NEXT GENERATION - CABLE ACCESS NETWORK

AN EXAMINATION OF THE DRIVERS, NETWORK OPTIONS, AND MIGRATION STRATEGIES FOR THE ALL-IP NEXT GENERATION – CABLE ACCESS NETWORK

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ABSTRACT

The Cable Industry is facing a decade of unprecedented change in the areas of video and high-speed Internet services. This change,driven by competition and consumer demand, will transform the cable network end-to-end. This paper will focus entirely on what we are calling the Next Generation Cable Access Network,examining the business drivers, network options, and migrations strategies in the access layer of the data and HFC network to provide more IP-based capacity to and from the home. The document covers in-depth the core business drivers and the technical options spanning animmense area of network disciplines and technologies, thus we have included a comprehensive executive summary at the conclusion of the report.

The analysis includes the allocation of existing spectrum and possible future spectrum expansion to accommodate consumer demand. Cable Operators and their competitors are enabling consumers to change their viewingoptions for video services and the usage of the high-speed Internet network.In the area of high-speed Internet service, competition and consumer demand is increasing the service speed tiers offered,and network traffic usage continues to rise at an alarming rate. Cable Operators like the United Kingdom's *Virgin Media*announced in April 2011 an Internet speed trial of up to 1.5 Gbps downstream and 150 Mbps upstream [1].The cable competitor *Verizon*is reportedly exploring plans to upgrade its FiOS system to XG-PON, the 10 Gbps downstream and 2.5 Gbps upstream technology [2]. New entrants in the video distribution space are capitalizing on the network investments made by the telecom industry, forcing changes in their video delivery network as well as the high-speed data network. A key challenge the cable industry will face in the future will be offering PON-like IP-based capacity in the downstream and the upstream to consumers, while leveraging their existing coaxial network.

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) How long willthe current spectrum split and 500 HHP nodelast? 2) What are the network technology and architecture options and what are the pros and cons? 3) How long will each of these new network architecture options last? 4) What are the financial

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

This paper will seek to provide some visibility and answers to these questions and key challenges. The paper will focus entirely on the network aggregation and access layer including the CMTS, HFC and home network. This paper will provide some predictions for service tier and traffic growth, which serve as the drivers for network capacity and network utilization forecasts that are used to predict the timing of the network changes and investment. We will examine the network technology and network architecture options from spectrum splits, data MAC and PHY technologies as well as network architecture options. This paper will consider the capabilities of a drop in upgrade with an effort to maintain a 500 HHP service group and typical number of actives and passivesto determine the viability and impact for upstream spectrum expansion. The funneling effect must be considered in the analysis for the NG Cable Access Network. The paper provides analysis and comparison of some of the network elements under consideration. The paper introduces a term called Digital Fiber Coax (DFC) as a next generation architecture, which may augment the HFC media conversion style architectures that utilize centralized data access/aggregation layer equipment.

We considered a couple of migration strategies as more viable than others and while not picking a particular end-state approach, our position is to examine the options and document the pros and cons of each network architecture and technology, so industry leaders may make an informed decision.These topics under consideration comprise several network technology disciplines, which are often separate areas of concentration. This paper is by no means conclusive; some of the areas under examination have not had significant study or have the absence of products to sufficiently examine and forecast the best path.There are also timing considerations and business trade-offs that will need to be considered.

INTRODUCTION – PLANNING FOR THE NEXT GENERATION – CABLE ACCESS NETWORK

A major challenge the cable industry will face in the future will be meeting the needs of the consumer and addressing the competitive threats of PON/FTTH systems all while leveraging the existing coax to the home. This will mean significant changes in the use of network technologies, spectrum allocation, and overall network architectures. Planning for the Next Generation – Cable Access Network is extremely difficult as this spans across several network disciplines within the cable industry and even technologies outside or not widely deployed in cable, such as PON, Wireless, and EoC. The span of network technology disciplines also reaches into the network elements and underlying sub-systems such as MAC layer, PHY layer, HFC optical transport components, as well as several access radio frequency technologies end-to-end such as amplifiers, passives, and coaxial cable. What is proving to be a significant challenge is the increase dependency between all of these traditionally separate network disciplines as part of the new cable access network architecture. In years past these technologies functioned in many ways independent of one another. This next generation cable access architecture will likely migrate to more IP based spectrum in the downstream cannibalizing existing technologies which are non-IP based creating a more efficient and competitive network transport platform to compete with PON on the downstream and simply have the versatility of IP based technology. The upstream will need more spectrum and it is the overall spectrum allocation and placement of this new spectrum, whichwill have the greatest impact on the cable industry for decades to come.

The challenge we have is predicting the timing of the change in the network and how long each change will last. Additionally and most importantly what are the impacts of each of the upstream spectrum options that may be considered for the future. This paper will provide predictions, such as the drivers for the use of the spectrum in the downstream and upstream. The paper considers the spectrum allocation options and predicts how long each will last beginning with the current sub-split options and several spectrum splits which add new upstream capacity and how long these will last. The report provides a technical comparison of the upstream spectrum options and the impacts that each has from services to overall network architecture and cost.

Our Goals for Next Generation – Cable Access Network include:

- Achieve upstream bandwidth requirements through this decade
- Achieve downstream bandwidth requirements through this decade
- Continued versatility to accommodate advances in networking technology without massive changes to the outside plant network.
- Flexibility to accommodate incremental allocation of IP/Bandwidth for smooth transition strategy and pay as you grow or just in time network planning
- DOCSIS Backwards Compatibility leverages MAC/PHY channel bonding groups previously deployed and occupying spectrum yielding investment protection delaying or avoiding significantly costly approaches to find new spectrum
- Investment protection by re-using spectrum already in service, DOCSIS, HE lasers/receivers, and CPE (STB/Data) as much as possible
- Leverage network passives the most numerous OSP element
- Avoid costly and unnecessary fiber builds
- Keep the OSP as Simple as Possible for as Long as Possible
- Leverage High densities and economies of scale

Importance of Backward Compatibility with DOCSIS 3.0 and Any Successor

The authors of this paper believe that DOCSIS and any successor should consider the value of backwards compatibility especially across channel bonding groups. This assures previous and future investment may be applied to create a large IP based bandwidthnetwork while not stranding previous capital investment and spectrum. The use of channel bonding leverages every MHz, which are finite and not free, this is all towardsan effort to create one large IP pipe to and from the home. The use of backwards compatibility has benefitted the cable industry as well as other industries which use technologies like IEEE Ethernet, WiFi, and EPON creating consumer investment protection, savings,and a smooth migration strategy. The adoption of backward compatibility simply allows the MSOs to delay and perhaps avoid major investment to the network such as adding more data equipment, spectrum, node splits, or running fiber deeper.

Overview of Our Methodology For Network and Capacity Planning

In our analysis and in the structure of this paper we have examined the Next Generation-Cable Access Network in several steps as captured in the illustration below (figure 1). As shown in the illustration our process was to first determine the future requirements. The first step examined the service tier and traffic growth estimates based on a model that captured a thirty-year history to make an attempt to predict the future network needs for perhaps the next two decades. In the second phase we considered the technology and most importantly the spectrum allocation options to forecast network capacity. Then after considering the Service and Traffic growth we measured this against the network capacity options, in the section referred to as Network Utilization and Capacity Planning. In this section we forecast the timing and duration of each network step. In step four we examine several of the network technology and architecture options under consideration. The Network Migration Analysis and Strategies consider all of the factors of the aforementioned steps and provides some analysis of possible migrations strategies to address the competitive threats and consumer drivers. The migration strategies selected by the cable operators are dependent on many factors, and there may not be a consistent approach selected across all MSOs. In fact, within a given MSO the analysis may vary by market. Our analysis measures the costs of several network options.

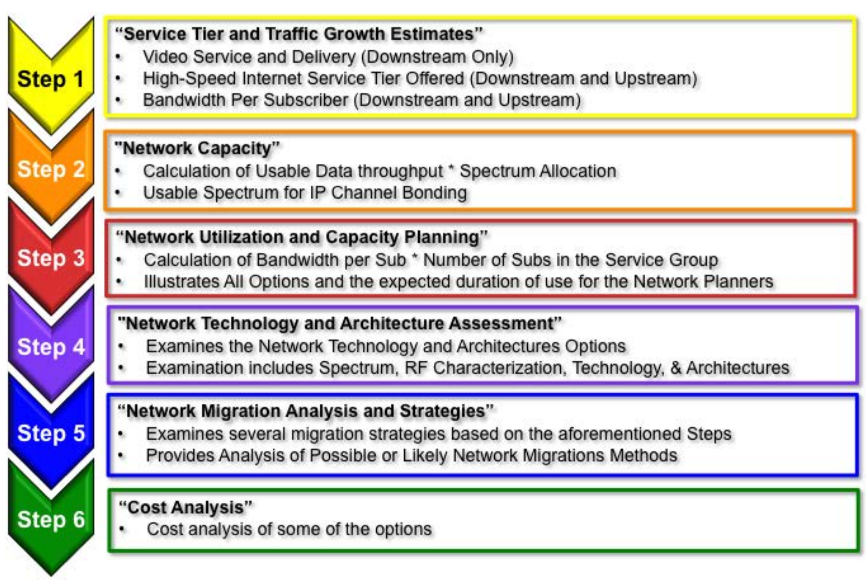


FIGURE1: METHODOLOGY FOR NETWORK AND CAPACITY PLANNING

SERVICE TIER AND TRAFFIC GROWTH ESTIMATES

Consumers and Competition Are Driving Change

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 Appleare becoming service providers enabling the video experience across all platformsand 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 systemequivalent 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 modeling 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 is very nimble and may increase the spectrum allocation beyond the current levels in either direction. This important fact is covered in detail in this paper. 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.

Upfront Disclaimer on Service Tier and Traffic Growth Estimates

In this report we will be making network traffic predictions for the next two decades and we acknowledge that these numbers are highly debatable.Theseforecasts may not match any particular cable or telecom provider.The modeling for the Internet portion of the traffic is based on modeling, which goes back nearly thirty 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. The data service portion of the model is predictable but at some point as with Moore's Law, the growth rate for Service Tiers Offered to Consumers as well as traffic usage may not continue on this trajectory for another 20 years.We are only using these Service Tier and Traffic Growth Estimates as ―rough ballpark numbers" to allow discussion and forward planning.The Network forecast will include Video Services offered by the cable provider as well asHigh-Speed Internet Services.

Video Service and Delivery Assumptions(Downstream Only)

We could have considered many factors for the video service network requirements. We could have done a year-by-year prediction of the allocation of linear programming, VoD, SDV, SDTV, HDTV, 3DTV, amount of in-home pre-caching, and service group size and number of tuners, etc, but we did not consider all of these areas individually as these may vary widely among MSOs and over time.

We simply will assume that Video Services will use all available capacity not being used by the High-Speed Internet Services. We will however make some forecast for what could be considered a minimum allocation of capacity for an MSO deliveredvideoservice, below are our Video assumptions and traffic forecast.

Video Assumptions	
Take-rate of the service	60%
Viewers are actively watching a program during the busy-hour/busy-day	60%
Average video viewers per active home	2
Linear Service (Broadcast)	0%
On-Demand Service (Unicast) (this worst-case assumption creates the biggest BW challenge)	100%
Average program bandwidth (assumes mix of SD, HD, and 3D in MPEG4)	10 Mbps
HHP Fiber Node or Service Group (SG)	250

FIGURE 2: VIDEO ASSUMPTIONS FOR FUTURE CAPACITY PLANNING

Video Calculatio	
250 HHP/Node * (0.6 take-rate) * (0.6 active) * (2 viewers/active home) * (10 Mbps/viewer)	1.8 G or 3.6 G

FIGURE 3: VIDEO TRAFFIC ALLOCATIONS FOR FUTURE CAPACITY PLANNING

The video service is projected be a unicast offering and the model essentially will always reserve or allocate 12 Mbps per video subscriber (1800 Mbps / 150 video subscribers) as illustrated in the figure 2 and 3. However, like today video services will dominate the spectrum allocation compared to High-Speed Internet for nearly the entire decade. The modeling in the remainder of this paper assumes that video services will consume all of the bandwidth that High-Speed Internet does not require, however the model reserves the 12 Mbps per video sub as a minimum allocation for a video service offered by the MSO, unless otherwise stated. Certainly the MSO's high-speed data subscribers may use the data network to view video content on devices like tablets, handhelds, TVs, PCs, and other devices.

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

The network traffic estimates need to consider the downstream and upstreamhigh-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. TheHigh-Speed Internet service tier and traffic will grow considerably during this decade moving from perhaps four6 MHz channels downstream, which is less than 4% of the MSO'stotal spectrum allocation and may grow to perhaps 40-50% in the next 10 years. The high-speed Internet service tier offering will be a key contributor to overall bandwidth drivers. The figure 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. As illustrated in the figures 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. This model assumes a 50% CAGR for the Internet service tier.

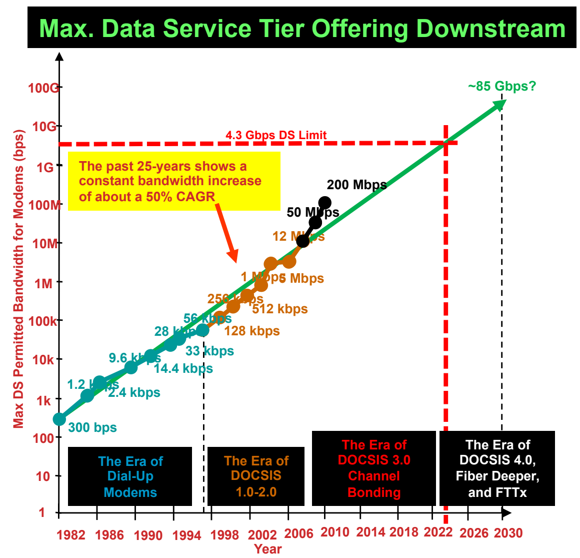


FIGURE 4: MAX INTERNET DATA SERVICE TIER OFFERING DOWNSTREAM

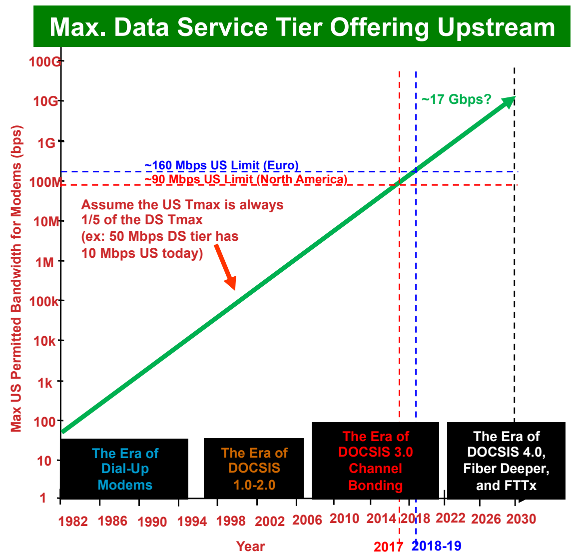


FIGURE 5: MAX INTERNET DATA SERVICE TIER OFFERING UPSTREAM

Year	Downstream Max Service Tier	Upstream Max Service Tier
2010	26	5
2011	38	8
2012	58	12
2013	86	17
2014	129	26
2015	194	39
2016	291	58
2017	437	87
2018	655	131
2019	983	197
2020	1,474	295
2021	2,211	442
2022	3,317	663
2023	4,976	995
2024	7,464	1,493
2025	11,196	2,239

FIGURE6: COMBINED INTERNET MAX SPEED PREDICTIONS

The table below captures the year-by-year predictions of the downstream and upstream service projections from the figures above. This table will be used for the capacity requirements found in the Network Utilization and Capacity Planning section later in this document. 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.

There has been a significant increase in the services offered resulting in an up tick off the linear progression. Additionally, announcements from cable operator Virgin Media of an Internet speed trial of up to 1.5 Gbps downstream and 150 Mbps upstream [1] and Verizon reportedly exploring plans to upgrade its FiOS system to XG-PON, the 10 Gbps downstream and 2.5 Gbps upstream technology may further move the model higher [2]. The rollout of downstream channel bonding was a key contributor to the expansion of the service offering as well as PON. As upstream channel bonding is deployed in the near term we expect an expansion of the upstream max service tier to increase as well, perhaps initially at a higher rate that the 50% CAGR as the model has captured over the last thirty years. This is critical information for the network planners; any acceleration in the service tier offered would change the predictions we have captured in this paper affecting the estimated migration timeline. The expansion of service tier often leads to higher per customer bandwidth usage or network traffic.

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).The bandwidth per subscriber is measured in the downstream and upstream direction. The downstream is currently measured at a 220 kbps per subscriber and the upstream at 36 kbps per subscriber, as illustrated in figure 7 and 8. The rate of growth is projected at a 50% CAGR. The bandwidth per subscriber and the CAGR may vary, however these numbers seem reasonable for the North American market. These numbers are used for planning purposes in this paper.

