The Evolution of Cable Access Technologies and Network Architectures

For This Decade and Beyond

A Technical Paper prepared for the Society of Cable Telecommunications Engineers
By

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Overview

The MSOs are facing a decade of unprecedented change, driven by competition and consumer demand, which will transform the cable network end-to-end. This paper will focus on the evolution of the cable network for this decade and beyond. We will examine the evolution of Coax to the Home (CTTH) technologies and architectures and the eventual migration to Fiber to the Home (FTTH).

This paper will examine several methods to expand capacity of the CTTH network, such as the use of new RF data technology (e.g. DOCSIS 3.1). The paper will introduce and examine new optical technologies and access architectures for Fiber to the Node (FTTN) that will emerge this decade in an effort to increase capacity and the life of the coax network. In a nutshell, today's cable access network uses FTTN technology called Amplitude Modulation (AM) optics, also known as Analog Optics, and in the future digital optical technology will be available for FTTN. The use of digital optical technology in the forward and return direction will place more intelligence in the fiber node and may change the access architecture platforms such as the CMTS, Edge QAMs, CCAP and/or headend optical transmission systems. The use of digital optics may remote or distribute functions that are currently in the headend and place these functions in the fiber node. The use of digital optics to and from the node will enable a new class of FTTN for cable, called Digital Fiber Coax (DFC) as well as a new access architecture called Distributed Access Architecture (DAA), first introduced by this author in an SCTE paper in 2011 [1]. While HFC will only enable a Centralized Access Architecture (CAA) whereby the CMTS, Edge QAM, or CCAP MAC and PHY functions are in the Headend (HE) or Primary (PH) only. The new FTTN class called DFC allows for two (2) access architectures either a CAA or a DAA. The DAA is where the CMTS, Edge QAM, or CCAP MAC and PHY or PHY functions are placed in the node. In the coming years our industry will begin to examine these new FTTN technologies and access architectures. This paper will be among the first to introduce and examine all of these future alternative architectures in detail.

We will predict some of the business drivers like service tier growth based on Nielsen's Law, Traffic Growth for High-speed data and video services, and future overall bandwidth requirements for service groups and subscribers. Understanding these business drivers and the capacities of various network alternatives will enable MSOs to predict the timing of the network evolution. This examination helps us determine the Fiber to the Home migration timing and strategies behind selecting the FTTH technologies.

The paper will be segmented into three eras, the Next Generation – Coax to the Home (CTTH) Data Technology Era, Next Generation - Fiber to the Node (FTTN) called Digital Fiber Coax (DFC) Era and also the Next Generation – Fiber to the Home (FTTH) Era. Below is an overview of these sections.

Next Generation – Coax to the Home (CTTH) RF Data Technology called the DOCSIS 3.1 Era:

We will examine the Next Generation - Coax to the Home (CTTH) era technology and architecture options serving CTTH. We will show the spectrum migration planning timeline. We will examine DOCSIS 3.1 MAC and PHY layer technologies. We will also discuss network aggregation and access layer technology and architecture options, including the optical transmission, spectrum splits, impacts to the architecture and the home network requirements to allow cable's coax to the home (CTTH) to deliver PON like speeds in the most cost effective and sustaining manner possible.

Next Generation – Fiber to the Node (FTTN) called the Digital Fiber Coax (DFC) Era:

In the area of CTTH this paper will cover two (2) fiber to the node (FTTN) network architecture classes for Cable. First, the existing FTTN network architecture class, called Hybrid Fiber Coax (HFC), which uses Amplitude Modulation (AM) Optics providing media conversion between the Optical and Coaxial domains, will be reviewed in this paper. We will also examine an emerging FTTN architecture class for cable that uses digital optical connections to and from the fiber node.

An attributed of the HFC class of FTTN that uses AM optics supports one and only one access architecture, called Centralized Access Architecture (CAA). In centralized access architecture, this places the DOCSIS and digital video MAC and PHY layer functions only in the headend (HE) or primary hub (PH) facilities, thus the node or outside plant does not contain DOCSIS or digital video MAC or PHY layer functions.

In the Digital Fiber Coax (DFC) class of FTTN, this uses digital optical technology to and/or from the fiber node and may support either a Centralized Access Architecture (CAA) or a Distributed Access Architecture (DAA). The DFC class of FTTN may keep the DOCSIS and digital video MAC and PHY layer functions in the HE or PH facilities, thus keeping a Centralized Access Architecture, however this uses digital optics by replicating some PHY layer functions in the headend optical shelf and placing some PHY functions in the node. The Digital Fiber Coax (DFC) class of FTTN may also support a Distributed Access Architecture (DAA) also referred to by the author as Remote Access Architecture (RAA). In the DAA or RAA, "all or some" of the DOCSIS and/or digital video MAC and/or PHY layer functions are placed in the node. These DFC architectures may use digital optical technologies such as Ethernet, G.709, EPON, or GPON [1]. These architectures will be examined in detail as MSOs seek to maximize capacity and reach of their networks to extend the life of the CTTH network and may use Digital Fiber Coax (DFC) to do so.

Next Generation – Fiber to the Home (FTTH) Era:

We will also examine the Next Generation - Fiber to the Home (FTTH) era and will consider two-deployment scenarios serving fiber to the home (FTTH): 1) New Build - Greenfield and 2) Legacy Transition. We will examine the four emerging NG-PON technologies: 1) OFDM over RFoG, 2) IEEE 10G EPON, 3) ITU-T 10G-PON (XG-PON), and lastly 4) WDM-PON using P2P Optical Ethernet and Wavelength to the Home (WTTH). These four alternatives will be examined as part of the New Build strategy and potentially the migration strategy of existing CTTH to FTTH in the decades to come.

Key Questions Examined in this Paper:

Some of the most often asked questions by cable industry forward-looking planners reflect the key challenges the industry is facing for this decade and beyond. Some of these challenges and questions include:

1) What are forecasted capacity requirements?
2) Are Cable Networks "Limited by" the RF Video and Data Technologies?
3) Are Current Cable Networks "Limited by" the FTTN Amplitude Modulation (AM) "Analog" Optical Technology?
4) Digital Fiber Coax (DFC) uses Digital Optics for FTTN will force us to place SOME PHY or MAC/PHY Access Layer Functions in the Node, so what stays in the headend and what moves to the node?
5) How long will the current spectrum and HHP per node last?
6) What are the best ways to leverage previous, current and future investment?
7) How does CTTH network capacity compare with FTTH technologies?
8) When and what could a migration strategy from CTTH to FTTH look like and why?

This paper will seek to provide some visibility and answers to these questions and key challenges.

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The Drivers of Service Change "plus" Traffic Growth

The MSO's competitive landscape has changed rapidly in just the last 12 months especially from Over The Top (OTT) video providers such as Apple TV, Amazon, Hulu, Netflix and others entering the On-Demand video market. In many ways the consumer electronic companies like Apple are becoming service providers enabling the video experience across all platforms and across any carriers' network. The OTT competition affects the MSOs in lost revenues for On-Demand services and perhaps a reduction in the subscription service. Adding to the lost revenue is increased costs to the high-speed data network due to increased consumer usage.

The recent completion of Verizon's FiOS roll out will undoubtedly remain a threat to the MSO's triple play offering. Additionally it was reported that Verizon will consider an upgrade to their FiOS network to the next generation Passive Optical Network (PON) technology known as XG-PON, the 10 Gbps downstream and 2.5 Gbps upstream system [2]. This could replace the earlier generation B-PON (622 Mbps down and 155 Mbps up) and the G-PON (2.5 Gbps down and 1.25 Gbps up) systems. The Verizon FiOS network also uses what is known as the video overlay network along with the PON technology. The video overlay network provides broadcast video services using technology similar to cable systems. The video overlay may employ a 750 MHz to 1002 MHz system equivalent over 4.3 - 6 Gbps of downstream capacity but it is unknown if all of this capacity is used. The PON network is used for IP based services like Internet, telephone and perhaps on-demand unicast video transmission. If we consider both the PON system as well as the video overlay system, the FiOS network capabilities may reach ~14 Gbps+ of downstream throughput (XG-PON 10 Gbps + 750 MHz at approximately 4 Gbps+) and upstream reaching 2.5 Gbps). This capacity may be more throughput than is needed for many years or even decades to come based on the modelling in the following sections. This level of capacity may not be needed until the year 2025-2030.

The cable network has a massive amount of capacity perhaps up to 6 Gbps to the home and perhaps 100 Mbps from the home. The cable industry is making investments in IP based video delivery technology and expanding the high-speed Internet IP capacity as well. The coaxial network may increase the spectrum allocation beyond the current levels in either direction. This important fact is covered in detail in this analysis. The amount of capacity needed in each direction is projected over a period of nearly two decades as well as several technical options are explored.

High-Speed Internet Maximum Service Tier Offered (Downstream and Upstream)

The network traffic estimates need to consider the downstream and upstream high-speed Internet service tier, in other words the data speed package the MSO offers to consumers. The highest data speed offered in either direction is a determining factor for sizing the network. The High-Speed Internet service tier and traffic will grow considerably during this decade moving from perhaps four 6 MHz channels downstream, which is less than 4% of the MSO's total spectrum allocation and may grow to perhaps 40-50% in the next 10 years.

This model illustrates Data Service Tiers offered to consumers increase at about a 50% compound annual growth rate (CAGR) and this model also is used to forecast actual consumer traffic usage which also grows at roughly a 50% CAGR. This is based on Nielsen's Law of Internet Bandwidth or Max Internet Service Tier. We have also combined Neislen's Law with the research of Dr. Thomas J. Cloonan, CSO of ARRIS and co-author. The research is captured in the "Max Internet Data Services Tier Offering Downstream and Upstream graphs in this section. Dr. Cloonan begins with the data rate offered since 1982 and charts growth through to the present day. This data is referred to as Cloonan's Curve also reflects the historical 50% CAGR as does Nielsen's Law. The data service portion of the model is predictable but at some point, as with Moore's Law, Nielsen's Law may not continue on this 50% CAGR trajectory for another 20 years, and break.

The high-speed Internet service tier offering will be a key contributor to overall bandwidth drivers. Figure 1 below shows a thirty-year history of the max bandwidth offered or available to consumers. This figure also attempts to predict the max service tier we may see in the future, if the growth trend aligns with the preceding years. Perhaps we will allocate the entire 750 MHz downstream spectrum or equivalent to Internet services by 2023 assuming DOCSIS 3.0, however DOCSIS 3.1 and more spectrum may get us further. As illustrated in the figure below, the downstream and upstream modeling began with the dial-up era, moving into the broadband era and now the DOCSIS channel bonding and PON eras. The models are a combination of Cloonan's Curve - a 30 Year History of Max Service Tier Offered and Nielsen's Law of 50% CAGR.

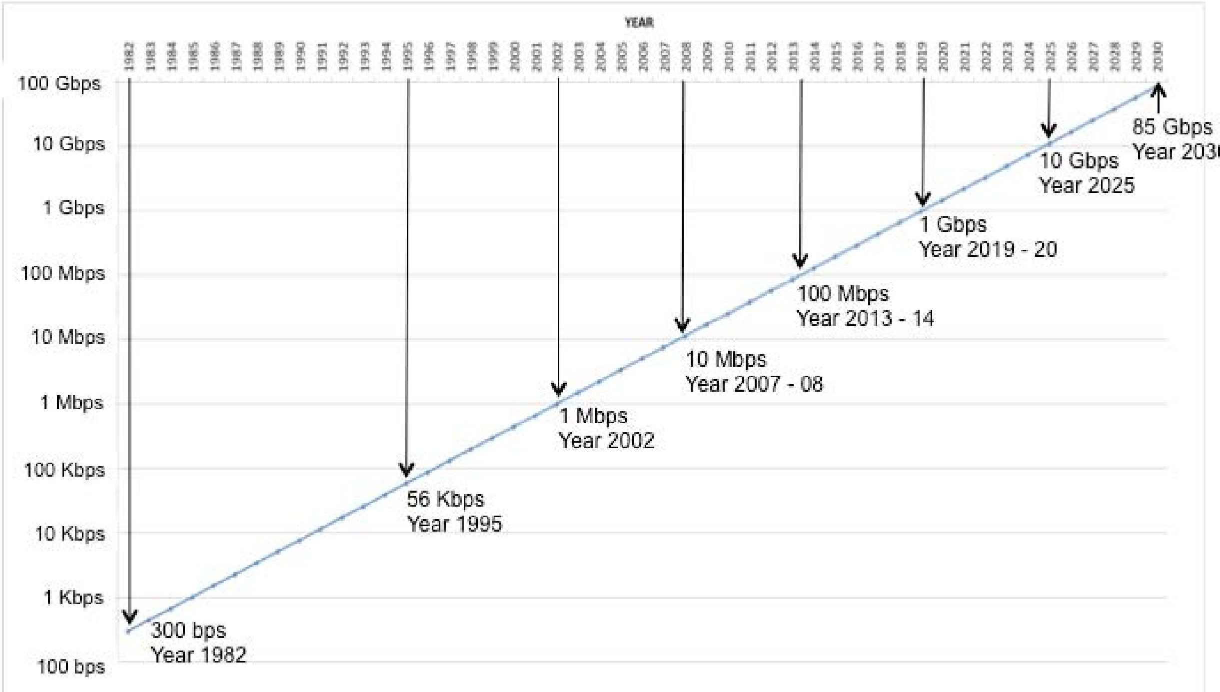

Figure 1 – Nielsen's Law and Cloonan's Curve of the Max Internet Service Tier Offered - Downstream

Table 1 below captures the year-by-year predictions of the downstream and upstream service projections from the figure above isolating years 2010 to 2025. This table will be used for the capacity requirements found in the Network Utilization and Capacity Planning section later in this analysis. It is uncertain if the Max Service Tier trends will continue for the next 15 years at a 50% CAGR. The service offerings will, from time-to-time, not maintain alignment with the projections. Typically leaps above the line happen when there are major technology advances, such as dial-up to cable modem/DSL, then to channel bonding and PON. So, if we analyze where the telecom industry is today with their max downstream and upstream service offerings this may not be in alignment with the predictions.

Year	50% CAGR - Downstream Max Service Tier	40% CAGR - Downstream Max Service Tier	30% CAGR - Downstream Max Service Tier	50% CAGR - Upstream Max Service Tier	40% CAGR - Upstream Max Service Tier	30% CAGR - Upstream Max Service Tier
2010	26	26	26	5	5	5
2011	38	36	33	8	7	7
2012	58	50	43	12	10	9
2013	86	70	56	17	14	11
2014	129	98	73	26	20	15
2015	194	138	95	39	28	19
2016	291	193	123	58	39	25
2017	437	270	160	87	54	32
2018	655	377	209	131	75	42
2019	983	528	271	197	106	54
2020	1,474	740	352	295	148	70
2021	2,211	1,035	458	442	207	92
2022	3,317	1,449	596	663	290	119
2023	4,976	2,029	774	995	406	155
2024	7,464	2,841	1,007	1,493	568	201
2025	11,196	3,977	1,309	2,239	795	262

Table 1: Various Internet Max Speed Predictions Table Shown in Mbps

Examining Various Max Internet Service CAGRs (When will Nielsen's Law Break?)

Is it possible that a service provider will offer a residential an 11 Gbps Internet service by 2025? When will Nielsen's Law Break? It is unlikely that a 50% CAGR for the Max Service Tier Offered will last forever. Moore's law broke and Nielsen's Law will too, but when and by what rate? This section examines some government and operator activity that illustrate vastly different forecast for service tier possibilities. Additionally, max Internet service tier offered is ultimately a decision of the service providers and they may simply pull the lever of growth back, as this is a driver for investment that is desired for only a small percentage of their Internet customer base. This section examines the activities of operators and government goals for service offerings. There are two examples in this section, the FCC goals for Internet service speed for this decade and service provider activities.

We have modeled various CAGRs in table 1 to illustrate that changes in this key driver, however slight, will have vast impacts on the end state architecture. Understanding previous and current trends will aid in planning, but past history does not guarantee future results. This section demonstrates the importance of CAGRs for planning purposes and that this is in the Service Providers control.

High-Speed Internet Bandwidth Per Subscriber (Downstream and Upstream)

In addition to the service tier offered to consumers, the actual usage of the network by the consumers is a critical factor for network planners. This is known as the bandwidth per subscriber (BW per Sub). The determination of bandwidth per sub is a measurement of the total amount of bandwidth or traffic in a serving area divided by the number of consumers in the serving area. This may be measured during busy hour(s) to drive operator traffic engineering limits. The bandwidth per subscriber is measured in the downstream and upstream direction. The downstream was measured at a 100 kbps per subscriber and the upstream at 43 kbps per subscriber in the year 2010, as illustrated in table 2 and 3. The bandwidth per subscriber CAGR may vary, so we have used several growth rates for the downstream and the upstream. These numbers are used for planning purposes in this analysis, it is important that each operator capture their own CAGRs.

DOWNSTREAM DATA NETWORK TRAFFIC PREDICTIONS			
North Amer. & Europe	Per Subscriber Traffic (Shown in Mbps)		
Year	40% CAGR Downstream	50% CAGR Downstream	60% CAGR Downstream
2010	0.10	0.10	0.10
2011	0.14	0.15	0.16
2012	0.20	0.23	0.26
2013	0.27	0.34	0.41
2014	0.38	0.51	0.66
2015	0.54	0.76	1.05
2016	0.75	1.14	1.68
2017	1.05	1.71	2.68
2018	1.48	2.56	4.29
2019	2.07	3.84	6.87
2020	2.89	5.77	11.00
2021	4.05	8.65	17.59
2022	5.67	12.97	28.15
2023	7.94	19.46	45.04
2024	11.11	29.19	72.06
2025	15.56	43.79	115.29
2026	21.78	65.68	184.47
2027	30.49	98.53	295.15
2028	42.69	147.79	472.24
2029	59.76	221.68	755.58
2030	83.67	332.53	1,208.93

Table 2: Downstream Bandwidth per Subscriber Table

UPSTREAM DATA NETWORK TRAFFIC PREDICTIONS				
North America	Per Subscriber Traffic (Shown in Mbps)			
Year	10% CAGR Upstream	25% CAGR Upstream	35% CAGR Upstream	50% CAGR Upstream
2010	0.04	0.04	0.04	0.04
2011	0.05	0.05	0.06	0.06
2012	0.05	0.07	0.08	0.10
2013	0.06	0.08	0.11	0.15
2014	0.06	0.10	0.14	0.22
2015	0.07	0.13	0.19	0.33
2016	0.08	0.16	0.26	0.49
2017	0.08	0.21	0.35	0.73
2018	0.09	0.26	0.47	1.10
2019	0.10	0.32	0.64	1.65
2020	0.11	0.40	0.86	2.48
2021	0.12	0.50	1.17	3.72
2022	0.13	0.63	1.58	5.58
2023	0.15	0.78	2.13	8.37
2024	0.16	0.98	2.87	12.55
2025	0.18	1.22	3.88	18.83
2026	0.20	1.53	5.23	28.24
2027	0.22	1.91	7.07	42.37
2028	0.24	2.39	9.54	63.55
2029	0.26	2.98	12.88	95.32
2030	0.29	3.73	17.38	142.99

Table 3: North America Upstream Bandwidth per Subscriber Table

The Internet Traffic CAGR is determined by the consumers, service provider speed tiers offered, and technologies that will influence network usage. The growth rate of traffic will vary widely even within a service provider, because usage patterns will be different between demographics. Traffic growth rates are very hard to forecast because there are so many possible influences to drive traffic growth. The Max Service Tier CAGR used in Nielsen's Law records the highest service tier offered and may be driven by the actions of a single service provider. However, the Internet Traffic CAGR may be based on samples of millions of subscribers. While just a few percent of users may be responsible for the Internet traffic usage, this is averaged among all users. In other words, the Internet Traffic CAGR does not record the traffic rate of a single user to generate the growth rate, but the average of all users in the sample. The Nielsen's Law or Cloonan's Curve does not average the Max service Tier offered from all service providers. Our analysis provides various CAGRs for both Max Service Tier and Traffic to illustrate the variations over the span of up to two decades.

Summaries for Service Tier and Traffic Growth Estimates

Again, as a disclaimer the Service and Traffic predictions for the next two decades is sort of difficult, but we can use history to help guide us! We acknowledge that these numbers are highly debatable and that these may not match numbers for any particular MSO. These should serve as "rough ballpark numbers" to allow discussion & forward planning. It's the methodology that is the key takeaway.

Service Providers will have to forecast their video network resources requirements and have an understanding that Internet Service Tiers and Traffic Growth rates may influence the video allocation over time. The model will use both High-Speed Internet projections, like the Service Tier Offering and bandwidth per subscriber to predict Network Utilization and Capacity Planning.

When will Nielsen's Law of 50% CAGR for Max Service Tier Offered Break? If the Nielsen's Law of 50% CAGR for Max Service Tier do not materialize (i.e. High-speed data service prediction over 4 Gbps Down and 1 Gbps Up in the year 2023) then nodes splits/node segmentation will solve the traffic growth projections for many more years. If neither the Service Growth Rates nor Traffic Utilization Growth Rates meet the 50% CAGR target, then the timing and drivers for investment will change and the HFC will last far longer, saving the MSO money.

Key Questions

- When will Nielsen's Law of 50% CAGR for Max Service Tier Offered Break?
- Which "Downstream Traffic" CAGR do you believe and when will it break?
- Which "Upstream Traffic" CAGR do you believe and when will it break?

Finally, operators will need to track these key drivers and levers that force network change, like Nielsen's Law of Max Services Tier Growth Rate and also Traffic Growth Rates for proper network planning. As shown in the tables in this section, there were several growth rate projections that did not follow Nielsen's Law, and this was to illustrate that variation in CAGRs will dramatically shift the needs for network change. Nielsen's Law will break as Moore's Law has, but predicting the date will be difficult. However, but continued observation and analysis will help network planners determine the best course of action. Finally, good network and capacity planning should provide sufficient network capacity to accommodate both service tier and traffic growth, as well as other overhead considerations.

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Next Generation – Coax to the Home (CTTH) RF Data Technology called the DOCSIS 3.1 Era

It is growth of unicast services and HSD service tier and traffic, which will have the greatest impact on the cable industry for decades to come. A major challenge the cable industry faces in the future is meeting the needs of the consumer and addressing the competitive threats of PON/FTTH systems while leveraging the existing coax to the home. This will mean significant changes in the use of network technologies, spectrum allocation, and overall network architecture. Planning for the Next Generation – Cable Access Network is extremely difficult as this spans several network disciplines within the cable industry such as, the outside plant (OSP) including the coaxial network components and topology, RF data networking technologies, network architecture for optical distribution and impact of spectrum selection. The span of network technology disciplines also reaches into the network elements and underlying sub-systems such as MAC layer, PHY layer, and HFC optical transport components, as well as the RF distribution network components - amplifiers, taps, passives, and coaxial cable. What is proving to be a significant challenge is the increased dependency of these traditionally separate network disciplines as part of the new cable access network architecture. In years past these technologies functioned mostly independent of one another. This next generation cable access architecture will likely migrate to more IP based spectrum allocation downstream, cannibalizing existing delivery technologies, which are non-IP based, and thereby creating a more efficient, versatile and competitive network transport platform to compete with PON.

The capacity of the cable access network depends on several factors. These factors may include network operations, network architecture, spectrum selection, spectrum allocation, spectral load, RF technology and optical technology. We are finding that overall MSO operations and design practices will not be the limiting factor to maximize capacity. This paper suggests that today's cable network capacity or b/s/Hz is limited by the Radio Frequency (RF) data technologies supporting Digital Video and Data Services (DOCSIS). This paper also suggest that as improvements are made to the RF Data Technology, such as DOCSIS 3.1, that the next limiting factor will be the Optical Technology to/from the HFC node. As our industry expands spectrum in the downstream and upstream the current optical technology will increasing become a limiting factor to maximize b/s/Hz. Additionally, as MSOs have a desire to reduce facilities and expand the optical distance between headend and fiber node this will also limit the system b/s/Hz, based on today's optical technology, Amplitude Modulation.

