Mission is Possible:
An Evolutionary Approach to Gigabit-Class DOCSIS

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Abstract

This paper is a joint paper presented by four leading suppliers to the cable industry, with the intent to move the industry forward in the area of next generation cable access network migration. To our knowledge, it is a first for four such suppliers to collaborate in this manner on a topic of such critical industry importance.

Cable operators are facing a rising threat associated with the limitations of today's 5 to 42 MHz return path. Constraints on capacity and peak service rate call for finding additional return spectrum to manage this emerging challenge.

We will explain how and why an approach based on the principle of an expanded diplex architecture, and using a "high-split" of up to 300 MHz, is the best path for operators to manage this growth. This includes considering the simultaneous expansion of the downstream capacity.

We will describe obstacles associated with legacy CPE in both Motorola and Cisco video architectures and propose solutions to these issues.

To use the reallocated HFC spectrum most effectively, we will consider an evolutionary strategy for DOCSIS and show how it capably meets the requirements ahead.

We will contemplate the application of new generations of communications technology, including a comparison of single-carrier approaches implemented today to multi-carrier techniques such as OFDM, including channelization options. We will consider higher order QAM formats as well as modern FEC tools such as LDPC.

We will discuss how these evolution alternatives can be harnessed to best extract network capacity. We will consider how evolution of the access architecture enables this new capacity, and how the end-to-end network components develop to support this growth.

In summary, we will present a strategy that preserves network investment, enables a versatile evolutionary path, and positions operators to create an enduring lifespan to meet the demands of current and future services.

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1 INTRODUCTION

The evolution of DOCSIS is bounded only by technology and imagination - both of which themselves are unbounded.

This white paper takes an in depth look into the technologies that are available to DOCSIS and then makes concrete recommendations on how DOCSIS should be taken to a new level of performance.

DOCSIS to Date

The original DOCSIS 1.0 I01 (Interim version 1) specification was released on March 26, 1997. DOCSIS technology has evolved very well since its inception over 15 years ago. Here are some of the interesting milestones from those first 15 years.

- 1997 Mar – DOCSIS 1.0 I01 released. Features basic data service.
- 1997 Dec – Cogeco has the first large scale DOCSIS 1.0 deployments
- 1999 Mar – First certified CM and qualified CMTS
- 1999 Apr – DOCSIS 1.1 released. Adds QoS.
- 1999 Dec – PacketCable 1.0 released. Adds voice over IP (VoIP)
- 2001 Dec – DOCSIS 2.0 released. Adds ATDMA and SCDMA.
- 2002 Feb – DSG released. Adds STB control channel to DOCSIS
- 2005 Aug – Modular CMTS (MHA) released. Shared EQAM between DOCSIS and video is added.
- 2006 Aug – DOCSIS 3.0 released. Adds bonding, IPv6, and multicast.

In the first phase of its life, DOCSIS focused on a moderately dense and complex MAC and PHY with a comprehensive set of features and services. DOCSIS now has a very rich and mature service layer.

If this was the first 15 years of DOCSIS, then what is the next 15 years of DOCSIS going to look like? How well will DOCSIS compete with other broadband technologies?

The Future Potential of DOCSIS

The next phase of DOCSIS will take it to gigabit speeds. DOCSIS needs to scale from a few RF channels within a CATV spectrum to being able to inherit the entire spectrum. And DOCSIS may not even stop there.

In the upstream, in an effort to get to gigabit speeds and beyond, DOCSIS needs to scale beyond its current 5 – 42 MHz (65 MHz In Europe) to multiple hundreds of megahertz. In the downstream, DOCSIS needs to extend beyond the current 1 GHz limit and set a new upper RF boundary for HFC Plant.

Table 1 shows where DOCSIS technology is today and where it is going.

Today, the deployed DOCSIS 3.0 cable modems have eight downstream channels (6 or 8 MHz) and four upstream channels (6.4 MHz). This provides an aggregate downstream data capacity of about 300 Mbps and an aggregated upstream data capacity of 100 Mbps.

Next year (2013), the market will see cable modems that have on the order of 24

Table 1 – The Future Potential of DOCSIS

	Parameter	Now	Phase 1	Phase 2	Phase 3
Downstream	Frequency Band	54 - 1002 MHz	108 - 1002 MHz	300 - 1002 MHz	500 - 1700 MHz
	Assumed Modulation	256-QAM	256-QAM	≥ 1024-QAM	≥ 1024-QAM
	Chan (or equiv)	8	24	116	200
	Data Capacity	300 Mbps	1 Gbps	5 Gbps	10 Gbps
Upstream	Frequency Band	5 - 42 MHz	5 - 85 MHz	5 - (230) MHz	5 - (400) MHz
	Assumed Modulation	64-QAM	64-QAM	≥ 256-QAM	≥ 1024-QAM
	Chan (or equiv)	4	12	33	55
	Data Capacity	100 Mbps	300 Mbps	1 Gbps	(2) Gbps

downstream channels and 8 upstream channels. DOCSIS 3.0 defines a mid-split upstream that takes the upstream spectrum up to 85 MHz and could contain at least 10 channels. That provides an aggregate data capacity of almost 1 Gbps in the downstream and 300 Mbps in the upstream.

The goal for the next generation of DOCSIS is to achieve 1 Gbps of data capacity in the upstream and to be able to scale to the full spectrum of the existing downstream. While the final spectrum plan has not been determined yet, an estimate would be a 5 Gbps down, 1 Gbps up system. That would maintain a 5:1 ratio between upstream and downstream bandwidth that is good for TCP.

As a stretch goal, there is additional spectrum above 1 GHz. If the downstream expanded into that spectrum, and the upstream spectrum was increased even further to keep the same 5:1 ratio, DOCSIS could become a 10 Gbps down and 2 Gbps up technology. This would enable cable data capacity equivalent to next generation PON systems.

While the final choices for these numbers (indicated with "( )") still needs to be made, there seems to be at least three progressions of technology. Phase 1 upgrades the upstream to 85 MHz and takes advantage of technology available today. Phase 2 upgrades the upstream to 1 Gbps and the downstream to 1 GHz if it is not there already. Phase 3 extends the downstream to 1.7 GHz and gives a second boost to the upstream.

Now that we have established our goals, let's look at how to achieve them.

2 CABLE SPECTRUM ANALYSIS

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 decade's problems now, however we should consider them as part of the analysis.

The cable operator has several spectrum split options available and some are examined in this analysis. [33] [34] [35] Figure 1 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 1, the Top-split (900-1050) options has 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.

2.1 Mid-split (85)

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

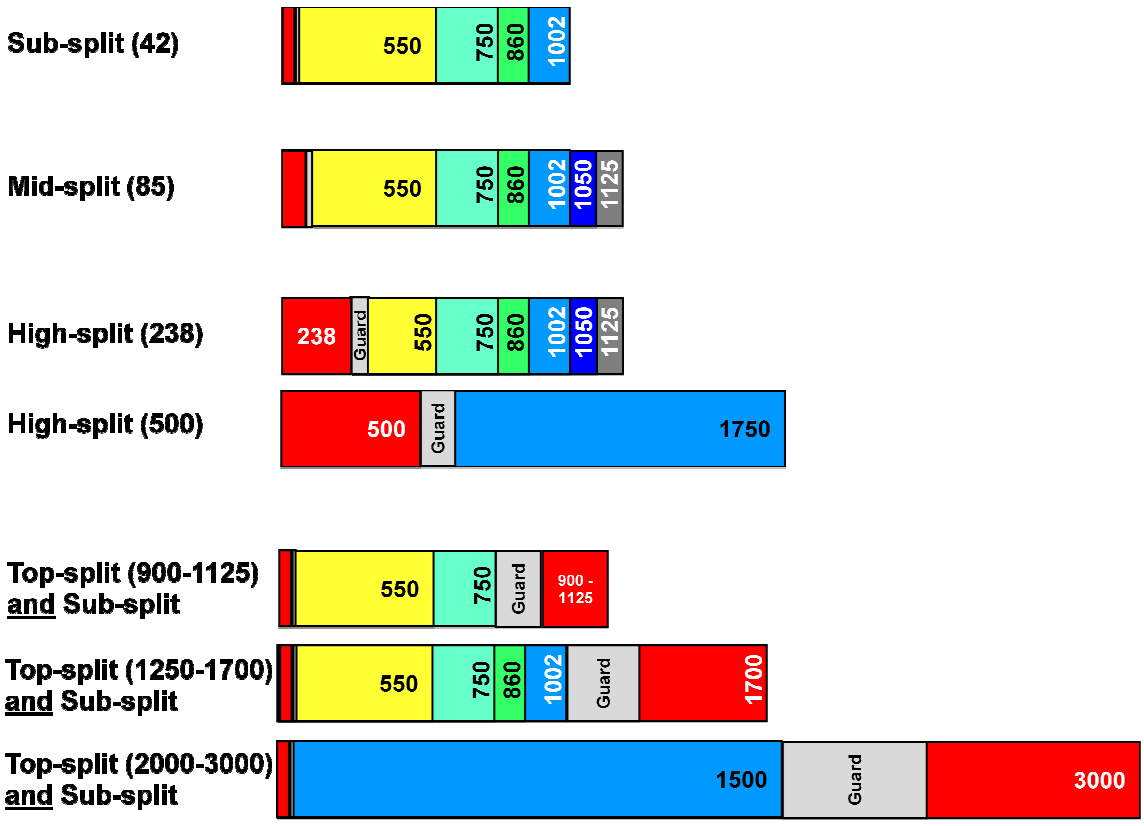

Figure 1 – Spectrum Allocation Options

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 MAC layer capacity estimated at ~310 Mbps
- Avoids conflict with OOB STB Communications
- Lowest cost option
- High order modulation possible 256-QAM perhaps higher
- The use of 256-QAM translates to fewer CMTS ports and spectrum (using 64-QAM would require approximately 33% more CMTS ports and spectrum)
- DOCISIS systems already support this spectrum (5-85)
- MSOs that have already deployed DTAs (Digital Terminal Adapters) should strongly consider thing approach
- 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); Thermal Equalizers EQT-85 enables +/-0.5 dB/amp delta

Cons

- Impacts Video Service (in low channels)
- Reduces low VHF video spectrum
- Throughput of 310 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 STB commutations. 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 option at that time. The Mid-split appears to be an excellent first step. MSOs that have already deployed DTAs should strongly consider using this approach.

2.2 High-split (200, 238, or 500)

Overview

The High-split Architecture has generally been defined as 5-200 MHz with the downstream starting at approximately 250-258 MHz crossover for the downstream. However, we believe that a High-split (238) or even High-split (270) options should be considered, as this will have enough spectrum capacity to reach the desired 1 Gbps data rate, with reasonable PHY and MAC layer overhead removed. [33] [34] [35]

Also it is uncertain if the entire region of spectrum between 5-238 may be used as there could be legacy channels in service as well as frequency bands undesirable performance or usable for interference

reasons. The use of High-split (500) has been mentioned as a possible long-term migration strategy if coaxial network want to offer the capacity of XG-PON1 systems.

In the case of 5-500 MHz our capacity targets assume a digital return HFC style optical connection and as will all architectures the paper model begins at a 500 HHP node to a 16 HHP node to determine capacity.

Pros

- High-split is far more predictable from an MSO deployment, operational, and service ability perspectives when compared with Top-split, as Top-split options have much tighter cable architecture requirements (refer to Cons of Top-split).
- Operates effectively at a typical 500 HHP node group using 256-QAM (see details in the sections later in this analysis)
- The use of 256-QAM translates to fewer CMTS ports and spectrum (using 64-QAM would require approximately 33% more CMTS ports and spectrum)
- High-split (238) using DOCSIS QAM reaches an estimated MAC layer capacity 1 Gbps
- However High-split (270) may be needed to allow for operational overhead
- High-split (500) at a 250 HHP through a 16 HHP optical node service group with digital return HFC optics is estimated to reach 2.2 Gbps DOCSIS QAM MAC layer capacity
- DOCSIS OFDM with LDPC may be able to use 2 orders higher modulation in same SNR environment
- Very low cost spectrum expansion option, especially considering similar capacity Top-split options (STB OOB cost was not considered in the analysis)
- The OOB STB problems will likely be reduced over time, and with the STB costs declining over time this will remove or reduce this issue to High-split adoption
- If DTAs are deployed or plan on being deployed High-split should be considered strongly, because DTA remove the Analog Video Service impact obstacle from High-split
- 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 does not waste a lot of capacity on guard band
- Level control using Thermal Equalizers EQT-200 (~2.2 times Sub-split cable loss)
- Downstream could expand to 1050 MHz or even 1125 MHz perhaps using the existing passives

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 or higher if the upstream stops at 238 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 has several key challenges or cons listed above, and the major concerns include 1) the impact OOB Set-top Box communications for non-DOCSIS Set-top Gateways, 2) the analog video service tier and the simplicity of connecting to an subscribers TV to enable services, and 3) we takeaway valuable capacity from existing video devices like STBs and existing TVs.

However, if the deployment of High-split (238) is planned later in time, this may allow these older STBs to be phased out or redeployed to other markets. There may also be workarounds to enable high-split and keep the legacy OOB in place. The impact to the analog service tier is a major concern, this accounts for a large portion of how customers received video services.

If a customer is a digital video subscriber they likely have TVs, in fact likely more TVs, which are served with no STB at all, and receive a direct coax connection. This is a valuable service feature for the MSO. However, we do recognized that many MSOs are considering the deployment of DTAs to recover analog spectrum, if the MSOs do a full all digital service and have no analog, this will make a migration to High-split a stronger consideration.

Additionally, MSOs could expand to 1050 MHz or even 1125 MHz perhaps using the existing passives, this very important because the technical benefits of using the bandwidth around 1 GHz are superior for the forward path compared with placing the return approaching or above 1GHz, discussed in detail in this analysis.

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 against the other split options considering just the network access layer.

If the STB Out of Band (OOB) and analog recovery need to be factored into to the High-split, the cost analysis will change, however these will continue to be phased out of the network. The costs to move analog services, which are non-STB subscribers, were not considered in the model. However many MSOs are already planning to use DTAs to reclaim the analog spectrum, this would make a migration to High-split more obtainable.

The High-split option may need to exceed 200 MHz and move to approximately 5-238 MHz to achieve a MAC Layer throughput around 1 Gbps. This would use the 22.4 MHz of spectrum in the existing Sub-split band and the new spectrum up to 238 MHz to allow thirty-three (33) 6.4 MHz wide DOCSIS 3.0 channels all using single carrier 256-QAM all in a channel bonding group.

2.3 Top-split (900-1125) Plus the use of Sub-split

Overview

A new spectrum split called Top-split (900-1125) defines two separate spectrum bands, which may use sub-split plus the new spectrum region of 900-1125 MHz for a combined upstream band. The total upstream capacity may be 262 MHz depending on the lower band frequency return selected and if the passives will allow 1125 MHz to be reached. The downstream would begin at either 54 MHz 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 however these defined spectrum splits will be used for our analysis. The placement of additional upstream atop the downstream has been considered for many years.

The Top-split (900-1125) 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 (900-1125):

Pros

- Operates at a typical 500 HHP node group but with no more than QPSK (see details in the sections later in this analysis)
- Top-split with Sub-split DOCSIS QAM MAC layer capacity ~315 Mbps given a 500 HHP Node/Service Group
- Top-split with Mid-split DOCSIS QAM MAC layer capacity ~582 Mbps given a 500 HHP Node/Service Group (less than High-split)
- Top-split 900-1125 does operate at a 500 HHP node but may operate at not full spectrum and will only be able to utilize 24 channels at 6.4 widths.
- Top-split (900-1125) plus Sub-split using DOCSIS QAM has an estimated MAC layer capacity of ~932 Mbps given a 16 HHP Node/Service Group
- With Sub-split "no" video services, devices, and capacity is touched
- STB OOB Communications are not affected
- Estimated that most passives will not be untouched (only Top-split that avoids touching passives)
- Existing 750 MHz forward transmitters are leveraged

Con

- The absolute major disadvantage for Top-split is cable network architecture requirements to make the solutions possible and the demands to reach high data capacity push FTTLA.
- A major finding of this report found that the effects of noise funneling force smaller and smaller node service groups to increase data capacity regardless if this is a DOCSIS / HFC solution or Ethernet over Coax (EoC) solution
- FTTLA is really fiber to All Actives, this will increase the number of node (HFC or EoC) to approximately 30 times the level they are now to reach the capacity level that High-split can reach with just the existing 500 HHP node location

- High-split can work at a 500 HHP node and while Top-splits must reach 16 HHP (FTTLA) depending on spectrum/cable architecture more HHP or even less than 16 HHP to reach the equivalent data capacity, lots of dependencies.
- Top-split from deployment perspective can be a challenge different cable type and distances play a major role is the architectures performance even if FTTLA is deployed
- No products in the market place to determine performance or accurate cost impacts
- 16 HHP upstream Service Groups will be required to approach 1 Gbps speeds comparable to High-split (238)
- 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 (900-1125) and High-split using similar spectral range.
- High-split has nearly 20% more capacity for revenue generation when compared to Top-split (900-1050) plus Mid-split at a 500 HHP node, this is because the guard band requirements waste bandwidth and low order modulation for Top-split
- 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 major consequence of the Top-split approaches, which use frequencies that approach or exceed 1 GHz, will have significant network cost impacts when compared with High-split. The number of nodes will increase 30 times to yield same capacity of High-split.

However, the Top-split (900-1125) 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 900-11125 option has additional benefits in that the Set-top box out of band (OOB) challenge is avoided and this option does not touch the passives.

This Top-split is estimated to cost more than the High-split. However, not included in this analysis is an economic forecast of the cost for Top-split to reach 1 Gbps upstream capacity which is estimated to be a 16 HHP architecture, the analysis examined economics 500 HHP and 125 HHP node architecture.

The migration for FTTLA to achieve 1 Gbps, would be 16 HHP and require all amplifier locations, thirty (30) in our model, to be a node location and this will require unground and aerial fiber builds to all locations. The MSOs will just begin to evaluate this option against the others.

2.4 Top-split (1250-1550) with Sub-split Overview and Top-split (2000-3000)

Systems designed to leverage unused coaxial bandwidth above 1 GHz have been around for many years. New iterations of these approaches could be considered to activate currently unoccupied spectrum for adding upstream.

The primary advantages of the top split are operational considerations – leaving current service alone – and the potential of 1 Gbps capacity or peak service rates in unused spectrum. In theory, not interrupting legacy services makes an IP transition path non-intrusive to customers, although the plant implications likely challenge that assertion.

The Top-split (1250-1700) Architecture will be defined as part of the 1250 – 1750 MHz spectrum band. Top-split (2000-3000) In our analysis we limited the amount of spectrum allocated for data usage and transport to 450 MHz and defined the placement in the 1250–1700 MHz spectrum band.

The allocation of 450 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

2.4.1 Implementation Complexity

A key additional complexity to the top split is working the spectrum around or through existing plant actives, all of which are low-split diplex architectures. For top split, a new set of actives supporting a triplex, or a bypass approach, or an N+0/FTLA are necessary to make the architecture functional.

All of these are intrusive, and have heavy investment implications, with the latter at least consistent with business-as-usual HFC migration planning. The top split is best suited to N+0 due to the complexity of dealing with current plant actives as well as for link budget considerations. N+0 at least removes the need to developing new amplifiers for the cable plant.

By contrast, node platforms have been and continue to evolve towards more features, functions, and flexibility. Of course, N+0 can be leveraged as a high-performance architecture whether or not a top split is implemented – top split, however, practically requires it to succeed as an architecture.

The outside plant architecture is not the only architecture affected by the approach. With the emphasis on upstream loss and degraded SNR as a primary issue for top split, a top split also virtually demands a point-of-entry (POE) Home Gateway architecture.

The variability of in-home losses in today's cable systems would seriously compound the problem if a top split CPE was required to drive through an unpredictable combination of splitters and amplifiers within a home.

The above issues apply to the case of Top-Split (900-1125) as well, but to a lesser degree with respect to RF attenuation and the inherent bandwidth capabilities of today's passives.

2.4.2 Spectrum Inefficiency

The penalty of the triplex architecture in terms of RF bandwidth and capacity can be substantial. A triplex used to separate current downstream from new top split bandwidth removes 100-200 MHz of prime

CATV spectrum from use in order that a less capable band can be enabled.

This spectrum trade reduces the total aggregate capacity of the plant. Under the assumption used (MPEG-4 HD/IPV), approximately 90 channels of 1080i HD programming are lost to guard band loss in a top split implementation compared to a high split alternative.

A primary objective of an HFC migration plan is to optimize the available spectrum, extending the lifespan of the network in the face of traffic growth for as long as possible, perhaps even a "forever" end state for all practical purposes that is competitive with fiber. RF spectrum in the prime part of the forward band is the highest capacity spectrum in the cable architecture.

To architect a system that removes on the order of 100 MHz from use is a loss of significant capacity, as quantified above, and works against the objective of optimizing the long-term spectrum efficiency.

The above issues apply to the case of Top-Split (900-1125) as well, but to a somewhat lesser degree associated with the percentage of crossover bandwidth required – that number is slight lower when the top split band chosen is slightly lower.

Pros

- Top-split 1250-1700 with Sub-split DOCSIS QAM MAC layer capacity ~516 Mbps given a 125 HHP Node/Service Group
- Top-split 1250-1700 with Mid-split DOCSIS QAM MAC layer capacity ~720 Mbps given a 125 HHP Node/Service Group
- Top-split (1250-1700) plus Sub-split using DOCSIS QAM has an estimated MAC layer capacity of ~883 Mbps given a 16 HHP Node/Service Group
- Top-split (1250-1700) plus Sub-split using DOCSIS QAM has 716 Mbps MAC layer capacity of ~1.08 Gbps given a 16 HHP Node/Service Group
- With Sub-split "no" video services, devices, and capacity is touched
- 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

- Much higher upstream loss = significantly more CPE power = lower modulation efficiency (less bps/Hz) for equivalent physical architecture
- Need to work around legacy plant devices incapable of processing signals in this band
- Altogether new CPE RF type
- New technology development and deployment risk
- Large lost capacity associated with triplexed frequency bands
- Bottlenecks downstream growth when used as an upstream-only architecture
- Let's elaborate on some of the key disadvantages identified above for an upstream top split
- Will operate at a typical 500 HHP node group but only capable of three of the

- 16 HHP Node and Use Mid-split and Sub-split spectrum meet the 1 Gbps capacity
- Highest cost solution compared with High-split and Top-Split (900-1050)
- The Top-split (1250-1700) with Sub-split cost more than High-split (200) and requires FTTLA
- 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 far more costly of High-split for the same capacity. 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.

A 500 HHP will not support Top-split 1250-1550, so the initial architecture will have to be a 125 HHP. However the requirements for higher capacity will force smaller node service group, which will add to 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.

The economic estimate used for Top-split was for 500 HHP and 125 HHP node architecture. The migration for FTTLA to achieve 1 Gbps, would be 16 HHP and require all amplifier locations, thirty (30) in our model, to be a node location and this will require unground and aerial fiber builds to all locations. This was not provided in the analysis.

Lastly, there is a significant penalty to downstream bandwidth in the form of triplex guard band – on the order of 100 MHz of RF spectrum is made unavailable for use. In the case of Top Split (900-1125), the band eliminated consists entirely of prime, very high quality forward path spectrum.

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.

2.5 Summaries for Cable Spectrum Band Plan

Continuing to leverage the current downstream and upstream spectrum will force operators to reduce service group size by using node splits and/or segmentation. This is ideal for MSOs that want to avoid re-spacing the amplifier network.

Additionally, spectrum changes will undoubtedly require service outages, because all the electronics and even passives (if above 1 GHz is selected) would have to be touched. Spectral changes may have higher service down time compared with node segmentation or node splits.

MSOs may want to consider spectrum expansion where node splits are costly. Depending on spectrum selection, the MSO could maintain large service group in the optical domain. In others words, the optical node could service a larger area and number of customers, if the MSO selects low frequency returns such as Sub-split, Mid-split, or High-split and if additional downstream spectrum is selected this will increase the length of time a optical node can support a given service group.

The channel allocation of video and data services will define the spectrum needs and node migration timing. Additionally, the service offering, such as network based PVR, will impact the spectral usages; thus drives toward more spectrum or smaller services groups.

There really are lots of levers that will drive the MSOs to changing spectrum and/or service group reductions, predicting with all certainty of how long a given network will last is greatly influenced by services and legacy devices that may need to be supported.

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 that may not need the advanced upstream spectrum options. Yet, another consideration is a down conversion of the OOB communications channel at the last amp or homes that have legacy two-way non-DOCSIS set-tops.

2.6 Spectrum Options, Capacity, and Timing Implications

We have discussed the Pros and Cons of the various upstream spectrum options. As discussed in Section 2.1, it is well-understood that a limitation of the 85 MHz mid-split architecture is that it cannot achieve 1 Gbps of capacity, at least not easily or in the near term. We will discuss upstream capacity itself in detail in Section 9.6 "Upstream Capacity".

While 85 MHz cannot achieve 1 Gbps of capacity, it is also not reasonable to jump to high-split in the near term because a plan must be in place to deal with the OOB channel, as shall be further described in Section 3.3.5 "Legacy OOB" and Section 3.4 "The Legacy Mediation Adapter (LMA)". As such, MSOs appear to be in a bind for handling upstream growth. Or, are they?

Let's consider defining the 1 Gbps requirement for upstream data capacity. How would such a system fare in supporting long-term capacity requirements? We can easily quantify how this would help manage long-term traffic growth and compare it to examples like the 85 MHz Mid-Split.

This comparison is examined in Figure 2. It shows three threshold cases – 100 Mbps (A-TDMA only), 85 MHz Mid-Split (in this case, including use of S-CDMA), and the case of 1 Gbps of capacity, however we manage to achieve it (high-split or top-split).

Zeroing in on the red arrow identifying the gap between Mid-Split and 1 Gbps at 40% CAGR – very aggressive relative to 2011 observed growth rates – in each case with a node split assumed in the intervening

years, we see that there exists about 2.5 years of additional growth. When we think of 1 Gbps, this intuitively seems odd. Why does migrating to Mid-Split buy a decade or more of traffic growth coverage, yet implementing a 1 Gbps system offers only a couple more years of survival on top of that decade?

This "linear" time scale on the y-axis is simply exemplifying how multiplicative compounding works. It is up to our own judgment and historical experiences to consider how valid it is to be guided by the compounding rules of CAGR originally identified by Nielsen, and if so what reasonable year-on-year (YOY) behavior assumption to assume.

However, the mathematical facts of CAGR-based analysis are quite straightforward: with CAGR behavior, it takes many YOY periods to grow from, for example, 5 Mbps services today, consuming or engineered for perhaps tens of Mbps of average return capacity, up nearly 400 Mbps or more. We will outline the data capacity possibilities for 85 MHz Mid-Split in Section 9.6, and then show a specific implementation in Section 7.1.2. However, once a 400 Mbps pipe has been filled, the subsequent annual steps sizes are now large. Because of this, consuming 1 Gbps is not many YOY periods of growth afterwards.

To demonstrate, we can calculate an example using 20 Mbps of average capacity satisfying demand today. At this aggregate demand, traffic can double four times and not eclipse 400 Mbps. It eclipses it in the 5th traffic doubling period. For ~40% CAGR (two years doubling), that's a total of ten years. For a CAGR of 25%, its about 15 years.

This is what Figure 2 is pointing out graphically. As such, relative to a solution that provides 1 Gbps, Mid-Split gets us through 80% of that lifespan under the assumption of an aggressive 40% CAGR and an intervening node split.

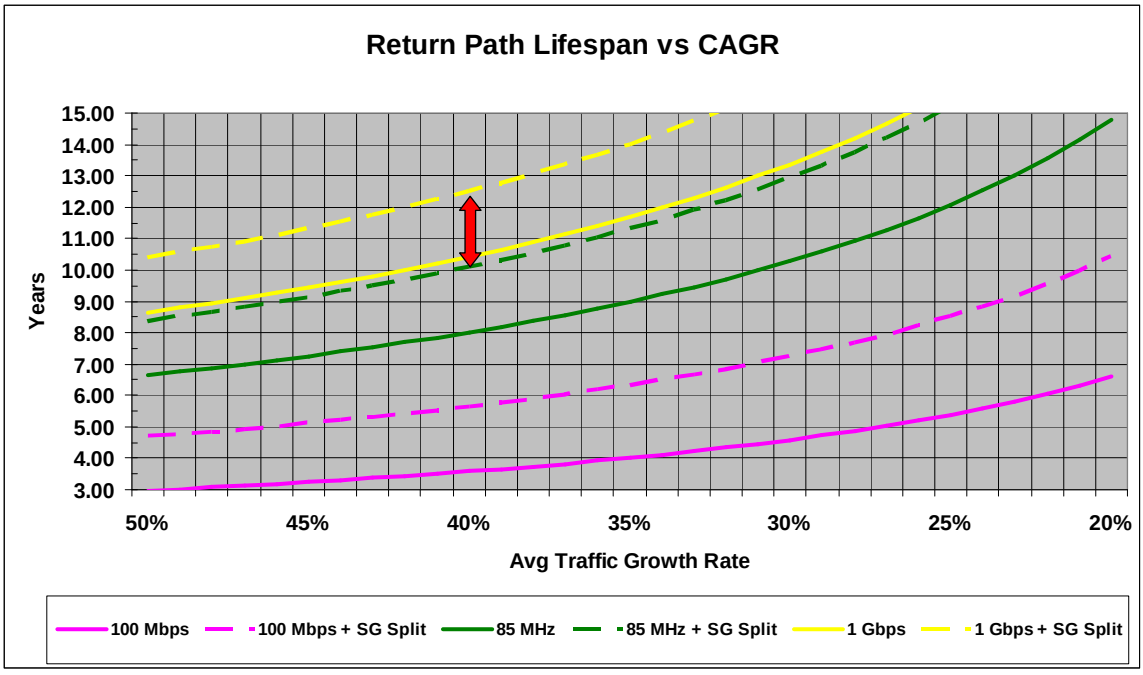

Figure 2 – Years of Growth: A-TDMA Only, 85 MHz Mid-Split, 200 MHz High Split

This Mid-Split vs. 1 Gbps lifespan analysis is an illustrative one in recognizing the long-term power of the 85 MHz Mid-Split. It provides nearly the same growth protection as a 1 Gbps solution would, if there even was one available. This means that the 1 Gbps requirement comes down to an operator's own considerations regarding the competitive environment, and whether a 1 Gbps market presence or service rate is important to their positioning for residential services.

3 SOLVING LEGACY ISSUES

3.1 Introduction

In order to significantly increase the upstream throughput in a DOCSIS system, more upstream spectrum is needed. That spectrum has to go somewhere. This white paper has examined multiple spectrum solutions and then different technology options within each spectrum solution.

Solutions are needed that allow an HFC plant to be migrated over to the next generation of DOCSIS without a full-scale replacement of subscriber equipment. Legacy and new equipment must co-exist in the same network.

The high level summary of the different spectrum solutions and their challenges is shown in Table 2.

This paper recommends mid-split and high-split as the best technical solutions. The attractiveness of top-split is that it interferes less with existing services. If the logistical problems of mid-split and high-split could be solved, then cable operators would be able to choose the best technical solution.

This section is going to specifically look at addressing the major logistical problems that the mid-split and high-split band plans face.

3.2 Summary of Operational Issues

Table 3 is a summary of the operational issue faced by each of the four upstream bandwidth solutions. This table is taken from [21].

There are several logistical challenges that are obstacles to the deployment of mid-split and high-split systems into an HFC plant that was designed for sub-split. The challenges include:

- Analog video
- FM band
- Aeronautical band interference
- Adjacent device interference
- Legacy OOB

Let's look at each one of these challenges in more detail.

Table 2 – Upstream Spectrum Comparison

Approach	Frequency	Comments
Sub-Split	5 - 42 MHz	Existing installed HFC plant. Add bandwidth with node splits.
Mid-Split	5 - 85 MHz	Technology available today with DOCSIS 3.0 CMTS and CM.
High-Split	5 - 200+ MHz	Best technical solution but challenging logistical solution
Top-Split	> 1 GHz	Tough technical solution but more attractive logistical solution

3.3 Analysis and Solutions

3.3.1 Analog Video

Problem Definition

There are many different channel plans in use around the world today. This white paper will choose the North American cable television plan as a specific example. This channel plan is defined in [20] and described in [18]. The upstream frequency cut-off is a maximum of 42 MHz. Some systems use a lower cutoff, depending upon the age of the system.

The downstream frequency range starts at 54 MHz. By convention, the analog

Table 3 – Summary of Operational Issues

Approach	Pros	Cons
Sub-Split	• All equipment already exists • No disturbance to spectrum • Simple	• Cost: Requires deeper fiber. • Cost: Requires more CMTS ports • Cannot hit peak rates over 100 Mbps of return path throughput
Mid-Split	• Supported by DOCSIS 3.0 equipment • Works with DS OOB	• All actives and some passives in HFC plant need to be upgraded • Cost about the same as high-split and only doubles the US throughput • Removes ch 2-6 of analog TV
High-Split	• Supports 1 Gbps throughput • Can co-exist with earlier versions of DOCSIS.	• All actives and some passives in HFC plant need to be upgraded • Does not work with DS OOB • New CM and CMTS components • Removes ch 2-36 analog TV • Removes FM band (issue in Europe)
Top-Split	• Leaves existing plant in place. • No impact to existing legacy customer CPE • Only customer taking new tiers would require new HGW CPE	• Requires triplexers • New active return path has to be built on top • High attenuation requires high RF power. Existing amplifier spacing may not be sufficient • Blocks expansion of downstream bandwidth directly above 1 GHz

channels are first in the spectrum followed later in frequency by the digital channels. The classic analog line-up is contained in channels 2 through 78 that occupy the spectrum from 54 MHz to 550 MHz. Within this spectrum are also channels 1 and 95 to 99.

The definition of the frequencies for a mid-split system has changed over the years. The mid-split for DOCSIS 3.0 is not exactly the same as legacy systems that used a return path upper frequency limit of 108 MHz ~ 116 MHz, with the downstream spectrum starting at 162 MHz~ 174 MHz (the actual frequencies varied among vendors).

The DOCSIS mid-split downstream frequency range starts at 108 MHz, which disrupts channels 1, 2-6 (54 MHz-88 MHz), and 95-97 (90 MHz-108 MHz) would be disrupted. A natural break point from a channel perspective would be to start the mid-split lineup at channel 14 a(120 MHz-126 MHz). If so, then channels 98-99 (108 MHz-120 MHz) would also be disrupted. Note that channels 7 through 13 (174 MHz-216 MHz) are located above channels 14 through 22 (120 MHz-174 MHz).

The upstream frequency range for high-split has not been chosen yet. If the high-split downstream frequency spectrum started at 300 MHz, then channels 1-36 and 95-99 would be lost.

Solutions

The first solution is to get rid of analog TV altogether on the cable spectrum. Any legacy TV that cannot receive direct digital QAM would have to be serviced with a digital transport adapter (DTA) or a conventional set-top box (STB). As radical as this idea may seem, several cable operators such as Comcast and CableVision are already free of analog channels on parts of their plants with plans to expand their no-analog foot print. The governments of many countries, including the USA, have already turned off most over the air analog broadcasts.

It costs money to retain analog channels. It is not that the money is spent on the analog channel equipment - which obviously is already paid for - it is that money needs to spent elsewhere to improve spectral efficiency. This may include plant upgrades, equipment upgrades or both.

Analog TV has only 5% of the efficiency of an MPEG-4 over IP video signal, yet analog TV typically occupies over 50% of the downstream spectrum. RF spectrum is always a scarce commodity, and this is a good example of where there can be a significant efficiency improvement.

The second solution would be to reduce the analog channels down to a smaller group of, say, 25 core channels. Then remap those analog channels into a higher channel space. For mid-split, only channels 2-6 need to be remapped. For high-split, it would be channels 2-36.

This may cause some channel confusion to the subscriber, but such a remapping trick has been done for high definition channels on STBs.

A semblance of continuity can be maintained by keeping the least significant digit the same. Remapping channel 2 to channel 62 is one example.

There are often contractual issues quoted, such as franchise agreements, market recognition, must-carry agreements, etc. These may have to be renegotiated. The driving force for doing so is a gigabit or more upstream speed. To the extent that

these legal requirements are driven by the requirements of the community, then which is the bigger market - analog TV or an incredibly fast Internet access? The answer has to be a fast Internet service or there would not be a need to upgrade in the first place.

Finally, now that the government has shut down most over-the-air analog TV, the cable operators are the last service provider to have analog TV. The telco and satellite service providers are all digital.

There are two perspectives that can be taken on this. The first is that having analog TV makes the cable operators unique in being able to offer analog TV, and this differentiates them from all the other providers. The second is that the cable operators are the last to move to all digital, and that the other service providers may have more spectrum or resources as a result.

So, again, if the costs are equal, does analog TV with a lower Internet access speed beat out a competitor who has a significantly higher speed Internet service? What if the competitor is a fiber-to-the-home company with gigabit-per-second service?

The choice is somewhat obvious, but also very painful. It requires pain of some sort. But, the new upstream spectrum has to come from somewhere. Keeping analog TV spectrum indirectly costs money due to investment on alternative solutions.

3.3.2 FM Band

Problem Definition

The FM radio band is from 88 MHz to 108 MHz. There are two potential concerns.

The first concern is the loss of the ability for the cable operator to provide FM radio service over the cable system. This is not much of an issue in North America, but it is a concern in Europe and elsewhere.

The second concern is if interference generated by the HFC plant that might interfere with the FM band (signal leakage) or if the FM band might interfere with the with the HFC plant (ingress).

Solutions

As with analog TV, the easiest solution to the first requirement is to no longer carry the content. For Europe, this may require some regulatory work. The worst case would be to carry the FM band at a higher frequency on the HFC plant and down-convert it locally with the LMA. Refer to Section 3.4.

As far the HFC plant interfering with local FM reception, this should not be a problem. The capture effect of FM receivers [24] will most likely reject noise-like digital signals leaking from a cable network as a weaker signal. A strong FM signal might interfere with the upstream signal on the HFC plant. This can be mitigated with good plant shielding, ingress cancellation techniques, or OFDM noise/ingress mediation.

3.3.3 Aeronautical Interference

Problem Definition

The new CM will be transmitting at frequencies above 54 MHz at a higher power level than when the frequencies are transmitted as part of the downstream spectrum. The inherent leakage in the plant might be sufficient enough to cause interference with existing services.

For example, the frequencies from 108 MHz to 137 MHz are used for Aeronautical Mobile and Aeronautical Radio Navigation.