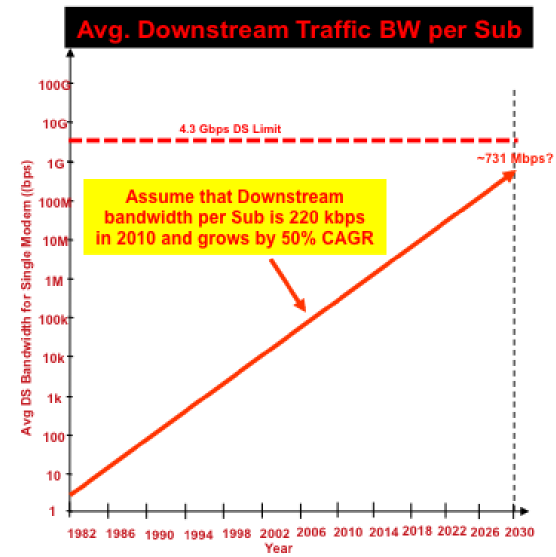


FIGURE 7: DOWNSTREAM BANDWIDTH PER SUBSCRIBER

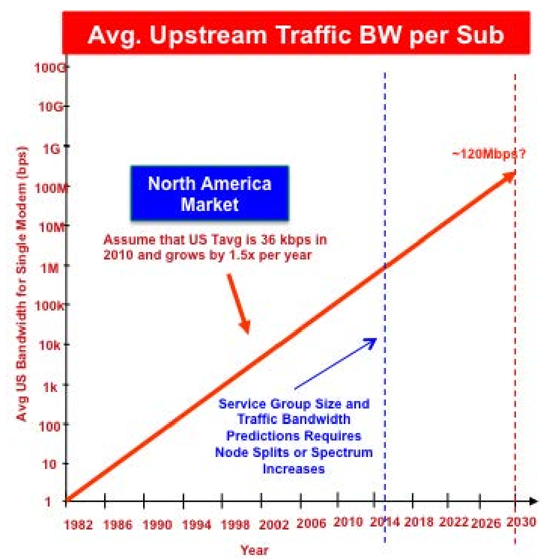


FIGURE 8: UPSTREAM BANDWIDTH PER SUBSCRIBER

Summaries for Service Tier and Traffic Growth Estimates

The video service offering will evolve over time from broadcast to unicast. The model plans for 3.6 Gbps of video traffic in a 500 HHP service group and 1.8 Gbps in a 250 HHP serving group. 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.

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. There are many factors that determine the amount of spectrum and data rate possible such as the location of the spectrum, noise, PHY/MAC layer efficiencies possible, and several other factors. We have modeled several spectrum allocation options as well as data rate possibilities. The analysis below captures the PHY layer throughput assumptionsof DOCSIS QAM (Quadrature Amplitude Modulation) forthe downstream and upstream. The analysis also considers a DOCSIS OFDM (orthogonal frequency-division multiplexing) based system that could emerge in the future. These are again PHY layer efficiency estimates additional MAC layer overhead has not been calculated. The authors wish to express that ARRIS is not aware of industry plans to adopt OFDM in the DOCSIS standard. Additionally, ARRIS has conducted internal studies for years examining the possibilities of an OFDM based systembut we have no plans to incorporate OFDM based systems into our products.

PHY Layer Throughput Assumptions

DOCSIS QAM Based

There are three figures which captures the assumptions of DOCSIS QAM based system. The first calculates the DOCSIS 256QAM downstream, figure 9. The remaining two tablesmodels the upstream using DOCSIS 64QAM and DOCSIS 256QAM each assumes ATDMA, figure 10-11. These tables measure the PHY layer spectral efficiency of DOCSIS QAM based solutions. These are used to calculate the network capacity of the cable network considering several spectrum options.

Downstream (assume Annex B 256QAM)
Bits/symbol = 8 In 1 Hz of bandwidth (with a raised cosine roll-off factor of 0.12), we can transmit 1/1.12= ~0.89 symbols/sec We must include J.83 bandwidth overhead reduction factors: •J.83 FEC addition factor = 122/128 •J.83 Trellis addition factor = 38/40 •MPEG-TS Header addition factor = 184/188
Resulting spectral efficiency = (8 bit per symbol)*(0.89 symbol per sec/Hz) *(122/128)*(38/40)*(184/188)= 6.3 bps/Hz

FIGURE9: DOWNSTREAM DOCSIS 256QAM

Upstream (assume 64QAM)
Bits/symbol = 6
-In 1 Hz of bandwidth (with a raised cosine roll-off factor of 0.25), we can transmit 1/1.25= ~0.8 symbols/sec
-We must include other bandwidth overhead reduction factors (assume 175-byte packet = 234 symbols):
-Guard-band= ~8 symbols
-Preamble = ~26 symbols
-FEC = ~6 symbols
-Bandwidth reduction factor = [1-(8+26+6)/(234+8+26+6)] = 0.854
-Resulting spectral efficiency = (6 bit per symbol)*(0.8 symbol per sec/Hz)*0.854 = 4.10 bps/Hz

Figure 10: Upstream DOCSIS 64QAM

Upstream (assume 256 QAM)
Bits/symbol = 8
-In 1 Hz of bandwidth (with a raised cosine roll-off factor of 0.25), we can transmit 1/1.25= ~0.8 symbols/sec
-We must include other bandwidth overhead reduction factors (assume 175-byte packet = 175 symbols):
-Guard-band= ~8 symbols
-Preamble = ~26 symbols
-FEC = ~4 symbols
-Bandwidth reduction factor = [1-(8+26+4)/(175+8+26+4)] = 0.82
-Resulting spectral efficiency = (8 bit per symbol)*(0.8 symbol per sec/Hz)*0.82 = 5.248 bps/Hz

Figure 11: Upstream DOCSIS 256QAM

A key take away is performance gap between 256QAM PHY and 64QAM layer efficiencies. The assumptions for 64QAM at 4.10 bps/Hz would require 28% more spectrum and DOCSIS channels to maintain the equivalent PHY layer throughput. The use of DOCSIS 256QAM for the upstream is not part of the DOCSIS standards, however some CMTS and CM products support this modulation profile in hardware. ARRIS believes that the DOCSIS specifications should be modified to include 256QAM upstream as well as 1024QAM in the upstream and downstream.

DOCSIS OFDM Based

For analysis purposes the paper provides measurements using OFDM/OFDMA, again OFDM is not part of the DOCSIS standards.

OFDM/OFDMA 1024 QAM Analysis	
FFT size	4096
Subcarriers	3800
Subcarriers spacing	50 KHz
Bandwidth	190 MHz
Modulation	1024 QAM (10 bits/symbol)
Synchronization overhead	8.33% (1 symbols per 12 symbols frame (11))
Cycle Prefix	1/8
OFDMA Symbol time	22.5 us
FEC	0.85
Aggregate PHY throughput	1315 Mbps
PHY Efficiency bits/Hz	6.92
Computation:	
3800*10*11= 418,000 bit per frame	
418,000 / (12*22.5) 1588 Mbps	
1548 * .85 = 1315 Mbps	
1315/190 = 6.92	

FIGURE 12: OFDM 1024QAM ANALYSIS

OFDM/OFDMA 256 QAM Analysis	
FFT size	4096
Subcarriers	3800
Subcarriers spacing	50 KHz
Bandwidth	190 MHz
Modulation	256 QAM (8 bits/symbol)
Synchronization overhead	8.33% (1 symbols per 12 symbols frame (11))
Cycle Prefix	1/8
OFDMA Symbol time	22.5 us
FEC	0.85
Aggregate PHY throughput	1052 Gbps
PHY Efficiency bits/Hz	5.54
Computation:	
3800*8*11= 334,400 bit per frame	
334,400 / (12*22.5) 1238 Mbps	
1238 * .85 = 1052 Mbps	
1052/190 = 5.54	

FIGURE 13: OFDM 256QAM ANALYSIS

In the figures above 256QAM was analyzedusing estimates for PHY layer efficiency comparing DOCSIS single carrier 256QAM and DOCSIS OFDM 256QAM. The analysis for the OFDM based approach shows a slightly higher PHY layer efficiency. The actual performance of either in real-world deployments is unknown. There are many attributes and assumptions than can be modified; we used an estimate that we considered to be fair for single carrier QAM and OFDM. These are subject to debate.

Downstream Capacity

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. This table provides capacity projections considering: 1) the upstream spectrum split, 2) the use of DOCSIS QAM or DOCSIS OFDM, 3) several downstream spectrum allocations from 750 MHz to 1002 MHz. Certainly there are other spectrum options that could be considered such as moving the downstream above 1 GHz and other spectrum options for the upstream. This table will calculate the estimated downstream PHY layer capacity using several spectrum options.

Split Type	MSO Downstream Channel Bonding Bandwidth Summaries	Spectrum Summaries				Technology Data Rates		Total Capacity Data Rate Usable (Mbps)
		Total Downstream Spectrum Available	Total Downstream Spectrum Usable for Channeling Bonding	Spectrum Usable for DOCSIS QAM	Spectrum Usable for DOCSIS OFDM	DOCSIS QAM Usable Data Rate Per MHz 256 QAM)	DOCSIS OFDM Usable Data Rate Per MHz (OFDM w/ LDPC))	
Mid-split	750 MHz (DOCSIS QAM) with Mid-split	645	645	645	0	6.3	7	4064
	750 MHz DOCSIS OFDM OFDM w/ LDPC with Mid-split	645	645	0	645	6.3	7	4515
	860 MHz (DOCSIS QAM) with Mid-split	755	755	755	0	6.3	7	4757
	860 MHz DOCSIS OFDM OFDM w/ LDPC with Mid-split	755	755	0	755	6.3	7	5285
	870 MHz (DOCSIS QAM) with Mid-split	765	765	765	0	6.3	7	4820
	870 MHz DOCSIS OFDM OFDM w/ LDPC with Mid-split	765	765	0	765	6.3	7	5355
	1002 MHz (DOCSIS QAM) with Mid-split	897	897	897	0	6.3	7	5651
	1002 MHz DOCSIS OFDM OFDM w/ LDPC with Mid-split	897	897	0	897	6.3	7	6279
High-Split (200)	750 MHz (DOCSIS QAM) with High-Split (200)	492	492	492	0	6.3	7	3100
	750 MHz DOCSIS OFDM OFDM w/ LDPC with High-Split (200)	492	492	0	492	6.3	7	3444
	860 MHz (DOCSIS QAM) with High-Split (200)	602	602	602	0	6.3	7	3793
	860 MHz DOCSIS OFDM OFDM w/ LDPC with High-Split (200)	602	602	0	602	6.3	7	4214
	870 MHz (DOCSIS QAM) with High-Split (200)	612	612	612	0	6.3	7	3856
	870 MHz DOCSIS OFDM OFDM w/ LDPC with High-Split (200)	612	612	0	612	6.3	7	4284
	1002 MHz (DOCSIS QAM) with High-Split (200)	744	744	744	0	6.3	7	4687
	1002 MHz DOCSIS OFDM OFDM w/ LDPC with High-Split (200)	744	744	0	744	6.3	7	5208
Top-split (900-1050)	750 MHz (DOCSIS QAM) with Top-split (900-1050)	696	696	696	0	6.3	7	4385
	750 MHz DOCSIS OFDM OFDM w/ LDPC with Top-split (900-1050)	696	696	0	696	6.3	7	4872
Top-split (1250-1750)	1002 MHz (DOCSIS QAM) with Top-split (1250-1750)	948	948	948	0	6.3	7	5972
	1002 MHz DOCSIS OFDM OFDM w/ LDPC with Top-split (1250-1750)	948	948	0	948	6.3	7	6636

FIGURE 14: DOWNSTREAM NETWORK CAPACITY ESTIMATES

The model used a lower order modulation assumption for QAM but high order modulations are certainly possible. The spectrum capacity of single carrier QAM and OFDM may actually be similar, however more real-world analysis is needed to accurately measure the performance of both technologies.

Upstream Capacity

The upstream capacity measurements are more complicated and not as straightforwardas the downstream capacity projections. In the table below, many of the spectrum split options were evaluated considering several PHY layer options and modulation schemeswithin each spectrum split.

These are some key assumptions about the upstream capacity estimates:

- Sub-split spectrum region considered 22.4 MHz eligible for channel bonding
- Sub-split spectrum was calculated with only DOCSIS 3.0 64QAM
- Sub-split channel bonding spectrum counted in capacity summaries with any new spectrum split
- All estimates use PHY layer efficiency estimates additional MAC layer overhead has not been calculated.

An important assumption is that the upstream capacity measurements assume that spectrum blocks from the sub-split region and any new spectrum split will all share a common channeling bonding domain. This is essentially assuming that backwards compatibility is part of the upstream capacity projections. The upstream capacity projections for each split will assume DOCSIS QAM and if adopted in the future DOCSIS OFDM based systems will all share the same channel-bondinggroup. This will allow for previous, current, and future investments made by the MSO to be applied to a larger and larger bandwidth pipe or overall upstream capacity. If backward compatibility were not assumed the spectrum options would have to allocate spectrum for DOCSIS QAM and separate capacity for any successor, resulting in a lower capacity throughput for the same spectrum allocation and would compress the duration of time the same spectrum may be viable to meet the needs of the MSO.

The upstream capacity measurements found in figure 15compares various spectrum splits, modulation types as well as single carrier QAM and OFDM. The spectrum splits found in the table include Sub-split, Mid-split, High-split (200), Top-split (900-1050), and Mid-split with Top-split (900-1050). The Top-split options above 1.2 GHz were not calculated in this table.

The spectrum split, PHY, and modulation type are examined in figure 15 to determine the ―Total PHY Channel Bond Capacity Usable", found on the last column. This was intended to delineate between single carrier QAM and OFDM omitting the MAC layer throughput calculations. Traffic engineering and capacity planning should consider the MAC overhead and headroom for peak periods. Similar to the examination of the downstream capacity projections above, the upstream projections illustrate that OFDM has more capacity compared to QAM; this may not be the case in real-world deployments.

Split Type	MSO Upstream Channel Bonding Bandwidth Summaries	Spectrum Summaries: Total US Spectrum	Spectrum Summaries: Total Upstream Spectrum Usable for Channeling Bonding	Spectrum Summaries: Sub-split Spectrum Likely Only used for DOCSIS 3.0	Spectrum Summaries: NEW Spectrum Usable for DOCSIS QAM	Spectrum Summaries: NEW Spectrum Usable for DOCSIS OFDM	Technology Data Rates Per MHz: DOCSIS QAM 64 Usable Data Rate Per MHz	Technology Data Rates Per MHz: DOCSIS QAM 256 Usable Data Rate Per MHz	Technology Data Rates Per MHz: DOCSIS OFDM Usable Data Rate Per MHz	Channel Bond Data Rate Capacity: DOCSIS QAM 64 Sub-split Spectrum Likely Only used for DOCSIS 3.0	Channel Bond Data Rate Capacity: DOCSIS QAM 64 Total Capacity Data Rate Usable (Mbps)	Channel Bond Data Rate Capacity: DOCSIS QAM 256 Total Capacity Data Rate Usable (Mbps)	Channel Bond Data Rate Capacity: DOCSIS OFDM Total Capacity Data Rate Usable (Mbps)	Total PHY Channel Bond Capacity (Usable)
Sub-split	DOCSIS QAM 64	37	22.8	22.4			4.1	5.2	6.28	92	-	-	-	92
Mid-Split	DOCSIS QAM 64	80	65.8	22.4	43.2		4.1	5.2	6.92	92	177	-	-	269
	DOCSIS QAM 256	80	65.8	22.4	43.2		4.1	5.2	6.92	92		225		316
	DOCSIS OFDM	80	65.8	22.4		43.4	4.1	5.2	6.92	92			300	392
High-split (200)	DOCSIS QAM 64	195	180.8	22.4	158.4		4.1	5.2	6.92	92	649	-	-	741
	DOCSIS QAM 256	195	180.8	22.4	158.4		4.1	5.2	6.92	92		824		916
	DOCSIS OFDM	195	180.8	22.4		158.4	4.1	5.2	6.92	92			1,096	1,188
Top-split (900-1050)	DOCSIS QAM 64	187	172.8	22.4	150.4		4.1	5.2	5.54	92	617	-	-	708
	DOCSIS QAM 256	187	172.8	22.4	150.4		4.1	5.2	5.54	92		782		874
	DOCSIS OFDM	187	172.8	22.4		150.4	4.1	5.2	5.54	92			833	925
Mid-Split + Top Split (900-1050)	Mid-split + Top-split (DOCSIS QAM)	230.4	216.2	22.4	193.6		-	-	-	92	617	225		933
	Mid-split + Top-split (DOCSIS QAM and OFDM)	230.4	216.2	22.4		193.6	-	-	-	92		225	833	1,150

FIGURE 15: UPSTREAM NETWORK CAPACITY ESTIMATES

A very important point is that the network architecture and performance characteristics of the plant in the real world will determine the spectrum capacity to be used. The determination of the network architectures that may work at various spectrum splits, modulations, and number of carriers was a critical finding of this report. We have modeled the network architecture and performance assumptions to estimate the modulation and capacity possible for each spectrum split. This allowed us to determine the overall requirements and impacts to cost of the various split options and the ability for the spectrum split to meet the business needs of the MSO. The network architecture requirements and impacts for each spectrum split will be found in the sections called ―Network Technology and Architecture Assessment" and the cost assessment section called ―Cost Analysis".

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 Video Traffic Predictions and another measurement will be forEstimated Bandwidth per Service Group.

Capacity Planning for High-Speed Internet Max Service Tier plus Video Traffic

The upstream and downstream High-SpeedInternet service tier growth by year and direction is used to forecast the date when the downstream may be at capacity, see figure 16. The HFC downstream capacity assumptions will usethe equivalent to a 750 MHz system, approximately 700 MHz of usable downstream spectrum to measures the date the capacity threshold is reached. The table shows that the MSO may offer a 2.2 Gbps Downstream High-Speed Data Internet service tier and support capacity for a managed video service package of about 1.8 Gbps, the year 2021. Additionally, if the High-Speed Internet growth rates remain at a 50% CAGR, that by about the year 2023 the existing downstream spectrum would be entirely needed for High-Speed Internet Services. It again should be stated that these are just prediction for the next decade or more, it is uncertain if speeds would be desired or offered at the levels shown.