The industry challenge is predicting the network demand and timing of the network change and how long each change will last. Additionally, and most importantly, defining the downstream spectrum allocation and the upstream spectrum decisions of the future. This analysis will provide predictions, such as the drivers for the use of the spectrum in the downstream and upstream.

Evaluating the Cable Network Capabilities

This section will examine the evolution of Coax to the Home (CTTH) and Fiber to the Node (FTTN) networking technologies and architectures. MSOs are maximizing capacity and performance of their current networks. However, MSOs are finding the improvements to operations can't yield any more bits per second per hertz (b/s/Hz). This section will examine the future evolution of the access network, to identify some of the problems and proposed solutions to maximize b/s/Hz and "widen the pipe" to increase the capacity of existing and future spectrum.

Key Drivers to Evaluate the Cable Network:

- Are cable networks "limited by" the RF video and data technologies, which are based on ITU-T J.83 annex A/B/C for downstream & CableLabs DOCSIS 2.0 Upstream?

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In order to determine the limiting factors of today's cable network an assessment of the data technology, attributes must be measured against the performance measurements of the cable network.

Overview of the "Current" RF Video and Data Technologies

The digital video and DOCSIS services deployed by cable operators around the world use an RF data technology defined in Recommendation ITU-T J.83 and the four Annexes (Annexes A, B, C, and D). This standard defined the physical (PHY) layer technology used for digital video MPEG-TS and DOCSIS downstream specifications through version 3.0.

The main differences in the ITU-T J.83 annexes will be the channel coding and modulation specified, as well as the channel width. The highest order modulation in all versions is 256-QAM. A key attribute of the annexes is the selection of error correction technology. Annex A/C/D define a single error correction technology called Reed-Solomon. The ITU-T J.83 Annex B uses outer FEC called Reed-Solomon (R-S) and an inner FEC called Trellis Coded Modulation (TCM). The use of trellis coding in J.83 annex B is embedded in the modulation process. The use of an inner and outer FEC means that J.83 annex B is more robust than the annex A/C/D versions. The impact of these differences in FEC means that J.83 Annex A/C will require about

2 dB better system performance than J.83 Annex B to support the same modulation format and assuming about the same code rate for each [3,5]. The applications that use J.83 annexes and the SNR (dB) requirements are found in tables 4 and 5 respectively.

J.83 Error Correction Technology [4]:
- ITU-T J.83 Annex A/C uses Reed-Solomon Downstream
- ITU-T J.83 Annex B uses Trellis Code Modulation (TCM) inner FEC and Reed Solomon (outer FEC)

ITU-T J.83-A	Euro-DOCSIS Annex A DVB-C
ITU-T J.83-B	DOCSIS Annex B Japanese DOCSIS Annex C ATSC/SCTE
ITU-T J.83-C	Japanese Digital Video

Table 4: ITU-T J.83 Applications

J.83 Annex	Coded SNR Assuming AWGN	Minimum Operating SNR Recommendation
J.83-A	29 dB	32 dB
J.83-B	27 dB	30 dB
J.83-C	29 dB	32 dB
Assumptions: The coded value assumes a ~ 90% code rate		

Table 5: SNR (dB) for 256 QAM

The upstream RF data technologies are based on CableLabs DOCSIS 2.0 standard called Advanced Time Division Multiplex Access (A-TDMA) and Synchronous Code Division Multiple Access (S-CDMA). These have different modulation and error correction technologies defined below:

Method	Error Correction Technology
A-TDMA	Reed-Solomon (R-S) 64 QAM
S-CDMA	Trellis Code Modulation (TCM) & Reed-Solomon (R-S) 128 QAM

Table 6: Upstream DOCSIS Error Correction Technologies

The use of Single Carrier QAM with A-TDMA and Reed-Solomon with 86% code rate will require at the slicer 22 dB in the CMTS receiver [5]. If we add 7 dB above the slicer the systems requirements reach 29 dB. Our models used for the upstream we allocate 10 dB of margin above the slicer, thus 32 dB for A-TDMA 64 QAM. In practice, MSOs may target between 30 dB to 33 dB for a minimum operating recommendation.

A very important take-away from this section are the minimum operating recommendations. The downstream RF technology to operate 256 QAM for EuroDOCSIS assuming 92% code rate is 32 dB, DOCSIS 256 QAM code rate of 90.5% is 30 dB, and A-TDMA DOCSIS upstream with 64 QAM and an 86% code rate is 32 dB. These values represent the minimum operating recommendations for the cable operators to enable the highest order modulations possible with the current RF technologies. If the operator's network exceeds these minimum operating recommendations thresholds by greater than 3 dB, then the RF data technology is the limiting factor.

Examining the "Current" Cable Network Downstream Performance

This paper will determine if today's cable network or if today's RF data technology is the limiting factor for MSOs to achieve more b/s/Hz, in other words capacity. In order to determine which is the limiting factor, the cable network or the RF technology, we need to understand the measurements of the cable network and the requirements of the RF data technology. The section above determined the minimum operating recommendations measured in dB to operate reliable service over time.

The author has received a contribution from Comcast Cable so that we may effectively assess the RF data technology against real-world network data. Dave Urban of Comcast Cable made this contribution and we thank him for this critical information for our study. Mr. Urban has completed pioneering research in measuring the performance of the cable network. His research as illustrated in figure 2, measures the downstream performance of 20 million cable modems. Mr. Urban has plotted these 20 million cable modems in a histogram by downstream signal to noise ratio (SNR) in dB. Note that when a CM reports an SNR, it is actually reporting a full end-to-end average MER. His ground-breaking findings proved several key points to the cable industry:

1. The existing cable network supported the highest order modulation possible using DOCSIS / J.83B for all users.
2. Though the distribution of cable modem performance is vastly different, nearly all devices could support higher order modulation formats or more b/s/Hz if available.
3. This work is credited with convincing the industry to support in the future the use of Multiple Modulation Profiles (MMP). The use of MMP enables groups of modems sharing common SNR the ability to use the highest order modulation possible, maximizing b/s/Hz.

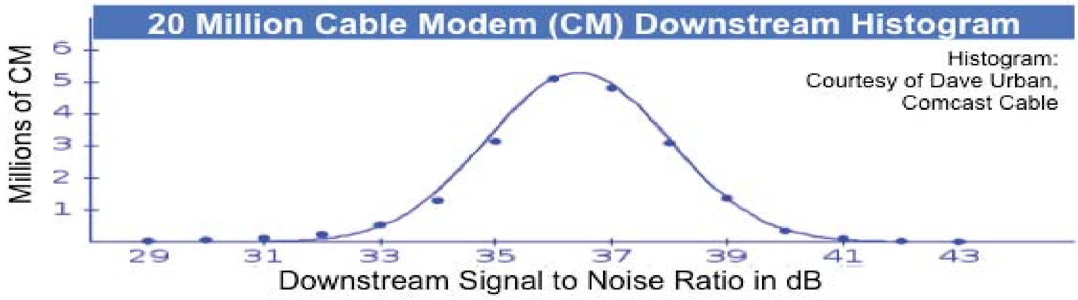

Figure 2: 20 Million Cable Modem Downstream Histogram

The cable modem (CM) measurements and other tools as well as test points will paint the entire picture for the operators to verify the use of higher order modulations. The CM histogram is a collection point; and others are needed as well, like EOL (end-of-line) measurements.

Estimating the Cable Network Upstream Performance

To estimate the use of the upstream cable plant and future spectrum splits ARRIS built a return path model. The ARRIS Upstream HFC Performance Model is an assessment of the Noise and Attenuation in the Optical and Coaxial Segments. The model considers many spectrum splits from 5-42, 5-85, 5-238, and 5-500 MHz, and several Top-split spectrum options. The model proved that Top-split, placing the upstream above 900 MHz or much higher, was too costly and consideration for Top-split was abandon by the industry in late 2011. The ARRIS model has been vetted by MSOs, fellow suppliers, and was contributed to CableLabs.

The main purpose of the ARRIS Upstream HFC Performance Model is an analysis of the HFC Optical and Coaxial segment of the network under "normal operating conditions". In a given spectrum split the model estimates the system carrier to noise (C/N) to determine the highest upstream modulation type that may be used. The estimated C/N is then matched using OFDMA with LDPC and BCH error correction technology, recommended for DOCSIS 3.1, and the highest modulation format, given the assumptions used in the model. The figure below illustrates the areas of study in the model.

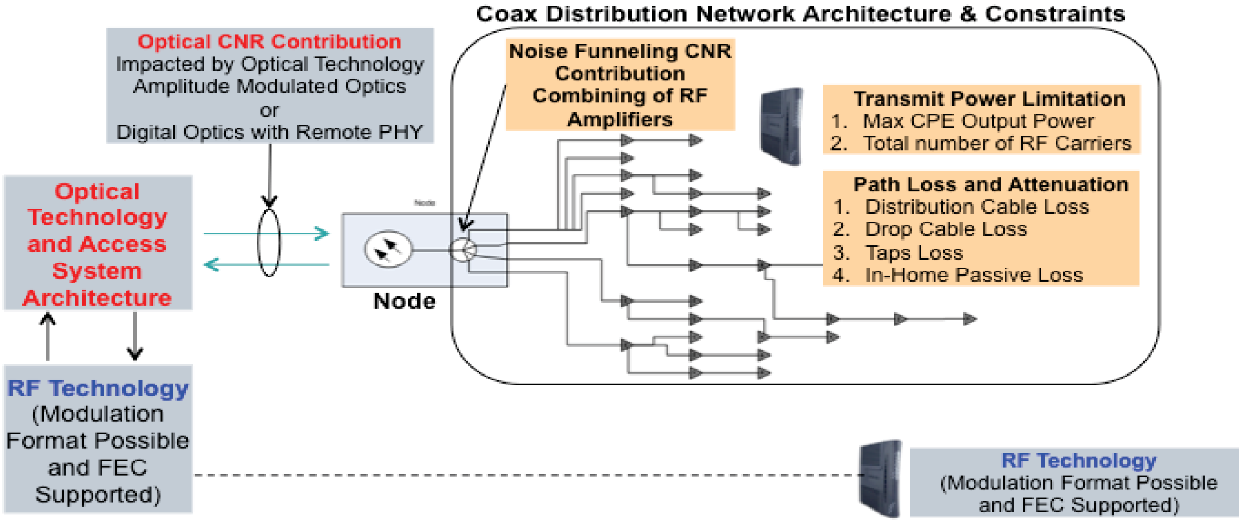

Figure 3: Major Considerations for Coaxial Network Performance

The key output of the model is the estimated system C/N and the modulation type as seen in the highlighted red boxes in Table 7. The model shows that the upstream could support higher order modulation to increase the b/s/Hz and overall system capacity if DOCSIS 2.0 had defined support. The model estimates the modulation type possible, assuming DOCSIS 3.1 technology.

Return RF System Performance		Sub-Split	Mid-Split	High-Split 238
Upper Frequency	MHz	42	85	238
Homes Passed		250	250	250
HSD Take Rate		50%	50%	50%
HSD Customers		125	125	125
Desired Carrier BW	MHz	6.4	6.4	6.4
Modulation Type		2048-QAM	1024-QAM	512-QAM
Bits/Symbol		11	10	9
Number Carriers in Bonding Group		3.5	10.25	33
Max Power per Carrier Allowed in Home	dBmV	59.6	54.9	49.8
Worst Case Path Loss	dB	29.1	30.1	33.5
Maximum Return Amplifier Input	dBmV	30	25	16
Actual Return Amplifier Input	dBmV	15	15	15
Assumed Noise Figure of Amplifier	dB	7	7	7
Return Amplifier C/N (Single Station)	dB	65	65	65
Number of Amplifiers in Service Group		15	15	15
Return Amplifier C/N (Funneled)	dB	53.4	53.4	53.4
Optical Return Path Technology		uDFB	uDFB	uDFB
Assumed Optical C/N	dB	44	41	37
System C/N	dB	43.5	40.8	36.9
Desired C/N	dB	41	38	35

Table 7: DOCSIS 3.1 Capacity Prediction with Several Upstream Splits and AM Optical Technology

Though the model suggests the use of very high order modulation, it is important to know this does not account for noise conditions related to external interference or burst noise events. The model suggests the C/N of the channel will support very high order modulation, however these modulation formats will need to be supported from the cable modem to the burst receiver in the headend. It is to early to tell if the upstream will support as high a modulation order as the model suggests, as these systems are not available at this time.

Background on the ARRIS Upstream Model

It is important to understand what the model is and what it is not. In summary, the model considers the components, which comprise the access layer for the upstream. This includes, the optical technology, distance between headend and node, coaxial electronics, passives, coaxial cable types and lengths, modem power, and many other factors. The diagram in figure 3 and table 7, illustrates the measured parameters in the ARRIS Model [3].

The model:

- Calculates the performance of the Optical and Coaxial segment
- Has flexibility to account for different network architectures and components
- Accounts for distance variations in the optical and coaxial segments
- Accounts for various service group sizes to adjust for noise funneling effects
- Accounts for noise contribution of the HFC Network
- Accounts for Attenuation
- Accounts for temperature variation in many areas
- Estimates DOCSIS 3.1 Capacity
- Model defines Operator Margin of 10 dB above the slicer for a “coded” LDPC and BCH modulation format

The model does not account for:

- Noise conditions related to external interference or burst noise events
- Faulty components
- Variables in Combining

Are Cable Networks “Limited by” the RF Video and Data Technologies?

The downstream and upstream capacity is limited by the current RF video and data technologies, based on ITU-T J.83 and DOCSIS 2.0. In figure 4, the current DOCSIS based systems using J.83 Annex B shows the highest order modulation of 256 QAM provides complete coverage for all users because the network supports greater than 30 dB. The use of EuroDOCSIS J.83 Annex A in this example provides near full coverage.

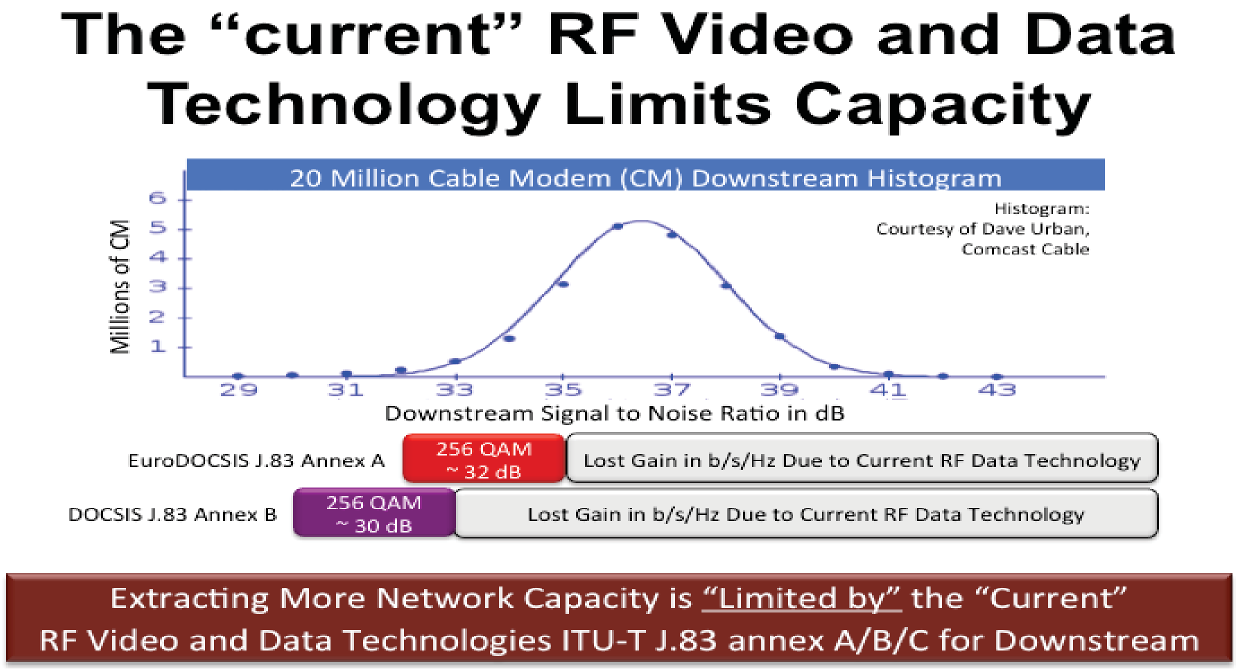

Figure 4: RF Data Downstream Technology based on J.83 is the "Limiting Factor"

Current Optical Technology and Coax Network CNR Channel Should Support DOCSIS 3.1

Return RF System Performance		Sub-Split	Mid-Split	High-Split 238
Upper Frequency	MHz	42	85	238
Homes Passed		250	250	250
HSD Take Rate		50%	50%	50%
HSD Customers		125	125	125
Desired Carrier BW	MHz	6.4	6.4	6.4
Modulation Type		2048-QAM	1024-QAM	512-QAM
Bits/Symbol		11	10	9
Number Carriers in Bonding Group		3.5	10.25	33
Max Power per Carrier Allowed in Home	dBmV	59.6	54.9	49.8
Worst Case Path Loss	dB	29.1	30.1	33.5
Maximum Return Amplifier Input	dBmV	30	25	16
Actual Return Amplifier Input	dBmV	15	15	15
Assumed Noise Figure of Amplifier	dB	7	7	7
Return Amplifier C/N (Single Station)	dB	65	65	65
Number of Amplifiers in Service Group		15	15	15
Return Amplifier C/N (Funneled)	dB	53.4	53.4	53.4
Optical Return Path Technology		uDFB	uDFB	uDFB
Assumed Optical C/N	dB	44	41	37
System C/N	dB	43.5	40.8	36.9
Desired C/N	dB	41	38	35

Cable Networks are "Limited by" the RF Data Technologies of CableLabs DOCSIS 2.0 Upstream

Figure 5: RF DOCSIS 2.0 Upstream Technology is the "Limiting Factor"

The key finding as seen in figure 4, is that DOCSIS J.83 based systems and as seen in figure 5, the DOCSIS 2.0 upstream that the limiting factor is the RF technology and not the cable plant.

Solution: Modernize RF Data Technology with A New PHY Layer: DOCSIS 3.1

The above analysis proves that the cable access network is now limited by ITU-T J.83 technology for the downstream and the DOCSIS 2.0 technology for the upstream. These technologies were defined as much as 15 years ago and by today's standard have low order modulation formats and an old FEC.

ARRIS Proposed DOCSIS 3.1 Features [2,3]:

- Enables Backward Compatibility (as opposed to Coexistence)
    - All CPE DOCSIS devices can share spectrum
    - DOCSIS MAC Channel Bonds legacy PHYs & new PHYs
    - Maximize Spectrum Usage
    - Delays / avoids major investment
    - Spectrum changes, node splits, or fiber deeper
    - Avoids Spectrum Tax (allocating separate spectrum for legacy and new)
    - Leverage DOCSIS MAC across legacy SC PHY & new OFDM PHY
    - Enable SC-QAM and OFDM to share a bonding group
- Data Rate Capacity Increases
    - CableLabs Target 10+ Gbps downstream capacity
    - CableLabs Target 1+ Gbps upstream capacity
    - The Maximum is unbounded (10 – 20 Gb/s or ??)
- Modernize the PHY Layer (to increase bits per Hz)
    - Extend Downstream & Upstream Modulation formats
        - Downstream Recommendation 4096 QAM (12 bits per symbol)
        - ARRIS recommends consideration for up to 16384 QAM Downstream
        - Upstream Recommendation 4096 QAM
        - ARRIS recommends consideration for up to 16384 QAM Upstream
    - Adds Downstream OFDM (Orthogonal Frequency-Division Multiplexing)
    - Adds Upstream OFDMA (Orthogonal Frequency-Division Multiple Access)
    - Adds Error Correction Technology
        - Outer FEC: Bose-Chaudhuri-Hocquenghem (BCH) codes
        - Inner FEC: Low-density parity-check (LDPC) codes
        - Use of higher order modulations in similar SNR environment

    - As measured against DOCSIS Upstream using A-TDMA the use of DOCSIS 3.1 with LDPC and BCH may enable a 2-order modulation rate increase in the same SNR environment, 64 QAM moves to 256 QAM.
    - As measured against EuroDOCSIS Downstream using J.83 annex A the use of DOCSIS 3.1 with LDPC and BCH may enable a 2 order modulation rate increase in the same SNR environment, 256 QAM moves to 1024 QAM.
    - As measured against DOCSIS Downstream using J.83 annex B the use of DOCSIS 3.1 with LDPC and BCH may enable a single order modulation complexity increase in the same SNR environment, 256 QAM moves to 512 QAM
- Defines New Cable Spectrum Band Plan
    - Upstream may extend to 300 MHz (D3.0 defines 5-85 MHz)
    - Downstream may extend to 1.2 GHz or 1.7 GHz (D3.0 defines 1 GHz)

DOCSIS 3.1 to the rescue! The future use of DOCSIS 3.1 has four core features that will allow the MSO to maximize the network capacity or b/s/Hz. Possible DOCSIS 3.1 key features:

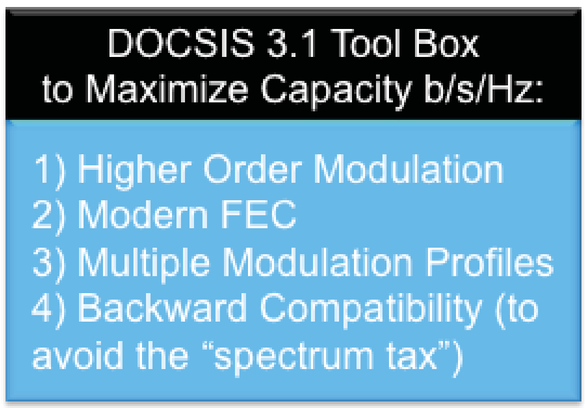

Figure 6: Possible DOCSIS 3.1 Tool Box to Maximize Capacity b/s/Hz

As illustrated in the downstream figure 4 and the upstream analysis as shown in the figure 5, that CNR of the channel could support higher modulation if available.

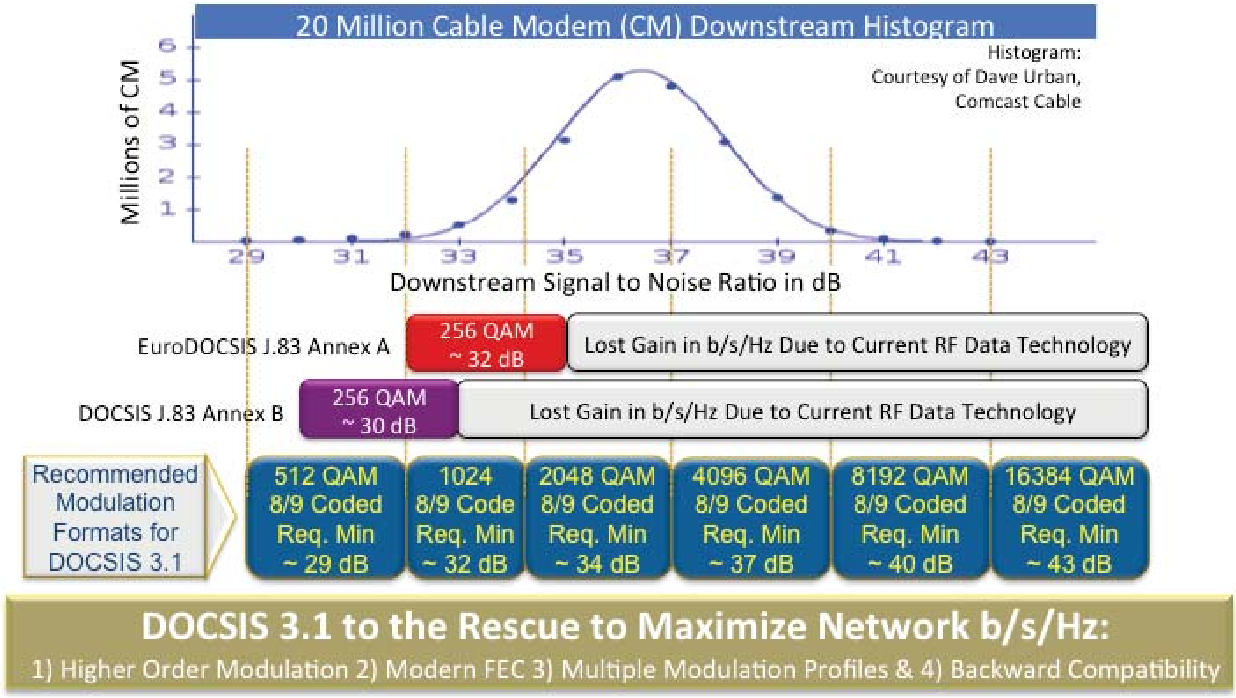

Figure 7: DOCSIS 3.1 Enables the MSOs to Maximize Spectrum Increasing b/s/Hz

The above figure 7, illustrates the point that the current RF data technology was the limiting factor preventing MSOs from increasing downstream network capacity in b/s/Hz. This also suggests the use of higher orders of modulation to obtain more capacity (that is possible with DOCSIS 3.1 over the "existing" Optical and Coaxial network). However, not all users can use the same order modulations and the introduction of the use of multiple modulation profiles (MMP) is important. 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. The use of backward compatibility allows spectrum to be shared between legacy cable modems and new modems, which support both legacy and new DOCSIS technology, avoiding a spectrum tax.

