

# The Capacity of Analog Optics in DOCSIS 3.1 HFC Networks

Zian He, John Skrobko, Qi Zhang, Wen Zhang  
Cisco Systems

## Abstract

*The DOCSIS<sup>®</sup> 3.1 (D3.1) HFC network, supporting OFDM, requires potentially higher system performance (CNR or MER) for both downstream (DS) and upstream (US) signals compared with the previous DOCSIS<sup>®</sup> 3.0 (D3.0) counterpart. This pushes the limitations of current analog optics technology. How much optical link budget can current technology support? It mainly depends on the per channel optical modulation index of the laser, and optical detection limitations which are dominated by receiver (Rx) equivalent input noise (EIN). This paper will mainly focus on evaluating the noise limitation of the downstream and upstream analog optical links. We explore whether D3.1 PHY layer defined OFDM/OFDMA QAM signals and the extended channel loading bandwidth can be satisfied using an analog optical link. The results show that DS 4K-QAM OFDM signals with full loading (5x192 MHz) can be supported when the optical Rx input power is no less than -2 dBm. Similarly, US 1K-QAM OFDMA signals with full loading (2x96 MHz) can be supported when the US optical Rx input power is -13 dBm. In other words, analog optical links can still support the D3.1 PHY layer defined 4K-QAM/1K-QAM for DS/US, but there are limitations of fiber link loss. Digitizing the optical link of HFC using EDR or Remote PHY can help break the power budget limitations of the analog optical link.*

The evolution of the DOCSIS specification has occasionally impacted the familiar HFC network. The D1.1 release had no impact because the addition of QOS using service flows improved utilization of existing bandwidth. The D2.0 release, on the other hand, added a higher order modulation format and wider channels. Although some effort was expended to increase robustness through enhanced FEC and interleaving, the inevitable increase in channel loading caused a review of the upstream plant. Upstream Fabry-Perot lasers, for example, fell out of favor. The significant milestone in throughput brought about by D3.0 and channel bonding had little impact on HFC because it was also an improved utilization of existing bandwidth. Our most recent evolutionary step to D3.1 has forced us to revisit HFC because of both new modulation formats and broadened bandwidth [1]. Higher modulation formats require review of CNR requirements and bandwidth changes require review of per channel power.

The D3.1 Physical Layer Specification defined the DS cable modem minimum required CNR performance of OFDM signals with LDPC error correction in AWGN (Additive White Gaussian Noise) channel as shown in Table 1 [2]. Typical 1K-QAM OFDM required signal performance is 34 dB CNR/MER (assuming CNR and equalized MER has a similar value in dB units), or ~41-41.5 dB CNR/MER for the 4K-QAM OFDM DS option. Note that these values of CNR are only meant to achieve post-FEC packet error ratios of less than or equal to  $10^{-6}$  with 1500 byte Ethernet packets.

## INTRODUCTION

Constellation (QAM)	CNR (dB) Up to 1 GHz	CNR (dB) from 1.0-1.218 GHz
4096	41.0	41.5

2048	37.0	37.5
1024	34.0	34.0
512	30.5	30.5
256	27.0	27.0
128	24.0	24.0
64	21.0	21.0
16	15.0	15.0

**Table 1 – CM Minimum CNR Performance in AWGN Channel**

A similar situation has occurred for the D3.1 US path. The US CMTS minimum received CNR of OFDMA signals is shown in Table 2.

Constellation (QAM)	CNR (dB)
4096	43.0
2048	39.0
1024	35.5
512	32.5
256	29.0
128	26.0
64	23.0
32	20.0
16	17.0
8	14.0
QPSK	11.0

**Table 2 – CMTS Minimum CNR Performance in AWGN Channel (non-boosted pilots)**

#### Fundamentals of CNR of a Linear Optical Link in Fiber Deep HFC

Generally, the quality of the RF signal channel can be described by Composite Carrier to Noise (CCN). The CCN of an HFC fiber link is the combination of noise components coming from the carrier to noise ratio (CNR), carrier to intermodulation noise (CIN), and the carrier to crosstalk noise (CXN). CCN can be written as [3]:

$$CCN^{-1} = CNR^{-1} + CIN^{-1} + CXN^{-1}$$

where:

- *CNR* is the total noise contribution of the Rx (thermal noise, shot noise) and the Tx (laser noise).