Year 2021: HSD Max Service Tier Prediction of 2.2 Gbps Plus 1.8 Gbps of MSO Video Traffic is sustainable (HSD Service Tier may reach 2.5 Gbps)

Year 2023: HSD Max Service Tier Prediction Consumes All Downstream Spectrum thus additional Spectrum Above 1 GHz is required or FTTx

Year	Downstream Max Service Tier	Upstream Max Service Tier
2010	26	5
2011	38	8
2012	58	12
2013	86	17
2014	129	26
2015	194	39
2016	291	58
2017	437	87
2018	655	131
2019	983	197
2020	1,474	295
2021	2,211	442
2022	3,317	663
2023	4,976	995
2024	7,464	1,493
2025	11,196	2,239

Figure 16: Downstream Service Tier and Network Capacity Estimates

Estimated Bandwidth Per Service Group (Downstream)

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 63 HHP. We use the modeling projections from the previous section and apply the capacity capabilities of the 750 MHz system or equivalent. The analysis predicts that a 500 HHP service group will meet the capacity needs for the future and a migration to each 250 HHP service group will last a full decade. The estimated bandwidth per service group is a measures based on the high-speed Internet user traffic, the call outs in figure 17 capture the video allocation estimates used for the 500 HHP and 250 HHP service group to estimate the date of the migration to a smaller service group.

Year 2017-18: Downstream 500 HHP Node is at capacity (assuming 250 HSD Subs with 2.1 Gbps of Traffic Plus 3.6 Gbps of MSO Video Traffic)

Year 2021: Downstream 250 HHP Node is at capacity (assuming 125 HSD Subs with 2.3 Gbps of Traffic Plus 1.8 Gbps of MSO Video Traffic)

DOWNSTREAM

ESTIMATED BANDWIDTH PER SERVICE GROUP (Shown in Mbps)

Year	Avg. Downstream Bandwidth Per Sub (Megabits)	HHP Per SG	1000	500	250	125	62.5
		% of HSD per SG	50%	50%	50%	50%	50%
		Customers Per SG	500	250	125	63	31
2010	0.22		110	55	28	14	7
2011	0.33		165	83	41	21	10
2012	0.50		248	124	62	31	15
2013	0.74		371	186	93	46	23
2014	1.11		557	278	139	70	35
2015	1.67		835	418	209	104	52
2016	2.51		1,253	626	313	157	78
2017	3.76		1,879	940	470	235	117
2018	5.64		2,819	1,410	705	352	176
2019	8.46		4,229	2,114	1,057	529	264
2020	12.69		6,343	3,172	1,586	793	396
2021	19.03		9,515	4,757	2,379	1,189	595
2022	28.54		14,272	7,136	3,568	1,784	892
2023	42.82		21,408	10,704	5,352	2,676	1,338
2024	64.22		32,112	16,056	8,028	4,014	2,007
2025	96.34		48,168	24,084	12,042	6,021	3,011
2026	144.50		72,252	36,126	18,063	9,032	4,516
2027	216.76		108,379	54,189	27,095	13,547	6,774
2028	325.14		162,568	81,284	40,642	20,321	10,161
2029	487.70		243,852	121,926	60,963	30,482	15,241
2030	731.56		365,778	182,889	91,445	45,722	22,861

FIGURE 17: DOWNSTREAM SERVICE GROUP CAPACITY PLANNING ESTIMATES

The Upstream

The network utilization and capacity planning forecast of the upstream may meet the capacity limits of the sub-split 5-42 in North America and Europe's 5-65 within this decade. Surprisingly, it could be the network utilization or traffic at a 500 HHP service group which meets the throughput capacity of the sub-split spectrum. The section below examines the spectrum split options and the timing impacts.

Capacity Planning for High-Speed Internet Max Service Tier

This section captures the duration of time each of the upstream split options under examination will last. In figure 18, the upstream max service tier used in the Service Tier section earlier in the paper is assessed with the network capacity data estimates for the split options found in the immediate preceding section. The service tier estimates along with the capacity estimates for each split option is used to predict the year each upstream split option will be at or near capacity.We again wish to point out that these are just estimates used for planning purposes.

Year 2022: High-Split 200 or Top-Split (+Mid-Split) along with DOCSIS QAM type technology carries the industry into the next decade & beyond

Year 2023: Upstream HSD Max Service Tier Prediction of 995 Mbps Upstream Service consumes High-Split 200 or Top-Split (+Mid-Split) Using DOCSIS QAM (~900 Mbps + or OFDM (~1.1 Gbps +)

Year 2024: MSOs touch the passives to increase spectrum above 1 GHz to achieve higher Upstream Speeds

Year	Downstream Max Service Tier	Upstream Max Service Tier
2010	26	5
2011	38	8
2012	58	12
2013	86	17
2014	129	26
2015	194	39
2016	291	58
2017	437	87
2018	655	131
2019	983	197
2020	1,474	295
2021	2,211	442
2022	3,317	663
2023	4,976	995
2024	7,464	1,493
2025	11,196	2,239

Year 2017: North America 5-42 HSD Service Tier Exhausted Touching the Actives to add more upstream Spectrum Required

Year 2018-19: Euro 5-65 HSD Service Tier Exhausted Touching the Actives to adding more upstream Spectrum Required

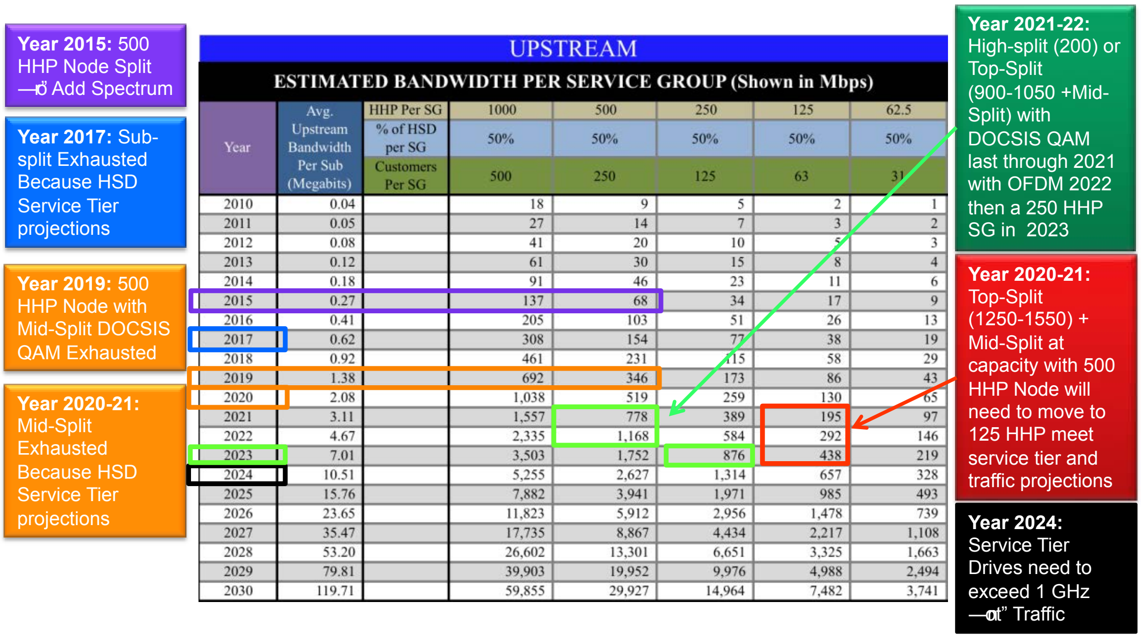
Year 2020: Mid-Split 5-85 with either DOCSIS QAM or OFDM is approaching capacity and in 2021 would be out of capacity driven by Service Tier Growth thus more upstream Spectrum is Required (High-Split or Top-Split)

FIGURE 18: UPSTREAM SERVICE TIER AND NETWORK CAPACITY ESTIMATES

Estimated Bandwidth Per Service Group (Upstream)

It is estimated that the major factor that may cause pressure on the upstream split options will be the capacity caused by traffic usage or bandwidth per service group. The table below estimates the traffic generated by the users in a service group. The network capacity estimates of each split option is then used to determine the year and service group size that may sustain a given split option. In the table below and discussed later in this paper are some assumptions to the usage and indeed relation of the spectrum options to the service group size at the upstream optical domain level. This table highlights the year, split option, and service group size that may sustain the traffic load and this table will also mention when service tier projection will force a split or spectrum increase.

It should be observed that a 500 HHP service group with 250 subscribers will last for a decade or more, however this assumes that spectrum increase like that to mid-split may happen in the year 2015 driven by traffic growth, this will be 2 years before sub-split is projected to run out because of service tier growth. Thus moving to mid-split in 2015 would allow the 500 HHP service group to be leverage until about the year 2019. If high-split (200) is added in 2019 this may allow the 500 HHP service group to remain until 2021-2022.



UPSTREAM

ESTIMATED BANDWIDTH PER SERVICE GROUP (Shown in Mbps)

Year	Avg. Upstream Bandwidth Per Sub (Megabits)	HHP Per SG	1000	500	250	125	62.5
		% of HSD per SG	50%	50%	50%	50%	50%
		Customers Per SG	500	250	125	63	31
2010	0.04		18	9	5	2	1
2011	0.05		27	14	7	3	2
2012	0.08		41	20	10	5	3
2013	0.12		61	30	15	8	4
2014	0.18		91	46	23	11	6
2015	0.27		137	68	34	17	9
2016	0.41		205	103	51	26	13
2017	0.62		308	154	77	38	19
2018	0.92		461	231	115	58	29
2019	1.38		692	346	173	86	43
2020	2.08		1,038	519	259	130	65
2021	3.11		1,557	778	389	195	97
2022	4.67		2,335	1,168	584	292	146
2023	7.01		3,503	1,752	876	438	219
2024	10.51		5,255	2,627	1,314	657	328
2025	15.76		7,882	3,941	1,971	985	493
2026	23.65		11,823	5,912	2,956	1,478	739
2027	35.47		17,735	8,867	4,434	2,217	1,108
2028	53.20		26,602	13,301	6,651	3,325	1,663
2029	79.81		39,903	19,952	9,976	4,988	2,494
2030	119.71		59,855	29,927	14,964	7,482	3,741

FIGURE 19: UPSTREAM SERVICE GROUP CAPACITY PLANNING ESTIMATES

The figure 19, does not capture all of the options but may be used for planning based on traffic forecasts. The selection of Top-split 900-1050 with a 500 HHP service group has an estimated capacity of ~700 Mbps coupled with the sub-split. The Top-split 900-1050 option with Mid-split may yield a capacity of ~930 Mbps in a 500 HHP service group given the assumption documented in the following section, see figure 23. The use of the Top-Split options at 1250-1550 will not be able to use the high order modulation if we assume a 500 HHP service group, however there is more spectrum available. The Top-split 1250-1550 option with Sub-split is estimated to have a capacity of ~500 Mbps and with Mid-split ~725 Mbps. All of the Top-split options are viable for a 500 HHP service group but at lower order modulation when compared to the low frequency return options of Mid-split or High-split. If we assume Mid-split is a first step and Top-split 900-1050 is consider yielding ~930 Mbps this has slightly more capacity than High-split (200) and the passives are not touched with this Top-split option and avoids the STB out of band communications challenge.

Summary of Capacity Planning

It is very important that the reader understands that our assumptions use HHP per service group, this may be a physical node or a logical node which uses segmentation to meet the sizing level. Another very important consideration is that the model assumes that over time that full spectrum would be allocated to the service group to meet the capacity projections for user traffic in the downstream. The upstream split options will have a direct relationship to the network architecture to include the size of the service group, number of actives, passives, cable portion of the network.

NETWORK TECHNOLOGY AND ARCHITECTURE ASSESSMENT

The goal of any cable operator is a drop in upgrade to add spectrum capacity when needed. This saves time and money in resizing the network such as node and amplifier location and spacing. Adding network elements or changing network element locations will impact cost for electrical powering requirements. Ideally, the upgrade would touch the minimum number of network elements to reduce cost and time to market. In the section, the technologies, systems and architecture options are explored. The paper will examine some of the pros and cons of several technologies and architectures, which could be used to provide additional capacity.

Overview of Important Considerations and Assumptions

This report has highlighted some important areas for network planners to consider while making the decisions for the next generation cable access network.

Avoidance of Small Node Service Groups or FTTLA

The analysis and conclusions found in this report indicates that the need for smaller node groups with few actives and passives such as Node +3 or even Fiber to the Last Active (FTTLA) is <u>not required</u> to meet capacity, service tier predictions or network architecture requirements for this decade and beyond.

500 HHP Node Long-Term Viability

Our analysis finds that upstream and downstream bandwidth needs may be met while leveraging a 500 HHP node service group for a majority of this decade and even beyond. The maintaining of a 500 HHP service group is of immense value to the MSOs. The ability to solve capacity changes while maintaining the node size and spacing enables an option for a drop-in capacity upgrade.

If the goal is to achieve 1 Gbps capacity upstream this may be achieved using a typical 500 HHP node service group with 30 actives and 200 passives, and over 6 miles of coax plant in the service area as fully described later in this paper, see figure 23.

The existing 500 HHP node has long-term viability in 750 MHz or higher systems providing enough downstream capacity to last nearly the entire decade. In the upstream a 500 HHP node is predicted to last until mid-decade when the sub-split spectrum may reach capacity and then a choice of node split, node segment or add spectrum like mid-split to maintain the 500 HHP service group are options. The physical 500 HHP node service group may remain in place with High-split (200)or Top-Split with Mid-split providing 900 to 1 Gbps capacity.

1 GHz (plus) Passives - A Critical Consideration for the Future

The industry will be considering several spectrum splits and special consideration should be made to the most numerous network elements in the outside plant, the passives. Avoiding or delaying modification to the existing passives will be a significant cost savings to the MSO. Below are key factors about the 1 GHz passives:

- Introduced in 1990 and were rapidly adopted as the standard
- This was prior to many major rebuilds of the mid-late 90s and early 2000s
- Prior even to the entry of 750 MHz optical transportandRF amplifiers/ products in the market place
- Deploymentof 1 GHz passives that would have more capacity than the electronics would have for nearly 15 years
- Passives are the most numerous network element in the Outside Plant (OSP)
- Volumes are astounding perhaps as many as 180-220 behind every 500HHP Node or about 30 per every plant mile (perhaps 40-50 Million in the U.S. alone)
- 1 GHz Passives may account for 85% of all passives in service today
- Vendor performance of the 1GHz Passives will vary and some support less than 1 GHz
- Our internal measurements indicate that most will support up to 1050 MHz
- Taps in cascade may affect capacity, thus additional testing is required

Assessment of the Passives

The authors believe that special consideration should be given to solutions that leverage the existing passive. This will avoid upgrades that may not be needed until the 2020 era when the MSOs may pursue spectrum above 1 GHz. If the 1 GHz passives are considered and the desired use is over 1 GHz we believe that 1050 MHz is obtainable. There will be challenges with AC power choke resonances, which may impact the use of these passive greater than 1050 MHz with predictably.

The Value of Time

The legacy STB out of band (OOB) communications which uses spectrum in the High-split area will be a problem for this split options; however a mid-split as the first step will provide sufficient capacity for nearly the entire decade according to our service and capacity predictions. The thinking is that another decade goes by and the legacy STBs may be few or out of the network all-together. If the STBs still remain in service another consideration is that these legacy STB may be retrieved and relocated to markets than may not need the advanced upstream spectrum options. Yet, another consideration is a down conversion of the OOB communications channel at the homes that have legacy two-way non-DOCSIS set-tops.

Overview Of Spectrum Splits

The spectrum allocation options should consider the impact to the overall end-to-end system architecture and cost. The solutions should also consider the timing of these changes as this may impact cost. The end-state architecture should be considered for this next touch to the HFC. We do not need to solve next decades problems now, however we should consider them as part of the analysis. The MSO has several spectrum split options available and some are examined in this paper. The figure below is an illustration of some of the spectrum split options; it also depicts a few other options, such as Top-split with Mid-split. In figure 20, the Top-split (900-1050) optionshas a 150 MHz block of spectrum allocated for guard band between 750-900 MHz and 150 MHz block of spectrum between 900-1050 MHz for upstream.

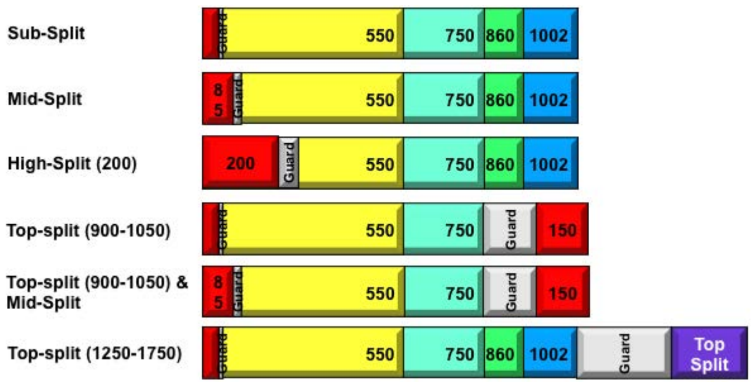


FIGURE 20: SPECTRUM ALLOCATION OPTIONS

Mid-split

Overview

The Mid-split Architecture is defined as 5-85 MHz upstream with the downstream starting at approximately 105 MHz; this may also be referred to as the 85/105 split. The mid-split architecture essentially doubles the current upstream spectrum allocation however this may triple or even quadruple the IP based capacity. The capacity increase in data throughput is a result of the high-order modulation and all of the new spectrum may be used for DOCSIS services, which is not the case with the sub-split spectrum that has generally accepted unusable spectrum and legacy devices consuming spectrum as well.

Pros

- Sufficient bandwidth to last nearly the entire decade
- DOCSIS QAM capacity approaching ~316 Mbps
- Avoids conflict with OOB STB Communications
- Lowest cost option
- High order modulation possible 256QAM perhaps higher
- The use of 256QAM translates to fewer CMTS ports and spectrum (using 64QAM would require approximately 28% more CMTS ports and spectrum)
- DOCISIS systems already support this spectrum (5-85)
- Some amplifiers support pluggable diplexer filter swap
- Some existing node transmitters and headend receives may be leveraged
- Does not touch the passives
- Upstream path level control is similar to the Sub-split (~1.4 times the loss change w/temp);

ThermalEqualizers EQT-85 enables +/-0.5 dB/amp delta

Cons

- Impacts Video Service (in low channels)
- Reduces low VHF video spectrum
- Throughput over 300 Mbps is less than the newer PON technologies

Assessment

The selection of Mid-split seems like an excellent first step for the MSOs. This split option has little impact to the video services and does not impact the OOB STBcommutations. This spectrum split may last nearly the entire decade, allowing time for the MSOs to assess future splits, if required, and the impacts to other split optionat that time.

