ESTIMATING DOWNSTREAM PERFORMANCE AND DOCSIS 3.1 CAPACITY IN CAA AND DAA SYSTEMS

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Abstract

Recently the most often asked questions by cable operators around the world surround the expectations of their "future" network performance and capacity when using DOCSIS 3.1 technology in CAA (Centralized Access Architecture) and DAA (Distributed Access Architecture) systems. Answering these questions can be complicated because there are so many different factors that must be examined to predict the "future" end-of-line (EoL) performance and resulting DOCSIS 3.1 capacity. Since MSO-to-MSO network architectures can vary widely, and even within a cable operator's own network architectures may vary, it is important that an understanding of performance impacting factors is identified to effectively predict EoL performance and DOCSIS 3.1 capacity.

This paper and underlying model will be the first published analysis of its kind, because it considers both current and future factors that determine end-of-line (EoL) performance, DOCSIS 3.1 capacity and/or CNR margin. The model is a comprehensive analysis based on real-world data of existing systems as well as predicting the performance of future DOCSIS 3.1 systems not yet created, all in an effort to estimate Downstream Performance and DOCSIS 3.1 Capacity in CAA and DAA Systems.

The model and paper identify four core areas impacting EoL performance: 1) Network Element and Configuration Settings, 2) Network Architecture and Topology, 3) Access Architecture (i.e. CAA & DAA), and 4) Network Condition and Performance.

These four areas influence EoL performance and ultimately D3.1 capacity and/or operator margin and will be examined, in detail in this paper. Specifically, the network element configuration settings such as transmitter MER, RF input levels, partial and full D3.1 spectrum loading, spectrum placement, and spectrum utilization of 750 MHz up to 1218 MHz. The network architecture and topology area examines parameters such as distance between facility and node, wavelength count, amplifiers cascade count, and CPE connection point. Access architectures such as CAA using amplitude modulated (AM) optics vs. future DAA using digital optics systems are examined. Network conditions that can degrade the performance and happen at any time and at any segment are also covered.

This paper will unveil for first time:

1) *The results of a new model, created by the authors of this paper, that predicts future downstream end-of-line (EoL) performance and DOCSIS 3.1 capacity in CAA and DAA systems.*
2) *That "all of the following factors" matter in predicting EoL performance including: 1) Network Elements and Configuration Settings, 2) Network Architecture and Topology, 3) CAA and DAA, and 4) Network Condition and Performance.*
3) *The variance in the maximum downstream EoL amplifier performance and DOCSIS 3.1 modulation possible, when operating CAA using AM optics with different network architectures and configurations.*
4) *Where CAA and DAA performance are differentiated, as this will be an option available later this decade.*

INTRODUCTION AND OVERVIEW

This paper sets out to perform the ambitious goal of estimating the future performance and capacity of DOCSIS 3.1 technology in CAA (Centralized Access Architecture) and DAA (Distributed Access Architecture) systems that in some areas do not exist. Specifically, our challenge was to develop an innovative and comprehensive model based on real-world data of existing systems, where available, as well as predict the performance of future DOCSIS 3.1 systems not yet created. The comprehensive results documented in this paper, for the first time in our industry, yield predictions or estimates of downstream performance and DOCSIS 3.1 capacity in CAA and DAA systems. We undertake this challenge because ever since the introduction of DOCSIS 3.1 technology the industry has wondered what level of performance and capacity could be achieved.

Recently, the industry is considering placement of DOCSIS 3.1 in two different classes of access architecture, CAA and DAA systems. Our industry is now questioning what level of performance and capacity could be achieved when using DOCSIS 3.1 technology in CAA using Amplitude Modulated (AM) optics versus future DAA using digital optics systems. The model can also predict where CAA and DAA performance are differentiated.

Finally, the model and paper define a set of network element configuration settings, network architecture and topology; access architecture use cases (i.e. CAA & DAA), and network condition and performance that are representative of the wide range of cable operator networks worldwide. The model and paper define a set of parameters that nearly every cable operator should find representative of their network architecture and topology that will then provide a prediction of their particular downstream performance estimate and possible DOCSIS 3.1 capacity in CAA and DAA systems.

Predicting or estimating the future performance of end-to-end systems and technologies that do not yet exist is difficult. We feel this is a useful undertaking by providing the most current information available in an effort to consider the potential of the downstream performance and DOCSIS 3.1 capacity in CAA and DAA systems. There is a lot of ongoing research studying bandwidth capacities for DOCSIS systems, performance end-to-end, and transitions strategies, please refer to additional areas of research found in the references [ALB] [CLO], and [MUT]. In the future, as complete DOCSIS 3.1 systems become available, we will likely publish other reports based on end-to-end lab results and ultimately real-world network deployment measurements (not just estimates as found in this paper).

The creators and authors of the model and this paper note the information provided is for educational purposes only and do not recommend sole reliance on this information for investment and operational decisions. The model values are predictions based on the combination of current and future product performance estimates, and may not represent actual performance. The information provided supersedes any previously issued estimates. The authors and ARRIS reserve the right to change these performance estimates without notice.

DOCSIS 3.1 OVERVIEW

This section will not review the details of DOCSIS 3.1 technology but rather cite some of the major technology benefits that will be used to maximize network capacity.

The section will highlight some of the requirements to support a given modulation scheme. If the reader would like to learn more about the features and functions of DOCSIS 3.1 technology, please review the CableLabs® DOCSIS 3.1 specification initially released in 2013, and subsequent releases in 2014. Additional presentations and papers published prior to the start of the DOCSIS 3.1 program defined many of the key attributes found in the current DOCSIS specifications. ARRIS released a series of presentations and papers published in the beginning of 2011 and the final release was February 2012, which defined many of the core features of what later became DOCSIS 3.1. [EMM1] [EMM3] In May 2012 at the NCTA conference, a paper published by John Chapman (Cisco), Michael Emmendorfer (ARRIS), Rob Howald (Motorola), and Shaul Shulman (Intel), referred to as the joint paper also called for another version of DOCSIS. [JOINT]. This paper too defined many of the core features for what later became DOCSIS 3.1.

DOCSIS 3.1 enables five core features that will allow cable operators to maximize, expand, and optimize network capacity. These are as follows:

- Adds Multicarrier Modulation Technology
  - Adds downstream OFDM (Orthogonal Frequency-Division Multiplexing)
  - Adds upstream OFDMA (Orthogonal Frequency-Division Multiple Access)

- Adds Error Correction Technology
  - Low-density parity-check (LDPC) codes (inner FEC) and Bose-Chaudhuri-Hocquenghem (BCH) codes (outer FEC)
  - Enables more spectrum capacity compared to legacy DOCSIS in similar SNR/MER

- Adds Multiple Modulation Profiles (MMP)
  - Allowing groups of customers to operate at highest capacity

- Expands Modulation Formats
  - Downstream up to 16384QAM and Upstream up to 4096QAM

- Expands Cable Spectrum Band Plan
  - Downstream may occupy 54 - 1218 MHz or up to 1.7 GHz
  - Upstream may extend to 5 - 204 MHz

The existing cable network downstream and upstream performance can support higher order modulation formats than those available today. [EMM1] [EMM2] [EMM3] The support of higher order modulations with the existing network may not be ubiquitous across the MSO footprint, or even within a serving group, as some segments of the network will differ in performance. [EMM4] This paper will show the use of higher orders of modulation to obtain more capacity with DOCSIS 3.1 over the "existing" Optical and Coaxial network. [EMM4]

Since not all users can utilize the same order modulations, the introduction of the use of multiple modulation profiles (MMP) is important. [EMM5] The use of MMP will allow groups of users the ability to reach the highest order possible, so that the network as a whole may be optimized and to maximize capacity and b/s/Hz. [EMM5] DOCSIS 3.0 and prior releases limited cable operators from increasing downstream and upstream network capacity or bits per second per Hz (b/s/Hz) for several reasons; first there was a limit set to 256QAM modulation and no support for MMP. [EMM4]

Key Takeaway Regarding DOCSIS 3.1

The authors believe that the DOCSIS 3.1 era should reexamine our industry approach determining the minimum performances allowed for 64QAM and 256QAM and adding six dB of margin. Our industry essentially cares about meeting a minimum target, because the network was only as good as the weakest link; the worst value determined the modulation order for the entire segment.

The authors believe that the DOCSIS 3.1 era will allow us to look at the “maximum” performance of the end-of-line, and not just the minimum value of the weakest link. This is because DOCSIS 3.1 does not require all users to use the same modulation orders, as was the case with all previous versions of DOCSIS. The use of DOCSIS 3.1 will introduce a new tool called multiple modulation profiles (MMP). This is an important addition to DOCSIS and this should also change the way our industry looks at network performance and capacity planning; this may have a profound impact on overall operations. The use of MMP will allow groups of users the ability to reach the highest order possible, so that the network as a whole may be optimized and to maximize capacity and b/s/Hz. We should no longer assign a large value of six dB of headroom and should no longer care only about minimum performance values of the network.

This paper suggests the use of higher orders of modulation to obtain more capacity is possible with DOCSIS 3.1 over the existing optical and coaxial network and may increase as the cable operators evolve their network to smaller service groups or uses of different access architectures, as discussed in the next section. The authors also suggest DOCSIS 3.1 use of OFDM, new FEC, expanded modulations orders, and the use of multiple modulation profiles (MMP) are important features that will also enable operators to reach the maximum capabilities of the network.

ACCESS ARCHITECTURE OVERVIEW

This section will describe centralized and distributed access layer architectures that represent the location of the access layer network elements. [EMM2] If all intelligent network elements of the access layer reside in the MSO facility like a headend or hub, then this type of system will be called centralized access layer architecture. However, if any of the intelligent network elements of the access layer are located in the outside plant or MDU location, then this type of system will be referred to as distributed access layer architecture. [EMM2] Today, the industry simply refers to these two different classes of network access architecture as Centralized Access Architecture (CAA) and Distributed Access Architecture (DAA).

Centralized Access Architectures (CAA) using Amplitude Modulated (AM) Optics

The centralized access layer architecture requires the MAC and PHY functions to reside at a cable operator facility. CAA allows the OSP, such as nodes, to be relativity simple devices and the network is in many ways transparent.

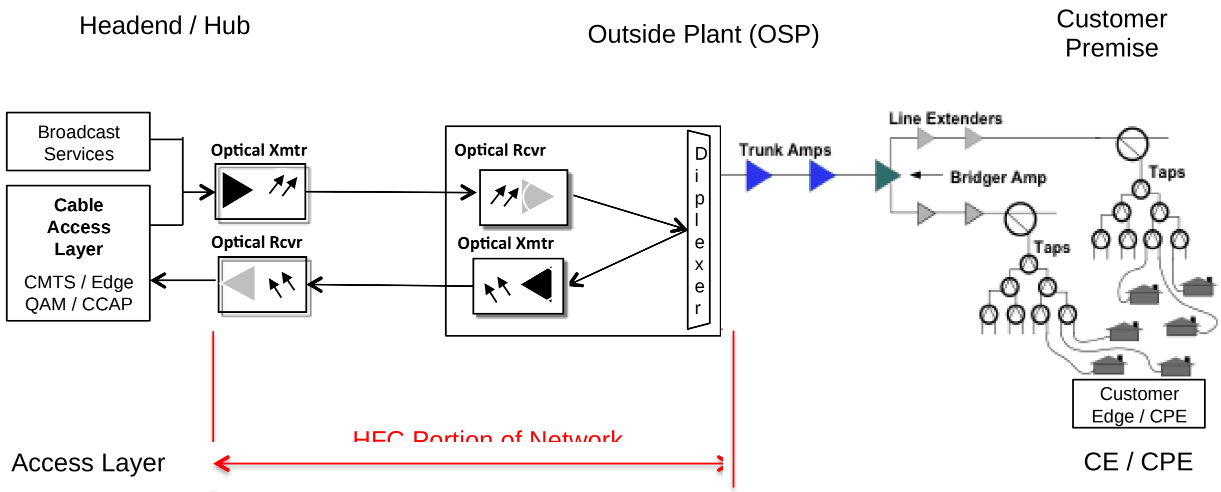


Figure 1: Centralized Access Architecture and HFC

Figure 1 is an illustration of an access layer network element over a transparent Outside Plant (OSP) to the customer edge / CPE with the HFC portion of the network highlighted. The HFC uses two technologies of optical transport in the return; amplitude modulated (AM) also referred to as analog return path and digital return, which may commonly be referred to as Broadband Digital Return (BDR), or simply Digital Return.

Amplitude Modulated (AM) or analog, is the optical technology used for optical forward path transmission of cable signals downstream. The advances in analog forward laser technologies enable transmission of the 54-1002 MHz of spectrum this is over 150 channels, each 6 MHz wide. This will expand to meet the DOCSIS 3.1 1218 MHz requirement. The forward path is layer 1 media converter style architecture and the optical transmission may be shared with multiple HFC nodes and may also carry many technologies transparently. There are two network architectures for the forward: Full Spectrum (illustrated in figure 2); and another called QAM Narrowcast Overlay, or simply Narrowcast Overlay (figure 3).

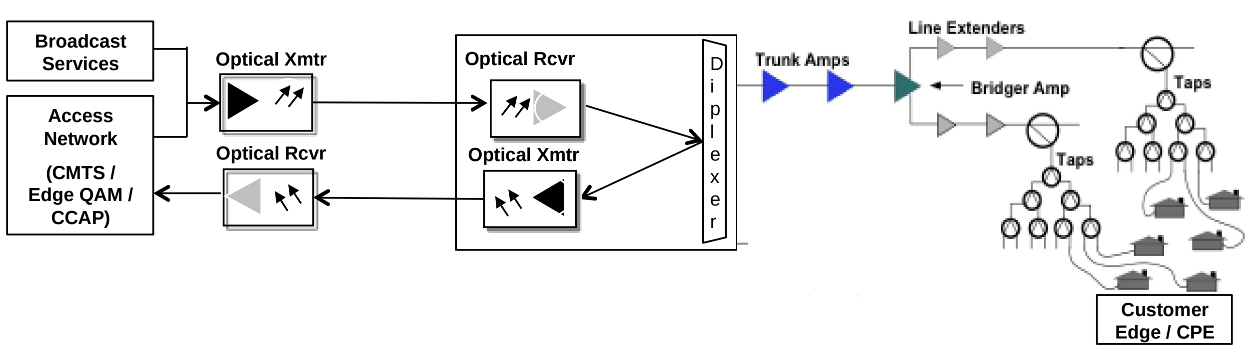


Figure 2: Hybrid Fiber Coax (HFC) with Full Spectrum and Node +N

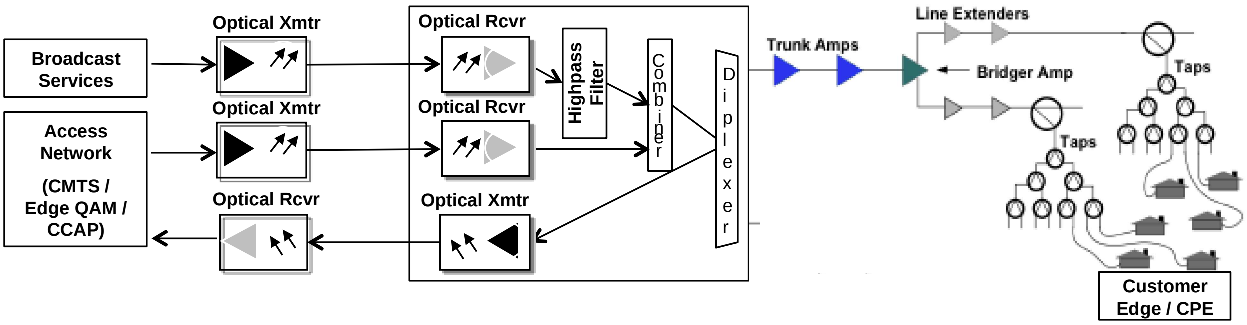


Figure 3: Hybrid Fiber Coax (HFC) with QAM Narrowcast Overlay and Node +N

The MSO serving area between headend and node will be in most cases less than 40 km; therefore this will be easily supported with HFC architecture. The support for extremely long distance to and from the node may be a factor for the HFC. The optical capabilities of HFC have many dependencies, variables, and trade-offs to determine the HFC optical link performance.

