31.7	36.8	38.6	1.1	-9.7	-1.8	11.0	5.6

Table 13. Summary of CNR Analysis for service Group X4 (N+3 network)

Parameter	Note	N+3	N+2	N+1	Node (N+0)
Number of Modems		41	44	4	5
Estimated Modem CNR (dB)	Max	38.6	38.8	38.8	38.2
back-calculated Node/AMP output CNR (dB)			38.7	38.9	39.0
Estimated Node/AMP output CNR (MAX[,]) (dB)		38.6	38.8	38.9	39.0
Estimated Modem CNR (dB)	Mean	36.8	37	37.1	37.9
CNR Delta from Node/Amp (dB)	Mean	1.8	1.8	1.8	1.1
Estimated Modem CNR (dB)	Min	31.7	32.9	35	37.3
CNR Delta from Node/Amp (dB)	Min	6.9	5.9	3.9	1.7

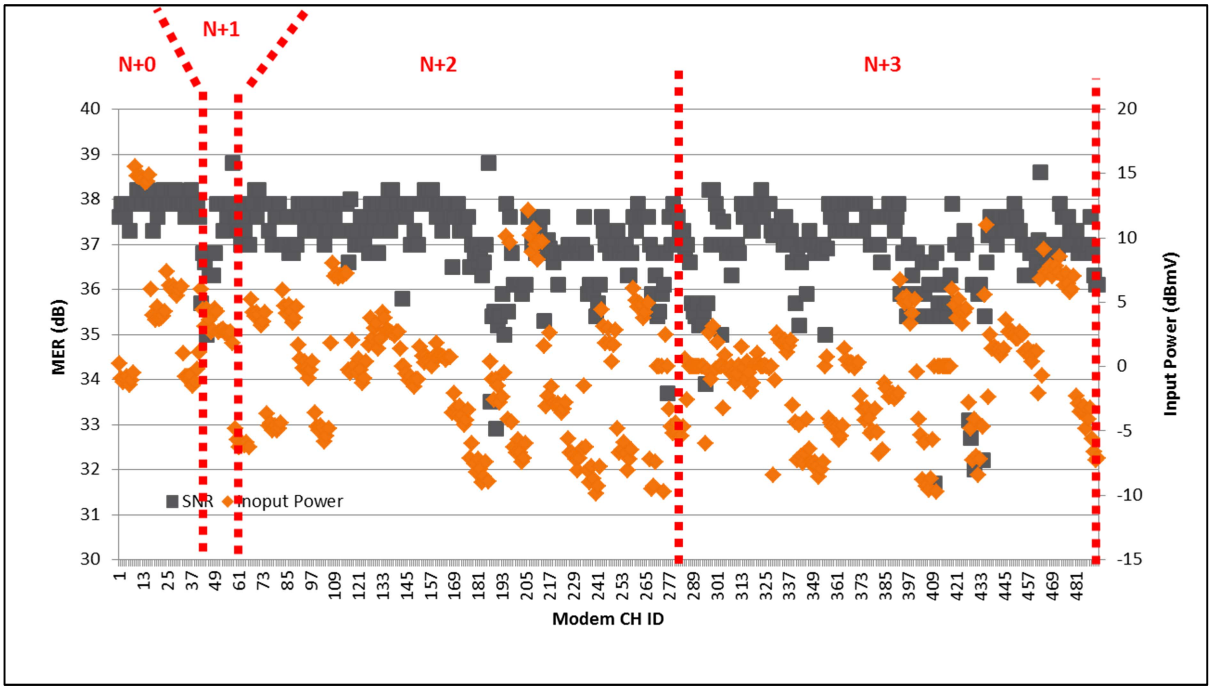

Figure 14. Cascade depth vs. RF power levels and MER values collected from CMs in service Group X4 (N+3 network)

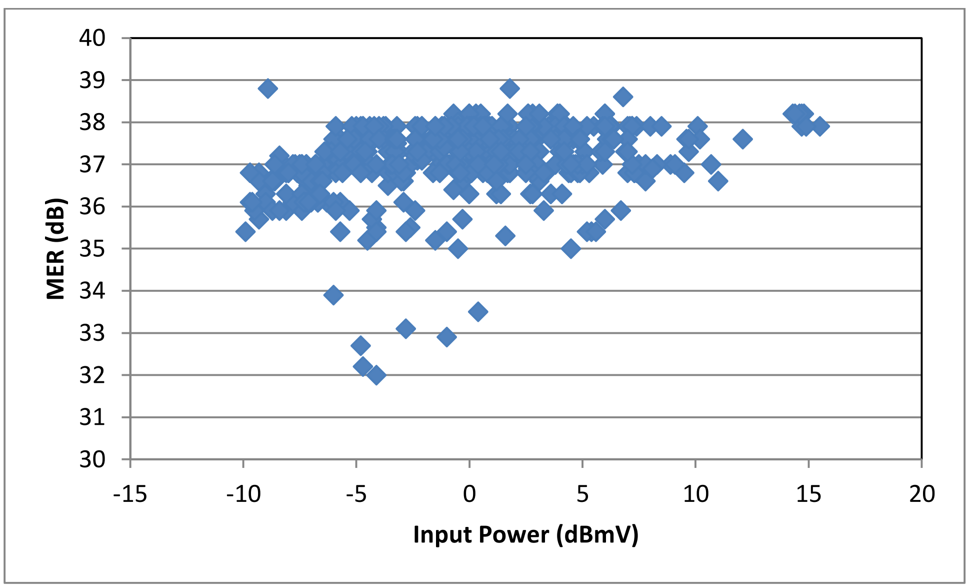

Figure 15. RF power levels vs. MER values collected from CMs in service Group X4 (N+3 network) showing RF levels limiting CNR performance