The existing cable network downstream and upstream performance can support higher order modulation formats than those available today. 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.

The adoption of higher modulation formats in DOCSIS 3.1 will increase b/s/Hz. A key finding is the use of DOCSIS 3.0 Single Carrier Reed Solomon versus OFDM using LDPC may allow two (2) orders of modulation increase.

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Next Generation – Fiber to the Node (FTTN) called Digital Fiber Coax (DFC) Era

Digital Fiber Coax (DFC) Introduction

As we examine the future to support higher data capacity in the optical and coax domain we may need to use digital optical technology for FTTN. We will examine this class of architecture we are calling Digital Fiber Coax (DFC). The DFC Architecture is a network class, which differs from HFC in that MAC/PHY or just PHY processing is distributed in the outside plant (node) or MDU. The DFC architecture also uses "purely digital" optical transport technologies such as standardized Ethernet, G.709, PON, or other transport methods providing optical capacity to and from the node. The industry may determine to call this class of architecture something else, but the functions, technology choices and architectures are different than HFC.

Digital Fiber Coax (DFC) is a "PHY or MAC/PHY Processing Architecture" in the node using Digital Optics to/from the node as seen in figure 8. Thus Digital Fiber Coax (DFC) uses digital optical technology to and/or from the node as well as supports two (2) different Access Architecture options for FTTN as seen in figure 9. DFC uses digital optics for FTTN (to/from) in either a Centralized Access Architecture (CAA) "or" a Distributed Access Architecture (DAA). DFC in a Centralized Access Architecture (CAA) the CCAP MAC and PHY functions in Headend (HE) or Primary Hub (PH) only. DFC in Distributed Access Architecture (DAA) the CCAP MAC and PHY or PHY functions are placed in a node. As with Centralized Access Architectures there are several platform access architectures, this is even more the case with Distributed Access Architectures that will split up the MAC and PHY layers of CCAP between the headend and the node. In the full Remote CCAP option for DFC, the entire CCAP MAC and PHY layers are placed in the node or MDU location. This section will provide terms and definitions to the different Fiber to the Node Classes cable may select, like HFC or DFC as well as the two different Access Architecture classes options that may emerge this decade and beyond as seen in figure 10.

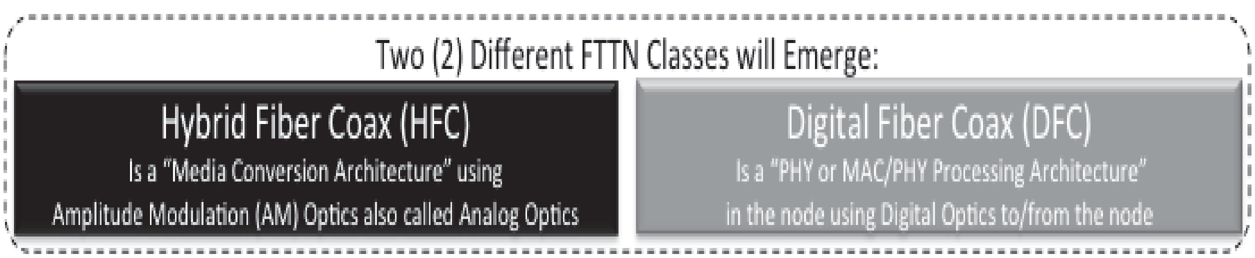


Figure 8 – Two (2) Different FTTN Classes for Cable will Emerge

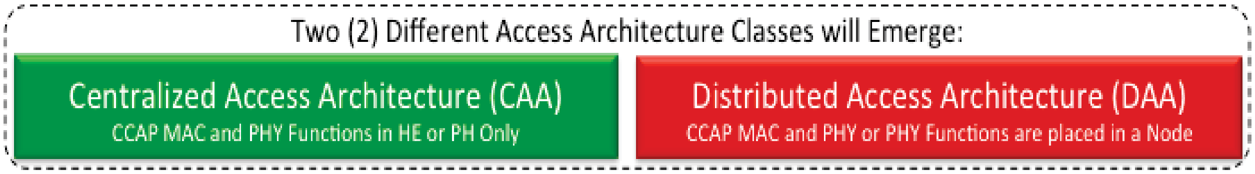


Figure 9 – Two (2) Different Access Architecture Classes for Cable will Emerge

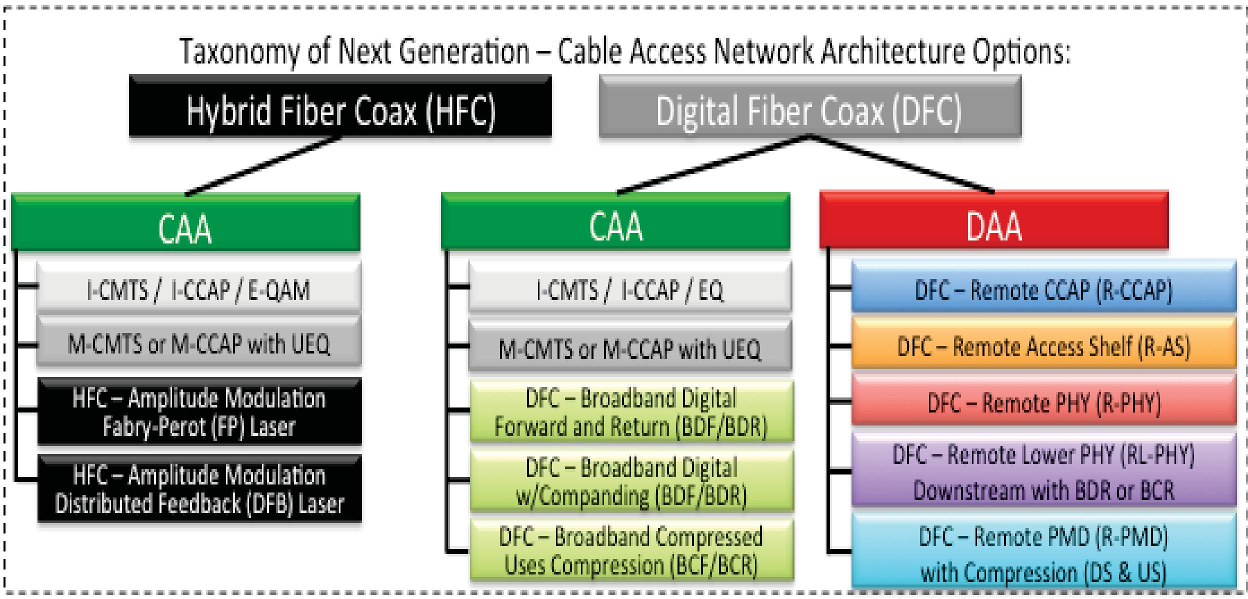


Figure 10 – Taxonomy of Next Generation – Cable Access Network Architecture Options

This next section will ask two (2) critical questions for the future of cable networking for this decade and beyond. These two (2) questions are arguably as or more important as the evaluation and later justification for the creation of DOCSIS 3.1. These next key technology and architecture questions are as follows:

1. **Are Current Cable Networks "Limited by" the FTTN Amplitude Modulation (AM) "Analog" Optical Technology?**

2. **Digital Fiber Coax (DFC) uses Digital Optics for FTTN will force us to place SOME PHY or MAC/PHY Access Layer Functions in the Node, so *what stays in the headend and what moves to the node?***

Are Current Cable Networks "Limited by" the FTTN Amplitude Modulation (AM) "Analog" Optical Technology?

The optical layer will be examined in this section. The paper will only examine the return path optical technologies and performance attributes. The optical transport return path technologies include: Amplitude Modulation (AM), commonly referred to as analog optics and Broadband Digital Return (BDR), which may be referred to as simply Digital Return.

This section will examine if the future capabilities of the cable access network will be limited by the fiber to the node (FTTN) optical technology. This section will examine the network capacity if we replaced the AM optics with digital optics, like those used for Broadband Digital Return.

In the section above it was proved that the RF data technology defined in the late 90's using Recommendation ITU-T J.83 Annex A/B/C, which is the basis for Cable's Digital Video and Data (DOCSIS) technologies of today, is the limiting factor in maximizing b/s/Hz. A 15-year run! We now realize the RF technology limitation, which was a driver to modernize DOCSIS with a new PHY layer.

The section above examined the downstream and upstream performance and showed that more capacity could be achieved with DOCSIS 3.1 using the existing network. This proved that AM optics used in today's HFC could support higher order modulations, such as those defined in DOCSIS 3.1. However, depending on upstream spectrum split, optical span, and optics type, use of the highest order modulations (yet to be defined) was not possible with current AM optics. There could be many other factors; the cable distribution network side, the size of the service group, the spectrum used, and it could be the optical technology.

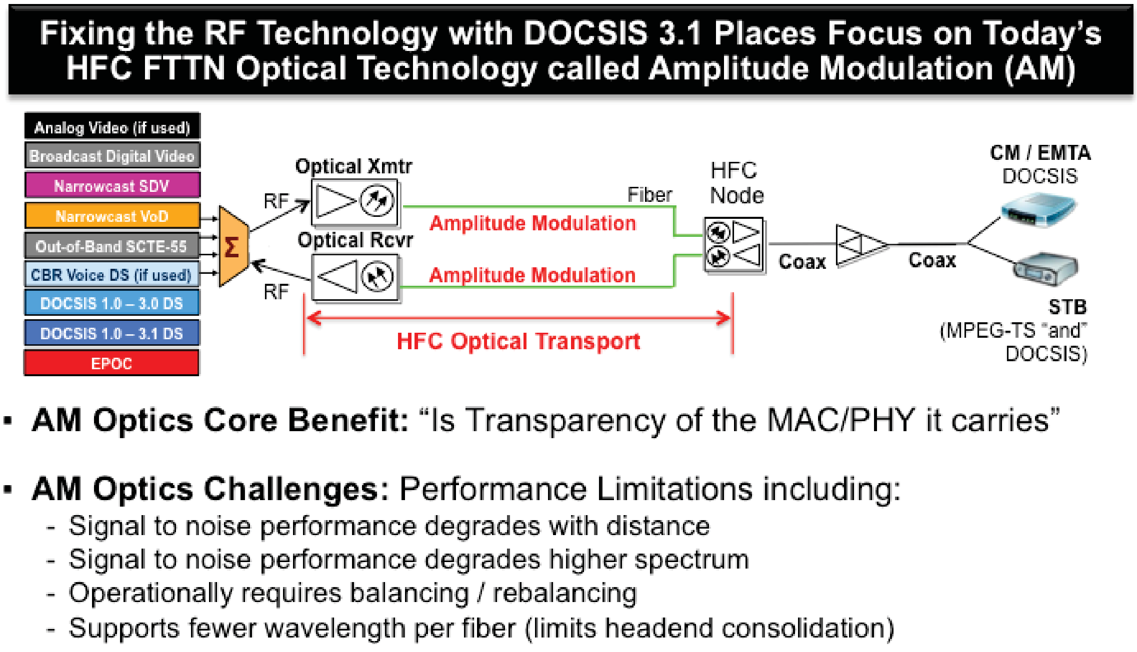


Figure 11: Overview of the Amplitude Modulation Optics

Overview of the "Current" FTTN Optical Technology

Amplitude Modulation (AM) optics when used in the return path had two types of lasers Fabry-Perot (FP) or Distributed Feedback (DFB) lasers. Though HFC Amplitude Modulation used DFB in the forward for many years. Analog return path transport is considered as a viable option for Mid-split and High-split returns; supporting short to moderate return path distances of 0-50 km. If the wavelength is changed to 1550 nm, with an EDFA, even greater distances are possible.

The analog optical return path transport presently supports up to 200 MHz loading; but typically only 5-42 MHz or 5-65 MHz is carried, depending on the distribution diplex filter split. The major benefit with analog optical return is its simplicity, lower cost, and flexibility, when compared with HFC style digital optical transmission. Distance is the chief challenge of analog optical transport and we will examine if support for very high order modulation, like that planned in DOCSIS 3.1, could be a factor.

Pros

The chief advantage of analog return is its cost effectiveness and flexibility. If analog return optics are in use in the field today, there is a good chance that they will perform adequately at 85 MHz; and even 200 MHz loading may be possible, if required in the future. This would allow an operator to fully amortize the investment made in this technology over the decade.

Important:

AM optics may support very high order modulation (4K & 16K QAM) though there are some restrictions mainly due to:

- Dependence on the type of optics in the forward and return
- Distance, spectral loading, spectral placement in the low frequency band to achieve the highest modulation order, and service group size (upstream)
- AM optics short distance or O-band optics will yield best performance
- Manufacturer consultation is needed to confirm performance thresholds

Cons

There are drawbacks to using analog optics. Analog DFB's have demanding setup procedures. RF levels at the optical receiver are dependent on optical modulation index and the received optical power level. This means that each link must be set up carefully to produce the desired RF output at the receiver (when the expected RF level is present at the input of the transmitter). Any change in the optical link budget will have a significant impact on the output RF level at the receiver, unless receivers with link gain control are used.

Also, as with any analog technology, the performance of the link is distance dependent. The longer the link, the lower is the optical input to the receiver, which delivers a lower RF output and lower C/N performance.

Here is a list of challenges that Amplitude Modulated links face:

- Distance Limitations
- Fiber distortions in AM optics can be much more disruptive to signal integrity than the coax distortions
- Many Noise Contributions in Fiber Transport Negatively Impact AM Optics
- Fiber Signal Distortions (Linear & Non-Linear)
    - Inter-channel Crosstalk
    - Intra-channel Crosstalk
    - Non-uniform Attenuation vs. wavelength
    - Chromatic Dispersion
    - Polarization Mode Dispersion
    - Cross-Phase Modulation
- Transmitter Electronics/Amplifier Signal Distortions (Linear & Non-Linear)
- Laser Signal Distortions (Linear & Non-Linear)
    - RIN (Relative Intensity Noise)
    - Laser Phase Noise
- Optical Amplifier Distortions (Linear & Non-Linear)
    - Spontaneous Emission Noise
    - Noise Beat components
- Photo-detector Signal Distortions (Linear & Non-Linear)
    - Quantum Shot Noise
    - Dark Current Noise
- Receiver Electronics/Amplifier Signal Distortions (Linear & Non-Linear)
    - Johnson-Nyquist Thermal Noise
    - 2nd and 3rd order Intermodulation

Question: Are Current Cable Networks "Limited by" the FTTN Amplitude Modulation (AM) "Analog" Optical Technology?

Answer: "Not Now, but in Future, Yes"

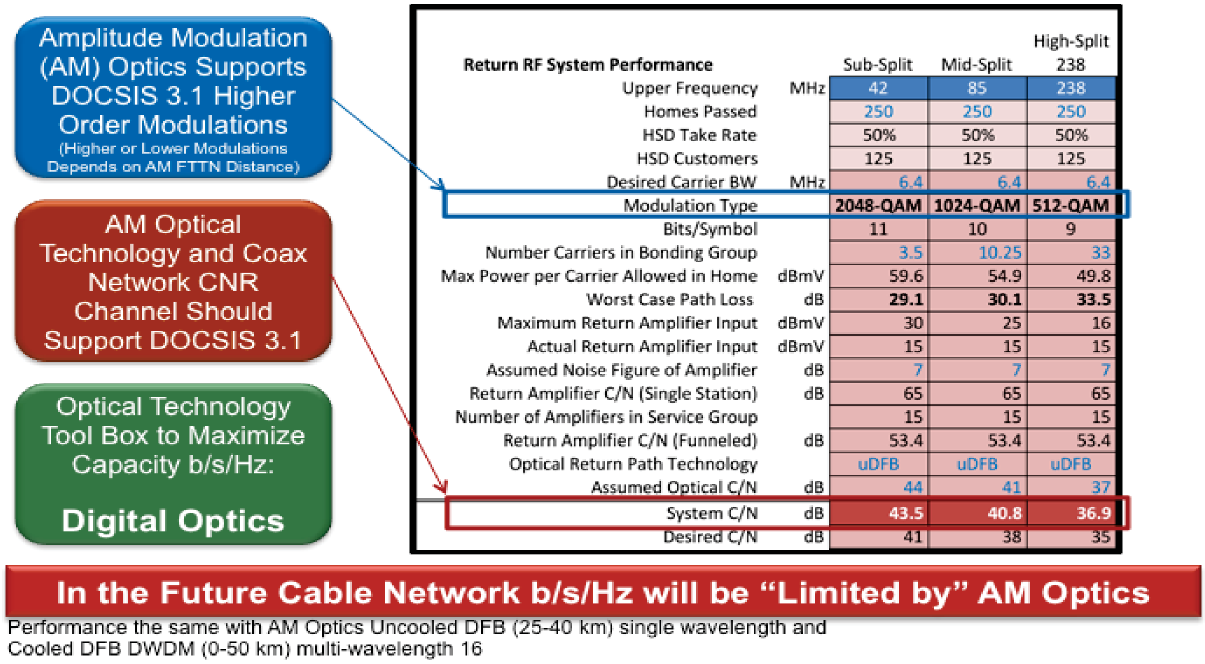
We have modeled the network architecture using DOCSIS 3.1 and keeping all other coaxial conditions the same, while only changing the AM optics to BDR to mitigate the effects of distance variation. The table illustrates AM and Broadband Digital Return (BDR) optical constraints that changed; this single change greatly impacts the performance of the system. The AM optical performance will be the "limiting factor" for using the highest order of modulation planned for DOCSIS 3.1 systems.

This analysis now has further shown that it is not just the DOCSIS 3.1 advanced FEC (LDPC and BCH) and defined higher order modulation that allows for a gain in b/s/Hz; it is also the gain in C/N from the use of Digital Optics. This allows for the use of even higher order modulation, and thus an increase in b/s/Hz of the system; especially for High-split architectures. Figure 12 illustrates the difference in performance of the return path amplitude modulated DFB optical technology versus Broadband Digital Return (BDR). In this paper we have selected one AM optical technology, which is listed in the model with the performance to support 40 km to 50 km. We could have selected a short span from the fiber node that would have yielded better results. We chose this distance, as this would likely cover 80% of all possible MSOs HHP configurations.

Optical Segment Characterization			Sub-Split	Mid-Split	High-Split 238
Upper Frequency		MHz	42	85	238
AM Optics Uncooled DFB (0-25 km) single wavelength	uDFB	dB	48	45	41
AM Optics Uncooled DFB (25-40 km) single wavelength	uDFB	dB	44	41	37
AM Optics Cooled DFB DWDM (0-50 km) single wavelength	cDFB	dB	48	45	41
AM Optics Uncooled DFB (0-25 km) multi-wavelength 8	uDFB	dB	44	41	37
AM Optics Uncooled DFB (25-40 km) multi-wavelength 8	uDFB	dB	40	37	33
AM Optics Cooled DFB DWDM (0-50 km) multi-wavelength 16	cDFB	dB	44	41	37
BDR (Not Impacted by Length "or" Multi-wavelength)	BDR	dB	48	48	48

Figure 12: Optical Technology Choices

The model assumed the use of an Amplitude Modulation (AM) Optical Link using an Uncooled DFB laser (for use up to 40 km), assuming a single wavelength. Then the model assumed the use of DOCSIS 3.1 with all of the new PHY layer improvements, such as OFDMA, a pair of error correction technologies (LDPC inner code with BCH outer code), and the expansion in the available modulation order up 4096 QAM. The model estimated Sub-split DOCSIS 3.1 modulation at 2048 QAM, Mid-split at 1024 QAM, and High-split at 512 QAM, as seen in the figure below. The model shows different modulation support depending on split option.



Return RF System Performance		Sub-Split	Mid-Split	High-Split 238
Upper Frequency	MHz	42	85	238
Homes Passed		250	250	250
HSD Take Rate		50%	50%	50%
HSD Customers		125	125	125
Desired Carrier BW	MHz	6.4	6.4	6.4
Modulation Type		2048-QAM	1024-QAM	512-QAM
Bits/Symbol		11	10	9
Number Carriers in Bonding Group		3.5	10.25	33
Max Power per Carrier Allowed in Home	dBmV	59.6	54.9	49.8
Worst Case Path Loss	dB	29.1	30.1	33.5
Maximum Return Amplifier Input	dBmV	30	25	16
Actual Return Amplifier Input	dBmV	15	15	15
Assumed Noise Figure of Amplifier	dB	7	7	7
Return Amplifier C/N (Single Station)	dB	65	65	65
Number of Amplifiers in Service Group		15	15	15
Return Amplifier C/N (Funneled)	dB	53.4	53.4	53.4
Optical Return Path Technology		uDFB	uDFB	uDFB
Assumed Optical C/N	dB	44	41	37
System C/N	dB	43.5	40.8	36.9
Desired C/N	dB	41	38	35

Figure 13: Support of High Order Modulation Varies with Spectrum Split

The model determines the modulation format based on the System C/N as shown in the figure above highlighted in red and with a red box. The model will select the highest modulation order supported based on the System C/N.

To verify if the Amplitude Modulation optical technology is the limiting factor, only this parameter will be changed in the model, as seen in table 7. This single parameter was changed, swapping the Amplitude Modulation optical technology with a Digital Optic using Broadband Digital Return (BDR). This single change may account for two (2) to three (3) orders of the modulations increase over use of AM optics when considering the high-split spectrum band. The Sub-split and Mid-split options will not see as much of a gain because of the spectrum location and channel load, which is much smaller than High-split.

Return RF System Performance		Sub-Split	Mid-Split	High-Split 238
Upper Frequency	MHz	42	85	238
Homes Passed		250	250	250
HSD Take Rate		50%	50%	50%
HSD Customers		125	125	125
Desired Carrier BW	MHz	6.4	6.4	6.4
Modulation Type		4096-QAM	4096-QAM	4096-QAM
Bits/Symbol		12	12	12
Number Carriers in Bonding Group		3.5	10.25	33
Max Power per Carrier Allowed in Home	dBmV	59.6	54.9	49.8
Worst Case Path Loss	dB	29.1	30.1	33.5
Maximum Return Amplifier Input	dBmV	30	25	16
Actual Return Amplifier Input	dBmV	15	15	15
Assumed Noise Figure of Amplifier	dB	7	7	7
Return Amplifier C/N (Single Station)	dB	65	65	65
Number of Amplifiers in Service Group		15	15	15
Return Amplifier C/N (Funneled)	dB	53.4	53.4	53.4
Optical Return Path Technology		BDR	BDR	BDR
Assumed Optical C/N	dB	48	48	48
System C/N	dB	46.9	46.9	46.9
Desired C/N	dB	44	44	44

Table 7: Swap AM Optics for BDR and Measure the Results

The use of BDR optics provides more operating margin and higher b/s/Hz because the assumed performance of BDR is better than that of AM optics. In the case of Sub-split and Mid-split covering shorter distances, or with a cooled DFB, AM optics performance may be at near parity with BDR. The move to High-split spectrum is when in all cases the use of BDR is better than that of AM optics.