The radio frequency spectrum usage is shown in Figure 3. [23]

Specifically, the 108-118 MHz band has always been problematic because any CATV signal leakage here could interfere with aviation localizer (108-110 MHz) and VOR signals (110-118 MHz). Hence, sometimes channels 98 and 99 (also called A-2 and A-1) are not used to avoid this problem. The localizer is especially important, as it is responsible for providing the left/right guidance in an ILS approach;

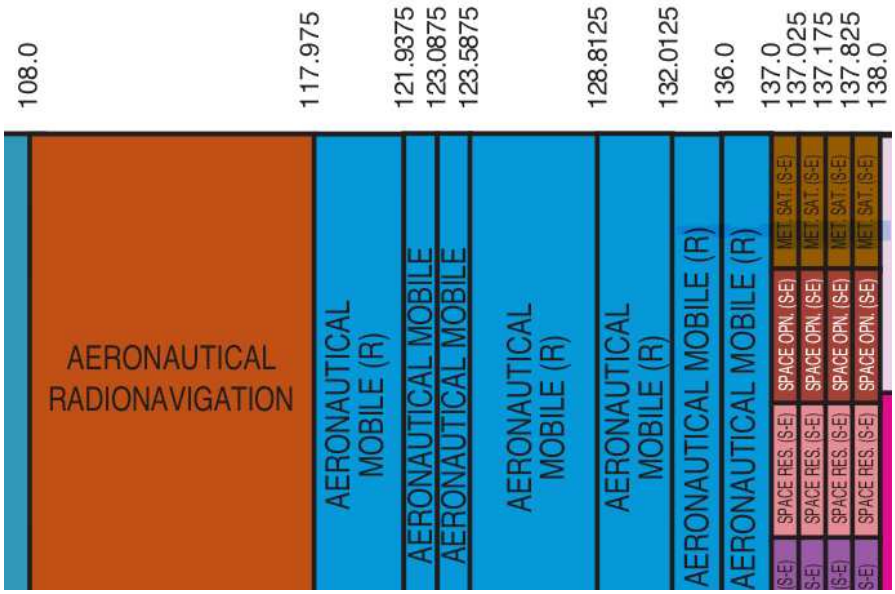

Figure 3 – Government Spectrum Allocation from 108 MHz to 138 MHz

VORs are also important but more often used at longer ranges as navigation beacons.

There is also the 121.5 MHz aeronautical emergency frequency, and the 243.0 MHz distress (SAR) that may be of concern.

If the upstream spectrum expands above 300 MHz, another sensitive aviation band comes into play. The glideslope frequencies are in the 328-335 MHz band. The glideslope is the x-y counterpart to the localizer as it provides up/down guidance in an ILS approach.

Solutions

Research would have to be done to validate these concerns. If it is a problem, then the plant will have to be cleaned up to reduce this leakage. Some of this leakage may come from bad home wiring. That makes it even more important that the CM installation is done professionally.

In the absolute worst case, some or all of these frequencies would have to be avoided. The impact of that is that a larger upstream spectrum would have to be dedicated to DOCSIS. This would be a loss of up to 29 MHz or more in some networks.

Some of these interfering carriers are quite narrow. Current DOCSIS tools handles very narrow interferers better than modulated, but increasingly struggles as multiple interferers occupy a single carrier band. OFDM will be quite useful for notching these out.

This concern also existed 15 years ago prior to the deployment of DOCSIS. The plant did require cleaning up in many cases. It was done and the result was a more reliable HFC plant. So, it is doable, but must be planned and budgeted for.

3.3.4 Adjacent Device Interference (ADI)

Problem Definition

ADI refers to the situation where the operation of one device - such as a high-split cable modem - interferes with another device - such as a legacy TV or legacy set-top box. This is not an official abbreviation (yet). We are borrowing the concept from the term adjacent channel interference that describes a similar phenomenon, except ACI is in the frequency domain, and ADI is in domain of physical space.

For the sake of example, let's assume the high-split spectrum goes up to 230 MHz, and the downstream starts at 300 MHz.

Tuners in STBs and TVs in North American receive above 54 MHz with an expected maximum per-channel input power of +17 dBmV. Low-split and top-split can thus co-exist fine with legacy tuners. Mid-split and high-split systems carry RF energy in the upstream direction that is within the downstream operating range of the legacy STB and TVs.

If those devices are located near a CM that is blasting out energy above 54 MHz at levels approaching +57 dBmV (DOCSIS 3.0 max power for single 64-QAM), poor isolation and/or return loss in splitters and other devices could cause a significant amount of that upstream power to appear at the input connector of the legacy devices, which might saturate their RF input circuits, thus preventing the devices from receiving a signal at any frequency.

The typical North American legacy tuner has an output intermediate frequency (IF) centered at 44 MHz. If 44 MHz was applied to the input of a tuner with poor IF rejection, that signal might cause interference in the tuner, even through the tuner is tuned to another band. How much of a problem this is requires more research.

There is some evidence that shows that the sensitivity of the video signal to ADI decreases significantly as analog signals are replaced with digital. This is a somewhat intuitive conclusion, but validating data to this effect is important.

Solutions

So, what to do?

One solution is to put a filter in front of the legacy devices that filters out all content below the high-split cut-off frequency (85 MHz or 230 MHz in this example). But, is this filter needed in all cases? And where would the filter go? Let's look at this problem in more detail.

The general problem is best split up into two smaller scenarios:

- Impact within the same home as the new high-split DOCSIS CM.
- Impact to adjacent homes that do not have the new high-split DOCSIS CM

Same Home:

When a home is upgraded, the new DOCSIS CM will likely be installed as a home gateway (HGW). There are at least two scenarios. The first is a home with MPEG video STBs, and the second scenario is an all IP video home.

In the home that requires digital MPEG video, the HGW can receive the spectrum from the plant, filter the signal below 200 MHz, and pass the filtered spectrum into the home. The main filtering it is trying to achieve is from its own upstream transmitter. If the upstream transmitter is

+50 dBmV, the internal combiner has 20 dB of signal rejection, and the max signal level allowed is +15 dBmV, then the additional filtering has to provide 15 dB of attenuation. This filter could be located internal to the HGW or be an external inline filter in order to manage HGW costs.

For this to work, the HGW would have to be wired in-line with the home. That is not how CMs are installed today. CMs today are installed using a home run system. The drop cable from the street is split between the CM and the home. In this new configuration, the CM would have to have a return cable that then fed the home. This could add additional loss to the video path. However, it could be a workable solution.

In the home where there are only IP STBs, the downstream from the HFC plant does not have to be connected to the home. DOCSIS could be terminated at the HGW and the HGW would drive the coax in the house with MoCA. Video and data would be deployed with IP STBs that interfaced to the MoCA network.

The HGW becomes a demarcation point between DOCSIS and the cable plant on one side, and MoCA and the home network on the other side. Again, the CM would have to be in-line with the coax from the drop cable and the home. This does imply the need for a professional installation.

This is an interesting proposal in several ways. First, it solves the in home legacy tuner interference problem. Second, it isolates all the return path noise generated by the home network and prevents it from entering the HFC plant.

Adjacent Home

The other half of the problem is the impact to adjacent homes. While the installer has access to the home he is upgrading and has several options available to him, the home next door may not be part of the upgrade.

The energy from the new high-split CM would have to travel up the drop cable from the home, travel between the output ports on the tap plate, back down the drop cable to the next house, and then into the home network of the next house.

The easiest solution would be to set the new upstream power budget such that the signal would be sufficiently attenuated by the path described above so that it would not be a problem. This solution becomes harder when the customers are in a multiple-dwelling unit (MDU) where the coax drops may be shorter.

Worst case, in-line filters would have to be applied in-line with the drop cables of the adjacent home or within the adjacent home. Another approach is to put filters into the tap plate that serves an upgraded home and its adjacent homes. This would prevent the upgraded home from impacting the adjacent homes.

Thus, tap plates would only have to be replaced as part of a new deployment so the overall cost would be lower than having to replace them all at once. This assumes that the additional upstream path attenuation between taps on separate enclosures is sufficient.

As far as potential tuner sensitivity, the upstream spectrum could skip the frequencies from 41 to 47 MHz. This can be done, but it is a loss of 6 MHz of spectrum. The better plan is to make sure that the attenuation of the upstream signals into the downstream is sufficient that even 41 to 47 MHz is fine.

Summary

In summary, an external filter may not be needed. The HGW can be used to protect the upgraded home, although it has to be wired in line. The adjacent home should have enough attenuation from the drop cables and tap assembly. More caution may be needed in MDUs. An external in-line filter should be made available to fix the exception condition. Filtered taps may be good for dense situations such as MDUs.

3.3.5 Legacy OOB

Problem Definition

The out-of-band (OOB) channel is used on legacy STB to provide information to the STB and get information back. The OOB channel was used prior to the development of DOCSIS Set-top Gateway (DSG).

The downstream carrier is 1 MHz wide for SCTE 55-2 (Cisco) and approx 1.7 MHz wide for SCTE 55-1 (Motorola). Typical placement of center frequency is between 73.25 and 75.25 MHz as there is a gap between channels 4 and 5. The older "Jerrold" pilot (prior to Motorola/GI) was at 114 MHz. By spec [25], the STB must be able to tune up between 70 MHz and 130 MHz.

There is an upstream OOB carrier as well that is usually placed below 20 MHz.

CableCards are one-way and typically use only a downstream OOB channel.

There are no compatibility issues with the STB OOB channel and low-split or top-split. For mid-split, if the OOB channel can be placed above 108 MHz in the downstream spectrum then the problem is solved. This should work except for very old STBs that are fixed frequency. These STBs would have to be upgraded.

For high-split, this is probably the biggest issue. The 200+ MHz target cutoff for high-split is well above the 130 MHz upper end of the OOB tuner range.

Solutions

This is primarily a North American issue. In the rest of the world where legacy STB penetration with OOB is much lower or non-existent, and may not be a significant issue.

Of the STBs deployed in North America, many of the newer ones can actually tune to a frequency greater than 130 MHz because it was just as cheap to use a full spectrum tuner. Cisco estimates that > 70% of the Tier 1 installed base of Cisco STBs in 2015 would have this capability. (Further research is required. Software upgrades may be required.).

Then there is DSG. DSG is basically OOB over DOCSIS. Many of the deployed STBs have DSG built in but the DSG has not been enabled. Cablevision is an exception who has 100% DSG deployed, as does South Korea. So, DSG is proven to work.

It turns out there was a financial hitch with DSG. The original plan was add the STBs to an existing DOCSIS upstream channel. These upstream channels are engineered to be transmitted from the CMs on a home run cable. The STBs in the home have more attenuation, as they are deeper into the home coax network, so they are not always able to transmit onto an existing DOCSIS channel.

The solution is to use a separate QPSK DOCSIS channel. If this channel were the same modulation and power level as the existing OOB channel - which it would be - then if the OOB upstream worked, the

DOCSIS OOB upstream would also work. The problem is that this requires a dedicated carrier in the CMTS. This might be additional expense or the CMTS may not have the extra capacity. With newer CMTSs, there will be more upstream carriers available, so dedicating one carrier per port to DSG is a very reasonable solution.

It is also reasonable that any home that gets upgraded to a new high-split CM could also have their STBs upgraded to DSG compatible STB.

The OOB CableCard is easily replaceable and can migrate to DSG.

So that leaves STBs in North America, in non-upgraded homes, that are over 10 years old (by 2015), that can't tune above 130 MHz, that are non-DSG, and are not CableCards. That is really not a lot of STB. It could be around 0% to 10% of the STB population rather than the originally estimated 100%.

There is a motivation to replace these old STBs. They are beyond their capital write-down period. Further, these STB usually do not have the CPU or memory capacity required to run new applications. This means that new services cannot be sold to these customers.

Just to be on the safe side, there is a solution that does not require upgrading the old STB. That solution would be to put an inexpensive LMA behind legacy STB that provided an OOB channel. These LMAs would go inline with legacy STB. They would be cheap enough that they could be mailed out to customers who complain or are known to have specific legacy STBs.

If that does not work, only then a truck roll might be needed.

Summary

At first pass, the loss of the OOB channel seems like a major problem. However, by the time the next generation of DOCSIS is deployed, and with the variety of solutions, it is not really a problem at all.

Bear in mind that before the first high-split CM can be used in the new spectrum, the plant needs to be upgraded. But after the plant is upgraded, homes can be upgraded on a per home basis. This helps keep costs contained. Also, in a phased approach to upstream bandwidth expansion, a mid-split architecture may buy yet more time to eliminate or actively retire the older STBs.

This is a far better proposition than if all legacy STBs had to be replaced prior to upgrading the plant.

3.4 The Legacy Mediation Adapter (LMA)

In several of the plans to deal with legacy, there is a back-up plan that involves an in-line device that we will refer to as a legacy mediation adapter (LMA).

- The LMA could be used for generating and receiving an OOB signals.
- The LMA could be used for blocking upstream energy from entering the downstream.
- The LMA could be used to isolate the ingress originating from the home when the home no longer needs a return path internal to the home.
- The LMA could even be used to generate an FM signal for European deployments.

There are at least two primary ways of designing this LMA. The first way uses a

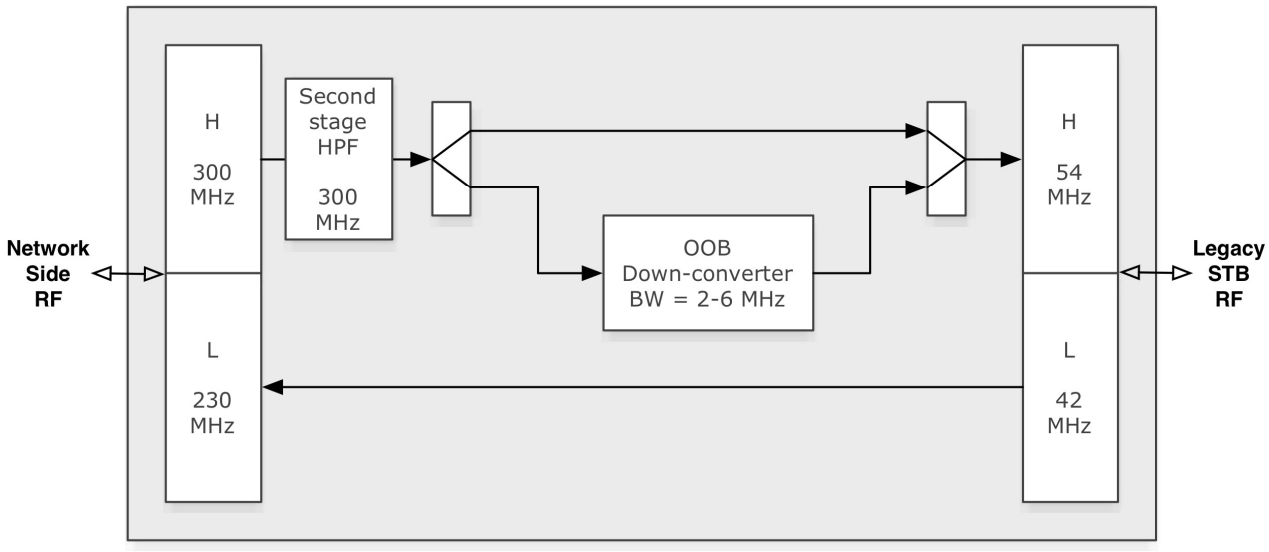

Figure 4 – LMA with Down-Conversion

simple down-conversion method. The second way uses an embedded circuit.

Another interest aspect of the LMA is that it interfaces between the new and old HFC spectrum plans. On the network side of the LMA, it interfaces into the high-split, 200 MHz (for example) plant. On the subscriber side of the LMA, it interfaces into the legacy sub-split 42 MHz plant.

3.4.1 LMA with Down-Conversion

In this approach, the headend would generate two OOB downstream carriers. The first one would be the standard downstream OOB carrier. This first carrier might be at 75 MHz for example.

The headend then generates a second OOB carrier at a frequency that is in the available downstream spectrum that is above the upstream cut-off frequency. This second carrier might be at 750 MHz for example.

This second carrier would fit into a 6 MHz or 8 MHz TV channel slot. This channel would be wide enough that multiple carriers could be fit. That way, any plants that are dual-carry with two STB manufacturers on it could be accommodated.

If necessary, the bandwidth could be expanded to allow for the FM band to be placed at a higher frequency as well.

The first carrier at the lower frequency would be received by legacy STB on areas of the plant that have not been upgraded. The second carrier would be received by the LMA that has been placed behind the legacy equipment.

The use of two carriers at different frequencies presumes a scenario where the LMAs are distributed over a period of time prior to the HFC plant upgrade. Thus, during the transition period, there would be legacy devices on both carriers.

A block diagram of the down-converting LMA is shown in Figure 4. Starting at the network side, the RF signal is separated with a diplexer into downstream and upstream frequency paths. The

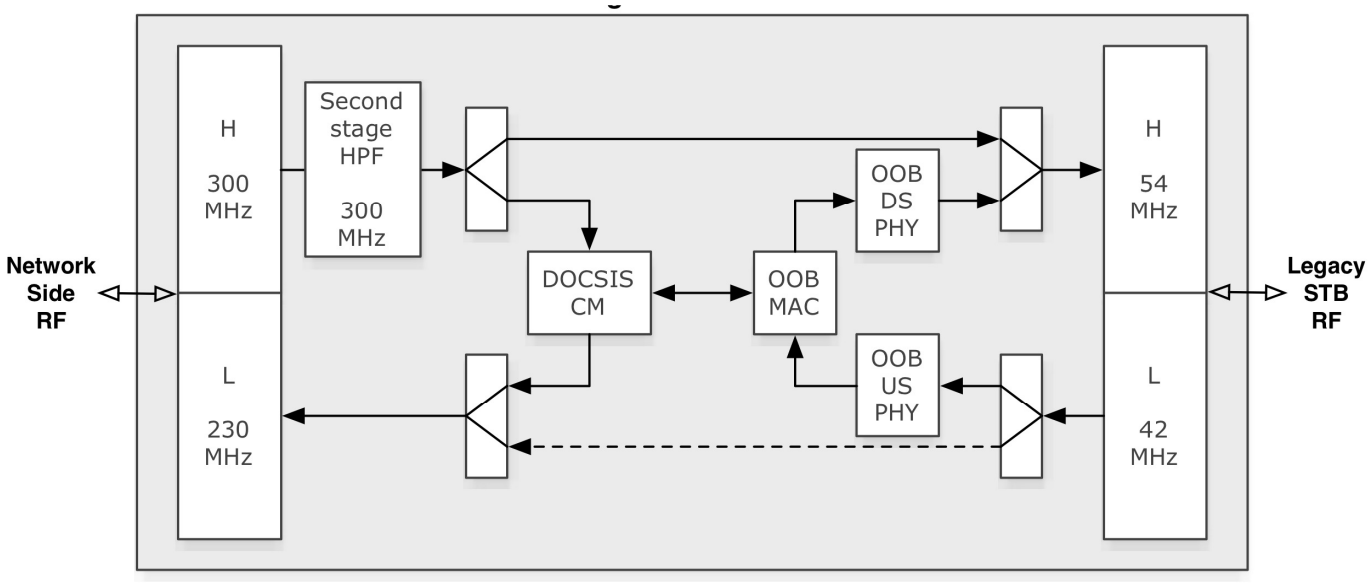

Figure 5 – LMA with CM

downstream path may require further filtering to remove any upstream energy.

The higher frequency OOB carrier is tapped off and passed to a down-converter. In the example used here, the down-converter would down convert from 750 MHz to 75 MHz. This carrier is then combined back into the downstream spectrum and then passed to the legacy STB.

To further reduce the cost of the LMA, the upper frequency that is used for the OOB carrier could be standardized through CableLabs. The LMA would then be a fixed frequency device and would not require any configuration.

The return path is left intact as the legacy STB will need to send an OOB carrier back to the headend.

3.4.2 LMA with DOCSIS CM

This approach achieves similar goals but with a different method. In this method, a DOCSIS CM is used to communicate the OOB information over IP from the headend to a local OOB circuit. This design would be good for operators who are using DSG as a baseline to control their network or for a scenario where the LMA needs to be configured.

DSG can be used on the network side in the downstream. Alternatively, a basic IP tunnel can be used to transport the raw OOB channel. An IP tunnel will have to be defined for the upstream that carries the upstream OOB information to the headend. This can be done at CableLabs.

The LMA has an entire two-way OOB MAC and PHY. This circuit generates a local OOB circuit. A clever implementation could implement both the SCTE 55-1 and SCTE 55-2 OOB standards. Otherwise, there would need to be two separate LMAs.

This design could use a DOCSIS 1.1 CM as part of a reduced cost implementation as only single carrier implementations are needed.

The return path from the home to the network could be disabled so that the LMA would isolate the ingress from the home from getting to the network.

3.5 Downstream Concerns

The downstream frequency band above 1 GHz will have a few challenges as well. In addition to the higher attenuation and micro-reflections, there are some frequency bands to be careful of. Here are two of the more common spectrum usages to be aware of.

3.5.1 MoCA®

MoCA is a technology that allows peer to peer communication across coax in a home environment. It typically is used for communicating between set-top boxes.

The concern would be that new frequencies on the cable plant above 1 GHz could interfere with MOCA in homes that are both upgraded to DOCSIS NG that don't isolate the HFC plant from the home and homes that are legacy.

MoCA 1.1 defines a 100 Mbps data channel that consumes 50 MHz of spectrum that can be located anywhere in between 1125 MHz and 1525 MHz.

MoCA 2.0 defines a 500 Mbps data channel that consumes 100 MHz of spectrum that can be located anywhere in between 500 MHz and 1650 MHz. MOCA 2.0 also has a special 1 Gbps data channel that is bonded across two 100 MHz channels.

A key observation is that MOCA does not occupy the entire operating frequency range. The large frequency range allows multiple MoCA system to coexist.

The most probably solution is to set aside some amount of downstream spectrum, say 200 MHz, for use by MoCA, and let MoCA find it.

3.5.2 GPS

GPS L3 (1381.05 MHz) is an encoded alarm signal broadcast worldwide by the GPS constellation. It is used by part of the US DOD Nuclear Detection System (NDS) package aboard GPS satellites (NDS description [29]). Encoding is robust and is intended for receipt by military ground-based earth stations. These installations are not susceptible to terrestrial signal interference (i.e. skyward-looking antennas).

Despite being so, large scale, wide area leakage into L3 (as from a distributed cable plant) would not be looked upon favorably by either the US or Canadian governments, or by radio astronomy organizations, who already suffer from GPS L3 signals corrupting “their” skyward-looking receive bands near 1381 MHz. [30]

In contrast, L1 (1575.42 MHz) and L2 (1227.60 MHz) are susceptible to terrestrial interference, despite CDMA encoding. This is due to the low-cost nature of the patch antennas and receivers used to detect them in consumer applications. Unlike the military receive systems and precision GPS packages used in commercial navigation (aviation and shipping), which are robust in the presence of terrestrial interference, consumer GPS are not so. Consumer GPS (including auto and trucking) navigation systems rely upon a wide-pattern patch antenna with a low-noise, high-gain preamplifier.

Such a configuration has no discrimination against terrestrial signals. The low level of received signal at the preamp creates a condition ideal for “blanking” of L1 and L2 should a terrestrial signal of sufficient spectral power density –

particularly from overhead cable plant – be present.

Finally, new applications of the latest civilian GPS frequency, L5 (1176.45 MHz), are currently emerging. Despite being CDMA encoded with FEC, it is not possible to predict how consumer receivers for this latest band will perform in the presence of broad-area interference.

It is of some interest to note that the target application for L5 is “life safety”, see [31]. To get a feel for a L1, L2, and L3 receiver architectures, see the following overview paper on civilian GPS receiver parameters, [32].

3.6 Summary

While initially there were many concerns about the logistics of implementing high-split, there are good mediation strategies. Analog video can be removed or remapped. Adjacent device interference should not be a general problem, and a filter LMA or tap plate filter can manage exception cases. Even the OOB channel is quite manageable with DSG or with an LMA.

This LMA can be multi-purpose and include OOB support and downstream high-split filtering. There may be other functions such as FM radio support that may also be interesting to consider.

The LMA has two different implementations. One is a down-conversion. The advantage is low cost, no ASIC needed, and re-use of OOB headend equipment. The second design could be low-cost if done right, requires ASIC integration, and is better suited to a DSG environment.

More research is needed on the impact to the aeronautical band and to the adjacent tuners below 54 MHz.

It is clear, however, that there are no logistical show stoppers in the deployment of a mid-split or high-split system.

4 COAXIAL NETWORK COMPONENTS AND TOPOLOGY ANALYSIS

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. [35]

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 analysis will examine some of the pros and cons of several technologies and architectures, which could be used to provide additional capacity.

The analysis considered the capabilities of a "Drop in Upgrade" to determine the viability and impact for upstream spectrum expansion as a starting point. [35]

- Target starting point is a "Typical" 500 HHP Node Service Group
- Typical number of actives (30) and passives (200)
- Existing spacing, cabling types and distance (see Figure 6)

4.1 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.

4.1.1 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

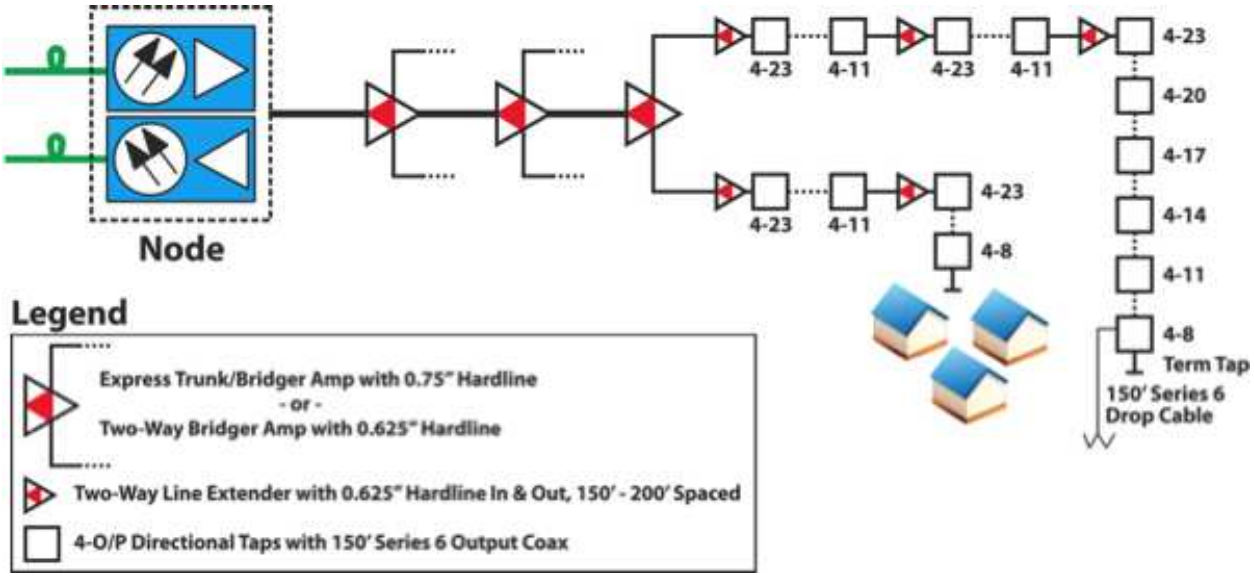

Figure 6 – Coaxial Network Assumptions

Active (FTTLA) is not required to meet capacity, service tier predictions or network architecture requirements for this decade and beyond.

4.1.2 500 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 analysis, see Table 5.

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 (238) beyond this decade providing 999 Mbps or 1 Gbps of MAC layer capacity. The Top-split 900-1050 with Sub-split has more capacity than Mid-split and will last through the decade.

4.1.3 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:

1. Introduced in 1990 and were rapidly adopted as the standard
2. This was prior to many major rebuilds of the mid-late 90s and early 2000s
3. Prior even to the entry of 750 MHz optical transport and RF amplifiers/ products in the market place
4. Deployment of 1 GHz passives that would have more capacity than the electronics would have for nearly 15 years
5. Passives are the most numerous network element in the Outside Plant (OSP)
6. Volumes are astounding perhaps as many as 180-220 behind every 500 HHP Node or about 30 per every plant mile (perhaps 40-50 Million in the U.S. alone)
7. 1 GHz Passives may account for 85% of all passives in service today
8. Vendor performance of the 1 GHz Passives will vary and some support less than 1 GHz
9. Our internal measurements indicate that most will support up to 1050 MHz
10. Taps in cascade may affect capacity, thus additional testing is required

4.1.3.1 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 passives greater than 1050 MHz with predictably.

4.2 Characterization of RF Components

The network components that most affect signals 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 QPSK for 300 MHz of RF spectrum (47 channels of 6.4 MHz each). Whereas below 200 MHz 256-QAM is possible (due to lower coaxial cable loss) and only 24 channels occupying about 180 MHz spectrum are required, using rough estimates.

Additionally, the over 1.2 GHz solutions will require a 125 HHP service group to support QPSK, where as the High-split 200 solution may use a 500 HHP service group, this is a key contributing factor to the cost deltas of the split options.

4.3 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 would have 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 256-QAM 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 256-QAM 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 16-QAM is uncertain. This illustrates (Table 4) the very high dynamic range of "Pure RF" (about 15 dB higher than when an electrical-to-optical conversion is involved).

Table 4 – Legacy Modulation and C/N Performance Targets

Modulation Type	Uncoded Theoretical C/N dB	Operator Desired C/N Target
QPSK	16	22
8-QAM	19	25
16-QAM	22	28
32-QAM	25	31
64-QAM	28	34
128-QAM	31	37

Theoretical SNRs Uncoded with BER of 10^-8
Practical C/N is chosen to give 6 dB headroom above Uncoded

Table 5 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.

4.4 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 7.

In the plot of Figure 8, the coax Return Loss (RL) did not vary as expected above 1200 MHz. This appears due to an internal low-pass matching structure in the hardline-to-75N connectors (apparently for optimizing the 1-1.2 GHz response). The connectors are an important element to return loss with signals above 1 GHz.

Table 5 – Node and Coaxial Network Assumptions Typical of U.S based MSOs

Typical Node Assumptions		
Homes Passed	500	
HSD Take Rate	50%	
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
Express Cable Type	.750 PIII	
Largest Express Cable Span	2000	ft
Distribution Cable Type	.500 PIII	
Distribution Cable to First Tap	100	ft
Largest Distribution Span	750	ft
Drop Cable Type	Series 6	
Largest Drop Span	150	ft
Maximum Modem Tx Power	65	dBmV

GENERAL NODE ASSUMPTIONS MID 1990S – 2004 REBUILD WITH .500 PIII DISTRIBUTION CABLE AND 750 FOOT DISTRIBUTION SPAN

OR

Typical Node Assumptions		
Homes Passed	500	
HSD Take Rate	50%	
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
Express Cable Type	.750 PIII	
Largest Express Cable Span	2000	ft
Distribution Cable Type	.625 PIII	
Distribution Cable to First Tap	100	ft
Largest Distribution Span	1000	ft
Drop Cable Type	Series 6	
Largest Drop Span	150	ft
Maximum Modem Tx Power	65	dBmV

GENERAL NODE ASSUMPTIONS SEE APPENDIX B: POST 2005 REBUILD WITH .625 PIII DISTRIBUTION CABLE AND 1000 FOOT DISTRIBUTION SPAN

USED FOR PAPER AND PRESENTATION

OR

Typical Node Assumptions		
Homes Passed	500	
HSD Take Rate	50%	
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
Express Cable Type	.750 PIII	
Largest Express Cable Span	2000	ft
Distribution Cable Type	.625 PIII	
Distribution Cable to First Tap	100	ft
Largest Distribution Span	750	ft
Drop Cable Type	Series 6	
Largest Drop Span	150	ft
Maximum Modem Tx Power	65	dBmV

GENERAL NODE ASSUMPTIONS POST 2005 REBUILD WITH .625 PIII DISTRIBUTION CABLE AND 750 FOOT DISTRIBUTION SPAN

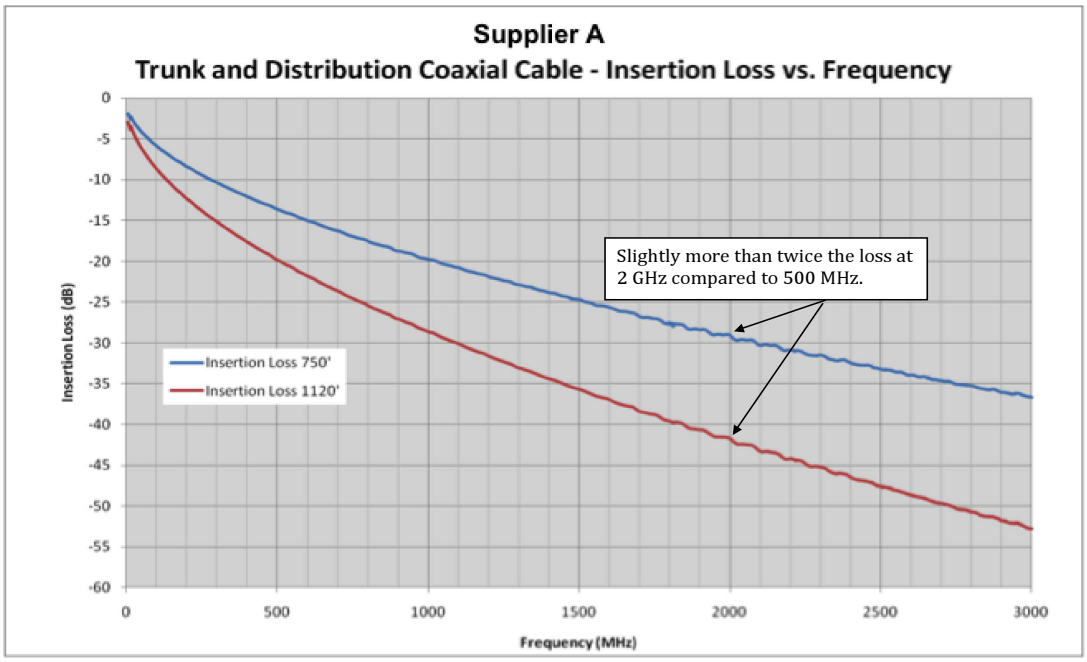

Figure 7 – Distribution Coaxial Cable – Insertion Loss vs. Frequency

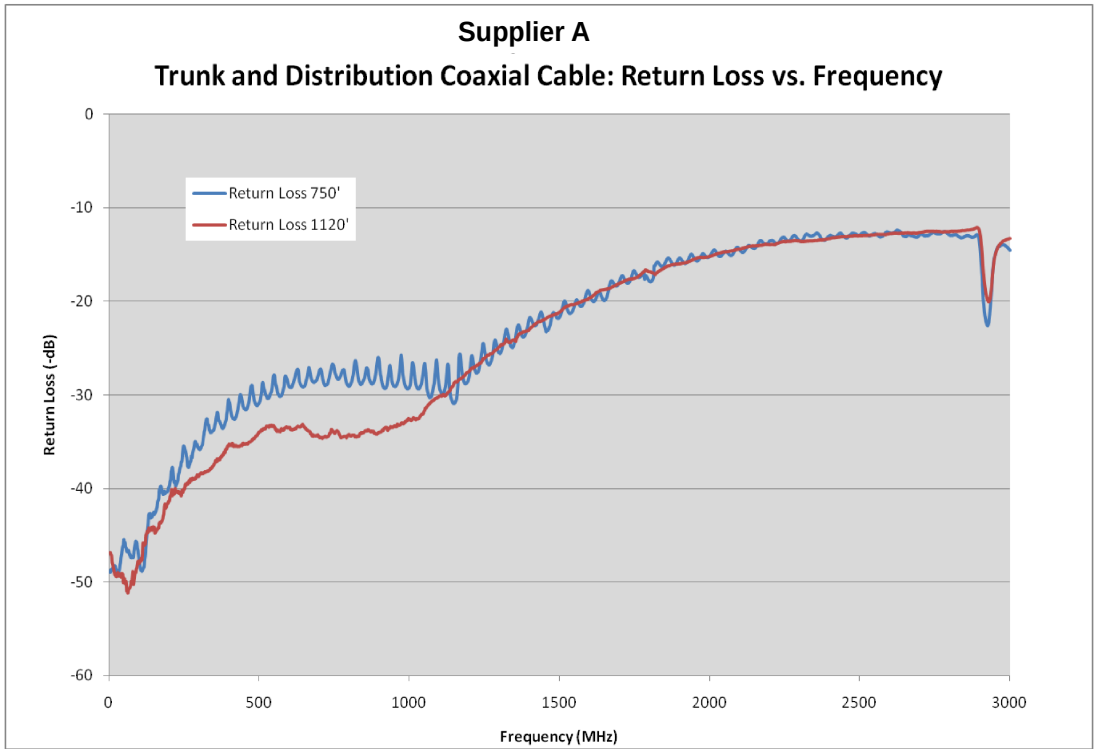

Figure 8 – Distribution Coaxial Cable – Return Loss vs. Frequency

4.5 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 to 1400 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.

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 to 1300 MHz range. Especially on the tap coupled port. However, most Taps work well to ~1050 MHz.

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 the actual pass band response due to close-by tap reflections.

Figure 9 to Figure 11 show examples of the variability of key RF parameters for an array of Taps evaluated.