4. FEC ANALYSIS

It should be understood that for the EoL performance and spectral efficiency analyses to be comprehensive, other field measurements beyond MER values may need to be considered. This is due to the fact that average MER measurements reported by the CMs may not reflect the plant actual CNR when the CNR values are high and also MER measurements may not reflect all types of plant noise and distortion. For example, the infrequent and irregular impulse noise events may not drop the average MER value reported by the CM. Similar behavior can also occur with optical/electric distortions as will be explained later in this section.

There are many parameters that can be collected in addition to the MER values to yield more comprehensive analysis. For instance, the RF signal levels measured at the CMs located in different parts of the cascades can help reveal plant issues and/or sources of performance degradation in some cases as was explained in the previous section. Another example of helpful parameters that can be collected via CMs is FEC codeword error statistics before and after FEC decoding is applied. FEC statistics are of significant importance as they indicate the actual performance level of the CM. In particular, the effect of any plant issue causing performance degradation and/or affecting customer service can be observed via collecting these counts.

It is important to realize that codewords errors can actually occur with CMs reporting high MER values. For example, Table 14, Fig. 16, and Fig. 17 show the error statistics for CMs within node X1 service group, where pre- and post-FEC events actually occurred with MER values making the two parameters look independent in those cases.

Table 14. Number of channels with pre- and post- FEC CWs corresponding to error threshold values in node X1

CER	# of channels with Pre-FEC	# of channels with Post-FEC
0	13	21
1E-10	0	0
1E-9	0	0
1E-8	1	0
1E-7	5	1
1E-6	2	594
1E-5	1661	2059
1E-4	1003	10
1E-3	0	0
1E-2	0	0

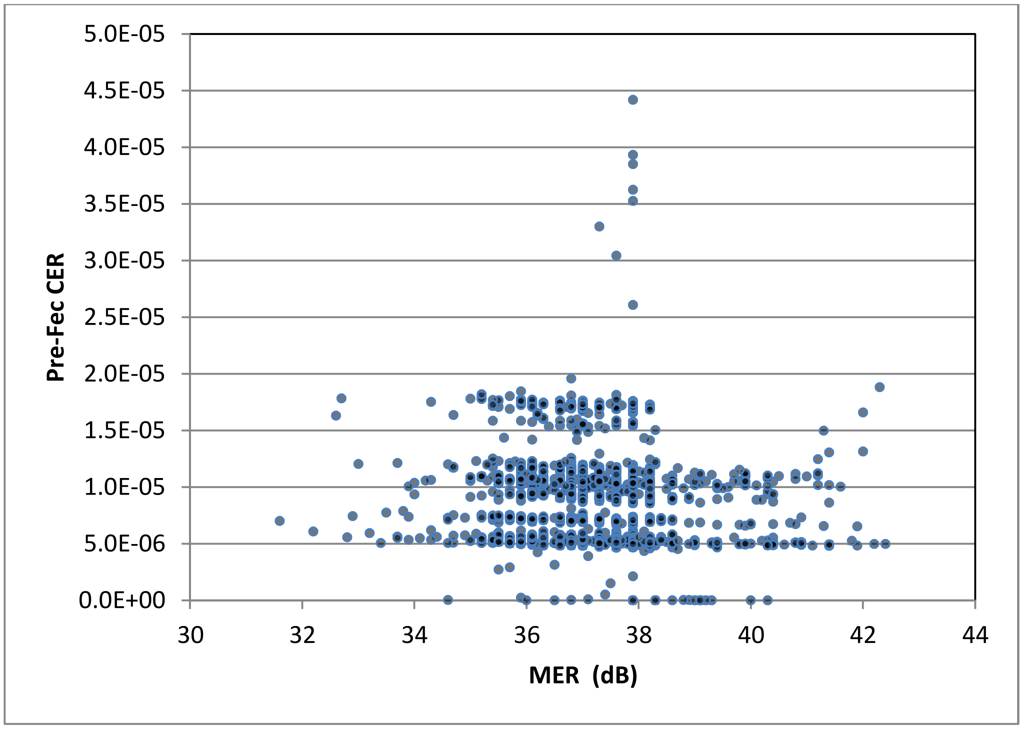

Figure 16. Pre-FEC counts vs. CNR levels corresponding to MER values reported by CMs in Node X1