Solution: Modernize Optical Technology: Digital Optics

In the future will the capability of the cable access network to increase b/s/Hz be “limited” by the fiber to the node (FTTN) optical technology? Yes, however the performance of AM optics when used for Sub-split and Mid-split may perform at near parity against digital optics depending greatly on both distance and AM laser selection.

In table 7 above and figure 14 below, the use of AM optics will enable higher order modulation to support DOCSIS 3.1. However, to maximize DOCSIS 3.1, and remove the optical layer from becoming the limiting factor, the move to digital optics in some cases will allow full support of the highest order modulations. In figure 14 is a side-by-side comparison of these findings.

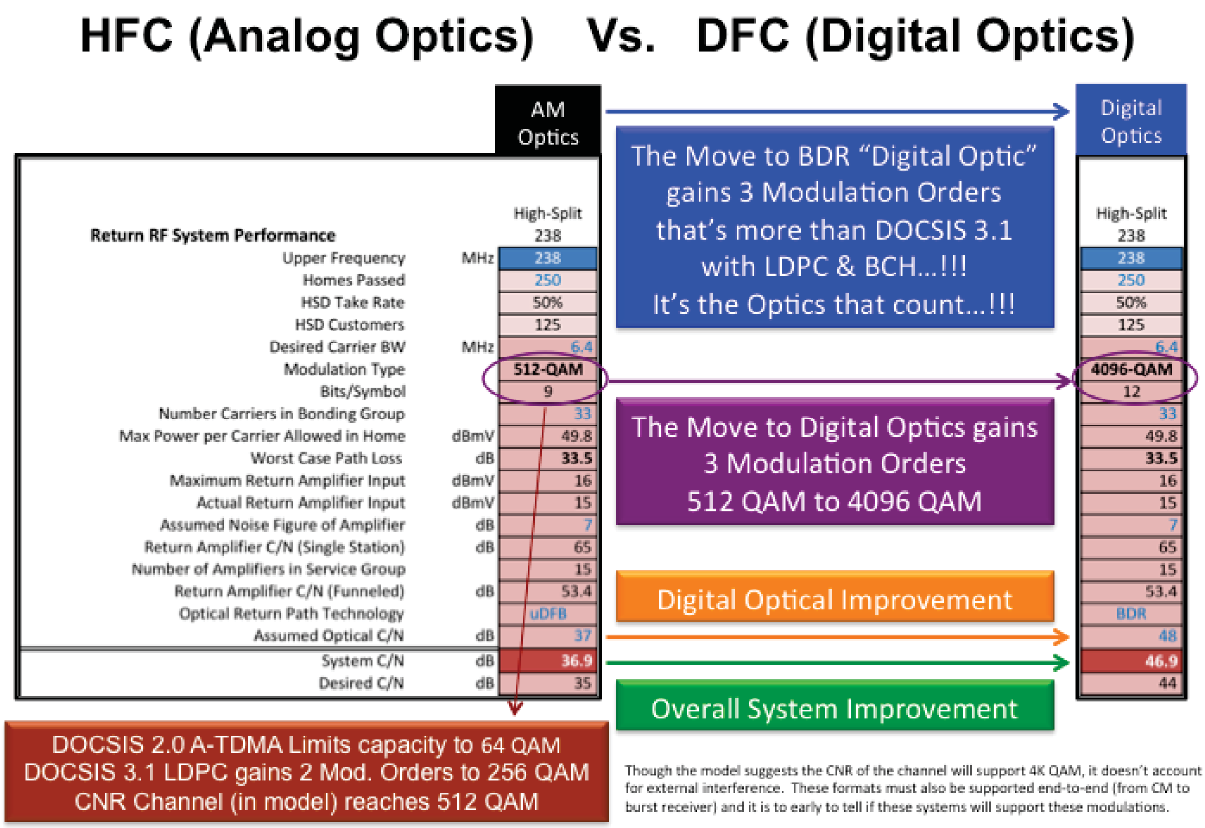


Figure 14: High-split AM Optics versus Digital Optics

The Paper Found New Key Findings with the Use of Digital Return

1. Digital Optics Maximizes Overall System Performance in terms of b/s/Hz by enabling 2 to 3 higher modulation orders over AM optics when considering High-split (Sub-split and Mid-split the gain is smaller)
2. To maximize DOCSIS 3.1 the optical link will need to be digital for High-split
3. The use of BDR style digital optics places only the lowest layer of the PHY in the node, known as the ADC (analog-to-digital converter).
4. This places the absolute least amount of the PHY in the node to enable use of digital optics, minimizing functionality in the outside plant.

As stated above and shown in figure 14 and 15, this paper proves that there are new drivers for use of Broadband Digital Return to maximize overall system performance.

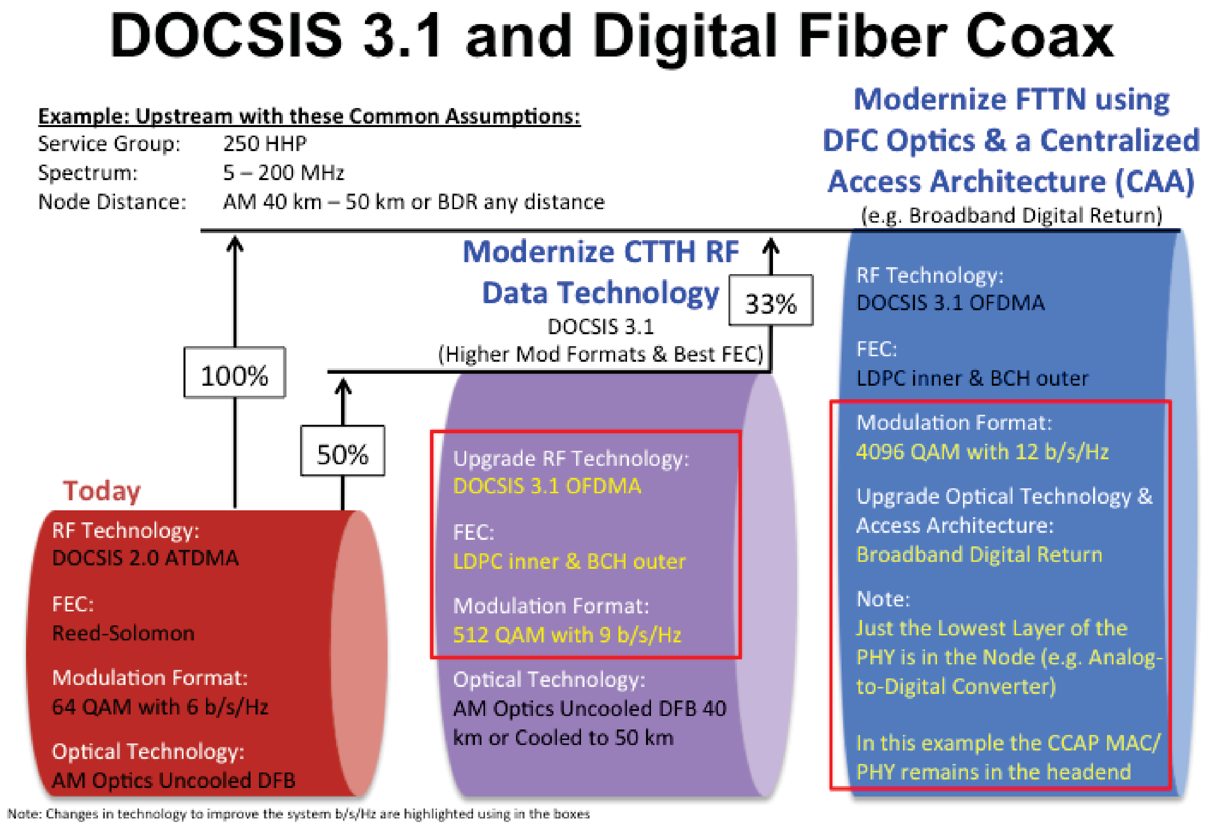


Figure 15: DOCSIS 3.1 Gain and Digital Optic Gain in b/s/Hz

Broadband Digital Return is better than AM Optics because:

1. Digital Optics has better Performance in the Optical Segment (when compared to AM optics)
2. Signal to noise performance does not degrade with distance
3. Signal to noise performance does not degrade with return path increase in spectrum and channel loading (assuming parity in ADC performance) up to High-split 238 MHz. (At higher frequencies the CM maximum output power is a limiting factor due to cable loss.)
4. More robust in the presence of Fiber-induced noise since decoding only 0's and 1's, resulting in better RF performance and lower BER

It's the Optics!!! HFC Digital Return Matters

Digital Fiber Coax (DFC) uses Digital Optics for FTTN will force us to place SOME PHY or MAC/PHY Access Layer Functions in the Node, so what stays in the headend and what moves to the node?

As stated in the section above there are benefits for using digital optics; but there may also be some drawbacks, such as placing more functionality in the outside plant. There are also benefits to placing lots of functions in the node as well, though this paper does not examine these attributes of different digital architectures and placement of PHY or MAC and PHY functions in the node

Moving from AM Optics to Digital Optics for FTTN will force us to place PHY or MAC/PHY Access Layer Functions in the Node. What stays in the headend and what moves to the node? The industry will need to define a new access network architecture supporting digital connections between headend and fiber node. This new access network architecture will redefine the CCAP architecture and other headend platforms (e.g. Digital Optical Platforms) as well as the node platforms.

In this section the uses of Digital Optics is required and this will place new functions in the Node and add or remove functions from the Headend. It is of critical importance that we understand the functional layers and building blocks of MPEG-TS and DOCSIS MAC and PHY Functions as these functions may be split between the headend and node in the future. This section ends with several examples of Remote PHY layer or MAC and PHY functions in the node the node to support Digital Forward solutions.

Functions Overview of MPEG-TS and Current and Future DOCSIS Technology

This section and associated figures are meant to align cable technologies to the OSI reference model. The technologies examined include DOCSIS 3.0 and Edge QAM functions to the left which both use Recommendation ITU-T J.83 as the Physical Layer. The right side of the figure 16 is an attempt to define the “possible” framework for DOCSIS 3.1 currently in development. This figure is based on the DOCSIS specifications, ITU-T J.83-B, and DVB-C2. This is aimed to help show the functions of the Remote Access Layer Architecture that may remain in the headend and that which is placed in the node.

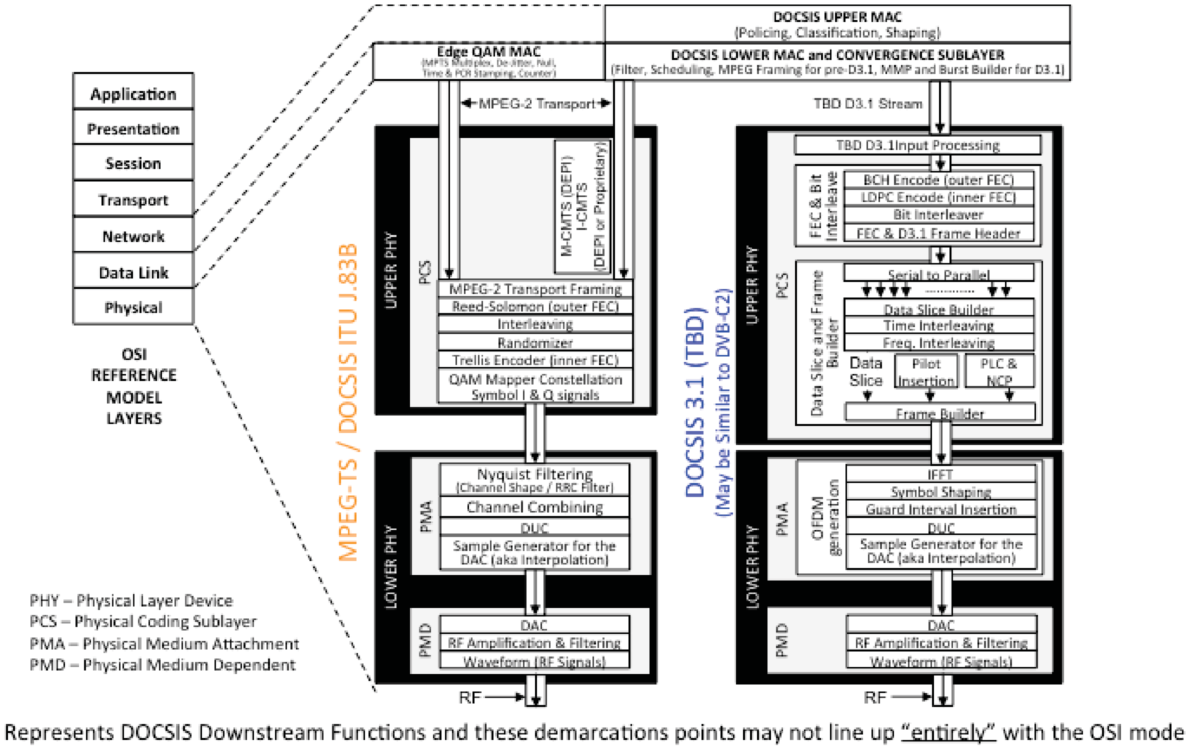


Figure 16: Functional Review of the RF MAC/PHY Layers Downstream Only

Overview of Current and Future FTTN Optical Technology

The optical layer and the relationship to the remote access layer architecture will be examined in this section.

Today, the two technologies used in optical transport for the return include Amplitude Modulation (AM) and Broadband Digital Return (BDR), as reviewed in the preceding section. The Broadband Digital term and current application is tied to the return path; **however, this could be used for the forward path as well.**

Broadband Digital Return places the lowest layer of the physical (PHY) layer called the PMD (Physical Medium Dependent) function in the Node. The PMD layer of the PHY is where the ADC/DAC (Analog-to-Digital or Digital-to-Analog) functions take place.

The FTTN technology and architecture for HFC has always retained one core function --- transparency of the underlying MAC/PHY technologies that travels through it. The transparency of the RF MAC/PHY technologies was possible because of the optical FTTN technology used to include either Amplitude Modulation optical technology or Broadband Digital.

In the future we need to consider the possibility of moving the IP/Ethernet transport past the HE/Hub locations to the node. We will examine what we are referring to as a new class of cable FTTN architecture called Digital Fiber Coax (DFC). The use of DFC may augment the existing HFC media conversion class of architecture that has been deployed for about two decades. We are suggesting that there are really two different Fiber to the Node (FTTN) architecture classes for Cable Networks. These will utilize FTTN and coaxial cable as the last mile media, but this is where the similarities will stop.

To simply summarize, the Two Different Cable FTTN network architecture classes are:

- HFC is a "Media Conversion Architecture"
- DFC is a "PHY or MAC/PHY Processing Architecture"

These new FTTN technologies and architectures have or will emerge, that if implemented "may" remove this transparency.

Should the cable industry change the definition of HFC to mean multiple functions, "or" define a new term(s) for this fundamentally different Class of FTTN Network Architecture that uses Digital Optics to/from the node and places PHY as seen in figure 19 or MAC/PHY functions in the node as seen in figure 20.

The figures in the sections represent the high-level functions and technology placement in the headend and node.

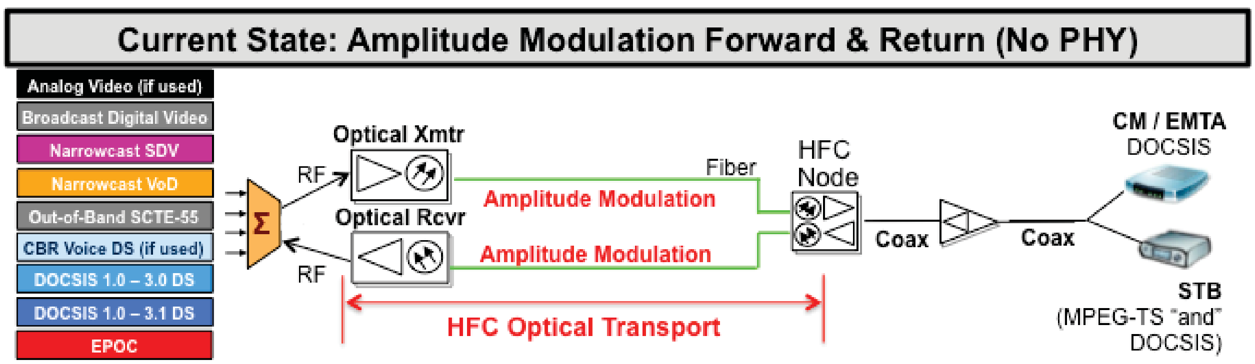


Figure 17: HFC Amplitude Modulation Forward and Return

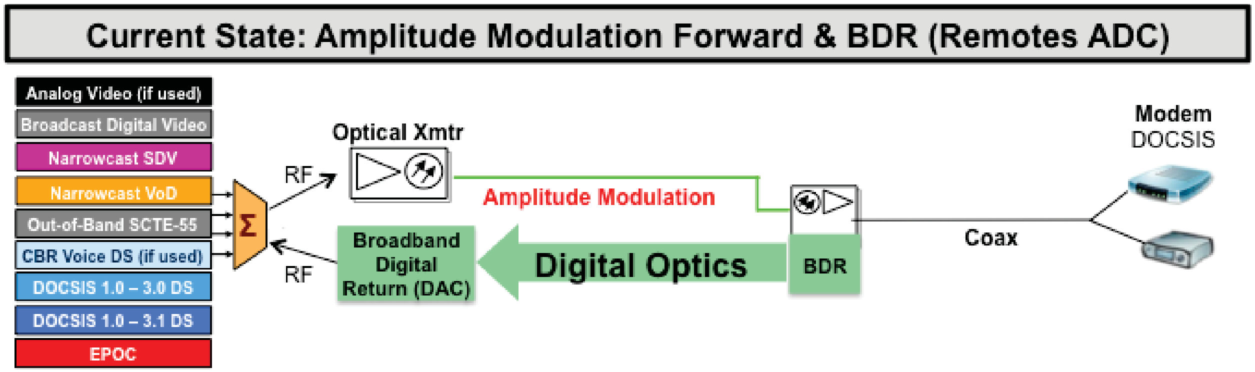


Figure 18: HFC Amplitude Modulation Forward and DFC Broadband Digital Return (BDR)

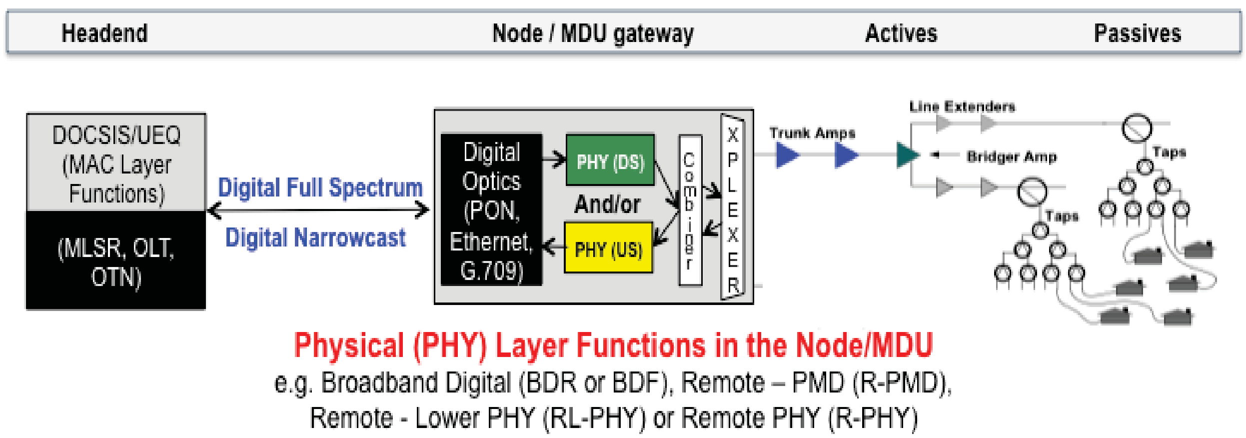


Figure 19: Digital Fiber Coax – Remote PHY Layer Options

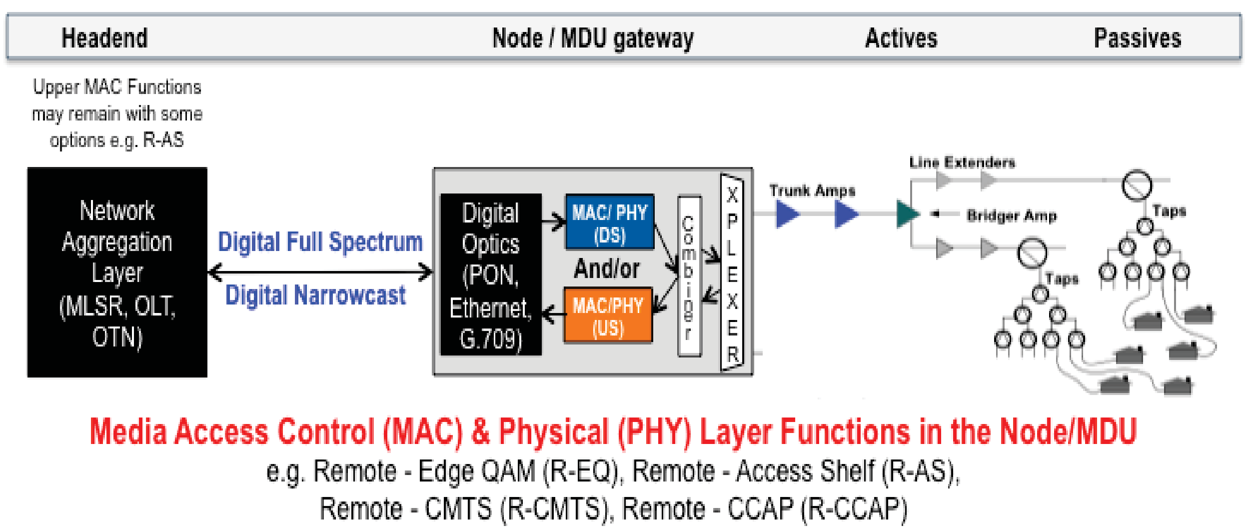


Figure 20: Digital Fiber Coax – Remote MAC/PHY Layer Options

"Two (2) Different" Fiber to the Node (FTTN) Architecture Classes for Cable and Two (2) Different Access Architecture Classes

In this section, we describe the functions of several approaches for fiber to the node (FTTN). The following figures will aid in aligning the definitions with the list of functions; please refer to figures 19 through 20, with emphasis on figure 21.