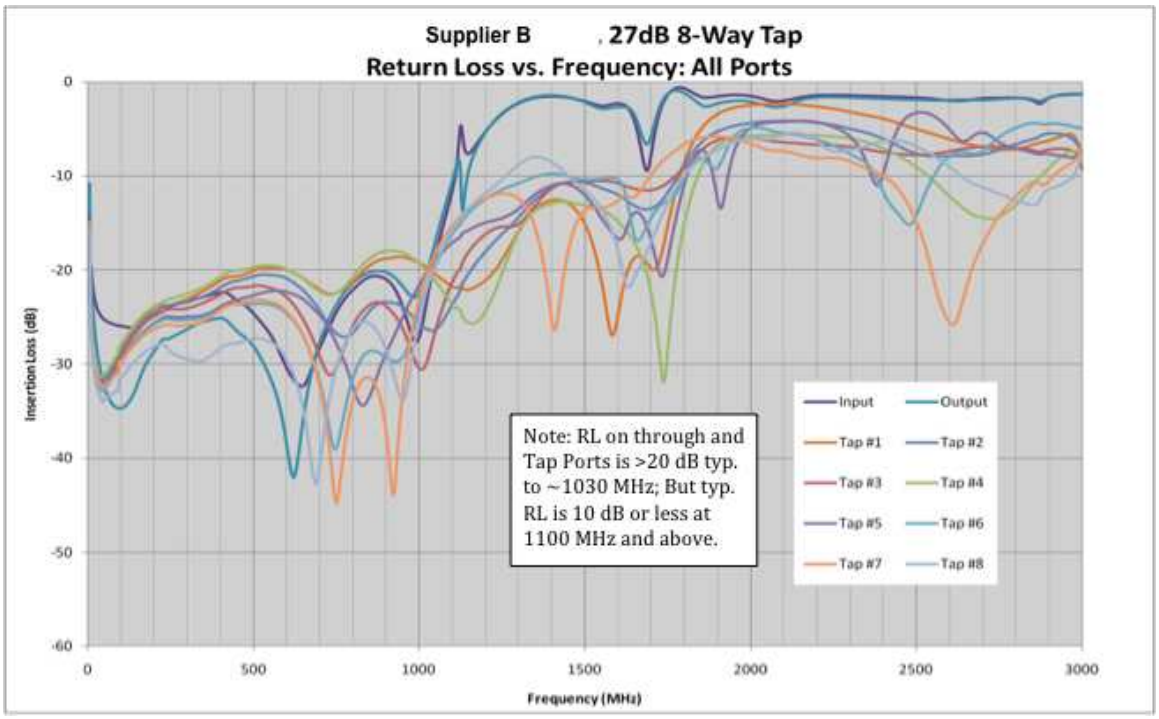

Figure 9 – 27 dB x 8 Tap - Return Loss vs. Frequency: All Ports

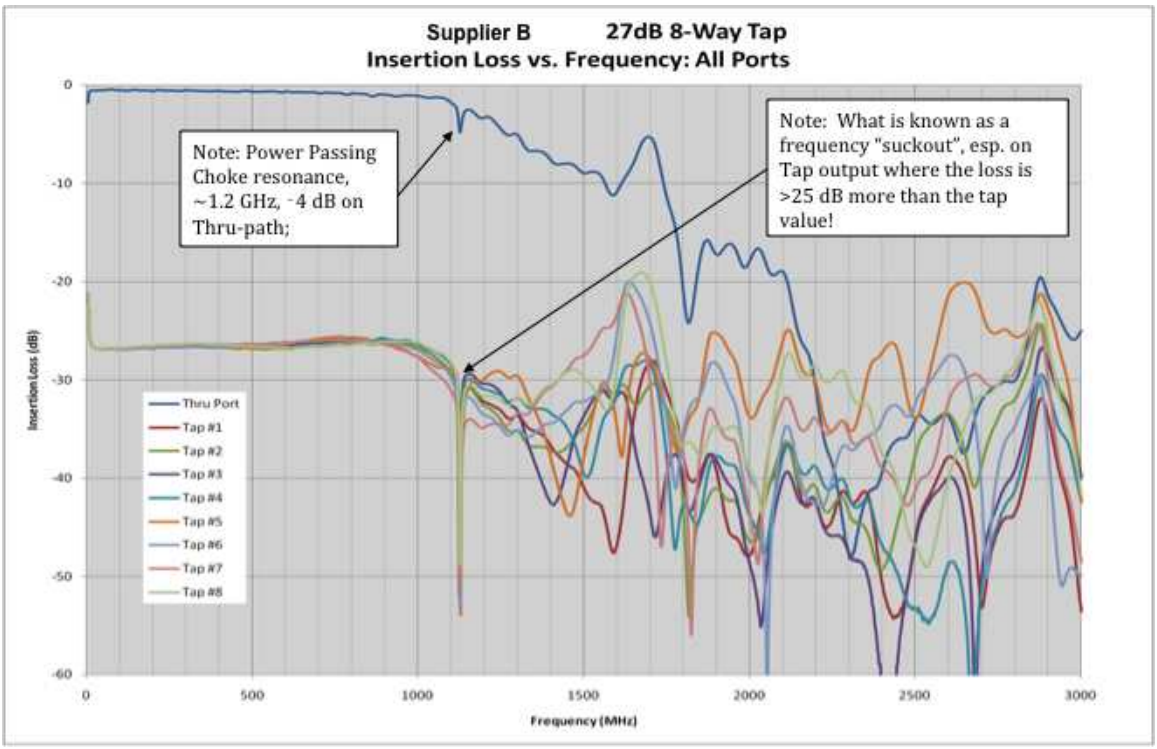

Figure 10 – 27 dB x 8 Tap - Insertion Loss vs. Frequency: All Ports

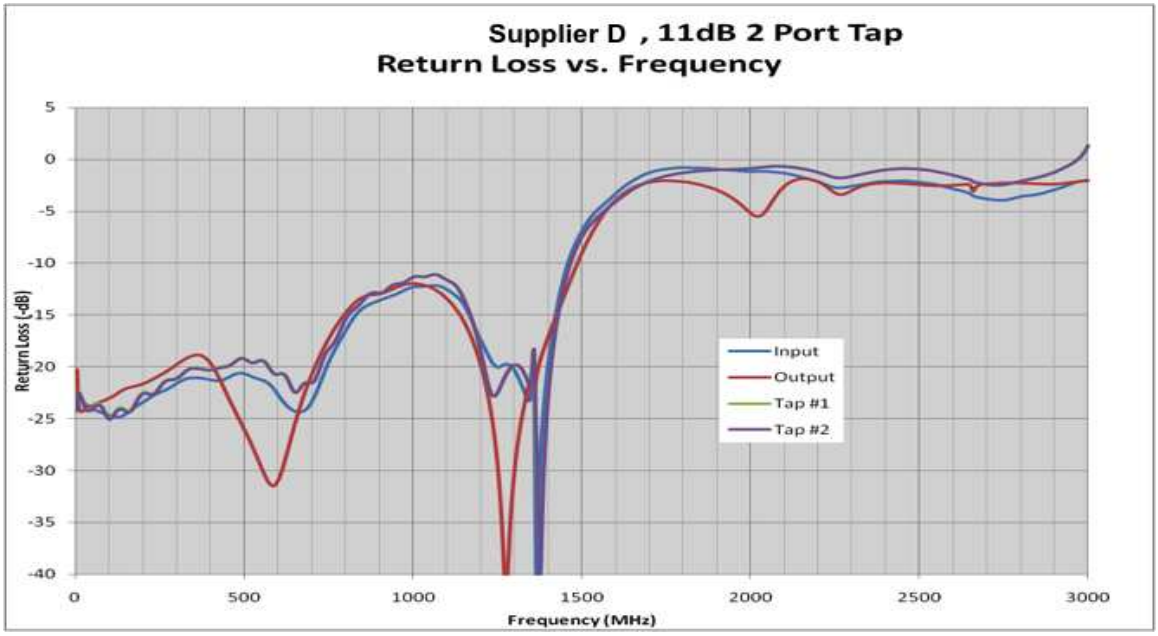

Figure 11 – 11 dB x 2 Tap - Return Loss vs. Frequency

4.6 Field Performance – Passive Coax Above 1 GHz

Let's pull together what we have discussed around taps and passives, the analysis of Section 4.2 and summarize how these components behave together in the context of recent field characterizations performed for the AMP initiative.

As discussed above, coaxial cable and even some current 1 GHz taps are indeed capable of supporting useful bandwidth above 1 GHz [4]. However, the frequency dependence of cable loss (see Figure 7) quickly attenuates signals above 1 GHz when we consider its use relative to attenuation characteristics of a low band upstream. The combination of drop cables, trunk cable, and taps add up to significant losses to the first active.

We can anticipate almost twice the loss (in dB) extending the return band to 200 MHz, such as in the high-split architecture introduced. However, above 1 GHz, the loss may increase by roughly a factor of five (in dB, dependent on Top-Split case chosen) compared to legacy return for such a span. CPE devices must make up for that loss to maintain equivalent performance, all else the same. As we observed in analyzing the case with an increasing amount of channel bonding, they also must generate additional total power associated with the wider bandwidth they would occupy to enable peak rates of a Gbps, relative to today's maximum of 6.4 MHz single or 2-4x bonded channel power.

This is not your father's cable modem – an L-Band, wideband, high power linear transmitter. It is a significantly more complex RF device. It is not a technology challenge, but it will come at a cost premium relative to retail CPE today. Quantifiably, the result is that very high CPE transmit power becomes necessary to close a bandwidth efficient link budget.

Conversely, for a given maximum transmit power, such as 65 dBmV chosen previously, we can favorably assume it is the same transmit power number for low split or for top split frequencies. The additional top-split loss translates to lower SNR at the first active, and every subsequent one if a cascade is in place. This impacts composite SNR formed by the combination of RF funneling and optical link performance.

The end result is that potential bps/Hz of top split is inherently lower for top split, and to achieve an equivalent modulation efficiency, the top split must be deployed over smaller service groups to reduce the noise contributions associated with the lower inherent SNR created by the loss. We will quantify this in further detail in Section 9.6.

However, Motorola performed field measurements as part of the AMP initiative, and the conclusions provide insight into the nature of this issue. We illustrate with a simple, and best case (N+0) example from field characterization done exactly for this purpose. Figure 12 shows field characterized loss [4] [5] of an RF leg of recently-built underground plant, measured from the end of a 300 ft coaxial drop from the final tap of a five-tap string on an otherwise typical suburban architecture.

The five taps, manufactured by Javelin Innovations, where extended bandwidth models, utilizing modified faceplates installed within existing tap housing to extend the RF passband of the network.

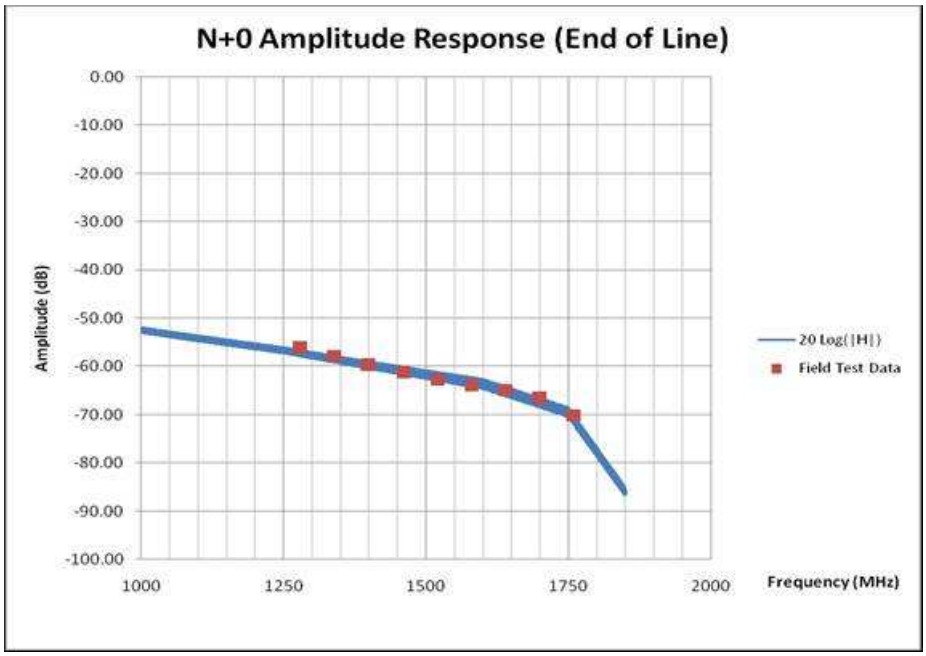

Figure 12 – Top Split Loss Characterization vs Model

Losses from 50-70 dB are observed, with measured data points highlighted in Figure 12. While the drop length represents an extended length scenario, the lack of any home connection removes any effects of additional splitters commonly found inside the home and outside the reach of the MSO until there is a problem in the home.

Let's take a look at the lowest, least attenuation part of the band, 1-1.2 GHz. A reasonable case can be made for a bandwidth efficient link budget for a remote PHY termination, as transmitters that increase the transmit power level over today's requirements to support 65 dBmV will reach the first active with solid SNR.

Mathematically, consider the following:

- Thermal Noise Floor: -65 dBmV/MHz
- Signal BW: 200 MHz
- Total Noise: -42 dBmV/200 MHz
- Active NF+Loss: 8 dB (est)
- Rx Noise Power, Plant Terminated: -34 dBmV

Using the 55 dB of loss observed at the low end of the band for the first 200 MHz, a 58 dBmV transmitter will leave us with an SNR of 37 dB. This is in the neighborhood of the SNR required, with margin, for 1024-QAM if advanced FEC is assumed. In Table 4,1024-QAM is quantified as SNR = 39 dB without FEC using typical HFC upstream optics. Higher orders would become challenging. A 65 dBmV capability would more ably support a higher modulation profile.

Based on the attenuation slope in Figure 12 above 1200 MHz, this gets more challenging as higher bands are considered. Note that the tap performance of the extended band units is very good, but there is simply unavoidable attention associated with deployed coaxial infrastructure that becomes the dominant SNR characteristic of the link.

Now, consider that the above characterization included the following favorable conditions:

- Faceplate tap replacements
- N+0
- Pristine, unused plant
- Extra transmit power assumed in a much higher frequency band
- No connected users
- No home losses

We can easily remove the first of these assumptions for most practical networks. Without the investment in tap faceplate change-outs, typical 1 GHz taps in the band directly above their specified maximum have more loss than these specially designed faceplates.

The additional loss observed is up to 9 dB for the cascade of taps at the end of the usable band, in this case characterized as 1160 MHz [5](worse above that, less below). More loss comes directly off of the SNR as the signal power is dropped into the noise floor.

Thus, in current tap architectures, under N+0 conditions, and constrained to the lowest end of "top-split," in good plant conditions, we are already seeing pressure on SNR for bandwidth efficient modulation profiles as the SNR drops to 30 dB or less. The sensitivity of QAM profile to SNR loss in Table 4 – Legacy Modulation and C/N Performance Targets shows that 2-3 modulation profiles, and the associated capacity, become compromised.

Now, to remove another assumption, if we instead think of the actives as amplifiers, and cascade them on the way to a node with equivalent degradation and potentially combining noise impacts at the node a described in Section 4.3, we find that a bandwidth efficient link budget becomes even more difficult to achieve.

Thus, top-split, while potentially within technology and investment reach, is off to a very difficult start as a viable alternative. The potential bps/Hz efficiency metric is inherently lower, and to achieve an equivalent modulation efficiency, the top-split must be deployed over smaller service groups to reduce the noise contributions associated with the lower inherent SNR created by the loss. This has been shown to be the case analytically as well as in field characterization in a better-than-typical environment.

4.7 Using "Top-Split" Spectrum for New Forward Path Capacity

While the challenges on the upstream above the forward band are significant obstacles to practical deployment, this is not necessarily so on the downstream. This is important, because as the upstream side of the HFC diplex extends, it intrudes on downstream bandwidth and thus removes available downstream capacity. We believe that use of new coaxial spectrum will be required in the evolution of HFC and of DOCSIS, and that both should be part of cable's migration plan. However, in the case of new spectrum above 1 GHz, we believe that is best utilized for new forward capacity.

We have discussed the possibility of a phased architecture. While forward bandwidth loss is relatively modest for an 85 MHz split, if the band extends further, such as to 200-300 MHz, then a significant chunk of downstream capacity is lost. Today, this band may be only carrying analog services, and thus is not reducing the actual deployed downstream capacity, but it is reducing the available capacity for future

growth – i.e. it is assumed that at some point analog services will be removed in favor of digital capacity.

With this loss of downstream bandwidth, it then becomes important to uncover new downstream bandwidth, and the logical place to find this is directly above today's forward band. If the architecture is 750 MHz or 870 MHz, then of course there is already technology in place to exploit out to 1 GHz. Beyond 1 GHz, there is very little outdoor gear designed to operate in this band, and no CPE designed to work in this band (just as is the case for upstream).

We can identify at least three compelling advantages to considering use of the band over the end of the defined tap bandwidth for forward services, as opposed to reverse:

1) High Fidelity Forward Path – The fundamental characteristics of the forward path have always been to around a high SNR, low distortion environment to ably support analog video. As we know, the reverse path was not originally architected with high fidelity in mind. Over time, technology has been introduced to enable a high-speed data channel, but the low noise and high linearity architected into the forward path is orders of magnitude above the return path. This difference translates to a much more straightforward exploitation of bandwidth with high performance on the downstream.

2) Broadband RF Power – The forward path levels are designed for RF path losses out to 1 GHz. Because of this, the parasitic losses above 1 GHz of the coax, and the minimal additional attenuation, are not a stretch to achieve when extending the forward path. It is an entirely different case in the return, where the architecture has relied on the low loss end of the band, which increases only modestly as it is extended to 85 MHz or even 200 MHz. This issue was highlighted in Sections 4.3 and 1.1.

3) Cost of New RF BW – Forward path RF systems already extend to the 1 GHz range, so are designed with the expectation of the loss implications. There has therefore been continuing investment in broadband RF hybrids driving higher levels over increasing forward bandwidths, still based on supporting a full analog and digital multiplex. As a result, the output levels of these hybrids and nonlinear characteristics have continued to improve. However, investment in these premium devices for the forward path is spread over the number of homes serviced by the actives. The HFC downstream delivers high linearity and high levels over multiple octaves, and the hybrids are shared, spreading the investment across a subscriber pool. In the reverse path, each home needs a high power, linear transmitter (though less than an octave), and also in a much higher frequency band that would likely require a higher cost technology implementation.

4) The use of spectrum above the forward band implies a new guard band. Since guard bands are a percentage of edge frequency, the lost spectrum is sizable, cost significantly lost capacity. The eliminated spectrum will remove prime forward path digital bandwidth from use, costing on the order of 1 Gbps for DOCSIS NG technology, in order to enable *less* capable upstream bandwidth above 1 GHz.

Without question, HFC will need to mine new bandwidth to enable new capacity for continued traffic growth. Today's coax remains unexploited above 1 GHz in all cases, and above 750 MHz and 870 MHz in other cases in North America. Current forward path technology is already within striking distance and readily capable of

being extended to take advantage of latent coaxial capacity above wherever the forward path ends today [6]. And, while this spectrum is non-ideal in the forward path as well, it will benefit from the introduction of OFDM for NG DOCSIS, but without the spectrum loss and RF power implications of use as upstream band.

Based on the above reasoning, our recommendation is to enable additional coaxial capacity above today's forward band, and to exploit this spectrum for downstream purposes exclusively. We will quantify this band for downstream use in subsequent sections derving data capacity, network performance, and lifespan.

In Section 0, we will estimate the available data capacity of the forward path under various implementations of an extended forward band.

Then, in Sections 10.2.1 and 10.2.2, we will quantify available network capacity and discuss the implications to forward path lifespan.

Finally, in Sections 10.2.3 and 10.2.4, we will describe how this bandwidth could be managed within the system engineering of downstream HFC, implemented within linear optics and RF (not an RF overlay).

5 HFC OPTICAL TRANSPORT TECHNOLOGY OPTIONS

The optical layer will be examined in this section. We will look at two technologies of optical transport return, analog return path and digital return, which may commonly be referred to as Broadband Digital Return (BDR), or simply Digital Return. First, we will review the forward path. [36]

5.1 Overview - Analog Forward Path Transport

Analog Forward path is currently the only economical method for the transmission of cable signals downstream. The advances in analog forward laser technologies enable transmission of the 54-1002 MHz of spectrum this is over 150 channels, each 6 MHz wide. This is approximately 6 Gbps of data capacity assuming the PHY layer transmission utilizing 256-QAM (8 bits per Hz BW efficiency, excluding overhead).

The forward path is a layer 1 media-converter style architecture. The optical transmission may be shared with multiple HFC nodes. There are two network architectures for the forward: Full Spectrum as illustrated in Figure 13; and another called QAM Narrowcast Overlay, or simply Narrowcast Overlay, as in Figure 14.

The MSO serving area between headend and node will be in most cases is less than 40 km. Therefore this will be easily

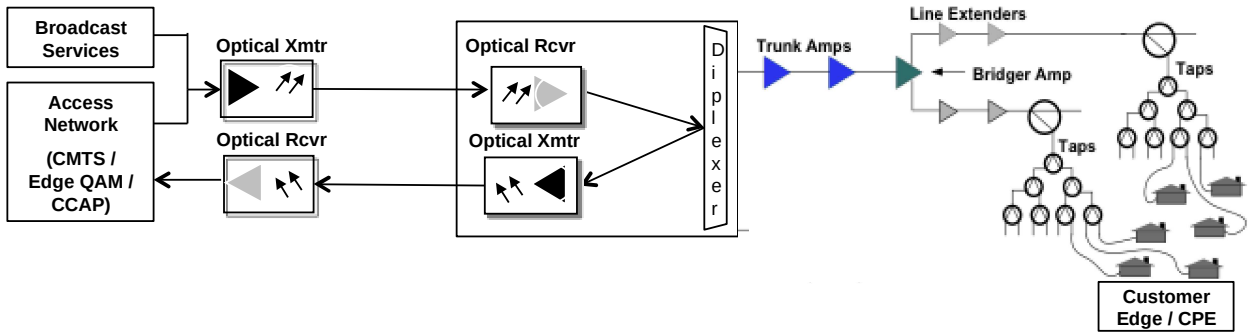

Figure 13 – Hybrid Fiber Coax (HFC) with Full Spectrum and Node +N

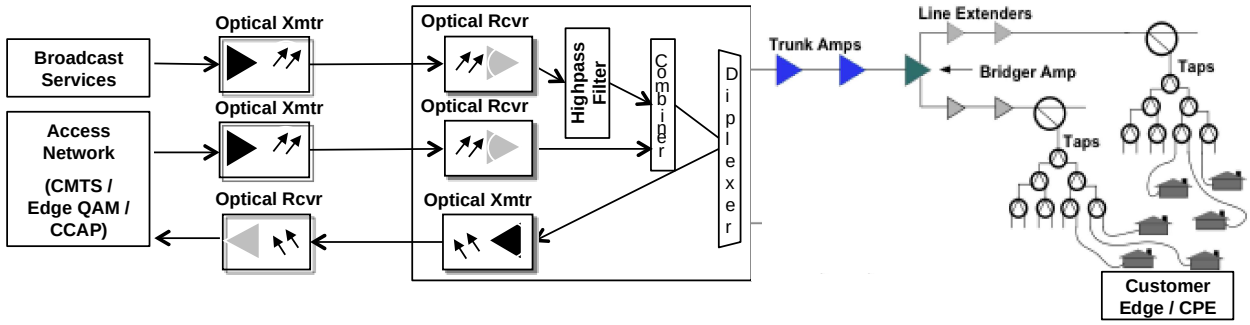

Figure 14 – Hybrid Fiber Coax (HFC) with QAM Narrowcast Overlay and Node +N

supported with an HFC architecture. The support for extremely long distance to and from the node may be a factor for the HFC. The optical capabilities of HFC simply have lots of dependencies, variables, and trade-offs to determine the HFC optical link distance.

We will use round numbers and generalities to discuss some the capabilities of HFC optical transport when considering long distances. So, we will use an example of HFC analog optical transmission of full spectrum, no analog video, and 150 QAM channels, we will assume a 100 km optical reach is achievable in most cases.

In a narrowcast overlay architecture, we assume as many as 40 wavelengths / lambdas per fiber, 80 QAMs of narrowcast spectrum, and a reach of approximately 100 km to the node. HFC optical distance will vary based on many factors, including narrowcast channel loading, the number of analog video channels, and many other factors. We could assume that a greater distance is achievable with an HFC Digital Forward, as well as DFC (Digital Fiber Coax) style optical transport, compared with HFC analog forward optics without the use of EDFAs (erbium-doped fiber amplifier).

In some cases, fiber count is insufficient, regardless of the distance. Therefore, to avoid over lashing new fiber to service groups, separate wavelengths are placed on the fiber. The use of HFC analog optics today supports far fewer optical wavelengths than that which is supported using optical Ethernet technology. This may be a challenge for HFC style architectures.

5.2 Overview - Analog Return Path Transport

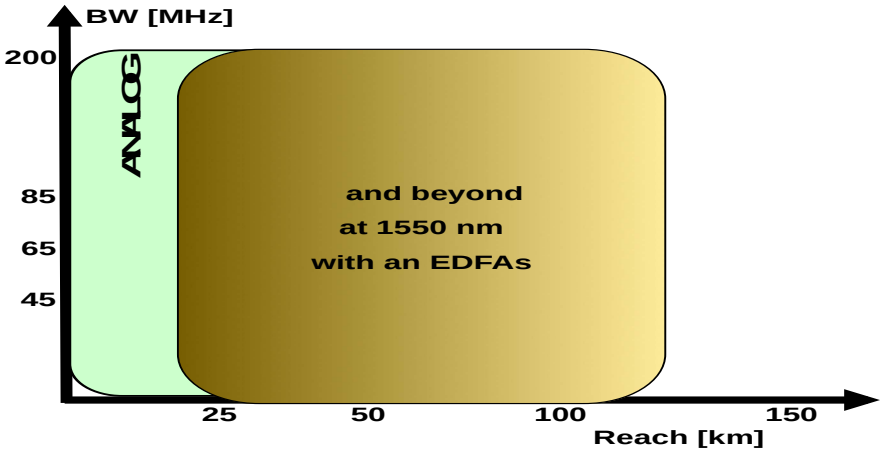

Figure 15 – Return Analog Optical bandwidth and Reach

Analog return path transport is now mostly done 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 Mid-split, High-split, and Top-split returns. Supporting short to moderate return path distances of 0-50 km with full spectrum High-split is achievable. If the wavelength is changed to 1550 nm with an EDFA, then greater distances are possible. This is shown in Figure 15.

The analog optical return path transport presently supports up to 200 MHz loading; but typically only 5-42 MHz or 5-65 MHz is carried, depending on the distribution diplex filter split. The major benefit with analog optical return is its simplicity and flexibility, when compared with HFC style digital optical transmission. Distance is the chief challenge of analog optical transport. Refer

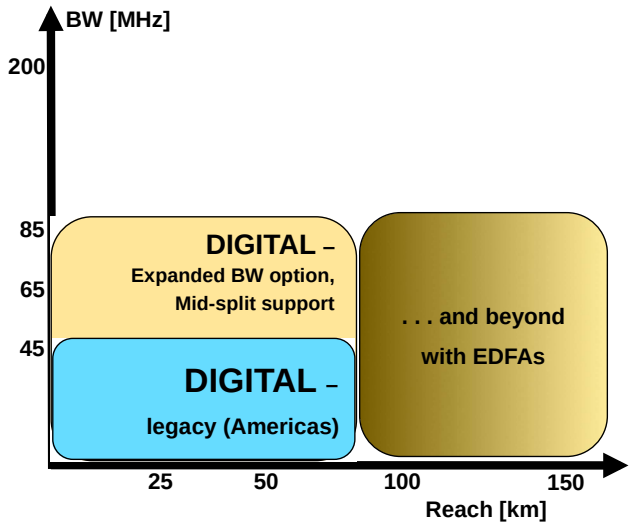

Figure 16 – Return Optical bandwidth and Reach

to the Figure 15 and Figure 16.

Pros

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

Cons

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

Also, as with any analog technology, the performance of the link is distance dependent. The longer the link, the lower the input to the receiver, which delivers a lower C/N performance. The practical distance over which an operator can expect to deliver 256-QAM 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 performance noise budgets. The distance of 0-50 km are reasonable and longer distance would be supported with an EDFA.

5.3 Overview – Digital Return Path

Digital return path technology is commonly referred to as broadband digital return (BDR). The digital return approach is "unaware" of the traffic that may be flowing over the spectrum 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 digital to analog conversion is performed and the sampled analog spectrum is recreated.

The parameters of analog to digital conversion will need to be considered when determining the Digital Return optical transport requirements. There are two important factors in the A-to-D conversion:

1. Sampling Rate and
2. Bit Resolution (number of bits of resolution).

Sampling Rate

- Inverse of the time interval of which samples of the analog signal are taken.
  - Referred to as Samples per Second or Sampling Frequency.
- Nyquist Sampling Theorem governs the minimum sampling rate.
- Minimum sampling frequency must be at least twice the frequency width of the signal to be digitized.
- Example: Return band from 5 – 42 MHz must be sampled at 84 MHz (at least). For practical filter realization, the sampling rate should be at least 10-20% greater.

Bit Resolution

- Number of bits to represent the amplitude for each sample taken.
- Each bit can be "1" or "0" only, but multiple bits can be strung together as "words" of "n" number of bits.
- Number of amplitude levels can be calculated as 2^n, where "n" is the number of bits of resolution. Example: 8 bits leads to 2^8 = 256 levels.

Pros

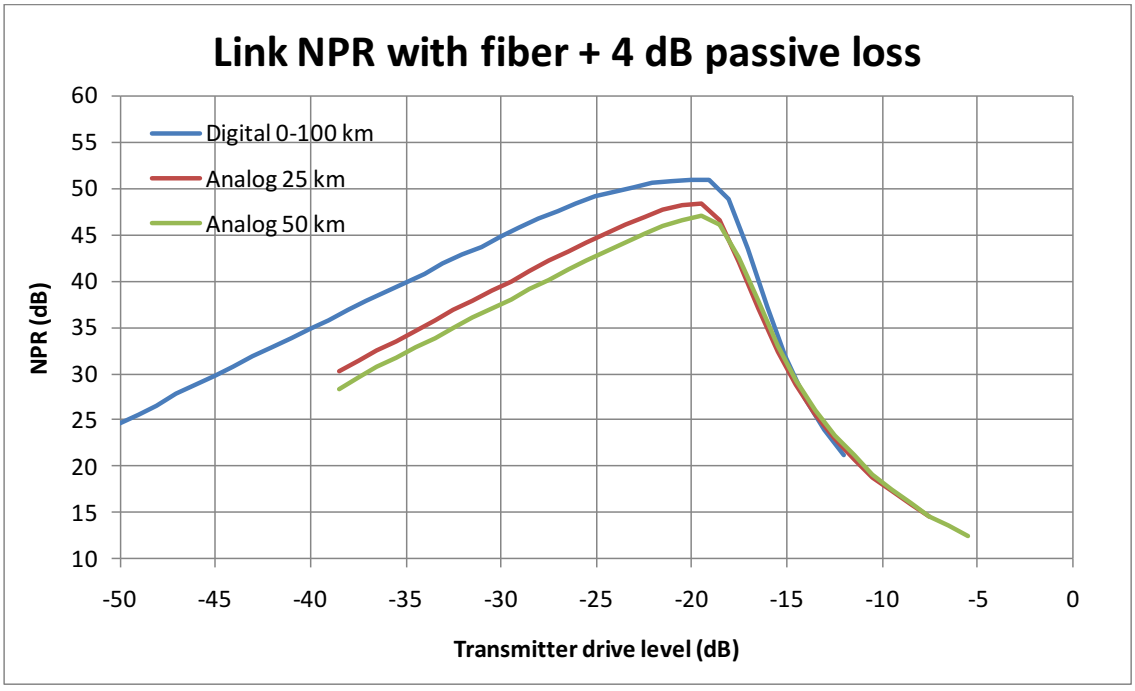

Figure 17 – Analog & Digital Return NPR

There are a number of advantages to the digital return 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 (Modulation Error Ratio) for 0 km as for 100 km, and even beyond as Figure 17 illustrates. 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 (<160 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. Figure 17 below is an illustration of performance and distance when examining the analog and digital optical transport methods. With regards to the link noise power ratio (NPR) with fiber and 4 dB optical passives loss, the digital return used 1470 – 1610 nm; analog 25 km used 1310 nm, while the analog 50 km used 1550 nm. The optical output power of each transmitter was 2 mW (+3 dBm).

The Digital Return main drivers are as follow:

- "Set it and forget it" – technician and maintenance friendly
- Signal to noise performance does not degrade with distance
- Supports redundancy over uneven lengths/longer lengths
- Pairs well with "fiber deep" architectures, enables "service group aggregation"
- Pluggable optics for less costly inventory

Cons

The chief drawback to digital return 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 frequencies. There is currently no standardization on the digital return modulation and demodulation schemes, or even transport clock rates.

Another chief drawback to digital return is the Nyquist sampling theorem. It requires a minimum sampling rate, $f_s > 2B$ for a uniformly sampled signal of bandwidth, B Hz. For n-bit resolution, this requires a Transport Clock frequency >2nB. It is assumed that the higher the transport clock, the more costly it is. And with higher clock speed, there is more fiber dispersion, which sets an upper limit on transport rate! This causes some practical limitations as to how high the return spectrum can cost effectively reach when considering digital return.

The key points about Nyquist Sampling are captured below. This may be a major driver for the use of analog optics when modest distances are possible and also a major reason to move away from HFC style architectures to a Digital Fiber Coax (DFC)

class of architecture when distance is a challenge.

Nyquist Sampling Theorem governs the minimum sampling rate

- Minimum sampling frequency must be at least twice the frequency width of the signal to be digitized

Nyquist Theorem causes some practical limitations

- A 6 MHz baseband signal requires a sampling frequency of 12 MHz minimum
- A 42 MHz return band requires 84 MHz minimum (at least)
- To digitize the entire forward band, we would need to sample at 1.1 GHz (550MHz system) to 2.0 GHz (1GHz system)
- Higher speed A/D converters typically have less Effective Number of Bits (ENOB), translating to decreasing performance at increasing clock speeds for a fixed number of bits.

The total data rate for any given digitized signal can be calculated as follows:

- Determine the minimum sampling rate. As discussed, this is always at least 2X the frequency width of the signal to be digitized (at least). Multiply by the number of resolution bits desired, n, to get the minimum transport clock. And add overhead bits for error correction and framing.

Example: Digital Return

- Typical Return band is 5-42 MHz
- Minimum Sampling frequency is 84 MHz (2*42 MHz) (at least for practical filter realization the sampling rate may be at least 10-20% greater to allow for an anti-aliasing filter.)
- For simple math, we will use 100 MHz or 100 Million samples/second
- Determine the bit resolution will be largely dependent on the SNR required
- For simple math we will use 10-bit resolution or 10 bits/sample
- Multiply bit resolution and sampling rate
  - 100 Million samples/second * 10 bits per sample = 1,000,000,000 bits/second
  - Approximately 1 Gb/s required to digitize the return band

Key Summary:

- >1 Gbps of optical transport was required to transport the 5-42 MHz of spectrum / data capacity
- Estimate of 4 Gbps plus of optical transport was required to transport the 5-250 MHz of spectrum / data capacity at 10 bits per sample (490 Million samples/second * 10 bits per sample = 4,900,000,000 bits/second. This is an estimate only)

Example: Digital Forward

- How about a 550 MHz forward band requiring 52 dB SNR?
- >1.1 Giga samples/second * 10 bits per sample = 11.0 Gb/s!!!

Assessment

It is more difficult and therefore more costly to manufacture digital return products. This may be a driver to use Analog DFB products for the new return applications. The selection of digital return products may be

driven by distance and performance requirements. Another driver to move to digital return will be when there is near cost parity with DFB. This may be the case in the future with the new spectrum returns.

5.4 HFC Return Path Analysis and Model

Analog return path transmitters used in HFC applications need to be examined to determine their capability to transmit higher orders of modulation or additional channel loading while maintaining adequate performance. Operating conditions such as the optical link budget, actual channel loading, and desired operational headroom are all contributing factors with respect to performance of these transmitters. Here, operational headroom can be defined as the amount of dynamic range required to provide sufficient margin against the effects of temperature variation, variation from system components (transmitter, receiver, CM/CMTS, etc…), and ingress noise.

In optical networking, the amount of dynamic range for a given modulation format needs to be considered to ensure proper operation of the transmitter under fielded conditions. Typically, 12dB of operational headroom has been recommended for robust operation. However, there may be opportunities in the future to reduce the operational headroom by up to 3dB (perhaps to 9dB). In the future, smaller node sizes and shorter cascades may reduce the amount of ingress noise and the impact of temperature can be lessened with the use of analog DWDM lasers, which are tightly controlled over temperature.

Testing conducted on a standard,

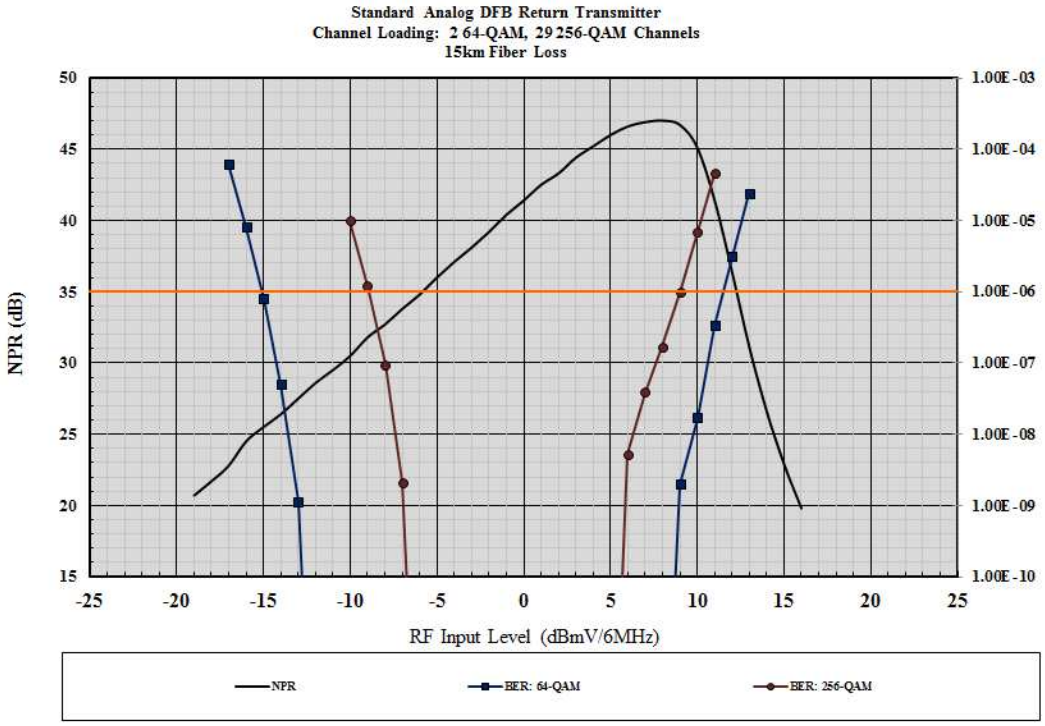

Figure 18 – High-split Standard Analog DFB Return Transmitter

analog DFB return transmitter (+3dBm) and

an analog DWDM return transmitter, under "high split" loading conditions yielded acceptable dynamic range for 256 QAM operation. Figure 18 provides the results of the +3dBm analog DFB return transmitter. This test was conducted over a 15km link budget with a received power of -3dBm. The RF channel loading consisted of 31 QAM channels upstream containing two 64 QAM channels and twenty-nine 256 QAM channels. The measured dynamic range for a BER< 1E-06 for the 256 QAM channels is 18dB, which provides adequate operational headroom.

Figure 19 and Figure 20 provide data, taken at three frequency splits (low, mid, and high) using 64 QAM and 256 QAM channel loading, for an analog DWDM return transmitter, operating at +8dBm output power over a 16dB optical link (40km of fiber plus 8dB of passive loss). In the "high split" case, this transmitter provides 13dB of dynamic range (1E-06) for 256 QAM, adequate both for present day scenarios where 12dB of operational headroom may be required and for future scenarios where reduced operational headroom is sufficient.