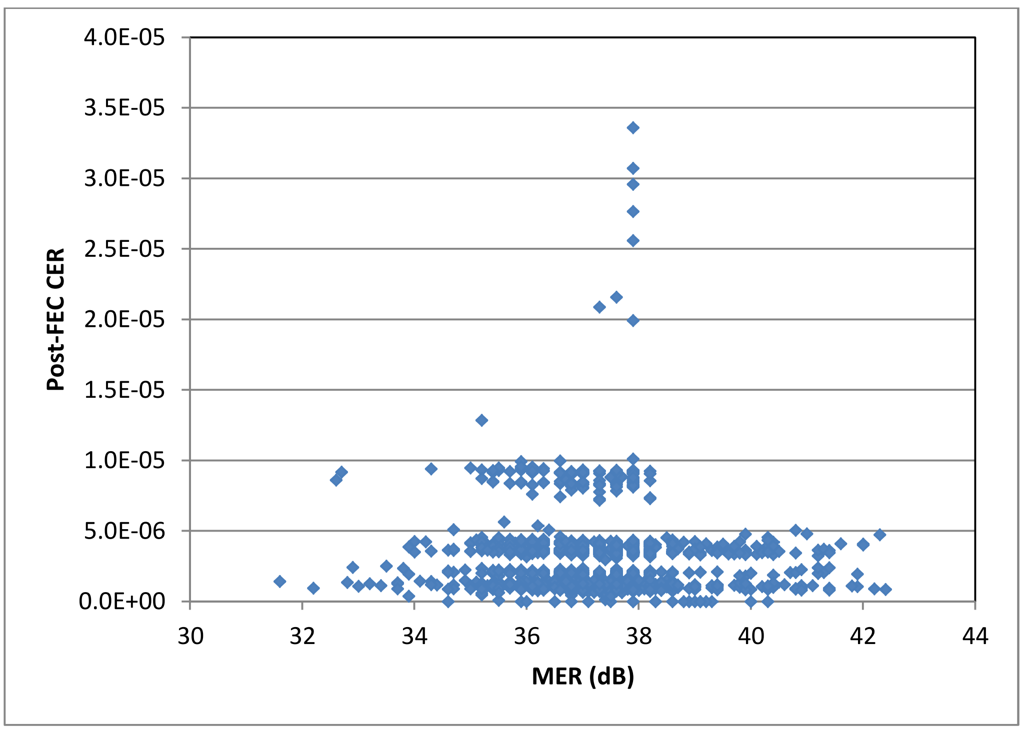

Figure 17. Post-FEC counts vs. CNR levels corresponding to MER values reported by CMs in Node X1

It was mentioned earlier that impulse noise events can cause such a scenario where FEC codeword errors are observed with high MER values. Another plant event that can cause this is distortion. In order to verify this, a laboratory experiment was conducted, where an amplifier was configured to introduce distortion products. The received signal is demodulate and decoded using a Sunrise Quadrature Amplitude Modulation (QAM) analyzer and a DOCSIS CM. The statistics reported by the Sunrise analyzer and the DOCSIS CM are summarized in Table 15, which actually shows correlation with the results observed in Fig. 16 and Fig. 17, where FEC errors can actually occur with high reported MER values (e.g., 40 dB).

This suggests that node X1 could have had distortion events, which were service impacting due to the fact there was significant number of channels with nonzero post-FEC errors. Similar to the previous nodes analyzed, the MER performance of this node is limited by one or combination of the TDHM pieces. However, due to the impact of distortion on the ability of the modem to correct codeword errors, it is likely that the optical modulation index (OMI) of this transmitter would need to be lowered in order to support higher orders of modulation.

Similar FEC statistics were collected for the three nodes discussed in the previous (i.e., X2, X3, and X4 with results summarized in Tables 16, 17, and 18 for service nodes X2, X3, and X4, respectively. Note that the events that caused pre-FEC errors in these service groups were not service impacting because it can be easily observed from these tables that most of the errors were corrected by the FEC decoder yielding insignificant number of channels with nonzero post-FEC errors.

Table 15. Distortion can cause pre- and post- FEC CWs event with high MER values

Sunrise QAM Analyzer @825MHz			Modem 1 @825MHz			Modem 2 @831MHz		
MER (dBc)	Pre-FEC BER	Post FEC BER	MER (dBc)	Pre-EFC CER	Post FEC CER	MER (dBc)	Pre-EFC CER	Post FEC CER
37.7	1.0E-04	1.0E-06	37.5	7.0E-02	5.4E-04	36.4	1.2E-01	2.2E-03
40.2	2.0E-05	5.0E-08	39.5	1.3E-02	1.8E-05	38.6	2.5E-02	6.6E-05
42.0	5.0E-07	0.0E+00	40.8	4.0E-04	3.0E-07	39.8	8.0E-04	5.0E-07

Table 16. Number of channels with pre- and post- FEC CWs corresponding to error threshold values in node X2