High-split (200)

Overview

The High-split (200) Architecture is generally defined as 5-200 MHz with the downstream starting at approximately 250-258 MHz. Though other High-split options may be considered above 200 MHz these were not part of the examination. High-split is being considered because full or partial analog reclamation is underway or planned by cable operators. This will allow a smoother transition when considering consumption of existing analog spectrum. As with mid-split DOCSIS 3.0 specifications systems may be used; however, to take advantage of thespectrum, additional development is required.

Pros

- Operates effectively at a typical 500 HHP node group using 256QAM (see details in the sections later in this paper)
- The use of 256QAM translates to fewer CMTS ports and spectrum (using 64QAM would require approximately 28% more CMTS ports and spectrum)
- DOCSIS QAM capacity approaching ~916 Mbps
- DOCSIS OFDM capacity exceeds 1.1 Gbps
- Very low cost spectrum expansion option, especially considering similar capacity Top-split options (STB OOB cost was not considered in the analysis)
- Lowest cost per Mbps of throughput
- Some existing HFC Equipment supports High-split like node transmitters and headend receivers
- DOCISIS systems already support some of this spectrum (5-85)
- Passives are untouched
- High-split provides sufficient upstream capacity and the ability to maximize the spectrum with very high order modulation
- High-split (200) does not waste a lot of capacity on guard band
- Level control using Thermal Equalizers EQT-200 (~2.2 times Sub-split cable loss)

Cons

- Conflicts with OOB STB Communications if DOCSIS Set-top box Gateway (DSG) is not possible

- Takes away spectrum from Video Services (54-258 MHz)
- Takes away spectrum from Video devices (TVs and STBs)
- Potentially revenue impacting because of spectrum loss supporting analog video service tier
- Downstream capacity upgrade from 750 MHz to 1 GHz to gain back capacity lost to upstream

Assessment

The use of high-split would impact OOB Set-top Box communications for non-DOCSIS Set-top Gateways were not possiblein the upgraded service area. If the deployment of High-split (200) is planned later in time,this may allow these older STBs to be phased out. This split provides lots of bandwidth with a minimal amount of prime spectrum wasted for guard band.

If the main challenges with the use of High-split are overcome, this seems like the ideal location for the new upstream(technically). The economics are also compelling for High-split (200) against the other split options considering just the network access layer. If the STB Out of Band (OOB) and analog recoveryneed to be factored into to the High-split, the cost analysis will change.

Top-split (900-1050)with Sub-split or Mid-split

Overview

A new spectrum split called Top-split (900-1050)defines two separate spectrum bands, which may either use sub-split or mid-split plus the new spectrum region of900-1050 MHzfor a combined upstream band. The total upstream capacity may be either 187 MHz or 230 MHz depending on the lower band frequency return selected.The downstream would begin at either 54MHz or 105 MHz and terminate at 750 MHz in the current specification.All of these architectures will share a 150 MHz guard band between 750-900 MHz, this may vary in the end-state proposal howeverthese defined spectrum splits will be used for our analysis. The Top-split (900-1050) with Sub-split and with the Mid-spilt option are compared in a table called Spectrum Allocation Comparison, figure 21. The placement of additional upstream atop the downstream has been considered for many years. The Top-split (900-1050) approach may be similar to a Time Warner Cable trial called the Full Service Network in the mid 1990’s, which is believed to have placed the upstream above the 750 MHz downstream. These are some of the pros and cons of Top-split (900-1050):

Pros

- Operates effectively at a typical 500 HHP node group but with no more than 64QAM (see details in the sections later in this paper)
- Top-split with Sub-split DOCSIS QAM capacity ~700 Mbps given a 500 HHP Node/Service Group
- Top-split with Mid-split DOCSIS QAM capacity ~933 Mbps given a 500 HHP Node/Service Group (equal to High-split)
- Top-split with Mid-split DOCSIS OFDM capacity exceeds 1.1 Gbpsgiven a 500 HHP Node/Service Group (equal to High-split)

- With Sub-split “no” video services, devices, and capacity is touched
- With Mid-split has a –low impact” to video
- STB OOB Communications are not affected
- Passives are untouched (only Top-splitthat avoids touching passives)
- Existing 750 MHz forward transmitters are leveraged

Cons

- No products in the market place to determine performance or accurate cost impacts
- The analysis estimates that Top-split (900-1050) is about 1.39 times the costof High-split (200) with a <u>500 HHP node</u> architecture
- The analysis estimates that Top-split (900-1050) with Sub-split is about 2.4 times the costof High-split (200) with a <u>125 HHP node</u> architecture
- Achieving similar capacity of High-split (200) and with Top-split (900-1050) with –Sub-split” will require a 125 HHP service group (node) which is a major cost driver.(Note the use of Mid-split with Top-split will provide 900+ Mbps more than High-split)
- Spectrum Efficiency is a concern because of guard band (wasted spectrum) and lower order modulation (less bits per Hz) resulting in lower throughput when measured by summing the upstream and downstream of Top-split (900-1050) and High-split using similar spectral range(see figure 21).
- High-split has 12% or more capacity for revenue generation when compared to Top-split (900-1050) plus Mid-split, this is because the guard band requirements waste bandwidth
- Will require more CMTS ports and spectrum when lower order modulation is used, perhaps 28% more CMTS base on the efficiency comparison estimates found on figures 10 and 11.
- Upstream is more of a challenge compared to using that same spectrum on the forward path
- Upstream is more of a challenge compared to using that same spectrum on the forward path (cable loss ~5x Sub-split, 2.3x High-split; ~+/-1 dB/amp level delta w/EQTs is unknown)
- Interference concerns with MoCA (simply unknown scale of impact but may affect downstream in same spectrum range)

Assessment

The Top-split (900-1050) options are being considered because option keeps the video network –as is” when considering sub-split and has marginal impact if mid-split is used. The Top-split 900-1050 option has additional benefits in that the Set-top box out of band (OOB) challenge is avoided and this optiondoes not touch the passives. This Top-split is estimated to cost more than the High-split; estimated at 1.3 to 2.4 times depending on the architecture selected. The MSOs will just begin to evaluate this option against the others.

Top-split (1250-1550) with Sub-split or Mid-split

Overview

The Top-split (1250-1550) Architecture will be defined as part of the 1250 – 1750 MHz spectrum band. In our analysis we limited the amount of spectrum allocated for data usage and transport to 300 MHz and defined the placementin the 1250–1550 MHz spectrum band. The allocationof 300 MHz provides similar capacity when compared to the other split option. The main consideration for this Top-split option is that it avoids consuming existing downstream spectrum for upstream and avoids the OOB STB communication channel.

Pros

- May operate at a typical 500 HHP node group but estimated to use QPSK, unless HHP is reduce to 125 then it is estimated the 16QAM may be used (described in more detail in the network architecture and cost sections of this report)
- Top-split 1250-1550 with Sub-split DOCSIS QAM capacity ~500 Mbps given a 500 HHP Node/Service Group
- Top-split 1250-1550 with Mid-split DOCSIS QAM capacity ~725 Mbps given a 500 HHP Node/Service Group
- Top-split 1250-1550 with Sub-split DOCSIS QAM capacity ~912 Mbps given a 125 HHP Node/Service Group
- Top-split 1250-1550 with Mid-split DOCSIS QAM capacity ~1136 Mbps given a 125 HHP Node/Service Group
- With Sub-split "no" video services, devices, and capacity is touched
- With Mid-split has a ―low impact" to video
- STB OOB Communication is not affected
- Placing the upstream spectrum beginning at 1250 MHz and up allows for the expansion of capacity without impacting the downstream

Cons

- Passives must be touched
- Smaller nodes or upstream Service Groups perhaps a 125 HHP will be required to approach or exceed the 1 Gbps speeds comparable to High-split (200) and Top-split (900-1050)
- Highest cost solution compared with High-split and Top-Split.
- The Top-split (1250-1550) with Sub-split is about 3 times the cost of High-split (200) for similar capacity without consideration to the DOCSIS layer.
- Will require more CMTS ports and spectrum when lower order modulation is used, perhaps 90-100% more CMTS base on the efficiency comparison estimates found on Figure 11 compared to the use of 16QAM estimated at 2.7 bps/Hz.
- No products in the market place to determine performance or accurate cost impacts.
- Return Path Gain Level Control: (cable loss >6x Sub-split, 2.8x High-

split; +/-2 dB/amp w/EQTs is unknown)
- Interference concerns with MoCA (simply unknown scale of impact but may affect downstream in same spectrum range)

Assessment

The Top-split (1250-1550) with Sub-split is about 3 times the cost of High-split (200).The placement of the return above 1 GHz requires the passives to be replaced or upgraded with a faceplate change. There are approximately 180-220 passives per 500 HHP node service group. It is estimated that the node service group of 500 HHP may be leveraged initially, however the requirements for higher capacity will force smaller node service group, which will addto the cost of the solution. The use of lower order modulations will require more CMTS upstream ports and more spectrum, which will impact the costs of the solution as well. Additionally, the conditioning of the RF components to support above 1 GHz may add to the costs of the solution. However determining the financial impacts of performing ―Above 1 GHz plant conditioning" is unknown and was not considered in the financial assessment found later in this report. If we consider the service and network capacity requirements for the upstream and downstream for the next decade and beyond, the cable industry should have sufficient capacity under 1 GHz, which is the capacity of their existing network.

Name of Spectrum Split	Mid-Split	High-Split (200)	Top-Split (900-1050)	Top-split (900-1050) & Mid-split	Top-split (1250-1550)	Top-split (1250-1550) & Mid-split)
Upstream Spectrum Range	5-85	5-200	5-42 & 900-1050	5-85 & 900-1050	5-54 & 1250-1550	5-85 & 1250-1550
Downstream Spectrum Range	> 105 MHz	> 258 MHz	54-750	105-750	54-1002	105-1002
Upstream Spectrum Bandwidth in MHz	80	195	187	230	337	380
Downstream Spectrum Bandwidth in MHz	897+	744+	696	645	948	897
Guard band Spectrum Allocation (wasted spectrum between US/DS)	20	58	162	170	260	268
Upstream PHY Layer Spectral Efficiency Capacity (assume QAM & 500 HHP SG) in Mbps	316	916	708	933	500	725
Downstream PHY Layer Spectral Efficiency Capacity (assume QAM) in Mbps	5651	4687	4385	4064	5972	5651
Total PHY Layer Spectral Efficiency Capacity Usable (Up+Down)	5967	5603	5093	4997	6472	6376
Video Service Impact	Yes	Yes	None, Assumes existing 750 System	Yes because Mid-split used in Lowband	None	Yes because Mid-split used in Lowband
Video Spectrum Loss Location (assuming 54 MHz-860MHz usable)	54-105	54-258	750-860	54-105	None	54-105
Video Spectrum Loss in MHz (assuming 54 MHz-860MHz usable)	51 Mhz	204 MHz	Assumes existing 750 System	51 MHz	None	51 MHz
OOB STB Communications ANSI/SCTE 55-2 2008 [4] (70 - 130 MHz) ANSI/SCTE 55-1 2009 [5] (70 - 130 MHz) Some STBs may be hard coded within the mid-split range (75.5 and 104.25 MHz)	Not likely, however some STBs may be hard coded within the mid-split range (75.5 and 104.25 MHz)	Impacted	No	No	No	No
Estimated Node Service Group Size per Return Laser in HHP (estimate & may vary)	500	500	500	500	500	500
Maximum number of Actives Supported (estimate & may vary)	30	30	30	30	30	30
Maximum number of Passives Supported (estimate & may vary)	200	200	200	200	200	200
Headend Optical Transmitter (Requirements, Replacement, Leverage)	Up to MSO	Up to MSO	Up to MSO	Up to MSO	Up to MSO	Up to MSO
Headend Optical Receivers (Requirements, Replacement, Leverage)	May Be Leveraged	May Be Leveraged	Replace	Replace	Replace	Replace
Nodes Optical Side (Requirements, Replacement, Leverage)	May Be Leveraged	May Be Leveraged	Replace	Replace	Replace	Replace
Node RF Side (Requirements, Replacement, Leverage)	Replace	Replace	Replace	Replace	Replace	Replace
Amplifiers (Requirements, Replacement, Leverage)	Best Case: Amp is removed from service if pluggable diplexer filter swap is supported (this is not a field upgrade). Worst case replace the Amp	Replace	Replace	Replace	Replace	Replace
Passives (Requirements, Replacement, Leverage)	Leverage	Leverage	Leverage	Leverage	Replace	Replace
House Amplifiers (Requirements, Replacement, Leverage)	Replace	Replace	Replace	Replace	Replace	Replace
Achieve Cable Modem Value not to exceed 65 dBmV	Yes	Yes	Yes	Yes	Yes	Yes
CPE Cost Impacts	$	$$	$$$	$$$	$$$	$$$
Interference Concerns with MoCA [6]: MoCA 1.0 and 1.1 Operating frequency 850 – 1500 MHz MoCA 1.1 Annex Expanded operating frequency of 500 MHz—1500MHz MoCA 2.0 Expanded operating frequency from 500 MHz – 1650 MHz	No Interference Concerns with New Upstream	No Interference Concerns with New Upstream	Yes Interference Concerns with New Upstream	Yes Interference Concerns with New Upstream	Yes Interference Concerns with New Upstream	Yes Interference Concerns with New Upstream
FM Radio Band, DTV and Aeronautical frequencies - avoidances of these bands reduces the overall spectrum bandwidth available for data services. Areas affected may have lower order modulation and smaller service group to attain desired capacity level.	No Interference Concerns with New Upstream	Yes Interference Concerns with New Upstream	No Interference Concerns with New Upstream	No Interference Concerns with New Upstream	No Interference Concerns with New Upstream	No Interference Concerns with New Upstream

[4], [5], [6]

FIGURE 21: SPECTRUM ALLOCATION COMPARISON

Characterization of RF Components

The network components that most affectsignals carried above 1 GHz are the coaxial cable, connectors, and taps. The characteristics of these components are critical, since the major goal in a next generation cable access network is to leverage as much of the existing network as possible.

Before getting into the specifics about the RF characterization and performance requirements, it is worthwhile to establish the quality of signals carried above 1 GHz and below 200 MHz. The bottom line is that while return path signals can be carried above 1 GHz, they cannot be carried with as high order modulation as is possible at lower frequencies. For example, if the goal is to meet similar return path data capacity the signal carriage above 1 GHz is possible using 16QAM with about 300 MHz of RF spectrum(47 channels of 6.4 MHz each). Whereas below 200 MHz 256QAM is possible (due to lower coaxial cable loss) and only 24 channels occupyingabout 180 MHz spectrum is required, using rough estimates. Additionally, the over 1.2 GHz solutions may require a 125 HHP service group to support 16 QAM, where as the 200 MHz solutions may use a 500 HHP service group, this is a key contributing factor to the cost deltas of the split options.

Path Loss and SNR

In a typical HFC Node + N architecture, the return path has many more sources for extraneous inputs, ―noise" than the forward path. This includes noise from all the home gateways, in addition to all the return path amplifiers that combine signals onto a single return path (for a non-segmented node). For now we will ignore the gateway noise, since in principle it could be made zero, or at least negligible, by only having the modem return RF amplifier turned on when the modem is allowed to ―talk".

The RF return path amplifier noise funneling effect is the main noise source that must be confronted; and it cannot be turned off! This analysis is independent of the frequency band chosen for the ―New Return Band" (e.g., Mid-split 5-85 MHz; High-split 5-200 MHz; or Top-split with UHF return), although the return path loss that must be overcome is dependent on the highest frequency of signals carried. For a first cut at the analysis, it suffices to calculate the transmitted level from the gateway required to see if the levels are even possible with readily available active devices. The obvious way to dramatically reduce the funneling noise and increase return path capacity is to segment the Node. That is not considered here to assess how long the network remains viable with a 4x1 configuration, a 500 HHP node service group.

The thermal mean-square noise voltage in 1 Hz bandwidth is kT, where k is the Stefan-Boltzmann constant, 1.38x10^-23 J/deg-K, and T is absolute temperature in degrees Kelvin. From this we have a thermal noise floor limit of -173.83 dBm/Hz. For a bandwidth of 6.4 MHz and 75-ohm system, this gives -57.0 dBmV per 6.4 MHz channel as the thermal noise floor. With one 7 dB noise figure amplifier in the chain, we wouldhave a thermal noise floor of -50 dBmV/6.4 MHz channel.

Two amplifiers cascaded would give 3 dB worse, four amplifiers cascaded give 6 dB worse than one. And since the system is balanced to operate with unity gain, any amplifiers that collect to the same point also increase the noise floor by 10*log(N) dB, where N is the total number of amplifiers in the return path segment. For a typical number of 32 distribution amplifiers serviced by one node, this is five doubles, or 15 dB above the noise from one RF Amplifier, or -35 dBmV/6.4 MHz bandwidth. The funneling effect must be considered in the analysis for the NG Cable Access Network.

If the return path signal level at the node from the Cable Modem (CM) is +15 dBmV, it is clear that the Signal-to-Noise Ratio (SNR) in a 6.4 MHz bandwidth is 50 dB; very adequate for 256QAM or even higher complexity modulation. But if the Return path level at the node port is 0 dBmV, the SNR is 35 dB; this makes 256QAM theoretically possible, but usually at least 6 dB of operating margin is desired. If only -10 dBmV is available at the node return input, the SNR is 25 dB; and so even the use of 16QAM is uncertain.This illustrates (figure 22) the very high dynamic range of "Pure RF" (about 15 dB higher than when an electrical-to-optical conversion is involved).