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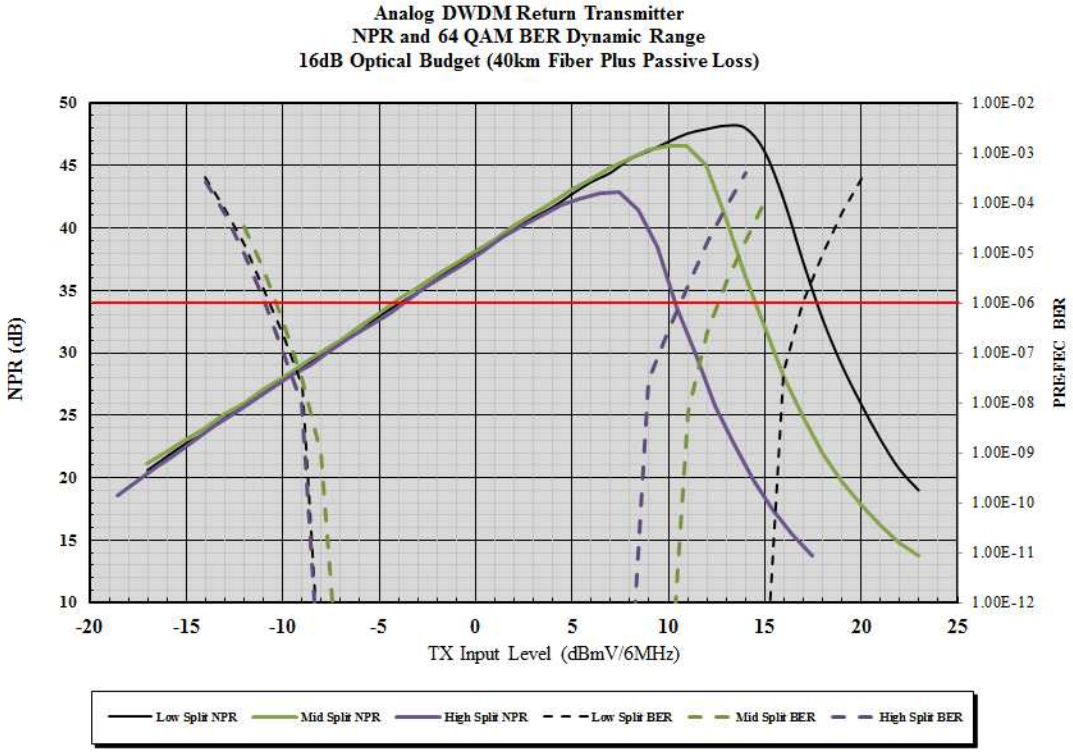


Figure 19 – Analog DWDM Transmitter: 64 QAM (Low/Mid/High Split)

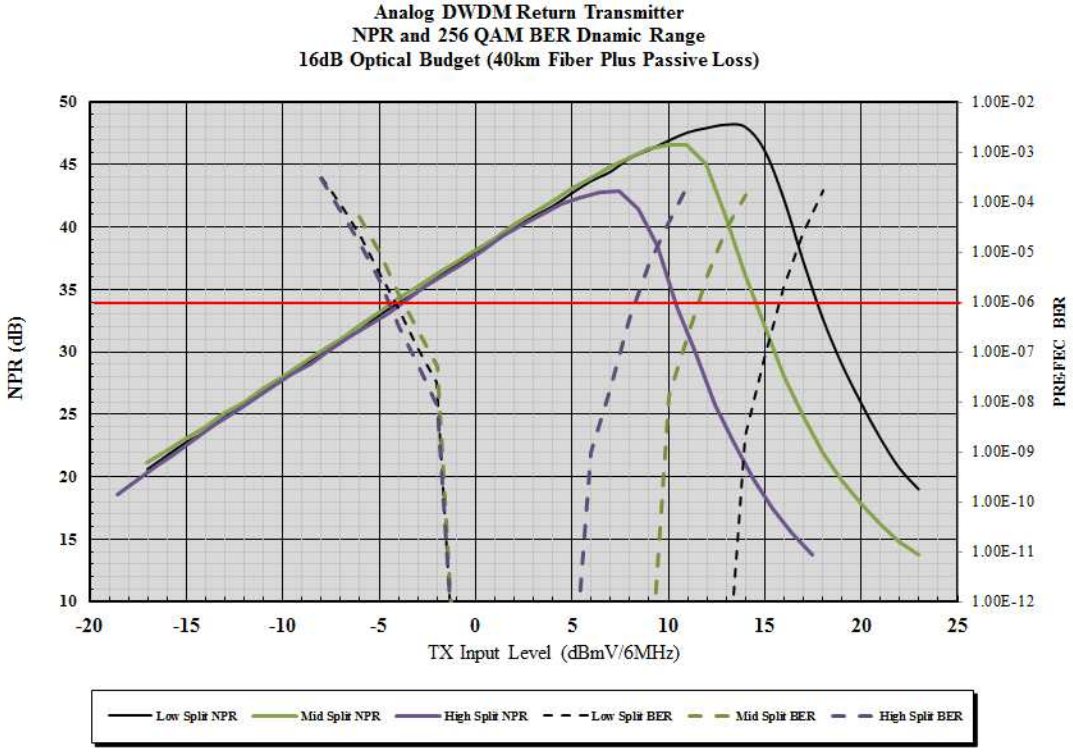


Figure 20 – Analog DWDM Transmitter: 256 QAM (Low/Mid/High Split)

6 SUMMARIES FOR HFC NETWORK COMPONENTS AND TOPOLOGY ANALYSIS

The analyses of the coaxial and optical network, the Hybrid Fiber Cox (HFC) network and the issues that need to be considered that may impact performance are summarized in Table 6. The spectrum selection will play a major role in terms of data capacity and network architecture.

6.1 Major Considerations for Coaxial Network Performance

- **First Major Consideration:** Spectrum Selection
- **Second Major Consideration:** Path Loss or Attenuation
  - Overall System loss progressively increases as frequency increases, thus a major factor when considering higher frequency return.
  - Path Loss from the Last Tap including: Tap Insertion, Tap Port, Cable Loss Hardline, Cable Loss Drop, In Home Passive Loss to Modem/Gateway (these impact Top-splits)
- **Third Major Consideration:** Transmit Power Constraints
  - Modem maximum power output composite not to exceed +65 dBmV (to minimize power and cost, and maintain acceptable distortion)
- **Fourth Major Consideration:** Noise Funneling Effect
  - The effects of large number of return path amplifiers. This is not a factor at low frequency because the cable loss is low enough that a cable modem can provide adequate power level to maintain high C/N.
- **Fifth Major Consideration:** Optical CNR Contribution
- **Sixth Major Consideration:** Error Correction Technology

6.2 Analysis

An analysis will be performed on the network in Figure 21 and described by Table 6

Table 6 – Node Service Group and Coaxial Network Assumptions

Typical Node Assumptions		
Homes Passed	500	
HSD Take Rate	50%	
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
Express Cable Type	.750 PIII	
Largest Express Cable Span	2000	ft
Distribution Cable Type	.625 PIII	
Distribution Cable to First Tap	100	ft
Largest Distribution Span	1000	ft
Drop Cable Type	Series 6	
Largest Drop Span	150	ft
Maximum Modem Tx Power	65	dBmV

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. Table 7 shows what the gain requirements would be for an upstream express amplifier at the ranges of Figure 21.

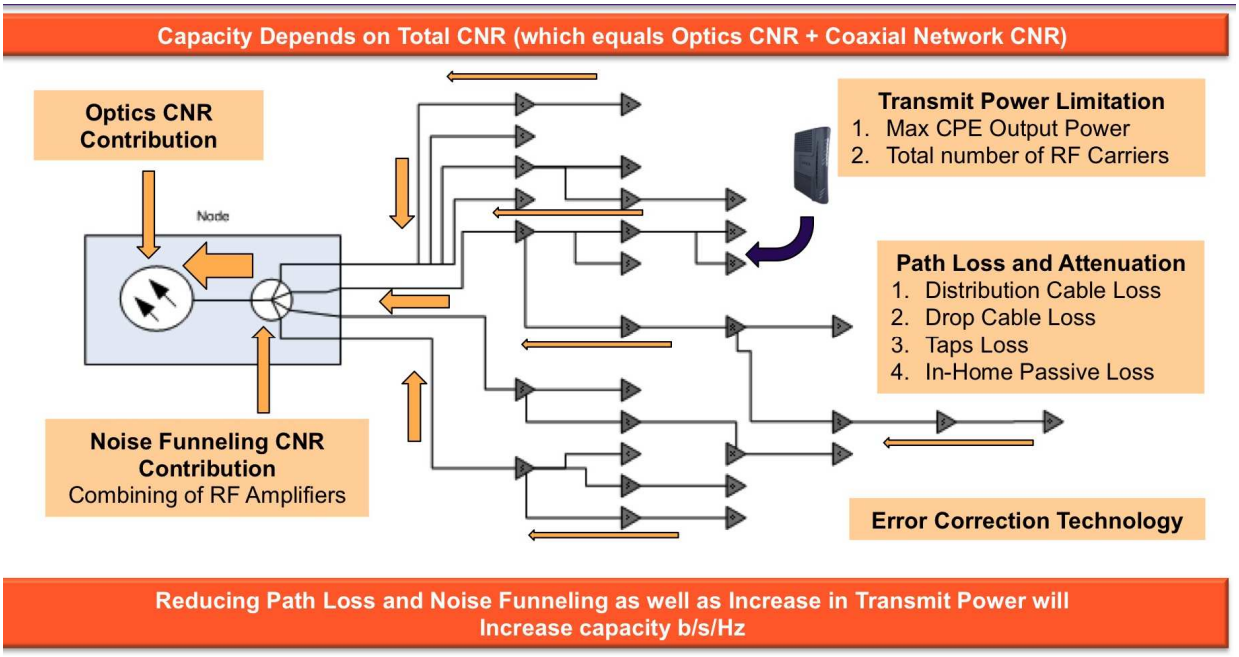


Figure 21 – Major Considerations for Coaxial Network Performance

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. Table 7 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.

Table 8 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 system performance can be calculated for each scenario.

Table 7 shows the compared performance calculations for the 500 home passed node outlined in Figure 21 and Table 6. The desired performance target is 256-QAM for each scenario; if it can be achieved, the throughput per subscriber will be maximized.

Table 7 – Express" (untapped) Segment Characterization

"Express" (untapped) Segment Characterization		Sub-Split	Mid-Split	High-Split 238	High-Split 500	Top-Split (900-1125) Plus Sub-split	Top-Split (1250-1700) Plus Sub-split	Top Split (2000-3000) Plus Sub-split
Upper Frequency	MHz	42	85	238	500	1125	1700	3000
Typical Maximum Cable Loss (Amp to Amp 70 deg F)	dB	6.5	9.2	14.6	24.8	36.9	45.4	60.3
Additional Gain Required for Thermal Control (0 to 140 deg F)	+/-dB	0.5	0.6	1.0	1.7	2.6	3.2	4.2
Total Reverse Amplifier Gain Required	dB	**6.9**	**9.8**	**15.7**	**26.5**	**39.5**	**48.5**	**64.5**

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.

The HFC return optical links considered in the model are the analog DFB lasers or broadband digital return (BDR) systems. The selection DFB option was selected for the low frequency returns up to the High-split of 238 MHz. However, High-split 500 was modeled with Digital HFC Return. All the Top-split spectrum options used the Digital HFC Return optics as well.

In the model used to determine the performance of the optical link at several we used the following inputs for the various spectrum options and as well as optical link types, see the Table 9 below.

Table 8 – "Distribution" (tapped) Segment Characterization

"Distribution" (tapped) Segment Characterization		Sub-Split	Mid-Split	High-Split 238	High-Split 500	Top-Split (900-1125) Plus Sub-split	Top-Split (1250-1700) Plus Sub-split	Top Split (2000-3000) Plus Sub-split
Upper Frequency	MHz	42	85	238	500	1125	1700	3000
Worst Case Path Loss	dB	**29.0**	**30.0**	**34.5**	**43.1**	**67.0**	**75.3**	**80.0**
Path Loss from First Tap	dB	*29.0*	*30.0*	*32.2*	*35.4*	*44.2*	*43.2*	*50.1*
Distribution Cable Loss	dB	0.4	0.6	0.9	1.5	2.2	2.7	3.6
Tap Port Loss	dB	23.0	23.0	23.0	23.0	27.0	23.0	24.0
Drop Cable Loss	dB	2.1	2.9	4.7	7.4	10.4	12.8	17.0
In Home Passive Loss to Modem	dB	3.5	3.5	3.5	3.5	4.6	4.7	5.5
Path Loss from Last Tap	dB	*25.5*	*28.0*	*34.5*	*43.1*	*67.0*	*75.3*	*80.0*
Distribution Cable Loss	dB	4.0	5.7	9.1	15.0	22.0	27.0	35.9
Tap Insertion Loss	dB	7.9	7.9	9.2	9.2	18.0	21.8	12.6
Tap Port Loss	dB	8.0	8.0	8.0	8.0	12.0	9.0	9.0
Drop Cable Loss	dB	2.1	2.9	4.7	7.4	10.4	12.8	17.0
In Home Passive Loss to Modem	dB	3.5	3.5	3.5	3.5	4.6	4.7	5.5

Table 9 – Optical Segment Characterization Assumed per Spectrum Split

Optical Segment Characterization		Sub-Split	Mid-Split	High-Split 238	High-Split 500	Top-Split (900-1125) Plus Sub-split	Top-Split (1250-1700) Plus Sub-split	Top Split (2000-3000) Plus Sub-split
Upper Frequency	MHz	42	85	238	500	1125	1700	3000
Optical Return Path Technology		DFB	DFB	DFB	Digital	Digital	Digital	Digital
Assumed Optical C/N	dB	45	45	41	48	48	48	48

The inputs and results in Table 9 show following:

- 5 - 238 MHz have sufficient performance to support 256-QAM modulation at a 500 HHP node.
- 5 - 500 MHz have sufficient performance to support 128QAM 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 (900-1125) may operate at QPSK modulation with only 24 carriers at 6.4 widths.
    - The Top-split (1250-1700) may operate at QPSK modulation with only 3 carriers at 6.4 widths.
    - The Top-split (2000-3000) may operate at QPSK modulation with only 1 carrier at 6.4 widths. .

Further analysis of the Top-split options as shown in Table 10 through Table 13 concludes that reducing the node size, and thereby the funneled noise in the serving group could yield higher modulation capability. In these tables are red arrows, which highlight the key service group size and performance.

The comparison of low spectrum return options like that of Sub-split, Mid-split, and High-split versus the Top-split spectrum choices are measured in the following tables.

These table show that spectrum selection is one of the most important choices the cable operators could make for expanding the upstream. The spectrum options have vastly different performance capabilities when compared in the same cable topology. The Top-split option "MUST" reduce the noise funneling level, which requires smaller service group to increasing loading. Top-split allows only low order modulation and few carries will operate.

All of these assumptions are based on the use of single carrier QAM based systems using Reed-Solomon codes. Section 7 "DOCSIS PHY Technologies" describes the use of different error correction technologies and improvement that may be achieved in operating conditions and use of higher order modulation.

The use of Top-split frequencies will drive higher costs for additional node segmentation, nodes splits, and even running fiber deeper in the network.

The existing passive have an AC power choke resonances, which varies between 1050 - 1400 MHz making portions unusable or predictable. The recommendation on the low side is not to exceed 1050 MHz and high side 1125 MHz. Some passives may not even reach 1 GHz in cascade, so test your passives.

Plan to use low frequency return (Mid-split and High-split) and allow the

downstream to use 1 GHz plus, like 1125 MHz or as high as the cascade of existing taps will allow.

Consider touching the taps as a last resort.

Table 10 – Network Performance of a 500 HHP Optical Service Group

Return RF System Performance		Sub-Split	Mid-Split	High-Split 238	High-Split 500	Top-Split (900-1125) Plus Sub-split	Top-Split (1250-1700) Plus Sub-split	Top Split (2000-3000) Plus Sub-split
Upper Frequency	MHz	42	85	238	500	1125	1700	3000
Homes Passed		500	500	500	500	500	500	500
HSD Take Rate		50%	50%	50%	50%	50%	50%	50%
HSD Customers		250	250	250	250	250	250	250
Desired Carrier BW	MHz	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Modulation Type		256-QAM	256-QAM	256-QAM	128-QAM	QPSK	QPSK	QPSK
Bits/Symbol		8	8	8	7	2	2	2
Number Carriers in Bonding Group		3.5	10.25	33	73	24	3	1
Max Power per Carrier Allowed in Home	dBmV	59.6	54.9	49.8	46.4	51.2	60.2	65.0
Worst Case Path Loss	dB	**29.0**	**30.0**	**34.5**	**43.1**	**67.0**	**75.3**	**80.0**
Maximum Return Amplifier Input	dBmV	31	25	15	3	-16	-15	-15
Actual Return Amplifier Input	dBmV	15	15	15	3	-16	-15	-15
Assumed Noise Figure of Amplifier	dB	7	7	7	7	7	7	7
Return Amplifier C/N (Single Station)	dB	65	65	65	53	34	35	35
Number of Amplifiers in Service Group		30	30	30	30	30	30	30
Return Amplifier C/N (Funneled)	dB	50.4	50.4	50.4	38.7	19.6	20.3	20.4
Optical Return Path Technology		DFB	DFB	DFB	Digital	Digital	Digital	Digital
Assumed Optical C/N	dB	45	45	41	48	48	48	48
System C/N	dB	**43.9**	**43.9**	**40.5**	**38.2**	**19.6**	**20.3**	**20.4**
Desired C/N	dB	40	40	40	36	20	20	20

Table 11 – 250 HHP Optical SG High-split 500 & Top-split Options

Return RF System Performance		Sub-Split	Mid-Split	High-Split 238	High-Split 500	Top-Split (900-1125) Plus Sub-split	Top-Split (1250-1700) Plus Sub-split	Top Split (2000-3000) Plus Sub-split
Upper Frequency	MHz	42	85	238	500	1125	1700	3000
Homes Passed		500	500	500	250	250	250	250
HSD Take Rate		50%	50%	50%	50%	50%	50%	50%
HSD Customers		250	250	250	125	125	125	125
Desired Carrier BW	MHz	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Modulation Type		256-QAM	256-QAM	256-QAM	256-QAM	QPSK	QPSK	QPSK
Bits/Symbol		8	8	8	8	2	2	2
Number Carriers in Bonding Group		3.5	10.25	33	73	35	7	2
Max Power per Carrier Allowed in Home	dBmV	59.6	54.9	49.8	46.4	49.6	56.5	62.0
Worst Case Path Loss	dB	**29.0**	**30.0**	**34.5**	**43.1**	**67.0**	**75.3**	**80.0**
Maximum Return Amplifier Input	dBmV	31	25	15	3	-17	-19	-18
Actual Return Amplifier Input	dBmV	15	15	15	3	-17	-19	-18
Assumed Noise Figure of Amplifier	dB	7	7	7	7	7	7	7
Return Amplifier C/N (Single Station)	dB	65	65	65	53	33	31	32
Number of Amplifiers in Service Group		30	30	30	15	15	15	15
Return Amplifier C/N (Funneled)	dB	50.4	50.4	50.4	41.7	21.0	19.7	20.4
Optical Return Path Technology		DFB	DFB	DFB	Digital	Digital	Digital	Digital
Assumed Optical C/N	dB	45	45	41	48	48	48	48
System C/N	dB	**43.9**	**43.9**	**40.5**	**40.8**	**21.0**	**19.7**	**20.4**
Desired C/N	dB	40	40	40	40	20	20	20

Table 12 – 125 HHP Optical SG Top-split Options

Return RF System Performance		Top-Split (900-1125) Plus Sub-split	Top-Split (1250-1700) Plus Sub-split	Top Split (2000-3000) Plus Sub-split
Upper Frequency	MHz	1125	1700	3000
Homes Passed		125	125	125
HSD Take Rate		50%	50%	50%
HSD Customers		62.5	62.5	62.5
Desired Carrier BW	MHz	6.4	6.4	6.4
Modulation Type		**8-QAM**	**QPSK**	**QPSK**
Bits/Symbol		3	2	2
Number Carriers in Bonding Group		35	13	4
Max Power per Carrier Allowed in Home	dBmV	49.6	53.9	59.0
Worst Case Path Loss	dB	**67.0**	**75.3**	**80.0**
Maximum Return Amplifier Input	dBmV	-17	-21	-21
Actual Return Amplifier Input	dBmV	-17	-21	-21
Assumed Noise Figure of Amplifier	dB	7	7	7
Return Amplifier C/N (Single Station)	dB	33	29	29
Number of Amplifiers in Service Group		8	8	8
Return Amplifier C/N (Funneled)	dB	23.7	19.7	20.1
Optical Return Path Technology		Digital	Digital	Digital
Assumed Optical C/N	dB	48	48	48
System C/N	dB	23.7	19.7	20.1
Desired C/N	dB	23	20	20

Table 13 – 16 HHP Optical SG Top-split Options

Return RF System Performance		Top-Split (900-1125) Plus Sub-split	Top-Split (1250-1700) Plus Sub-split	Top Split (2000-3000) Plus Sub-split
Upper Frequency	MHz	1125	1700	3000
Homes Passed		16	16	16
HSD Take Rate		50%	50%	50%
HSD Customers		8	8	8
Desired Carrier BW	MHz	6.4	6.4	6.4
Modulation Type		**64-QAM**	**QPSK**	**QPSK**
Bits/Symbol		6	2	2
Number Carriers in Bonding Group		35	70	37
Max Power per Carrier Allowed in Home	dBmV	49.6	46.5	49.3
Worst Case Path Loss	dB	**67.0**	**75.3**	**80.0**
Maximum Return Amplifier Input	dBmV	-17	-29	-31
Actual Return Amplifier Input	dBmV	-17	-29	-31
Assumed Noise Figure of Amplifier	dB	7	7	7
Return Amplifier C/N (Single Station)	dB	33	21	20
Number of Amplifiers in Service Group		1	1	1
Return Amplifier C/N (Funneled)	dB	32.8	21.4	19.5
Optical Return Path Technology		Digital	Digital	Digital
Assumed Optical C/N	dB	48	48	48
System C/N	dB	32.6	21.4	19.5
Desired C/N	dB	33	20	20

7 DOCSIS PHY TECHNOLOGIES

7.1 ATDMA & J.83 (Single Carrier QAM)

7.1.1 Potential for Higher Symbol Rate A-TDMA

With the increasing deployment of wideband (6.4 MHz) 64-QAM upstream channels and in some cases bonding of upstream channels, operators are beginning to take advantage of the most powerful set of DOCSIS 2.0 and DOCSIS 3.0 tools available for maximizing capacity of a given channel and delivering higher peak service rates.

Nonetheless, as these advancements have matured – they are 11 years and 6 years since initial release, respectively – the pace of bandwidth consumption and market demand for higher rate service has continued. While it has slowed in the upstream relative to the downstream, it has nonetheless marched forward such that we speak of 10 Mbps and 20 Mbps upstream service tiers today, with an eye towards 100 Mbps in the near future.

The nature of reasonable traffic asymmetry ratios for efficient operation of DOCSIS may pull 100 Mbps along as well as the downstream heads towards a 1 Gbps. Certainly, for DOCSIS-based business subscribers – already outfitted with CMs, for example, or without convenient access to a fiber strand – 100 Mbps is often not just an objective but a requirement.

It is also likely one that operators can derive increased revenue from and consider SLA management options to deliver higher-end services.

7.1.1.1 100 Mbps Residential Upstream

For residential services, while a need for a 1 Gbps service appears far off into the next decade, a 100 Mbps offering is a reasonable target for the near term, and projects as the CAGR-based requirement in 4-6 years for 20 Mbps services today using traffic doubling periods of every two years (approximately 40%) or every three years (approximately 25%).

Unfortunately, today, only through bonding four 64-QAM carriers can 100 Mbps service rate, accounting for overhead loss to net throughput, be provided. The addition of 256-QAM as a modulation profile, to be described in the next section, helps to alleviate this somewhat by enabling a 100 Mbps rate to be offered over three bonded upstreams.

In either case, however, the added complexity of latency of bonding is required to achieve what is expected to be a fundamental service rate target to likely be implemented in bulk. Latency in particular has become a topic generating much interest because of the impact packet processing delay can have on gaming.

While relatively low average bandwidth, high quality gaming demands instantaneous treatment for the fairness and QoE of the gaming audience. Performance has been quantified against latency and packet loss by game type [1], and the variations in performance have led to solution variation exploiting the video architecture, managing server locations, and using potential QoS or priority mapping schemes. While bonding is not the dominant network constraint, elimination of

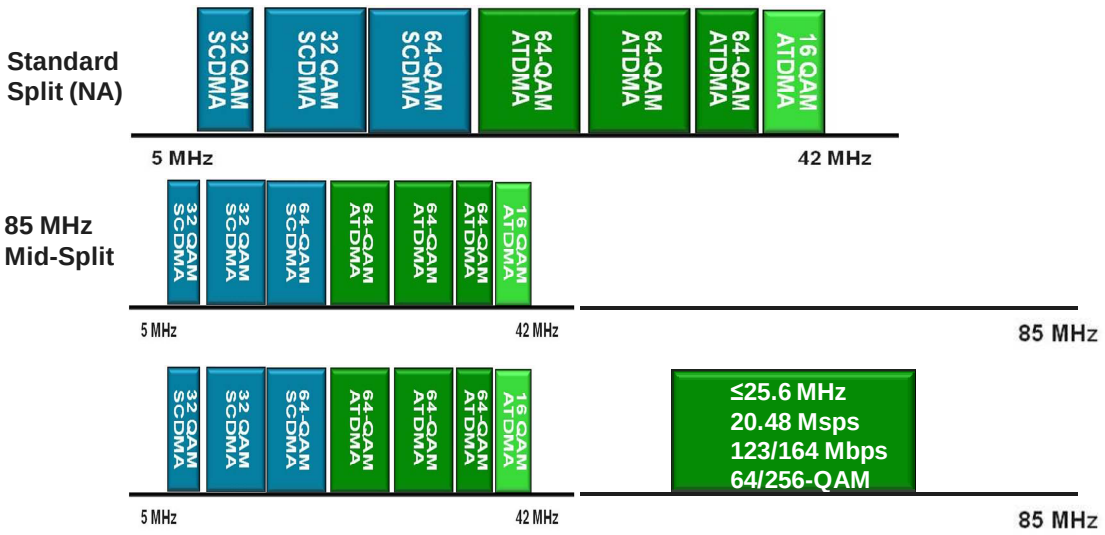


Figure 22 – Higher Symbol Rates Applied Over an 85-MHz Mid-Split Architecture

bonding is favorable for improving processing latency for gaming and other latency-sensitive applications that may arise in the future.

There is also a concern that upstream bonding capability will be limited to a maximum of 8 carriers, due to the increasing complexity associated with the tracking of packets and scheduling operation to process the payload across PHY channels. While operators are not ready to bond even four channels today, if this eight-channel limit were indeed the case, then peak upstream speeds could never exceed 240 Mbps at the PHY transport rate, or 320 Mbps under a 256-QAM assumption.

So, while 1 Gbps of capacity or service rate is likely not a near-term concern, a path to achieve that within the HSD infrastructure should be made available for the long-term health and competitiveness of the network.

Both concerns – 1 Gbps and the bonding implementation for 100 Mbps services – are addressed by a straightforward, integer-scale widening of the symbol rate of today's robust, single-carrier architecture. This approach is shown in Figure 22, where it is displayed as it might be implemented with an 85 MHz Mid-Split architecture. While not obvious from Figure 23, because of the full legacy band, two wider symbol rate channels could be operated within an 85 MHz architecture.

With an excess bandwidth (α) of 15%, there would be a reduced relative bandwidth overhead over today's $\alpha = .25$. This represents a savings of over 2 MHz of excess bandwidth at 20.48 Msps symbol rates, and two channels would consume less than 48 MHz of spectrum. This leaves plenty of additional spectrum for legacy carriers in a clean part of the lower half of the upstream.

By increasing the maximum symbol rate by a factor of four, from 5.12 Msps to 20.48 Msps, a basic unit of single-carrier operation now is capable of being a 100 Mbps net throughput channel, and simple delivery of this key peak speed service rate is achieved.

7.1.1.2 Achieving 1 Gbps

By bonding eight such carriers together, coupled with the introduction of 256-QAM,

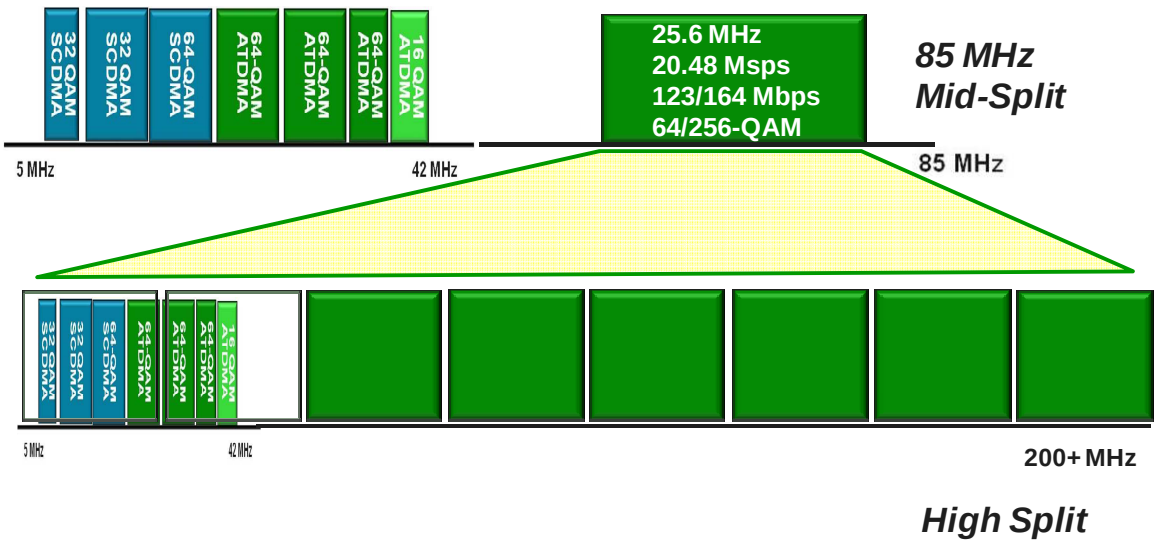


Figure 23 – 8x Bonded Higher Symbol Rates Over a "High-Split" Architecture

an aggregate throughput of over 1 Gbps can also now be enabled with a 4x symbol rate approach, when required. While it is not clear yet if there is an 8-bonded upstream limit, this technique takes that potential risk off of the table. This scenario is shown in Figure 23. In principle, these eight carriers can fit within 200 MHz of spectrum, making the approach comfortably compatible, even with the minimum bandwidth "high-split" spectrum architecture.

In practice, given that legacy services already populate the return path and will only grow between now and any new evolution of the channel or architecture, a high-split based upon a 250 MHz or 300 MHz upstream band is the more likely deployment scenario, with the possibility that it could increase further over time. A flexible FDD implementation would allow the traffic asymmetry to be managed as an operator sees fit based upon need.

7.1.1.3 Wider Band Channel Implications

The complexity of DOCSIS 2.0's wideband 64-QAM is largely around the ability to equalize the signal under frequency response distortions. The 24-Tap architecture evolved from the 8-Tap structure of DOCSIS 1.0, providing a very powerful tool for both ISI mediation as well as for plant characterization and diagnostics through the use of the pre-equalization (pre-EQ) functionality.

Every individual CM has its RF channel effectively characterized for reflection content and frequency response distortions, such as roll-off and group delay distortion. Use of pre-EQ has become an immensely powerful tool for MSOs in optimizing their return and efficiently diagnosing and zeroing in on problem locations. Optimization of use has matured and MSOs have learned how best to make use of this powerful tool as wideband 64-QAM has become a critical component of the upstream strategy.

Today's equalizer architecture is also, therefore, quite mature, and the ability to provide real-time processing of burst upstream signals has advanced considerably in the intervening years per Moore's Law as it pertains to processing power. This is

important to consider as we ponder higher symbol rates.

Higher symbol rates translate directly to wider channel bandwidths, and thus the equalizer is impacted by this technique. For the T-Spaced implementation of DOCSIS 3.0, if the symbol rate increases by a factor of four, then time span of an equalizer using the same number of taps has *shrunk* by a factor of one-quarter. In other words, the equalizer length must be increased by a factor of four to provide the same span of compensation for micro-reflections, for example.

Since equalizer taps are a complex multiply operation, it means 16x as many calculations take place in the equivalent algorithm. While this sounds imposing, considering that the 24-Tap structure is over ten years old, a 16x increase in processing is actually well below the "Moore's Law" rate of compute power capability growth.

For example, at a doubling of capability even every two years, this would project out to more than 32x the processing power available today than was available when the current equalizer was *deployed*, much less designed. The technology capability to achieve a 96-Tap structure does not appear to be an obstacle, although its fit within modest variations to existing silicon is an important consideration.

There is some evidence that the 4x symbol rate may be a reasonable extension for today's equalizer architecture to handle. Recent characterization of wideband channels in the > 1 GHz band has shown that the dithering on the last few taps in the equalizer may be minimal for short cascades.

In these environments, spectral roll-off caused by many filters in cascade is limited, as is the group delay impact of this roll-off. Also, fewer connected homes means fewer opportunities for poor RF terminations and the micro-reflections they cause.

Table 14 quantifies test results for a 4x symbol width in an unspecified part of the coaxial band at 1.5 GHz through a cascade of taps in the passive leg of the plant. The frequency response above 1 GHz is generally not specified today. However, this characterization was done with taps with faceplates installed to extend their bandwidth to about 1.7 GHz.

Table 14 – Post-EQ MER as a Function of Tap Span

Equalizer Length =	NMTER (dB)	EQ-MER (dB)
33 Symbol	24.99448720	36.160
41 Symbol	24.83685835	37.780
49 Symbol	**24.78437291**	**38.515**
61 Symbol	24.77453160	38.730
73 Symbol	24.77427723	38.779
97 Symbol	24.77380599	38.791

Table 15 – A-TDMA Narrowband Interference Suppression Capability

1518-Byte Packets			
Noise Floor = 27 dB	MER	CCER/UCER %	PER
None	26.90	0 / 0	0.00%
CW Interference			
1x @ -5 dBc	26.00	8.6 / 0.018	0.10%
1x @ -10 dBc	26.20	7.02 / 0.00176	0.00%
3x @ -10 dBc/tone	26.00	9.5 / 0.08	0.50%
3x @ -15 dBc/tone	26.10	9.5 / 0.0099	0.06%
3x @ -20 dBc/tone	26.10	8.2 / 0.00137	0.00%
FM Modulated (20 kHz BW)			
1x @ -10 dBc	25.80	15.66 / 0.33166	1.00%
1x @ -15 dBc	26.40	6.2 / 0.0008	0.04%
3x @ -15 dBc/tone	25.50	19.48 / 0.639	2.00%
3x @ -20 dBc/tone	26.00	10.68 / 0.00855	0.03%
Noise Floor = 35 dB	MER	CCER/UCER	PER
None	32.60	0 / 0	0.00%
CW Interference			
1x @ +5 dBc	28.50	0.24 / 0.09	0.50%
1x @ 0 dBc	30.00	0.006 / 0.013	0.00%
1x @ -10 dBc	31.40	0 / 0.0065	0.00%
3x @ -10 dBc/tone	31.20	0.002 / 0	0.00%
3x @ -15 dBc/tone	31.50	0 / 0	0.00%
FM Modulated (20 kHz BW)			
1x @ -5 dBc	30.60	0.004 / 0	0.04%
1x @ -10 dBc	31.10	0.003 / 0	0.00%
3x @ -10 dBc/tone	30.00	0.01 / 0.0009	0.08%
3x @ -15 dBc/tone	30.80	0 / 0	0.00%

Evident in this essentially "N+0" segment is that the MER after equalization improves only incrementally as we include more taps up to about T = 49 symbols. The T=48 symbols would, of course, mean a doubling of the Tap span for a quadrupling of the symbol rate.

As cascades reduce and new, cleaner upstream bands are used to exploit more capacity, favorable channel condition with respect to frequency response are likely to result. This data certainly is favorable to the thought that even above 1 GHz, where little has been defined for CATV, a 4x symbol rate can be accommodated for the downstream.

Now, switching to the upstream, the spectrum expected to be exploited is in fact well-defined – return loss requirements and all – and will benefit from the same architectural migration shifts to shorter cascades and passive coax architectures. Because of this, the potential complexity increase of a 96-Tap equalizer and the corresponding time span that it supports may not be necessary to effectively use an extended upstream with 4x symbol rate transport. This may be valuable news to silicon implementers who may then be able to allocate silicon real estate and MIPS to other receiver processing functions.

7.1.1.4 Narrowband Interference

Another concern associated with increased symbol rates is the increased likelihood by a factor of four on average (slightly less with less excess bandwidth, of course) that narrowband interference will fall in-band and degrade the transmission. Unlike multi-carrier techniques, which can drop sub-channels out that can become

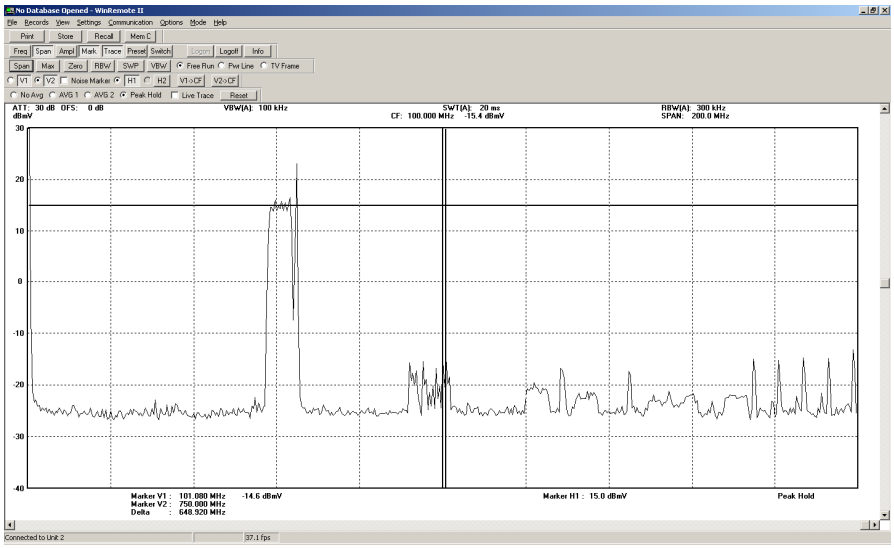


Figure 24 – Observed FM Band Interference on Deliberately Poor CM RF Interface

impaired by such interference (at the expense of throughput), a single carrier system must find a way to suppress the interference and reconstruct the symbol without it.

Fortunately, such techniques have matured, and today's ingress cancellation technology is very powerful in delivering full throughput performance in the face of strong narrowband interference. These processing algorithms sense ingress and adapt the rejection to the location and level of detected interference.

Table 15 quantifies the measured robustness under controlled testing of the DOCSIS 3.0 narrowband interference mechanism in suppressing interference [8]

It is readily apparent that today's DOCSIS 3.0 narrowband incision capability handles in-band interference very effectively over a range of much-worse-than-typical SNR, impulse, and interference conditions.

For example, at an SNR of 27 dB, which represents the return path quality of very old Fabry-Perot return paths long since replaced in most cases (DOCSIS minimum being 25 dB), it takes three tones of 20 kHz bandwidth a piece and adding up to about a 10 dB C/I to register a PER that might be considered objectionable (2%) from a user QoE perspective.

A borderline 1% PER occurs at C/I = 10 dB for a single interferer. These C/I values represent very high levels of plant interference in practice, although not completely uncommon, especially at the low end, shortwave area of the return band.

At SNRs closer to what is expected today (35 dB), no static interference case has PER of any consequence, even with C/I taken to 5 dB (modulated) and -5 dB (unmodulated) tones. This data suggests that wider symbols in the ever-cleaner part of the spectrum are likely to comfortably operate, quite robustly.

As the high-split architecture is deployed, interference levels over the air bands – particularly FM radio in North America, as discussed in Section 3.3.2– become important to understand. Figure 24 shows a field test with a diplex split extended above the 85 MHz Mid-Split for

purposes of quantifying the potential for such interference.

In what was a very harsh metropolitan environment, with older plant cabling and nearby FM towers, a deliberately loose fitted CM resulted in relatively modest. However, because it is a wideband spectrum of channels, it would not be able to be compensated for by receiver ingress suppression. The roughly 30 dB of SNR would still yield high throughput, though because the interference effect may have non-Gaussian qualities, the uncorrected error rates may be higher.

However, it is expected this would be well within FEC capability to yield error-free output. Similar C/I's resulted with various arrangements of splitters, modems and deliberately radially and longitudinally damaged cables. While only one example, given the ground conditions, this trial was highly encouraging with respect to the high split running well in the region of spectrum occupied by FM radio over the air.

Note that the ingress-only performance shown in Table 16 in fact identifies a potential *advantage* of the single carrier approach to interference suppression relative to OFDM – there is no loss of available data rate; there is instead an overhead increase for channel knowledge. In OFDM, the C/I on a single sub-channel and closest neighbors, must be removed or have their modulation profile decreased at the cost of available data rate. If the C/I environment worsens however, OFDM can gracefully degrade where SC has threshold behavior.