CER	# of channels with Pre-FEC	# of channels with Post-FEC
0	191	308
1E-10	0	0
1E-9	0	0
1E-8	11	0
1E-7	100	0
1E-6	7	1
1E-5	0	3
1E-4	2	1
1E-3	2	0
1E-2	0	0

Table 17. Number of channels with pre- and post- FEC CWs corresponding to error threshold values in node X3

CER	# of channels with Pre-FEC	# of channels with Post-FEC
0	1	1301
1E-10	0	0
1E-9	0	0
1E-8	2	0
1E-7	1051	2
1E-6	248	13
1E-5	16	13
1E-4	14	6
1E-3	4	1
1E-2	0	0

Table 18. Number of channels with pre- and post- FEC CWs corresponding to error threshold values in node X4

CER	# of channels with Pre-FEC	# of channels with Post-FEC
0	5	461
1E-10	0	0
1E-9	0	0
1E-8	1	0
1E-7	143	0
1E-6	309	1
1E-5	4	0
1E-4	24	24
1E-3	2	2
1E-2	0	0

The above measurements and analyses show that the potential capacity gain or delivered service level in a network should not be taken for granted when performing MER-based analyses. In particular, it is important to collect FEC measurements to verify that the MER values that represent the base of the analysis actually reflect the real plant situation of the network under question.

5. PERFORMANCE OF DIFFERENT NETWORK SEGMENTS, NETWORK EOL PERFORMANCE, AND POTENTIAL DOCSIS 3.1 SYSTEM CAPACITY

The performance analysis that was presented in section 3 characterized the coaxial portion of the network (i.e., cascade, TDHM). The analysis in this section builds on top of that analysis to characterize the performance of the optical links. Recall that the analysis in section 3 proposed a methodology to estimate the CNR value at the output of the fiber node for some example cases. Large numbers of service nodes were analyzed offline for the network in question and it was found that many of the nodes were able to achieve about 45 dB CNR at the output of the fiber node (similar to node X1's node output CNR estimated value in Table 5).

Assuming a node's output CNR of 45 dB and a typical QAM signal source CNR range of 48-50 dB, then the performance of the fiber links is estimated to be about 47-48 dB, which is in agreement with published numbers [9] and is comparable to the quality of the QAM signal source. Computer simulations were performed to validate the results, where C-band optics were simulated with +9 dBm launch power, 1GHz video loading with optical modulation index of 33%, and receiver power set to -1dBm to 1 dBm. The results of the computer simulations are displayed in Fig. 18, which show that one wavelength over 30 km fiber link has about 48 dB CNR which agrees with the above conclusions.

Given the analysis presented thus far in this article, the performance of different portions of the N+6 network in question can be deduced as shown in Table 19, where the performance ranges for different segments (source, optical link, RF trunk, tap, drop, in-home network (IHN), modem) were extended to accommodate wider selection of equipment performance, network parameters, and time/temperature variations. In fact, over the course of collecting field measurements and analyzing them, it was observed that MER typically varies by 1- 3 dB per week, over time and temperature while RF power typically varied by 1 – 5dB per week, over time and temperature.

To pictorially depict the importance of performance ranges listed in Table 19, the noise contributions from each of these network portions are shown in Fig. 19, which plots the inverse of linear CNR values. Observe that the noise contributions from the TDHM pieces are significant for low performing CMs in this scenario.

The performance of an N+3 and N+0 networks can be inferred based on the values presented in Table 19. For instance, the length of the AM fiber link may increase as the cascade length decreases. Additionally, more wavelengths may be used on the same fiber link to service more fiber nodes. Both of these variations may decrease the performance of the fiber link as assumed in Table 20 for an N+3 network. Note that the cascade length decreases from 6 to 3 which shifts the cascade performance range in Table 19 by about 4 dB to yield the cascade performance range in Table 20. Using the same logic, the performance range for different portions of an N+0 network can be summarized as shown in Table 21.