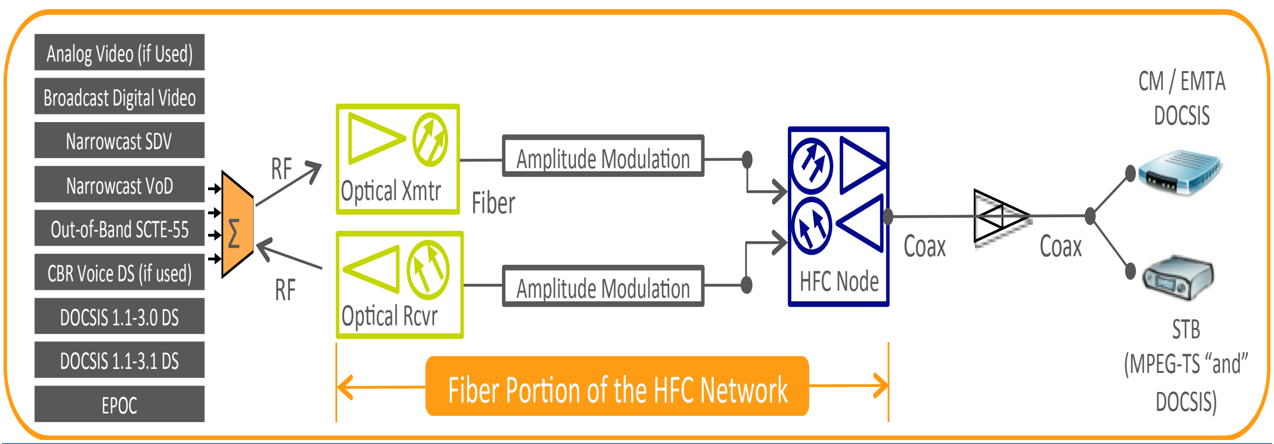


Figure 4: Amplitude Modulated (AM) Optics Flexibility

Amplitude Modulated (AM) core benefits include: (shown in figure 4)

- Transparency and flexibility of the MAC/PHY it carries
- Places least complexity in the node
- Enables CAA keeping complex software and hardware in the headend

Summary of Amplitude Modulated (AM) Performance Challenges and Limitations:

- CNR performance degrades with distance (Facility to Node)
- CNR degrades with when adding wavelengths
- CNR degrades with higher spectrum 750 MHz to 1.2 GHz
- CNR performance varies at different spectrum bands
  (so does remote PHY) below 700 MHz has best End-of-Line
- Partial Loading of D3.1 performs better than Full Spectrum
- Operationally requires rebalancing (in narrowcast overlay

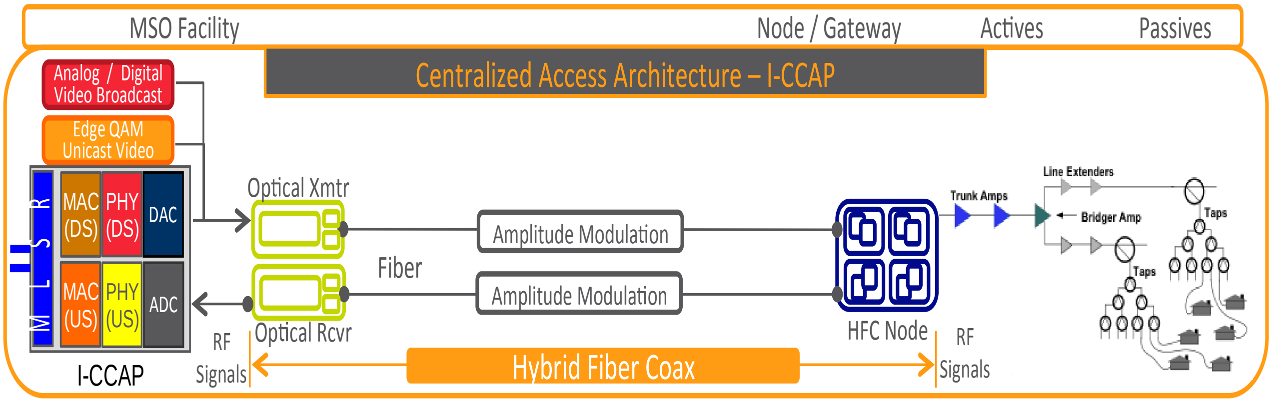


Figure 5: Centralized Access Architectures (CAA) using Amplitude Modulated (AM) Optics

Figure 5 illustrates the Centralized Access Architectures (CAA) using Amplitude Modulated (AM) optics used in today's cable network. This depicts the DOCSIS MAC and PHY layers in the I-CCAP located at the MSO facility and the transport of other services and technologies implemented in different network elements all connected and transported across hybrid fiber coax use of amplitude modulated optical transport.

Figure 6 identifies optical impairments that can impact AM optical systems. We have highlighted several areas from non-linear such as those found in single wavelength and multiple wavelength systems. The optical linear impairments include the fiber linear effects and impairments due to optical passives. In the 2013 NCTA paper we analyzed the Amplitude Modulation (AM) optics challenges and causes that impact overall performance; please refer to that paper for greater detail and understanding of the optical impairments found in single wavelength and multiple wavelength AM optical systems. [EMM4]

<u>Highlights of the Optical Impairments</u>

Single Wavelength or More

- SBS (Stimulated Brullion Scattering)
- SPM (self phase modulation)

Multiple Wavelength Challenges

- SRS:
  - Creates RF crosstalk. Most severe with large wavelength spacing and low RF frequencies
  - SRS induced CSO is a relatively minor secondary effect primarily when the BC load is maximum
- XPM:
  - Creates RF crosstalk
  - Most severe with small wavelength spacing, long fiber links and high RF frequencies
- 4WM:
  - Creates OBI between beats and the carriers
  - If unresolved impacts CCN
  - If severe impacts BER
  - Optical passives: Create CSO due to passives slope (dB/nm)

Long Distance Challenges and Support for High Frequencies

- Fiber Dispersion:
  - Creates composite second order (CSO)
  - CSO increases with longer fiber links and higher frequencies
- Optical Link budget: AWGN

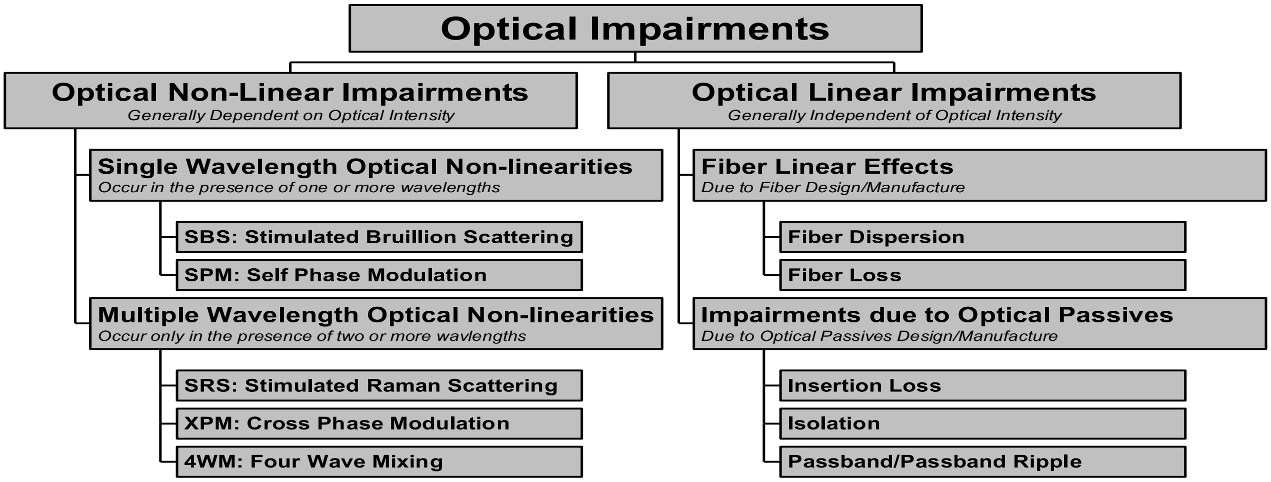


Figure 6: Identifying Optical Impairments for Amplitude Modulated (AM) Optics

Important Takeaway Regarding CAA using AM Optics

We compare single wavelength systems, multiple wavelength systems, several headend to node optical distances, and different amount of frequency or spectrum loading when using AM optics. Essentially the challenges we identified with CAA using AM optics above are examined in this paper. This downstream model and analysis measures the impacts of CAA using AM optics considering a vast set of use cases that represents the majority of MSO networks today and in the future. The differences in performance between CAA using AM optics and DAA using digital optics are documented in this paper.

Distributed Access Architectures (DAA) using Digital Optics

There is another Cable FTTN network architecture class that is not an HFC architecture or technology. This will extend the IP/Ethernet delivery network beyond the hub location to the node (or even MDU) where PHY layer or MAC/PHY layer processing would occur. “Distributed Access Layer Architecture” is when PHY layer or MAC/PHY layer processing takes place outside the headend or central office facility; this processing would take place in the Node, Cabinet, or Basement of MDU. [EMM2] Today, the industry simply refers to this as Distributed Access Architecture (DAA).

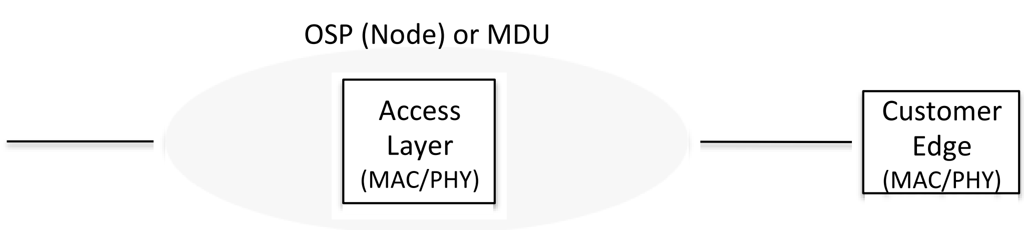


Figure 7: Distributed Access Layer Reference Architecture

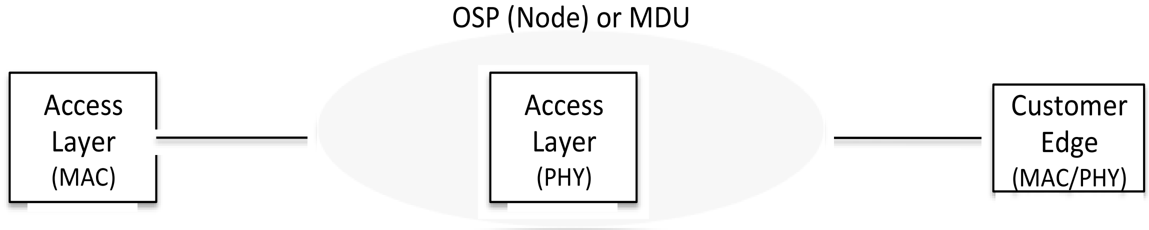


Figure 8: Partial Distributed Access Layer Reference Architecture

Figure 7 is an illustration of an access layer network element that is distributed in the OSP or MDU basement location; this moves the access layer closer to the customer edge/CPE. This architecture does not use the HFC optical network. However, it will use the coaxial cable network, going through amplifiers and passives. In figure 8, just a portion of the access layer is placed in the outside plant or MDU basement. [EMM2]

Moving from AM optics to digital optics for fiber-to-the-node (FTTN) will force us to place PHY or MAC/PHY access layer functions in the node. The use of digital optics is required and this will place new functions in the node and add or remove functions from the headend. Figures 9, 10, and 11 illustrate the functional layers and building blocks of MPEG-TS and DOCSIS MAC and PHY function, as these functions may be split between the headend and node in the future.

The industry terms and definitions used below for Distributed Access Architecture (DAA) were defined in previous papers. [EMM6] Excerpts below are from the "Side-by-Side Comparison of Centralized vs. Distributed Access Architectures" published at 2014 NCTA. They describe the three leading approaches for DAA. [EMM6]

1) Remote PHY (R-PHY): This places the full PHY layer including the FEC, symbol generation, modulation, and DAC/ADC processing in the node. This is analogous to the Modular Headend Architecture (MHA), but different in many ways; such as timing and support for extreme separation of the MAC and PHY layer and support for DOCSIS 3.1 would have to be written. This approach could be called Remote PHY Architecture (RPA). Please refer to Figure 9.

2) Remote - Access Shelf (R-AS): Places the entire "Edge QAM" MAC and PHY layer functions in the node. Video security and encryption may or may not be placed in the node. The lower DOCSIS MAC functions for scheduling and the entire PHY functions are placed in the node. This could be referred to as the R-AS. The M-CCAP packet shelf remains in the headend and performs the DOCSIS upper MAC functions while the M-CCAP Remote Access Shelf performs Edge QAM MAC and Lower DOCSIS MAC functions. Please refer to Figure 10.

3) Remote CCAP (R-CCAP): Places the entire upper and lower MAC and PHY layer functions in the node. This places the CMTS, Edge QAM and CCAP functions into the node. Please refer to Figure 11.

<u>Remote PHY (R-PHY) Architecture</u>

In figure 9 please refer to the definition above called Remote PHY (R-PHY). The architecture of using a CCAP MAC Shelf with a Remote PHY could be called Remote PHY Architecture (RPA), as this resembles in some ways the Modular Headend Architecture (MHA) defined by CableLabs.

Figure 9: Remote PHY Architecture (RPA) Detailed View

Remote Access Shelf Architecture

In figure 10, please refer to the definition above called Remote Access Shelf (R-AS). This is very similar to the Modular CCAP architecture that defined a Packet Shelf containing the DOCSIS upper MAC functions and the Access Shelf (AS) containing the DOCSIS lower MAC and full PHY functions.

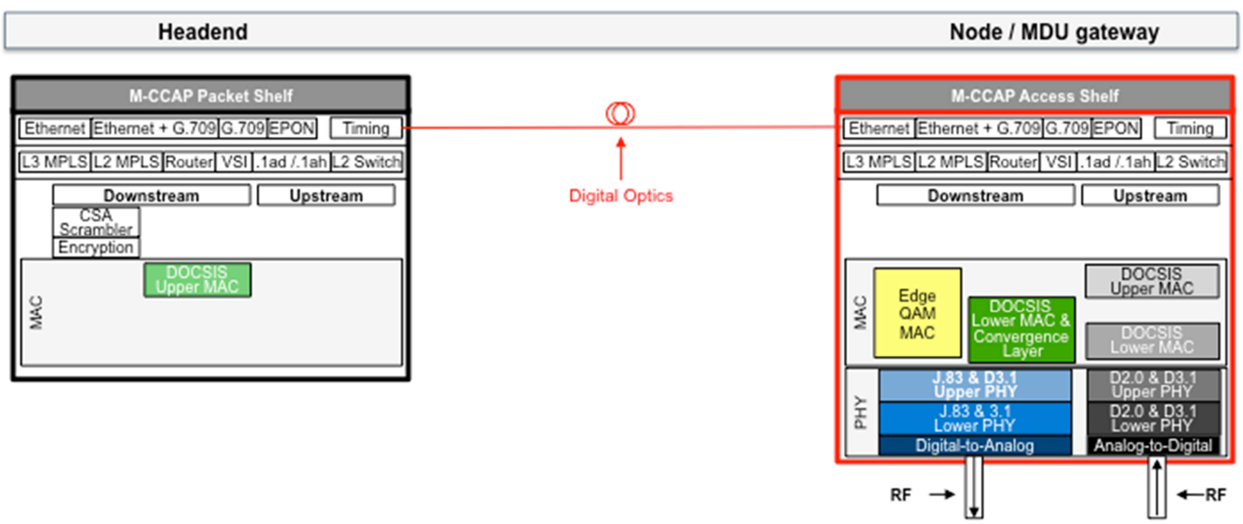


Figure 10: Remote Access Shelf (R-AS) Architecture Detailed View

Remote CCAP Architecture

In figure 11 please refer to the definition above called "Remote CCAP (R-CCAP)". This is the entire CCAP in the node minus the CSA Scrambler and Video Encryption.

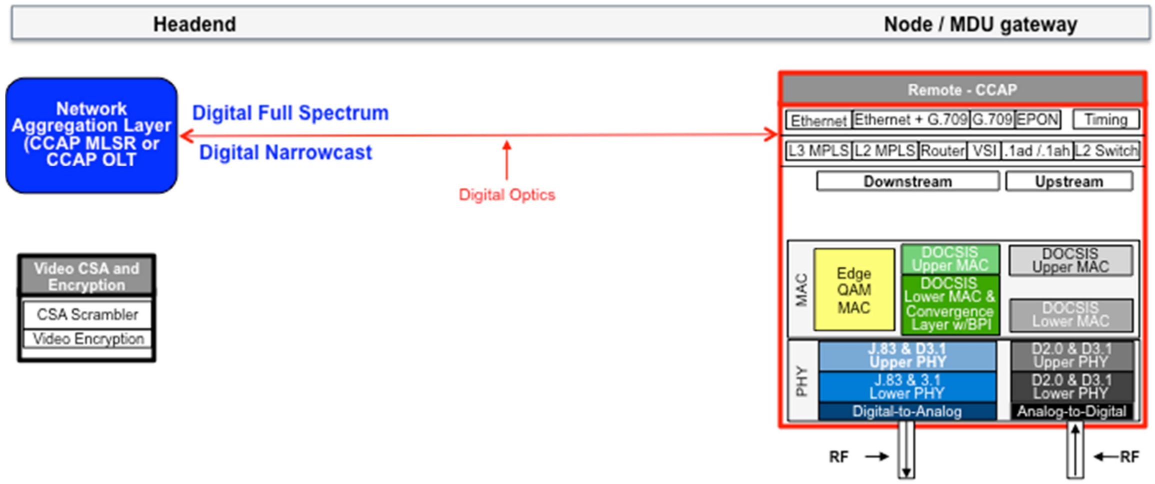


Figure 11: Remote CCAP (R-CCAP) Architecture Detailed View

The two illustrations in figures 12 and 13 represent the Remote PHY and Remote CCAP and for the purposes of this paper these are grouped together to be referred to as Remote Gadget.