- *CIN* is the distortion noise that comes from second, third, and higher order components.
- *CXN* is noise coming from crosstalk noise from non-linear fiber interactions, or other fiber transmission induced noise.

For a well-designed linear optical link, the RF non-linear distortion can be controlled to making a very low contribution (CSO, CTB <-65dBc), if the gain block is kept in a linear operation range and the laser is not pushed to clipping. For mitigating the optical non-linear interaction, it is a more complicated topic, which should also consider Four-Wave-Mixing (FWM), Cross-phase-modulation (XPM), Raman Crosstalk, and WDM filter slope induced distortion. But by careful configuration, such optical crosstalk can be reduced to an acceptable level [4, 5]. With

these pre-conditions,  $CCN = CNR$  for linear optical downstream and upstream path design.

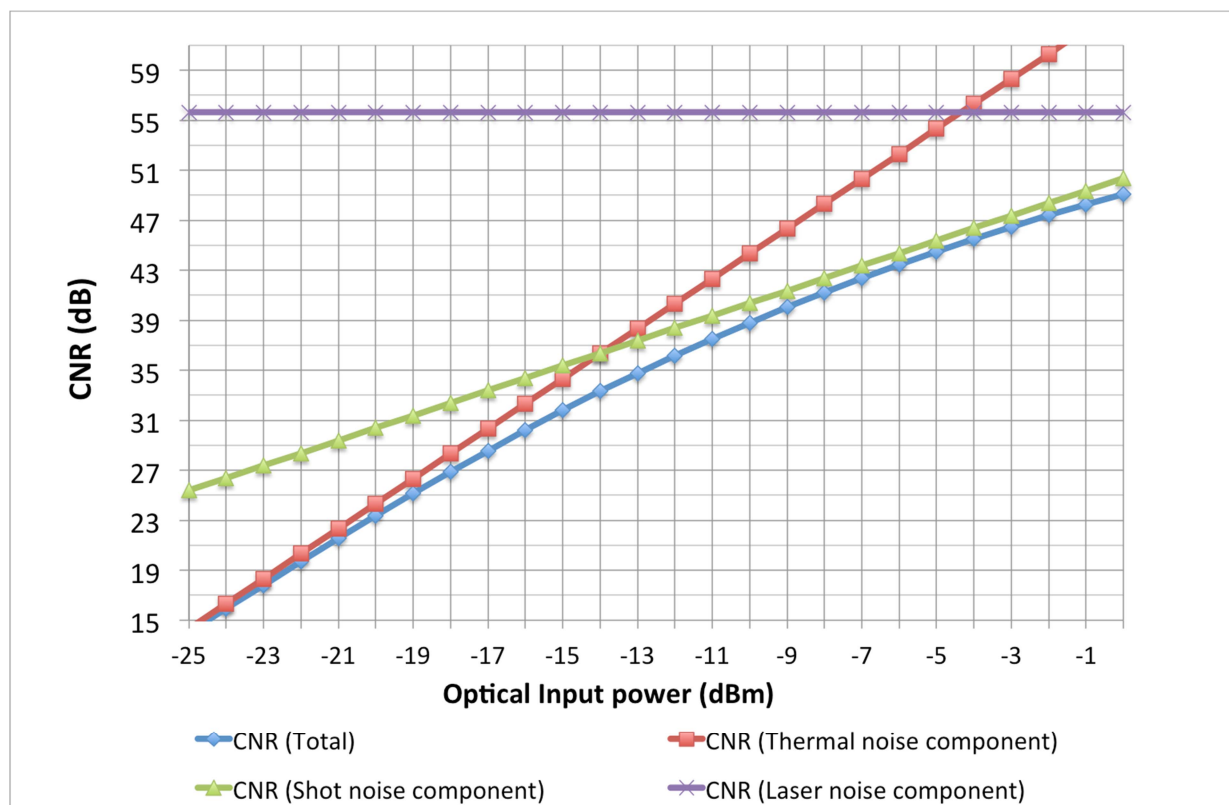
### DS Analog Optical Link

Refer to the CNR equation of a linear optical link [6]. The calculation parameters of a typical downstream path are shown in Table 3.

Parameter	Value
Rx Input power (dBm)	-25 to 0
Rx Responsivity (A/W)	0.95
OMI per 6 MHz	0.021
RIN (dB/Hz)	-155