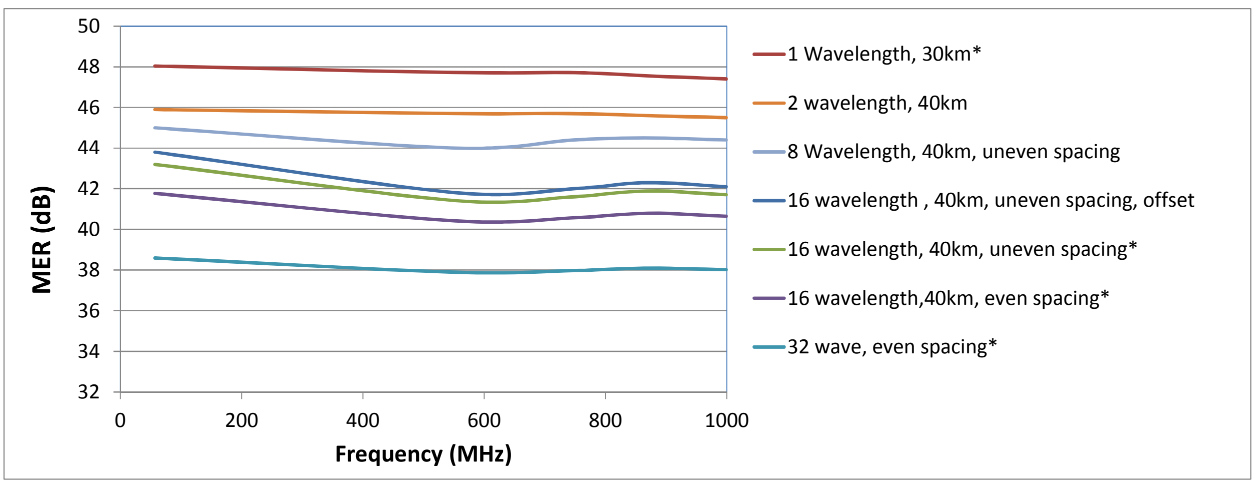

Figure 18. Computer simulations of different optical links scenarios

Table 19. Performance ranges for different segments of an N+6 network (centralized architecture)

Segment	Low	Typical	High
Source	43 dB	47 dB	51 dB
Optical Link	40 dB	44 dB	47 dB
RF Trunk (N+6)	43 dB	46 dB	49 dB
Tap, Drop, IHN, Modem	32 dB	38 dB	44 dB

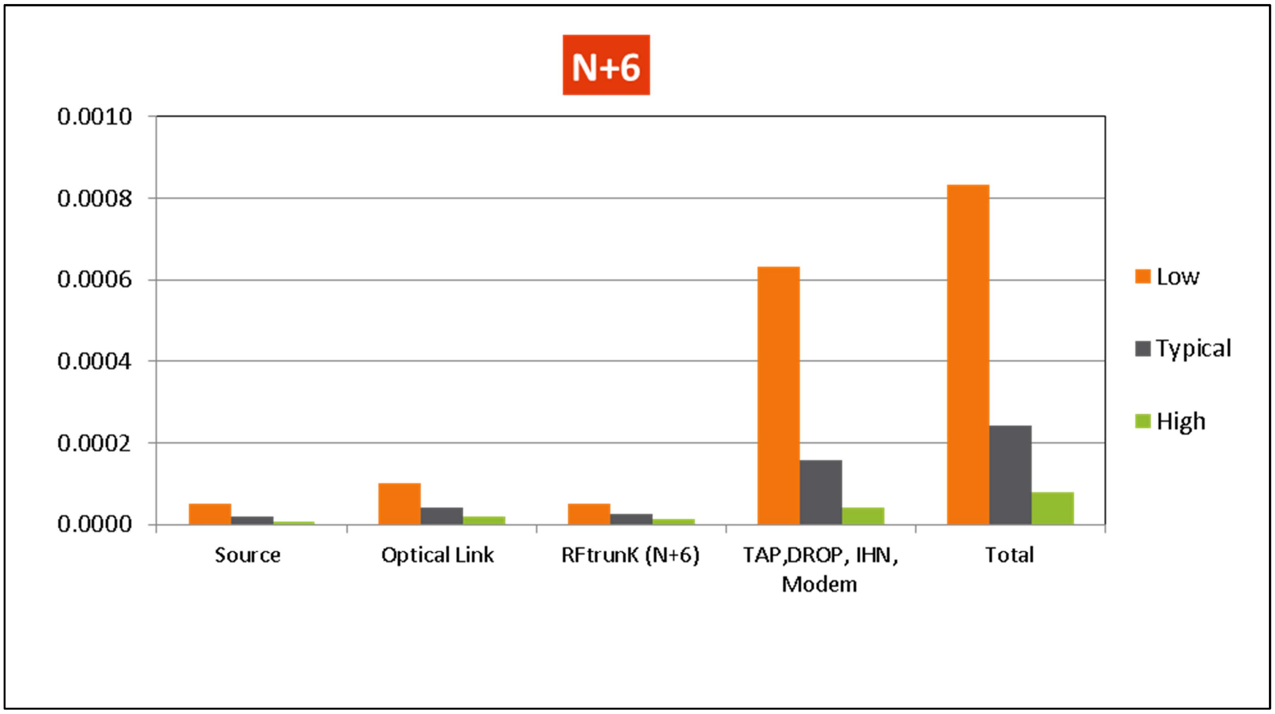

Figure 19. 1/CNR (linear scale) for different segments composing the N+6 network (centralized architecture)

Table 20. Performance ranges for different segments of an N+3 network (centralized architecture)

Segment	Low	Typical	High
Source	43 dB	47 dB	51 dB
Optical Link	39 dB	43 dB	47 dB
RF Trunk (N+3)	47 dB	50 dB	53 dB
Tap, Drop, IHN, Modem	32 dB	38 dB	44 dB

Table 21. Performance ranges for different segments of an N+0 network (centralized architecture)

Segment	Low	Typical	High
Source	43 dB	47 dB	51 dB
Optical Link	38 dB	42 dB	46 dB
RF Trunk (N+0)	N/A	N/A	N/A
Tap, Drop, IHN, Modem	32 dB	38 dB	44 dB

The above tables can be used to infer performance ranges for distributed architectures in N+6, N+3, and N+0 networks, as summarized in Tables 22, Table 23, and Table 24, respectively. Note that the ranges stay the same except for the source range, which has been de-rated to compensate for outdoor operation, higher phase noise, potential time/frequency locking, etc. Observe that the optical range is not a factor in the performance analysis in this case.