7.1.1.5 Joint Impairment Thresholds

When impulse noise is added as a joint impairment, we can then begin to count more cases of potentially objectionable PER from a user QoE perspective. However, it is quite clear from the comparison that the error rate is being dictated by the very impulse noise component. This is indeed an area where OFDM would have benefits, much like will be seen with S-CDMA, through the use of longer symbol times to outlast the impulse events.

Of course, impulse noise tends to be restricted to the low end of the return band. Above about 20 MHz, there is little evidence that the joint impairment scenario occurs in a meaningful way to degrade A-TDMA performance. Indeed, where A-TDMA is the most vulnerable is relative to impulse noise. It is left to defend itself only with FEC today, and this has been proven to be sufficient in the vast majority of 64-QAM deployments implemented in the middle to high end of the 42 MHz upstream spectrum.

7.1.1.6 Summary

DOCSIS is currently a predominantly A-TDMA system, and exclusively so in the vast majority of deployment worldwide. As such, a natural and simple extension, with perhaps only minor impact on silicon development, is the increase the symbol rate of the already existing protocol to be better aligned with service on the near-term horizon, but also compatible with the direction of data services requirements for the long term.

Table 16 – A-TDMA Performance with Interference and Impulse Noise

	None - Narrowband Interference Only		Impulse Noise: 4 usec @ 100 Hz			
			-10		-5	
SNR = 35 dB	**MER**	**PER**	**MER**	**PER**	**MER**	**PER**
None	32.60	0.00%	32.30	0.00%	32.30	0.30%
CW Interference						
1x @ -10 dBc	31.40	0.00%	31.30	1.40%	31.20	2.50%
3x @ -15 dBc/tone	31.50	0.00%	31.40	1.50%	31.50	2.80%
3x @ -20 dBc/tone	31.60	0.00%	31.60	1.00%	31.40	2.20%
3x @ -25 dBc/tone			31.70	0.40%	31.60	1.70%
3x @ -30 dBc/tone						
FM Modulated (20 kHz BW)						
1x @ -10 dBc	31.10	0.00%	31.00	0.10%	30.60	3.70%
3x @ -15 dBc/tone	30.80	0.00%	30.60	2.80%	29.90	3.70%
3x @ -20 dBc/tone	31.20	0.00%	31.10	1.70%	31.00	3.50%
3x @ -25 dBc/tone			31.50	0.70%	31.40	2.10%
3x @ -30 dBc/tone						
SNR = 27 dB	**MER**	**PER**	**MER**	**PER**	**MER**	**PER**
None	26.90	0.00%	26.70	0.01%	26.70	0.50%
CW Interference						
1x @ -10 dBc	26.20	0.00%	26.30	0.50%	26.10	1.60%
3x @ -15 dBc/tone	26.10	0.06%	25.90	0.90%	26.10	2.50%
3x @ -20 dBc/tone	26.10	0.00%	26.10	0.50%	26.10	2.50%
3x @ -25 dBc/tone			26.20	0.10%	26.20	1.50%
3x @ -30 dBc/tone						
FM Modulated (20 kHz BW)						
1x @ -10 dBc	25.80	1.00%	25.60	6.00%	25.60	5.00%
3x @ -15 dBc/tone	25.50	2.00%	25.40	5.00%	25.40	6.00%
3x @ -20 dBc/tone	26.00	0.03%	25.90	1.00%	25.80	0.60%
3x @ -25 dBc/tone			26.20	0.20%	26.20	1.70%
3x @ -30 dBc/tone						

While many advances in PHY technology have occurred, the existing signal flow, knowledge base, silicon maturity, and understanding of management of the single carrier approach all favorably weigh in towards working to tweak something that doesn't need outright fixing. Couple this maturity with the ability of single carrier tools to handle the upstream channel environment across the vast majority of the spectrum, creating a higher symbol rate of 4x, as described here, represents a logical, incremental, low-risk step for the transmission system portion of the PHY.

7.1.2 256-QAM Upstream

With the introduction of DOCSIS, cable operators created a specification for high speed data services that was built around the architecture and technology realities of the time – large serving groups of subscribers funneled through deep cascades of amplifiers and onto into a single laser transmitter – typically of the low-cost, low quality, Fabry-Perot variety – and with the anticipation of a lot of unwanted interference coming along for the ride.

The resulting requirements spelled out ensured robust operation under the condition of a 25 dB SNR assumption, among other impairments defined. Robust performance was assured through the use of relatively narrowband, robust modulation formats (QPSK and 16-QAM), a limited number of channels competing for spectrum power , and the ability to use powerful forward error correction.

Now, of course, many of the characteristics that defined the return have changed significantly, and DOCSIS 2.0 took advantage of many of them by calling for support of a 64-QAM modulation profile of up to twice the bandwidth if conditions allowed it.

It was not the case everywhere that it could be supported, but all phases of evolution were trending towards the ability to squeeze more and more capacity out of the return. Better, Distributed Feedback (DFB), analog optics became cost effective, digital return optics came on the scene, cascades shortened as serving groups shrunk during node splitting operations, and lessons learned over the years brought improvements in return path alignment and maintenance practices.

These same lessons brought about the introduction of S-CDMA, based on a better understanding of the characteristics of the low end of the return spectrum.

DOCSIS 2.0 itself is now over ten years old. DOCSIS 3.0 subsequently added channel bonding for higher peak speeds, as well as calling our support for return path extension in frequency up to 85 MHz.

Fortunately, the HFC architecture and supporting technology has continued to evolve favorably towards more upstream bandwidth, used more efficiently. In Section 2, the case was made for the use of the 85 MHz mid-split as an excellent first step for cable operators looking to add essential new bandwidth for upstream services. In this section, we will show how today's return paths, extended to 85 MHz, are now capable of exploiting this band while also increasing the modulation profile to 256-QAM. It is within the capability of the upstream and demonstrably proven in the field that a 256-QAM modulation profile can be supported, and over a wider band than the legacy 42 MHz bandwidth in North America and the 65 MHz Euro split.

7.1.2.1 Upstream Link Analysis

While early generation CMTS equipment was designed to support 16-QAM as the maximum modulation profile, vendors generally provided enough margin in their systems to enable 64-QAM once networks evolved towards better HFC optics. 64-QAM was subsequently embraced in DOCSIS 2.0.

In Figure 17 through Figure 20 in Section 5, we introduced noise power ratio (NPR) curves to characterize return path optical technologies. NPR curves have the desirable feature of representing a worst-case (no TDMA operating) fully loaded return link from a signal stimulus standpoint while simultaneously quantifying the SNR and S/(N+D) on a single curve.

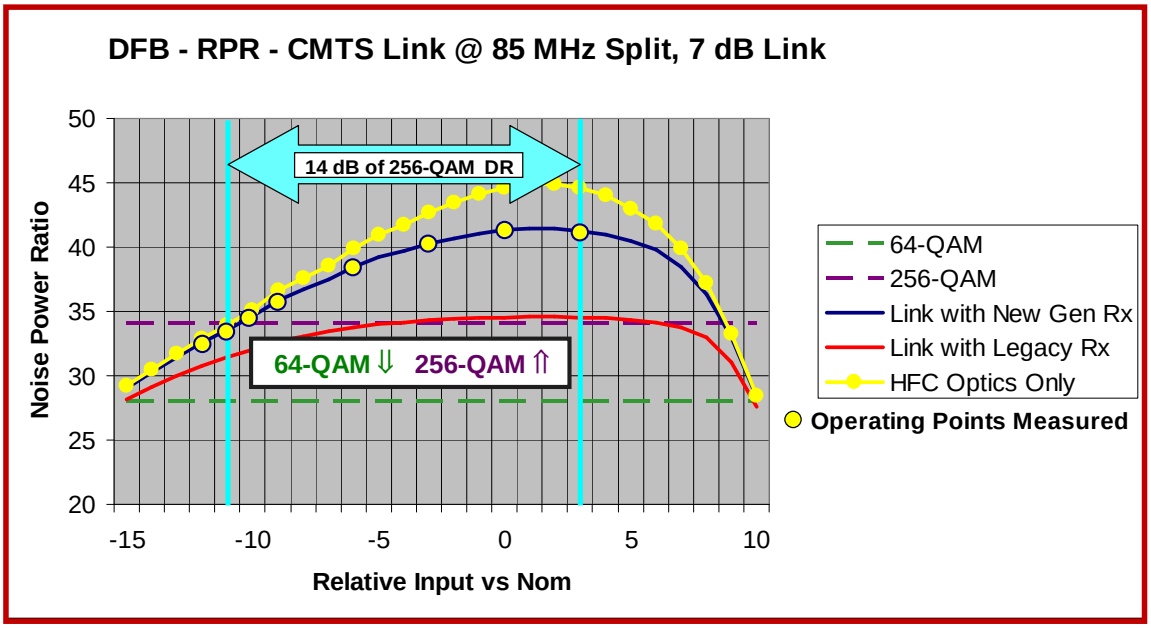


Figure 25 – HFC DOCSIS System Performance

In the NPR curves shown in this section, the optical performance will be augmented with other contributors to the link SNR – in particular RF contributions in the form of noise funneling previously discussed, and receiver noise figures associated with receivers, such as DOCSIS CMTS front ends. We will consider "legacy" DOCSIS receiver – designed originally for 16-QAM maximum profiles, and modern receivers aimed at higher sensitivity for better modulation efficiency.

Consider Figure 25. The red curve marks the performance characteristics of and HFC+CMTS link for legacy-type receivers optimized for 16-QAM and a DFB-RPR link of nominal length under an assumption of 85 MHz of spectrum loading. Clearly, it shows margin over and above the (green) 64-QAM threshold (chosen at 28 dB – an uncorrected 1e-8 error rate objective).

DFB HFC optics plus most of today's CMTS receivers comfortably support 64-QAM with sufficient, practical, operating dynamic range. This lesson is being proven everywhere DOCSIS 3.0 is being deployed. In some cases newer, high quality FP lasers can support 64-QAM as well. While DFBs are recommended for upstream as new channels are added and profiles enabled, it is comforting to realize that newer FPs can get 64-QAM started while the large task of exchanging lasers methodically takes place.

Though legacy receiver exceeded their original design requirements in being extended to 64-QAM (with the help of plant upgrades), enabling 256-QAM design margin – an additional 12 dB of performance over 16-QAM – was not cost effective to consider in early stages of DOCSIS.

As a result, there is zero margin to run 256-QAM (purple), as shown in Figure 25, or otherwise insufficient margin if we aid the factor in more power-per-Hz by limiting the bandwidth to the 65 MHz Euro split by comparison (about 1 dB higher peak) or the 42 MHz split (about 3 dB higher peak).

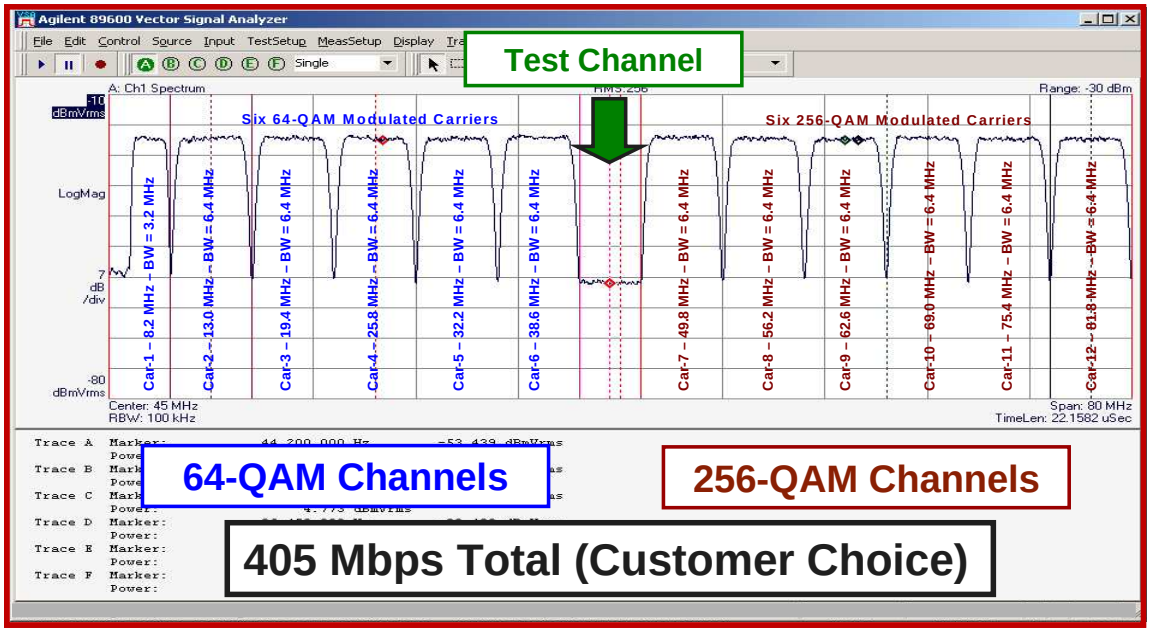


Figure 26 – Mid-Split Channel Loading

New receivers, however, provide a higher fidelity upstream termination in order to support 64-QAM with margin and S-CDMA synchronization. Because of these requirements and the continued advances in performance of DFB return optics (higher power laser transmitters), 256-QAM can now be comfortably supported.

The performance of the combined HFC+CMTS link for modern receivers is shown in the blue curve of Figure 25. DOCSIS does not yet call out 256-QAM, although this is a change currently in process.

However, much of the existing silicon base already supports this mode. Note that the yellow points on the blue curve represent points measured in the field that achieved low end-of-line packet error rate performance, as a way of verifying the predicted dynamic range on a real HFC link (NPR would be an intrusive measurement).

Note also that the dynamic range supported for 256-QAM is nearly the same dynamic range that existing receivers provide for 64-QAM – an indication of the robustness potential for 256-QAM links.

Finally, comparing the HFC (yellow) NPR trace to the HFC+CMTS (blue) trace, it is apparent also how little loss of NPR is incurred by new high fidelity CMTS receivers.

Figure 26 shows a snapshot of a recent trial of an Mid-Split architecture, where the upper half of the band was used to support 256-QAM channels, but with all signals at the same power level except for the lowest frequency (narrower) channel. A mid-band test channel was left unoccupied for monitoring the most probable location of maximum distortion build-up as dynamic range was exercised.

Evident from Figure 26 is the high available SNR delivered by the HFC link using existing analog DFB return optics at nominal input drive. The available SNR as measured at the input to the CMTS receiver

is about 45 dB. In this case, the tested link was an N+3 architecture.

Table 17 shows a full 85 MHz optimization, using 12 carriers of both S-CDMA and A-TDMA, employing modulations from 32-QAM to 256-QAM across the band. The results indicate a maximum of nearly 400 Mbps of Ethernet throughput under the packetized traffic conditions used.

7.1.2.2 Extended HFC Performance

To show the robustness potential of 256-QAM upstream, we can extend the performance calculations in Figure 25 to include longer HFC links and the contribution of potentially long RF cascades summed together, resulting in the "noise funnel" aggregation of amplifier noise figures.

The cases shown in Figure 27 assumes a deep cascade (N+6) in a 4-port node, and thus 24 amplifiers summed, and optical links of 7 dB and 10 dB. While the yellow curve still represents 7 dB optics only, both 7 dB and 10 dB links are shown with the RF cascade included (dashed), and then each of the same with the CMTS receiver contribution included (solid).

The loss due to an analog optical link length is very predictable, as the optical receiver SNR drops as input light level drops. The RF cascade can be shown to create the effect of pushing the performance peak down, reflecting the SNR contribution of amplifier noise to the optical link. However, its effect on the dynamic range for supporting 256-QAM is negligible.

The stronger dynamic range effect is the extended optical link of 10 dB, which ultimately reduces 256-QAM dynamic range by about 2 dB, but with the dynamic range still showing a healthy 11 dB of robust wiggle room.

5 MHz to 85 MHz Channel Allocation

	Frequency	Bandwidth	Symbol Rate	Modulation	Bits/sym	Data - $R	MOD	FEC-T	FEC-K	DOCSIS OH	ETH TP	MOD-PRO#
Car-1	11.4	6.4	5.12	32	5	25.60	S-CDMA	4	232	0.8242	21.10	431
Car-2	17.8	6.4	5.12	64	6	30.72	S-CDMA	4	232	0.8236	25.30	432
Car-3	24.2	6.4	5.12	64	6	30.72	A-TDMA	12	232	0.8724	26.80	522
Car-4	30.6	6.4	5.12	128	7	35.84	A-TDMA	8	232	0.9040	32.40	523
Car-5	37.0	6.4	5.12	128	7	35.84	A-TDMA	12	232	0.8705	31.20	524
Car-6	43.4	6.4	5.12	256	8	40.96	A-TDMA	10	232	0.8887	36.40	525
Car-7	49.8	6.4	5.12	256	8	40.96	A-TDMA	10	232	0.8887	36.40	525
Car-8	56.2	6.4	5.12	256	8	40.96	A-TDMA	8	232	0.9058	37.10	526
Car-9	62.6	6.4	5.12	256	8	40.96	A-TDMA	8	232	0.9058	37.10	526
Car-10	69.0	6.4	5.12	256	8	40.96	A-TDMA	8	232	0.9058	37.10	526
Car-11	75.4	6.4	5.12	256	8	40.96	A-TDMA	8	232	0.9058	37.10	526
Car-12	81.8	6.4	5.12	256	8	40.96	A-TDMA	8	232	0.9058	37.10	526
						445.44					395.10	

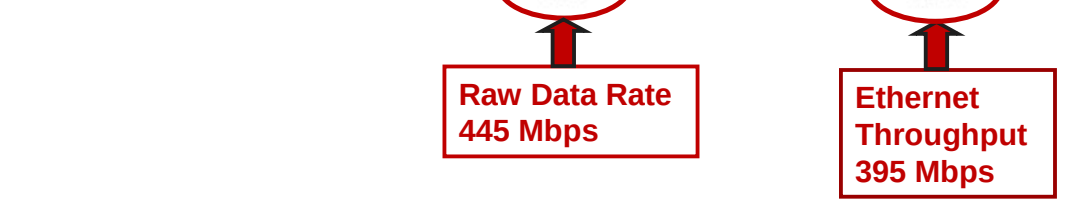


Table 17 – Optimized 85 MHz Mid-Split Channel Loading

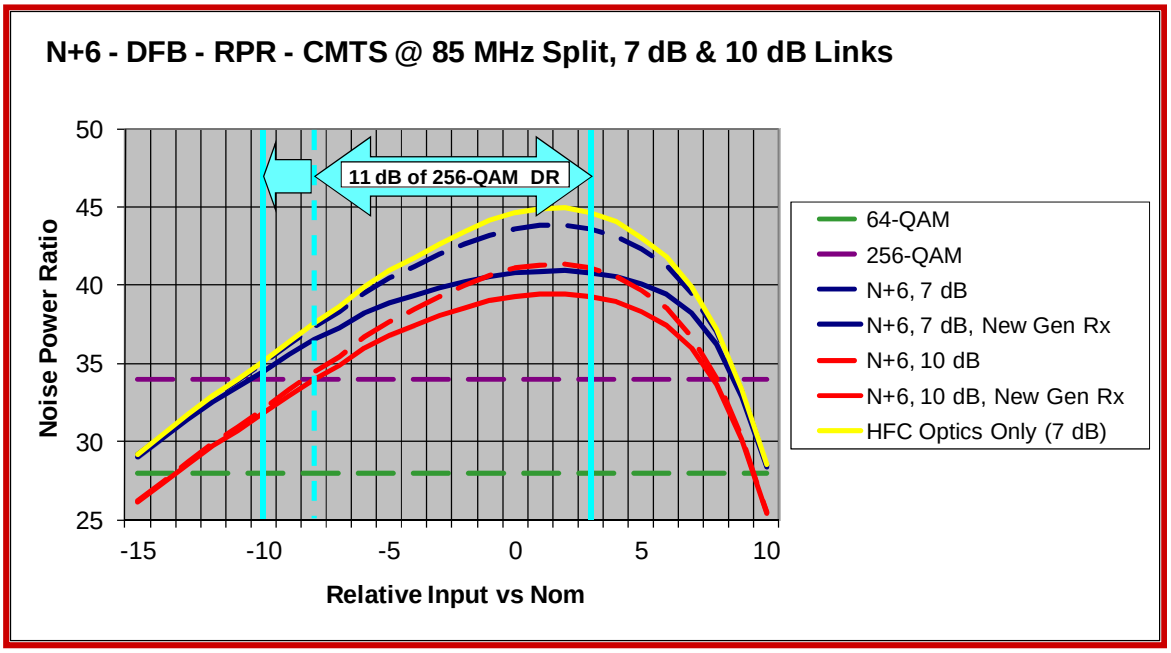


Figure 27 – HFC DOCSIS System Performance for Longer RF Cascades

7.1.2.3 Extended "High-Split" Bandwidth Projection

A 1 Gbps capacity threshold upstream requires the split to move to 200 MHz or higher. The 5-200 MHz bandwidth itself supports well over 1 Gbps of theoretical capacity, but legacy use may not make the full spectrum available for higher efficiency, and overhead loss will decrease transport capacity to a lower net throughput.

A higher spectrum diplex will likely therefore be required. However, we quantify the 200 MHz case because of its potential compatibility with current equipment outfitted with 200 MHz RF hybrids, or with minor modifications thereof.

Figure 28 is the analogous figure to Figure 25 for 85 MHz Mid-Split, showing, in this case, projected performance on a 200 MHz "high" split when factoring in an "equivalently performing" CMTS receiver (DOCSIS does not extend to 200 MHz) and DFB optics performing at today's noise density (adjusted only for power loading).

As would be expected, with the receiver performance equivalent to legacy CMTS receivers, inherently not equipped for 256-QAM, performance does not even breach the threshold. However, with a new generation of high fidelity receivers, system analysis projects that there exists 10 dB of dynamic range to 256-QAM performance over a fully loaded 200 MHz return path.

This would see degradation when RF amplifiers are included, but again to minor effect on dynamic range. Conversely, it is anticipated that by the time the need for high split is required, very small serving groups have already been established, leading to a much less significant noise funnel.

While dynamic range (10 dB) is still relatively high, there is observable loss of peak above the 256-QAM threshold, meaning much of the dynamic range exists over a relatively low steady-state operating margin. This could make the link more

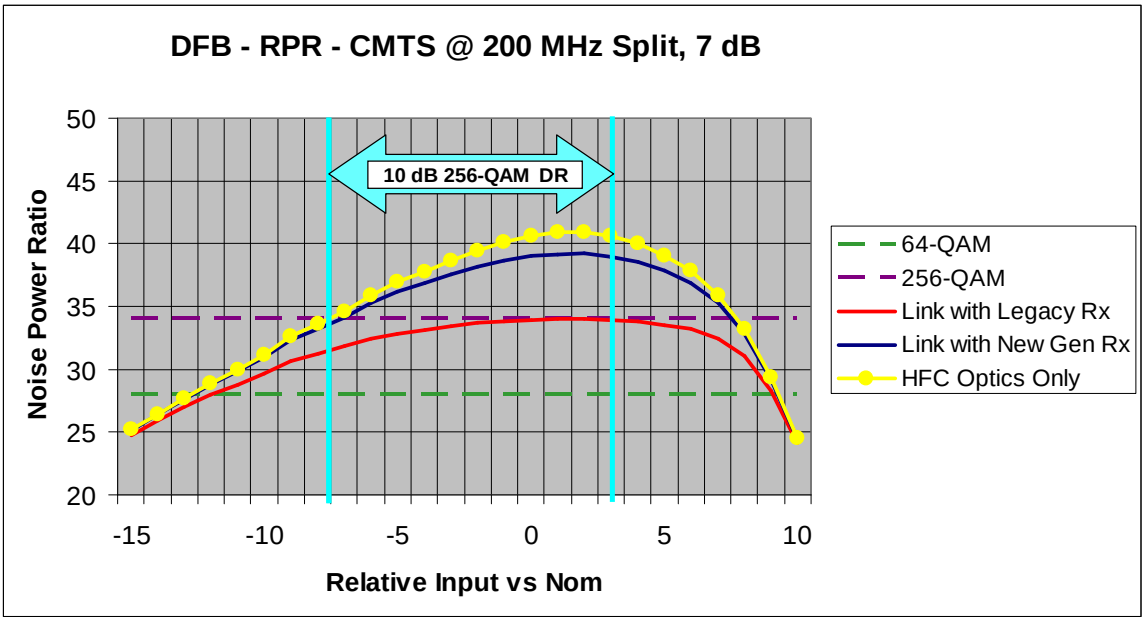


Figure 28 – HFC-DOCSIS System Performance using 200MHz "High Split"

susceptible to moderate transients, drift, temperature extremes, or misalignment, and thus require more regular maintenance.

As such, Figure 28 points out the near term potential for high split operation over HFC optics, but also indicates that performance improvements over time will be welcome to ensure robust operations. Also, note that measured performance for a high split return to 185 MHz, shown in Figure 20, is similar to the analysis in Figure 28. In fact, measured performance of the 1550 nm DWDM return in Figure 20 is slightly better (by about 1.5 dB) than the extrapolated performance in Figure 28 using a standard 1310 nm DFB, pointing out additional margin for the high split case already existing today.

7.1.2.4 Modem Performance Characterization Findings

Recent results [17] have evaluated 256-QAM transmission in the presence of narrowband interference to assess the capability of the ingress suppression capability for the higher order of modulation. Table 18 quantifies these results in terms of Codeword Errors (CCER, UCER) and Packet Errors (PER) as are calculated and made available in the DOCSIS MIB.

Results for 64-QAM were shared, along with results for 256-QAM, in [16]. However, Table 18 updates the results for 256-QAM with a more robust performance assessment using higher performance recovers for the proper SNR baseline. This is simply mirroring what was already described and identified in Figure 25 – legacy DOCSIS receivers do not have acceptable margin to run a robust 256-QAM profile.

Nonetheless, it is difficult to make apples-to-apples ingress suppression comparisons, as the SNR margin for 64-QAM offers inherently 6 dB more room for the ingress cancellation to operate under than 256-QAM.

The DFB-RPR link in Table 18 was setup to provide higher SNR than the 64-QAM case in [16] in order than a very low

Table 18 – 256-QAM Interference Performance Low PER Thresholds

	256-QAM				
	Level (dB, dBc)	**UNCORR%**	**CORR%**	**PER%**	**MER (dB)**
Baseline - AWGN	**36**	0.000%	0.000%	0.000%	37
Single Ingressor Case					
QPSK 12kHz 0.5%	3	0.254%	0.435%	1.060%	34
QPSK 12kHz 1.0%	1	0.447%	0.944%	2.300%	34
FSK 320ksym/s 0.5%	29	0.278%	0.032%	0.110%	35
FSK 320ksym/s 1.0%	27	0.633%	0.230%	0.810%	35
FM 20kHz 0.5%	2	0.128%	0.295%	0.750%	34
FM 20kHz 1.0%	1	0.187%	0.554%	1.260%	34
Three Ingressor Case					
CPD 0.5%	28	0.297%	0.041%	0.190%	34
CPD 1.0%	27	0.698%	0.144%	0.750%	33

BER threshold in each was a baseline. However, it was not the same absolute margin of the M-QAM to the SNR of the link (5 dB vs 2 dB). It did lead to a very important conclusion, however.

With this low BER steady state case in [8] for 256-QAM, for nearly equivalent relative performance (6 dB difference) for nominal single-interference cases was observed. However, for multiple interferers and for wideband (100's of kHz) there was still substantially more robustness in the case of 64-QAM. Refer to [8] for full details.

Overall, proof of the functionality of ingress cancellation was achieved for 256-QAM, but with degraded performance when the channel is at its noisiest. Of course, the strategy for deploying 256-QAM is to place in the clean part of the upstream, where it can be supported – above 25 MHz. And, certainly consider it to extract capacity in the 85 MHz Mid-Split case above 42 MHz.

This is the approach used to "optimize" the 85 MHz band and shown in Table 18 – a mixture of 256-QAM, 128-QAM, 64-QAM, and S-CDMA based 64-QAM and 32-QAM.

This is the upstream line-up that led to the 445 Mbps transport rate proof of concept reported in [12].

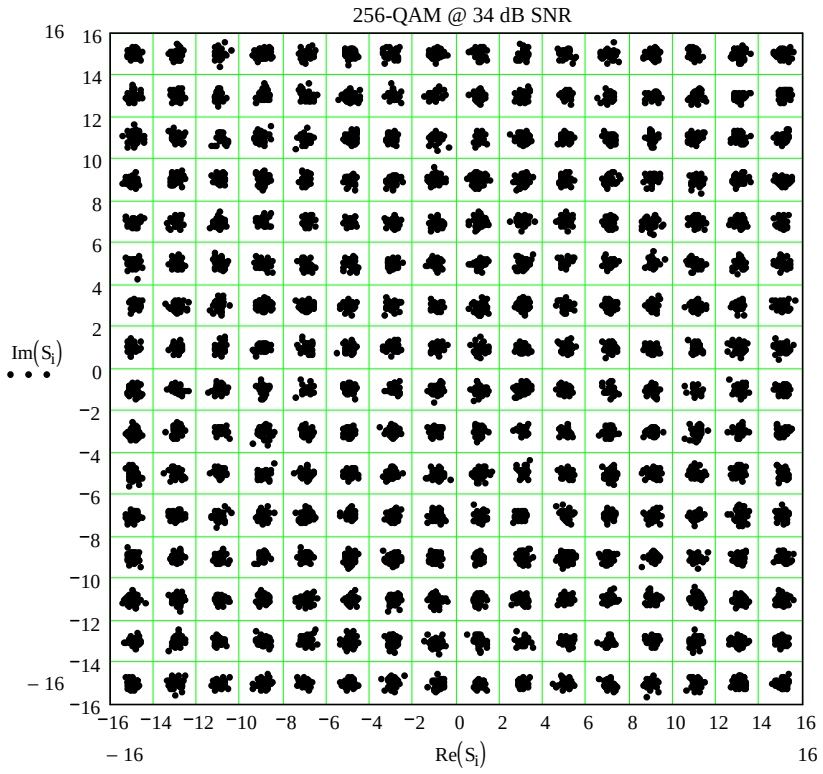


Figure 29 – 256-QAM @ 34 dB SNR

7.1.3 1024-QAM Downstream

In Section 9.5 "Downstream Capacity", we will calculate the downstream capacity for a fully digitized forward band, multiplying the number of 6 MHz slots by the modulation profile allowed by DOCSIS (256-QAM) to arrive at data capacities for 750 MHz, 870 MHz, and 1 GHz networks. We then calculated the case for a Next Generation PHY using LDPC and OFDM, making the reasonable assumption that by updating the FEC, we can achieve two QAM orders of modulation higher in bandwidth efficiency, which effectively suggests 6 dB can be gained.

However, not all of this may be in the FEC (depending on code rate). Some incremental link budget dB may be obtained through some of the business-as-usual operations of fiber deeper and cascade reduction, which reduces noise and distortion accumulation, and through the conversion of analog carriers to digital, which reduced (2x analog + digital) composite carrier-to-noise (CCN) distortion effects. Lastly, newer STBs in the field tend to higher sensitivity (lower noise figure).

Because of this, the FEC is not left to make up all of the dB between 256-QAM and 1024-QAM. And, in fact, it is now possible to make a case based only on these HFC changes that 1024-QAM may be possible in evolved architectures today, even without the addition of new FEC on silicon that can support this QAM mode. This offers the potential for 25% more bandwidth efficiency. This section quantifies this potential.

Let's begin the discussion with the use of QAM over HFC for downstream video as it has evolved to date.

The cable plant has kept up with the bandwidth consumption by adding RF bandwidth and using efficient digital modulations to mine the capacity effectively and with robustness. What started as 64-QAM digital signals became yet more bandwidth efficient with the deployment of 256-QAM downstream, the dominant QAM approach today. The ability to successfully deploy such schemes is due to the very high SNR and very low distortion downstream.

This was to ensure proper conditions for supporting much less robust analog video. In addition to high linearity and low noise, the downstream channel has a flat frequency response on a per-channel basis, minimizing both amplitude and phase distortion, although it can be prone to reflection energy.

As a simple example of the possibilities, the theoretical capacity of a 6 MHz channel with a 40 dB SNR is approximately 80 Mbps. Yet, for J.83-based 256-QAM, the transmission rate is only about 40 Mbps. When accounting for overhead, there is even less throughput.

The next higher order, square-constellation, modulation is 1024-QAM. This technique achieves an efficiency of 10 bits/symbol, or another 25% efficiency over 256-QAM, and an impressive 67% improvement relative to 64-QAM. To support 1024-QAM, a more stringent set of specifications must be met.

Analysis was performed to identify implications to the plant and its performance requirements for robust downstream transmission [1]. The analysis quantified SNR, beat distortion interference, and phase noise, and interpreted the results. We summarize the problem statement here and describe the conclusions.

7.1.3.1 SNR

Let's consider the implications of 1024-

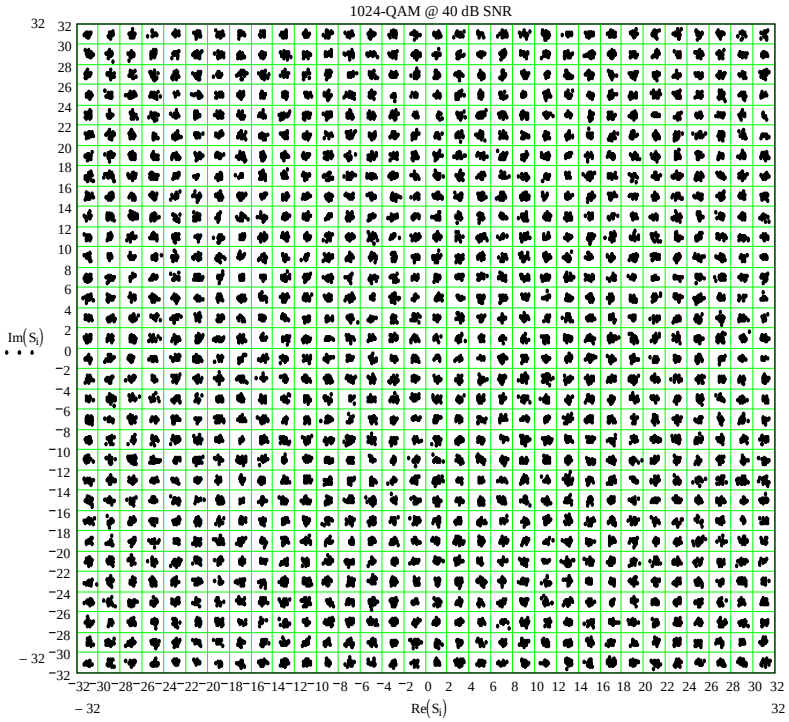


Figure 30 – 1024-QAM @ 40 dB SNR

Table 19 – Power Loading Effects of Analog Reclamation - 870 MHz

	Channel Uptilt @ 870 MHz					
	Flat		12 dB		14 dB	
	Delta Ref	QAM Increase	Delta Ref	QAM Increase	Delta Ref	QAM Increase
79 Analog	Ref Load	---	Ref Load	---	Ref Load	---
59 Analog	-0.7	2.5	-1.0	1.5	-0.9	1.5
39 Analog	-1.6	3.5	-1.7	2.5	-1.6	2.0
30 Analog	-2.1	4.0	-2.0	2.5	-1.9	2.5
All Digital	-4.5	4.5	-2.8	3.0	-2.5	2.5

QAM. Figure 29 and Figure 30 show constellation diagrams of 256-QAM @ 34 dB SNR and 1024-QAM @ 40 dB SNR. Being 6 dB apart, these are equivalent uncorrected error rate cases (@1E-8). The congested look of the 1024-QAM diagram, emphasized by the small symbol decision regions, signals the sensitivity this scheme has to disturbances.

Now consider what 40 dB means in terms of use on the plant. For an end-of-line 46 dB of plant (analog) CNR, QAM SNR becomes 40 dB when backed off by 6 dB. We've thus removed virtually all link available margin under an objective of 1E-8, and are now into a region of measurable errors, relying on FEC to finish the job under even the most benign circumstance of thermal noise only.

On the STB side, there is similar margin-challenged mathematics. For a STB noise figure of 10 dB, and for QAM signals arriving at the STB at the low end of the power range, some simple math shows the following:

- Residual Thermal Noise Floor: -58 dBmV/5 MHz
- STB Noise Figure, NF = 10 dB: -48 dBmV/5 MHz
- Analog Level into STB: 0 dBmV
- Digital Level into STB: - 6 dBmV
- STB SNR contribution: -6 -(-48) = 42 dB

Note that NF = 10 dB is not a technically difficult performance requirement. However, in practice, given the cost sensitivity of CPE equipment and without a historical need to have better RF sensitivity, 10 dB and higher is quite normal.

The combined link delivers an SNR of about 38 dB. This simple example leads to the conclusion that existing conditions and existing deployment scenarios create concerns for a seamless 1024-QAM roll-out under a "J.83"-type PHY situation. It reveals the necessity of at least 2 dB of coding gain to ensure robust link closure.

Improving the noise performance of CPE is of course one option to enable more bandwidth efficient link budgets, particularly as yet more advanced modulation profiles beyond 1024-QAM are considered. The sensitivity of CPE cost and the existing deployment of 1024-QAM capable receivers and current noise performance, however, leads to a desire to remain conservative in the expectation of CPE performance assumptions.

7.1.3.2 Favorable Evolution Trends

A couple of favorable trends are occurring in HFC migration that potentially free up some dB towards higher SNR of the

Table 20 – Noise and Distortion @ 550 MHz vs Analog Channel Count

	CCN		CTB		CSO	
Analog Channels	N+6	N+0	N+6	N+0	N+6	N+0
79	48	51	58	70	56	64
59	48	52	60	70	59	65
30	48	52	68	74	67	70

QAM channels – analog reclamation and cascade shortening.

Table 19 shows the potential for higher SNR by taking advantage of the RF power load when compared to a reference of 79 analog channels for 870 MHz of forward bandwidth. In the table, the left hand column for each case – Flat, 12 dB tilt, 14 dB tilt – represents the decrease in total RF load compared to the 79-analog channel reference. The right column for each case represents how much more power could be allocated to each digital carrier in order to maintain the same total RF power load. This is the potential available theoretical SNR gain.

The flat case represents the effect on the optical loading of the analog reclamation process. There is headroom that can be exploited in the optical link and RF cascade by increasing the total power of the analog plus digital multiplex, gaining SNR for all channels and offering potential mediation against the 6 dB increased SNR requirement.

The SNR discussion above refers only to the improvement relative to the thermal noise floor. The additional distortion component (composite inter-modulation noise or CIN) and practical RF frequency response means not all of the theoretical dB will be realized (refer to [1] for details).

Now consider Table 20 quantifying modeled performance for a sample HFC link under different assumptions of line-up and cascade. The data underscores the impact on noise and distortion of decreasing analog channel loads and shorter RF cascades. CCN represents Composite Carrier-to-Noise – a combination of the CNR or SNR and digital distortion products.

Moving across rows, noise and distortion improvements associated with the elimination of the RF cascade (N+6 to N+0) is clear. Moving down columns, the benefits of doing analog reclamation also becomes clear. Both activities enable the network to more ably support higher order modulation SNR performance requirements.

From the perspective of noise (CCN), shortening of the cascade reduces the accumulation of amplifier noise, freeing up 3-4 dB additional SNR available relative to a typical line-up and cascade depth of today. When coupled with possible loading adjustments with the larger digital tier and new headroom available – a few dB here and a few dB there approach – we can come close to 6 dB of new SNR as we evolve the network and use the gains to our benefit. This is, of course, the amount of increased SNR sensitivity of 1024-QAM compared to 256-QAM.