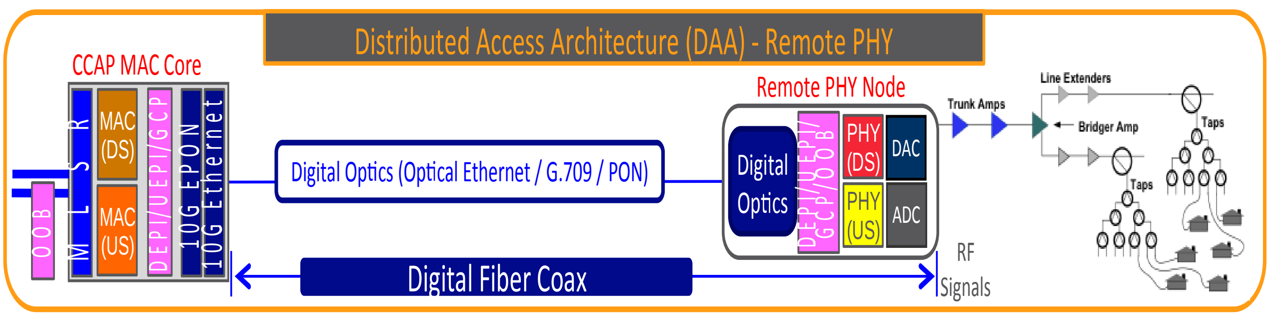


Figure 12: Remote PHY (R-PHY)

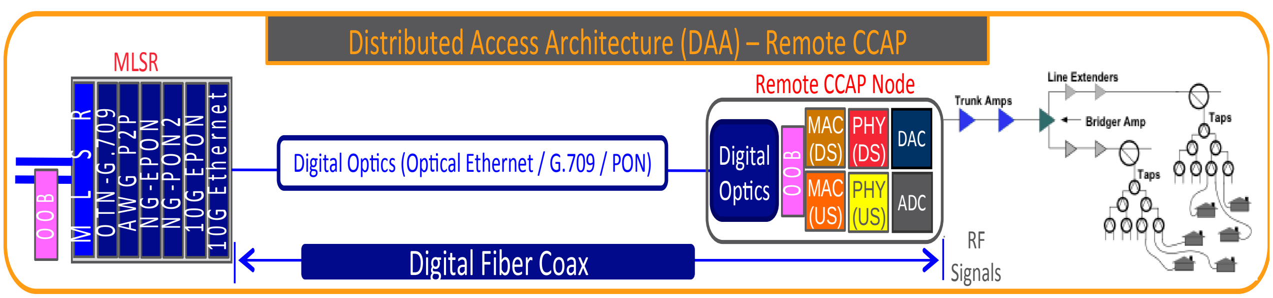


Figure 13: Remote CCAP (R-CCAP)

<u>Important Takeaways Regarding DAA using Digital Optics</u>

DAA will use a digital optical link to the node avoiding the use of amplitude modulated optics and the noise contribution that it adds to the overall cable system's end-of-line (EoL) performance. The figures above represent Remote PHY (R-PHY) and Remote CCAP (R-CCAP). Later in this paper our analysis will define these architectures as simply DAA or Remote Gadget. In either case digital optics between facility and node are used removing the noise contribution found in

CAA use of amplitude modulated optics. The relevance of using digital optics vs. amplitude modulated optics is a core part of this paper.

UNDERSTANDING THE PERFORMANCE IMPACTS TO END-OF-LINE (EOL)

The section above examined the centralized access architectures and distributed access architectures this paper will highlight key differences in both capabilities and performance. This section takes into account several areas that may impact end-of-line (EoL) performance, DOCSIS 3.1 capacity and/or operator margin. Each one of these areas is broken down into separate levers that are examined to account for a different parameter under test, which will yield a different result in many cases. The areas are described below and though the paper illustrates some of the results, our model has approximately 2000 outputs.

Network Element and Configuration Settings

- Network element and configuration settings of today are measured against future settings
  - o Overall operating configuration settings (worst, intermediate, and best case)
- Transmitter MER for CAA CCAP and DAA CCAP
  - o Transmitter MER CCAP settings (worst, intermediate, and best case)
- RF input levels
  - o DOCSIS 3.1 at ~9 dBmV per 6 MHz (6 dB Down from analog)
  - o DOCSIS 3.1 at ~15 dBmV per 6 MHz (not 6 dB Down from analog)
- Spectral width used 750, 1002, & 1218 MHz & impacts of Sub, Mid, and High-Split
- Partial or full spectrum loading of DOCSIS 3.1 vs. SC-QAM
- Spectrum band placement of DOCSIS 3.1 (regardless of CAA or DAA)

Network Architecture (Topology)

- Network architecture / topology Impact analysis from facility to home gateway
- Fiber distance between facility and node
  - o Parameters examined facility to node distance of 15, 25, 40, 80 km
- Wavelength or lambda count and type of optical band used
  - o Parameters examined 1, 4, 8, and 16 wavelength systems
- Amplifiers cascade depth
  - o Parameters examined node +6 amps, +5, +4, +3, +2, +1, +0
- End-of-Line at point-of-entry to CPE or use of in-home wiring to CPE

Access Architecture (CAA and DAA)

- This model estimates the DOCSIS 3.1 network capacity using CAA and DAA
- This model also identifies conditions where CAA and DAA are differentiated
- DAA is termed Remote Gadget (Inclusive of Remote PHY or Remote CCAP)

Network Condition and Performance

- Network condition and performance can impact EoL performance & D3.1 capacity
- Equipment (CCAP source, AM optics & node (if used), amplifier, tap and CPE)
- Coaxial cable condition and type (express cable, distribution cable, drop cable)
- Use and condition of in-home wiring Network (not assumed in this version)
- Accounting for noise and additional Noise Margin

INTRODUCTION TO THE ARRIS DOWNSTREAM PERFORMANCE MODEL

Our model can be customized for any cable operator. The model takes into account the core areas impacting EoL: Network architecture (topology); network element configuration settings; and access architecture (CAA & DAA). The network architecture / topology examines parameters such as fiber distance between facility and node, lambda count, amplifiers cascade count, and spectrum (750 MHz, 1002 MHz, and plans to use 1.2 GHz). We can also assume network element configuration settings that can calculate the current configuration setting of today to support both analog video and digital and then future configuration setting that may be all digital, thus no analog. Finally, we can measure the impact of the access architecture, which examines the use of CAA and AM optics vs. DAA and digital optics impacts on EoL.

Model Objectives

Estimate Downstream Network Performance and D3.1 Capacity:

- Estimate the end-of-line (EoL) CNR performance to the last active
- Estimate maximum D3.1 modulation orders and thus maximum capacity

Estimate downstream performance considering variables the will impact performance:

- Network elements and configurations
- Network architectures
- CAA and DAA
- Network condition and performance

Model Methodology

In our model we used existing products and real-world configurations and/or those recommended to our customers. The model and paper's focus is on estimating or predicting the performance of DOCSIS 3.1 technology in CAA and DAA systems, all of which do not exist at this time. For the products that do not exist performance estimates have been placed in the model. Every effort is made by ARRIS design and implementation experts to estimate accurately the performance range of future D3.1 products used to predict future performance. These numbers have and will change as we learn more. As productions systems end-to-end become available we will evaluate the current model input with the data from our lab testing and then in field deployments.

Model Mechanics and Assumptions

The output of the model is a maximum value that could be attained under the assumptions and parameters of each use case while assuming a network in normal working order. Our model will provide an estimate of the maximum EoL as defined at the amplifier location for node +6 to +1 and amplifier 0 will be the HFC node or DAA remote gadget device. To determine the DOCSIS 3.1 modulation order a measurement at the RF connector of the CPE will need to be performed on a per subscriber basis, this is not currently possible because DOCSIS 3.1 end-to-end systems do not exists. The authors will not estimate the average or worst case CNR at the subscriber's home until end-to-end DOCSIS 3.1 systems can be tested in a lab and then field deployments.

The paper defines end-of-line (EoL) as the maximum estimated CNR at the amplifier. The EoL values will vary because of network element configuration settings, network architecture and topology, and access architecture (i.e. CAA & DAA).

The segment between the amplifier and the RF connector of the Dual Port D3.1 gateway may be less than or equal to the maximum estimated CNR amplifier values. The CNR at the CPE can vary based on network condition and performance. The segment between amplifiers contains roughly about 750 to 1000 feet of coaxial cable with approximately five through taps and a terminating tap and from each tap a drop cable spanning approximate 75 to 150 feet or more connects the subscriber's home. In the model and paper we assume the DOCSIS 3.1 Dual-Port Gateway is located at the point-of-entry of the home to terminate the connection to the cable operator's access network. The IHN (In-Home Network) is not used for DOCSIS 3.1 in our current version of the model. The in-home network (IHN) is just a Local Area Network (LAN) to deliver cable operator services to data home networking and video rendering devices in the home. Figure 14 provides an illustration of the scope of the model and illustrates the architecture assumptions.

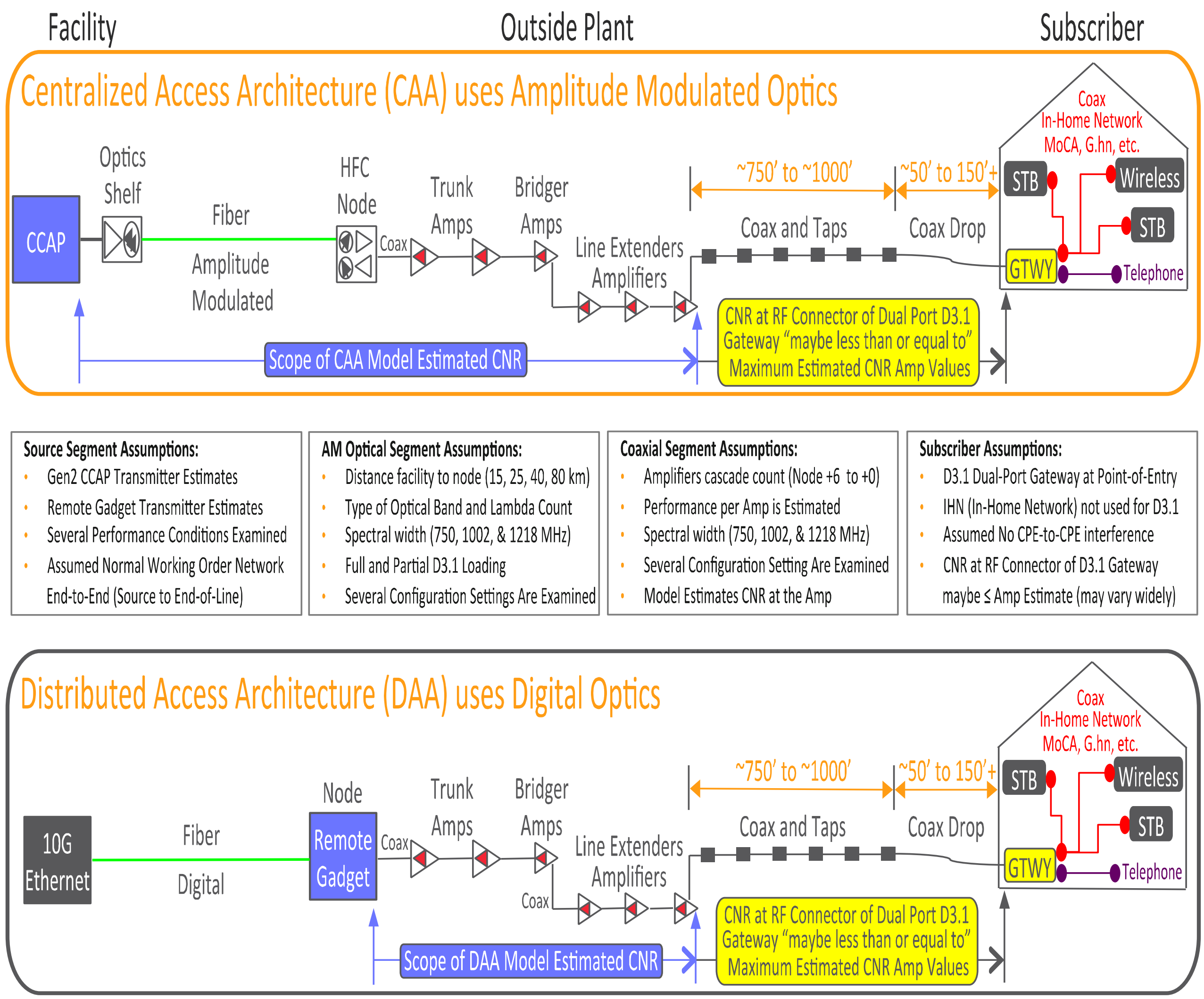
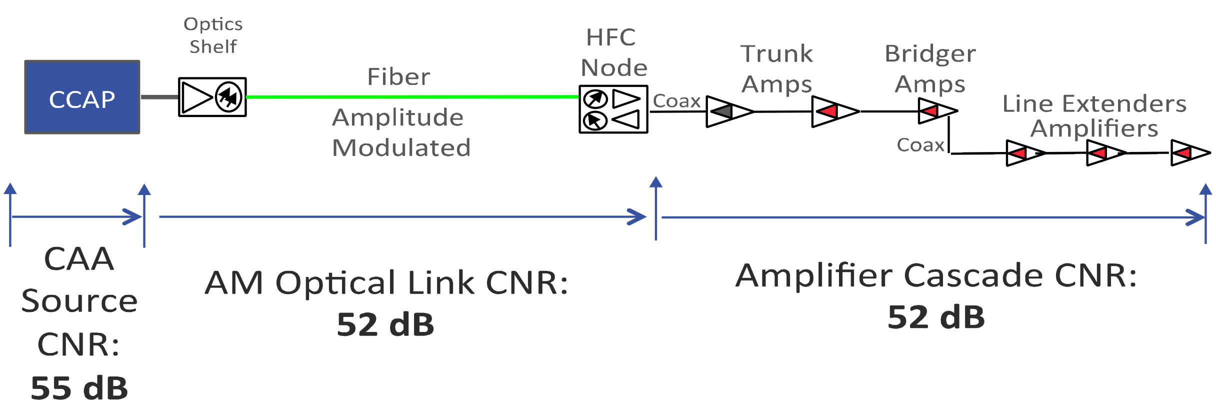


Figure 14: Diagram and Assumptions to Scope of DOCSIS 3.1 CAA & DAA Analysis

Carrier to Noise (CNR) and Signal to Noise (SNR) ratios both represent signal power to noise power ratios and are often used interchangeably, with the most recent trend to reserve SNR for a baseband and CNR for an RF band signal, as codified in DOCSIS 3.1 specifications. Similarly, Modulation Error Ratio (MER) represents average signal constellation power over average constellation error power and is often interchanged with SNR. In this paper, we refer to CNR in the spirit of DOCSIS 3.1 specifications.

In an HFC transmission system, it is often insightful to analyze of a cascade of variously performing system elements such as: signal source, optical transmission, coaxial plant RF amplifier chain, tap and coaxial distribution segment, drop cable and in-home coaxial network (if used) to list a few. Each of these can be individually characterized by the standalone link CNR. One way to track the CNR of the whole system exactly is to analyze the signal's progression from the start to the end of the system, and to add noise contributions along the way. However, a simplified approach, which makes assumptions of properly selected level ranges at each of the links, can use individual link CNR to estimate the end-to-end CNR.

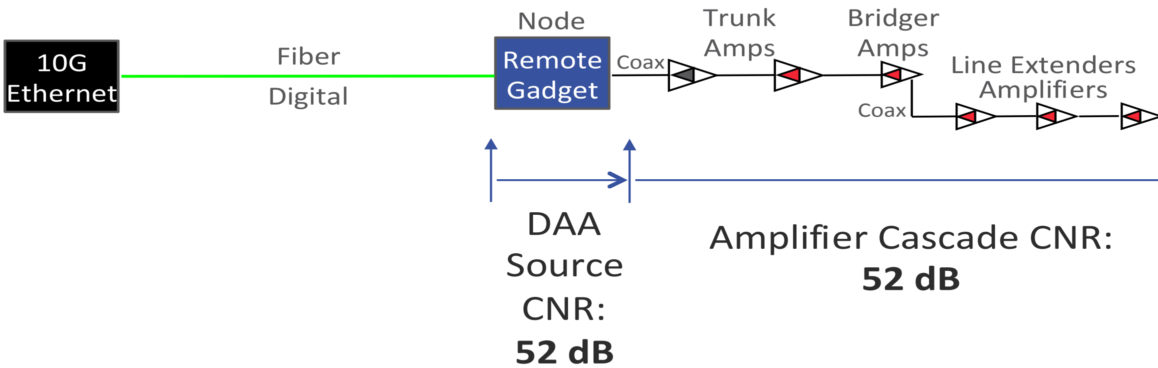
Figure 15 and figure 16 illustrate the approach the model uses to calculate CAA end-of-line CNR and DAA end-of-line CNR respectively. The difference as illustrated in both the network diagram and the equation is that CAA includes the AM optical link CNR contribution, while the DAA does not require an optical contribution to be added to the CNR equation. The values used are for illustration purposes only.