Table 22. Performance ranges for different segments of an N+6 network (distributed architecture)

Segment	Low	Typical	High
Source	43 dB	46 dB	48 dB
Optical Link	N/A	N/A	N/A
RF Trunk (N+6)	43 dB	46 dB	49 dB
Tap, Drop, IHN, Modem	32 dB	38 dB	44 dB

Table 23. Performance ranges for different segments of an N+3 network (distributed architecture)

Segment	Low	Typical	High
Source	43 dB	46 dB	48 dB
Optical Link	N/A	N/A	N/A
RF Trunk (N+3)	47 dB	50 dB	53 dB
Tap, Drop, IHN, Modem	32 dB	38 dB	44 dB

Table 24. Performance ranges for different segments of an N+0 network (distributed architecture)

Segment	Low	Typical	High
Source	43 dB	46 dB	48 dB
Optical Link	N/A	N/A	N/A
RF Trunk (N+0)	N/A	N/A	N/A
Tap, Drop, IHN, Modem	32 dB	38 dB	44 dB

The performance measures for the different network pieces with ranges summarized in the above tables can be combined to yield an EoL CNR performance *range* for different network architectures as listed in Table 25. Observe that each of the networks has a performance range and not a single value! This means that a CM in a network (e.g., N+0) that is expected to have superior average performance can actually perform worse than a CM in another network (e.g., N+6) that is expected to have inferior average performance and vice versa. For instance, a CM in an N+0 network with performance dominated by one or combination of the TDHM pieces will perform worse than a CM in an N+6 network where the performance is not limited by the TDHM pieces.

For all network architectures, it is important to realize that CMs with no performance issues in the TDHM pieces will have EoL performance at top of the range and will *always* achieve higher capacities than CMs at the bottom end of the range with performance degradation caused by issues in the TDHM pieces. The CNR ranges, listed in Table 25, and their corresponding noise contributions (inverse of linear CNR) are shown in Fig. 20 and Fig. 21, respectively.

Table 25. EoL CNR Performance ranges for different network architectures

Architecture	Low	Typical	High
Centralized (N+6)	30.8 dB	36.1 dB	41.0 dB
Centralized (N+3)	30.8 dB	36.5 dB	41.4 dB
Centralized (N+0)	30.8 dB	36.2 dB	41.4 dB
Distributed (N+6)	31.4 dB	36.8 dB	41.7 dB
Distributed (N+3)	31.5 dB	37.1 dB	42.2 dB
Distributed (N+0)	31.7 dB	37.4 dB	42.5 dB