Table 21 – Inner (5/6) LDPC Coded M-QAM Throughput and Comparison to J.83 [2]

Mode	Efficiency (bits/symbol)	Representative Symbol Rate (Msps)	Representative Inner Code Bit Rate (Mbps)	TOV Es/No (dB)	Delta from Capacity* (dB)
Proposed 64QAM	5.333	5.056	26.96	18.02	0.52
Proposed 256QAM	7.333	5.361	39.31	24.27	0.46
Proposed 1024QAM	9.333	5.361	50.03	30.42	0.50
J83.B 64QAM	5.337	5.056	26.97	20.75	3.25
J83.B 256QAM	7.244	5.361	38.84	26.90	3.44
"J83.B" 1024QAM	9.150	5.361	49.05	33.03	3.80

*Note that "Capacity" in this case is an abbreviation for *Constrained* Capacity, as opposed to Shannon Capacity. For this example, the constraint is a symbol set of uniformly distributed QAM symbols. Please refer to above text and [2] for details.

7.1.3.3 Modern FEC

So far, we have considered only existing FEC with 1024-QAM, relying on HFC migration phases to extract additional dB from the plant to create sufficient operational margin. Fortunately, we are not limited to legacy error corrections schemes. While powerful in its day, concatenated Reed-Solomon FEC used in J.83 is now roughly 15 years old – an eternity in information theory technology development. While J.83 leaves us several dB from theoretical PHY performance, modern FEC, typically built around Low Density Parity Check (LDPC) codes – also concatenated to avoid error flooring – achieves performance within fractions of dB of theoretical.

A proposal made during DOCSIS 3.0 discussions [2] quantified additional gains available using LDPC for current 64-QAM and 256-QAM systems, as well as for potential 1024-QAM use. Table 21 summarizes some of the core findings of that system design. The analysis references a common Threshold of Visibility (TOV) threshold for video of 3e-6 and compares constrained capacity (limited to QAM signal sets) of the various profiles. This constraint has an inherent offset from Shannon capacity that grows as a function of SNR.

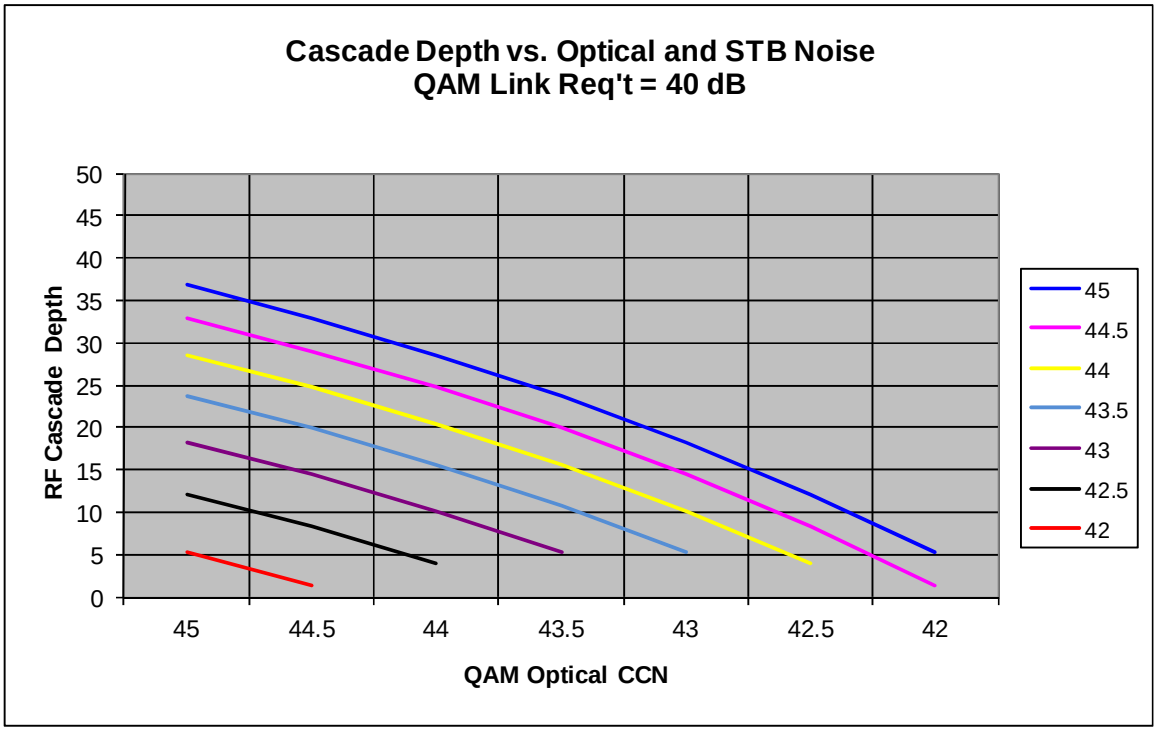


Figure 31 – 1024-QAM, Noise, and Cascade Depth – 40 dB Link Requirement

With the recognition of another 3.3 dB of coding gain, the proposal pointed out the accessibility of 1024-QAM for the downstream channel in a legacy 6 MHz format. This constraint (6 MHz) can also be removed for wider band channels, leading to more flexibility in code design and thus more available coding gain. However, we will see below that even just assuming a modest 3 dB more coding gain provides very meaningful SNR margin for robust 1024-QAM.

We can now execute architecture trade-offs of noise contributions and the depth of the RF cascade to evaluate support for 1024-QAM. HFC cascade thresholds are shown in Figure 31 and Figure 32, as a function of STB noise figure and optical link CCN, as a function of a pre-defined overall SNR link objective (40 dB or 37 dB). Each curve represents a different value of SNR as set by the STB alone, associated with the noise figure and digital level (de-rated from analog) at its input.

Note from the figures that there is a wide range of SNR combinations that essentially offer no practical limit to RF cascade depth as it relates to noise degradation. Clearly, tolerating a 37 dB link requirement is exactly this scenario, and this is quite a reasonable requirement under the capability of new FEC. It provides a very comfortable range of operation, even for poor performing optical links with respect to noise.

However, the 40 dB range includes conditions that could lead to a sharp reduction in the cascade acceptable. From a sensitivity analysis standpoint, such conditions hinge on small dBs and even fractions thereof. This makes it more valuable to be able to earn back, for example, just 1-2 dB SNR in the analog reclamation process.

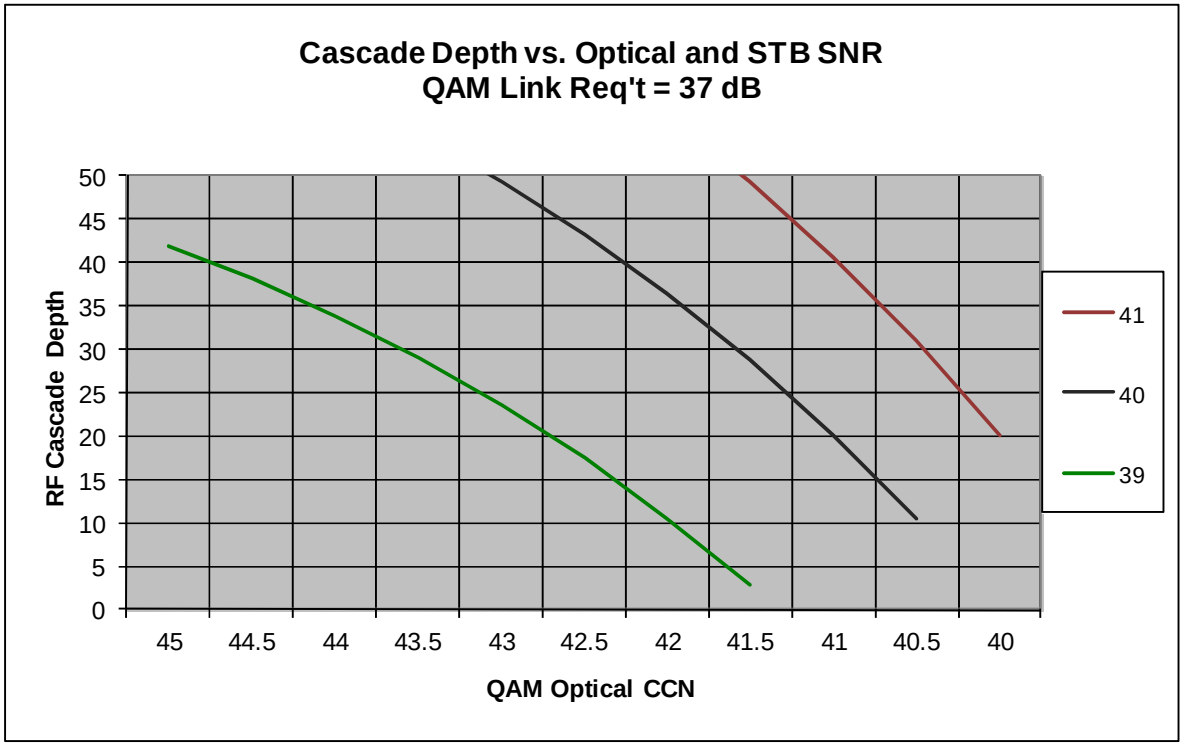


Figure 32 – 1024-QAM, Noise, Cascade Depth – 37 dB Link Requirement (Improved FEC)

Finally, note specifically the SNR = 42 dB at Optical CCN = 45 point on the bottom left of Figure 31. For a quite typical 51 dB Optical CNR requirement, a digital CCN of 45 dB would occur under 6 dB back-off. These conditions yield a cascade depth of five (N+5) as tolerable. Note, however, that 42 dB was a NF = 10 CPE, and, as previously identified, higher NF's (10-14 dB) may be the case.

This points out simply that STB clients of higher NF than 10 dB, under nominal optical link performance and deeper cascades may struggle to achieve the 40 dB requirement for 1024-QAM. FEC may save the link from a QoE perspective, but this example points out how relatively nominal conditions of legacy plant add up to make 1024-QAM a challenge. It also emphasizes the value of the dB available in migration, and especially the value of new FEC, most readily observable in Figure 32.

7.1.3.4 Distortion

As observed in Table 20, in addition to its positive effects on digital SNR, analog reclamation offers benefits in the distortion domain as well. Table 20 results are arrived at through tools such as shown in Figure 33 – a sample of a distortion beat map for 79 analog channels on a 12 dB tilt to 870 MHz. Such analysis is used to calculate the impact of varying channel line-ups on relative distortion level. Coupled with the sensitivity of 1024-QAM under CTB/CSO impairment, we can then evaluate the ability of an HFC cascade to support 1024-QAM.

The performance thresholds for CTB were taken from laboratory evaluation of error-free or nearly error-free 1024-QAM with actual live-video CTB generated as the impairment source [1]. It is interesting to note in that testing how pre-FEC and post FEC results are related, indicative of CTB as a "slow" disturbance relative to the symbol

rate, and thus a burst error mechanism that challenges FEC decoding.

A result of the use of these CTB thresholds to find HFC architecture limitations is shown in Figure 34. It plots cascade depth thresholds over a range of given RF amplifier CTBs, specified at typical RF output levels, and varying analog channel counts used using a CTB threshold of 58 dBc [1].

It is clear to see that analog reclamation to 30 channels enables virtually any practical RF cascade depth. However, it also becomes clear how for 79-channel systems and 59-channel systems, some limitations may appear.

Prior analysis had investigated the effects of analog beat distortions on 256-QAM, developing relationships for the comparative performance of 64-QAM and 256-QAM [3]. It was observed that 10-12 dB difference existed in susceptibility to a single, static, in-band narrowband interferer at the main CTB offset frequency. Under the assumption that ingress mediation performance can achieve equivalent rejection relative to the M-QAM SNR (potentially an aggressive assumption), this relationship might be assumed hold between 256-QAM and 1024-QAM for narrowband interference.

7.1.3.5 Phase Noise

Untracked phase error leads to angular symbol spreading of the constellation diagram as shown in Figure 35 for 1024-QAM with .25° rms of Gaussian-distributed untracked phase error imposed. This non-uniform impact on symbols is critical to understand to explain phase noise sensitivities for increasing M in M-QAM. It was observed in [1] that .25° rms represents a loss due to phase noise of about 1 dB, assuming low error rate conditions, and with no practical phase noise-induced BER floor.

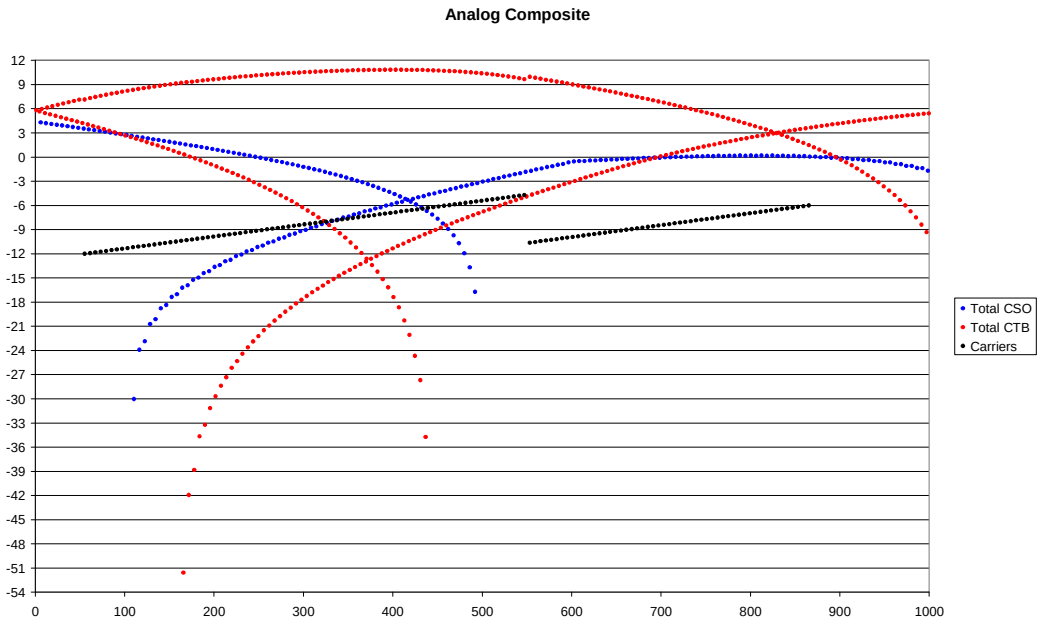


Figure 33 – Distortion Map - 79 Analog Channels, 12 dB Tilt

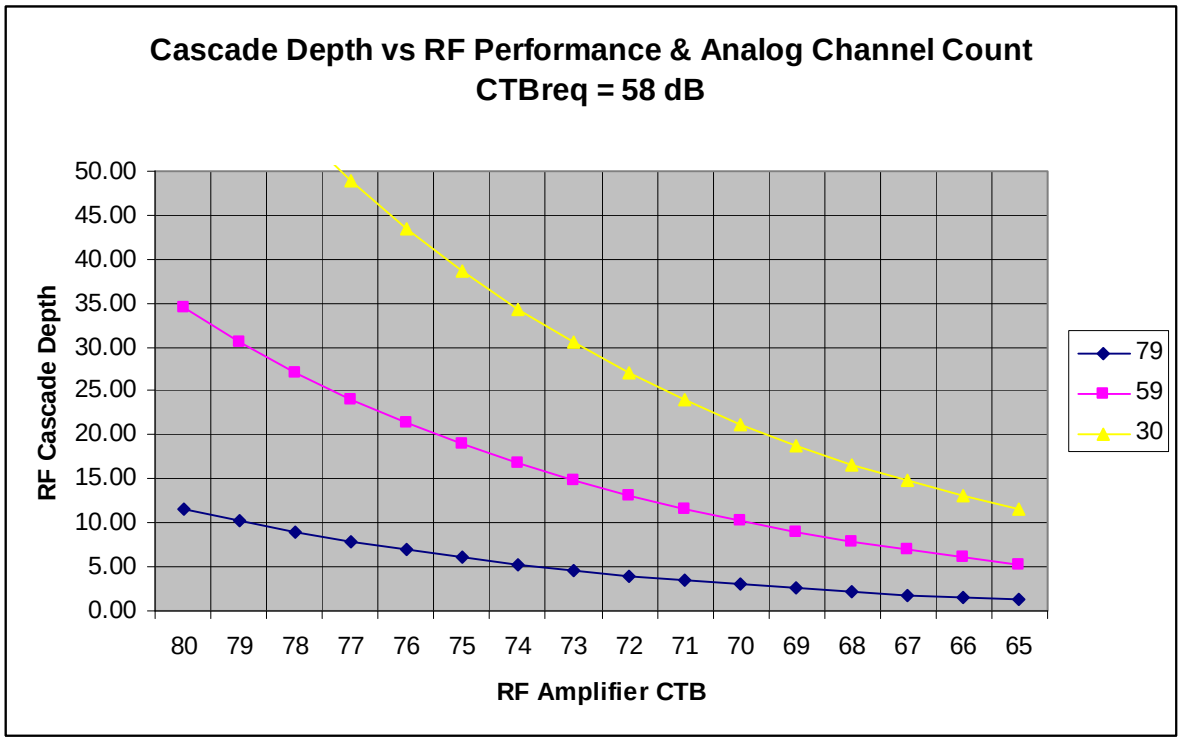


Figure 34 – 1024-QAM, CTB, and Cascade Depth, Thresh = 58 dB

A floor in the 1E-8 or 1E-9 region will be induced at roughly 50% more jitter, or .375 deg rms. Measurements of phase noise showed that for high RF carrier frequencies, typically associated with higher total phase noise, wideband carrier tracking still left about .33 deg rms of untracked error, enough to cause a BER floor to emerge at very high SNR.

The use of degrees rms is more easily understood when expressed as signal-to-phase noise in dB. Note that 1° rms is equivalent to 35 dBc signal-to-phase noise. Doubling or halving entails 6 dB relationships. Thus, we have the following conversions:

1 deg rms = 35 dBc SNRφ

.5 deg rms = 41 dBc SNRφ

.25 deg rms = 47 dBc SNRφ

The values .33 deg rms and .375 deg rms represent 44.6 dBc and 43.5 dBc, respectively. This is instructive to compare to the SNR under AWGN only (40 dB used above), as it illustrates the nature of the phase noise impairment on M-QAM with high M.

Error rate measurements [1] show that error flooring appears to be occurring as measured by pre-FEC errors, suggesting that there have not been significant enough tuning (historically analog, now full-band capture) noise improvements or carrier recovery system changes to mitigate this effect.

However, although phase noise is a slow random process that challenges burst correcting FEC, the combination of the interleaver, Reed-Solomon, and the relatively low floor, has been seen to result in zero post-FEC errors. Note that the phase noise alone is requiring the FEC to work to

clean up the output data, and is thus consuming some FEC "budget" in the process.

Phase noise can be improved through design as well, almost without limit, but as strong function of cost for broadband performance. Current performance appears sufficient, although perhaps coming at the expense of increased sensitivity to other impairments that may also require FEC help.

These observations are likely a harbinger of issues to come as M increases further in search of higher bandwidth efficiency, such as 4096-QAM.

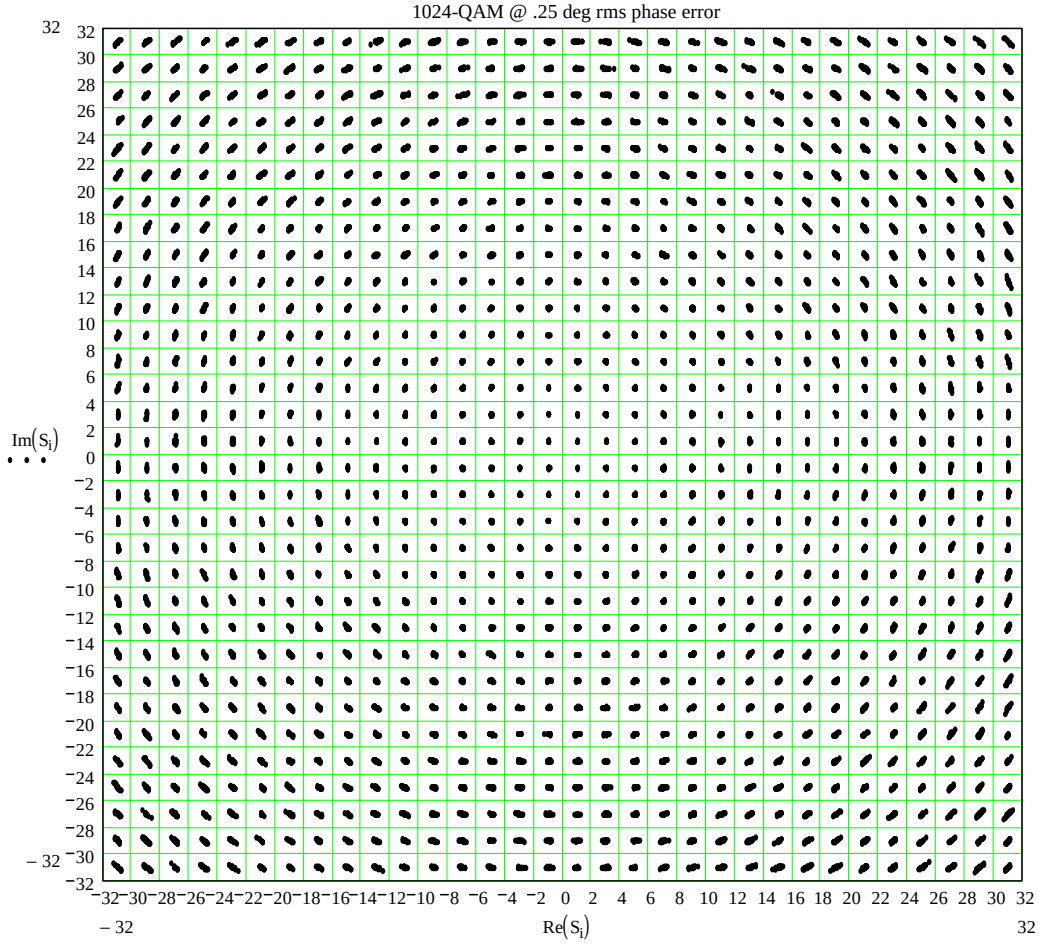


Figure 35 – 1024-QAM with .25° RMS Phase Noise

7.2 S-CDMA

Leveraging S-CDMA has many benefits, including reclamation of regions of upstream spectrum considered previously unusable with TDMA, lower overhead for FEC, and even feasibility of higher-order constellations. Some frequency regions are, of course, readily accessed leveraging Advanced Time Division Multiple Access (A-TDMA).

A-TDMA can be made very robust to a broad set of impairments including noise, distortion, and interference when it's coupled powerful tools such as Forward Error Correction (FEC), Equalization, and Ingress Cancellation. Problems arise when impairments exceed the performance limits of what A-TDMA can mitigate, resulting in objectionable codeword errors and packet loss.

Fortunately, DOCSIS 2.0 and later includes Synchronous Code Division Multiple Access (S-CDMA), which offers additional robustness against impairments, and in particular against impulse noise. This robustness against impulse noise exceeds that of A-TDMA by a factor of 100 times or more [14].

As powerful as DOCSIS 2.0 S-CDMA has been proven to be in field trials, DOCSIS 3.0 has S-CDMA features that further enhance robustness against impairments. These techniques were standardized to create a very high-performance, sophisticated PHY for cable, capable of supporting high data rates in the most difficult of environment.

The latest features include Selectable Active Codes (SAC) Mode 2, Trellis Coded Modulation (TCM), Code Hopping, and Maximum Scheduled Codes (MSC). Despite these advances aimed at adding more capability to the upstream, most of the DOCSIS 3.0 features remain largely unused, and DOCSIS 2.0 deployments are minor in scale in North America.

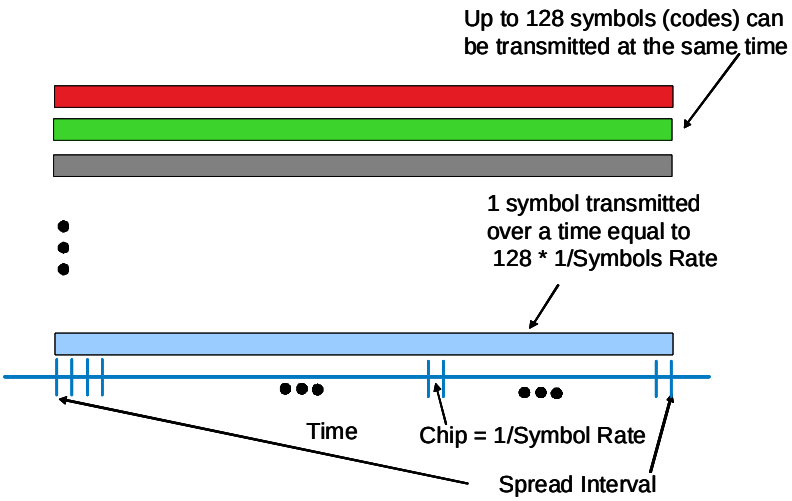


Figure 36 – S-CDMA Parallel Symbol Transmission

Let's take a look at what is available in DOCSIS to maximize the throughput of the upstream band, and discuss how today's PHY toolsets complement one another. First, let's understand what S-CDMA does best – high throughput performance under difficult channel conditions.

7.2.1 Impulse Noise Benefits of S-CDMA

There are several benefits to S-CDMA, but the most important by far is its burst protection capability. The ingredient that makes the robustness to impulse noise possible is the spreading out of the symbols by as much as 128 times in the time domain, which directly translates to stronger protection against impulse noise.

This spreading operation is pictured in Figure 36. Noise bursts that may wipe out many QAM symbols of an A-TDMA carrier must be two orders of magnitude longer in duration to have the same effect on S-CDMA, which is very unlikely. It is the spread signaling approach itself, without even considering FEC settings, that enables S CDMA to withstand much longer impulsive events.

There is no reduction in throughput as a result of this spreading, of course, because the slower symbols are transmitted simultaneously. S-CDMA has similarities conceptually to OFDM in this manner, with the difference being S-CDMA's use of the orthogonality in the code domain versus OFDM's use of orthogonality in the frequency domain.

Now consider Figure 37, which illustrates how S-CDMA's primary benefit translates to return path bandwidth access. Through its effectiveness against impulse noise, S-CDMA facilitates efficient use of what is otherwise very challenging spectrum for A-TDMA. It is a critical tool for squeezing every last bit-per-second possible out of return spectrum.

Additionally, the lower the diplex split used in the system, the more important S-CDMA becomes. It has become well-understood that the most consistently troublesome spectrum is at the low end of the band, typically 5-20 MHz.

This region is where S CDMA shines in comparison to A-TDMA. As such, S-CDMA matters more for maximizing use of 42 MHz than it does to 65 MHz (Euro Split) or 85 MHz (Mid-Split) because of the percentage of questionable spectrum.

Purely in terms of spectrum availability then, S-CDMA is most valuable to the North American market, where upstream spectrum is the scarcest and use of DOCSIS services is high. Depending on the upstream conditions, about 35-50% of extra capacity can be made available using S-CDMA.

Nonetheless, S-CDMA's benefits have been largely unused in practice by operators, despite its availability in DOCSIS 2.0 and DOCSIS 3.0 certified equipment.

7.2.2 Quantifying Performance

Again, by far S-CDMA's most compelling advantage is its ability to perform in harsh impulse noise environments. Impulse noise is, by definition, a transient event – interference of finite duration and often periodic or with

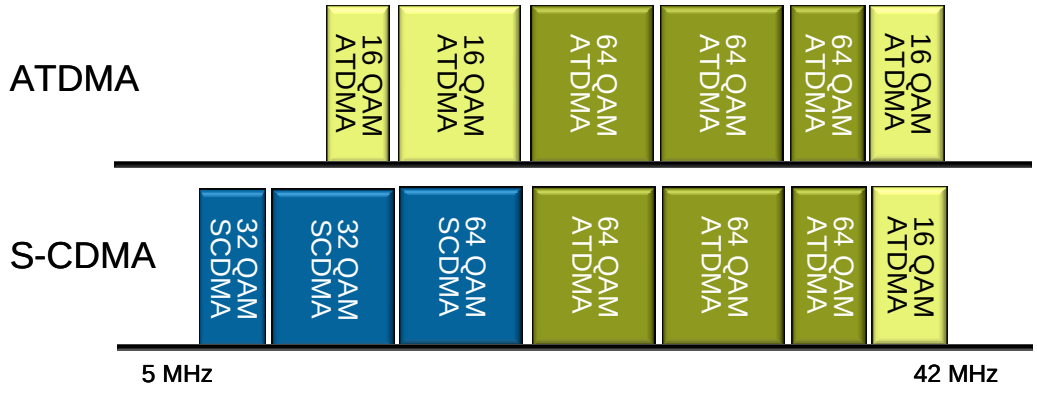


Figure 37 – Maximizing 5-42 MHz Throughput Using S-CDMA

repetitive frequency of occurrence.

Characterization of impulse noise includes duration, rate, and amplitude. It is generated in a variety of ways. When noisy devices such as dimmer switches, hair dryers, garage door openers, power tools, automobile ignition circuits – the list goes on – are in close proximity to the cable network, impulse noise may enter into upstream. The majority of impulse noise originates in and around the home.

Figure 38 is a spectral snapshot of impulse noise, where a noticeable wideband burst above the noise average (red) is very likely interfering with DOCSIS signaling by creating a temporary condition whereby the SNR is only about 18 dB.

The impact of such a burst on a discrete set of QAM symbols is to cause the symbols to jump decision boundaries, or increase the probability that they will do so, resulting in codeword errors, as shown in Figure 39. Note the wideband nature of the degradation in the frequency domain of short duration impulse noise.

Consider just the DOCSIS-described scenario of duration 10µs and rate 1 kHz. A 10 usec burst will corrupt 52 symbol at 5.12Msps, which translates to 39 bytes of data for 64-QAM. This is beyond the capability of the Reed-Solomon FEC, with a maximum burst protection of t = 16 bytes.

For this scenario, the FEC cannot be effective without assistance of interleaving. An interleaver, in theory, could be used to break-up clusters of impacted bytes so that they span multiple codewords, allowing FEC to be more effective. However, byte interleaving requires longer packets for adequate shuffling of the bytes. Minimum packet lengths of 2x the designated codeword length are necessary, and the longer the better.

Unfortunately, of course, most upstream packets tend to be short and not suited to effective interleaving.

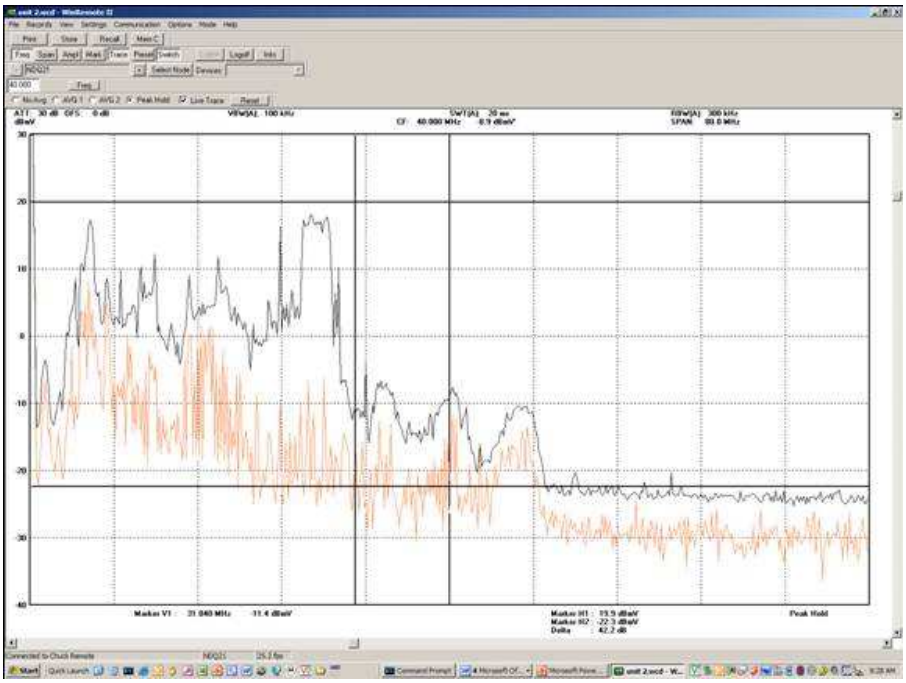


Figure 38 – Impulse Noise Illustration, -18dBc

Such situations are where S-CDMA is the best choice for achieving high throughput. S-CDMA has greater ability to recover transmissions through long noise bursts, and is not sensitive to packet size the way interleaving is in a burst environment.

A most recent head-to-head comparison under simultaneous RF impairments of impulse noise and interference is shown in Table 22.

Three impulse noise sources were used:

1. Duration = 10µs, Rate = 1kHz (per DOCSIS specification)
2. Duration = 20µs, Rate = 4kHz
3. Duration = 40µs, Rate = 4kHz

Three interference patterns used, centered around the signal center frequency:

- A. 4x π/4-DQPSK Carriers @16ksym/s, Spacing = 400kHz
- B. 2x π/4-DQPSK Carriers @16ksym/s, Spacing = 1600kHz
- C. 1 π/4-DQPSK Carriers @16ksym/s

The interference was modulated in order to randomize it and give it some spectral width, which makes ingress cancellation more challenging.

Table 22 shows the comparative results, with S-CDMA clearly and significantly outperforming A-TDMA under the dual impairment conditions. A-TDMA FEC is working much harder in each of the cases evaluated, primarily because of the impulse noise.

Uncorrected Codeword Error Rate (UCER) and packet error rate (PER) for A-TDMA under each of the impairment conditions shows performance that would

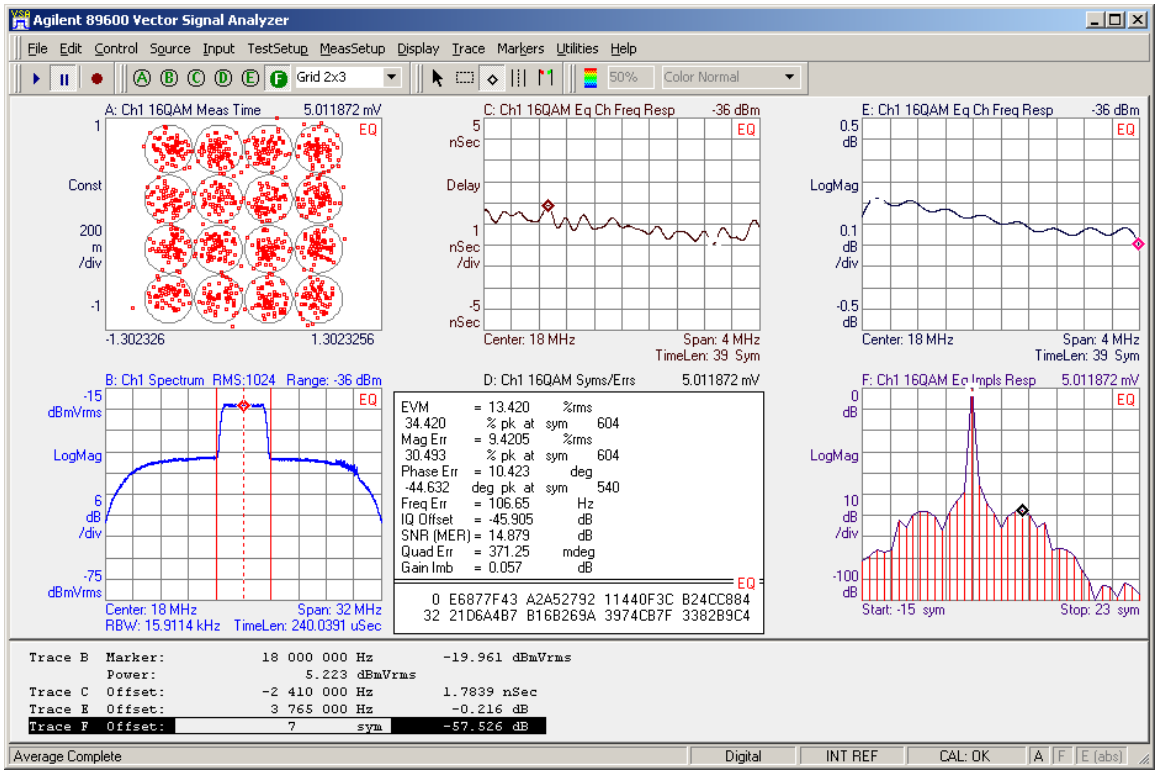


Figure 39 – Impulse Noise Impaired 16-QAM

likely noticeably degrade the customer experience.

Not only is the S-CDMA FEC not working as hard as A-TDMA FEC, there is also less S-CDMA FEC applied. FEC for A-TDMA was at its maximum setting of t=16, and k=219, whereas field trial results previously published [1] resulted in lower FEC for S-CDMA of t=6, and k=239.

As previously discussed, FEC operating requirements can be lowered for S-CDMA because the robustness of the spreading function itself.

Clearly, for equal or even more strenuous impairment scenarios than the A-TDMA cases, S-CDMA offers error-free UCER and PER with no impact to the customer experience.

Additionally, proactive monitoring of Corrected Codeword Error Rate (CCER) with S-CDMA could better facilitate impulse noise problem diagnostics, whereas A-TDMA links would not.

Additional testing in the field on live plants has confirmed the advantage that S-CDMA delivers in the poorer part of the upstream spectrum. A result from a comparison of S-CDMA and A-TDMA on the same return path channel using logical channel operation, centered in a noisy portion of the upstream (about 13 MHz), is shown in Figure 40.