CAA EoL CNR Equation:

$$-10\log\left(10^{-\frac{55}{10}} + 10^{-\frac{52}{10}} + 10^{-\frac{52}{10}}\right) = 48\ dB$$

Figure 15: CAA End-of-Line CNR and Equation (values used are for illustration purposes only)



DAA EoL CNR Equation:

$$-10\log\left(10^{-\frac{52}{10}} + 10^{-\frac{52}{10}}\right) = 49\ dB$$

Figure 16: DAA End-of-Line CNR and Equation (values used are for illustration purposes only)

In figure 17, the DOCSIS 3.1 specifications defined the modulation and associated CNR at the RF connector of the cable modem. The authors are estimating the use of 8192QAM and 16384QAM, along with the required CNR. The required level for CM downstream post-FEC error ratio is defined as less than or equal to 10-6 PER (packet error ratio) with 1500 byte Ethernet packets.

CableLabs DOCSIS 3.1 Specifications (Downstream)			
Modulation	Coding	Required CNR at Connector up to 1 GHz	Required CNR at Connector 1 GHz to 1.2 GHz
512QAM	8/9 LDPC	30.5 dB [1]	30.5 dB [1]
1024QAM	8/9 LDPC	34 dB [1]	34 dB [1]
2048QAM	8/9 LDPC	37 dB [1]	37.5 dB [1]
4096QAM	8/9 LDPC	41 dB [1]	41.5 dB [1]
8192QAM	8/9 LDPC	45 dB	45.5 dB
16384QAM	8/9 LDPC	49 dB	49.5 dB

[1] CM-SP-PHYv3.1-I04-141218 - Table 7–41 -
CM Minimum CNR Performance in AWGN Channel

Figure 17: DOCSIS 3.1 Modulation Capabilities with Required CNR at RF Connector

Model Estimates

The creators and authors of the model and this paper note the information provided is for educational purposes only and do not recommend sole reliance on this information for investment and operational decisions. The model values are predictions based on the combination of current and future product performance estimates, and may not represent actual performance. The information provided supersedes any previously issued estimates.

The authors and ARRIS reserve the right to change these performance estimates without notice.

ESTIMATING DOWNSTREAM D3.1 CAPACITY IN CAA AND DAA SYSTEMS

The CAA class of access architecture places the DOCSIS MAC and PHY layers in the cable operator's facility and uses AM optical technology, referred to as analog optics, to carry the DOCSIS signals to the node. The optical span between headend and node may vary widely from several kilometers (km) apart to over 100 km. The DAA class of access architecture places some or all of the DOCSIS functions in the outside plant, like a node or cabinet and use digital optical transport to the node, such as 10 Gigabit Ethernet. The use of CAA and AM optics is thought to lower overall performance compared to DAA systems that use digital optics. This section will predict downstream DOCSIS 3.1 performance in CAA and DAA systems.

The CNR estimates in the figures represent the maximum estimated CNR amplifier values under the defined parameters for each use case under study. This means that the EoL is the amplifier; this is the generally accepted meaning for the term EoL and it may also apply to the tap port as well. In normal working order systems the CNR measured at the amplifier should also be the measurement found at the tap port, which is between 100 to 1,000 feet away from the amplifier. In DOCSIS 3.1 the defined CNR value that determines the modulation order is the CNR value at the RF connector of the cable modem. In this paper, we state that the CNR at RF connector of dual port DOCSIS 3.1 gateway may be less than or equal to maximum estimated CNR amplifier values.

Network Element and Configuration Settings Estimates

The model and paper defines three operating configurations (worst case, intermediate case, and best case), as seen in figure 18. A major difference between them will be the settings assumed for all of the equipment. The worst case will assume that DOCSIS 3.1 will operate in CAA using AM optics 6 dB down from analog video services as it has since the inception of the service. This approach was successful at operating analog services that needed high performance as well as digital services that needed 256QAM. Cable operators may still operate the digital and DOCSIS channels at 6 dB down even without the presence of analog video services. For example a typical RF input levels of ~15 dBmV per 6 MHz channel analog and ~9 dBmV per 6 MHz channel digital, 256 QAM could be found in most cable operators deployments worldwide.

Segment	Worst Case Operating Configuration	Intermediate Case Operating Configuration	Best Case Operating Configuration
Description	Current Configuration Settings for AM optics and RF cascade at "6dB below analog" levels	Configuration Setting NOT Operating 6 dB below analog levels supporting for full spectrum D3.1	Highest Design Targets of Future Products
Source	Minimum Transmitter MER Target	+2 dB Above Minimum Transmitter MER Target	+3 to 4 dB Above Min. Transmitter MER Target
Optical Segment	QAM channels at "6 dB below analog" levels	Optimizing OMI for QAM Channels for Full Spectrum NOT 6 dB below analog levels	"Future" AM Product
RF Cascade Segment	QAM channels at "6 dB below analog" levels	Optimizing RF Levels for QAM Loading for Full Spectrum NOT 6 dB below analog levels	Highest Optimizing RF Levels for QAM Loading for Full Spectrum

Figure 18: Operating Configuration Assumptions

Worst Case Operating Configuration

This assumes that DOCSIS and digital services would continue to operate at an RF input level of 6 dB down with or without the presence of analog video services. In this worst case example, DOCSIS 3.1 would operate as it has for the last a decade at ~9 dBmV per 6 MHz channel where it only needed enough performance to achieve 256QAM. Additionally, the worst case example assumes minimum settings for CCAP source transmit MER, AM optics (if used), and amplifiers.

Intermediate Case Operating Configuration

This assumes that analog services which operated with a ~15 dBmV per 6 MHz channel analog is no longer present and the model assumes that DOCSIS 3.1 could operate with this RF input level. The intermediate case model also assumes a normal CCAP source transmit MER, AM optics (if used), and amplifiers, which we predict are achievable in real-world deployments.

Best Case Operating Configuration

This assumes that all of the network elements are operating at the highest design targets. Figure 19, defines parameters options and parameters used for the three Operating Configurations (worst case, intermediate case, and best case). This table will be used in the subsequent sections and the text in the table highlighted in red illustrates the key area under assessment. The resulting maximum estimated CNR amplifier value is captured in the line graph following the parameters table.

Category	Parameters Options	Parameters Used
Network Element and Configuration Settings	Overall Operating Configuration Settings (Worst, Intermediate, Best Case)	Under Assessment
	Transmitter MER CCAP Settings & RF input levels (Worst, Intermediate, Best)	Under Assessment
	Spectral Width used 750, 1002, & 1218 MHz (amount of spectrum in use)	1218 MHz
	Partial or Full Spectrum Loading of DOCSIS 3.1 vs. SC-QAM	Full Spectrum D3.1
	Spectrum Band Placement of DOCSIS 3.1 (regardless of CAA or DAA)	Full Spectrum D3.1
Network Architecture (Topology)	Facility to Node Distance (15, 25, 40, 80 km)	ALL
	AM Optical Wavelength or Lambda Count (1, 4, 8, or 16)	1 Wavelength
	Amplifiers Cascade Depth (6, 5, 4, 3, 2, 1, 0)	ALL
	End-of-Line at Point-of-Entry to CPE or Use of In-Home Wiring to CPE	Point-of-Entry to CPE
	CPE Type (Single-Port CM, Single-Port Gateway, Dual-Port Gateway)	Dual-Port Gateway
Access Architecture	CAA and DAA	Both
Network Condition and Performance	Network Equipment and Coaxial Condition / Performance	Normal Working Order
	Accounts for AM Optical and Plant Noise / D3.1 Spec CMTS & CM Noise Req.	Included
	Additional Noise Margin	None

Figure 19: Parameters for Network Element and Configuration Settings Estimates

The analysis results for the above parameters are illustrated in Figures 20, 21, and 22. The mode uses the network elements settings defined in figures 18 and 19. The line graphs headings located above the line values describe system under test. The CNR values at the amplifiers as well as the associated DOCSIS 3.1 modulation format defined assuming spectrum up to 1 GHz are defined in the graph and defined in figure 17. When considering spectrum between 1 GHz and 1.2 GHz, this will require a slightly higher CNR as defined in Figure 17.

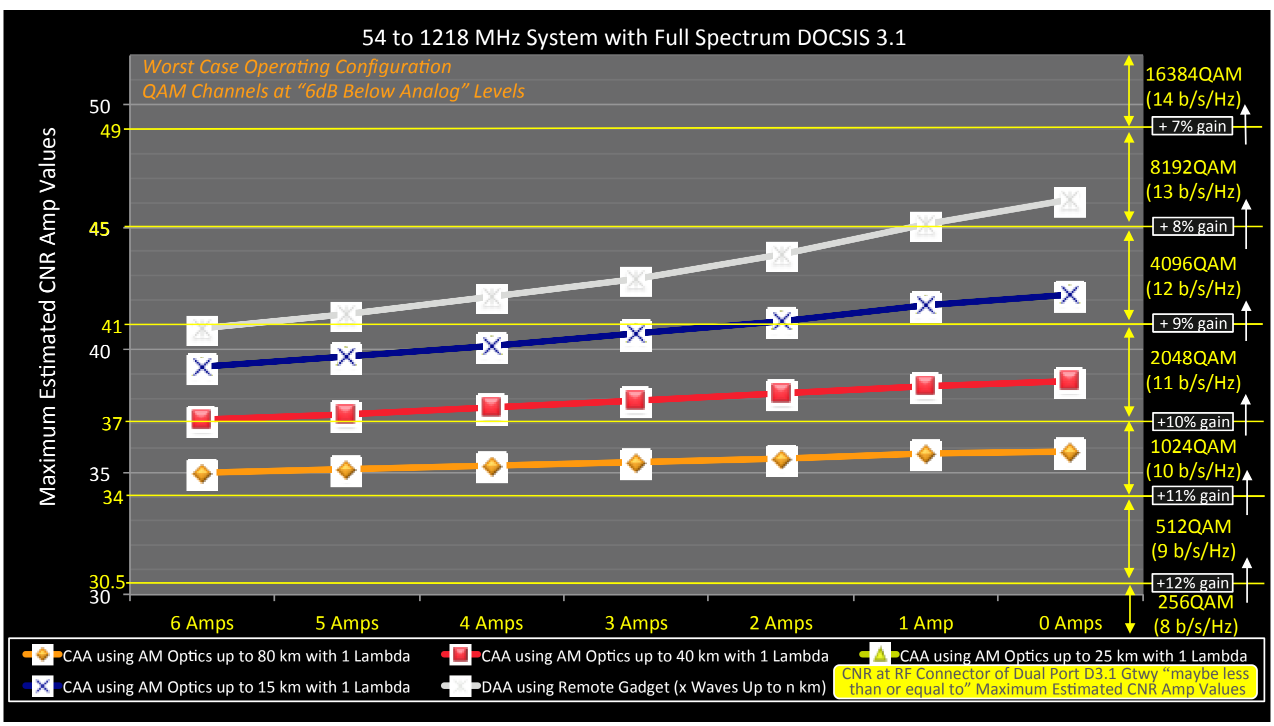


Figure 20: Worst Case Operating Configuration Settings – 1218 MHz

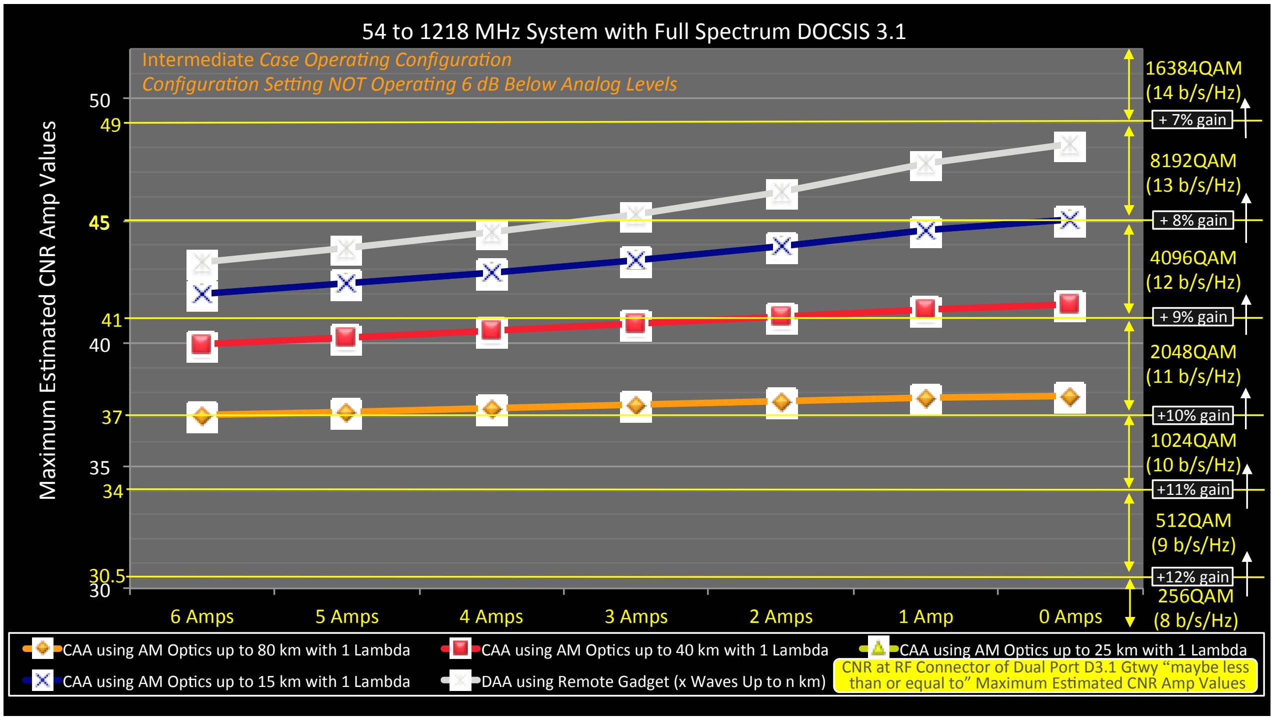


Figure 21: Intermediate Case Operating Configuration Settings – 1218 MHz

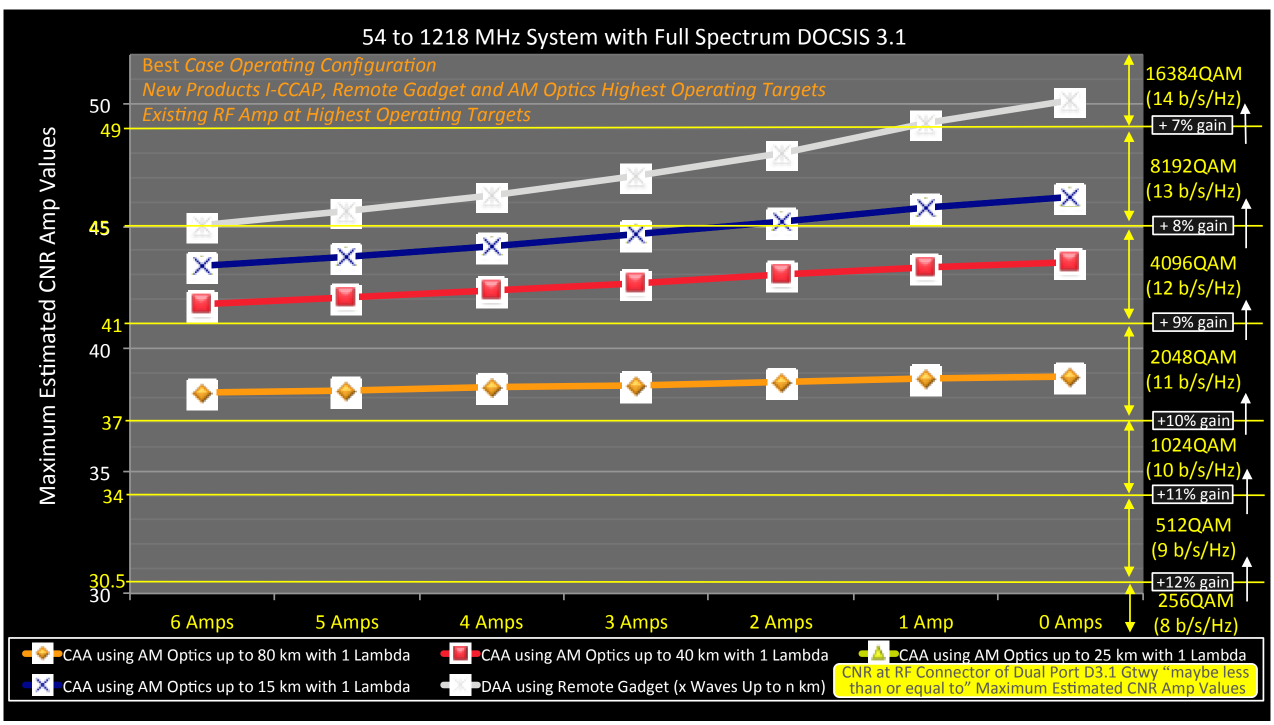


Figure 22: Best Case Operating Configuration Settings – 1218 MHz

Conclusions for Network Element and Configuration Settings Estimates

- Worst case operating configuration use is not ideal
  - Uses DOCSIS 3.1 in a 6 dB down from analog configuration (not ideal for all digital)
- Best case operating configuration use is not ideal
  - Uses the highest design targets of future products
  - Uses the highest optimizing RF levels for QAM loading for full spectrum
- Intermediate case operating configuration is recommended
  - Uses currently available product configured to support digital not 6 dB down
  - Uses average / moderate design targets of future products
  - The additional analysis will assume the intermediate case settings

A Key Takeaway from this Analysis

Considering network element and configuration settings estimates, the graphs clearly show a major variation in performance. If just considering the worst case versus the intermediate case for CAA architectures, there are major differences in end-of-line. When considering the element settings, specifically operating DOCSIS 3.1 at 6 dB down as currently implemented in today's DOCSIS network this will limit overall performance, as seen in figure 20. While operating the DOCSIS 3.1 with the same RF input level as analog, performance will improve at the end-of-line amplifiers, as seen in figure 21.