Modulation Type	Theoretical C/N	Desired C/N
QPSK	14 dB	20 dB
16-QAM	21 dB	27 dB
64-QAM	27 dB	33 dB
256-QAM	34 dB	40 dB

FIGURE 22: MODULATION AND C/N PERFORMANCE TARGETS

The table below, figure 23, documents many important assumptions and assumed node configuration conditions. An important assumption is the CM maximum power output level of +65 dBmV into 75 ohms. What this means is that if many channels are bonded (to increase the amount of data transmitted), the level of each carrier must be decreased to conform to the CM maximum power output constraint. Two channels bonded must be 3 dB lower each; four channels must be 6 dB lower than the Pout(max). Since the channel power levels follow a 10*log(M) rule, where M is the number of channels bonded to form a wider bandwidth group. For 16 channels bonded, each carrier must be 12 dB lower than the Pout(max).

For 48 channels bonded, each must be 16.8 dB lower than the Pout(max). So for 48-bonded channels, the level per channel is at most 65 dBmV -17 dB = +48 dBmV. If there is more than 48 dB of loss in the return path to the node return input, the level is <0 dBmV and 64-QAM or lower modulation is required. The node and system configuration assumptions are as follows.

Typical Node Assumptions		
Homes Passed	500	
Home Passed Density	75	hp/mile
Node Mileage	6.67	miles
Amplifiers/mile	4.5	/mile
Taps/Mile	30	/mile
Amplfiers	30	
Taps	200	
Highest Tap Value	23	dB
Lowest Tap Value	8	dB
Largest Amplifier Span	2000	ft
Largest Feeder Span	1000	ft
Largest Drop Span	150	ft
Home Split Loss to Modem	4	dB
Maximum Modem Power	65	dBmV

FIGURE 23: TYPICAL NODE ASSUMPTIONS

Cable Loss Assessment

Two different lengths of 1/2" diameter hardline coax were tested for Insertion Loss and Return Loss (RL). The loss versus frequency in dB varied about as the square root of frequency. But as can be seen below, the loss at 2 GHz is about 5% higher than expected by the simple sq-rt(f) rule. The graph below illustrates a slightly more than twice the loss at 2 GHz compared to 500 MHz, see figure 24.

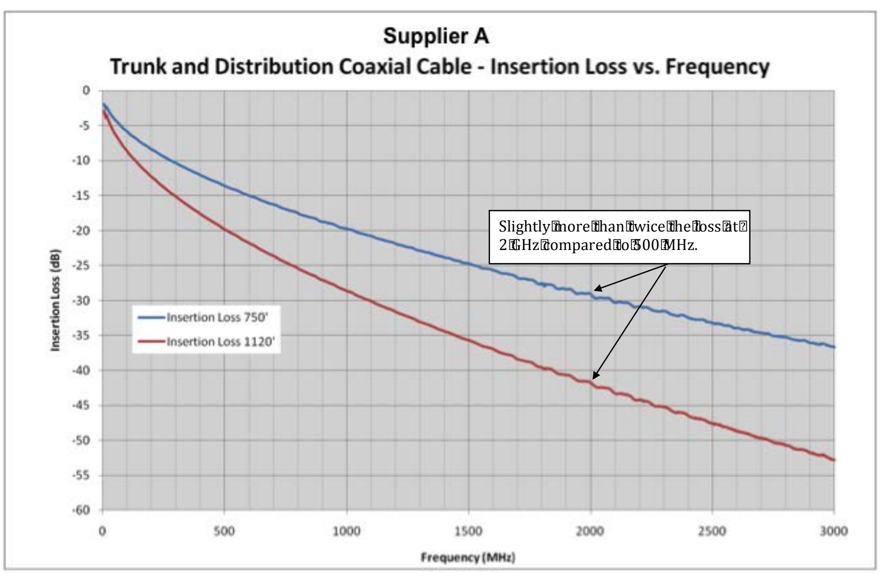


FIGURE 24: DISTRIBUTION COAXIAL CABLE – INSERTION LOSS VS. FREQUENCY

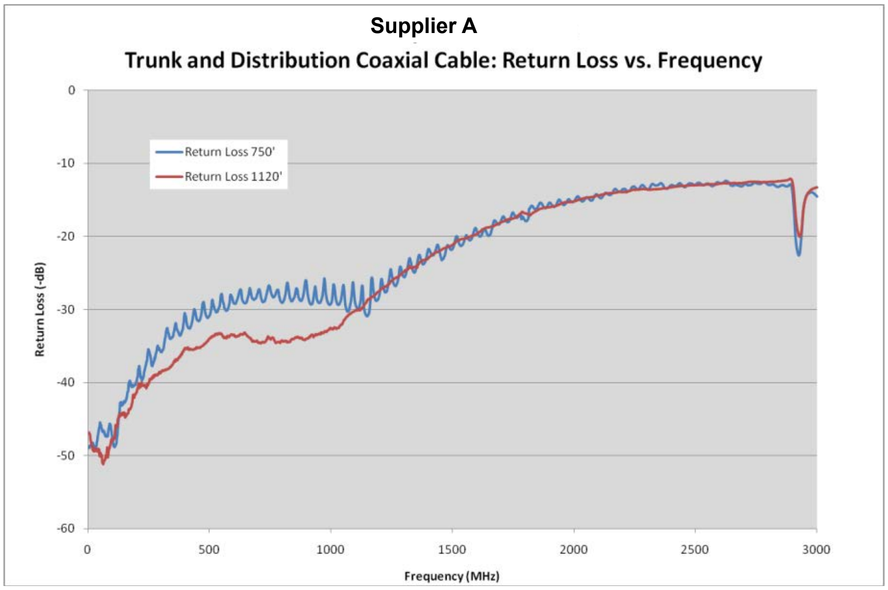


FIGURE 25: DISTRIBUTION COAXIAL CABLE – RETURN LOSS VS. FREQUENCY

In the plot (figure 25),the coax Return Loss (RL) did not vary as expected above 1200 MHz. This appears due to an internal lowpass matching structure in the hardline-to-75N connectors (apparently for optimizing the 1-1.2 GHz response). The connectorsare an important element to return loss with signals above 1 GHz.

Tap Component Analysis

Taps are the components with the most variability in passband characteristics, because there are so many different manufacturers, values, and number of outputs. Most were designed more than ten years ago, well before >1 GHz bandwidth systems were considered. One of the serious limitations of power passing taps is the AC power choke resonance. This typically is around 1100 MHz, although the “notch” frequency changes with temperature. Tap response resonances are typical from ~1050 to1400 MHz.A limitation of power passing taps is the AC power choke resonance. This is an important finding when leveraging the existing passives; therefore the use above 1050 MHz may not be predictable or even possible.

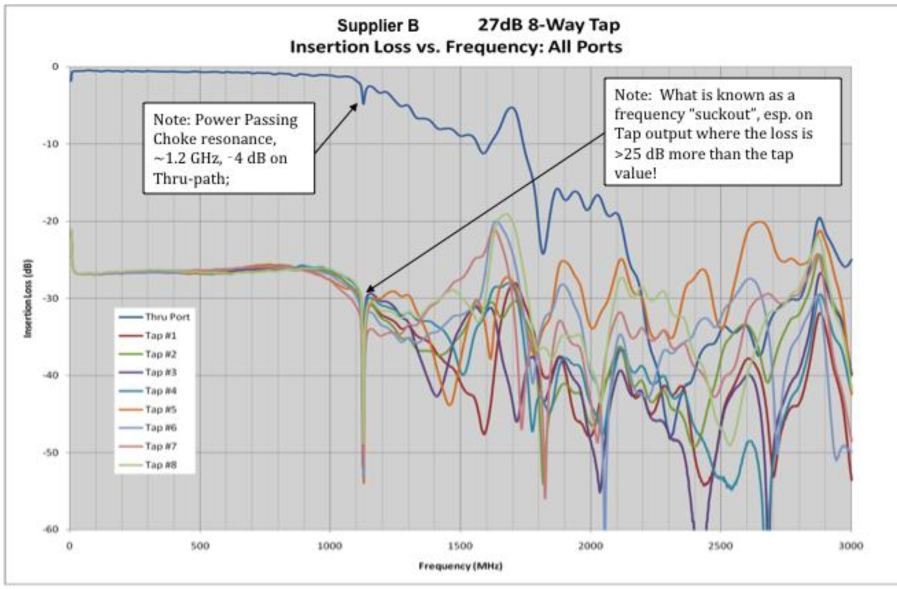


FIGURE 26: 27 DB X8 TAP - INSERTION LOSS VS. FREQUENCY: ALL PORTS

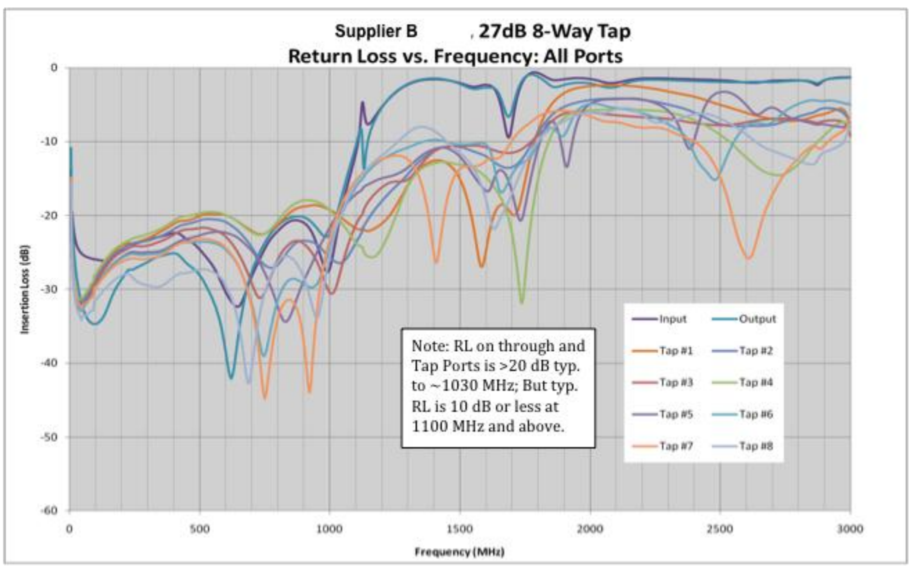


FIGURE 27: 27 DB X 8 TAP - RETURN LOSS VS. FREQUENCY: ALL PORTS

Even the newer, extended bandwidth taps, with passband specified 1.8 GHz or 3 GHz, the taps usually have power choke resonances (or other resonances, e.g., inadequate RF cover grounding) resonances in the 1050 MHz to1300 MHz range. Especially on the tap coupled port. However, most Taps work well to ~1050 MHz.

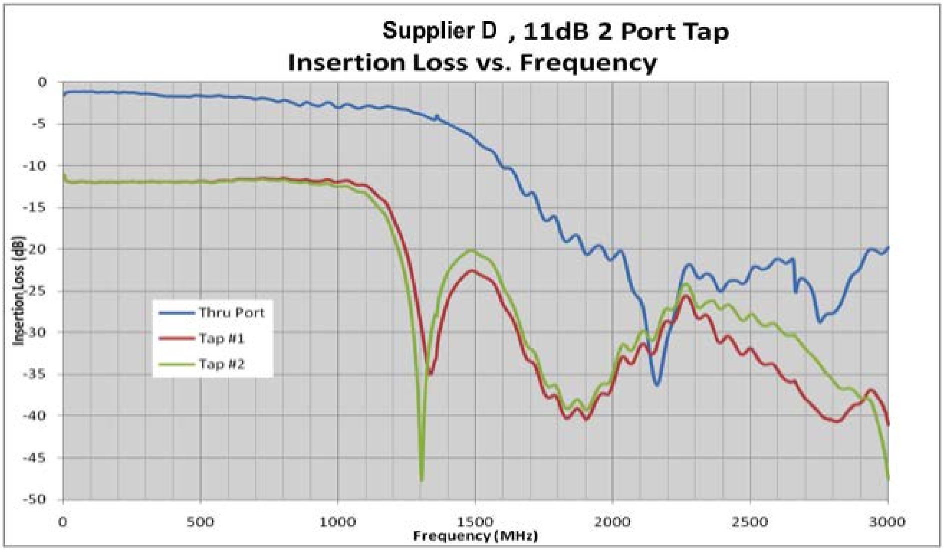


FIGURE 28: 11 DB X 2 TAP- INSERTION LOSS VS. FREQUENCY

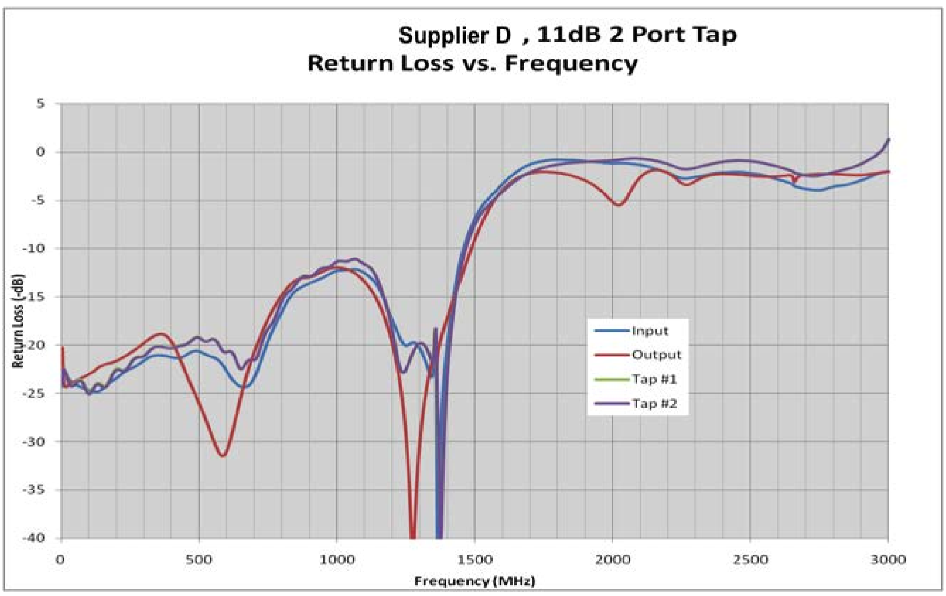


FIGURE 29: 11 DB X 2 TAP - RETURN LOSS VS. FREQUENCY

Nearly all taps exhibit poor RL characteristics on all ports above 1400 MHz. Some are marginal for RL (~12 dB), even at 1 GHz. Therefore tap cascades must be tested and over temperature to verify theactual pass band response due to close by tap reflections.

HFC Optical Return Path Transport Architecture

As we have analyzed several areas of the network to assess the impact and requirements to support additional upstream capacity we will now turn to the optical portion of the HFC network. The optical layer will be examined to support the additional upstream capacity. We will look at two classes of HFC optical transport, analog return path and the second type is digital return, which is commonly referred to as Broadband Digital Return (BDR).

Overview - Analog Optical Return Path

Analog return path transport is accomplished with a Distributed Feedback (DFB) laser located in the node housing and an analog receiver located in the headend or hub. Analog return path transport is considered as a viable option for sub-split, mid-split, and high-split returns.

Pros

The chief advantage of this method is its cost effectiveness and flexibility. If the 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, if required in the future. This would allow an operator to fully amortize the investment made in this technology over the decade.

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 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 dramatic impact on the output 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 the input to the receiver, which delivers a lower C/N performance. The practical distance over which an operator can expect to deliver 256QAM payload on analog return optics is limited.

Assessment

The analog return transmitter will work well for the low and high frequency return. Analog return path options should be available for the higher frequency return options at 900-1050 MHz and 1200-1500 MHz. However the cost vs. performance at these frequencies when compared to digital alternatives may make them less attractive. There will be distance limitations and EDFAs will impact the overall system perform noise budgets. The distances of 25-30 km are reasonable and longer distance would be supported.

Overview - Digital Optical Return Path

Digital return path technology is commonly referred to as broadband digital return (BDR). The BDR approach is ―unawar" of the traffic that may be flowing over the band of interest. It simply samples the entire band and performs an analog to digital conversion continuously, even if no traffic is present. The sampled bits are delivered over a serial digital link to a receiver in the headend or hub, where a digital to analog conversion is performed and the sampled analog spectrum is recreated.

Pros

There are a number of advantages to the BDR approach. The output of the receiver is no longer dependent on optical input power, which allows the operator to make modifications to the optical multiplexing and de-multiplexing without fear of altering RF levels. The link performance is distance independent – same MER (magnitude error ration) for 0 km as for 100 km. The number of wavelengths used is not a factor since on/off keyed digital modulation only requires ~20dB of SNR; thus fiber cross-talk effects do not play a role in limiting performance in access-length links (<100 km)

The RF performance of a Digital Return link is determined by the quality of the digital sampling rather than the optical input to the receiver, so consistent link performance is obtained regardless of optical budget. The total optical budget capability is dramatically improved since the optical transport is digital. This type of transport is totally agnostic to the type of traffic that flows over it. Multiple traffic classes (status monitoring, set top return, DOCSIS, etc) can be carried simultaneously.

Cons

The chief drawback to BDR is the fact that nearly all equipment produced to date is designed to work up to 42 MHz. Analog receivers are not useable with Digital Return transmissions. Further, the analog-to-digital converters and Digital Return Receivers aren't easily converted to new passbands. It requires ―forklift upgrades" (remove and replace) of these optics when moving to 85 MHz and 200 MHz return frequency. There is currently no standardization on the Digital Return modulation and demodulation schemes, or even transport clock rates.

Assessment

It is more difficult and therefore more costly to manufacture BDR products. This may be a driver to use DFB products for the new returns. The selection of BDR products may be driven by distance and performance requirements. Another driver to move to BDR will be when there is near cost parity with DFB, today this is the case with the 5-42 MHz optical transport systems and this may be the case in the future with the new spectrum returns.