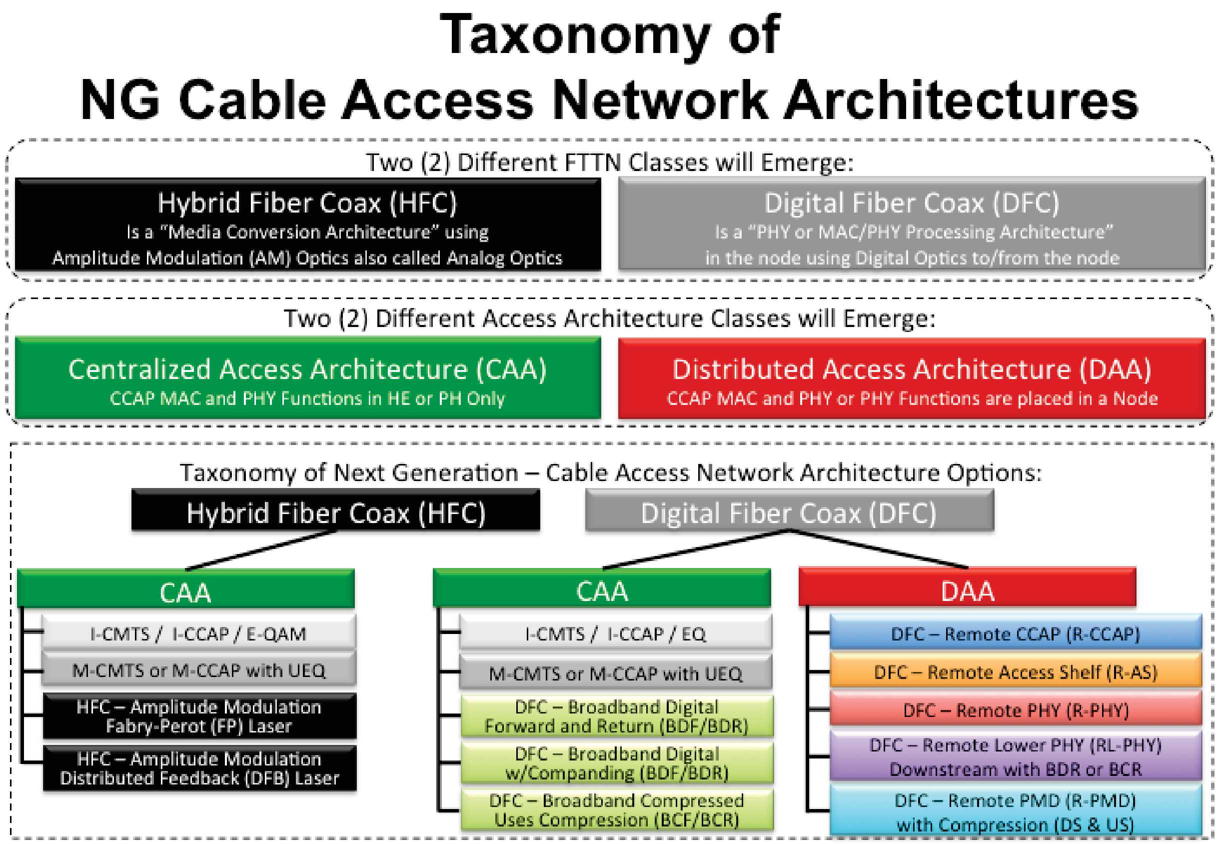


Figure 21 – Summary of Next Generation – Cable Access Network Architecture Options

Hybrid Fiber Coax (HFC) Class of FTTN

1. Optical Amplitude Modulation uses Media Conversion (Optical-to-Electrical or Electrical-to-Optical) allowing for transparency of the RF MAC/PHY technologies. This is what we have used for decades. **Please refer to figures 11, 17 and the Downstream only on figure 18**

Digital Fiber Coax (DFC) Class of FTTN

1. **Broadband Digital:** Assumes a separate optical shelf receiving RF sources from analog video, Edge QAM, CMTS, CCAP, RF Out-of Band, and RF Test equipment. The Broadband Digital equipment receives RF and digitizes the spectrum transported to or from the node.

Key components of this process are the Analog-to-Digital Converter (ADC) and Digital-to-Analog Converter (DAC). This approach allows transparency of the RF MAC/PHY technologies in the outside plant. This is in use today for the upstream called Broadband Digital Return (BDR) and this type of approach may be used in the downstream direction as well called Broadband Digital Forward (BDF). Suppliers may add innovations to reduce the capacity requirements imposed when the analog signal and spectrum is digitized. These are proprietary solutions today but could easily be standardized. This approach is the "only" Remote PHY architecture that maintains the transparency of the underlining MAC/PHY technologies that travels through it and uses digital optics. **Please refer to figure 27**

2. **Remote PMD (R-PMD):** The term PMD refers to the Physical Medium Dependent sub-layer of the PHY that contains the ADC/DAC (Analog-to-Digital or Digital-to-Analog). The PMD layer is part of the CMTS, Edge QAM or CCAP platforms. This is similar to Broadband Digital, however this just removes the PMD layer in the CMTS, Edge QAM or CCAP platform and places this function in the node or MDU location. This type of architecture has not been done in the cable space, but if desired could be called Remote Physical Medium Dependent (R-PMD). We are suggesting the term Remote PMD because this better defines the remote PHY layer that is placed in the node. The cable industry could define a standards based Remote PMD Architecture for the return and forward path similar to that, which was done when the PHY layer was removed from the CMTS in the Modular Headend Architecture (MHA). As in the case with Broadband Digital suppliers may add innovations to reduce the capacity requirements imposed when the analog signal and spectrum is digitized and this could also become standardized. **Please refer to figure 28**

3. **Remote Lower PHY (RL-PHY):** Remote Lower PHY is placed in the node where constellation symbols or groups of constellation symbols are received from the headend to the node lower PHY for modulation. This represents the modulation functions and is sometimes called Remote Mod. Remote Lower PHY is only an option for the downstream and not the upstream. **Please refer to figures 29 and 30**

4. **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 analogues to the Modular Headend Architecture (MHA), but of course different in may ways, such as timing and support for extreme separation of the MAC and PHY layers as well as support for DOCSIS 3.1 would have to be written. This approach could be called Remote PHY Architecture (RPA). **Please refer to figure 31**

5. **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 Remote Access Shelf. 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 32**

6. **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 33**

Downstream DOCSIS and Edge QAM Functional Alignment to Headend and Node Platforms

The figure below captures the downstream DOCSIS and Edge QAM functions. The figure is intended to show the relationship with headend functions defined today and functions that will change in the headend CCAP and the node to support Remote Access Layer Architectures. The red boxes represent node functions and all align with the functions defined on the left of the figure. Please note that the figure above places the Edge QAM MAC functions partially in the PHY layer and this is because all edge QAMs products contain the Edge QAM MAC and the J.83 PHY used for video and DOCSIS. The figure below remove the Edge QAM MAC functions from the PHY and places this alongside the DOCSIS MAC functions see figures 22 and 23.

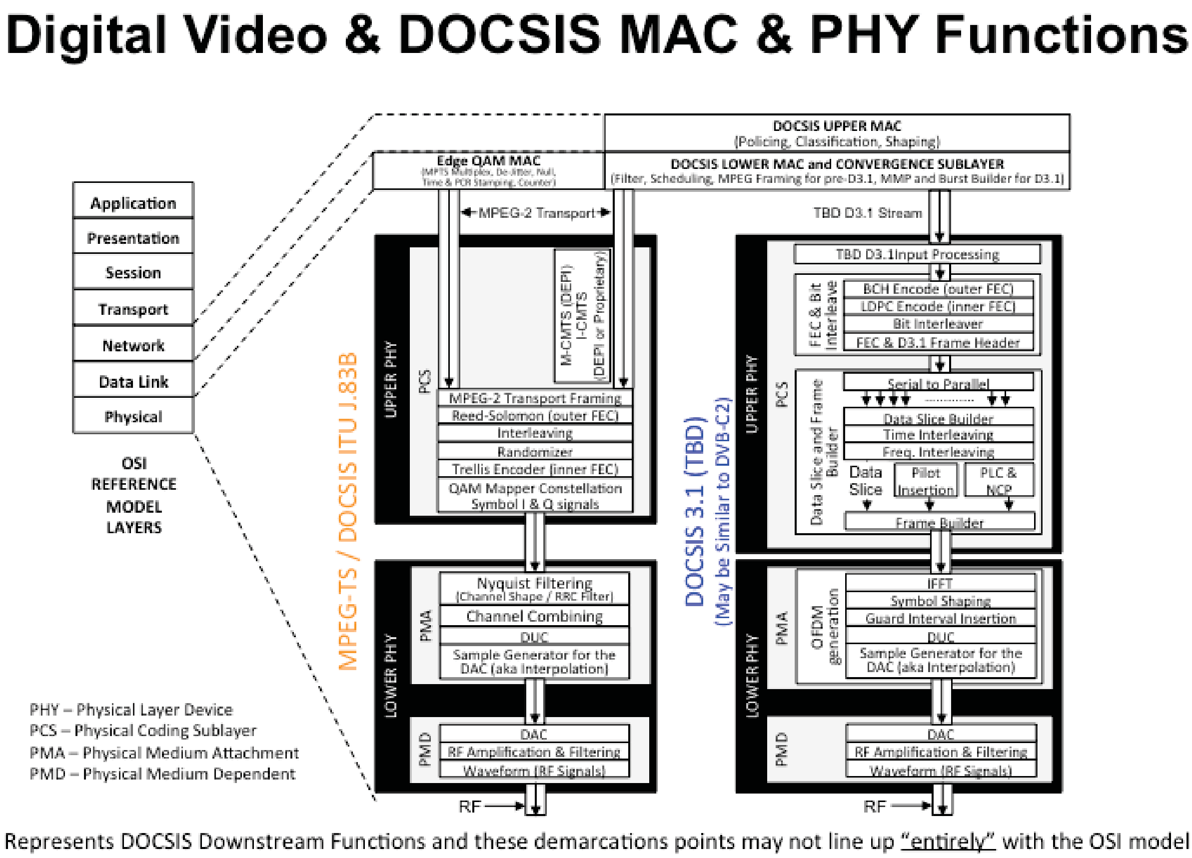


Figure 22: Detailed Digital Video and DOCSIS MAC and PHY Functions for the Downstream

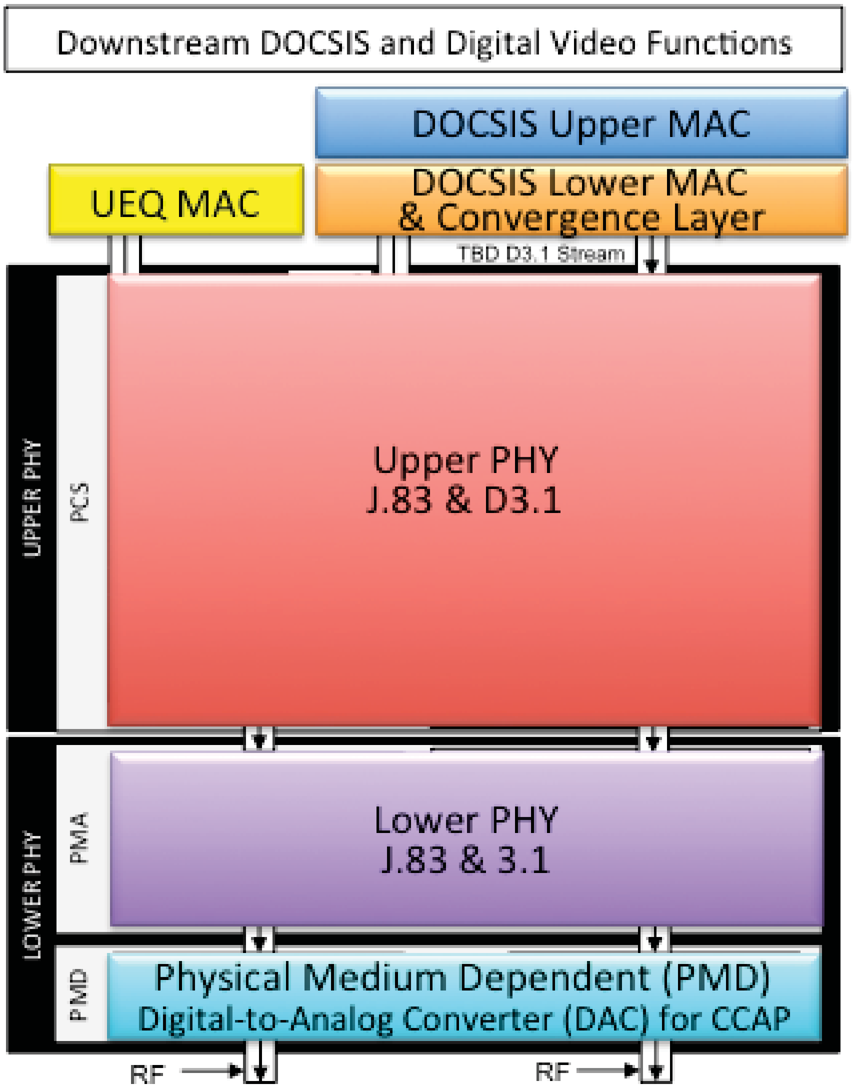


Figure 23: Summary Digital Video and DOCSIS MAC and PHY Functions for the Downstream

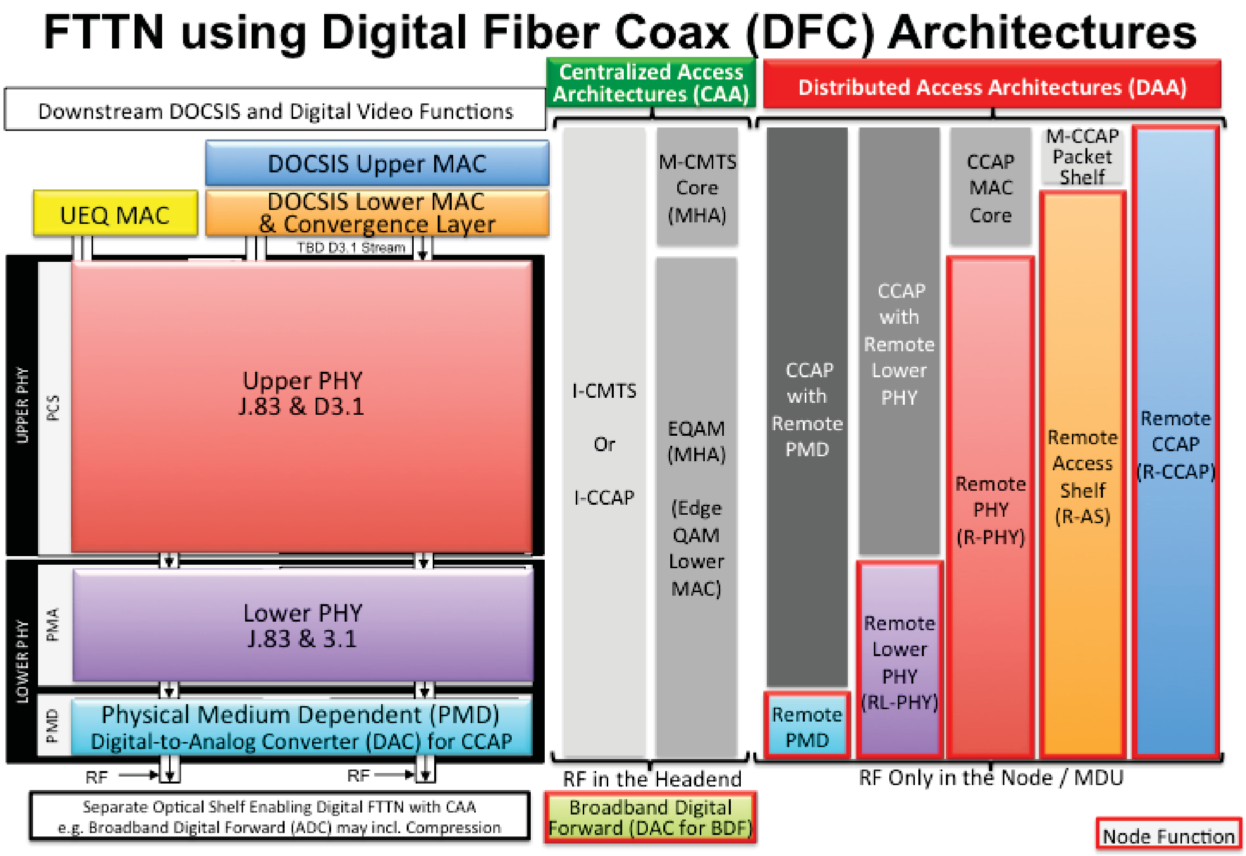


Figure 24: Platform / System Architectures (Headend + Node)
MPEG TS & DOCSIS Downstream

In figure 24, the left side of the figure summarizes the functional layers for downstream DOCSIS and digital video. The right side of the image captures the platform or system architectures, or the network elements and what functions each contain. For example, I-CMTS or I-CCAP has a bar spanning from the top to the bottom of the functional diagram, thus all the functions are in those platforms. Likewise the far right bar, called Remote CCAP (R-CCAP) contains all the function as well, but this has a red highlight around it meaning that this is all in a node housing. The color codes represent the highest layer of function in the node and any of the gray bars represent functions that will remain in the headend. At the top of the bar charts these are group by Centralized Access Architectures (CAA) and Distributed Access Architectures (DAA). Please note that the two Centralized Access Architectures have RF outputs in the headend or primary hub but these may be part of Digital Fiber Coax when a separate optical shelf is used in the headend to enable digital communications to and from the fiber node. In the CAA all of the Edge QAM, CMTS, or CCAP functions and network elements remain intact maintaining the MAC and PHY layers in the headend. The DAA distributes the entire MAC and PHY functions "or" may distribute portions of the CCAP to the node keeping the remainder in the headend, thus in DAA there is no CCAP RF ports in the headend.

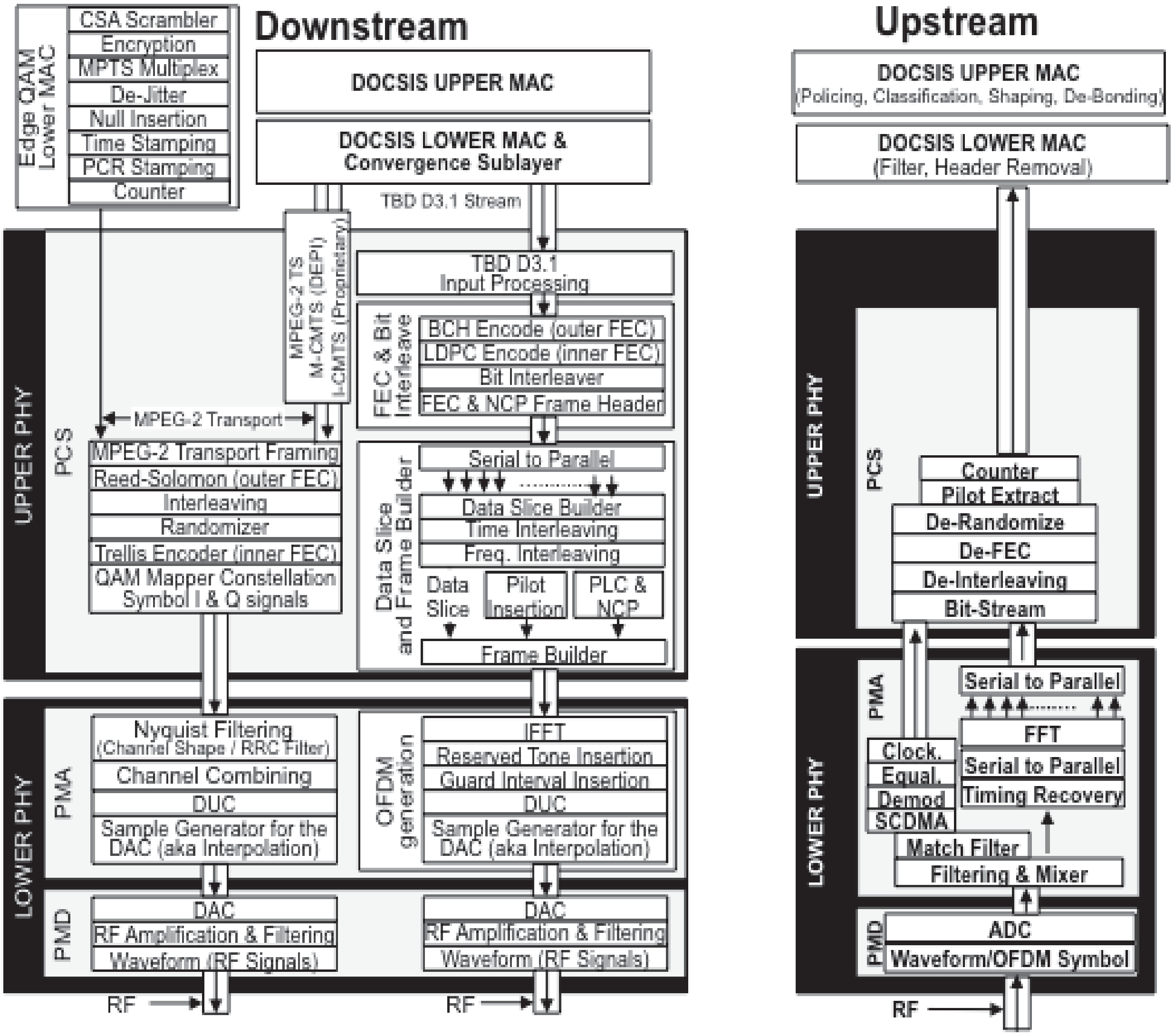


Figure 25: Functional Review of the RF MAC/PHY Layers Downstream and Upstream

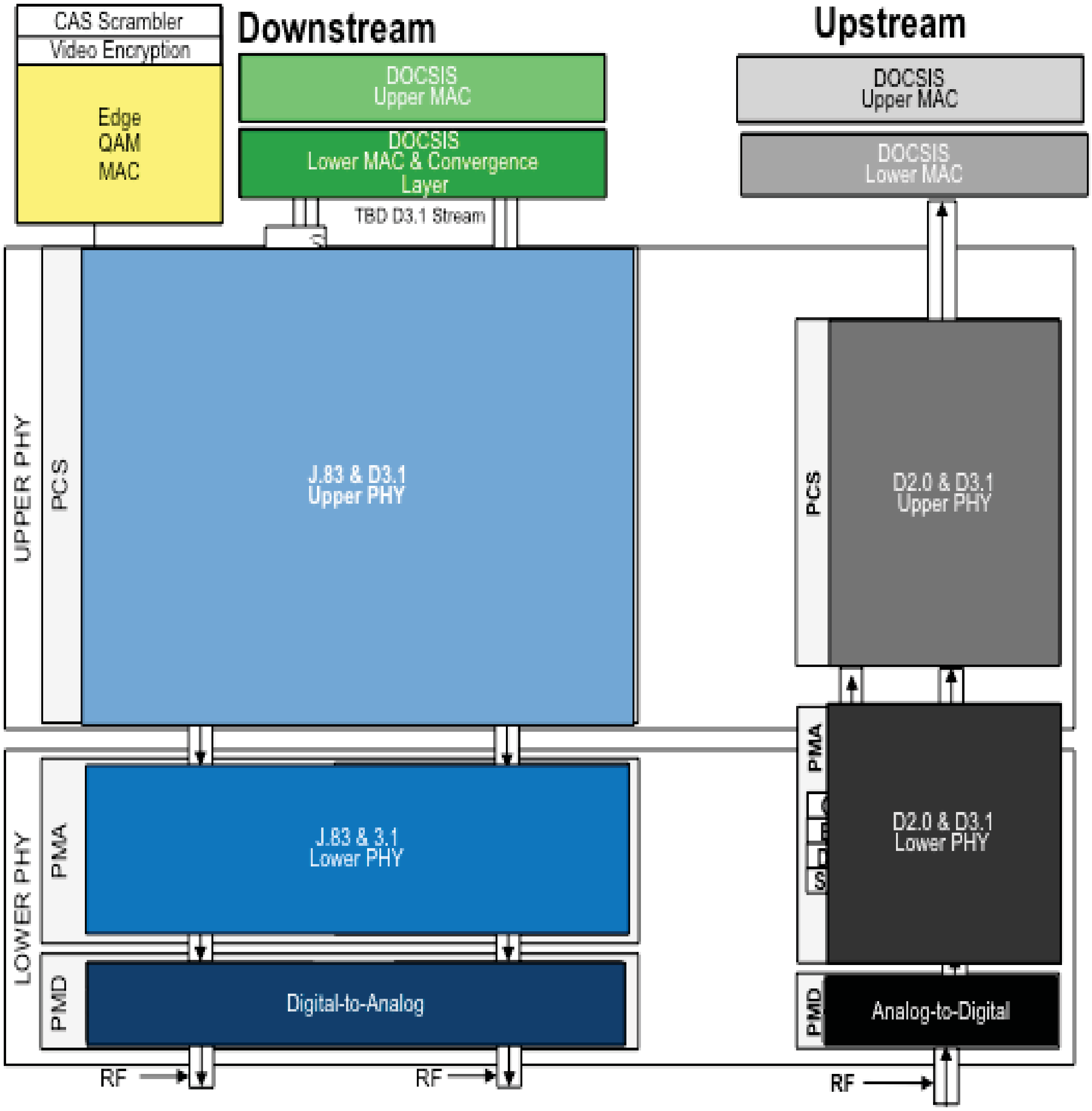


Figure 26: Simplified View of the RF MAC/PHY Layers Downstream and Upstream

These fundamental building blocks as illustrated above may serve as demarcation for functions that may be kept in headend platforms and those placed in Node or MDU locations. The next section takes these blocks and moves them to headend or node locations to illustrate the different architectures that may exist in the future to enable Digital Fiber Coax (DFC).