EIN (pA/√Hz)	3.5
Noise Bandwidth (MHz)	5.36

**Table 3 – CNR calculation parameters**

The calculated CNR result of the downstream optical link is shown in Figure 1. The EIN of the state of the art is 3.0-3.5 pA/√Hz for a 1.2GHz DS Rx so here we use 3.5 pA/√Hz in the calculation. The per channel (6 MHz) OMI used in the calculation is 2.1% for typical HFC DS with SC-QAM full loading (190 QAM channels, ~20% composite OMI). The noise bandwidth is 5.36 MHz for a DS 6 MHz SC-256QAM. It can be seen in Figure 1 that for the optical input power ( $P_{in}$ ) above -8 dBm, the total CNR is dominated by shot noise. The thermal noise of the Rx does not contribute much to the total CNR. The total CNR curve deviates from the linear relation with the shot noise line when  $P_{in}$  goes below -8 dBm.  $P_{in} = -14$  dBm is a turning point, where below it the total CNR is, instead, overtaken by the thermal noise of the optical Rx.



**Figure 1 – CNR vs Optical Input Power (Downstream path)**

Modulation error ratio (MER) is a “CNR-like” parameter for QAM signals compared

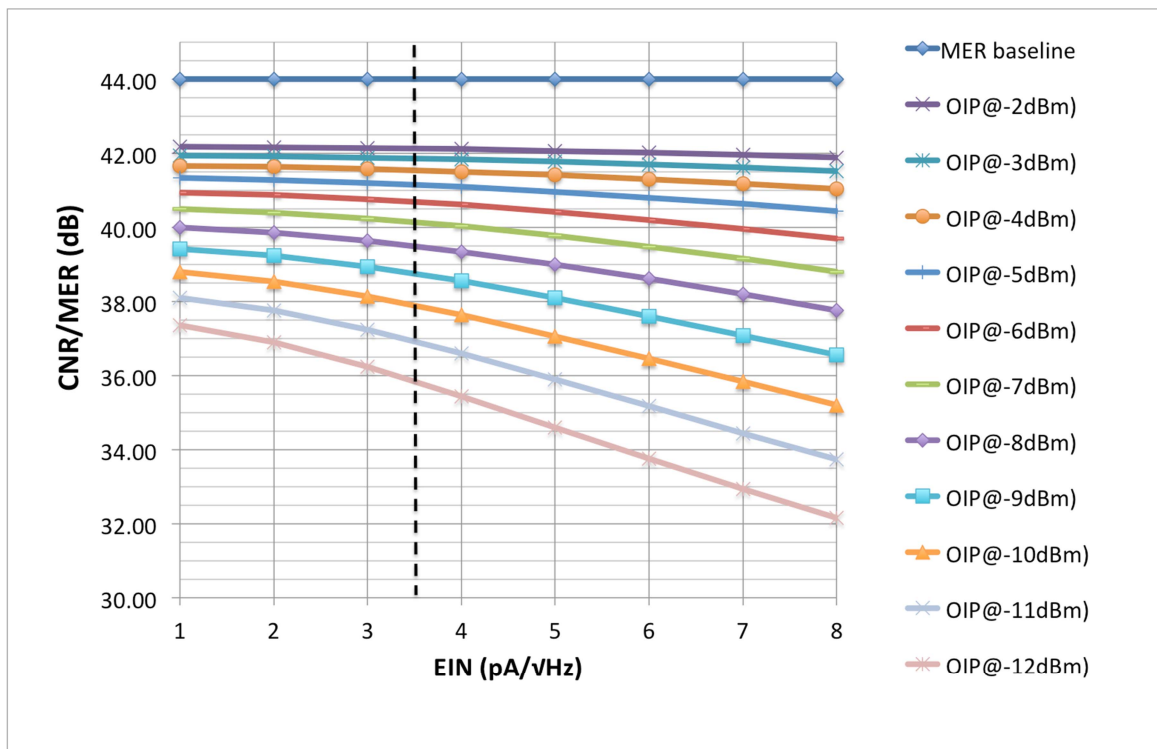
with analog signals. To be simplified, in this paper we assume equalized MER and CNR