Review of HFC / Centralized Access Layer Architecture

The HFC has been around for nearly two decades and has evolved to include many technologies and architectures. Some of these include analog and digital optical transmission technologies and HFC architectures such as Node+N, Node+0, RFoG, QAM overlay, full spectrum, etc. But regardless of HFC technology and architecture selectedthe function of an HFC class of network remains constant, it has always been a ―media conversion technology" using analog, and today digital methods,to joindissimilar media types like fiber and coaxial. The HFC architecture being a ―conversion technology" allows the outside plant to remain relatively simple and very flexible to changes at the MAC and

PHY layers. The HFC architecture is also a ―centralized access layer architecture" where all of the MAC/PHYprocessing takes place at the headend.

The HFC architecture has proven to be a valuable asset for the MSO, enabling the evolution to next generation access layer technologies while avoiding changes to the HFC layer of the network, with the exception of adding spectrum and capacity. Examples of this transition include analog video systems, digital video systems, EQAM, UEQ, SDV, CBR voice systems, pre-DOCSIS data systems, DOCSIS 1.0, 1.1, 2.0, 3.0 and so on. This entire multi decade transition did not fundamentally change the HFC architecture. HFC remained simple and carried the next generation data technology through it transparently; these are clear examples of its flexibility. Additionally, HFC may have carried all of these technologies simultaneously to support a seamless migration to the next generation; a clear example of versatility! The evolution of the cable network primarily is achieved by changing the bookends and not the plumbing in-between. It is hard to imagine the impact if the outside plant, such as nodes, needed to be changed to support each next generation MAC/PHY technology that came along over the last 20 years.

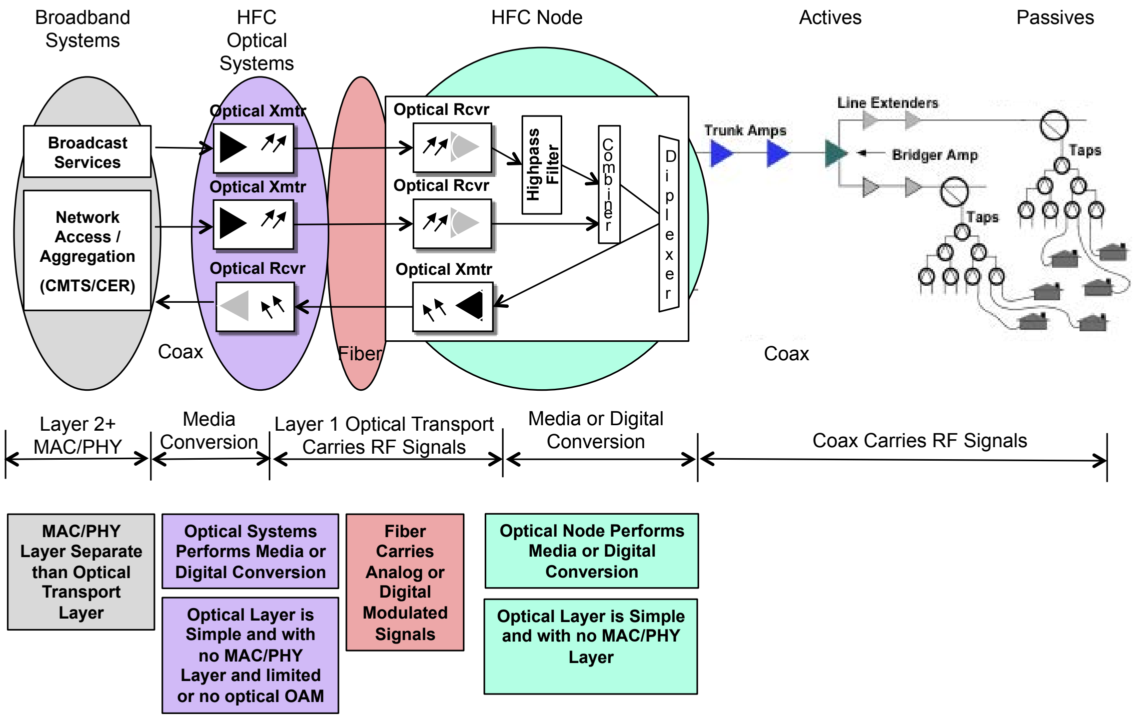


FIGURE 30:HFC A "MEDIA OR DIGITAL CONVERSION ARCHITECTURE"

Introduction to DFC (Digital Fiber Coax) / Distributed Access Layer Architecture

As we examine the future to support higher IP upstream data capacity and a transition of the downstream to more IP capacity for data and IPTV, the underlining architecture of HFC and centralized access layer may be placed into question. This is certainly nothing new. With each major shift in technology or major investment planned, the question of centralized vs. distributed appears. We will examine this class of architecture we are calling Digital Fiber Coax (DFC).

The Digital Fiber Coax Architecture label is for a network class which differs from HFC in that MAC/PHY or just PHY processing is distributed in the outside plant (node) or MDU and also uses ―purely digital" optical transport technologies such as Ethernet, PON, or others to/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.

As described in the following sections there are many technologies and architectures that could all be categorized asthe class of architecture we defineas Digital Fiber Coax (DFC). This term may certainly change and is just used for discussion purposes within this document, however it is clear that the functions of DFC are not similar to HFC, the industry should consider naming this class of architecture.

The underpinning of this style of distributed access layer architecture is not new and goes back to the CMTS in the node discussions in the late 1990's and early 2000's for the cable industry. These concepts arose when the DOCSIS technology was emerging to replace proprietary data and CBR voice systems and was also considered during a period when HFC upgrades were still underway or planned. These distributed access layer architectures were discussed again in the late 2000's when DOCSIS 3.0 was emerging, this time referred to as M-CMTS (modular-CMTS) or P-CMTS (partitioned CMTS), which could place some CMTS functions in the node, perhaps just the PHY layer. Again, in late 2010 with the announcement of DOCSIS-EoC (Ethernet over Coax) from Broadcom, placing the CMTS in the node or MDU revived the industry debate. Though DOCSIS-EoC is mainly focused on the China and worldwide MDU market. In addition to the CMTS in the node, the cable industry has considered QAM in the Node as well.

The diagram below illustrates an example of Digital Fiber Coax Class of Network Architecture using CMTS as the coax technology and PON or Active Ethernet as the optical transport to the node. The illustration is a node but could be an MDU. Additionally any optical technology or coaxial data technology could be employed, as discussed in detail below.

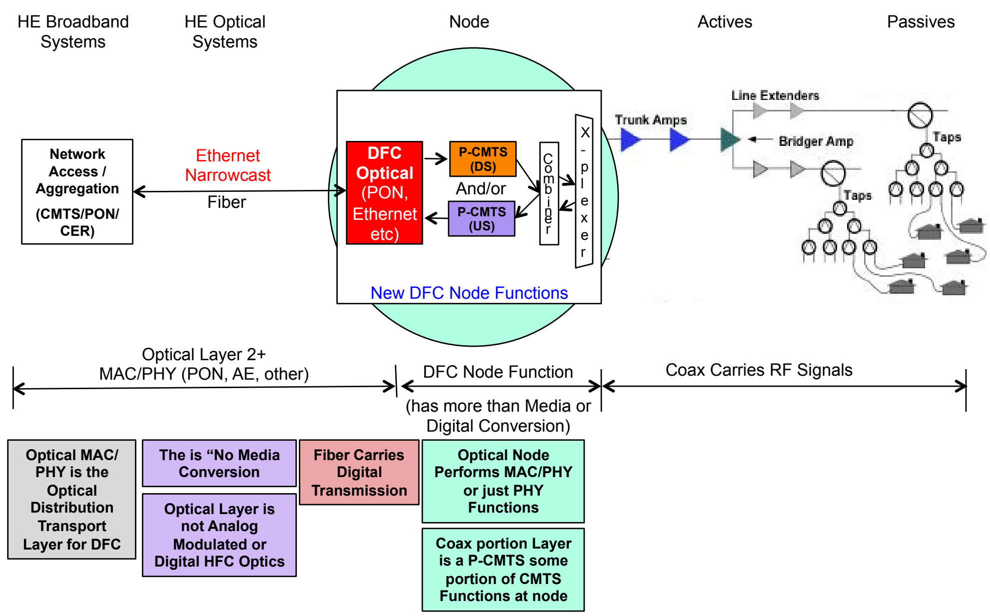


FIGURE 31: DIGITAL FIBER COAX A "PHY OR MAC/PHY PROCESSING ARCHITECTURE"

The actual development of a CMTS in the node, referred to as DOCSIS EoC by Broadcom, is a direct response to several other technologies morphing to be used as a coaxial access layer technology. While DOCSIS was designed from the ground up to be a cable access layer technology, the only architecture that a DOCSIS system was designed for was a centralized access layer approach, to be carried over an HFC network. The centralized access layer approach is a valuable approach to MSOs that have full two-way HFC and customers spread over vast outside plant areas. However, not all MSOs worldwide have full two-way, high capacity, and suitable HFC networks for data service; thus making a centralized CMTS architecture a challenge. A network architecture or suite of technologies used over coax referred to as Ethernet over Coax" (EoC) emerged to compete against DOCSIS; and the architecture was distributed, placing the CMTS-like functions in the node or MDU gateway.

The functions of EoC technologies are similar in many ways to DOCSIS, as most have a device, which functions like the CMTS, a central controller for scheduling network resources in a multiple or shared access network with end points like modems. The EoC architecture uses a fiber connection, likely Ethernet or PON to the node or MDU, where this transport is terminated and the data is carried to/from the CMTS-like function in the node/MDU and to/from customers over the coax.

Ethernet over Coax may be considered as an access layer technology where many consumers gain access to the service provider's network. However, some of the technologies in the EoC space may have started as home networking technologies such as MoCA, BPL, HomePlug, HPNA, G.hn, HiNOC, WiFi over Coax, and more. The placement of any of these technologies in a node to interface with coax in our view is not HFC style architecture, but rather DFC style architecture, as the MAC and the PHY processing takes place at the node.

Overview - DFC is a New Architecture Class for Cable

There are two different Fiber to the Node (FTTN) architectures, which utilize coax as the last mile media. If we consider HFC an architecture class with several technologies and architectures that may be employed, the same could be applied for the DFC architecture class.

To simply summarize the delta between HFC and DFC Architecture Classes:

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

Technology Optionsfor DFC

The DFC class of architecture could use several optical transport technologies to/from the Headend link to the node; this is called ―Ethernet Narrowcast". The optical technologies could employ PON, Active Ethernet, G.709, or others to carry data and management communications to/from the node.

The DFC class of architecture could use several coaxial-based MAC/PHY technologies such as DOCSIS, Edge QAM MPEG TS, MoCA, BPL, HomePlug, HPNA, G.hn, HiNOC, WiFi over Coax.

Architecture Options for DFC

The DFC architecture could consist of MAC/PHY or simply PHY functions in the Node. The architecture could support downstream and upstream functions or just a single direction.

Examination of DFC with EPON and P-CMTS

We have examined many layers of the network architecture and considered many approaches for upstream spectrum expansion and performance as well as optical transport in HFC style architectures. We wish to consider a distributed access layer architecture approach the digital fiber coax (DFC) style architecture.

The differences have been defined already between HFC and DFC. In addition, several technology and architecture choices that could be grouped under the DFC Class of Architecture were also covered. This section examines the use of DFC style architecture.

The DFC Architecture selected as an example in figure 32, illustrates 10G/10G EPON as the optical transport placing the optical MAC/PHY in the optical node and the second selection is DOCSIS as the RF technology. The architecture is an upstream only PHY in the node.

Consider then the use of HFC and DFC to support the legacy and new architecture simultaneously, this approach may be referred to as the DFC Split Access Model, as illustrated in figure 32. The HFC is usedto support legacy transport technology, services, and most importantly the centralized access architecture for the downstream such as the very high capacity CMTS/UEQ and the plus side is the massive and existing downstreamoptical transport is leveraged. There is no need to place downstream RF MAC or PHYs in the node in most configurations.

In the DFC split access model, the HFC upstream optical transport is leveraged as well, which may include the Sub-split 5-42 MHz band and even perhaps Mid-split. The HFC upstream optical transport will support a centralized access layer. The HFC with centralized access layer may be considered as the high availability architecture, because the OSP performs just media conversion and the centralized access layer systems, like a CMTS have highly redundant systems.

The DFC style architecture is used for two-way high capacity optical transmission to the node (like 10G Ethernet or 10G EPON) however initially this architecture will just consider using the upstream for the expanded coax upstream, see figure 32. The Partitioned CMTS (aka P-CMTS) using upstream only is examined in this paper, however additional downstream capacity could use the existing optical connection and the placement of a future P-CMTS for the downstream could be added later if needed, perhaps over 1 GHz spectrum range.

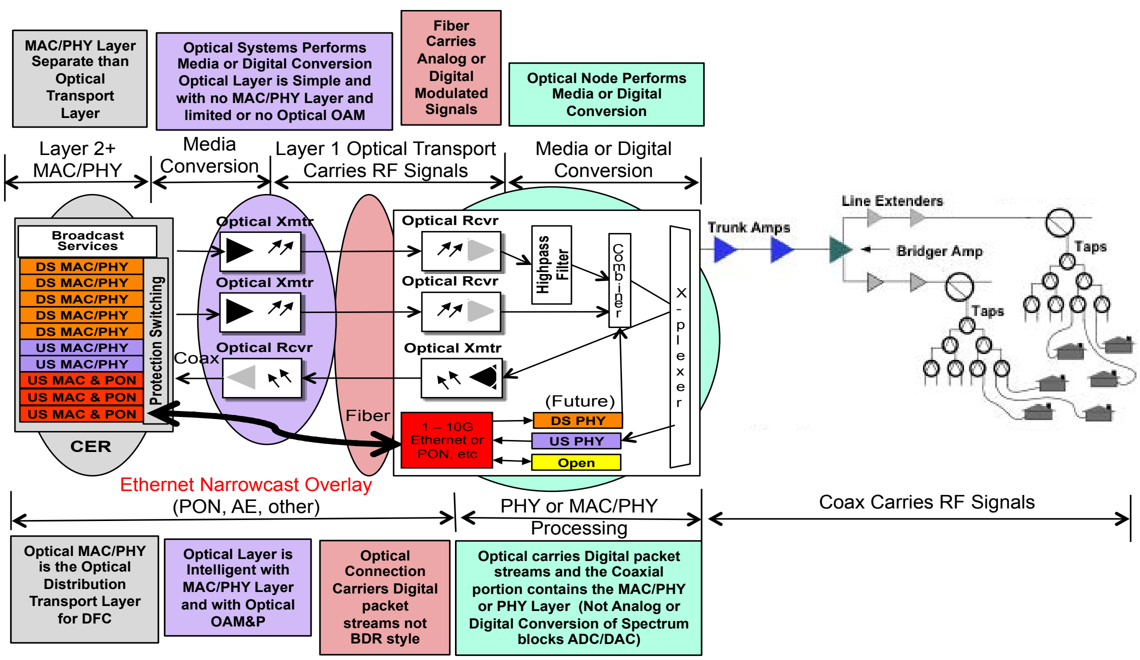


FIGURE 32: DIGITAL FIBER COAX (DFC) SPLIT ACCESS

Defining an architecture that placed the downstream PHY in the node was not financially prudent since the HFC forward already exists and has massive optical capacity. Centralized access layer architecturesover HFC have proven to be flexible, economical and will keep the outside plant (nodes) as simple as possible. The P-CMTS using just the PHY and just the upstream was selected to keep costs down as much as possible and may only be used ifconditions would require a distributed architecture. An example could be in situations where the use of an extremely long distancelink above 50 km or much higher is required. We believe the MSOs will want to keep the outside plant (OSP) as simple as possible for as long as possible; this has proven to be a very valuablecharacteristicfor 50 + years. Placing the entire CMTS in the node was not considered prudent because of the very high capital cost and it is least flexible for the future.

Description of P-CMTS (upstream only)

This paper has created a few new labels for cable networking architectures just for use within the paper. Another term that was created in a 2008 whitepaper but perhaps not well known is the Partitioned CMTS (aka a P-CMTS) [6]. The P-CMTS proposes to remote the DOCSIS PHY sub-system from the core CMTS chassis. The primary reason for the P-CMTS is that it can potentially permit the PHY sub-systems to be located a long distance from the MAC sub-systems, such as the node, and use the optical transport options defined above for Digital Fiber Coax to/from the node. The digital packet streams carrying the DOCSIS-encapsulated packets are transmitted across the optical link between the external PHY (node) and the core CMTS chassis.

Pros

The advantages of this approach are that the system would perform as if there were no optical link at all. The RF plant would essentially connect directly to the CMTS upstream port in the node as if it would have been in the headend. The advantages of this approach would be the same as the advantages of BDR with the exception of begin agnostic to the traffic. Its performance would be slightly better than BDR since the A to D and D to A conversions are eliminated.

The DFC style architecture would use optical technology that would have less configuration and two-way transport capacity with optical monitoring. The other advantage is distance and performance when compared with HFC style optical transmission. The DFC style architecture could be a QAM narrowcast overlay competitor, where typically optical links are long, costly, and challenging to optically configure.

Cons

The disadvantages of the DFC style architecture in this case using P-CMTS approach are that the solution would only work with DOCSIS returns (or the specific demodulations for which it was programmed) and would be ―unaware" of any other traffic that may exist on the network.

Placing MAC/PHY or just PHY functionsin the node may be difficult to change as new technology becomes available. This should be a very important consideration for MSOs as they reflect on the MAC/PHY technology changes in just the last 10-15 years, as described in the preceding HFC architecture section. The thought of touching every node to make a MAC or PHY change may be unthinkable to some operators.