<u>Spectral Width Analysis 750 MHz vs. 1002 MHz vs. 1218 MHz with Full Spectrum DOCSIS 3.1</u>

Spectrum width or loading was identified as a performance impacting area with CAA using amplitude modulation optics; refer to figure 6 highlights of the optical impairments. In this section we examine the spectrum width and loading of full spectrum DOCSIS 3.1 up to 750 MHz vs. 1002 MHz vs. 1218 MHz to determine performance differentiation of CAA and DAA. Figure 23 identifies the parameters used in the analysis.

Category	Parameters Options	Parameters Used
Network Element and Configuration Settings	Overall Operating Configuration Settings (Worst, Intermediate, Best Case)	Intermediate
	Transmitter MER CCAP Settings & RF input levels (Worst, Intermediate, Best)	Intermediate
	Spectral Width used 750, 1002, & 1218 MHz (amount of spectrum in use)	Under Assessment
	Partial or Full Spectrum Loading of DOCSIS 3.1 vs. SC-QAM	Full Spectrum D3.1
	Spectrum Band Placement of DOCSIS 3.1 (regardless of CAA or DAA)	Full Spectrum D3.1
Network Architecture (Topology)	Facility to Node Distance (15, 25, 40, 80 km)	ALL
	AM Optical Wavelength or Lambda Count (1, 4, 8, or 16)	1 Wavelength
	Amplifiers Cascade Depth (6, 5, 4, 3, 2, 1, 0)	ALL
	End-of-Line at Point-of-Entry to CPE or Use of In-Home Wiring to CPE	Point-of-Entry to CPE
	CPE Type (Single-Port CM, Single-Port Gateway, Dual-Port Gateway)	Dual-Port Gateway
Access Architecture	CAA and DAA	Both
Network Condition and Performance	Network Equipment and Coaxial Condition / Performance	Normal Working Order
	Accounts for AM Optical and Plant Noise / D3.1 Spec CMTS & CM Noise Req.	Included
	Additional Noise Margin	None

Figure 23: Parameters for Spectrum Width Analysis 750 MHz vs. 1002 MHz vs. 1218 MHz

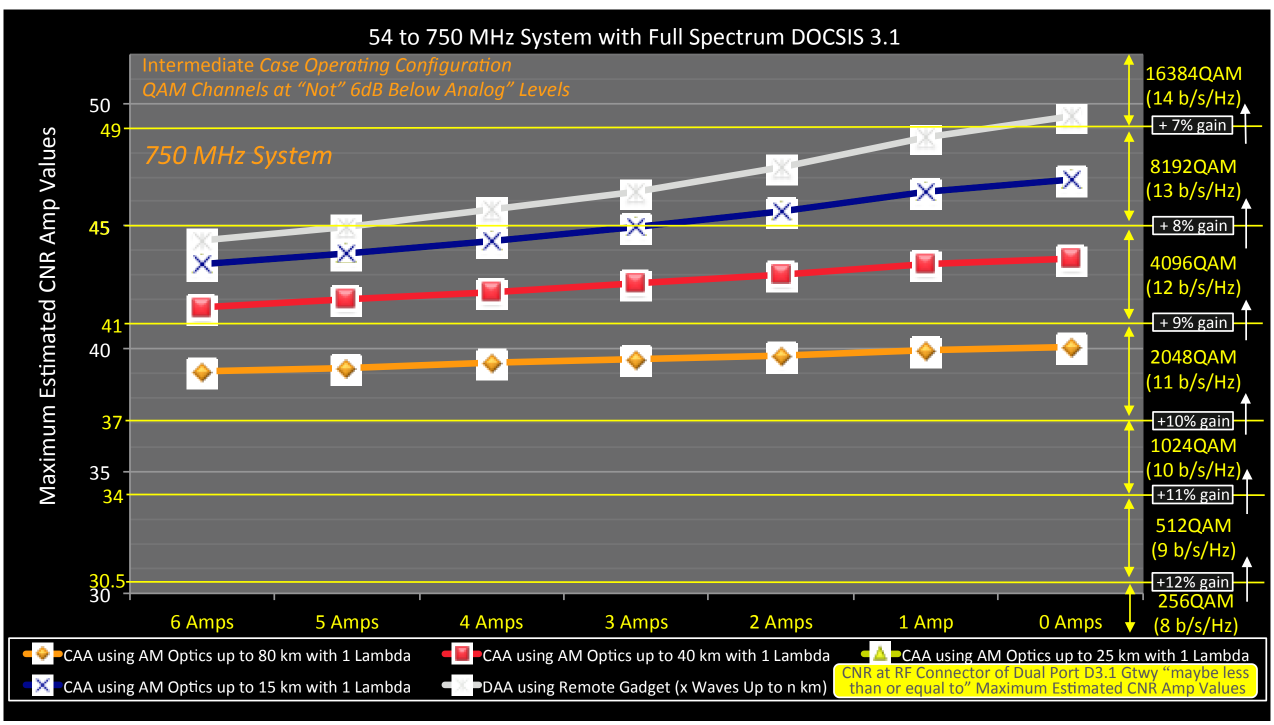


Figure 24: Spectral Width Analysis 750 MHz with Full Spectrum DOCSIS 3.1

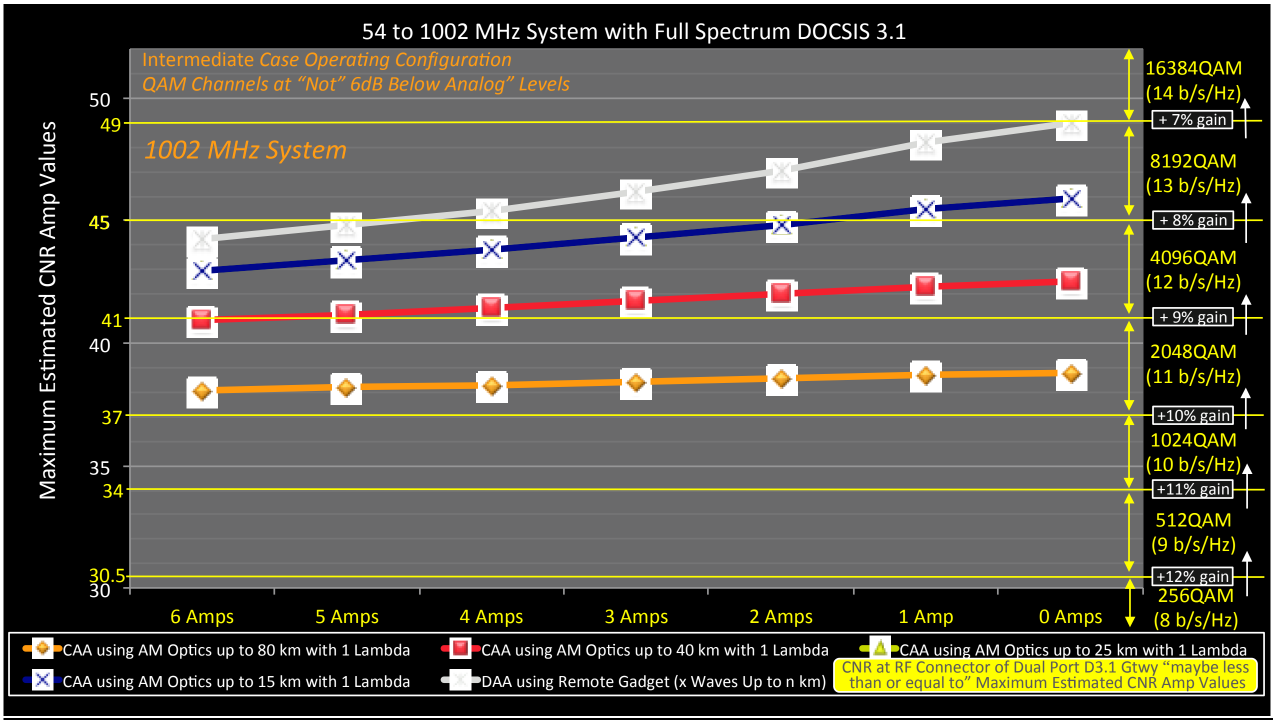


Figure 25: Spectral Width Analysis 1002 MHz with Full Spectrum DOCSIS 3.1

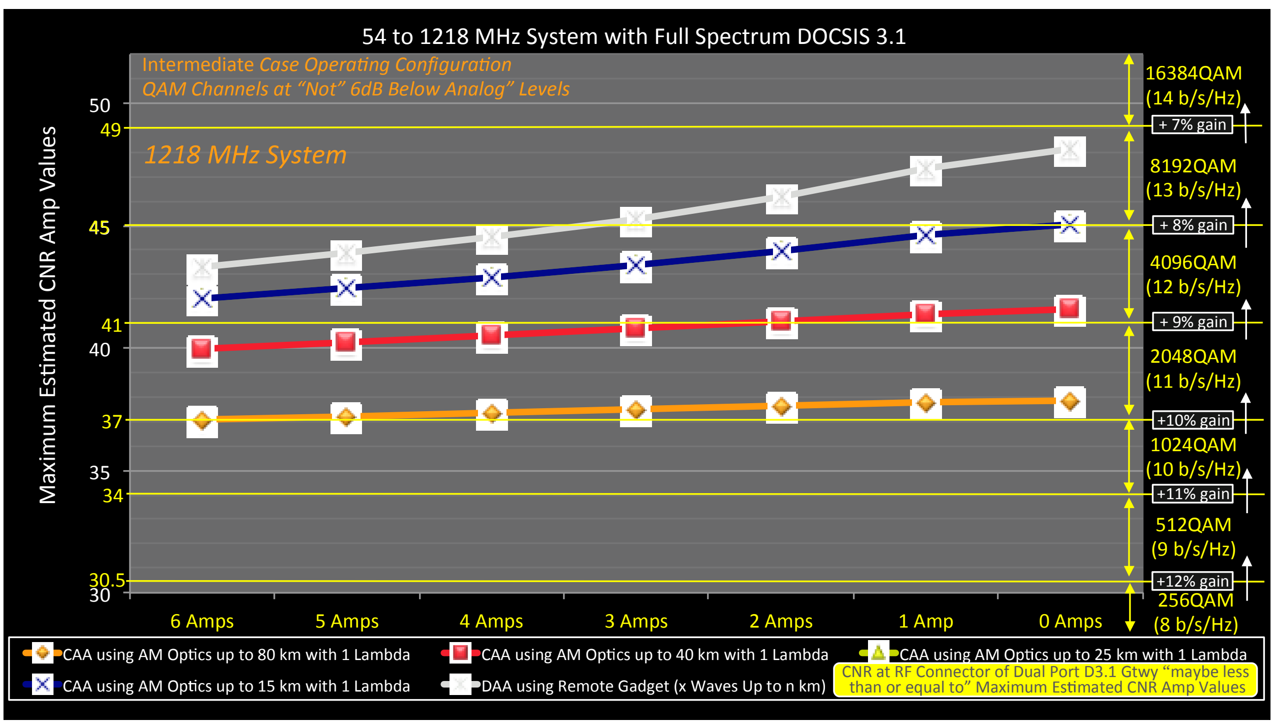


Figure 26: Spectral Width Analysis 1218 MHz with Full Spectrum DOCSIS 3.1

Additional Spectrum Level and Tap Component Analysis Considerations

Taps are the components with the most variability in passband characteristics, because there are so many different manufacturers, values, and number of outputs. Most were designed more than ten years ago, well before >1 GHz bandwidth systems were considered. One of the serious limitations of power passing taps is the AC power choke resonance. This typically is around 1100 MHz, although the notch frequency changes with temperature. Tap response resonances are typical from ~1050 to 1400 MHz. This is an important finding when leveraging the existing passives; therefore the use above 1050 MHz may not be predictable or even possible. Taps in cascade may affect capacity, thus additional testing is required [EMM1]

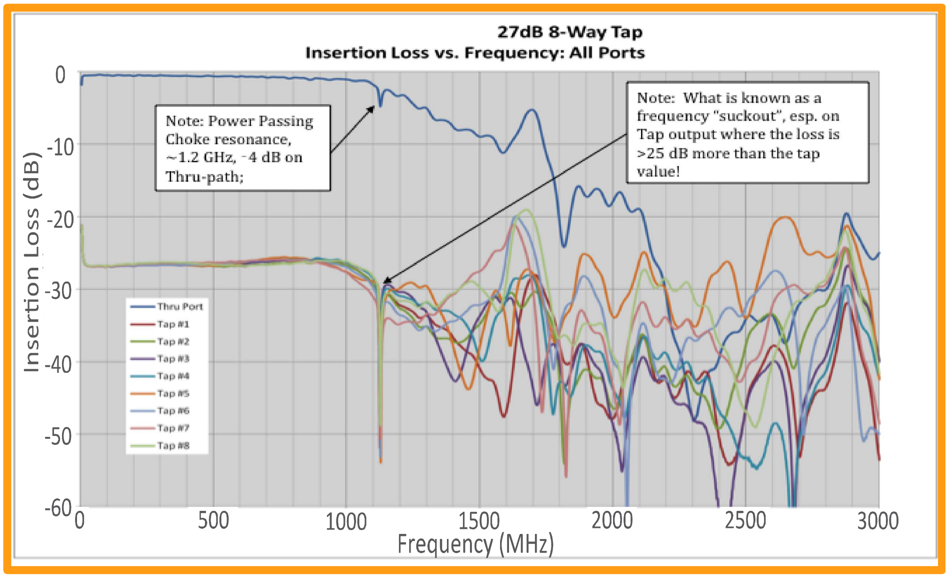


Figure 27: Spectrum Level and Tap Component Analysis Considerations

Use up to 1218 MHz Could be Difficult

- Tap performance can vary widely
- Tap performance may not yield up to 1218 MHz (above 1100 MHz could be a challenge)
- Modulation orders will likely be Lower than those used below 1 GHz
- AM optics and remote gadget perform better below 1 GHz
- Model estimates to the amplifier
- The authors have modeled up to 1218 MHz though use is not assured

Conclusions for Spectral Width Analysis 750 MHz vs. 1002 MHz vs. 1218 MHz

The tap performance as our industry approaches 1 GHz or even higher to 1.2 GHz could exhibit variation in performance depending on manufacture, model used, date of production, conditions in the field, and other factors. [EMM1] Assuming all parameters are the same except for spectrum load of 750 MHz, 1002 MHz, and 1218 MHz, figures 24, 25, and 26 show a minor decline in end-of-line as estimated at the amplifier, 2 dB delta comparing 750 MHz and 1218 MHz.

AM Optical Wavelength Count of 1, 4, 8, 16 with DOCSIS 3.1 Full Spectrum 1218 MHz

A major concern in the industry has been the uncertainty of performance of CAA using amplitude modulation optics when increasing the number of wavelengths. The performance may also be impacted when other parameters are assumed, such as full spectrum DOCSIS 3.1 to 1218 MHz and long distances. The AM optical concerns were raised earlier in the paper as well as other papers reference for more detail. What was unclear we estimate in end-of-line CNR to the amplifier values, assuming the parameters used in Figure 28.