have the same value in dB units for a QAM signal [7]. In addition, the total CNR/MER should include the signal source baseline. In the past, we have been satisfied with SC-QAM baseline MER values of 44 dB. Figure 2 shows the calculated CNR/MER with this limitation. With the introduction of higher order modulation and OFDM, we are using source baselines at and above 50 dB. Figure 3 demonstrates the impact of this higher expectation. The optical input power in simulation ranges from -12 to 0 dBm. It can be seen in Figures 2 and 3 that as EIN increases, it induces a CNR/MER degradation, especially at lower optical input power levels. So, for higher loss links, such as for fiber deep applications using WDM, an

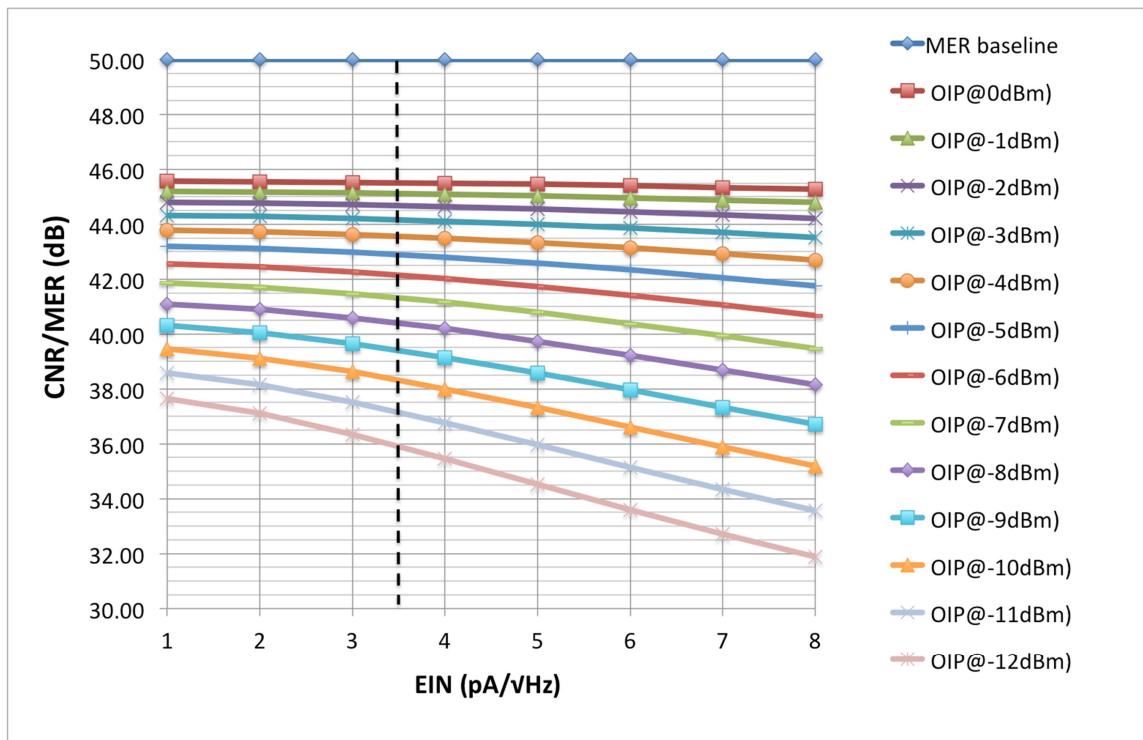
optical Rx with low EIN is even more important than previous HFC scenarios.