Costs is an additional concern, when placing MAC/PHY or just PHYs in the node this means each node may need to be configured with enough capacity to meet the servicetier offeringand traffic capacity estimates up front. Another option is to make the node configurable to add capacity, this would mean visiting each node when additional capacity is needed.The MSOs have typically allocated capacity in the largestserving area possible, to gain economies of scale and additional capacity.

There may also be performance concerns with TCP latency with distributed architectures. The reliability and redundancy is also a consideration, there are more active components in the field.

Overall Assessment of DFCStyle Architectures

The HFC Architecture enables centralized access layer architectures; and DFC enables distributed access layer architecture. As discussed above, the industry since the 1990s has examined the placement of intelligence in the nodes; like CMTS and since then different part of the CMTS has been considered for the node, Edge QAM, PON, and many other technologies have been considered.

The main consideration for DFC style architecture may be the very long links of QAM overlay in the forward and in the future the new high capacity upstream. In those markets, there may be benefits from a DFC style architecture, but more study is needed and there are trade-offs.

MSOs using HFC and DOCSIS have benefited from leveraging DOCSIS capacity across many service groups expanding and contracting service group size at the DOCSIS layer where and when needed. Placing the CMTS functions of any kind or any MAC/PHY or PHY technology may have higher start-up costs and total cost of ownership could be a challenge. More study in needed to determine the viability of this type of architecture. Placing the intelligence in the node and distributing the architecture may limit future flexibility. Additional concerns of power and space will need to be explored if remote DOCSIS P-CMTS Upstream is explored.

NETWORK MIGRATION ANALYSIS AND STRATEGIES

This section provides analysis of someof the migration strategies. It is very important to note that the starting points of the MSO will greatly influence the selection of a particular network technology and architecture path. Additionally, the network utilization and capacity planning forecast in the local market will be a major driver for the migration strategy selected and timing by the cable operator. These are some of the factors that may influence the operator's selection path:

- Competitive and user consumption levelHigh-Speed data
- Video services offering
- Deployment level of STB which use Proprietary OOB or DSG
- Deployment level of DTA in market
- All Digital Offering
- Desire to offer analog service tier

- Current system spectrum capacity level (750 MHz or 1 GHz)

Downstream Migration Analysis

The findings of this report illustrate the MSOs existing downstream capacity is sufficient for this decade and beyond at the spectrum level 750 or equivalent assuming the upstream split options. There will be reclamation of the analog service tier and spectrum, reduction in the service group size, and reallocation of the distribution network from MPEG TS to IP.The downstream migration will be managed mainly from the headend systems and CPE migration to IP. Additionally, investment in full spectrum to each node will be need this decade and an additional forward transmitter to the node service group based on our service and capacity projections.

Upstream Migration Analysis

The cable industry has existing spectrum capacity and channel bonding capability in the upstream that will meet their service and capacity needs for many years to come, perhaps 2015-2017.

A migration to Mid-split first in the 2015 timeframe or when the capacity of Sub-split is exhausted by the technical and business analysis a good first step.

The next choice is High-split or a Top-split option. All of these solutions may start with 500 HHP node service group, but this will depend on the capacity requirement and split option selected.The service tier, customer traffic, and the node service group network elements will influence the service group size.

The Top-split analysis for a 500 HHP node has 64QAM as possible for Top-split (900-1050) and QPSK for Top-split (1250-1550) but neither achieve the capacity of High-split. Top-split (900-1050) with Mid-split in a 500 HHP node may reach the capacity of High-split.

The Top-split migration to a 125 HHP Service Group, reduces the funneling noise by 6 dB, which permits 256QAM for Top-split (900-1050) and 16QAM for Top-split (1250-1550) and both of these Top-split options coupled with Sub-split will yield the capacity of High-split.

Below are some high-level considerations for the migration and split selection.

- Consider Mid-split first (This buys about a decade and churns out old STBs to avoid the OOB)
- Consider an eventual High-splitupgrade path capable of 200-300 MHz
- If there are concerns with video service, STB OOB, and want to avoid touching the passives, consider Top-Split (900-1050)<u>with</u> Mid-split and a 500 HHP node as this has same capacity as High-split (200).
- Consider reserving the above 1 GHz for the next decade.
- A migration to Top-split (1250-1550) with Sub-split will require a 125 HHP service group to have the capacity of High-split.

COST ANALYSIS

The report has covered some of the key inputs and levers to begin to assess the costs of the upstream spectrum options. The underlining requirementsof the network architecture to meet the capacity targets have been documented. In this section some of those key technical assumptions will be covered to provide perspective as to the drivers and considerations in the cost analysis. The cost analysis makes some estimates to cost for products that have not yet been invented, so these are rough estimates used for discussions purposes only. The actual relationship between the upstream migration options may vary.

The HFC network allows operators to employ a number of methods to manage the abundant downstream spectrum. Some of these options include analog reclamation, switched digital video delivery of multicast content and service group size management, mainly achieved by node segmentation or node splitting to achieve the desired ratios. The relative costs and benefits of these downstream augmentations are well understood and used extensively today. As shown in the previous sections, the upstream spectrum has been sufficient to meet the demand, but before the end of the decade, additional spectrum may be required, in some MSO markets.

Downstream Cost Analysis

- Converged Edge Router DOCSIS/Edge QAM device will enable an effective migrations
- The Downstream may leverage a 6MHz by 6MHz channel investment which supports a smooth and economical transition while assuring revenue targets per 6 MHz channel for the MSO are met
- High-Split 200 may requirea forward laser upgrade to 1 GHz to gain the spectrum lost to upstream
- Top-split (900-1050) or Top-split 1250-1550 will leverage existing lasers for downstream
- Full Spectrum to a 500 HHP Node to 250 HHP segmentation is expected within the decade
- QAM overlay solutions may need to migrate to full spectrum
- Passive changes may be avoided for entire decade and beyond
- FTTLA may be avoided for entire decade and beyond

UpstreamCost Analysis

The following analysis is focused on a number of upstream options. The feasibility and relative cost of each path is compared. The analysis assumes a ―typical" HFC node has the following characteristics shown in Figure 33.

Beginning with a 500 home passed node, the first approach was to determine what might be possible without having to disturb the layout of the physical plant.

Figure 34 shows what the gain requirements (excluding port, EQ losses) would be for an upstream amplifier at the ranges of operating frequencies reviewed earlier in this paper. For this analysis, 0.75" PIII class cable was assumed for express amplifier spans and 0.625" PIII class cable was assumed for tapped feeder spans.

Typical Node Assumptions		
Homes Passed	500	
Home Passed Density	75	hp/mile
Node Mileage	6.67	miles
Amplifiers/mile	4.5	/mile
Taps/Mile	30	/mile
Amplfiers	30	
Taps	200	
Highest Tap Value	23	dB
Lowest Tap Value	8	dB
Largest Amplifier Span	2000	ft
Largest Feeder Span	1000	ft
Largest Drop Span	150.0	ft
Home Split Loss to Modem	4	dB
Maximum Modem Power	65	dBmV

FIGURE 33: GENERAL NODE ASSUMPTIONS

		Sub-Split	Mid-Split	High-Split 200	Top-Split (900-1050)	Top Split (1250-1550)
Upper Frequency	MHz	42	85	200	1050	1550
Typical Maximum Cable Loss (Amp to Amp 70 deg F)	dB	7.1	10.1	15.5	35.5	43.1
Aditional Gain Required for Thermal Control (0 to 140 deg F)	+/-dB	0.5	0.7	1.1	2.5	3.0
Total Reverse Amplifier Gain Required	dB	**7.6**	**10.8**	**16.6**	**38.0**	**46.1**

FIGURE 34: RETURN AMPLIFIER GAIN CALCULATION

It is worth noting that the Sub-split, Mid-split and High-split gain requirements can be satisfied with commonly available components that are currently used in amplifier designs today and would likely involve no cost premium. However, the Top-Split options would likely require multistage high gain amplifiers to overcome predicted losses, which would be more costly. It is also important to note that thermal control would likely become a major issue in the Top-split designs. Figure 34 shows seasonal temperature swings of 5 to 6 dB loss change per amplifier span would be likely in the top split solutions. Reverse RF AGC systems do not exist today, and could be complex and problematic to design. Thermal equalization would be sufficient to control the expected level changes at 200 MHz and below, but it is not certain that thermal equalization alone will provide the required control above 750MHz. This needs more study.

Figure 35 is a summary of path loss comparisons from home to the input of the first amplifier, which will ultimately determine the system operation point. It is interesting to note that as soon as the upper frequency is moved beyond the Sub-split limit, the maximum loss path tends toward the last tap in cascade as opposed to the first tap. There is a moderate increase in expected loss from 42 to 200 MHz, and a very large loss profile at 1000 MHz and above. The expected systemperformance can be calculated for each scenario.

		Sub-Split	Mid-Split	High-Split 200	Top-Split (900-1050) with Sub-split	Top Split (1250-1550) with Sub-split
Upper Frequency	MHz	42	85	200	1050	1550
Worst Case Path Loss	dB	**29.4**	**30.8**	**35.6**	**53.1**	**59.8**
Hardline Cable Type		0.625 PIII	0.625 PIII	0.625 PIII	0.625 PIII	0.625 PIII
Cable Loss/ft	dB/ft	0.0042	0.0060	0.0092	0.0211	0.0256
Drop Cable Type		Series 6	Series 6	Series 6	Series 6	Series 6
Cable Loss/ft	dB/ft	0.0134	0.0190	0.0292	0.0669	0.0812
Path Loss from First Tap	dB	*29.4*	*30.5*	*32.3*	*39.1*	*41.7*
Hardline Cable to First Tap	ft	100	100	100	100	100
Cable Loss	dB	0.42	0.60	0.92	2.11	2.56
Tap Port Loss	dB	23	23	23	23	23
Total Drop Loss	dB	2.0	2.9	4.4	10.0	12.2
In Home Passive Loss to Modem	dB	4	4	4	4	4
Path Loss from Last Tap	dB	*28.2*	*30.8*	*35.6*	*53.1*	*59.8*
Hardline Cable to Last Tap	ft	1000	1000	1000	1000	1000
Cable Loss	dB	4.21	5.99	9.19	21.06	25.59
Tap Insertion Loss	dB	10	10	10	10	10
Tap Port Loss	dB	8	8	8	8	8
Total Drop Loss	dB	2.0	2.9	4.4	10.0	12.2
In Home Passive Loss to Modem	dB	4	4	4	4	4

FIGURE 35: PATH LOSS FROM HOME TO FIRST AMPLIFIER

Figure 36 shows the compared performance calculations for the 500 home passed node outlined in Figure 33. The desired performance target is 256QAM for each scenario; if it can be achieved, the throughput per subscriber will be maximized. For each approach, it is assumed that a CPE device is available with upstream bonding capability that can use the entire spectrum available at a reasonable cost. The number of bonded carriers transmitting must not exceed the maximum allowable modem transmit level, so the maximum power per carrier is calculated not to exceed 65 dBmV total transmitted power. The maximum power, along with the worst-case path loss, yields the input level to the reverse amplifiers in the HFC Network. If the return level was greater than 15 dBmV, it was assumed that it would be attenuated to 15 dBmV.

Armed with the input level and station noise figure, the single station amplifier C/N is calculated and then funneled through the total number of distribution amplifiers serving the node to yield the C/N performance expected at the input of the node. Worst case performance and lowest cost for return optical links was assumed to be obtained from analog DFB lasers up to 200 MHz which suggests staying with Analog Return; but cost parity between analog and broadband digital return (BDR) systems at 1000 MHz and above is now possible.

The results show that the solutions up to 200 MHz have sufficient performance to support 256QAM modulation at a 500 HHP node.The top split options suffer from cable loss, not to exceed +65 dBmV, and noise funneling.The Top-split (900 -1050) may operate at 64QAM and Top-split (1250-1550) may operate at QPSKand stay within margin budget using a 500 HHP node. Cost projectionsfor the various solutions show that High-split 200 MHz return delivers the highest throughput per subscriber at the lowest relative cost.

		Sub-Split	Mid-Split	High-Split 200	Top-Split (900-1050) with Sub-split	Top Split (1250-1550) with Sub-split
Upper Frequency	MHz	42	85	200	1050	1550
Homes Passed		500	500	500	500	500
HSD Take Rate		50%	50%	50%	50%	50%
HSD Customers		250	250	250	250	250
Desired Carrier BW	MHz	6.4	6.4	6.4	6.4	6.4
Modulation Type		**64-QAM**	**256-QAM**	**256-QAM**	**64-QAM**	**QPSK**
Bits/Symbol		6	8	8	6	2
Desired C/N	dB	33	40	40	33	20
Number Carriers in Bonding Group		3.5	11	29	23	47
Max Power per Carrier Allowed in Home	dBmV	60	55	50	51	48
Worst Case Path Loss	dB	**29.4**	**30.8**	**35.6**	**53.1**	**59.8**
Maximum Return Amplifier Input	dBmV	30	24	15	-2	-11
Actual Return Amplifier Input	dBmV	15	15	15	-2	-11
Assumed Noise Figure of Amplifier	dB	7	7	7	7	7
Return Amplifier C/N (Single Station)	dB	65	65	65	48	39
Number of Amplifiers in Service Group		30	30	30	30	30
Return Amplifier C/N (Funneled)	dB	50.4	50.4	50.4	33.7	23.9
Optical Return Path Technology		DFB	DFB	DFB	BDR	BDR
Assumed Optical C/N	dB	48	45	41	50	50
System C/N	dB	**46.0**	**43.9**	**40.5**	**33.6**	**23.9**
Expected Maximum Datarate after Overhead	Mbps	91.8	370.2	975.9	603.2	455.3
Extra Datarate from Sub/Mid Bands					91.8	91.8
Total Datarate from all Bands		91.8	370.2	975.9	694.9	547.1
Throughput/Customer	Mbps	0.37	1.48	3.90	2.78	2.19
Cost Scale			100%	100%	139%	218%
Solution Figure of Merit (Throughput/Cost Scale)			1.48	3.90	2.00	1.00

FIGURE 36: PERFORMANCE OF 500 HP NODE

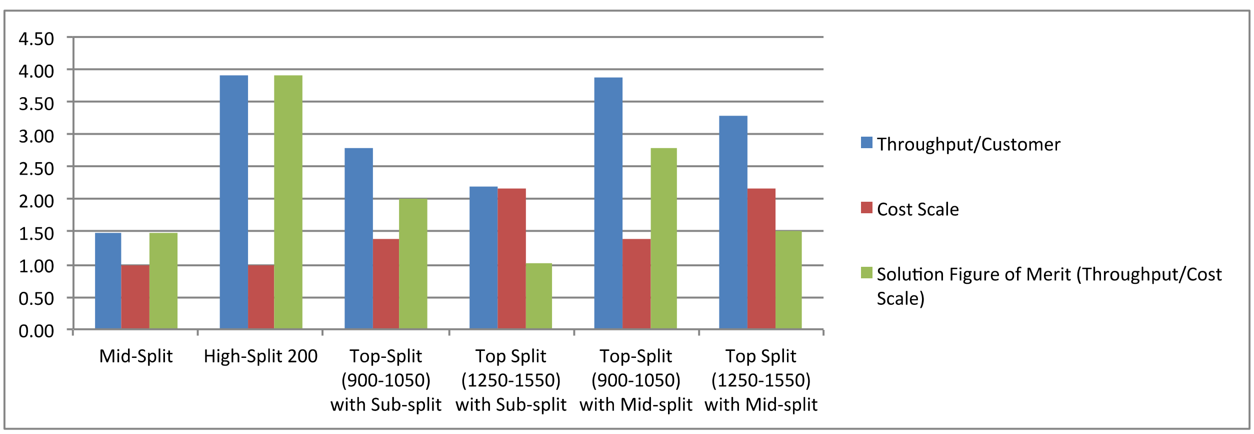


FIGURE 37: RELATIVE COST AND THROUGHPUT COMPARISON 500 HP NODE SOLUTIONS

Further analysis of the Top-split options concludes that reducing the node size, and thereby the funneled noise in the serving group could yield higher modulation capability. Figure 38 shows the comparison again with the Top-split scenarios including a four way node split. The noise funneling is reduced to a level where higher order modulations are possible. The costs of the additional node splits seem to scale appropriately with the additional throughput per subscriber.