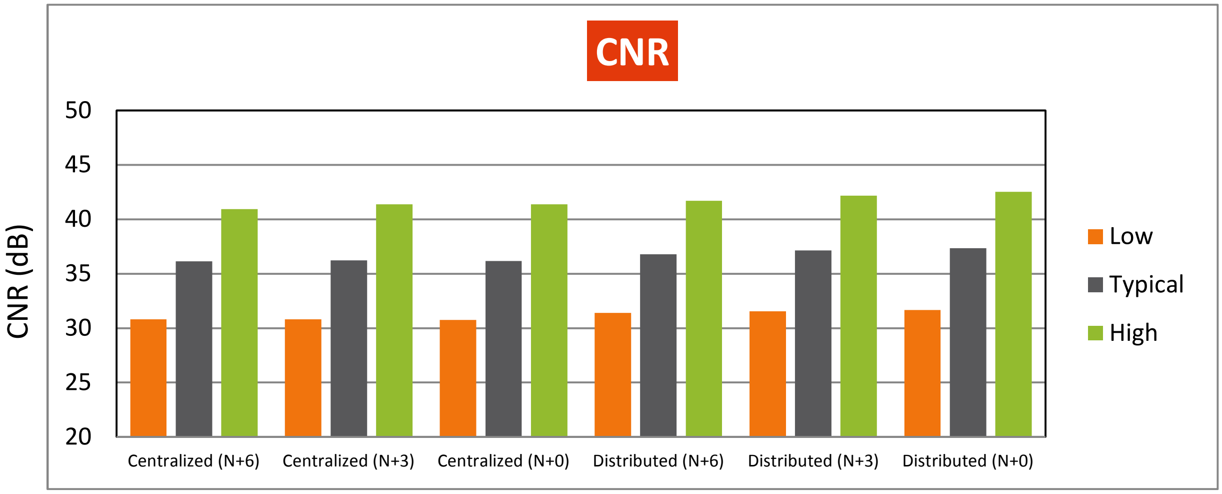

Figure 20. EoL CNR Performance ranges for different network architectures

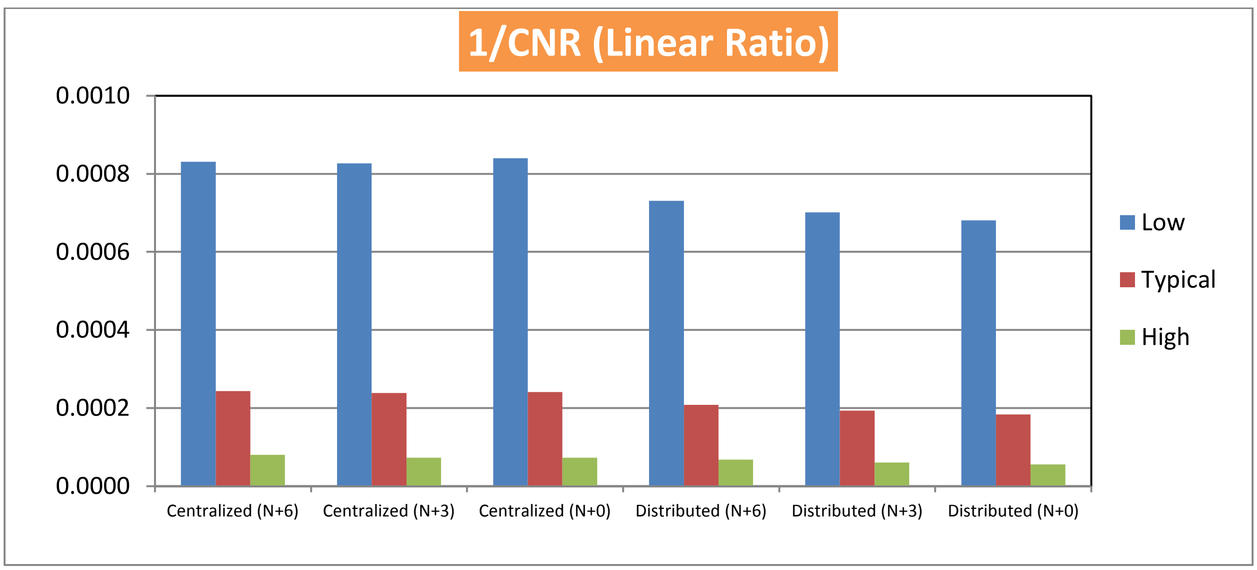

Figure 21. Noise contributions (1/EoL CNR linear scale) for different network architectures

The DOCSIS 3.1 spectral efficiency analysis for different architectures is performed as described earlier with the assumptions listed in Table 7. DOCSIS 3.1 spectral efficiency is calculated for certain CNR values, as shown in Fig. 22, where each CNR value is assumed to represent the mean value of a Gaussian CNR distribution with 1.18 dB standard deviation. Observe that low performing CMs do always exist regardless of the network architecture. In particular, poor performance for TDHM pieces can dominate the network performance for CMs affecting by those pieces for each and every network architecture.