Parameter	Value
Rx Input power (dBm)	-12 to 0
Rx Responsivity (A/W)	0.95
OMI per 6 MHz	0.021
RIN (dB/Hz)	-155
EIN (pA/ $\sqrt{\text{Hz}}$ )	1.0 to 8.0
Station base MER (dB)	44 (SC-QAM)/50 (OFDM)
Noise Bandwidth (MHz)	5.36 (SC-QAM)/6.0 (OFDM)

**Table 4 – QAM CNR/MER calculation parameters**



**Figure 2 – CNR vs EIN of SC-QAM (calculated)**



**Figure 3 – CNR vs EIN with improved baseline (calculated)**

Practically, we need to keep a certain margin (usually 3 ~ 6 dB) above the minimum required CNR for both SC-QAM and OFDM signals [1]. Table 5 shows the marginal CNR (with 3 dB margin) and the corresponding required minimum optical input power (OIP), while assuming the current achievable EIN is ~3.5 pA/√Hz (the vertical dashed line in

Figures 2 and 3). The result demonstrates that the optical Rx with 3.5 pA/√Hz EIN can support SC-256 QAM and OFDM 1024QAM if the OIP is above -11 dBm, which is enough for most of the existing homes passed (HP) coverage. However, for D3.1 4K-OFDM DS signal, the OIP should be no less than -2 dBm.

Constellation (QAM)	SC-QAM		OFDM	
	Marginal CNR (dB)	Min OIP (dBm)	Marginal CNR (dB)	Min OIP (dBm)
4096	NA		44.5	-2
2048	NA		40.5	-8
1024	NA		37	-11
512	NA		33.5	< -12
256	37	-11	30	