Apparent from Figure 40 is that A-TDMA is taking errors in transmission at a nearly 20% clip, while S-CDMA is taking

Table 22 – S-CDMA & TDMA Performance against Impulse Noise + Interference

16-QAM. 6.4MHz						
1518-Byte Packets	S-CDMA			ATDMA		
Noise Floor = 35dB	MER	CCER/UCER	PER	MER	CCER/UCER	PER
Interference Characteristics	Impulse Noise Characteristics: Duration = 10us, Rate = 1kHz, Level = -11dBc					
Pattern A @ -20dBc	33.1	3.2653%/0.0000%	0.00%	32.2	9.8190%/0.3643%	1.82%
Pattern B @ -18dBc	33.3	2.2164%/0.0004%	0.00%	30.4	9.4996%/0.4362%	1.84%
Pattern C @ -16dBc	33.6	6.0938%/0.0000%	0.00%	30.5	9.1357%/0.9920%	4.86%
Interference Characteristics	Impulse Noise Characteristics: Duration = 20us, Rate = 4kHz, Level = -13dBc					
Pattern A @ -22dBc	29.0	6.2512%/0.0000%	0.00%	29.6	39.7214%/0.2657%	1.46%
Pattern B @ -22dBc	23.0	6.4386%/0.0000%	0.00%	28.2	36.8949%/0.0730%	0.39%
Pattern C @ -20dBc	33.5	5.3450%/0.0000%	0.00%	25.6	36.5901%/1.1087%	4.61%
Interference Characteristics	Impulse Noise Characteristics: Duration = 40us, Rate = 4kHz, Level = -14dBc					
Pattern A @ -22dBc	17.3	13.1082%/0.0000%	0.00%	26.6	39.7623%/0.0639%	0.40%
Pattern B @ -22dBc	26.1	13.8848%/0.0000%	0.00%	20.3	35.1569%/0.0079%	0.05%
Pattern C @ -13dBc	34.2	7.6259%/0.0000%	0.00%	28.0	38.3802%/1.7060%	6.91%

16-QAM. 3.2MHz						
1518-Byte Packets	S-CDMA			ATDMA		
Noise Floor = 35dB	MER	CCER/UCER	PER	MER	CCER/UCER	PER
Interference Characteristics	Impulse Noise Characteristics: Duration = 10us, Rate = 1kHz, Level = -7dBc					
Pattern A @ -22dBc	32.2	6.9036%/0.0000%	0.00%	33.5	18.1515%/2.7396%	14.87%
Pattern B @ -26dBc	21.1	4.0558%/0.0000%	0.00%	28.9	19.2957%/0.7367%	3.99%
Pattern C @ -11dBc	33.1	3.6618%/0.0000%	0.00%	34.0	16.8403%/5.2196%	22.86%
Interference Characteristics	Impulse Noise Characteristics: Duration = 20us, Rate = 4kHz, Level = -10dBc					
Pattern A @ -23dBc	25.6	8.1255%/0.0005%	0.00%	26.2	79.9084%/4.3388%	22.07%
Pattern B @ -24dBc	19.5	17.1071%/0.0000%	0.00%	24.8	81.1037%/0.1378%	0.85%
Pattern C @ -12dBc	32.6	13.3983%/0.0000%	0.00%	18.0	65.1727%/20.9625%	65.44%
Interference Characteristics	Impulse Noise Characteristics: Duration = 40us, Rate = 4kHz, Level = -12dBc					
Pattern A @ -20dBc	22.9	15.8017%/0.0000%	0.00%	18.6	85.0225%/2.8658%	13.41%
Pattern B @ -23dBc	31.3	16.5487%/0.0000%	0.00%	20.0	83.8348%/0.4118%	2.01%
Pattern C @ -13dBc	31.6	24.5632%/0.0000%	0.00%	23.0	71.7126%/17.3259%	56.71%

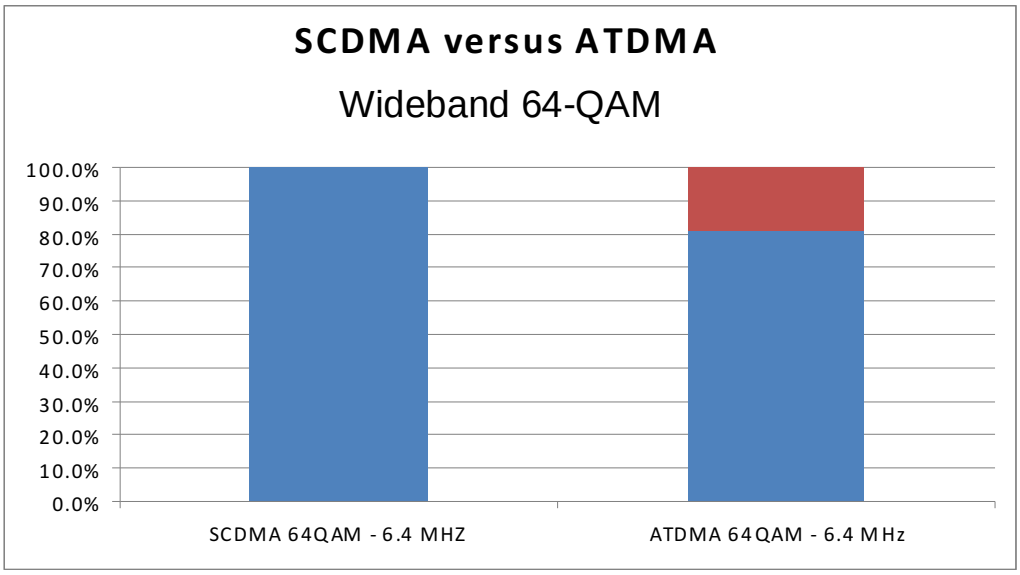


Figure 40 – Corrected Error Statistics

none. In this case, FEC settings for A TDMA are again t=16, while for S-CDMA, they are set to just t=2. S-CDMA inherently takes advantage of its impulse immunity properties rather than relying on FEC.

It is worth noting that, for A-TDMA, impulse noise can also wreak havoc on adaptive processes such as equalization and ingress cancellation, resulting in appreciable variation in cancellation estimates. For example, Figure 41 shows Non-Main Tap to Total Energy Ratio (NMTER) for a population of eight cable modems where impulse noise caused significant variation in equalizer correction.

NMTER is useful as a Figure of Merit to describe the linear distortion level of the upstream path. Here, it is indicating that the frequency response correction process is being significantly disturbed, resulting in a period of increased ISI until the impulse noise subsides and the taps updated.

Even should FEC be able to handle the impulse duration, this increase in ISI can degrade performance because of the increased susceptibility to detection errors at the slicer. The FEC budget may be required to deal with both ISI and burst correction, and is therefore more likely to be overwhelmed until the next tap update can be processed.

7.2.3 More Capability Remains

S-CDMA's impulse noise robustness has been demonstrated, but there is still more that can be leveraged to take advantage of all of the DOCSIS 3.0 features of S-CDMA.

Additional features include Selectable Active Codes (SAC) Mode 2, Trellis Coded Modulation (TCM), Code Hopping, and Maximum Scheduled Codes (MSC). These features provide more flexibility and capability for extracting bandwidth from noisy, limited spectrum, and yet remained largely unused despite more being standardized for many years.

Briefly, these features provide the following:

SAC Mode 2 – Allows for customization of the active codes. Instead of fixed active codes (SAC Mode 1) codes

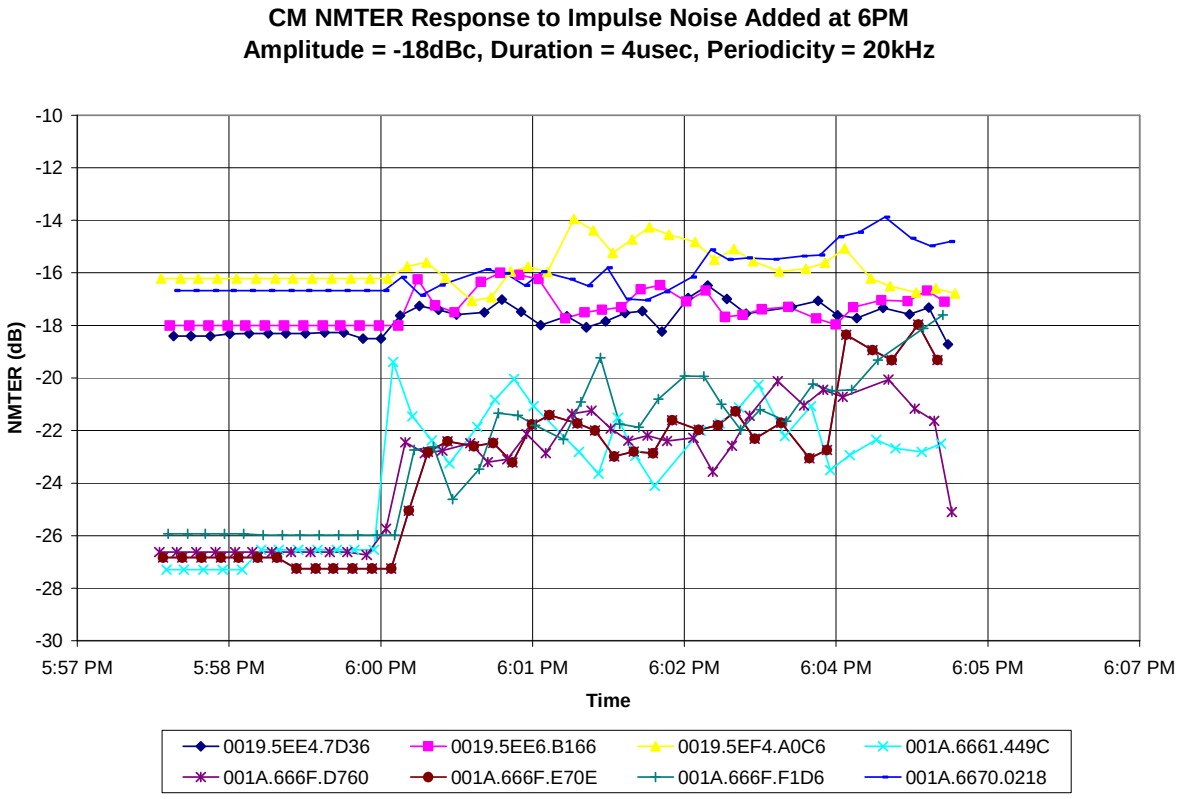


Figure 41 – NMTER vs. Time Impaired by Impulse Noise

may now be optimally allocated between spreading and ingress cancellation.

Trellis-Coded Modulation (TCM) – The well-known technique for optimizing coding structure through integration with symbol mapping, adding gain without adding bandwidth overhead to do so.

Code Hopping – Provides cyclic shifts of the active code set at each spreading interval, further randomizing code allocation to achieve a uniformity of robustness of performance

Maximum Scheduled Codes (MSC) – Offers the flexibility to trade-off between the power allocated per-code and the number of codes turned on. For example, if 128 codes are on transmitting at Pmax, each code is allocated Pmax/128. If only 64 codes are used, each code is allocated Pmax/64, or 3 dB more power per code. This comes at the expense of throughput, but offers some choices to the operator that may be better than an equivalent A-TDMA alternative.

7.2.4 Summary

S-CDMA delivers proven, substantial gains in impulse noise robustness – performance verified in detailed lab testing and in the field, around the world.

It clearly outperforms A-TDMA on difficult channels, enables high-throughput access to the otherwise abandoned lower portion of the return spectrum, and has been shown to operate robustly on channels where A-TDMA will not operate at all.

Many available, but as yet unused, features of S-CDMA, including SAC Mode

2, MSC, Code Hopping, and TCM, provide further capability against upstream impairments. Nonetheless, while a long-standardized tool in DOCSIS, operators have not widely deployed S-CDMA.

In low-diplex architectures, where DOCSIS extensions may be the most straightforward, low-complexity way to light up new spectrum, S-CDMA already exists to support the delivery of high throughput on difficult low-end spectrum. It is capable of providing the same benefits as in any new spectrum deployed for upstream that becomes prone to high interference and noise levels.

The combination of updated A-TDMA with the full features of S-CDMA may, in fact, be a sufficient PHY toolset for upstream growth and lifespan extension, eliminating the need to develop a third upstream PHY, such as an OFDM-based system.

7.3 OFDMA, OFDM & LDPC (A Proposal for a New PHY)

7.3.1 Problem Statement

Once it is acknowledged that current DOCSIS 3.0 MAC provides all the necessary capabilities to extend DOCSIS service to future gigabit rates, the challenge becomes optimizing the PHY layer.

Before choosing the technology for that new PHY, key selection criteria need to be established. These criteria apply to both upstream and downstream.

1. Bandwidth capacity maximization
2. Transparency toward the existing D3.0 MAC
3. Robustness to interference
4. Robustness to unknown plant conditions
5. Throughput scalability with plant condition (SNR)
6. Implementation complexity and silicon cost
7. Time to market
8. PAPR considerations
9. Frequency agility

7.3.1.1 Bandwidth Capacity Maximization

According to Shannon theorem the maximum achievable throughput capacity for a communication system is a function of signal to noise ratio and bandwidth. Both of these resources, the signal power relative to an unavoidable noise and the useful bandwidth of the coaxial part, are limited in an HFC plant.

An upgrade of the HFC plant is costly, and therefore before (or in parallel with) this upgrade, the available SNR and bandwidth utilization can, and must be maximized using state-of-the-art modulation and coding techniques.

7.3.1.2 Transparency Toward the Existing D3.0 MAC

One of the extremely useful features of the D3.0 MAC is the physical channel bonding. This feature allows trafficking of logical flows on information through multiple and different physical channels. Apart from the lower level convergence layer features, the DOCSIS 3.0 MAC is not aware what type of Physical channel(s) the information is flowing through, be it 256-QAM or 64-QAM in downstream, or ATDMA or SCDMA in upstream.

Allowing the new PHY to follow the same transparency will allow the products introduced to the market migrate gradually from using the old PHY to using the new PHY by utilizing (rather than giving up) throughput from existing legacy channels, until these are gradually replaced with new ones. For example, there are CMs deployed in the field with eight downstream channels. Until all these CMs are replaced, those eight channels will continue to occupy the shared spectrum. A transition period product will be able to make use of both the legacy PHY and the new PHY through channel bonding; and hence will maximize the data throughput as illustrated in Figure 42 and Figure 49.

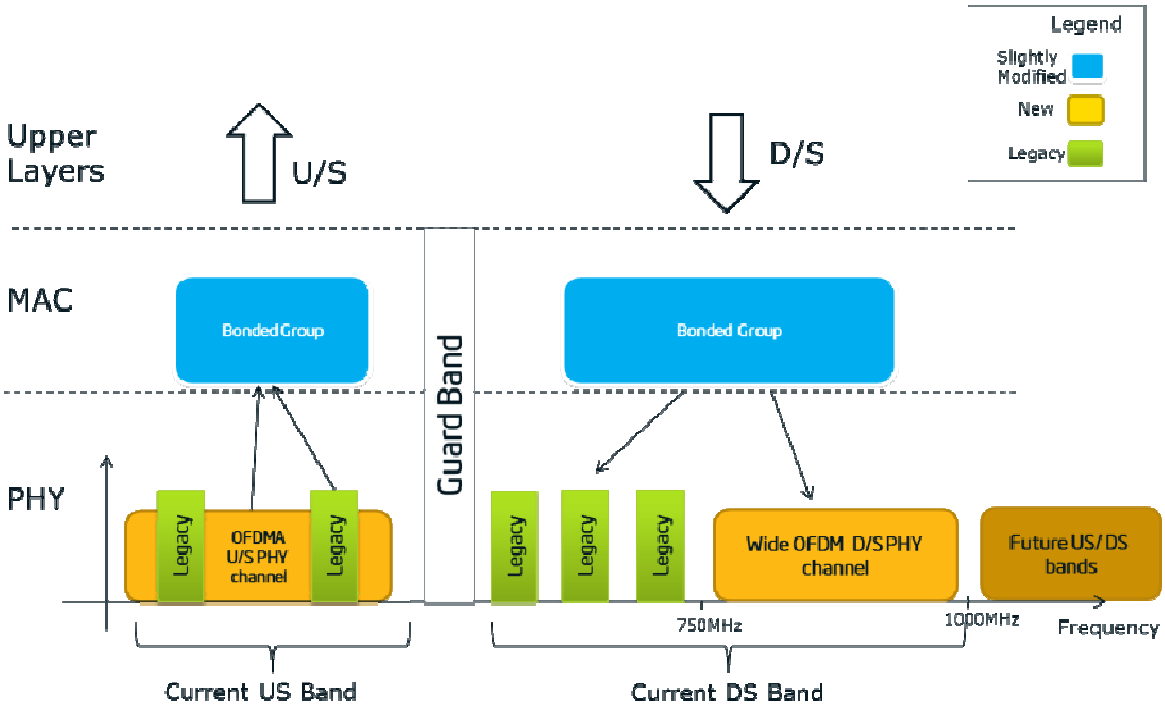


Figure 42 – Illustration of bonding the legacy and the new PHY channels

As a comparison, a non-DOCSIS technology will not be able to benefit from the bandwidth occupied by legacy.

7.3.1.3 Robustness to Interference

As the home and business environment becomes flooded with electronic equipment, the level of interference becomes a significant limiting factor of bandwidth usage in some regions of the HFC spectrum, particularly in the upstream. A modulation scheme of choice should be designed to minimize the effect of interference on the achievable throughput.

7.3.1.4 Robustness to Unknown Plant Conditions

The new PHY should be well equipped to be deployed in spectrum that is currently unused for cable systems, such as spectrum beyond 1GHz. Also, it should be equipped to maximize throughput given unknown parameters in the existing installation, as these differ significantly by region, type of installation, countries, etc. Planning for the worst case adds inefficiency and cost, hence agility to optimize capacity per given condition is required.

7.3.1.5 Throughput Scalability with Plant Condition (SNR)

As mentioned above, SNR sets the maximum achievable capacity over a given bandwidth. Ability to scale the throughput accordingly with the SNR available to the modem will allow squeezing the maximum throughput possible per given installation condition. Simply put, more bits/sec/Hz configurations are needed with finer granularity, spanning a wide SNR scale.

7.3.1.6 Implementation Complexity and Silicon Cost

Adding more throughput capability to the modem will result in more silicon complexity that translates to silicon cost. It is essential that the new PHY technology chosen is able to offer cheaper implementation in terms of dollars per bits/sec/Hz over other alternatives. As a side note, one thing worth noting is that process technology scaling (Moore's law) allows increasing the PHY complexity without breaking the cost limits.

7.3.1.7 Time to Market

It is important to isolate the proposed changes to specific system elements without affecting system concepts. Changing only the PHY channel, without any significant changes to the MAC minimizes the scope of impact of the change and allows quicker standardization and implementation of the change. Utilizing existing, proven, and well-studied technologies helps accelerate the standardization and the productization.

7.3.1.8 PAPR Considerations

Good (low) peak to average ratio properties of the modulation technique may help in squeezing more power out of the amplifiers in the system by moving deeper into the non-linear region. Hence, good PAPR properties are desirable, as these have system impact beyond the end equipment.

7.3.1.9 Frequency Agility

The ability of the new PHY channel to be deployed in any portion of the spectrum is a great advantage. This is especially useful during the transition period where various legacy services occupy specific frequencies and bands and cannot be moved.

Next we consider the alternatives of the PHY channels in light of the above-mentioned criteria, focusing on the parameters of the suggested proposal.

7.3.2 Solution Analysis

7.3.2.1 Channel Coding – Optimizing Spectral Efficiency

FEC has the most significant impact on spectral efficiency. Traditional error control codes such as J.83 Annex B are concatenations of Trellis and Reed-Solomon block codes. Modern coding techniques such as LDPC and Turbo use iterative message passing algorithms for decoding, thereby yielding significant coding gains over traditional techniques. LDPC has been shown to out-perform Turbo codes at relatively large block sizes. LDPC also has the parallelism needed to achieve high throughputs.

Figure 43 shows a comparison of different coding schemes used in Cable technologies[1]. 256-QAM modulation is taken as baseline for comparison. The horizontal axis is the code rate and the vertical axis shows the SNR required to achieve a BER of 1e-8. The two DVB-C2 LDPC codes are shown, the long code with a block size of 64800 bits and the short code with a block size of 16200 bits. [28]

As expected, the code with the longer block size does provide better performance

[1] Although code rate 0.8 is not present in current J83 specification, the system was simulated with RS codes (204, 164) for J.83 Annex A and (128, 108) for J.83 Annex B to get the effective performance of these codes at a rate of 0.8.

although the difference is very small (0.2 dB) for high code rates needed for cable applications. The two DVB-C2 LDPC codes do include a weak BCH code to assist with the removal of the error floor.

The graph in Figure 43 shows that the DVB-C2 LDPC offers about 3 dB more coding gain over J.83 Annex B code for a code rate of 0.9 implying an increase of capacity of 1 bit/s/Hz, i.e. a 12.5% increase with respect to 256-QAM. The increase in coding gain and hence the capacity is much higher (about 5 dB) with respect to just the RS code used in J.83 Annex A, i.e. DVB-C.

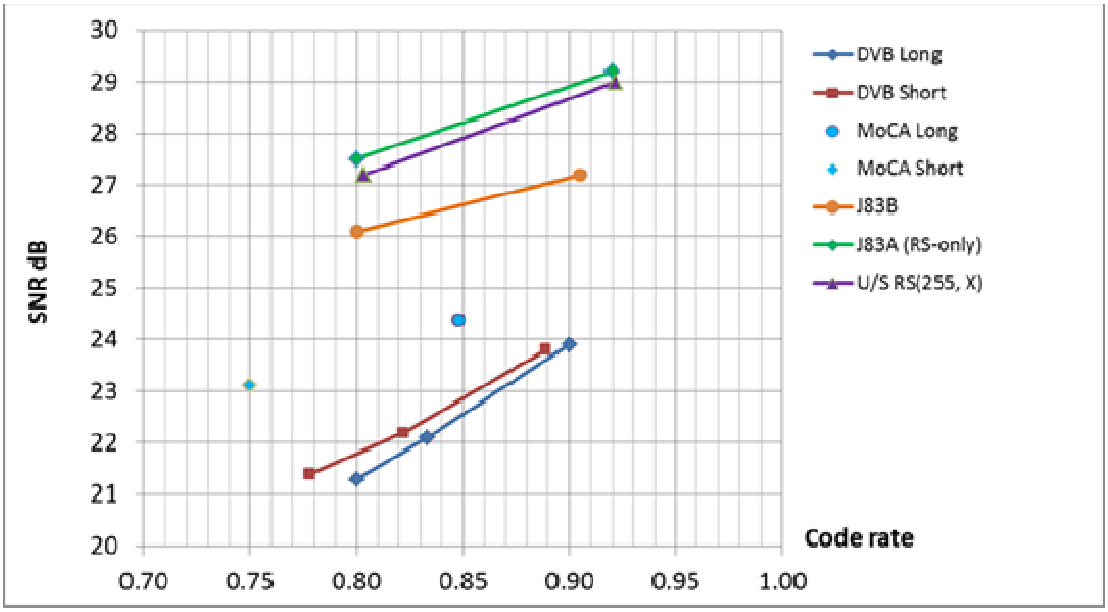


Figure 43 – FEC Comparison for 256-QAM Modulation

Note that since existing coding schemes are compared, the code word lengths are not the same, implying an advantage to longer code words. Theoretically, if the J.83 Annex B FEC is extended to a longer code word, the difference will be less than 3 dB, but the DVB-C2 code will still give the better performance.

To enable efficient stuffing of upstream bursts with code words, two types of codes with different code word length are necessary. A short code word for short bursts, and a long code word for long bursts are recommended. Since the ambitious throughput requirements are usually on the long bursts (streaming data, rather than maintenance messages), no system throughput loss is expected due to usage of shorter code word.

7.3.2.2 Modulation Scheme

The options considered for the modulation scheme of the next gen PHY are as follows:

1. Legacy modulation, narrow Single Carrier QAM, 6/6.4 MHz channels
2. A new, wide Single-Carrier channel modulation, e.g. Single Carrier QAM 24 MHz channel
3. A new, wide Multi-Carrier OFDM channel modulation

A comparison of these options is discussed next against the established criteria.

7.3.2.3 Implementation Complexity

To contain the total complexity increase due to scaling to gigabit throughputs, both PHY layer implementation itself, and its effect on the MAC layer need to be considered.

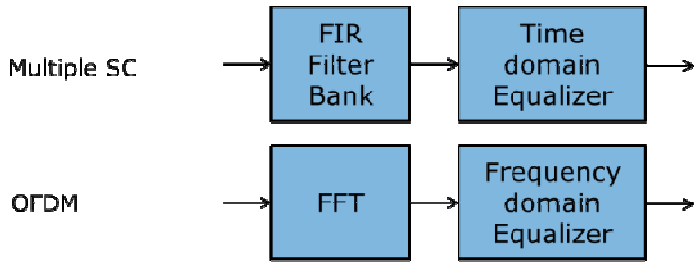


Figure 44 – Signal Processing Block for Computational Complexity analysis

If narrow channels are used to attain the high throughputs, a large number of such channels will be required, which may lead to a non-linear increase in the MAC complexity. Hence, there is a benefit of using wide channels to reduce the total number of bonded channels.

However, only OFDM out of the three options considered can give a computational benefit given a wide channel, due to differences in channel processing and equalization. The channelization for OFDM is based on FFT, which is computationally more efficient than the multiple sharp channel filters required for single carrier. Also the frequency domain equalization in OFDM is much lighter computationally than time domain equalization required with SC-QAM. Figure 44 and Table 23 show the processing power analysis of the options based on the number of real multiplication per second required. A clear advantage of OFDM is observed.

Another thing worth noting in favor of wide channels is that since today's analog front end technology for cable is based on direct digital-to-analog and analog-to-digital conversion, having wide channels does not pose a new implementation challenge for the analog front end design. All the channelization and up/down frequency conversion can be done digitally.

7.3.2.4 Channel Equalization

A common assumption for OFDM modulation is that the guard interval (GI) needs to be of a length equal to or higher than the longest reflection in the channel. However, this does not have to be the case. The reflection that is not completely covered by the GI affects only small part of the

Table 23 – Number of Multiplications per sec (real*real) for different modulations schemes

Function	32x6 MHz SC	8x24 MHz SC	16K OFDM
Modulation	1024-QAM	1024-QAM	1024-QAM
Channelization	32 FIR (sym.) filters 6.9e9 (40-tap)	8 FIR (sym.) filters 6.9e9 (40-tap)	16K FFT: 2.6e9
Equalizer	32e9 (40-tap)	125e9 (160-tap) 100e9 (128-tap) 75e9 (96-tap)	5.0e9

symbol, reducing the power of the inter-symbol-interference (ISI) on the entire symbol accordingly (approximately by 10log(T_interference_overlap/T_symbol) on top of the already weak power of the long echoes).

The result is extra gain in throughput of OFDM symbol, due to the GI being shorter than the longest anticipated reflection. To illustrate this, a simulation result of a 16K FFT OFDM system with 200 MHz channel bandwidth and DVB-C2 LDPC code with rate 8/9 is depicted in Figure 45. SCTE-40 reflection profile (SCTE-40) is simulated, as well as AWGN.

The 4.5 us SCTE-40 echo (-30 dB) is outside the 3.33 us cyclic prefix guard interval. However, the loss with respect to the 5 us guard interval is only 0.15 dB because the ICI/ISI noise floor due to echo outside guard is at -42 dB.

An OFDM scheme can have multiple options for guard intervals without any silicon cost penalty, whilst the SC time equalizer approach needs to be designed for the worst case. As DOCSIS moves into new spectrum, this additional flexibility gives OFDM an advantage over SC.

7.3.2.5 Robustness to Interference

In OFDM, narrow interference typically affects only a small number of carriers, causing only a minor loss in capacity. If the locations of the interferences are known, it is possible not to transmit at those carriers or reduce the modulation order of transmission for those carriers only. Also, since the LDPC decoding is done based on SNR estimation per carrier, the error contribution of the noisy carriers will be minimized by the LDPC decoder even if the location of the interference is not known.

Robustness to interference of wide single carrier channels would be based on the same ingress cancellation techniques

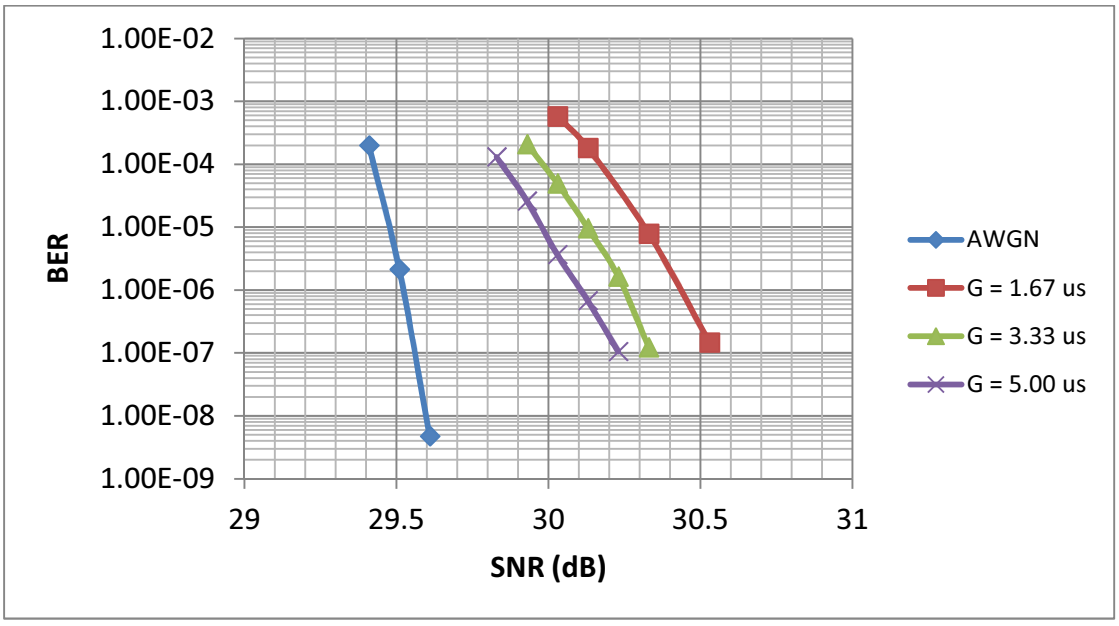


Figure 45 – OFDM/LDPC system performance in presence of SCTE-40 channel echoes

currently used in downstream and upstream receivers. However, for wider channels, these functions could become more challenging because of the increased probability of multiple interferers. This would result in inferior performance compared to today's single carrier in spectral regions beset by interference, or an increase in complexity to achieve the same performance.

In general, OFDM offers particular, understood simplicity and flexibility advantages for dealing with the narrowband interference environment. These could benefit DOCSIS, particularly as previously unused, unpredictable bands become used.

7.3.2.6 Throughput Scalability with SNR

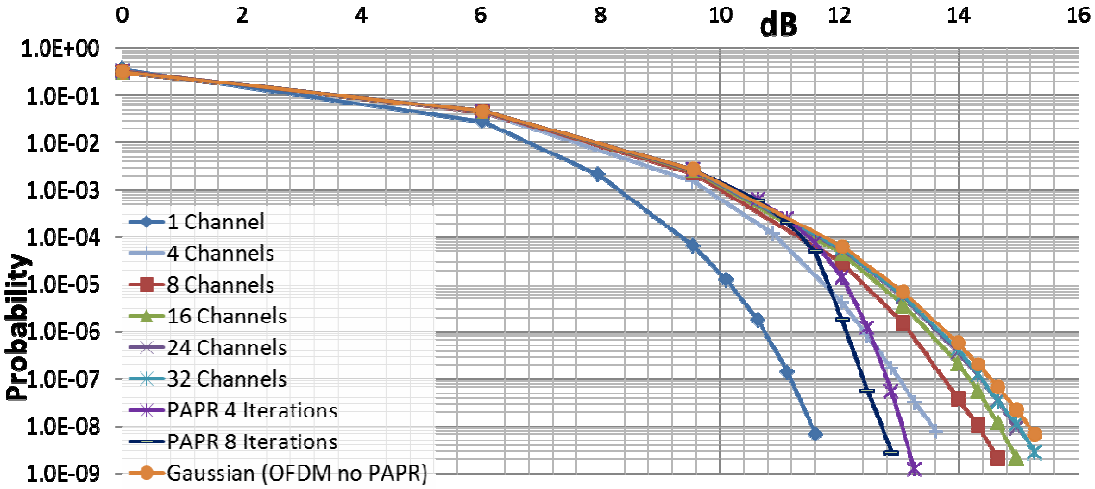
Another useful feature of OFDM modulation is that it enables use of different QAM constellations per carrier (also known as "bit loading"). This allows keeping all the benefits of a wide channel, while having the ability to fit modulation per the existing SNR at a narrow portion of spectrum. This enables maximizing throughput when the SNR is not constant within the channel band.

The non-flat SNR case is especially relevant for spectrum beyond 1 GHz, where signal attenuation falls sharply with frequency, or above the forward band of sub-1 GHz systems. Using a wide single carrier channel in this case would mean a compromise on throughput, and using a narrow singe carrier channel would require a myriad of channels.

7.3.2.7 Peak to Average Power Ratio (PAPR)

Peak to Average Ratio of OFDM modulation is frequently considered as its disadvantage due to the fact that OFDM symbol has Gaussian amplitude distribution (that's because of its multicarrier nature). It is true, but mainly in comparison to a single channel or a small number of channels.

DOCSIS 3.0 systems have at least 4 upstream channels, and this number will continue going up as long as single carrier channels are used to reach higher rates.



Notes: 6 MHz channels with 0.15 alpha and wide OFDM with Peak to Average Reduction Algorithm.

Figure 46 – Probability of Clipping as a Function of Peak to RMS Ratio

Figure 46 shows the PAPR profiles for OFDM and different numbers of single-carrier channels. The vertical axis is the clipping probability for the clipping threshold given in the horizontal axis.

The Gaussian profile is for OFDM with no PAPR reduction. Graphs for different numbers (1, 4, 8, 16, 24 and 32) of single-carrier channels are also shown (each with 0.15 RRC roll-off). It is seen that even when the number of single carrier channels is as low as four, the PAPR is not too different from Gaussian.

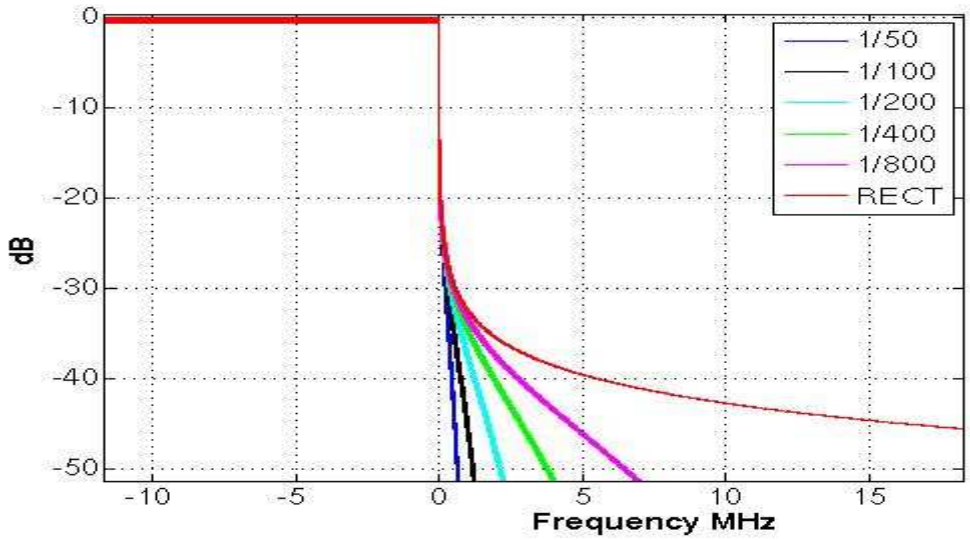
However, unlike single-carrier, OFDM offers ways of reducing peak-to-average power. One such method illustrated using this graph is called tone reservation. In this method a few (< 1%) of the tones are reserved to reduce the high amplitudes in an OFDM FFT. The results shown have been obtained by simulating the specific method given in the DVB-T2 specification. It is seen that the peak power of OFDM can be made to be less than four single-carrier channels at clipping probabilities of interest to cable applications.

Hence, as far as next gen DOCSIS PHY is concerned, OFDM actually has an advantage over bonded single carrier modulation of four channels or greater in terms of PAPR.

7.3.2.8 Frequency Agility

All options considered for downstream have width of multiples of 6 MHz or 8 MHz, for compatibility with the existing downstream grid.

A wide OFDM channel allows creating a frequency "hole" in its spectrum to enable legacy channels inside it, should there be a frequency planning constraint (as graphically shown in Figure 42. With this feature, OFDM retains the frequency agility of a narrow channel, while keeping all the benefits of a wide channel. A wide single carrier channel will be at a disadvantage in that respect.



Notes: lengths (ratio to total number of carriers)

Figure 47 – 16K symbol frequency response with different pulse shaping

To reduce the interference of OFDM

channel to the QAM channel inside it, an OFDM symbol shaping (windowing) can be employed as shown on Figure 47. This windowing makes the OFDM symbol length longer which implies a reduction in the bit rate. Nevertheless, as seen from the figure, windowing significantly sharpens the edge of the OFDM spectrum. This allows data carriers to be inserted until very close to the edge of the available bandwidth. So we have a capacity loss seen from the time domain representation and a capacity gain seen from the frequency domain representation. The net effect is a significant capacity gain and the optimum excess time for windowing has been found (for 12.5 KHz carrier separation) to be 1% of the useful OFDM symbol period (black line in Figure 47).

7.3.2.9 Upstream Multiple Access Considerations

Allowing simultaneous access of multiple CMs is essential for containing latency and for ease of CM management. OFDM modulation can be extended into an OFDMA (Orthogonal Frequency Division Multiple Access) modulation where several modems can transmit on different carriers at the same time.

The good news is that the DOCSIS 3.0 MAC convergence layer already supports that type of access for a case of SCDMA modulation in DOCSIS 3.0. The same concepts can be adopted with minor adjustments for OFDMA convergence layer. The concept of minislots that serves as an access sharing grid for the upstream transmission opportunities can be kept. The two dimensional minislot numbering used in SCDMA can also be kept for OFDMA. The contention, ranging and station maintenance arrangements can be kept.

In order to allow different bit loading per carrier, the minislots, if chosen as constant in time, may be different in size. That would be a change from constant size minislots in legacy DOCSIS, but this is an isolated change. Figure 48 shows an example of such access.