Category	Parameters Options	Parameters Used
Network Element and Configuration Settings	Overall Operating Configuration Settings (Worst, Intermediate, Best Case)	Intermediate
	Transmitter MER CCAP Settings & RF input levels (Worst, Intermediate, Best)	Intermediate
	Spectral Width used 750, 1002, & 1218 MHz (amount of spectrum in use)	1218 MHz
	Partial or Full Spectrum Loading of DOCSIS 3.1 vs. SC-QAM	Full Spectrum D3.1
	Spectrum Band Placement of DOCSIS 3.1 (regardless of CAA or DAA)	Full Spectrum D3.1
Network Architecture (Topology)	Facility to Node Distance (15, 25, 40, 80 km)	ALL
	AM Optical Wavelength or Lambda Count (1, 4, 8, or 16)	ALL Under Assessment
	Amplifiers Cascade Depth (6, 5, 4, 3, 2, 1, 0)	ALL
	End-of-Line at Point-of-Entry to CPE or Use of In-Home Wiring to CPE	Point-of-Entry to CPE
	CPE Type (Single-Port CM, Single-Port Gateway, Dual-Port Gateway)	Dual-Port Gateway
Access Architecture	CAA and DAA	Both
Network Condition and Performance	Network Equipment and Coaxial Condition / Performance	Normal Working Order
	Accounts for AM Optical and Plant Noise / D3.1 Spec CMTS & CM Noise Req.	Included
	Additional Noise Margin	None

Figure 28: Parameters for AM Optical Wavelength with D3.1 Full Spectrum 1218 MHz

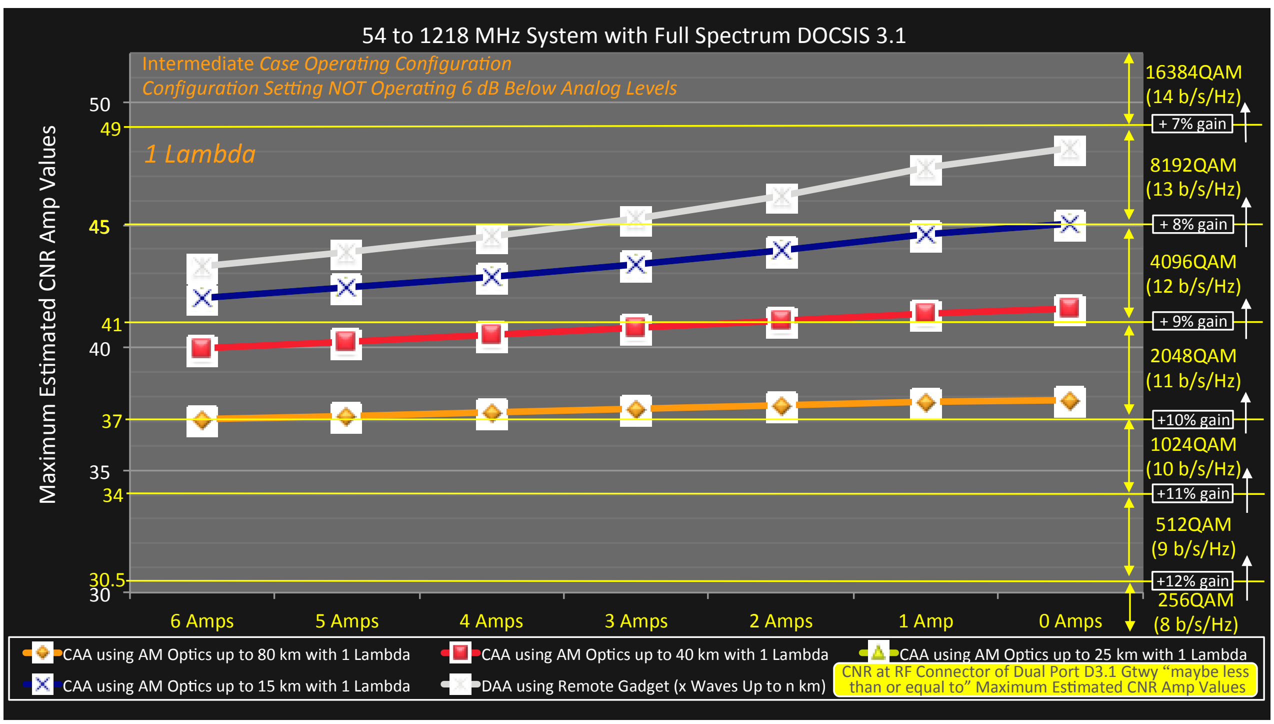


Figure 29: DAA vs. CAA with Amplitude Modulated (AM) Optical – One (1) Wavelength

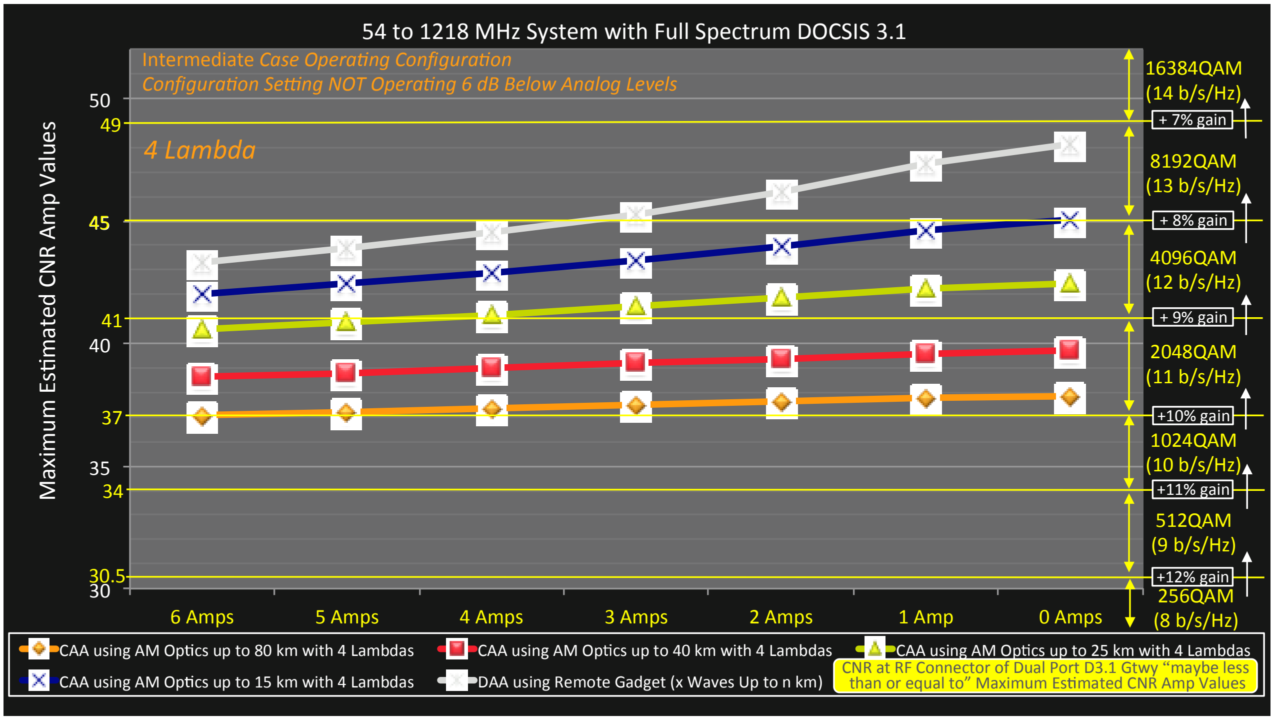


Figure 30: DAA vs. CAA with Amplitude Modulated (AM) Optical – Four (4) Wavelengths

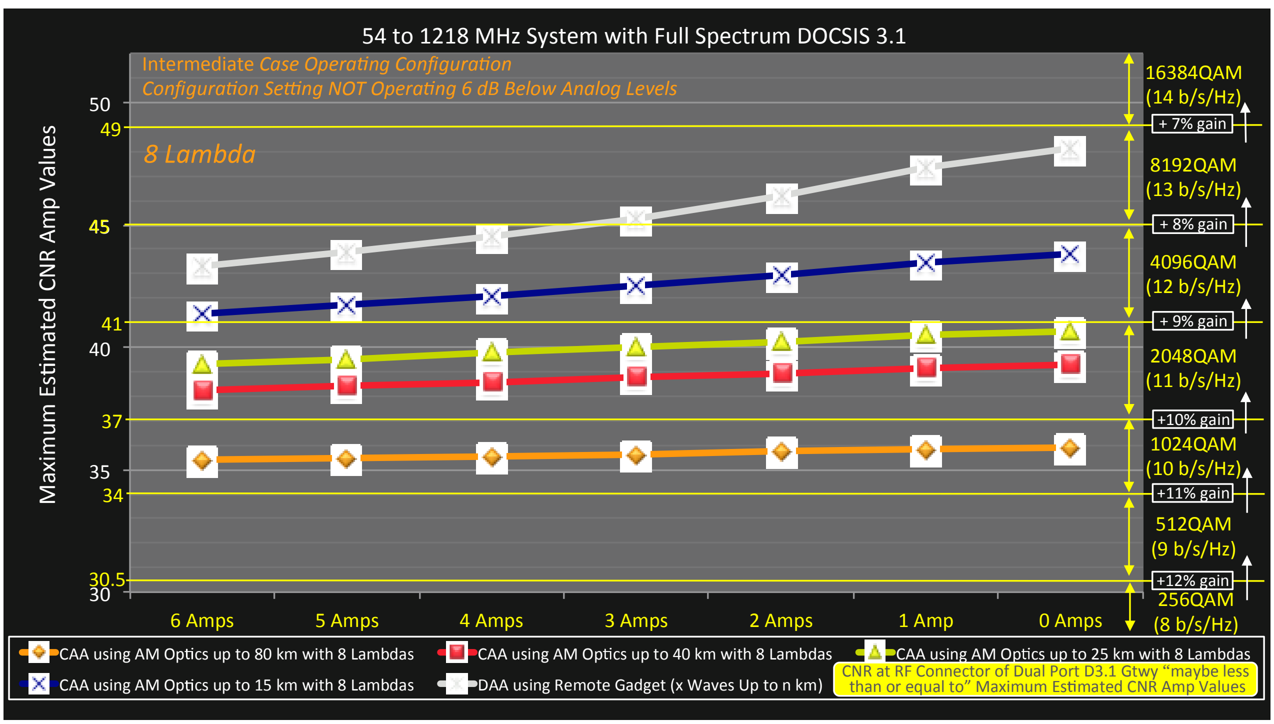


Figure 31: DAA vs. CAA with Amplitude Modulated (AM) Optical – Eight (8) Wavelengths

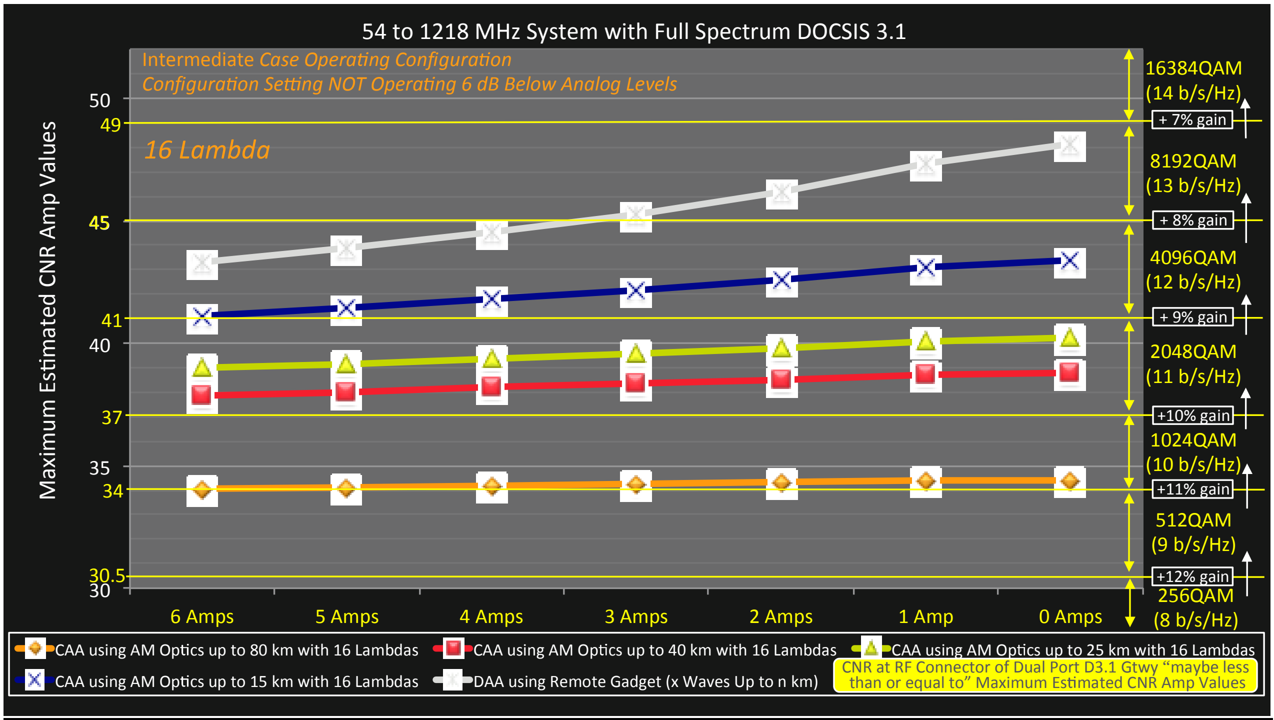


Figure 32: DAA vs. CAA with Amplitude Modulated (AM) Optical – Sixteen (16) Wavelengths

Conclusions for AM Optical Wavelength Count of 1, 4, 8, or 16
(Figures 29, 30, 31, and 32)

This single analysis captures the major differentiation that may exist in end-of-line CNR at the amplifier when comparing CAA and DAA systems. This may also mean a difference in DOCSIS 3.1 modulation seen at the cable modem. This list below captures the key highlights of this analysis.

1) There is a very long distance between facility and node using AM optics impacts modulation order more than any other factor, thus DAA "may" yield a 30% gain compared to CAA 80 km links (9-14 dB at the Amp with 16 waves).

2) Wavelengths (1 - 16) & Distance (25 - 40km) CAA using AM optics will support high order modulation and DAA "may" yield 0% to 18% capacity gain (1-9 dB at Amp with 16 waves).

3) Amplifier count DAA affects modulation order yielding a 0% to 8% gain (5 dB) and CAA has 0-2 dB improvement with fewer amps.

4) Overall the model and paper EoL estimates to the amplifier in CAA and DAA systems will set the maximum DOCSIS 3.1 modulation order possible, the difference in performance between CAA vs. DAA varies widely from DAA having 0% to 30% capacity gain over CAA systems.

Partial DOCSIS 3.1 with Placement Under 600 MHz and Remaining Spectrum SC-QAM

All of the analysis previously captured in this paper assumed that DOCSIS 3.1 would be used in full spectrum environments as this may represent end state architecture. However, our industry is a long way from full spectrum DOCSIS 3.1 and even the use of 1218 MHz. The parameters defined in this section examine the use of partial DOCSIS 3.1 spectrum and placement under 600 MHz with the remaining spectrum used for single carrier QAM (SC-QAM). In this analysis, the maximum spectrum used is 750 MHz or 1002 MHz as this represents many Cable operators current spectrum band plan. Figure 33 defines the parameters used in this section.

Segment	Partial Spectrum Case Operating Configuration	Partial Spectrum Case Operating Configuration
Description	Configuration Setting NOT Operating 6dB below analog levels supporting for 2-3 blocks of 192 below under 600 MHz	Configuration Setting NOT Operating 6dB below analog levels supporting for 2-3 blocks of 192 below under 600 MHz
Spectrum	54 – 750 MHz Full Spectrum DOCSIS 3.1	54 – 1002 MHz Full Spectrum DOCSIS 3.1
Source	+2 dB Above Minimum MER Transmitter Target	+2 dB Above Minimum MER Transmitter Target
Optical Segment	"Current" AM Optical Product Carrying 2 to 3 Blocks of 192 OFDM below 600 MHz	"Current" AM Optical Product Carrying 2 to 3 Blocks of 192 OFDM below 600 MHz
RF Cascade Segment	Optimizing RF Levels for QAM Loading for Full Spectrum NOT 6dB below analog levels	Optimizing RF Levels for QAM Loading for Full Spectrum NOT 6dB below analog levels

Figure 33: Operating Configuration Assumptions for Partial Spectrum Loading

Category	Parameters Options	Parameters Used
Network Element and Configuration Settings	Overall Operating Configuration Settings (Worst, Intermediate, Best Case)	Intermediate
	Transmitter MER CCAP Settings & RF input levels (Worst, Intermediate, Best)	Intermediate
	Spectral Width used 750, 1002, & 1218 MHz (amount of spectrum in use)	750 and 1002 MHz
	Partial or Full Spectrum Loading of DOCSIS 3.1 vs. SC-QAM	Partial D3.1 & SC-QAM
	Spectrum Band Placement of DOCSIS 3.1 (regardless of CAA or DAA)	D3.1 Under 600 MHz
Network Architecture (Topology)	Facility to Node Distance (15, 25, 40, 80 km)	ALL
	AM Optical Wavelength or Lambda Count (1, 4, 8, or 16)	4
	Amplifiers Cascade Depth (6, 5, 4, 3, 2, 1, 0)	ALL
	End-of-Line at Point-of-Entry to CPE or Use of In-Home Wiring to CPE	Point-of-Entry to CPE
	CPE Type (Single-Port CM, Single-Port Gateway, Dual-Port Gateway)	Dual-Port Gateway
Access Architecture	CAA and DAA	Both
Network Condition and Performance	Network Equipment and Coaxial Condition / Performance	Normal Working Order
	Accounts for AM Optical and Plant Noise / D3.1 Spec CMTS & CM Noise Req.	Included
	Additional Noise Margin	None