		Sub-Split	Mid-Split	High-Split 200	Top-Split (900-1050) with Sub-split	Top Split (1250-1550) with Sub-split
Upper Frequency	MHz	42	85	200	1050	1550
Homes Passed		500	500	500	125	125
HSD Take Rate		50%	50%	50%	50%	50%
HSD Customers		250	250	250	62.5	62.5
Desired Carrier BW	MHz	6.4	6.4	6.4	6.4	6.4
Modulation Type		**64-QAM**	**256-QAM**	**256-QAM**	**256-QAM**	**16-QAM**
Bits/Symbol		6	8	8	8	4
Desired C/N	dB	33	40	40	40	27
Number Carriers in Bonding Group		3.5	11	29	23	47
Max Power per Carrier Allowed in Home	dBmV	60	55	50	51	48
Worst Case Path Loss	dB	**29.4**	**30.8**	**35.6**	**53.1**	**59.8**
Maximum Return Amplifier Input	dBmV	30	24	15	-2	-11
Actual Return Amplifier Input	dBmV	15	15	15	-2	-11
Assumed Noise Figure of Amplifier	dB	7	7	7	7	7
Return Amplifier C/N (Single Station)	dB	65	65	65	48	39
Number of Amplifiers in Service Group		30	30	30	7	7
Return Amplifier C/N (Funneled)	dB	50.4	50.4	50.4	40.0	30.2
Optical Return Path Technology		DFB	DFB	DFB	BDR	BDR
Assumed Optical C/N	dB	48	45	41	50	50
System C/N	dB	**46.0**	**43.9**	**40.5**	**39.6**	**30.2**
Expected Maximum Datarate after Overhead	Mbps	91.8	370.2	975.9	774.0	863.8
Extra Datarate from Sub/Mid Bands					91.8	91.8
Total Datarate from all Bands		91.8	370.2	975.9	865.8	955.6
Throughput/Customer	Mbps	0.37	1.48	3.90	12.38	13.82
Cost Scale			100%	128%	240%	302%
Solution Figure of Merit (Throughput/Cost Scale)			1.48	3.06	5.17	4.58

FIGURE 38: COMPARISONS WITH TOP SPLIT ONLY AT 125 HP NODE

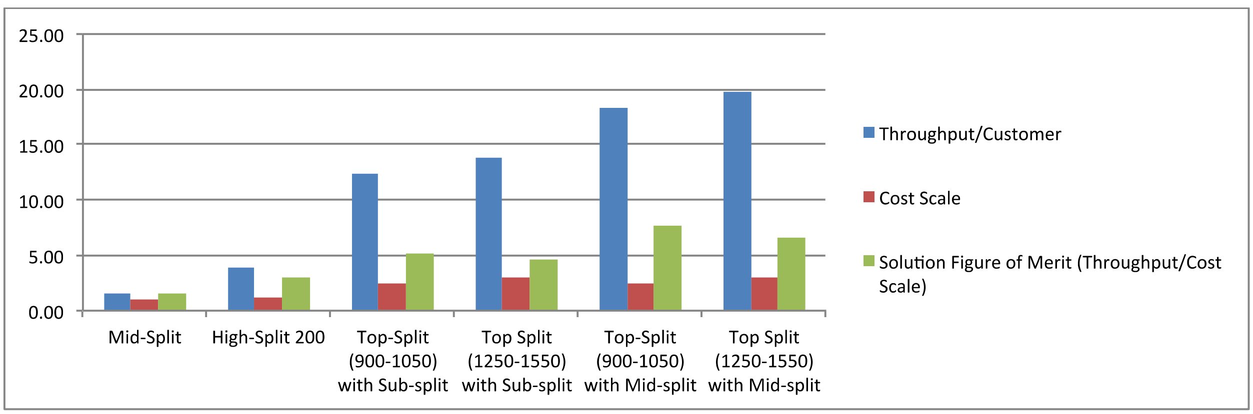


FIGURE 39: COST AND THROUGHPUT COMPARISON WITH TOP SPLIT ONLY AT 125 HP NODE

Summary of Cost Analysis

As stated in the opening of this section, the cost analysis providesestimates for discussion purposes only. The actual cost relative to one another may vary widely when products have been developed and released to market.

Perhaps a reasonable way to consider the data found in figures 36 and 37is that these may represent ―initial costs" to provide capacity above Mid-split. The cost analysis material in figures 38 and 39 may represent the ―end state cost analysis" to achieve the capacity requirements for this decade and beyond (approximately up to 2021 to 2023 timeframe). Moreover, these last analysesalso provide apple-to-apples cost estimates of High-split and the two Top-split options to reach similar network capacity targets.

The cost analyses capture the equipment and labor cost estimates for the optical transport and HFC systems. The cost analysis predicts that Mid-split and High-split will share similar costs on the return path systems, however the loss of downstream spectrum will have to be replaced if High-split is selected, captured in figures 38 and 39. The costs to solve the STBOut of Band (OOB), impacts to analog service tier, and loss of video spectrum for STBs and TVs was not calculated in the analysis of High-splits.

The two Top-split options do not account for the cost ofMid-split this isassumed to be the first upstream augmentation selection by the MSOs. Additionally, the High-split option uses the spectrum of Mid-split thus we considered this a sunk cost. The use of either Top-split (900-1050) option with Mid-split should achieve similar or greater upstream capacity compared to High-split. Either Top-split optionwith Sub-split will need to move to a 125 HHP node service group to achieve the capacity of High-split. The Top-split options do not account for the additional DOCSIS capacity because more channels are needed to achieve the capacity level of High-split (200).

The cost analysis intentionally excluded the items related to High-split and Top-split mentioned above in order to illustrate the relative cost for the spectrum split. We have additionalanalyses, which includesome of the items which were excluded from High-split and the Top-split options.

These are the findings of the cost analysis comparing four spectrum split options. The costs of the spectrum option to yield similar data capacity consideringHigh-split (200) and both Top-split options are illustrated in figure 40.

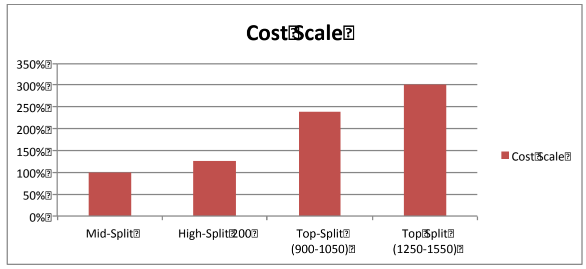


FIGURE 40: COST ANALYSIS

The Top-split (900-1050) with Mid-split given a 500 HHP may reach the capacity of High-split. The analysis estimates that Top-split (900-1050) is about 1.39 times the costof High-split (200), in this HFC topology. Again the Mid-split cost is not considered.

The Top-split options that avoid using Mid-split spectrum but does use the existing Sub-split spectrum will need to move to a 125 HHP node service group to achieve similar capacity to High-split. The analysis estimates that Top-split (900-1050) with Sub-split is about 2.4 times the costof High-split (200). The Top-split (1250-1550) with Sub-split is about 3 times the costof High-split (200).

EXECUTIVE SUMMARY AND CONCLUSIONS

The cable industry will transition and evolve their existing networks from largely broadcast video to unicast, likely using IP-based delivery technology. The High-Speed Internet Service and networks will continue to expand, meeting the needs for higher service tiers and more capacity downstream and upstream.

The paper provides assumptions and predictions for the evolution of advanced video and high-speed Internet services. The report assesses the timing and drivers of network change, possible technologies, architectures, migration options, and a cost vs. performance analysis.

The comparisons found in the report are at nearly every layer of the MSO's Next Generation Cable Access Network. These areas include spectrum splits, data network technology, and network architecture options. The examination will include a look at the traditional centralized access layer data architecture used over cable HFC networks.

We also define a possible alternative architecture to HFC, which we refer to as Digital Fiber Coax (DFC). This is a distributed access layer architecture using EPON or Ethernet style optical transport to the node where a coax based MAC/PHY or PHY resides supporting downstream and upstream; or just one direction (upstream).

Additionally, as the industry considers the future evolution of the network the report examines the importance of backward compatibility and the drivers behind this methodology.

Video and High-Speed Data Service Estimates

- Unicast services like On-Demand Video and High-Speed Internet will dominate the MSO service offering and spectrum allocation for the coming decade.
- Today, less than 4% of the MSO's downstream spectrum is allocated to High-Speed Data; however, it is forecasted that this might be 50% within the next 10 years.
- An industry accepted modeling tool based on a thirty-year history of Data Service offerings and capabilities predicts a ~ 2.5 Gbps Downstream and 500 Mbps Upstream Internet service offering in 10 years.
- The recent announcements from the United Kingdom's cable provider *Virgin Media* of a 1.5 Gbps Down / 150 Mbps Up trial and *Verizon's* FiOS reports of upgrades to 10 Gbps Down / 2.5 Gbps Up, is disrupting this thirty-year industry benchmark study of data service growth.

Cost Analysis & Performance Summaries

The upstream spectrum split options reviewedhave vastly different HFC topology and data network layer requirements, which have significant impact to the cost estimates. The cost analyses capture the equipment and labor cost estimates for the optical transport and HFC systems.

The cost analysis predicts that Mid-split and High-split will share similar costs for return path electronics, however the loss of downstream spectrum will have to be replaced if High-split is selected. The High-split option will have some impacts to network functions and services. The costs to solve the STB Out of Band (OOB), impacts to analog service tier, and loss of video spectrum for STBs and TVs was not calculated in the analysis of High-split.

The two Top-split options do not account for the additional DOCSIS channels needed to achieve the capacity level similar to High-split (200). The Top-split (900-1050) with Mid-split (given a 500 HHP service area) may reach the capacity of High-split. The analysis estimates that Top-split (900-1050) is about 1.39 times the costof High-split (200), in this HFC topology. Again, the Mid-split cost is not considered.

The Top-split options that avoid using Mid-split spectrum, but does use the existing Sub-split spectrum, will need to move to a 125 HHP node service group to achieve similar capacity to High-split. The analysis estimates that Top-split (900-1050) with Sub-split is about 2.4 times the costof High-split (200). The Top-split (1250-1550) with Sub-split is about 3 times the cost of High-split (200).

The cost analysis intentionally excluded the items related to High-split and Top-split mentioned above in order to illustrate the relative cost for the spectrum split. We have additional analyses, which include some of the items that were excluded from High-split and the Top-split options, that were not included in this report.

Top-split costs are driven by the network characteristics including: cable loss that progressively increases as frequency increases, modem maximum power output composite not to exceed +65 dBmV and the funneling effect of a large number of return path amplifiers. These critical factors andkey findings of the report illustrate the impacts to the HFC network topology, such as the size of the node service group. Additionally, the Top-split options must use lower order modulations, resulting in more spectrum and more CMTS ports needed to sustain equivalent capacity of High-split.

Key Network Performance Factors

- Network data capacity parity between High-split and the Top-split Options have vastly different network topologies and costs.
- The major reasons why lower frequency return (Sub-, Mid-, and High-split) and higher frequency return (Top-split options) have such performance differences which impact network architecture, capacity, and cost are as follows:
- First Major Reason: Cable loss progressivelyincreases as frequency increases, thus a major factor when considering higher frequency return.
- Second Major Reason: Modem maximum power output composite not to exceed +65 dBmV (to minimize power and cost, andmaintain acceptable distortion)

- Third Major Reason: Funneling effects of a large number of return path amplifiers. This is not a factor at low frequency because the cableloss is low enough that a cable modem can provide adequate power level to maintain high C/N.
- Existing 5-42 / 750 MHz system with a 500 HHP node may remain unchanged until 2015 and then a series of network migration steps that are defined in this paper may occur
- Existing 1 GHz Passives do not have to be touched until perhaps the year 2023
- Existing Passives may support up to 1050 MHz for additional upstream or downstream capacity
- A limitation of power passing taps is the AC power choke resonance. This is an important finding when leveraging the existing passives; therefore the use above 1050 MHz may not be predictable or even possible
- Passives represent approximately 180-220 devices per 500 HHP node group
- Small Nodes and FTTLA are not required until perhaps the second half of the 2020's decade.
- Downstream spectrum recovery methods will support the transition from broadcast to unicast service delivery and will help solve the downstream capacity challenge
- Downstream (assuming an equivalent 750 MHz system) will need to support full spectrum per node service group within the decade
- Mid-split is an excellent first step: low cost, small spectrum, high data capacity which lasts about a decade
- Mid-split in place of a node split may enable a 500 HHP node to last about a decade
- HFC Conclusions 1: architecture remains viable well through this decade and beyond
- HFC Conclusions 2: existing technology, costs, flexibility and versatility to support transport of virtually any new MAC/PHY technology remains a core benefit and value
- HFC Conclusions 3: Optical transport supported with DFB analog lasers and BDR last throughout the decade
- HFC Conclusions 4: HFC allows the outside plant to remain simple, just performing media and/or digital conversion (for BDR), thus no MAC or PHY layer processing is required in the node
- HFC Conclusions 5: enables a centralized access layer for economies of scale and just in time investment in capacity
- Digital Fiber Coax (DFC)
  DFC Conclusion 1: A distributed MAC or PHY architecture that would compete or complement HFC is not a viable replacement in nearly all cases, except extremely long distance to the node,as discussed in the report, however more study is required.

- DFC Conclusion 2: A distributed architecture and its risks include: stranding capital, low flexibility and limited versatility
- DOCSIS Conclusion 1: enables the full spectrum migration to IP in both the downstream and upstream
- DOCSIS Conclusion 2: enables a smooth channel-by-channel migration, this is key for the MSO to maximize revenue per MHz and allowing just in time investment while converting to IP
- DOCSIS Conclusion 3: DOCSIS will support new upstream spectrum, increase modulation schemes, may add MACand PHY layer improvements (perhaps OFDM)
- Figure 41:DOCSIS QAM Estimates for:HFC Topology, Spectrum Split and PHY Capacity Comparison

DOCSIS QAM	Sub-split	Mid-split	High-split 200	Top-split (900-1050) with Sub-split	Top split (1250-1550) with Sub-split	Top-split (900-1050) with Mid-split	Top split (1250-1550) with Mid-split	Top-split (900-1050) with Sub-split	Top split (1250-1550) with Sub-split	Top-split (900-1050) with Mid-split	Top split (1250-1550) with Mid-split
Node Service Group	500	500	500	500	500	500	500	125	125	125	125
Capacity from Sub-split	92	92	92	92	92	92	92	92	92	92	92
Capacity from Mid-split		225	225			225	225			225	225
Capacity from High-split			599								
Capacity from Top-split				617	410	617	410	782	820	782	820
Total PHY Channel Bond Capacity (Usable) in Mbps	92	316	916	708	502	933	726	874	912	1,099	1,136

Figure 41: HFC Topology, Spectrum Split and PHY Capacity Comparison

Network Evolution Prediction Summary

- **Year 2015:**Upstream 500 HHP Node Split/Segment —ởř add new spectrumupstream& keep node size
- **Year 2017:** North America 5-42 is exhausted because of High-Speed Internet Service Tier, more upstream spectrum required.
- **Year 2017-18:** Downstream 500 HHP Node is at capacity (assuming 250 Subs with 0.9-1.4 Gbps of Traffic Plus 3.6 Gbps of MSO Video Traffic)(reduce SG or add spectrum)
- **Year 2018-19:**Euro 5-65 is exhausted because of High-Speed Internet Service Tier,more upstream spectrum required.
- **Year 2019:** Upstream 500 HHP Node with Mid-split DOCSIS is exhausted (reduce SG or add spectrum)
- **Year 2020:** Mid-split (5-85) with either DOCSIS QAM or OFDM is approaching capacity and in year 2021 would be out of capacity driven by Service Tier growth; thus more upstream Spectrum is Required (High-split or Top-split)
- **Year 2021:** HSD Max Service Tier prediction of 2.2 Gbps + 1.8 Gbps of MSO Videoapproaching capacity of 750 MHz system
- **Year 2021:** Downstream 250 HHP Node is at capacity (assuming 125 HSD Subs with 2.3 Gbps of Traffic

Plus 1.8 Gbps of MSO Video Traffic) change SG size or service

- **Year 2021-22:** Upstream 500 HHP Node nears capacity with High-split 200 or Top-split (900-1050)+Mid-split Using DOCSIS QAM or OFDM (use of OFDM bought a few months of capacity)
- **Year 2023:**Upstream HSD Max Service Tier Prediction of 995 Mbps Upstream Serviceconsumes High-split 200 or Top-split (+Mid-split) Using DOCSIS QAM or OFDM
- **Year 2023:** Downstream HSD Max Service Tier Prediction Consumes All Downstream Spectrum thus additional Spectrum Above 1 GHz is required or FTTx
- **Year 2023 - 2024: MSOs touch the passives to increase spectrum above 1 GHz to achieve higher Downstream and Upstream capacity based on HSD predictions**
- <u>**If these do not materialize**</u> (i.e. High-speed data service prediction over 4 Gbps Down and 1 Gbps Up in the year 2023) nodes splits/node segmentation will solve the traffic growth projections for many more years
- **Finally,**if neither the Service Growth Rates nor Traffic Utilization Growth Rates are maintained at a 50% CAGR, then the timing and drivers for investment will change and the HFC will last far longer.

Importance of Backward Compatibility

- DOCSIS 3.0 QAM based and any successorshould consider that every MHz should all share the same channel bonding group, this maximizes the use of existing spectrum and delays investment
- Sharing channel bonding groups with DOCSIS 3.0 and Any Successor creates “one” IP Network (cap and grow networks hang around awhile)
- Sharing the same bonding group assures previous and future investment may be applied in creating larger IP based bandwidth and not stranding previous capital investment
- Backward Compatibility has benefitted industries like the IEEE Ethernet, WiFi, and EPON saving the entire eco-system money
- Backward Compatibility simply allows the MSOs to delay and perhaps avoid major investment to the network such as adding more spectrum or running fiber deeper.
- All of our analysis in this report assumes backward compatibility with DOCSIS 3.0 QAM and any successor, like DOCSIS OFDM; thus creating a larger and larger IP bonding group with each year’s investment. If this is not the case the investment in HFC upgrades will pull forward. It is uncertain of the exact level of financial impact but the total cost of ownership may be higher when deploying two separate IP based network technologies.

These are the major takeaways of this paper, however additional information is contained in the report providing perspective and details to the conclusions cited above.

The examination of the next generation cable access network spans several disciplines and this report is not a complete analysis of all of the possibilities.

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LIST OF ABBREVIATIONS AND ACRONYMS

BPON	Broadband PON
CAGR	Compound Annual Growth Rate
CBR	Constant Bit Rate
DBS	Digital Broadcast System
DFC	Digital Fiber Coax
DOCSIS	Data Over Cable Service Interface Specifications
DSG	DOCSIS Set-top Gateway
DTA	Digital Terminal Adapter
EoC	Ethernet over Coax
EPON	Ethernet Passive Optical Network
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
HPNA	HomePNA Alliance
HSD	High Speed Data
IP	Internet Protocol
IPTV	Internet ProtocolTV
MAC	Media Access Layer
Mbps	Megabit per Second
MoCA	Multimedia over Coax Alliance
MSO	Multiple Systems Operator
OFDM	Orthogonal Frequency Division Multiplexing
OSP	Outside Plant
OTT	Over The Top
P2P	Peer-to-peer
PHY	Physical Layer
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RFoG	RF Over Glass
SDV	Switch Digital Video
UHF	Ultra High Frequency
US	Upstream
VoD	Video on Demand