**Table 5 – Minimum Optical Input Power for Downstream D3.1 HFC**

### US Analog Optical Link

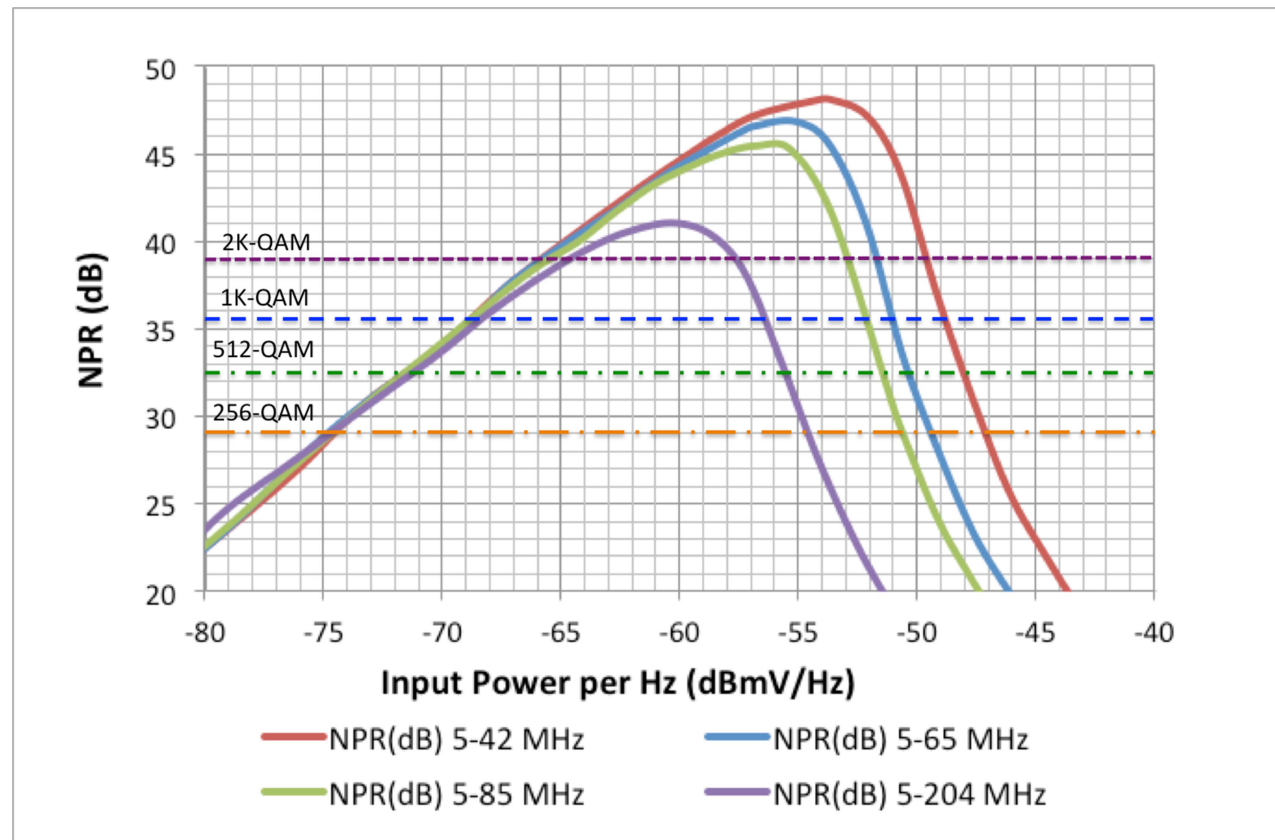
For upstream, the Noise-Power-Ratio (NPR) dynamic range is often used to specify the operational range of the upstream RF or

optical link [8]. The NPR value can be loosely interpreted as CCN of the QAM signal. The left side of the NPR curve is mostly established by the system noise, while the middle and right side are dominated by

distortion and laser clipping. In practice, a minimum NPR dynamic range is required for an US analog link. Typically it should be >12 dB [1]. To provide more data throughput upstream, D3.1 extends the upstream bandwidth from 5-85 MHz to 5-204 MHz, more than twice the bandwidth compared with D3.0. At the same per channel power, the heavier channel loading of 5-204 MHz will inevitably overdrive the optical Tx “earlier” than light loading.

Figure 4 shows the measured NPR curves of different channel loading. The upstream Tx used in this test is a 1550 nm DFB type. The upstream Rx input power is -13 dBm after 25

km of fiber and optical attenuation. The EIN of the Rx is  $\sim 1.3 \text{ pA}/\sqrt{\text{Hz}}$ . It can be seen that the right side of the NPR curve shifts to the left with the increase of the noise loading bandwidth. The dynamic range difference between 5-85 MHz and 5-204 MHz loading is about 4-4.5 dB, which also matches well with the theoretical expectation. Notice for this example of -13 dBm optical input power, the 5-204 MHz loading NPR curve has 12 dB of dynamic range @ 35.5 dB NPR. This is what is required for transmission of a 1K-QAM OFDMA signal. In addition, the same dynamic range is available for a 2K-QAM OFDMA signal transmission with 5-85 MHz loading at this optical input level.