Figure 34: Parameters for Partial Spectrum and Spectrum Placement for D3.1

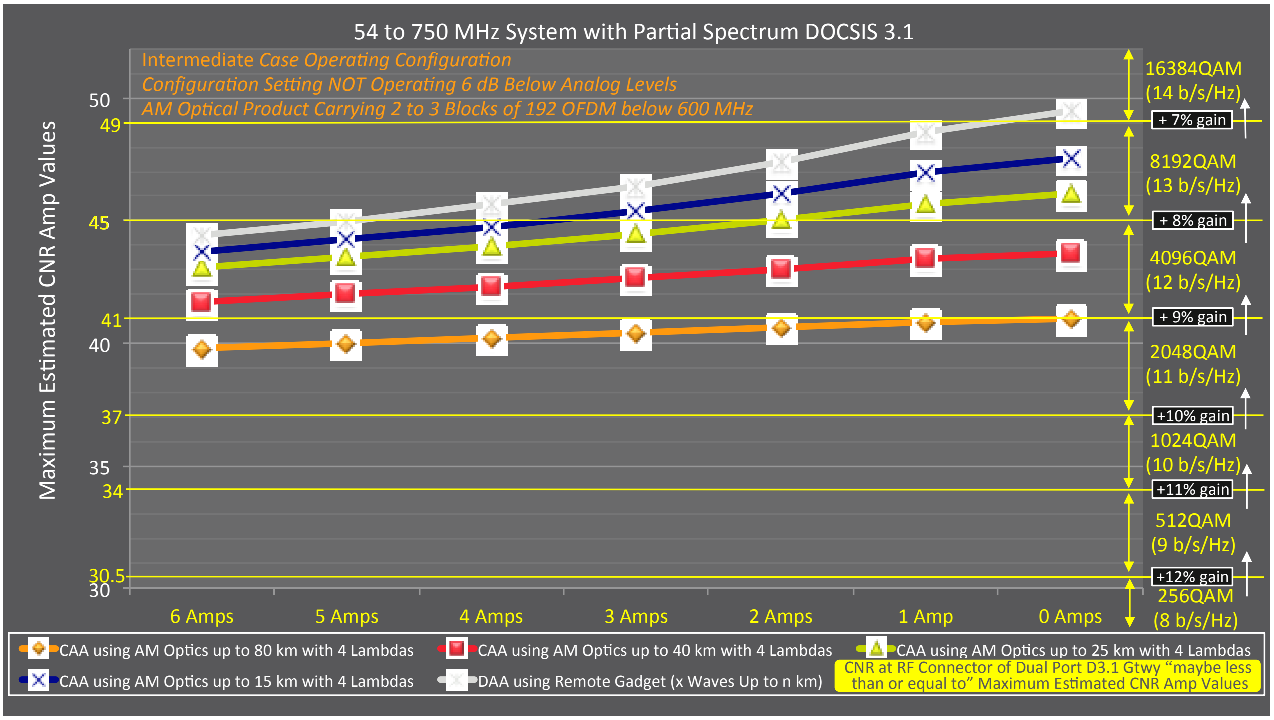


Figure 35: Partial Spectrum and Spectrum Placement for D3.1 – 750 MHz System

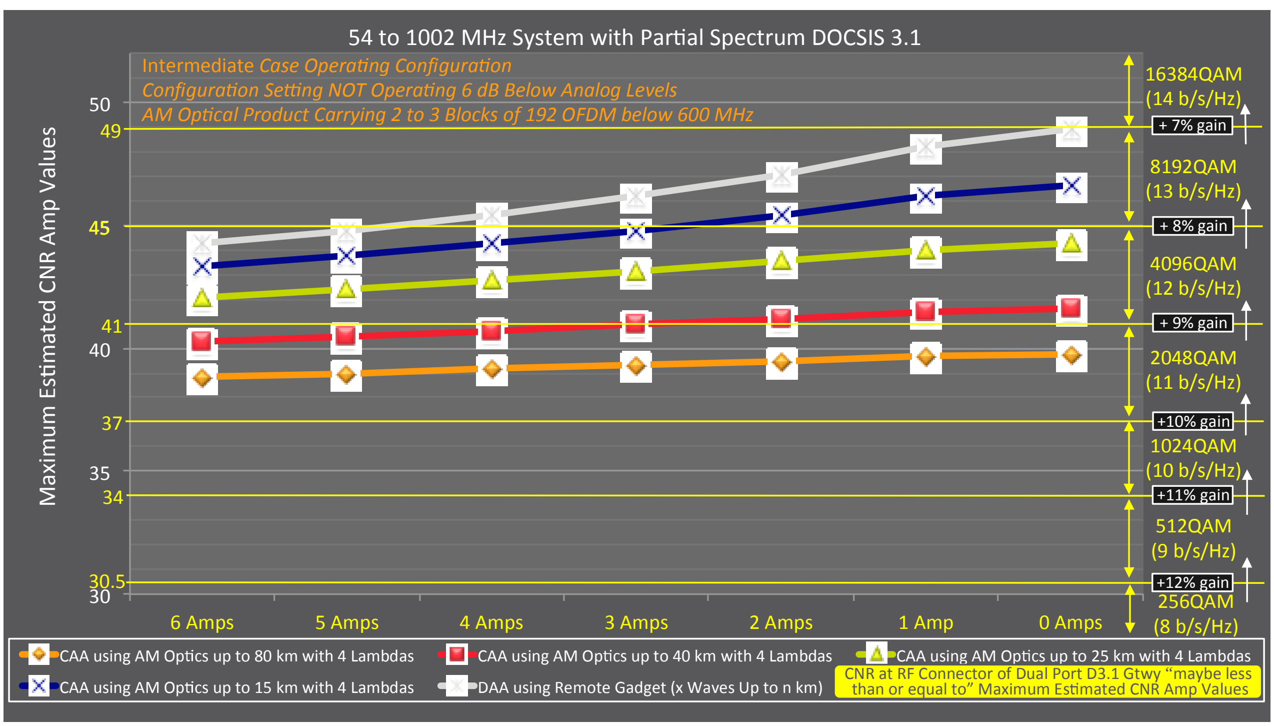


Figure 36: Partial Spectrum and Spectrum Placement for D3.1 – 1002 MHz System

Figure 35 Conclusions Using Partial DOCSIS 3.1 Spectrum in 750 MHz Systems

- 80 km links 2K QAM appears possible
- 40 km links 4K QAM appears possible
- 25 km links 4K to 8K QAM appears possible
- 15 km links 4K to 8K QAM appears possible

Figure 36 Conclusions Using Partial DOCSIS 3.1 Spectrum in 1002 MHz Systems

- 80 km links 2K QAM appears possible
- 40 km links 2K to 4K QAM appears possible
- 25 km links 4K QAM appears possible
- 15 km links 4K to 8K QAM appears possible

Conclusions for Partial Spectrum and Spectrum Placement for D3.1

- All MSOs will begin with partial spectrum DOCSIS 3.1
- Full spectrum D3.1 will not be used for a long time!
- Some MSOs may not upgrade spectrum or OSP to 1218 MHz
- Some MSOs will mine all they can out of 750 MHz and 1002 MHz Systems
- Some MSOs will wait for further analysis of actual spectral use above 1 GHz
- The best DOCSIS 3.1 spectrum is lower than 600 to 700 MHz
- Placement of DOCSIS 3.1 spectrum to take the place of analog video
- Analog needed the best spectrum and so does DOCSIS 3.1
- Both AM optics and remote gadget perform best at lower spectrum bands
- Using low frequency band and partial D3.1 spectrum loading maximizes CAA performance (compressing DAA gains)
- Perhaps DOCSIS 3.1 could replace location of analog video as it is removed

KEY SUMMARIES

The paper illustrated that network element configuration settings matter and can impact performance. The network element configuration settings such as transmitter MER, RF input levels, partial and full D3.1 spectrum loading, spectrum placement, and spectrum utilization of 750 MHz up to 1218 MHz can all influence the estimated EoL CNR at the amplifier and the maximum possible DOCSIS 3.1 modulations that may be supported at a given service group.

The paper also illustrated that network architecture and topology parameters matter and can impact performance. Network architecture and topology parameters such as distance between facility and node, wavelength count, and amplifiers cascade count can all influence the estimated EoL CNR at the amplifier and the maximum possible DOCSIS 3.1 modulations that may be supported at a given service group. The paper has illustrated that access architectures such as CAA using AM optics vs. future DAA using digital optics systems can both influence the estimated EoL CNR at the amplifier and the maximum possible DOCSIS 3.1 modulations that may be supported at a given service group.

The paper illustrates and states that the network conditions that can degrade the performance and happen at any time and at any segment, thus it is important to note that CNR at RF connector of dual port DOCSIS 3.1 gateway may be less than or equal to the maximum estimated CNR amplifier values and this value will determine the actual subscriber DOCSIS 3.1 modulations supported. The paper shows that tap performance in high frequencies approaching and above 1 GHz may be performance impacting.

The summary of the entire paper can be summarized in the following six figures. All of these figures will assume an intermediate network elements configuration setting as described earlier in the paper. The paper and model has shown the partial DOCSIS 3.1 spectrum use and placement of two to three 192 MHz DOCSIS 3.1 blocks below the 600 to 700 MHz bands will yield the best results.

This paper also focused on the end-state architecture that would eventually use full spectrum DOCSIS 3.1 across the entire spectrum bands of either 750 MHz, 1002 MHz, or 1218 MHz. The following figures estimate the EoL CNR performance at the amplifier assuming full spectrum DOCSIS 3.1. The intermediate settings are used and these assume that analog services which operated with a ~15 dBmV per 6 MHz channel analog is no longer present. The model assumes that DOCSIS 3.1 could operate with the analog RF input level. Today DOCSIS 3.0 and prior systems as well as digital video operates at about ~9 dBmV per 6 MHz channel, known as 6 dB below analog. The intermediate case model also assumes a normal CCAP source transmit MER, AM optics (if used), and amplifiers, which we predict achievable in real-world deployments.

The following six figures illustrate the key differences in the estimated EoL CNR amplifier performance as well as the associated percentage of gain DAA – remote gadget systems could have when compared with CAA using AM optics. In all cases DAA has an estimated EoL CNR amplifier performance better than CAA. Each of the figures illustrate the percentage of gain DAA has against several CAA using AM optics use cases. The DAA – remote gadget percentage gain will be measured against the estimated EoL CNR measurements at the amplifiers 0 or node measurement. The figures also illustrate the maximum DOCSIS 3.1 modulation possible for a given use case or service group and the maximum percentage of increase DAA may have in DOCSIS 3.1 data capacity. These figures estimate the maximum performance possible as estimated at the amplifier and as stated before it is important to note that the CNR at RF connector of dual port DOCSIS 3.1 gateway may be less than or equal to maximum estimated CNR amplifier values. This paper illustrates the maximum estimated performance for a given use case or service group. The paper did not predict the any performance ranges at the subscriber homes in real-world deployments. The authors will wait until end-to-end DOCSIS 3.1 systems are available for lab and field examination, and we fully expect to revise this model and paper estimates using actual measurements when possible.

Figure 37 and Figure 38 summarizes the performance estimates for a 750 MHz system with full spectrum DOCSIS 3.1. Figure 39 and Figure 40 summarizes the performance estimates for a 1002 MHz system with full spectrum DOCSIS 3.1. Figure 41 and Figure 42 summarizes the performance estimates for a 1218 MHz system with full spectrum DOCSIS 3.1.

Figures 37, 39, and 41 summarize the estimated maximum EoL CNR amplifier performance as well as the associated percentage of gain DAA – remote gadget systems could have when compared with CAA using AM optic, several use cases or service groups are examined. Figures 38, 40 and 42 summarize the estimated maximum DOCSIS 3.1 modulation and maximum data capacity possible as well as the associated percentage of gain DAA – remote gadget systems could have when compared with CAA using AM optics, several use cases or service groups are examined. The maximum data capacity for CAA and DAA will vary depending on many factors, such as node +6 through node+0 (the node), figures 38, 40 and 42 illustrate the percentage range of DAA improvement when compared with CAA using AM optics.

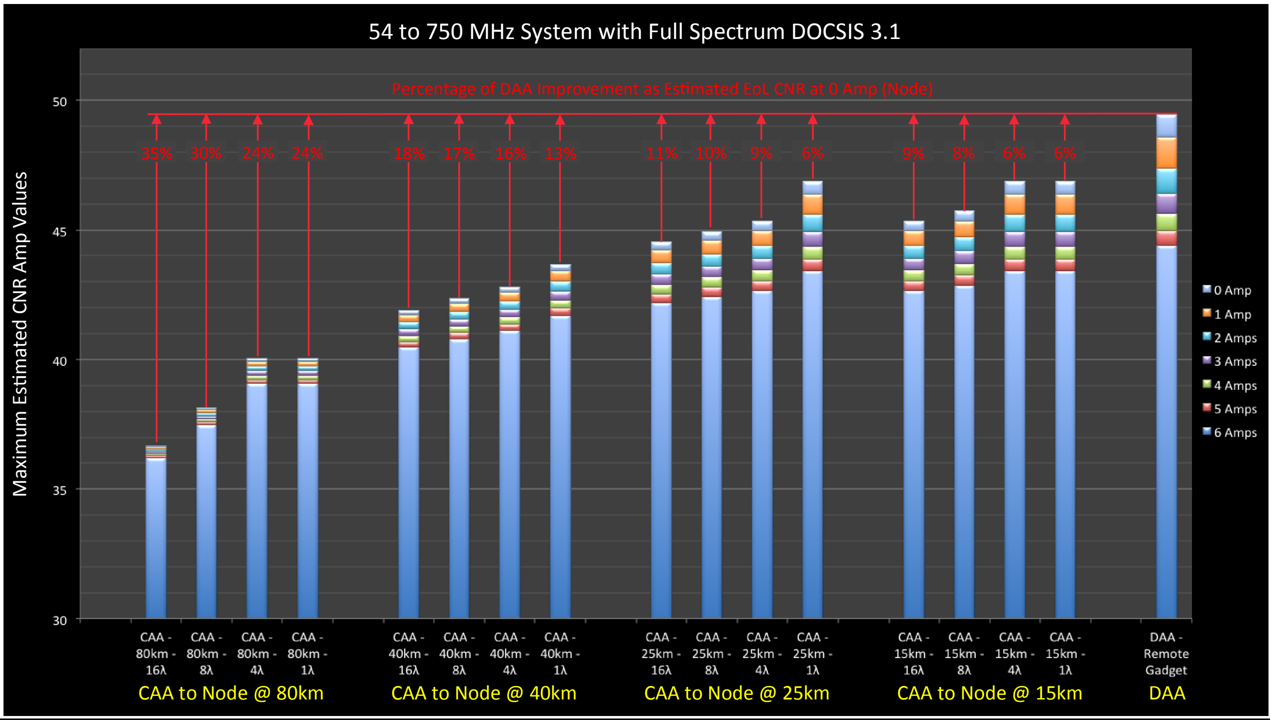


Figure 37: Estimated Maximum EoL CNR Amplifier Performance and Percentage of Gain DAA – Remote Gadget Against CAA using AM Optic Systems – DOCSIS 3.1 Full Spectrum 750 MHz

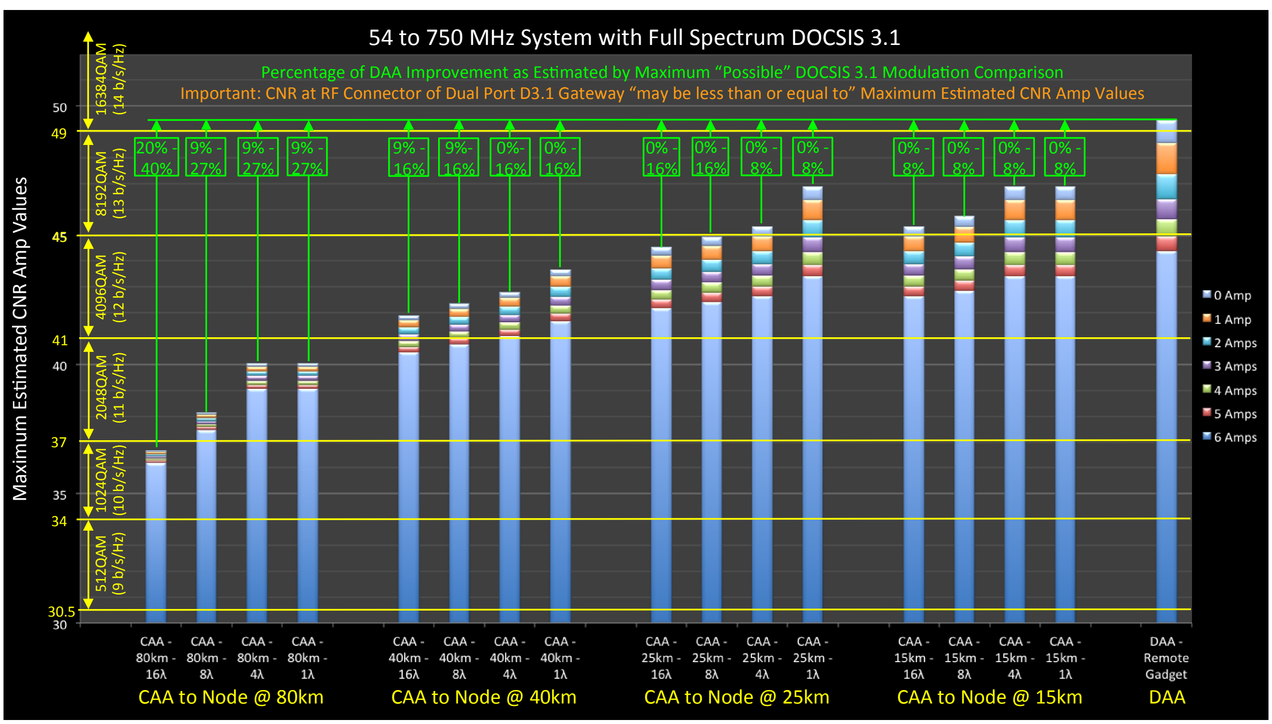


Figure 38: Estimated Maximum D3.1 Data Capacity Gain Possible and Percentage of Gain DAA – Remote Gadget Against CAA using AM Optic Systems – DOCSIS 3.1 Full Spectrum 750 MHz