Example Platform and Network Architectures

Broadband Digital Return and Forward Architecture

In figure 27 please refer to the definition above called "Broadband Digital" above but as far as a brief description Broadband Digital Return and Forward will be a separate optical shelf that interfaces with devices with RF ports and digitizes the signals between the headend and node. Today, Broadband Digital is used only for the return path. In the figure the I-CCAP has all functions for video, DOCSIS J.83, DOCSIS 2.0, and DOCSIS 3.1 all in a single platform, however a MHA could have been used with RF outputs in the headend. The key point for Broadband Digital is that RF interfaces remain in the headend and these devices interface with an optical shelf that enables a digital connection between headend and node. Like Amplitude Modulated (AM) optics used in HFC, Broadband Digital is completely transparent.

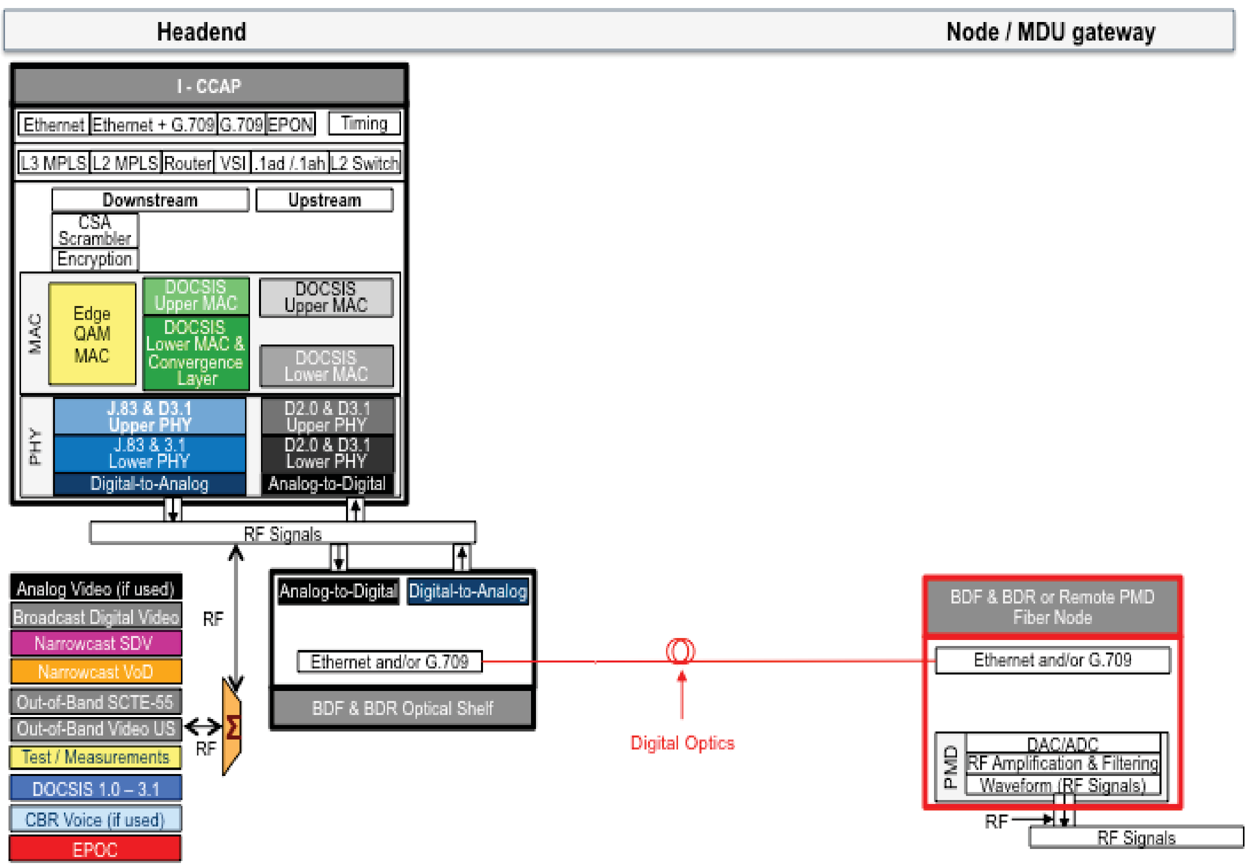


Figure 27: Broadband Digital Return and Forward Architecture

Remote PMD Architecture

In figure 28 please refer to the definition above called "Remote PMD (R-PMD)". In this architecture the term PMD refers to the Physical Medium Dependent sub-layer of the PHY that contains the ADC/DAC (Analog-to-Digital or Digital-to-Analog). The PMD layer is part of the CMTS, Edge QAM or CCAP platforms. This is similar to Broadband Digital, however this just removes the PMD layer in the CMTS, Edge QAM or CCAP platform and places this function in the node or MDU location.

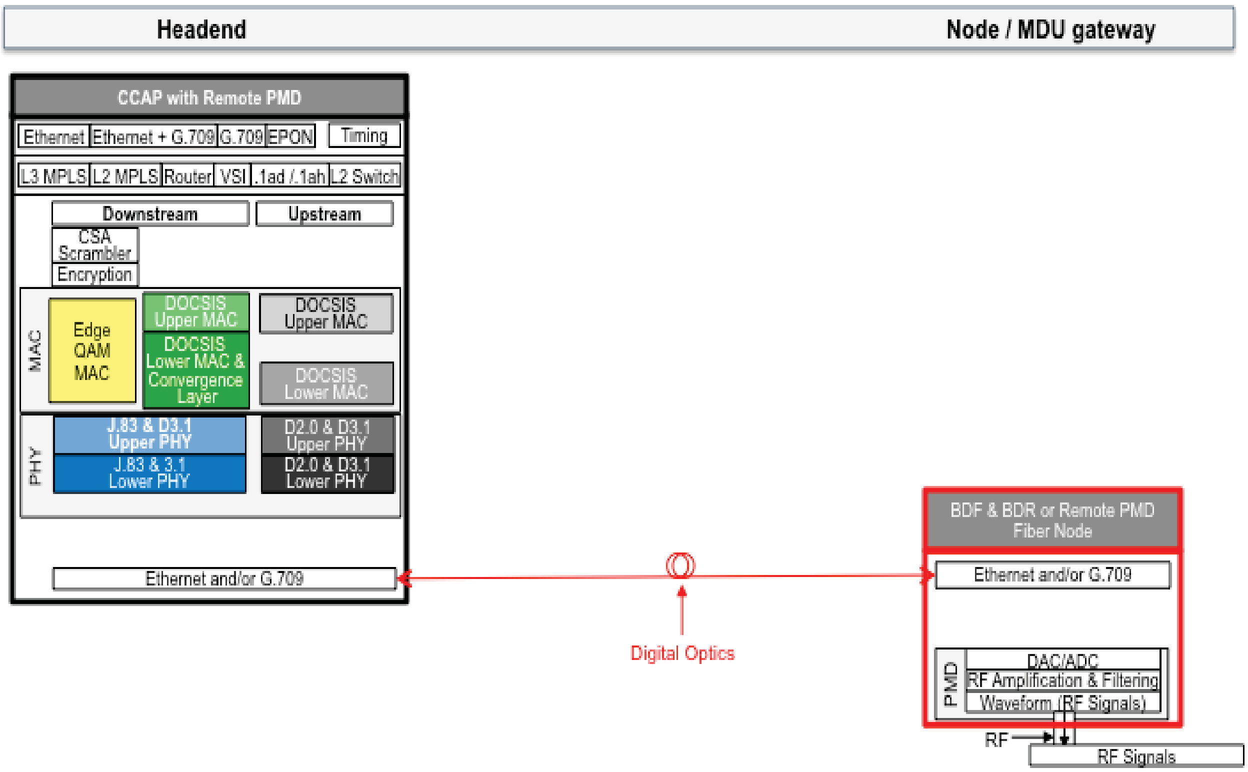


Figure 28: Remote PMD Architecture

Remote Lower PHY (RL-PHY) Architecture

In figures 29 and 30 please refer to the definition above called "Remote Lower PHY (RL-PHY)". These represent two different architectures to implement Remote Lower PHY. As with Remote PMD a portion of the PHY is removed from the headend and placed in the node location.

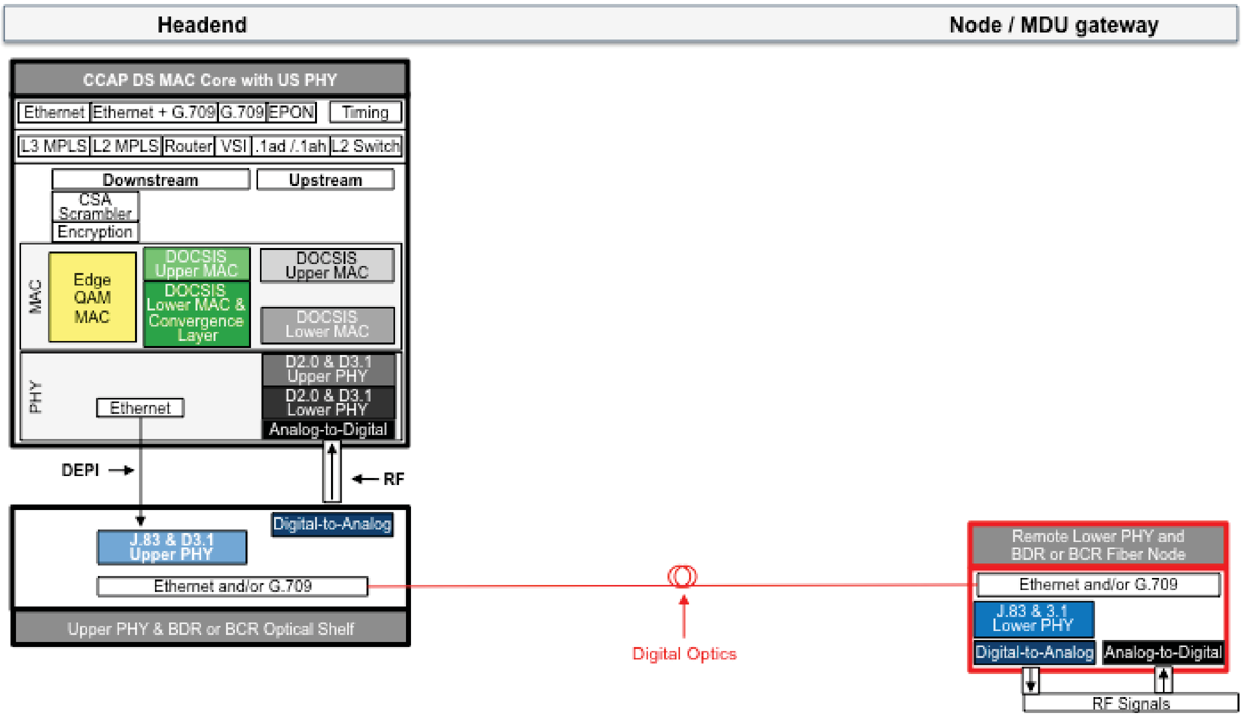


Figure 29: Remote Lower PHY and BDR Separate Headend Optical Shelf Architecture

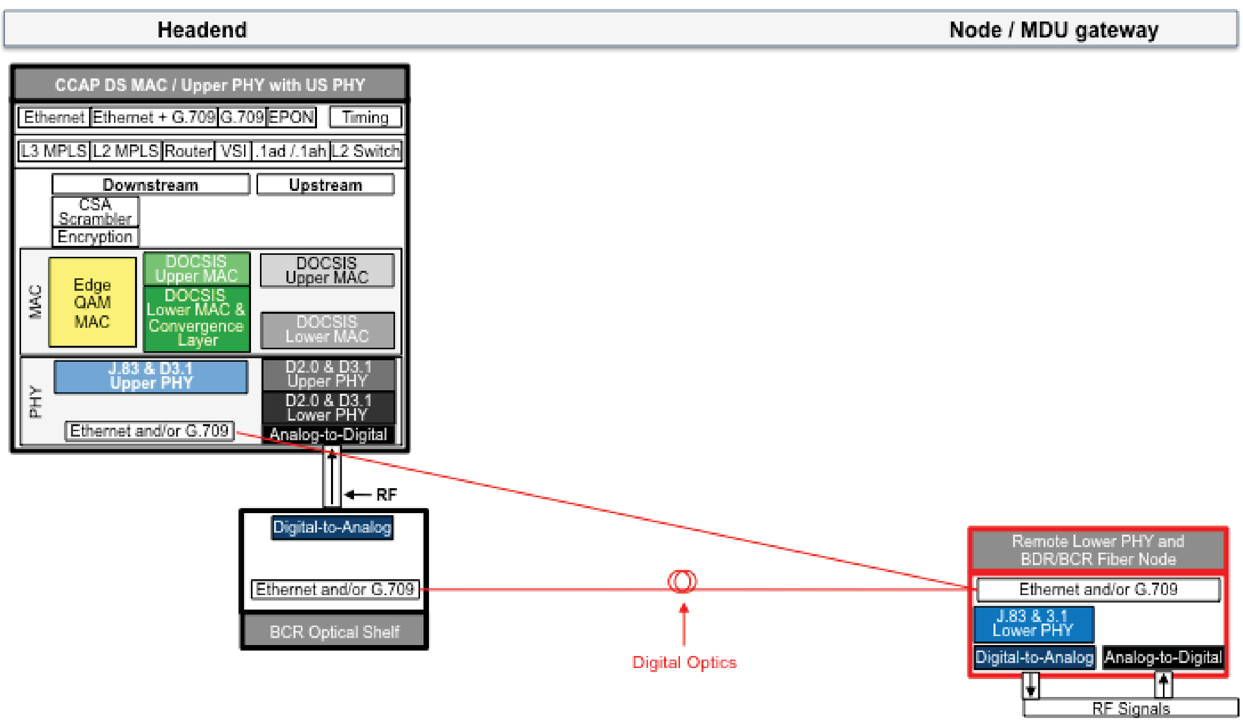


Figure 30: Remote Lower PHY CCAP and BDR Separate Headend Optical Shelf Architecture

Remote PHY (R-PHY) Architecture

In figure 25 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.

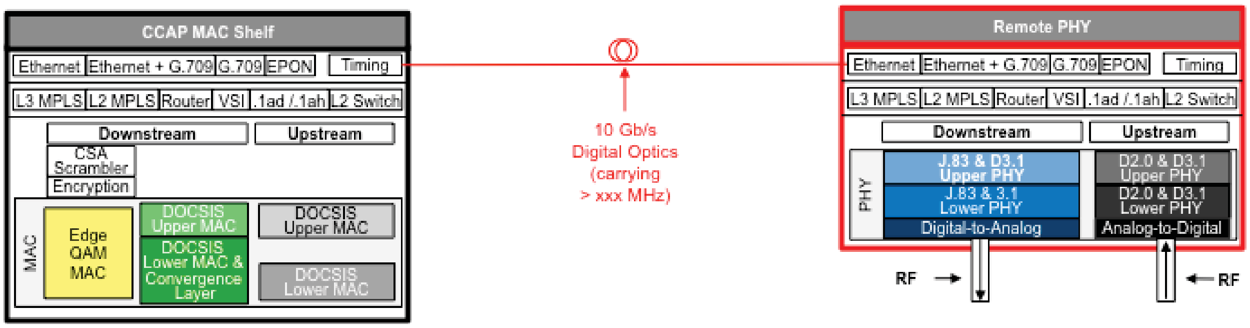


Figure 31: Remote PHY Architecture (RPA)

Remote Access Shelf Architecture

In figure 26 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.

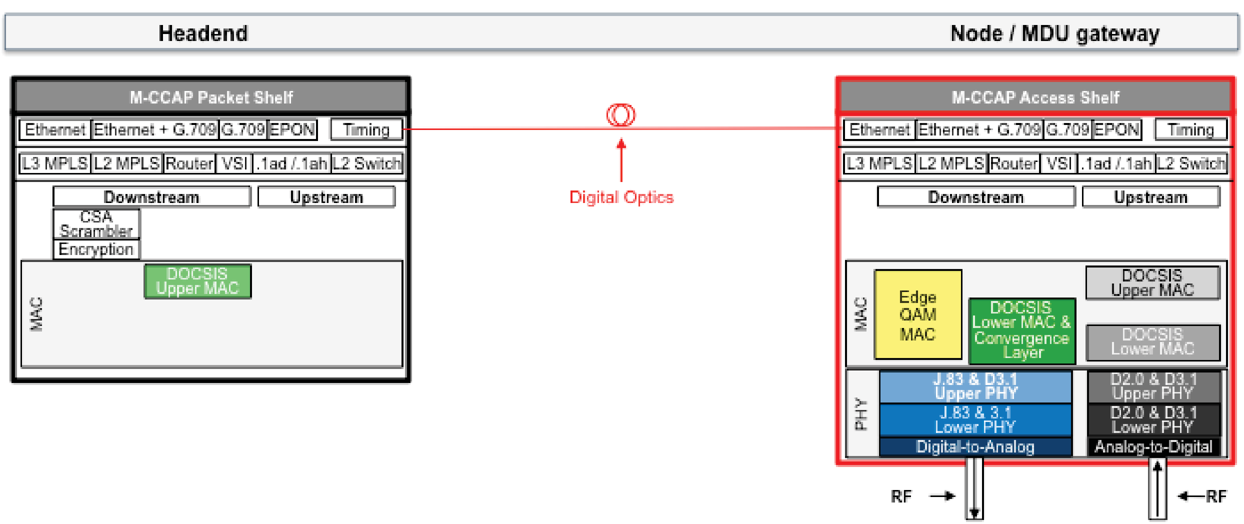


Figure 32: Remote Access Shelf (R-AS) Architecture

Remote CCAP Architecture

In figure 32 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.

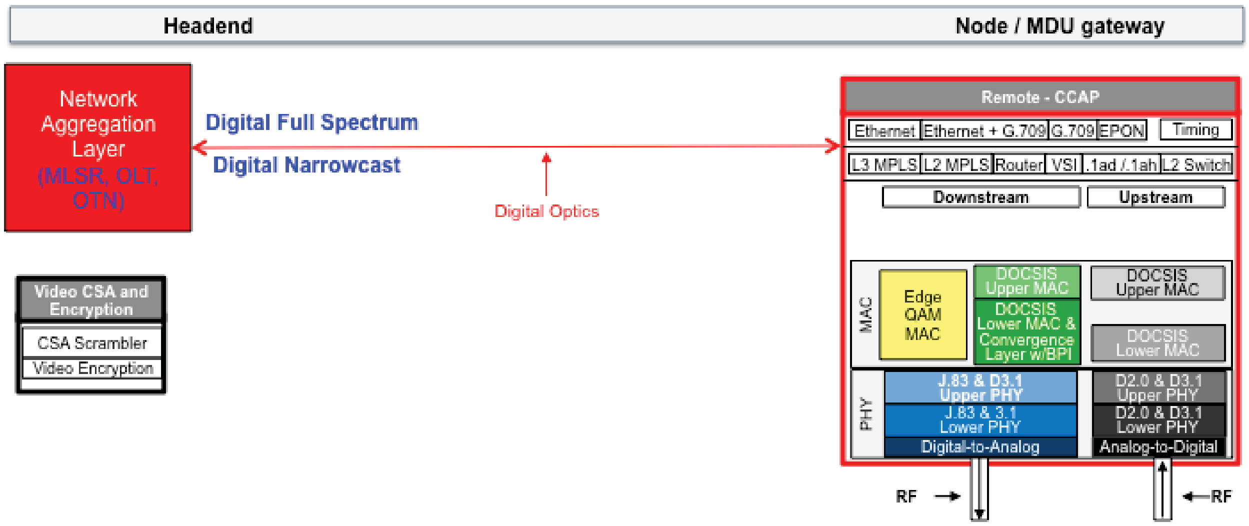


Figure 33: Remote CCAP (R-CCAP) Architecture

Conclusions - A New Era in Cable Networking Called Digital Fiber Coax (DFC)

The drivers and summaries for Digital Fiber Coax are as follows:

- Maximizing Coaxial Segment Revenue Spectrum Capacity (b/s/Hz)
  - DFC maximizes b/s/Hz without lambda, distance, spectrum location and spectrum size limitations which are all found with AM optics
  - DFC with CAA or DAA will increase modulation (b/s/Hz) regardless of frequency
- Maximizing Optical Segment Wavelength Capacity
  - Digital Optics Maximizes Optical Segment Wavelength Capacity (3 to 4 times AM Optics Wavelength capacity
- Enabling Facility Consolidation & Managing Space/Power/Conditioning
  - DFC exceeds HFC-AM optics reach enabling consolidation (DOCSIS 160km limiting factor)
  - Remote MAC/PHY enables consolidation (no DOCSIS distance limit)
  - Very Small DOCSIS & Unicast Service Groups drives Space / Power / Conditioning

  - Removing RF from the headend reduces Space & Power (but places complexities in OSP)
  - Full spectrum CCAP saves Space / Power / Conditioning
- DFC in a Centralized Access Architecture (CAA) has the benefits of Digital Optics while not placing or separating the CCAP MAC / PHY in the node

The use of Digital Forward and Return may place the lowest layer of the PHY in the node, like the ADC and DAC to the entire PHY and may also place the entire MAC and PHY in the node. It is too early to tell which Remote Access Layer architecture is best to enable digital optics. It should be noted that AM optics will support high order modulations in the majority of MSO FTTN applications today, but there are limitations. The use of digital forward and return independent of which architecture may not be desired or used by all MSOs and even within an MSO. Further industry research is needed to determine the best DFC architecture.

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Network Capacity

The network capacity of the cable access network is determined by the amount of spectrum available and the data rate possible within the spectrum. The modern cable network is incredibly flexible allowing the MSO to make targeted investments where and when needed to either incrementally or in some cases substantially increase network capacity depending on the capacity expansion method selected. The use of capacity expansion methods may be applied across an entire network footprint or with laser beam focus to address capacity challenges.

The most critical determination for the capacity of the network is the amount of spectrum available. The determination of the downstream capacity will assume the eventual migrations to an all IP based technology. The migration to all IP on the downstream which will optimize the capacity of the spectrum providing the versatility to use the network for any service type and provide the means to compete with PON and the flexibility to meet the needs of the future.

In figure 34 below estimate the data rate for downstream minus PHY and MAC overhead for the DOCSIS 3.0 using the max 256 QAM and DOCSIS 3.1 using 4096 QAM. The figure measures megabits per second DOCSIS 3.0 vs. DOCSIS 3.1 (4096 QAM) minus 25% overhead.