**Figure 4 – Measured NPR of different channel loading**

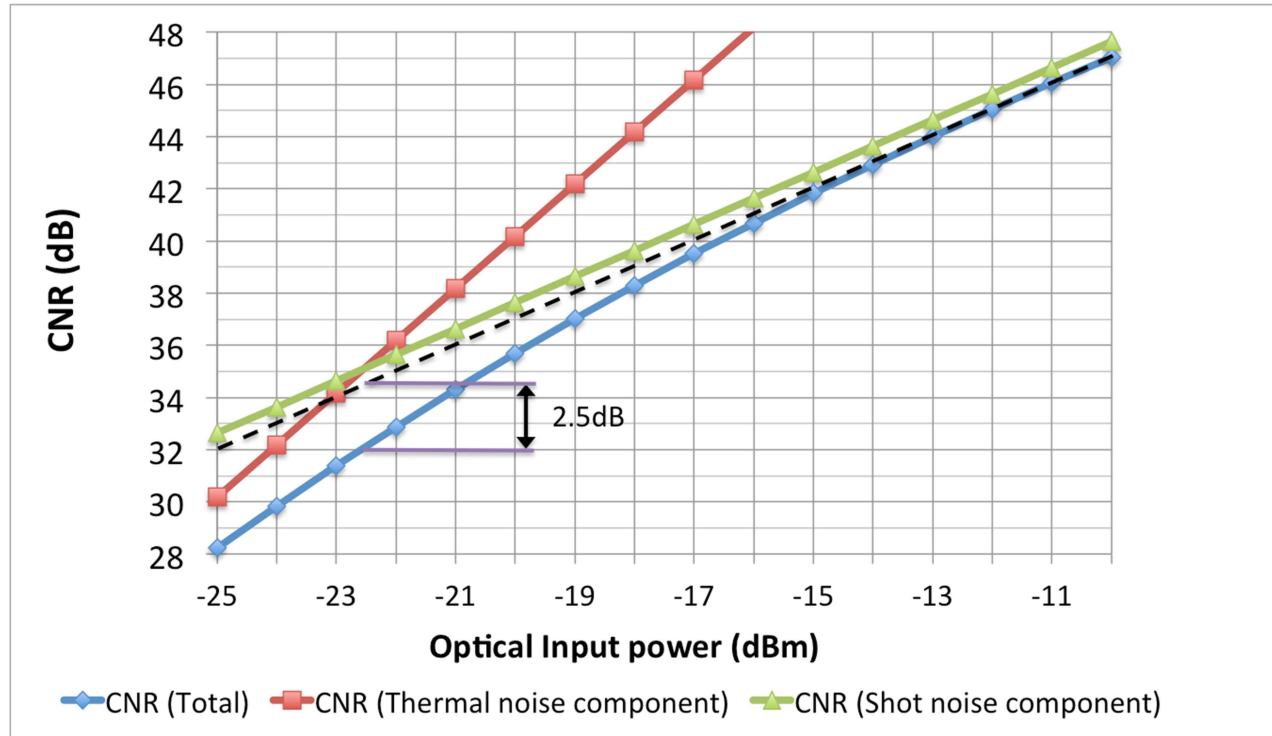
However, -13 dBm may not be a low enough optical input power for an analog fiber deep (especially for cascaded WDM scenario) or RFoG application. Assuming the EIN of an US optical Rx to be  $1.3 \text{ pA}/\sqrt{\text{Hz}}$ , the CNR

result in Figure 5 shows that the total CNR deviates from the linear relation with optical input power when the optical input power is lower than -17 dBm. If looking at -22.5 dBm optical input power, the total CNR will be 2.5

dB lower than the linear extrapolation, which means the NPR dynamic range at -22.5 dBm will have  $-13 - (-22.5) + 2.5 = 12$  dB degradation compared to -13 dBm. Consider that at -13 dBm OIP, 24 dB dynamic range of 29 dB NPR is achievable for 5-85 MHz loading, then at -22.5 dBm OIP, 5-85 MHz signal loading will have 12 dB dynamic range at 29 dB NPR, which can only be used for an OFDMA-256QAM signal.