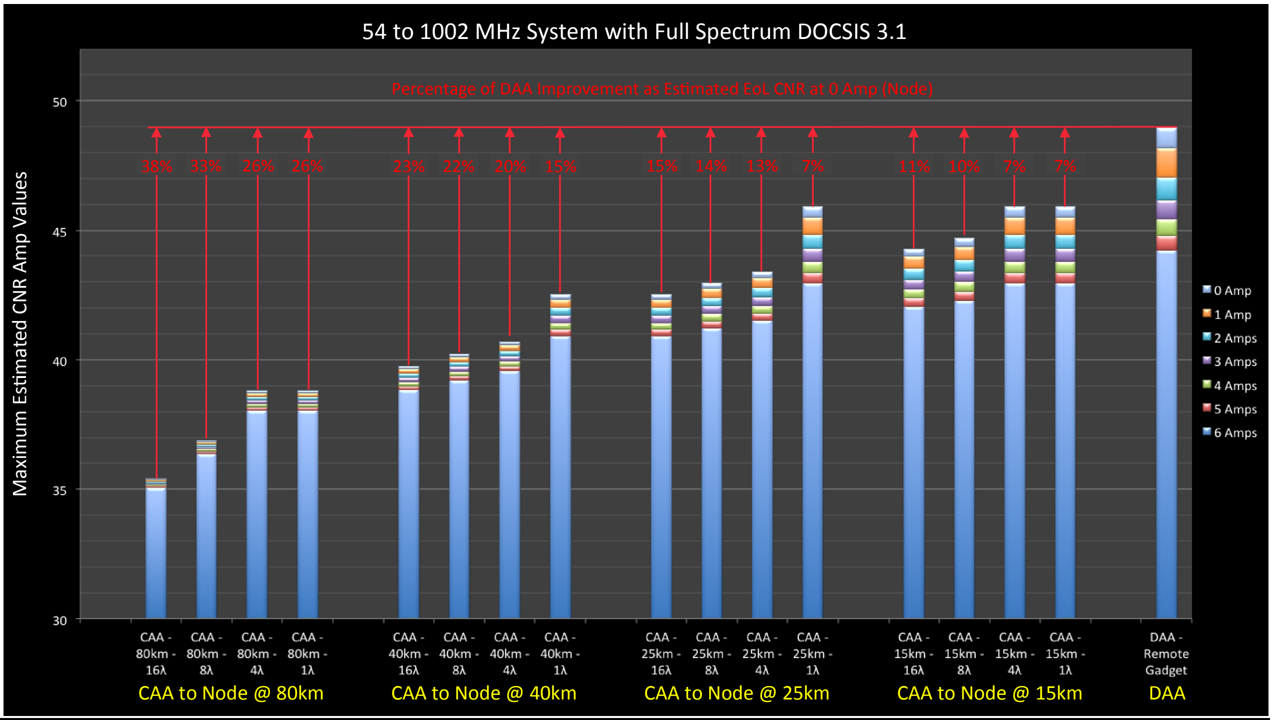


Figure 39: Estimated Maximum EoL CNR Amplifier Performance and Percentage of Gain DAA – Remote Gadget Against CAA using AM Optic Systems – DOCSIS 3.1 Full Spectrum 1002 MHz

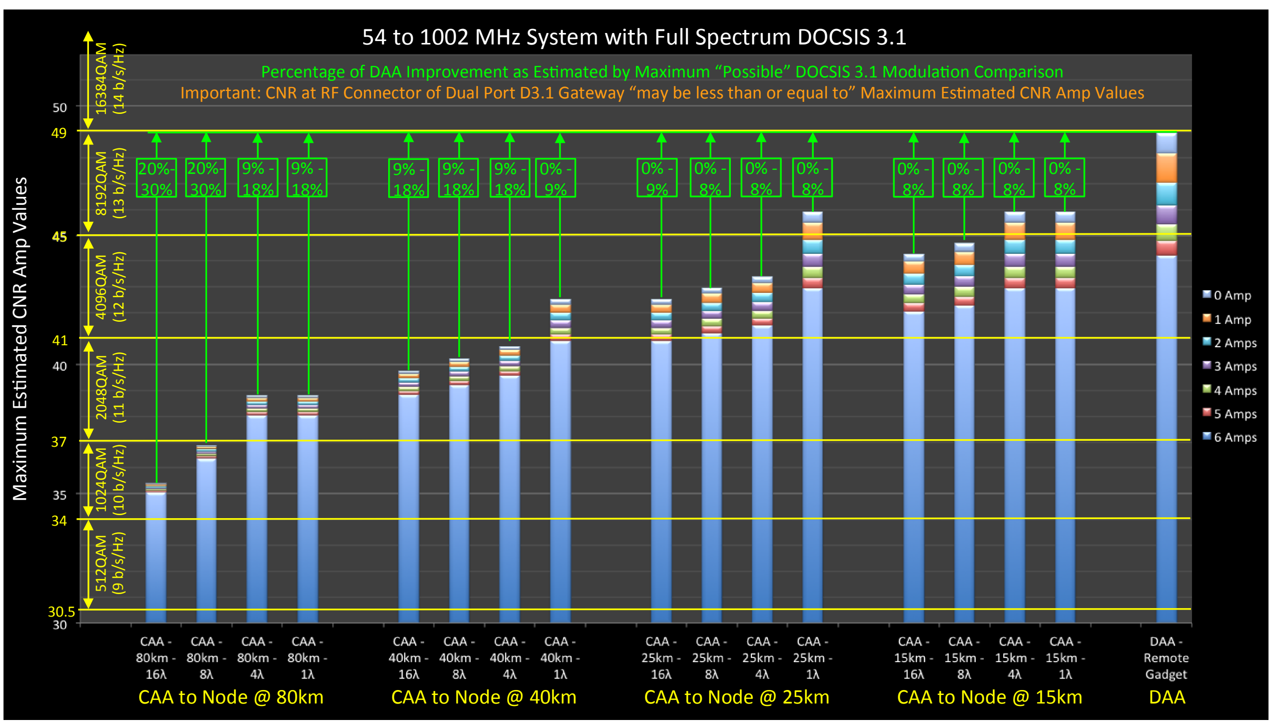


Figure 40: Estimated Maximum D3.1 Data Capacity Gain Possible and Percentage of Gain DAA – Remote Gadget Against CAA using AM Optic Systems – DOCSIS 3.1 Full Spectrum 1002 MHz

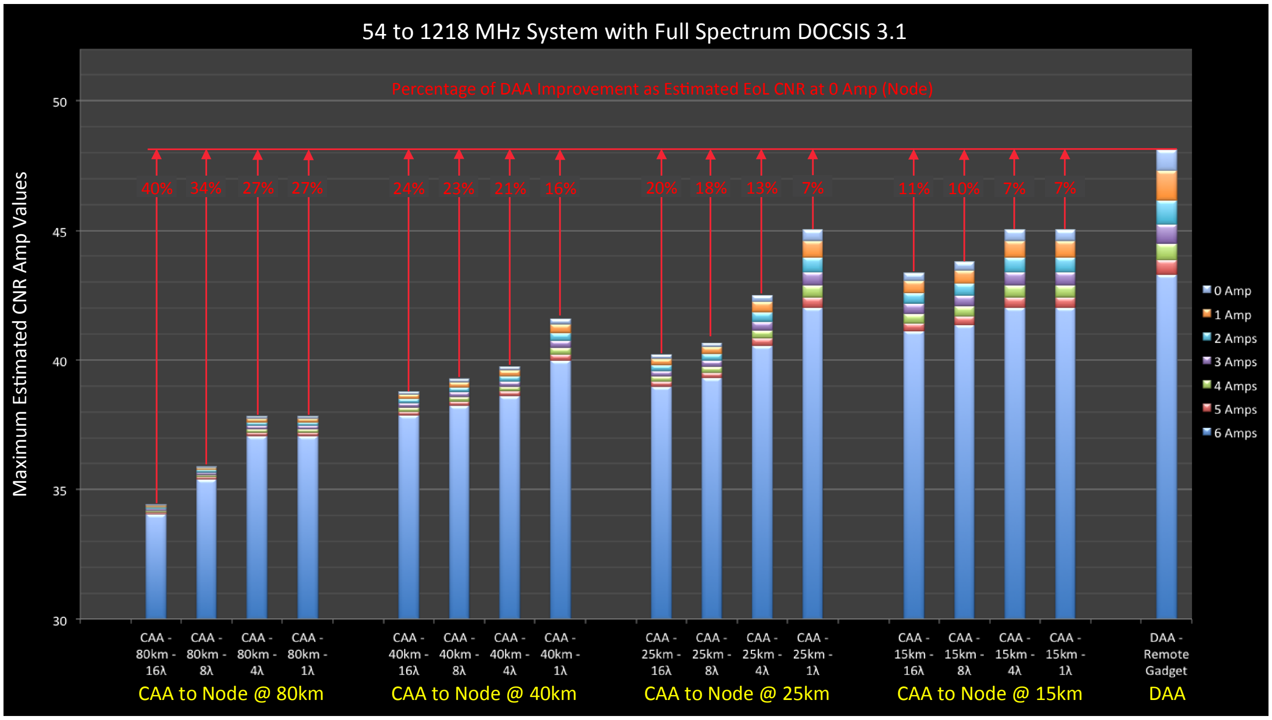


Figure 41: Estimated Maximum EoL CNR Amplifier Performance and Percentage of Gain DAA – Remote Gadget Against CAA using AM Optic Systems – DOCSIS 3.1 Full Spectrum 1218 MHz

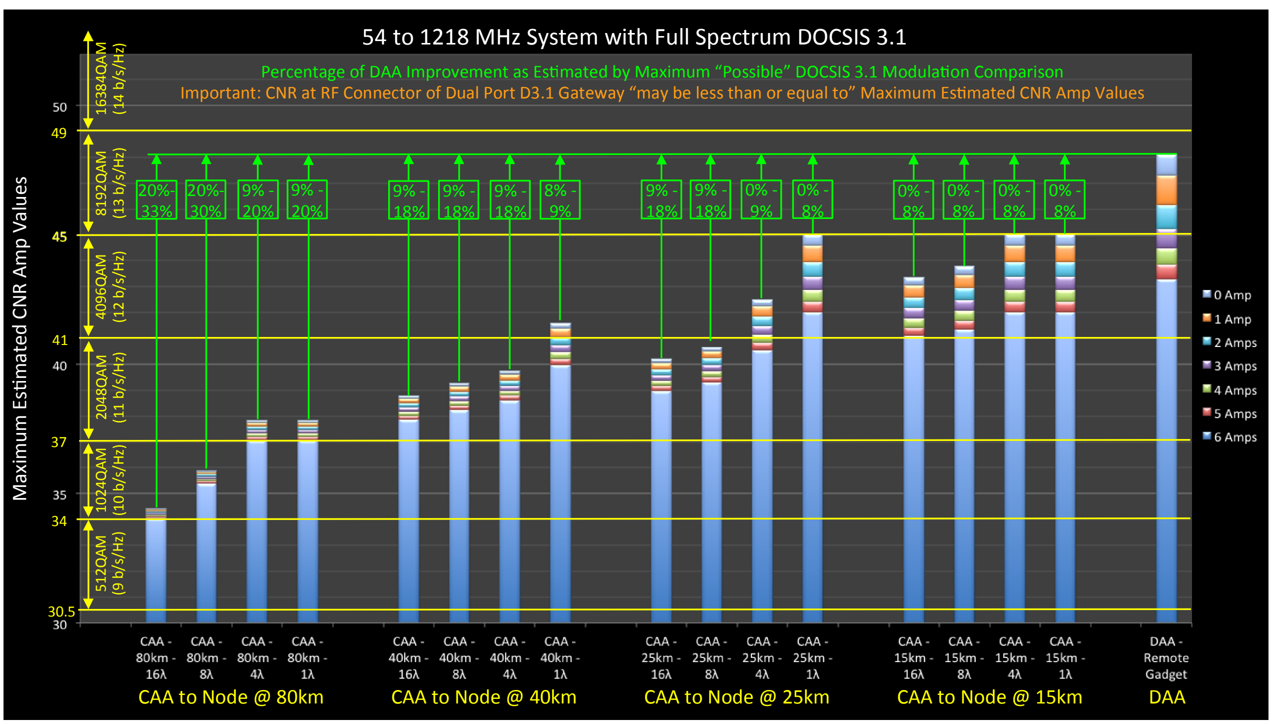


Figure 42: Estimated Maximum D3.1 Data Capacity Gain Possible and Percentage of Gain DAA – Remote Gadget Against CAA using AM Optic Systems – DOCSIS 3.1 Full Spectrum 1218 MHz

CONCLUSIONS

The previous section captures the key summaries of the model and paper. Cable operators may utilize different network configurations and have different network conditions resulting in overall performance variation. Considering the network architecture and topology variation that exist among cable operators around the world, we needed to define a set of parameters. Accounting for a wide variation in real-world network conditions and performance that is representative for all cable operators and subscribers served is nearly impossible. Since network condition and performance may also vary widely among cable operators, our model accounts for some noise conditions and defines a network under normal working order.

The best way to resolve a wide variation in both network architecture and actual system performance is to define several network element configuration settings, network architectures and topologies that we feel are representative of the vast majority of cable operator worldwide. The end-of-line (EoL) defined as the maximum estimated CNR at the amplifier. The segment between the amplifier and the RF connector of Dual Port D3.1 gateway “maybe less than or equal to” the maximum estimated CNR amplifier values, and this can vary as well based on network condition and performance.

When end-to-end DOCSIS 3.1 systems become available, additional lab testing and ultimately field data will determine the actual end-of-line performance. The authors believe that the DOCSIS 3.1 era will allow us to look at the “maximum” performance of the end-of-line and not just the minimum value of the weakest link. This is because DOCSIS 3.1 does not require all users to use the same modulation orders, as was the case with all previous versions of DOCSIS. The use of DOCSIS 3.1 will introduce the use of new tool called multiple modulation profiles (MMP).

Overall Key Findings in Order of Importance:

1) The maximum Downstream EoL performance estimates to the amplifier and resulting maximum DOCSIS 3.1 modulation order possible will vary widely between CAA and DAA systems based on many factors.

2) Network Architecture (Topology) matters:
   a. The distance between headend and node matters in system using CAA with AM optics, thus the longer the link the worse the performance, while DAA has no degradation
   b. The number of wavelengths matters in system using CAA with AM optics, thus the more wavelengths the worse the performance, while DAA has no degradation
   c. Number of amplifiers matters in estimating the EoL performance in either CAA or DAA, with DAA estimates show the largest EoL improvement as amplifier cascade is reduces
   d. Short optical spans between headend and node with few wavelengths yields the best performance for CAA using AM optics reducing the performance gap with DAA systems
   e. We recommend a dual port home gateway architecture to avoid using the in-home wiring network and to block noise impairments from entering the access network
   f. We recommend finding and removing CPE-to-CPE interferers

3) Network configuration settings matters: running D3.1 at 6 dB down from analog will limit performance / capacity

4) Spectrum usage such as up to 750 MHz, 1002 MHz, or 1218 MHz matters: the less amount of spectrum the greater the performance per MHz in in both CAA and DAA systems. The increased performance while occupying less spectrum will not offer more overall capacity when compared with 1002 or 1218 MHZ systems

5) Spectrum placement matters: in both CAA and DAA see benefits of using the lower spectrum band

6) Partial D3.1 spectrum loading matters: maximizes CAA performance reducing the performance gap with DAA systems

7) Network elements matter: D3.1 will have better equipment from CCAP to cable modem

8) The authors believe that the DOCSIS 3.1 era should reexamine our industry approach determining the minimum performances allowed for 64QAM and 256QAM. Our industry essentially cares about meeting a minimum target, because the network was only as good as the weakest link; the worst value determined the modulation order for that the entire segments. DOCSIS 3.1 and MMP this may not be a driver and knowing maximum is of interest

9) We should no longer assign a large value of six (6) dB of headroom with MMP

10) It’s too early to know for sure the DOCSIS 3.1 capacity using CAA or DAA systems, as we need end-to-end DOCSIS 3.1 equipment and field measurements. The industry needs to measure the EoL at the drop and in the home for D3.1 CNR in current and future network architectures and configurations

<u>Overall Estimates of EoL CNR at the Amp</u>

1) The very long distance between the facility and a node using AM optics will impact modulation order more than any other factor, thus DAA “may” yield a 30% gain compared to CAA 80 km links (9-14 dB at the Amp with 16 waves)

2) Wavelengths (1 - 16) & Distance (25 - 40km) CAA using AM optics will support high order modulation and DAA “may” yield 0% to 18% capacity gain (1-9 dB at Amp with 16 waves)

3) Amplifier count DAA affects modulation order yielding a 0% to 8% gain (5 dB) and CAA has 0-2 dB improvement with fewer amps

4) Spectrum Band and Full Spectrum D3.1 for 750 MHz vs. 1.2 GHz have little impact to EoL (2 dB)

5) Overall the model and paper EoL estimates to the amplifier in CAA and DAA systems will set the maximum DOCSIS 3.1 modulation order possible, the difference in performance between CAA vs. DAA varies widely from DAA having 0% to 30% capacity gain over CAA systems.

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