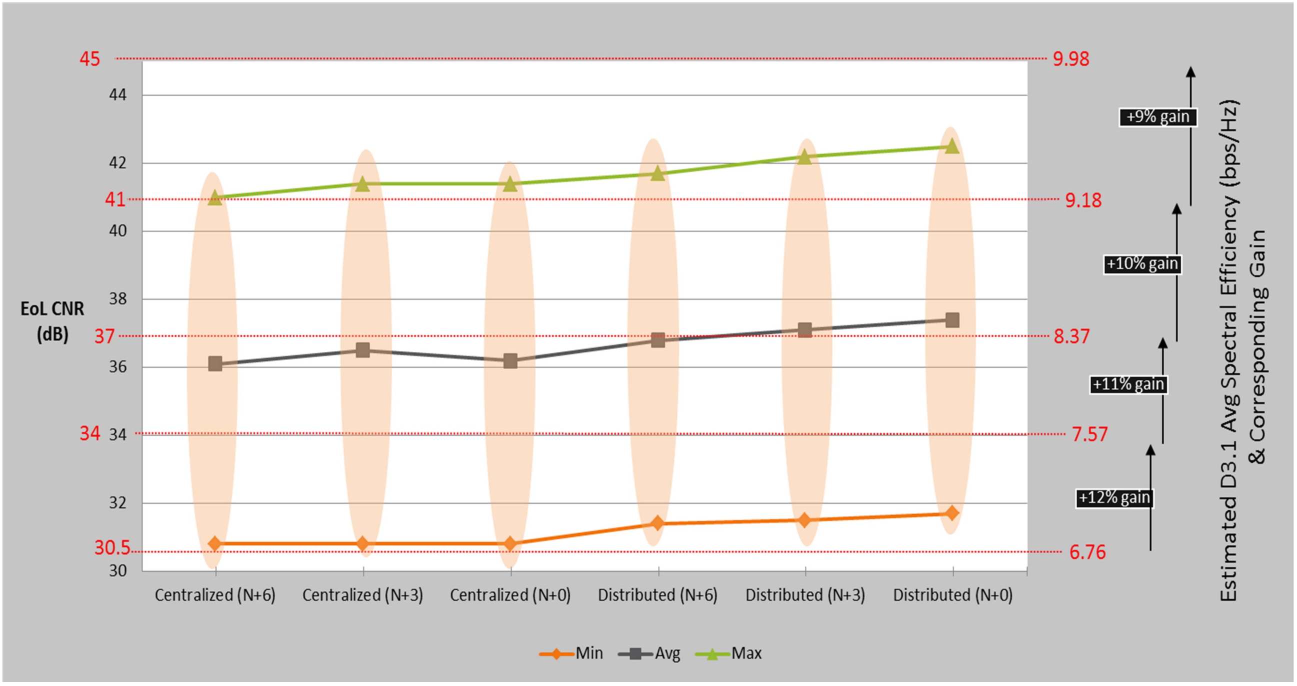

Figure 22. DOCSIS 3.1 Spectral efficiency corresponding to
EoL CNR distributions/ranges for different network architectures

6. NETWORK OPTIMIZATION

One of the key benefits of DOCSIS 3.1 is the ability to operate at significantly higher orders of modulation than DOCSIS 3.0, but in order for this to occur, it is also necessary to operate the HFC plant at much higher CNR levels. In many cases, there will be modems that will require plant maintenance, repairs or upgrades in order to realize DOCSIS 3.1 throughput gains. In the majority of the nodes that were evaluated in this analysis, it was found that the dominant limitation in CNR performance was found in the final portion of the network: the tap, the drop, the in-home network, or the modem itself.

Each element in the final portion of the network presents a unique set of challenges and resolution techniques. In this analysis, it was found that the tap was the least likely source of degradation in this portion of the network. Tap issues were most readily identified by evaluation of the receiver and/or transmitter equalizers in the modems. In this analysis, the drop was most commonly found to be dominant limitation.

This finding emphasizes the importance of performing drop certification when installing DOCSIS 3.1 subscribers and continuing to monitor this portion of the network with proactive HFC monitoring tools. The in-home network was found to be the second most common source of performance limitation, with particular emphasis on the impact on upstream performance, stressing the value of deploying a 2-port RF gateway at the home PoE in order to isolate in-home networks from the common portion of the HFC plant. The cable modem was found to be the primary limitation only slightly more often than the tap. In most cases, it was found that resetting the modem resolved the issue.

7. CONCLUSIONS

The article analyzed different network segments based on real-world field measurements. In this study, it was found that the link segment composed of the Tap, drop, Home network, and CM (TDHM) pieceparts is one of the main factors that can dominate the performance of the whole network. CMs that are affected by these situations will perceive plant upgrades negatively compared to other CMs that do not suffer from these issues. Cable modems whose performance is dominated by the TDHM pieces will always have poor performance regardless of the network architecture. In particular, it was shown that reducing the coaxial cascade length and/or moving to distributed network architecture will not likely increase the capacity of those CMs affected by issues in the TDHM pieces. The analysis also showed that CMs that do not have these issues can experience very high spectral efficiencies in existing networks and gaining more benefit as coaxial cascades get shorter and/or distributed architectures are considered. In a nutshell, the analysis showed that the performance of two CMs on the same network and located in similar network topology locations can be very different.

The analysis showed that the EoL performance of a network is best represented with a range of values, rather than a single number. In particular, it was shown that the performance of an N+6 network spans a 10 dB range (i.e., from 31 dB to 41 dB) with an average EoL CNR of 36.1 dB. The performance range shifts to higher average values as cascade length decreases and/or distributed architectures are deployed. For instance, the EoL performance range of an N+0 distributed architecture network is estimated to be between 32 dB and 43 dB with an average EoL CNR of 37.4 dB.

Understanding the impact of the final segment of the network, including the TDHM pieces is crucial for the efficient investment of time and resources in the HFC plant. In particular, deployment of a 2-port RF gateway at the PoE for network isolation, continued drop certification practices in order to identify degradation and verify performance, and the use of Proactive Network Maintenance (PNM) features and proactive HFC monitoring tools in order identify and resolve issues before they become service affecting will help MSOs to address the performance limitations observed in this analysis. Identification and resolution of the sources of performance limitations within the HFC plant is the key to optimizing the network in order to realize the full potential of DOCSIS 3.1 and maximize the throughput gains that will be achieved.

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ACRONYMS AND ABBREVIATIONS

AMP	Amplifier
AWGN	Additive White Gaussian Noise
CER	Codeword Error Rate
CM	Cable Modem
CNR	Carrier to Noise Ratio
DS	Downstream
EoL	End of Line
FEC	Forward Error Correction
HFC	Hybrid Fiber Coax
IHN	In-Home Network
MER	Modulation Error Ratio
OMI	Optical Modulation Index
pdf	Probability density function
PNM	Proactive Network Maintenance
QAM	Quadrature Amplitude Modulation
SNR	Signal to Noise Ratio
Rx	Receive/Receiver
TDHM	Tap/Drop/In-Home-Network/Modem
Tx	Transmit/Transmitter
US	Upstream