Parameter	Value
Rx Input power (dBm)	-25 to -10
Rx Responsivity (A/W)	0.95
OMI per 6.4 MHz	0.05
RIN (dB/Hz)	-155
EIN (pA/ $\sqrt{\text{Hz}}$ )	1.3
Noise bandwidth (MHz)	6.4 (OFDMA)

**Table 6 – CNR calculation parameter**



**Figure 5 – CNR vs Optical input power (Upstream path)**

As a summary for the upstream path, we list the required minimum optical input powers for different OFDMA QAM levels and different loading cases in Table 7. The

result shows that 1K-QAM OFDMA can be supported with OIP higher than -17 dBm for 5-85 MHz loading, and -13 dBm for 5-204 MHz loading.

Constellation (QAM)	Required CNR (dB)	5-85 MHz loading (1x24 MHz+1x48 MHz)	5-204 MHz loading (2x96 MHz)
		Required Min OIP (dBm)	
1024	35.5	-17	-13
512	32.5	-20	-16
256	29	-22.5	-19

**Table 7 – Minimum Optical Input Power for Upstream D3.1 HFC**

## Advances of Digital Optical Link

Based on the analysis above, we know that for D3.1 HFC, the analog optical link is still workable for 4K OFDM DS and 1K OFDMA US, but the optical link budget has certain limitations. For the DS, the typical Tx output power is +10 dBm, while for the US, it could be +3 dBm. So the DS & US link budget is 12 dB and 16 dB, respectively. From the analysis above we can see analog optical links will degrade the CNR with the reduction of the Rx

input power. Alternatively, digital optical links are less affected by link loss providing the optical input power is above the digital Rx receiving sensitivity. EDR (Enhanced Digital Return) and R-PHY are two viable digital methods for HFC fiber links. Consider typical 10GE optical transmission link budgets (excluding the dispersion penalty), with the EML Tx minimum output of 0 dBm, and APD Rx receiving sensitivity of -23 dBm. The link budget is 23 dB, much better than the analog optical link (see Table 8).

OFDM/ OFDMA	Constellation (QAM)	OFDMA signal bandwidth (MHz)	Optical link budget (dB)		
			Analog Link	EDR	R-PHY
DS	4096	5x192	-12	NA	-23
US	1024	2x96	-16	-23	-23

**Table 8 – Optical Link Budget Comparison**

## CONCLUSION

We have analyzed the current analog optical Tx/Rx performance for its data transmission capability in DOCSIS 3.1 defined OFDM (OFDMA) HFC networks. The results show that analog optical links can still support most of the scenarios which DOCSIS 3.1 requires with a proper optical link budget.

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## ABBREVIATIONS

APD	avalanche photodiode
AWGN	additive white Gaussian noise
bps	bits per second
BW	bandwidth
CCN	composite carrier to noise ratio
CNR	carrier to noise ratio
CIN	carrier to interference noise
CXN	carrier to crosstalk noise
CSO	composite second order
CTB	composite triple beat
D3.1	DOCSIS <sup>®</sup> 3.1
DFB	distributed feed back
EDR	enhanced digital return
EIN	equivalent input noise
EML	externally modulated laser
FEC	forward error correction
FWM	Four-Wave-Mixing
GHz (MHz)	giga Hertz (mega Hertz)
HFC	hybrid fiber-coax
LDPC	low-density parity-check
MER	modulation error ratio
MSO	Multiple system operator
NPR	noise power ratio
OFDM(A)	orthogonal frequency-division multiplexing (assess)
OIP	optical input power
OMI	optical modulation index
QAM	quadrature amplitude modulation
RIN	Relative intensity noise
R-PHY	Remote PHYsical interface
Rx	receiver
SNR	Signal to noise ratio
Tx	transmitter
WDM	wavelength division multiplexing
WL	wavelength
XPM	Cross-phase-modulation