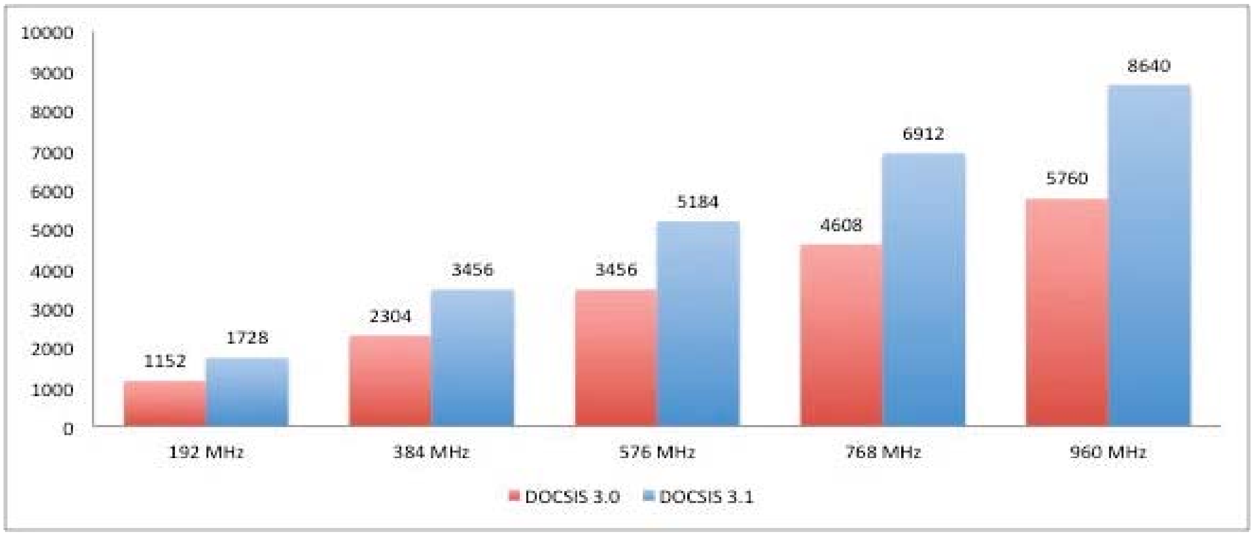

Figure 34 – DOCSIS 3.0 vs. DOCSIS 3.1 (4096 QAM) Minus 25% Overhead

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Network Utilization and Capacity Planning

If you are wondering how long a spectrum split may last or the sizing of the service group in the downstream or upstream this sections will provide some estimates for consideration. In this section of the report the network utilization estimates and capacity planning forecasts are examined. This section will predict the year and potential driver for network change. The information found in this section will be based on the findings of the preceding sections, which forecasted the service usage for video and High-Speed Internet as well as network usage on a per-subscriber basis. Additionally this section will use the network capacity estimates for the downstream and upstream.

An important attribute of cable systems is that the HFC optical and RF network as well as the data access layer network like the DOCSIS CMTS allows for upstream and downstream capacity upgrades may be made separately, where and when needed per service group. The report separates the utilizations and capacity planning results for the downstream and upstream to take advantage of this key feature. A key factor for the calculations will be the service tier growth forecast and the per subscriber usage, which have been separated as well. As stated previously these are just predictions and there are many factors that may influence change and the rate of change, so these findings should just be used for discussion purposes only.

The Downstream

The downstream network capacity drivers will be separated into High-Speed Internet Max Service Tier "plus" Data Service Group Traffic "plus" Video Traffic Predictions should all be included in the Estimated Bandwidth per Service Group.

Capacity Planning for High-Speed Internet Max Service Tier plus Data Traffic Per Service Group

The downstream High-Speed Internet service tier growth from 2010 through 2030 is estimated and direction is used to forecast the date when the downstream may be at capacity see figure 35. The HFC downstream capacity assumptions will use several reference points, these include, 192 MHz, 384 MHz, 576 MHz, 768 MHz and 960 MHz of usable DOCSIS downstream spectrum. These measure the capacity of DOCSIS 3.0 using 256 QAM and DOCSIS 3.1 using 4096 QAM. These assumes High-Speed Internet Max Service Tier "and" Traffic continues at a 50% CAGR. It again should be stated that these are just prediction for the next decade or more, it is uncertain if growth for either or both will continue at this pace.

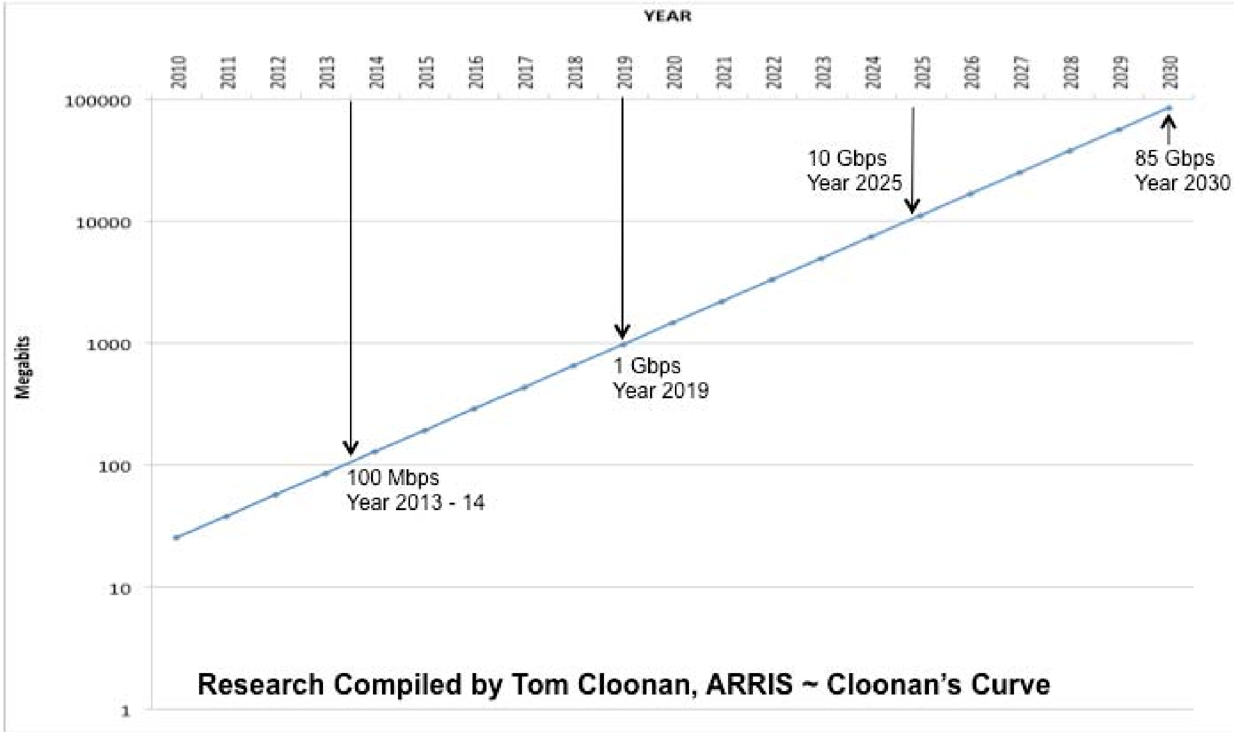

Figure 35: Nielsen's Law of Internet Bandwidth Time Periods From 2010 to 2030

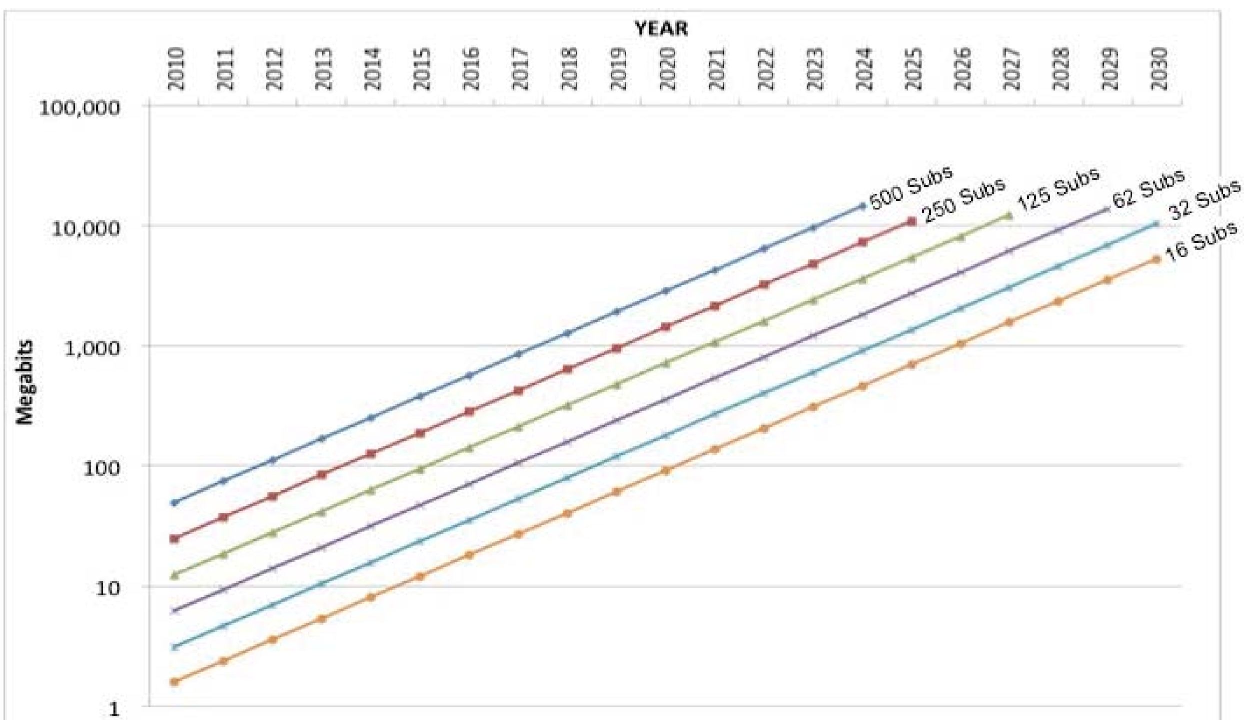

Figure 36: Estimated Traffic Per Service Group at 50% CAGR From 2010 to 2030

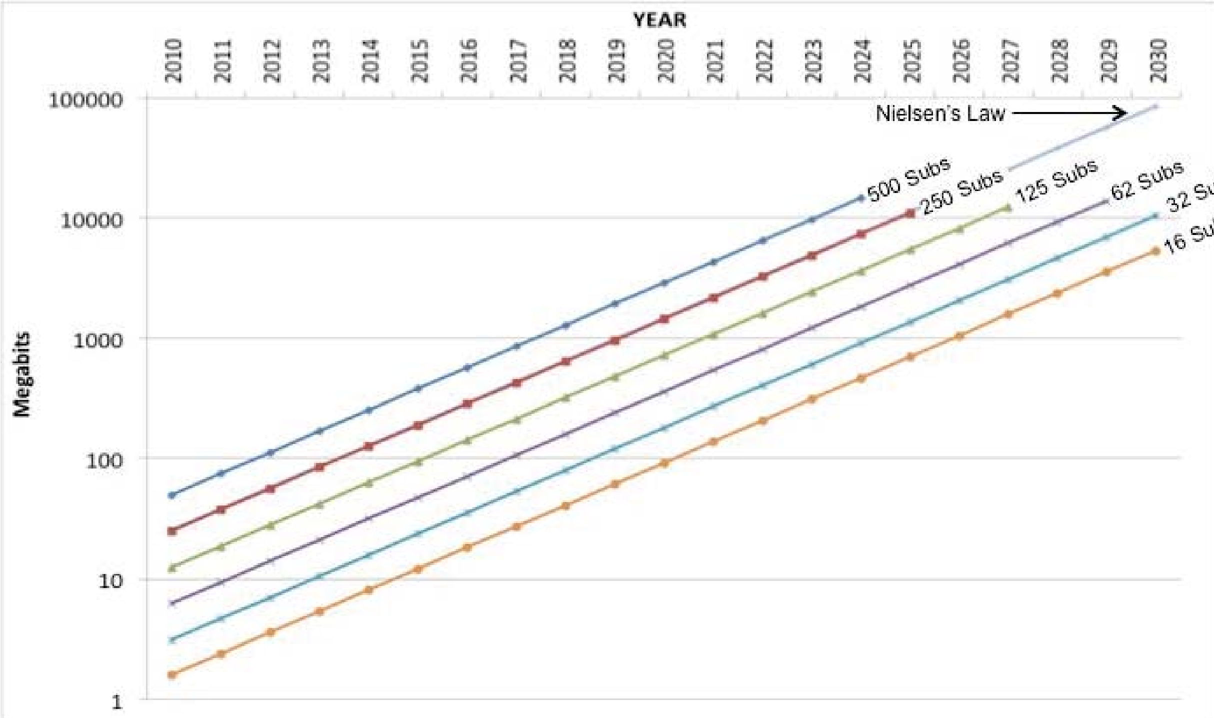

Figure 37: Nielsen's Law with Traffic Per Service Group Estimates 2010 to 2030

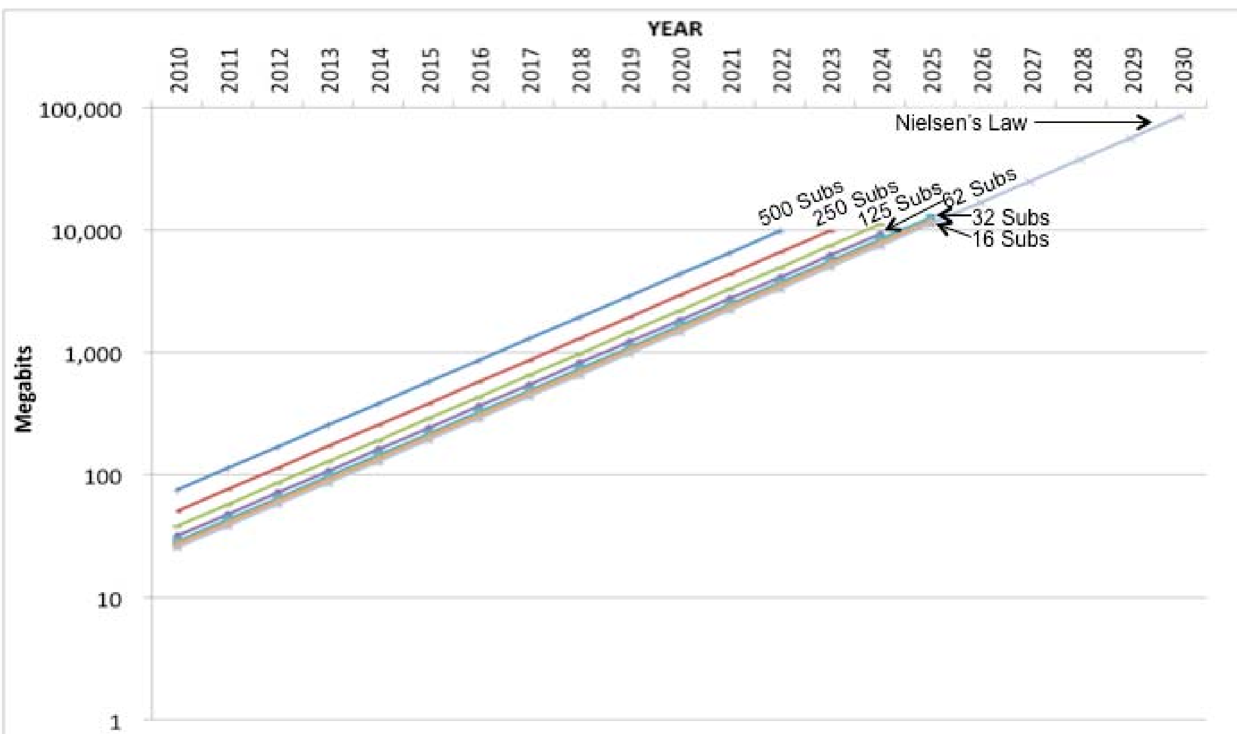

Figure 38: Nielsen's Law "Plus" Traffic Per Service Group 2010 to 2030

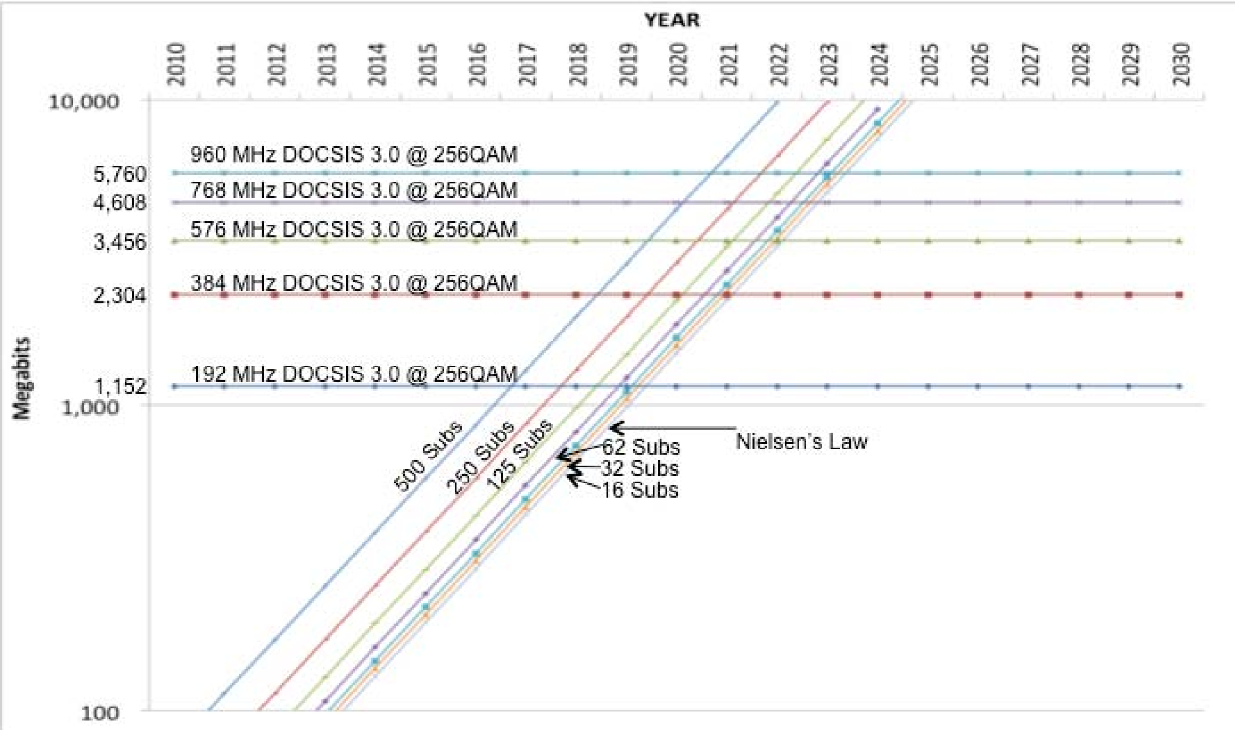

Figure 39: Nielsen’s Law “Plus” Traffic Per Service Group D3.0 Capacity Estimates

Nielsen's Law "Plus" Traffic Per Service Group
DOCSIS 3.1 & Digital Forward Capacity Estimates

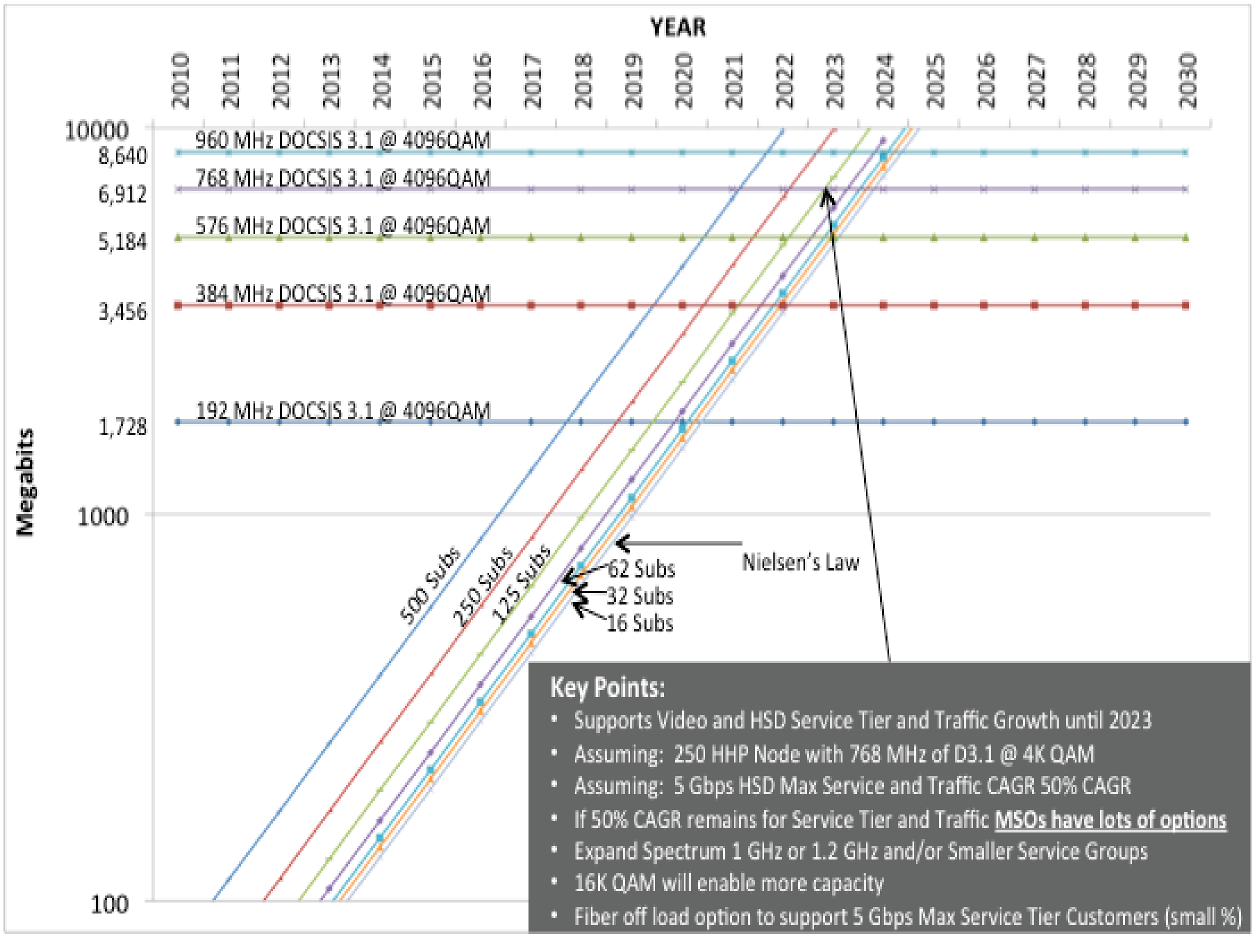

Figure 40: Nielsen's Law "Plus" Traffic Per Service Group DOCSIS 3.1 & Digital Forward Capacity Estimates

There are several contributing factors used to forecast the capacity for a service group. They include, the size of the service group, take rate of the services, estimated per subscriber data usage, and the allocation of capacity for an MSO managed video service offering. The model defines a service group as a collection of HHP beginning at 1,000 HHP to 32 HHP. We use the model projections from the earlier section and apply the capacity capabilities of the 750 MHz, 1000 MHz and 1250 MHz system and the Sub-split, Mid-split, and High-split spectrum that is removed. The estimated bandwidth per service group is a measurement based on the high-speed Internet Downstream traffic CAGRs, at 50%. Please see figure 40 as this represents the combination of figures 35 through 38, which uses the combination of Nielsen's Law "plus" Traffic per Service Group for the estimated service capacity. The horizontal lines represent spectrum allocation and modulation to determine the network capacity. Figure 40 captures the key points in the box at the bottom right.

CCAP Enabling an Uncertain Network Spectrum Allocation

In the preceding sections the paper highlighted the legacy RF technology based on ITU J.83 PHY supporting MPEG-TS for Video and DOCSIS versions through 3.0. The paper justified the drivers for DOCSIS 3.1 to harness more b/s/Hz of current and existing spectrum. The paper illustrated the versatility of Amplitude Modulated Optical technology and Broadband Digital Technology to transparently carry different technologies. The paper provided cases whereby digital optics in some cases could enable high order modulation found in DOCSIS 3.1 and other benefits of digital optics. The headend based CCAP may work over AM optics or Broadband Digital optics.

In this section of the paper we are predicting the allocation of DOCSIS capacity estimates and the use of DOCSIS 3.0 and DOCSIS 3.1. MSOs must also support video services as well and this spectrum mix may changes of time but this really is hard to predict. As seen in figure 41 the spectrum allocation between MPEG-TS and DOCSIS will change over time and CCAP may enable this transition.

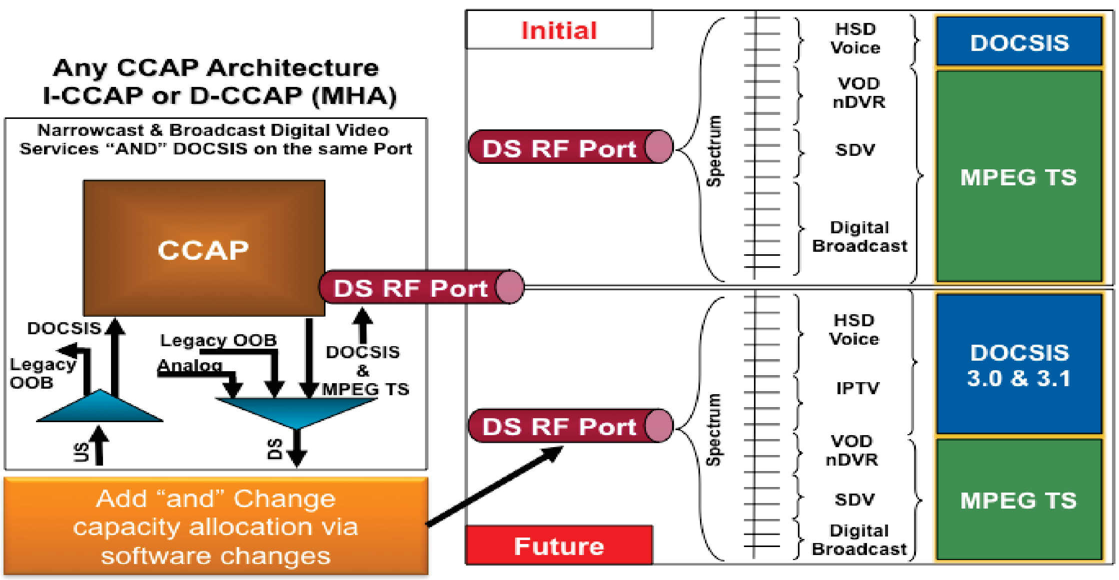

Figure 41 – CCAP Enabling an Uncertain Network Spectrum Allocation

CCAP Enabling the Best Migration Strategy

- **Same Port Supports MPEG-TS "and" DOCSIS**
    - MPEG TS (digital video, switch digital video (SDV), and VoD)
    - DOCSIS (1.0, 1.1, 2.0, 3.0, and 3.1)
- **Future CCAP using MPEG-TS and DOCSIS enables**
    - One Access Layer platform for all services

   - The creation of larger and larger DOCSIS / IP bonding groups with each year's investments
   - Allows a channel-by-channel migration from MPEG TS to DOCSIS "without" changing the headend access layer ports and even the CPE (Hybrid MPEG TS and DOCSIS gateway).
- **Full Spectrum CCAP will reduce space and power requirements in the headend**
- **CCAP in the headend may support AM optics and/or Broadband Digital Optical architectures**

Summary of Network Utilization and Capacity Planning

It is very important that the reader understands that our assumptions use subscribers per service group and that the estimated Nielsen's Law estimates are added together to determine the long term capacity needs as seen in figure 40. The paper highlights DOCSIS 3.0 and DOCSIS 3.1 capacity estimates and the capacity needs of Subs per SG "plus" Nielsen's Law support for max service tier. As stated several times in the paper, these are estimates and if the 50% CAGR for Nielsen's Law for Maximum Service Tier "plus" subscribers per service group traffic.

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Next Generation - Fiber to the Home (FTTH) Era

The Next Generation - Fiber to the Home (FTTH) era capacity of emerging NG-PON technologies: 1) OFDM over RFoG, 2) IEEE 10G EPON, and 3) ITU-T 10G-PON (XG-PON). The Wavelength Division Multiplexing – Passive Optical Network (WDM-PON) was not modeled because this uses Point-to-Point (P2P) Optical Ethernet and Wavelength to the Home (WTTH) the capacity may vary from 100 Mbps to 10 Gbps. What was observed in figures 42 through 44 is that the share media technologies of 10G EPON and DOCSIS 3.1 with 1 GHz or 1.2 GHz along with High Spit meets of exceeds the capacity 10G x 1G EPON which would like be used for FTTH application. When the shared media technologies like CTTH with DOCSIS, RFoG with DOCSIS 3.1, and EPON are all exhausted the MSOs could move to Wavelength Division Multiplexing – Passive Optical Network (WDM-PON). The transition plan is illustrated in the figure below.

The figures also estimate the PHY layer data rate with FEC for the DOCSIS 3.1 as well as the Fiber to the Home (FTTH) technologies such as EPON, 10G x 1G EPON, GPON, and Next Generation RFoG assume spectrum of 1750 MHz plus downstream at 1024 QAM and 350 MHz plus upstream at 1024 QAM.

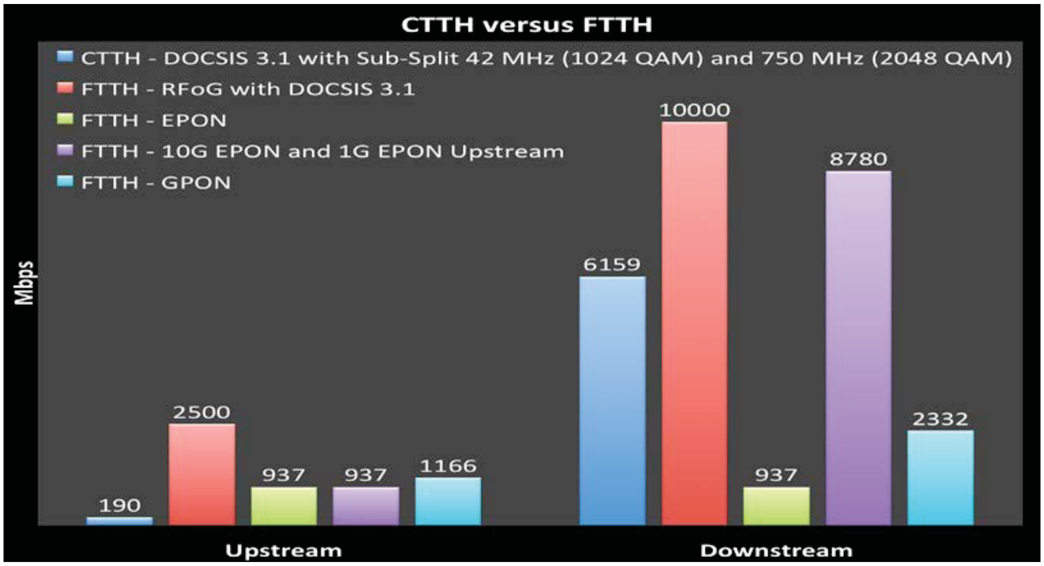

Figure 42 – 5-42 Sub-split and 750 MHz DOCSIS 3.1
vs. Alternative Access Layer Technologies

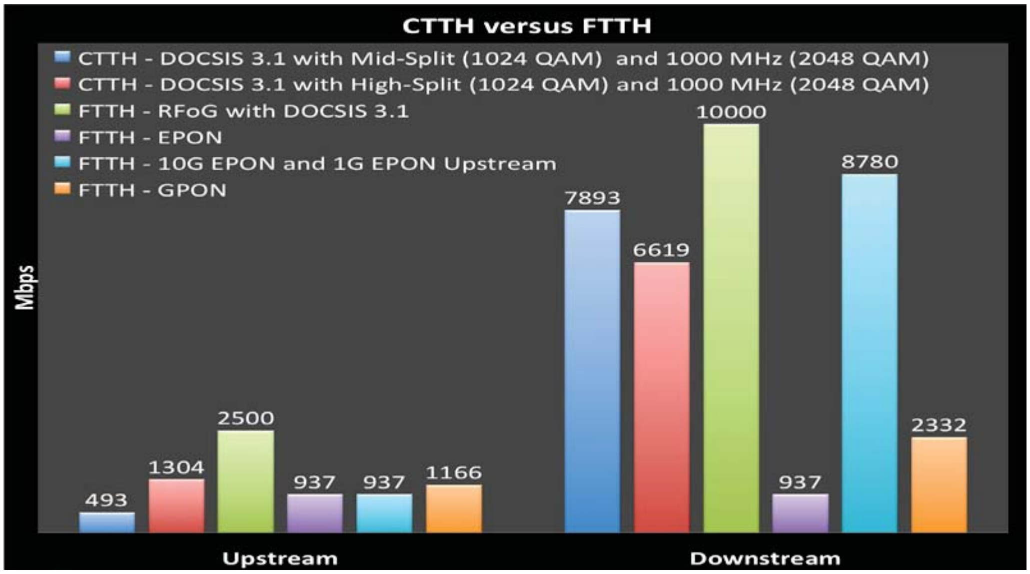

Figure 43 – Mid-split with 1000 MHz and High-split with 1000 MHz DOCSIS 3.1 vs. Alternative Access Layer Technologies

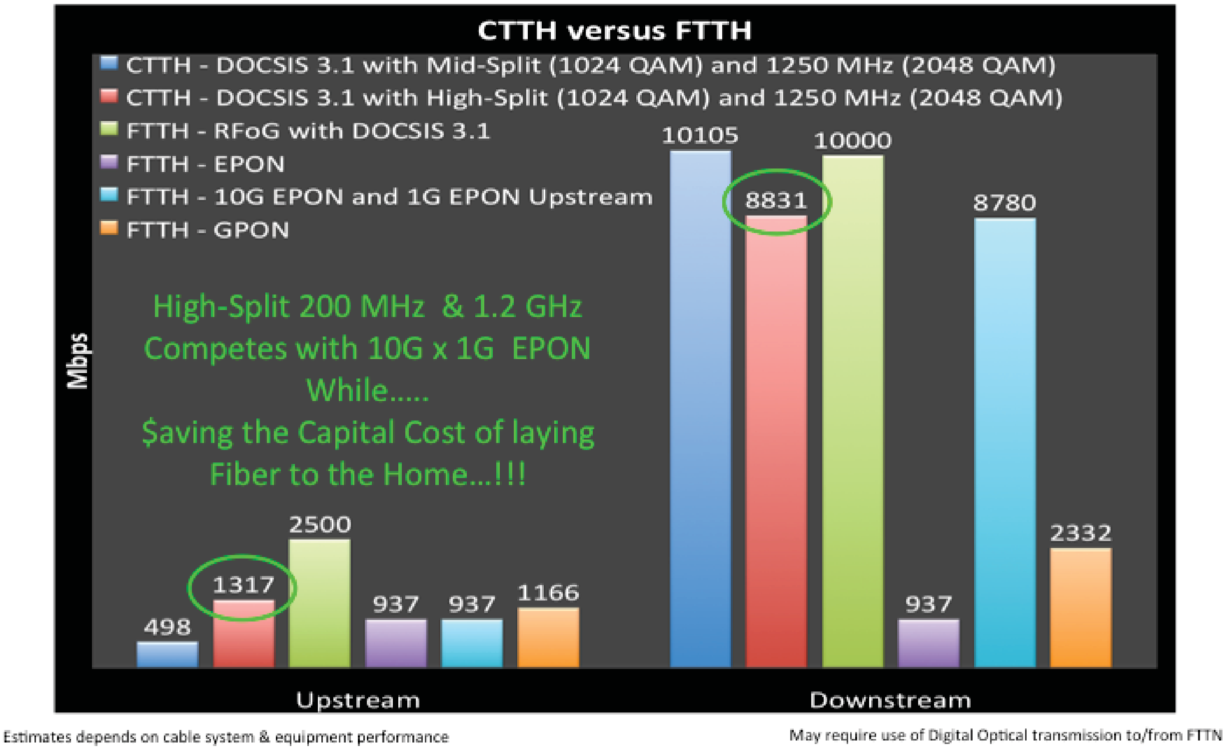

Figure 44 – Mid-split with 1250 MHz and High-split with 1250 MHz DOCSIS 3.1 vs. Alternative Access Layer Technologies

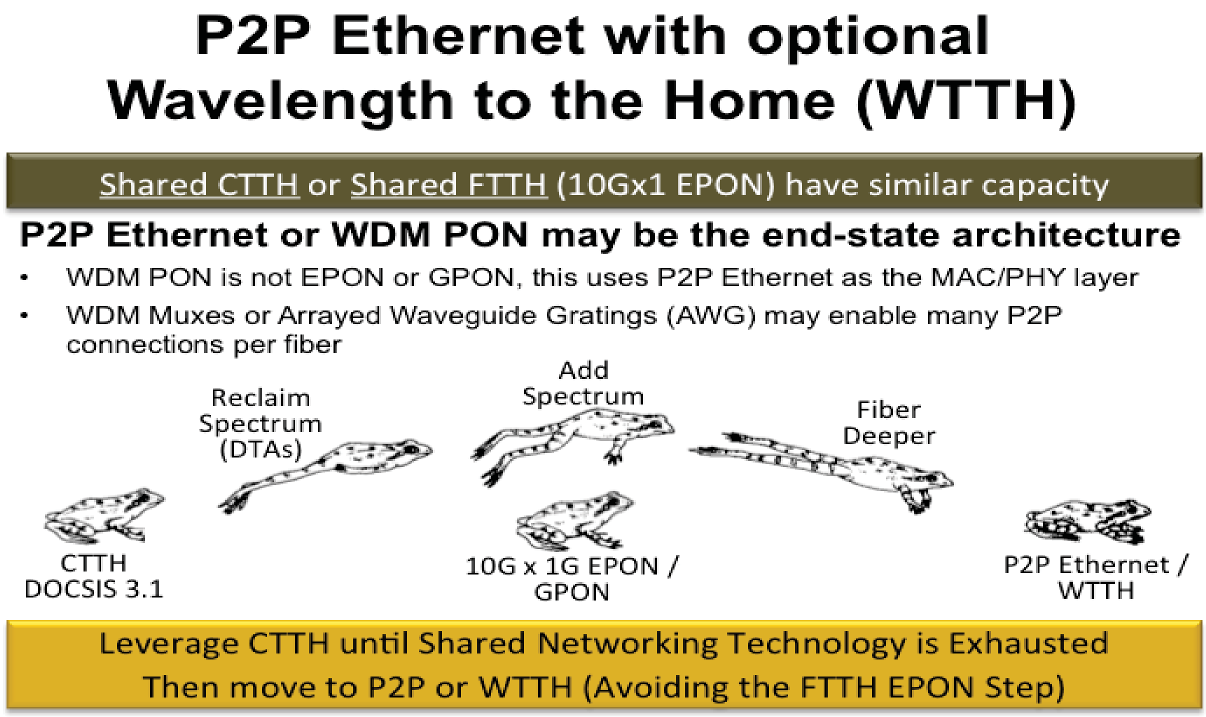

Figure 45: CTTH to P2P Ethernet with optional Wavelength to the Home (WTTH)

We believe there are two-deployment scenarios serving fiber to the home (FTTH): 1) New Build -Greenfield and 2) Legacy Transition. The legacy transition is mention above and as far new build, once IPTV is deployable MSOs will utilize EPON. New build represents a low per cent of the overall MSO HHP, perhaps this is 1% per year. Additionally, residential subscribers needing or requesting services tiers out sided the current DOCSIS capacity limits account for far less that 1% of all High-speed Data subscribers. Thus, the demand for extremely high or full spectrum DOCSIS allocation is in the next decade.

The paper suggests that CTTH DOCSIS 3.1 compared with other shared media technologies like GPON and EPON 10G x 1G will have similar capacity levels, and thus MSOs should stick with their existing coax until share media capacity runs out. Then move the P2P Ethernet technology like perhaps WDM PON of Wave Length to the Home (WTTH).

This paper suggests the MSO migration strategy could be:

1. CTTH Using DOCSIS 3.1
2. Reclaim Spectrum (DTAs)
3. Consider DOCSIS 3.1 Modem swap out expand upstream capacity (and downstream)
4. Add Spectrum (Move to 1 GHz or 1.2 GHz)
5. Fiber Deep (Place more nodes in existing serving area to reduce service group size)
6. P2P Ethernet with dedicated fiber or use WDM PON for Wavelength to the Home (WTTH) and P2P Ethernet.

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CONCLUSIONS

The key takeaways for extracting more capacity and the Evolution of Cable Access Technologies and Network Architectures for this decade and beyond may be summarized.

Next Gen – Coax to the Home (CTTH) Data Technology Era

- "Current" DOCSIS Data Technology limits capacity based on old PHY technology
- **Solution: DOCSIS 3.1 Era New PHY & Higher Modulations increases b/s/Hz**

Next Gen – Fiber to the Node (FTTN) Digital Fiber Coax (DFC) Era

- Uses Digital Optical Technology "and" has New Access Architecture Options for FTTN
- DFC uses Digital Optics for FTTN (to/from) in either a Centralized Access Architecture (CAA) "or" a Distributed Access Architecture (DAA)
- "Current" HFC Amplitude Modulation (AM) FTTN Optical Technology limits D3.1 network capacity (b/s/Hz) in some cases (e.g. long fiber spans & high-split)
- **Solution: Digital Fiber Coax (DFC) Era maximizes D3.1 b/s/Hz and lambdas**
  - DFC used where/when/if needed (analog optics meets needs in many cases)
  - DFC uses Digital Optical Technology "and" supports "either" a Centralized Access Architectures (CAA) "or" a Distributed Access Architecture (DAA)

Next Gen – Fiber to the Home (FTTH) Era

- Shared CTTH (D3.1) or Shared FTTH (10Gx1 EPON) have similar capacity
- **Solution: CTTH until Shared Networking Technology is Exhausted then move to P2P Ethernet / Wavelength to the Home (WTTH) Era – Avoiding the EPON Step**

For the summary of the paper the questions addressed as the beginning of the paper will be addressed.

1) What are forecasted capacity requirements?

We have forecasted the video allocation that may not represent the MSOs plans and as for Internet services this assumed 50% CAGR for the Service Tier but this will likely reduce as speeds have risen quickly and the telecom industry will not likely sustain those growth rates. As far traffic, this may grow at 50% or so for the downstream but the upstream is far less, perhaps 10% CAGR.

2) Are Cable Networks "Limited by" the RF Video and Data Technologies?

This paper proves that the cable access network is now limited by ITU-T J.83 technology for the downstream and the DOCSIS 2.0 technology for the upstream. These technologies were defined as much as 15 years ago and by today's standard have low order modulation formats and an old FEC.

3) Are Current Cable Networks "Limited by" the FTTN Amplitude Modulation (AM) "Analog" Optical Technology?

In the future will the capability of the cable access network to increase b/s/Hz be "limited" by the fiber to the node (FTTN) optical technology? Yes, however the performance of AM optics when used for Sub-split and Mid-split may perform at near parity against digital optics depending greatly on both distance and AM laser selection. The use of AM optics will enable higher order modulation to support DOCSIS 3.1. However, to maximize DOCSIS 3.1, and remove the optical layer from becoming the limiting factor, the move to digital optics in some cases will allow full support of the highest order modulations.

4) Digital Fiber Coax (DFC) uses Digital Optics for FTTN and will force us to place SOME PHY or MAC/PHY Access Layer Functions in the Node, so what stays in the headend and what moves to the node?

The use of Digital Forward and Return may place the lowest layer of the PHY in the node, like the ADC and DAC to the entire PHY and may also place the entire MAC and PHY in the node. It is too early to tell which Remote Access Layer architecture is best to enable digital optics. It should be noted that AM optics will support high order modulations in the majority of MSO FTTN applications today, but there are limitations. The use of digital forward and return independent of which architecture may not be desired or used by all MSOs and even within an MSO. Further industry research is needed to determine the best DFC architecture.

5) What are the best ways to leverage previous, current and future investment?

Throughout this paper we have shown methods that the CTTH network can evolve to meet the needs of the consumer and the MSO. DOCSIS will update and modernize the RF technology with DOCSIS 3.1. This will backwards compatible with DOCSIS J.83 versions and DOCSIS 2.0. The network technologies for FTTN (Fiber to the Node) will evolve with better AM optics and Broadband Digital solutions to maximize b/s/Hz or capacity of the existing and future spectrum.

6) How does CTTH network capacity compare with FTTH technologies?

This paper proves that the cable access network capacity downstream and in the future when need the upstream may meet or exceed the capacity of FTTH EPON and GPON technologies, even the 10G x 1G EPON technology.

7) When and what could a migration strategy from CTTH to FTTH look like and why?

The paper suggests that CTTH DOCSIS 3.1 compared with other shared media technologies like GPON and EPON 10G x 1G will have similar capacity levels, and thus MSOs should stick with their existing coax until share media capacity runs out. Then move the P2P Ethernet technology like perhaps WDM PON of Wavelength to the Home (WTTH).

1. CTTH Using DOCSIS 3.1
2. Reclaim Spectrum (DTAs)
3. Consider DOCSIS 3.1 Modem swap out expand upstream capacity (and downstream)
4. Add Spectrum (Move to 1 GHz or 1.2 GHz) Downstream and upstream if needed
5. Fiber Deep (Place more nodes in existing serving area to reduce service group size)
6. P2P Ethernet with dedicated fiber or use WDM PON for Wavelength to the Home (WTTH) and P2P Ethernet.

Bibliography

[1] Emmendorfer, Michael J, Shupe, Scott, Maricevic, Zoran, and Cloonan, Tom, "Examining HFC and DFC (Digital Fiber Coax) Access Architectures, An examination of the All-IP Next Generation Cable Access Network," 2011 SCTE Cable-Tec Expo, New Atlanta, GA, Nov. 14-17, 2011.

[2] Emmendorfer, Michael J, Shupe, Scott, Cummings Derald, Cloonan, Tom, and O'Keeffe, Frank "Next Generation - Cable Access Network (NG-CAN), Examination of the Business Drivers and Network Approaches to Enable a Multi-Gigabit Downstream and Gigabit Upstream DOCSIS Service over Coaxial Networks", 2012 SCTE Canadian Summit Toronto, Canada., March 27-28, 2012

[3] Emmendorfer, Michael J, and Cloonan, Tom "Examining the Future Evolution of the Access Network" NCTA, Washington, D.C., June 11, 2013

[4] Recommendation ITU-T J.83 Digital multi-programme systems for television, sound and data services for cable distribution

[5] "Mission is Possible: An Evolutionary Approach to Gigabit-Class DOCSIS", Authors J. Chapman, M. Emmendorfer, R. Howald, & S. Shulman, (Cisco, ARRIS, Motorola, and Intel) published paper in the Proceedings of the May 2012 NCTA Cable Show

Abbreviations and Acronyms

AM	Amplitude Modulated
ATDMA	Advanced Time Division Multiple Access
BDR	Broadband Digital Return (also referred to as Digital Return)
BPL	Broadband over power line
BPON	Broadband PON
CAGR	Compound Annual Growth Rate
CBR	Constant Bit Rate
CPE	Customer Premise Equipment
DBS	Digital Broadcast System
DFC	Digital Fiber Coax
DOCSIS	Data Over Cable Service Interface Specifications
DIG	Digital Return Optical Transport (also referred to as BDR)
DSG	DOCSIS Set-top Gateway
DTA	Digital Terminal Adapter
EoC	Ethernet over Coax
EPON	Ethernet Passive Optical Network
EPOC	EPON Protocol over Coax
FTTH	Fiber To The Home
FTTLA	Fiber to the Last Active
FTTP	Fiber to the Premise
FTTx	see (FTTH, FTTP, etc)
Gbps	Gigabits per Second
GPON	Gigabit PON
HFC	Hybrid Fiber Coaxial
HHP	Households Passed
HiNOC	High performance Network over Coax
HPNA	HomePNA Alliance
HSD	High Speed Data
IP	Internet Protocol
IPTV	Internet Protocol TV
LDPC	Low Density Parity-Check
MAC	Media Access Layer
Mbps	Megabit per Second
MoCA	Multimedia over Coax Alliance
MSO	Multiple Systems Operator
NG-CAN	Next Generation – Cable Access Network
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OSP	Outside Plant
OTT	Over The Top
P2P	Peer-to-peer
PHY	Physical Layer
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
QoS	Quality of Service
RF	Radio Frequency
RFoG	RF Over Glass
RS	Reed-Solomon Codes
SCDMA	Synchronous Code Division Multiple Access
SDV	Switch Digital Video
TCP	Transmission Control Protocol
UHF	Ultra High Frequency
US	Upstream
VoD	Video on Demand