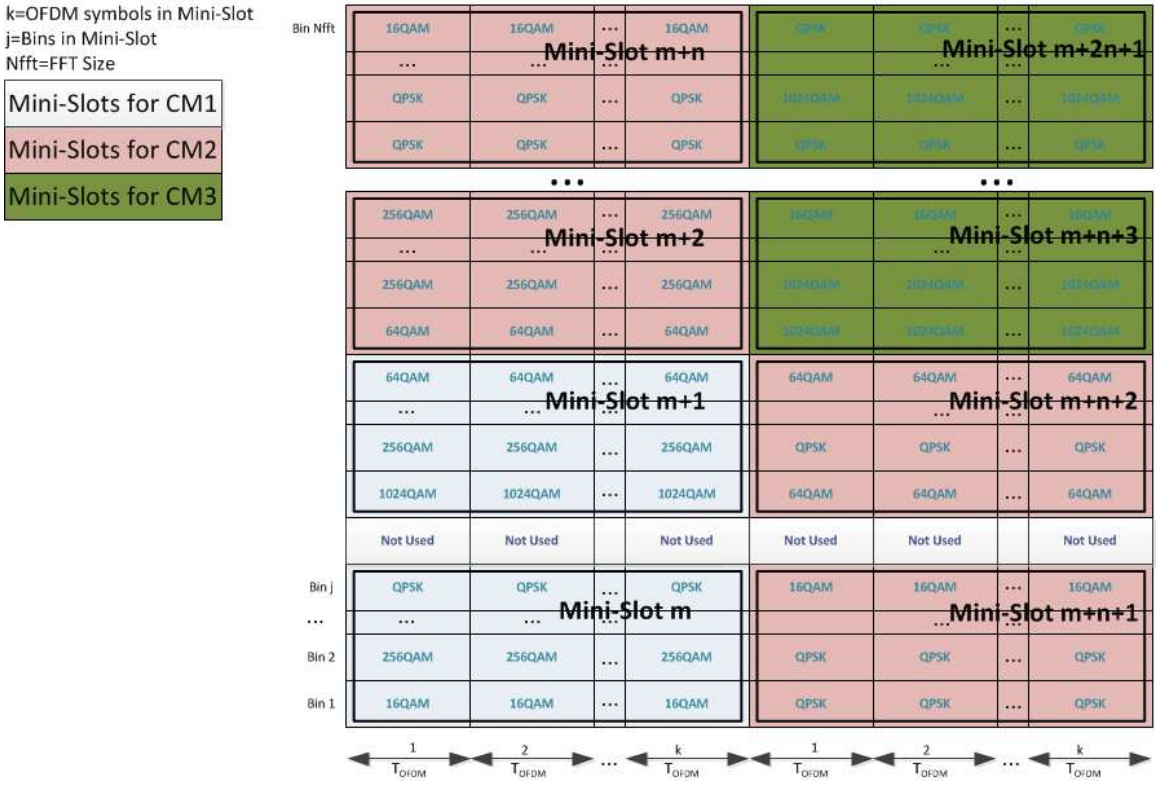


Figure 48 – Mini-slot based scheduling for OFDMA

7.3.3 OFDM Channel Parameter Examples

Table 24 – OFDM Channel Parameters for 192 MHz Wide Channel

Parameter	Value
Channel bandwidth	192 MHz
Useful bandwidth	190 MHz (-95 MHz to +95 MHz) -44 dB attenuation at 96 MHz band-edge
FFT size	16384
FFT sample rate	204.8 MHz (multiple of 10.24 MHz)
Useful symbol time	80 us
Carriers within 190 MHz	15200
Guard interval samples	683 (ratio=1/24; 3.33 us)
Symbol shaping samples	164 (ratio=1/100; 0.8 us)
Total symbol time	84.13us
Continuous pilots	128 (for synchronisation)
Scattered pilots	128 (for channel estimation)
PAPR pilots	128 (for PAPR reduction)
Useful data carriers per symbol	14816
QAM Constellations	4096-QAM, 1024, 256, 64, 16
Bit rate for 4096-QAM w/o FEC	2.11 Gbit/s (11.0 bits/s/Hz)
Bit rate for 1024-QAM w/o FEC	1.76 Gbit/s (9.17 bits/s/Hz)

Table 25 – OFDM Channel Parameters for 96 MHz Wide Channel

Parameter	Value
Channel bandwidth	96 MHz
Useful bandwidth	94 MHz (-47 MHz to +47 MHz) -44 dB attenuation at 48 MHz band-edge
FFT size	8192
FFT sample rate	102.4 MHz (multiple of 10.24 MHz)
Useful symbol time	80 us
Carriers within 94 MHz	7520
Guard interval samples	341 (ratio=1/24; 3.33us)
Symbol shaping samples	82 (ratio=1/100; 0.8 us)
Total symbol time	84.13us
Continuous pilots	64 (for synchronisation)
Scattered pilots	64 (for channel estimation)
PAPR pilots	64 (for PAPR reduction)
Useful data carriers per symbol	7328
QAM Constellations	4096-QAM, 1024, 256, 64, 16
Bit rate for 4096-QAM w/o FEC	1.05 Gbit/s (10.9 bits/s/Hz)
Bit rate for 1024-QAM w/o FEC	0.87 Gbit/s (9.07 bits/s/Hz)

Table 26 – OFDM Channel Parameters for 48 MHz Wide Channel

Parameter	Value
Channel bandwidth	48 MHz
Useful bandwidth	46 MHz (-23 MHz to +23 MHz) -44 dB attenuation at 24 MHz band-edge
FFT size	4096
FFT sample rate	51.2 MHz (multiple of 10.24 MHz)
Useful symbol time	80 us
Carriers within 46 MHz	3680
Guard interval samples	171 (ratio=1/24; 3.33us)
Symbol shaping samples	41 (ratio=1/100; 0.8 us)
Total symbol time	84.13us
Continuous pilots	32 (for synchronisation)
Scattered pilots	32 (for channel estimation)
PAPR pilots	32 (for PAPR reduction)
Useful data carriers per symbol	3584
QAM Constellations	4096-QAM, 1024, 256, 64, 16
Bit rate for 4096-QAM w/o FEC	0.51 Gbit/s (10.65 bits/s/Hz)
Bit rate for 1024-QAM w/o FEC	0.43 Gbit/s (8.88 bits/s/Hz)

Table 27 – OFDM Channel Parameter for 37 MHZ Wide Channel, Upstream NA Band

Parameter	Value
Channel bandwidth	37 MHz
Useful bandwidth	36 MHz (-18 MHz to +18 MHz) -40 dB attenuation at 18.5 MHz (TBC)
FFT size	2048
FFT sample rate	51.2 MHz
Sub-carrier spacing	25 KHz
Useful symbol time	40 us
Carriers within 36 MHz	1440
Guard interval samples	192(ratio=3/32; 3.75 us)
Symbol shaping samples	41 (ratio=1/50; 0.80 us)
Total symbol time	44.55us
Continuous pilots	16 (for synchronisation)
Scattered pilots	none (Channel est. via preamble)
PAPR pilots	16 (for PAPR reduction)
Useful data carriers per symbol	1408
QAM Constellations	1024-QAM, 256, 64, 16, QPSK
Bit rate (for 1024-QAM)	0.32 Gbit/s (8.56 bits/s/Hz)

7.3.3.1 Modulation Summary

DOCSIS 3.0 equipment, completed in 2006, is now seeing increasing field deployment. While deployed CM percentages are still modest, CMTS capabilities are being installed and spectrum plans have been put into place. It has been proven to be rugged and capable, and it is now timely to consider the next phase of DOCSIS evolution. And, as powerful as DOCSIS 3.0 may be, it most certainly can be enhanced by taking advantage of modern tools and the continued advancement in cost-effective, real-time processing power.

Two such approaches have been identified here – adding new symbol rates, similar to the DOCSIS 2.0 extension in 2002 that introduced 5.12 Msps, or introducing multi-carrier modulation, which has been embraced in standards bodies across industries. Table 28 summarizes various attributes of these PHY modulation alternatives relative to today's available DOCSIS 3.0 baseline for the scaling of services to Gbps rates.

7.3.4 In Summary

By first stating the criteria, and then analyzing the available options against the criteria, it is suggested that the OFDM/OFDMA/LDPC wide channel is the best candidate for next generation gigabits capable DOCSIS PHY layer. This scheme is based on well-studied, widely adopted methods, allowing quick standardization turn around.

It enables to maximize the throughput with the available and future bandwidth and SNR resources. It is flexible enough to cope

Table 28 – Relative Impact of Extensions to DOCSIS 3.0 for Gigabit Services

Attribute	Wide SC	Wide OFDM	Comments
Silicon Complexity (cost per bit)	-	+	Based on # of real-time multiplication operations
Transparency to existing D3.0 MAC	Same		OFDM: Minor mods to convergence layer
Field Technician Familiarity	+	-	
Robustness to interference	-	+	SC-QAM improved with SCDMA (upstream only)
Robustness to unknown plant (e.g. > 1 GHz operation)	-	+	
Throughput scalability per plant condition (SNR)	-	+	
Peak-to-Avg Power Ratio (PAPR)	Same		OFDM: better with PAPR reduction algorithms
Spectrum Allocation Flexibility	-	+	
New Requirements Definition	+	-	

Notes: Wide SC-QAM refers to 8x24 MHz. Wide OFDM refers to 16k IFFT 192 MHz.
"+" and "-" compare wide SC and wide OFDM to a 6.4 Mhz channel-bonded DOCSIS 3.0 baseline.

with new, less studied spectrum portions and interferences. It is more cost efficient than other alternatives for same throughputs (cost per bit). All these traits suggest that this PHY can optimally serve the DOCSIS evolution going into the gigabit rates, minimizing the investment needed by doing it “once and for all”.

8 DOCSIS MAC TECHNOLOGIES

8.1 DOCSIS Channel Bonding

DOCSIS Channel bonding may support full spectrum downstream. Additional DOCSIS channel bonding upstream may support higher upstream capabilities with targets to 1 Gbps. Achieving larger bonding group will require software, hardware and perhaps specification changes.

A future release of DOCSIS should enable bonding across legacy DOCSIS 3.0 and the new DOCSIS NG, even if they use dissimilar PHY technologies. The MAC layer and IP bonding will stitch the PHY systems together.

8.2 DOCSIS Scheduler Benefits

The DOCSIS protocol allows multiple users to "talk" or transmit at same moment in time and on the same channel, this was part of DOCSIS 2.0 introduction of SCDMA. The introduction of channel bonding allowed ATDMA based system to transmit at the same moment in time on differ frequencies while part of a channel bonding group.

Unlike DOCSIS, the EPON MAC allows "only one" subscriber to "talk" or transmit at any given moment in time. If we consider a single Home Gateway with multiple services and devices behind it, these will contend with each other and neighbors for time slots for transport of voice service, video conferencing, real-time data services, and even normal data and IPTV TCP acknowledgments.

Now, we must consider all the Home Gateways in a serving area domain competing for time slots allocated only on a "per home" basis, if the MSOs move to this style of architecture.

In many ways the EPON and EPOC MAC is most equivalent to a DOCSIS 1.1 MAC, of the 2000 era, because this supports multiple service flows, however allows only "one" user to talk or transmit at a time. The DOCSIS 2.0 and 3.0 specifications changed this limitation to accommodate for more devices, bandwidth, services, and concurrency of users and latency sensitivity; this is a powerful difference between the MAC standards.

The DOCSIS MAC designers knew that shared access meant contention for both bandwidth resources "and" time, this is why DOCSIS 2.0 and 3.0 support simultaneous transmission upstream enabling Quality of Service (QoS) and Quality of Experience (QoE).

There is another major factor with the DOCIS MAC, the development and feature set is controlled by the Cable Industry and not a third party standards organization, like the IEEE or ITU. This allows the MSO to make design request directly to systems vendors for continue innovation and support for new features that come along over time.

The DOCSIS MAC continues to change as the MSOs think of new service differentiation features and the flexible DOCISS MAC enable this support and creating a best in breed and cost effective MAC for the cable industry.

8.3 Services Enabled by DOCSIS

The DOCSIS technology can support virtually any service. DOCSIS technology

may enable support for the full range of IP and Ethernet based services. The challenges for support for advanced layer 2 and layer 3 VPN services are not found in the DOCSIS access layer technology, but rather the network elements.

The DOCSIS CMTS will need to add support for desired layer 2 and layer 3 VPN services. The DOCSIS protocol with the use of the advanced MAC should support Ethernet Services types and Bandwidth Profiles defined by the Metro Ethernet Forum (MEF).

8.4 Importance of Backward Compatibility with DOCSIS 3.0 and Any Successor

The authors of this analysis 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 bandwidth network while not stranding previous capital investment and spectrum.

The use of channel bonding leverages every MHz, which is finite and not free, this is all towards an 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, and running fiber deeper.

The Data over Cable System Interface Specification (DOCSIS) began development in the late 1990's and has since had four versions released. DOCSIS standards include DOCSIS 1.0, 1.1, 2.0 and 3.0. The standards allowed for backwards compatibility and coexistence with previous versions of the standard.

As the needs of subscribers and providers continued to evolve, the DOCSIS standard was progressively upgraded to accommodate the change in services. The DOCSIS 2.0 standards increased upstream speeds and the DOCSIS 3.0 standard dramatically increased upstream and downstream bandwidth to accommodate higher speed data services.

These transitions capitalized on the availability of new technologies (ex: SCDMA) and the processing power of new silicon families (ex: Channel Bonding).

The authors of this analysis 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 bandwidth network 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 towards an 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.

1. DOCSIS 3.0 QAM based and any successor should consider that every MHz should all share the same channel bonding group, this maximizes the use of existing spectrum and delays investment

2. Sharing channel bonding groups with DOCSIS 3.0 and Any Successor creates "one" IP Network (cap and grow networks hang around awhile)

3. 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

4. Backward Compatibility has benefitted industries like the IEEE Ethernet, WiFi, and EPON saving the entire eco-system money

5. 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.

6. Avoids the MSO having a RF Data Simulcasting Tax (as discussed in this report)

7. 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.

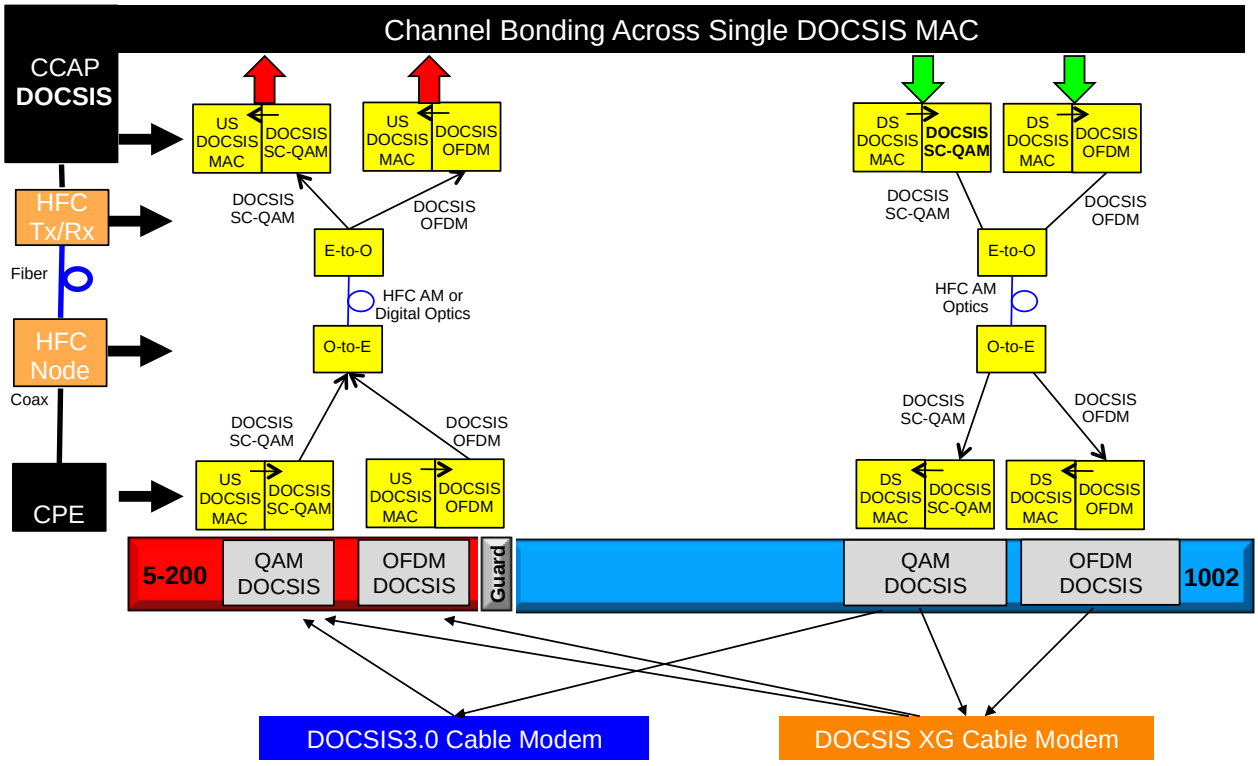


Figure 49 – Channel Bonded DOCSIS 3.0 and DOCSIS NG System

This is an illustration of channel bonding across a DOCSIS 3.0 and potential DOCSIS NG system. Figure 49 shows a DOCSIS 3.0 system coexisting with a DOCSIS NG system, then adding a DOCSIS NG system this platform could support legacy DOCSIS 3.0 SC-QAM, modulation and perhaps add 256-QAM upstream and 1024-QAM downstream, and RS and also supporting the new DOCSIS NG PHY. This will allow backward compatibility for the DOCSIS 3.0 cable modems and CMTS, while supporting the new PHY and likely in new spectrum.

Figure 50 is an illustration of the possible integration of HFC optics in the CCAP that will support DOCSIS 3.0 and DOCSIS NG. DOCSIS 3.0 and DOCSIS NG will likely be supported on the same card in the future without requiring HFC optical integration to the CCAP.

8.5 RF Data Simulcasting Tax

We would recommend strongly examining the history and impact of simulcasting services. If an alternative to DOCSIS is considered this will require new spectrum. The existing DOCSIS service and spectrum allocation may actually continue to grow during the initial introduction of the new data MAC/PHY technology, such as EPOC.

New spectrum that likely mirrors the size of DOCSIS would have to be found, so that at least the same services may be offered using an EPOC technology. The amount of new spectrum allocated by the MSO for DOCSIS and EPOC would begin the RF Data Simulcasting Tax Period.

It is true, that legacy networks tend to hang around for a long time. For example,

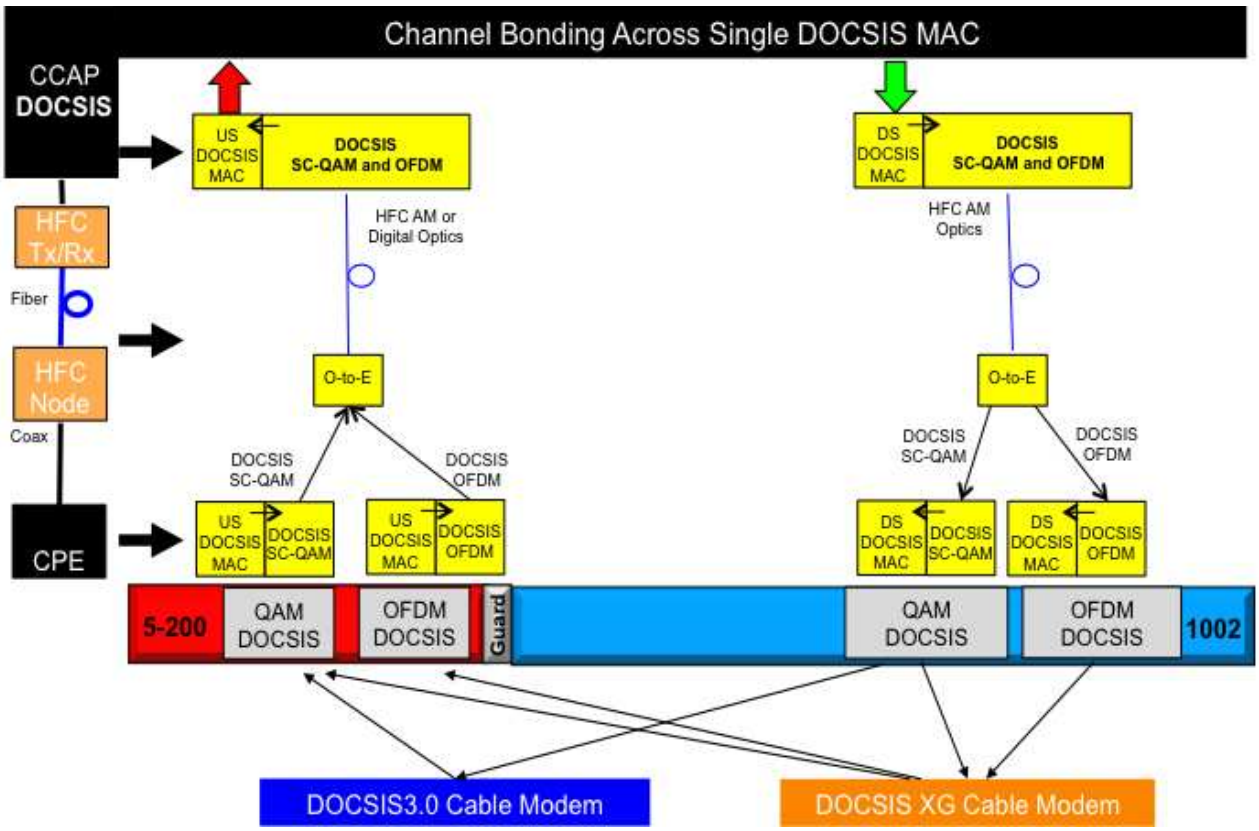


Figure 50 – Channel Bonded DOCSIS 3.0 and 4.0 System with CCAP Integrated HFC Optics

MSOs that deployed constant bit rate voice services, known as CBR voice, may still have these technologies occupying spectrum, even though they also have voice services using DOCSIS in the same network. The challenge is cost; the cost to reclaim spectrum is substantial, it requires new CPE and Headend systems, for no additional revenue.

The additional impact is finding new spectrum to offer what is a duplicate service using a different technology. It is fair to say that the cost for supporting parallel RF data networking technologies will have a capital and operational impact that will likely be more than expanding the current technology over the existing HFC network.

DOCSIS has the ability with each passing year investment to create larger and larger IP bonding groups, to enable higher speed service tiers and support traffic growth. Additionally, the DOCSIS CPEs may be channel bonded with legacy PHY and/or new PHY technologies, while all sharing the same MAC layer-bonding group.

Also, not a single DOCSIS CPE would be required to change to reclaim spectrum, because of backward compatibility or to eliminate the RF data simulcasting tax, as this network tax could be avoided with DOCSIS current and future systems.

This is a compelling feature of continuing to leverage DOCSIS 3.0 and why next generation DOCSIS needs to be

backward compatible at the MAC layer, with different PHYs.

1. The amount of new spectrum allocated by the MSO for DOCSIS and EPOC would begin the RF Data Simulcasting Tax Period.
2. The existing DOCSIS service and spectrum allocation may actually continue to grow during an initial introduction of a new data MAC/PHY technology, such as EPOC.
3. Legacy networks tend to hang around for a long time, CBR Voice.
4. A challenge is the cost to reclaim spectrum is substantial; it requires new CPE and Headend systems, for likely no additional revenue.
5. The additional impact is finding new spectrum to offer what is a duplicate service offering using a different technology, to find capacity node splits, new node placement in the field, and/or spectrum expansion, new powering for the OSP equipment, and more are all impacts.
6. It is fair to say that the cost for supporting a parallel RF data networking technology will have a capital and operational impact.
7. The ability that DOCSIS has is that with each passing year spectrum is allocated creating larger and larger IP bonding groups, to enable higher speed service tiers and support traffic growth.
8. This is a compelling feature of continuing to leverage DOCSIS 3.0 and why next generation DOCSIS needs to be backward compatible.

9 NETWORK CAPACITY ANALYSIS

9.1 Intro

The network capacity of the cable access network is determined by the amount of spectrum available and the data rate possible within the spectrum. The modern cable network is incredibly flexible allowing the MSO to make targeted investments where and when needed to either incrementally or in some cases substantially increase network capacity depending on the capacity expansion method selected.

The use of capacity expansion methods may be applied across an entire network footprint or with laser beam focus to address capacity challenges. Figure 51 is an attempt to capture the various methods available to increase or improve capacity of the network. The diagram brings together methods and techniques used by various disciplines within the MSO, such as outside/inside plant, IP/Data, SDV, and Video Processing. The techniques will allow the MSO to transform their network from broadcast to unicast and from analog/digital to IP.

Today, in fact MSOs may use techniques to increase capacity without touching the outside plant; this is dramatically different than the approaches that were used for decades. The technique referred to as Bandwidth Reclamation and Efficiencies, as illustrated in the top of Figure 51 is becoming the primary method to address system wide capacity challenges. In most cases this technique may be implemented with equipment in the headend and home, thus not requiring conditioning of the outside plant or headend optics.

A technique recently put into practice by some cable operators is partial or even full analog reclamation. This enables the operator to transition the channels currently transmitted in analog and to transmit them only in digital format allowing greater bandwidth efficiencies by requiring the use of a digital terminal adapter (DTA) alongside televisions that may have only had analog services.

Another technique for Bandwidth Reclamation and Efficiencies is the use of Switch Digital Video (SDV). The use of SDV allows the cable operator to transmit in the network only the video streams that are being viewed by consumers. This allows the operator to increase the number of channels offered to consumers, in fact the actual channels offered to the consumers may exceed the throughput capabilities of the network but through careful traffic engineering and capacity planning this approach is an excellent way of adding additional capacity to the network.

This technique is a form of over-subscription and has been in practice for decades by the telecommunication industry. The items captured in Bandwidth Reclamation and Efficiencies are the modern methods to expand capacity. In many respects the Bandwidth Expansion “upgrade” approach as illustrated in Figure 51 whereby the entire network was upgraded to increase capacity, may be seldom used in the future. If used, this may be part of a joint plan to increase the spectrum allocation of the return path.

In the future, the use of IP for video delivery will provide even greater bandwidth efficiencies. IP used for digital video transmission and will also provide functionality similar to the techniques used in SDV. Another key advantage is that IP allows for the use of variable bitrate (VBR)

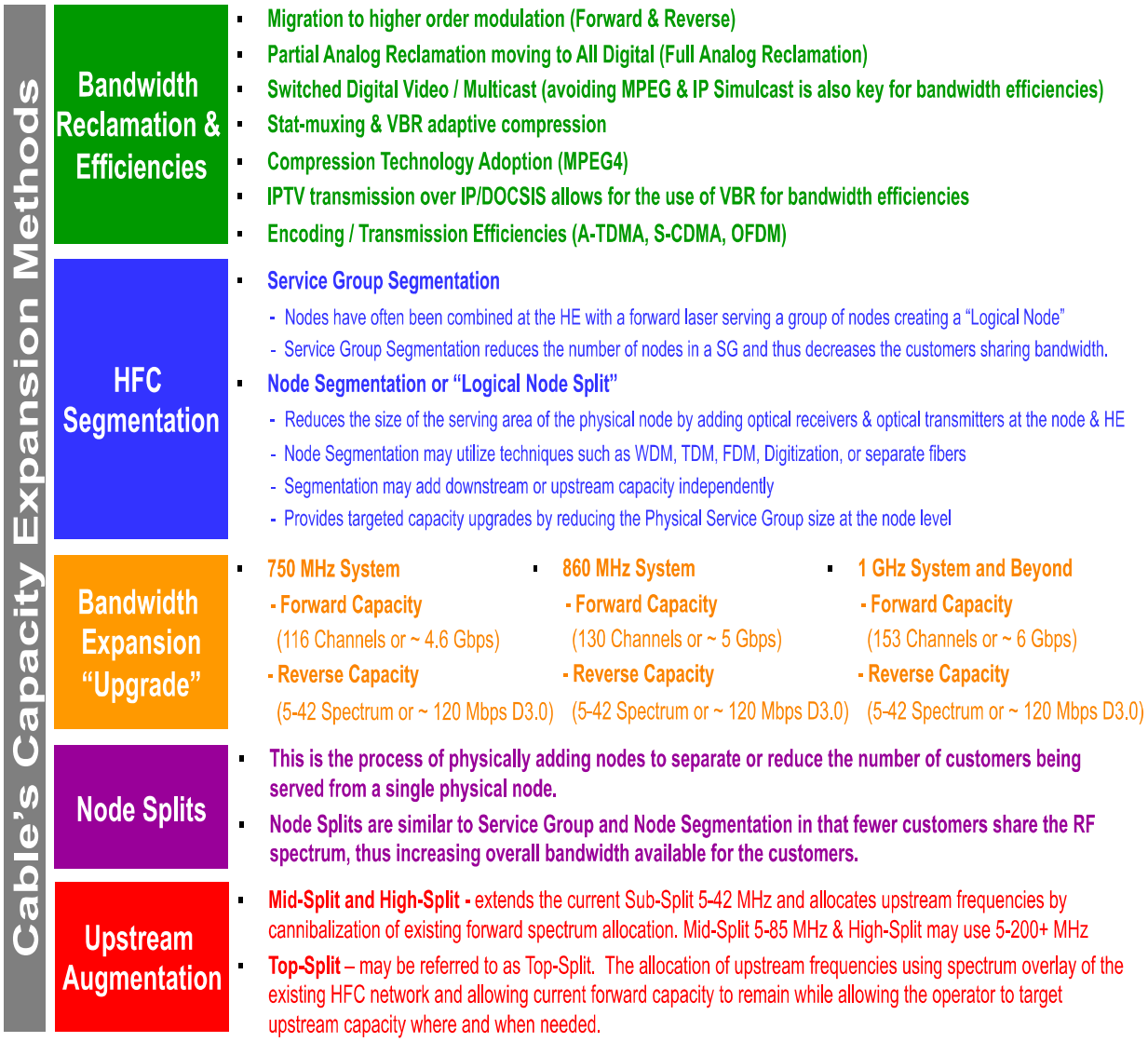


Figure 51 – Cable's Capacity Expansion Methods

encoding increasing the capacity of the network and the utilization of higher order compression techniques.

Cable operator's selection priority of the capacity expansion methods has and will continue to vary. The cable operators will eventually use all or nearly all of the capacity expansion methods in Figure 51

9.2 Importance of Error Correction Technologies

The paper by David J.C. MacKay and Edward A. Ratzer, titled "Gallager Codes for High Rate Applications", published January 7, 2003 [27], examines the improvements obtained by switching from Reed-Solomon codes to Gallager codes or Low Density

Parity-Check (LDPC) code. It is the opinion of this author, that the MacKay paper is one of the best comparisons of illustrating the benefits of switching to LDPC from Reed-Solomon. The paper initially released in 2003, suggests some modifications to Gallager codes to improve performance. The paper suggest about a 5 dB gain. The paper lists further ideas worth investigating that may improve performance.

The use of LDPC has expanded recently with the adoption by the IEEE WiMAX 802.16e, ITU-T G.hn. and the cable industry use for downstream transmission in DVB-C2. The use of LDPC may be used in any carrier modulation method, such as SC-QAM, OFDM, or Wavelet, and the expectation is the use of higher order modulation is achievable compared with Reed-Solomon based systems. It is reasonable to suggest a 6 dB gain is possible by switching from Reed-Solomon to LDPC and this will allow an increase in modulation by perhaps two orders, in other words perhaps one could move from 64-QAM to perhaps 256-QAM. In Table 29, the R-S using approximately 86-87% coding and LDPC using the inner code of 5/6 or 83% yields a 6 dB difference and will allow an increase of two orders of the modulation.

The key takeaway is the use of LDPC will improve network capacity or actual bit per second per Hertz over Reed-Solomon based systems, and this is achieved by enabling the use of higher order modulation with the same signal-to-noise ratio (SNR) condition. This allows operators to allocate less spectrum compared to Reed-Solomon based systems or have more network capacity in occupied spectrum.

The benefits of the cable industry's use can be seen in DVB-C2 systems. However, the use of LDPC for upstream cable data use is still under study as seen in this report. There are also other error correction technologies to consider that have been adopted by other standards groups.

This section will state the major differences and reasons why the use of modern error correction technology is key to increasing network capacity. The new error correction technology and the assumed two-order increase in modulation while operating in the same Signal to Noise Ratio (SNR) environment is the major reason there is an improvement in capacity.

Refer to Table 29 to Table 31 for the DOCSIS Single Carrier-QAM with Reed-Solomon system verse the performance estimates of a DOCSIS Multi-carrier OFDM with LDPC system and also refer to Table 32 to Table 34 for the analysis of these competing PHY layer technologies.

This section compares DOCSIS Single Carrier QAM and the current error correction technology with the proposed DOCSIS NG use of OFDM and the modern LDPC error correction technology.

9.3 DOCSIS 3.0 Single Carrier-QAM with Reed-Solomon

The DOCSIS SC-QAM 256-QAM downstream, as shown in Table 29 and the following two tables models the upstream using DOCSIS SC-QAM 64-QAM and DOCSIS 256-QAM. Each scenario assumes ATDMA.

These tables measure the PHY layer spectral efficiency of DOCSIS QAM based solutions. The channel coding for controlling errors in data transmission for the DOCSIS examples use Reed-Solomon forward error correction (RS-FEC) and Trellis Modulation or also known as Trellis Coded Modulation (TCM).

These are used to calculate the network capacity of the cable network considering several spectrum options found in the Network Capacity section.

A key take away is performance gap between 256-QAM PHY and 64-QAM layer efficiencies. The assumptions for 64-QAM at 4.1 bps/Hz would require 33% more spectrum and DOCSIS channels to maintain the equivalent PHY layer throughput. The use of DOCSIS 256-QAM for the upstream is not part of the DOCSIS standards. However some CMTS and CM products support this modulation profile in hardware.

Table 29 – Downstream DOCSIS 3.0 256-QAM with Reed-Solomon & TCM

DOWNSTREAM DOCSIS 3.0				
Single-Carrier QAM with Reed-Solomon				
Function	Attribute	Parameter	Value	Measurement / Comment
Spectrum				
	Available BW		48	MHz
	DS channel BW (MHz)		6	MHz
Spectrum Usage				
	BW efficiency (symbol rate/BW)		0.893	for Annex B. It is 0.869 for Annex A
Modulation				
	Modulation format	256 QAM	8	bits per symbol
Error Correction Technology				
	TCM		0.95	
	RS FEC		0.953125	
	FEC framing inefficiency		0.999493	
PHY Overhead				
	MPEG framing	184/188	0.978723	Net data throughput < MPEG bitrate
Total PHY Only Bandwidth Efficiency			6.328	Bps/Hz

The DOCSIS specifications could be modified to include 256-QAM upstream as well as 1024-QAM in the upstream and downstream. However, the real major gains would be achieved by changing the error correction technology.

Table 30 – Upstream DOCSIS 3.0 64-QAM with Reed Solomon

UPSTREAM DOCSIS 3.0				
Single-Carrier QAM with Reed-Solomon				
Function	Attribute	Parameter	Value	Measurement / Comment
Modulation				
	Bandwidth	6.4 MHz		
	QAM level	64 QAM	6	bits per symbol
Error Correction	Technology			
	RS code rate	(k,t) =(100,8)	0.862	Or (200,16)
Spectrum Usage				
	Excess BW (Root Raised Cosine)	alpha=0.25	0.8	efficiency = 1/(1+alpha)
PHY Overhead				
	Grant size/Burst length (concat on)	2048 symbols	2048	e.g. 400 us grant @ 5.12 MS/s
	Guard band	8 symbols	8	
	Preamble	32 symbols	32	
	Usable burst size (symbols)		2008	
	Total burst overhead (PHY)		0.9805	
Total PHY Only Bandwidth Efficiency			4.057	Bps/Hz
MAC and Signaling Overhead				
	Avg US packet size	170 bytes	170	
	MAC header size	6 bytes	6	Most headers are simple
	No. of MAC headers in burst (avg)	burst bytes/(170+6)	8.5	Non-integer, assuming frag is on
	Subtotal: MAC header overhead		0.9659	
	Ranging and contention slots	5%	0.9500	Arbitrary 5%, depends on mapper
	Other MAC overheads	1%	0.9900	Piggyback requests, frag headers, etc.
	Total MAC & signalling		0.9084	
Total MAC and PHY Bandwidth Efficiency			3.686	Bps/Hz

Table 31 – Upstream DOCSIS 3.0 256-QAM with Reed Solomon

UPSTREAM DOCSIS 3.0				
Single-Carrier QAM with Reed-Solomon				
Function	Attribute	Parameter	Value	Measurement / Comment
Modulation				
	Bandwidth	6.4 MHz		
	QAM level	256 QAM	8	bits per symbol
Error Correction	Technology			
	RS code rate	(k,t) =(100,8)	0.862	Or (200,16)
Spectrum Usage				
	Excess BW (Root Raised Cosine)	alpha=0.25	0.8	efficiency = 1/(1+alpha)
PHY Overhead				
	Grant size/Burst length (concat on)	2048 symbols	2048	e.g. 400 us grant @ 5.12 MS/s
	Guard band	8 symbols	8	
	Preamble	32 symbols	32	
	Usable burst size (symbols)		2008	
	Total burst overhead (PHY)		0.9805	
Total PHY Only Bandwidth Efficiency			5.409	Bps/Hz
MAC and Signaling Overhead				
	Avg US packet size	170 bytes	170	
	MAC header size	6 bytes	6	Most headers are simple
	No. of MAC headers in burst (avg)	burst bytes/(170+6)	11.4	Non-integer, assuming frag is on
	Subtotal: MAC header overhead		0.9659	
	Ranging and contention slots	5%	0.9500	Arbitrary 5%, depends on mapper
	Other MAC overheads	1%	0.9900	Piggyback requests, frag headers, etc.
	Total MAC & signalling		0.9084	
Total MAC and PHY Bandwidth Efficiency			4.914	Bps/Hz

9.4 DOCSIS NG Multi-carrier OFDM with Low Density Parity-Check (LDPC) code

The analysis in this section provides measurements using OFDM/OFDMA. Again OFDM is not part of the DOCSIS 3.0 standard. The channel coding for controlling errors in data transmission is assumed to use Low Density Parity-Check (LDPC) code also referred to as Gallager codes.

The analysis also uses values as described in Section 7.3.3 OFDM Channel Parameter Examples discuss in this paper. The target for these DOCSIS NG OFDM and LDPC estimates is to use an error correction amount referred to as 5/6 inner code rates or .833. The strong error correction used for the LDPC is modeled to achieve the Carrier to Noise target of 6 dB below Reed Solomon code rate of 86%. This will mean for the same modulation format R-S will yield greater b/s/Hz than LDPC using a stronger FEC in this effort to achieve a 6 dB decrease in C/N.

performance improvement of DOCSIS SC-QAM 256-QAM with Reed-Solomon. This is attributed primary to the FEC and not to the change in multi-carrier OFDM. The modern FEC will support greater Modulation QAM Format in the same SNR.

In the previous figures, 256-QAM was analyzed using estimates for PHY and MAC layer efficiency comparing DOCSIS single carrier 256-QAM and DOCSIS OFDM 256-QAM. The use of LDPC may allow higher upstream modulation schemes to be used compared with Reed-Solomon based approaches.

This could mean that 64-QAM Reed-Solomon system may actually be compared with an OFDM 256-QAM LDPC based system in the same Signal to Noise Ratio environment. Moreover, a 256-QAM Reed-Solomon system may actually be compared with a OFDM 1024-QAM LDPC based system in the same SNR environment.

The goal to target the OFDM and LDPC

Table 32 – Downstream DOCSIS OFDM 1024-QAM with LDPC

DOWNSTREAM DOCSIS NG				
OFDM with LDPC				
Function	Attribute	Parameter	Value	Measurement / Comment
Spectrum				
	Channel Bandwidth		192	
Modulation				
	Modulation format	1024 QAM	10	
Error Correction Technology				
	BCH		0.9978	
	LDPC FEC		0.8	
	FEC framing inefficiency		0.9988	
PHY Overhead				
	Pilots and PAPR reduction Pilots	2.5%	0.9747	
	Occupied Spectrum in Channlel Band	99.0%	0.9896	
	Guard Interval and Symbol Shaping	4.9%	0.951	
	Total PHY Overhead		0.917	
Total PHY Only Bandwidth Efficiency			7.313 bps/Hz	

The downstream DOCSIS OFDM 1024-QAM with LDPC system has about a 20%

system to operated in the same SNR environment and with two orders increase in

QAM level, required us to apply more error correction codes to LDPC.

Again, because we are assuming that LDPC will be capable of operating in the same SNR environment while using 2 orders higher modulation than a Reed Solomon system. This accounts for the added FEC overhead and lower performance when using the same QAM level.

The actual performance of either system in real-world HFC 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 until systems are tested in a cable system.

Table 33 – Upstream DOCSIS OFDM 256-QAM with LDPC

UPSTREAM DOCSIS NG				
OFDMA with LDPC				
Function	Attribute	Parameter	Value	Measurement / Comment
Modulation				
	Channel Band	37 MHz	37	
	QAM level	256 QAM	8	bits per symbol
	Subcarrier size	25 kHz	0.25	
	total number of subcarriers used		1440	
Error Correction Technology				
	LDPC code rate	5/6 inner code	0.833	
	BCH	99% outer code	0.99	
	Total FEC		0.825	
PHY Overhead				
	Pilots and PAPR reduction pilots	2.2%	0.97778	
	Occupied Spectrum in Channlel Band	97.3%	0.9730	
	Guard Interval and Symbol Shaping	10.2%	0.898	
	Total burst overhead (PHY)		0.854	
Total PHY Only Bandwidth Efficiency			5.638	Bps/Hz
MAC and Signaling Overhead				
	MAC header overhead		0.9659	
	Ranging and contention slots	5%	0.9500	Arbitrary 5%, depends on mapper
	Other MAC overheads	1%	0.9900	Depends on MAC
	Total MAC & signalling		0.9084	
Total MAC and PHY Bandwidth Efficiency			5.121	Bps/Hz

Table 34 – Upstream DOCSIS OFDM 1024-QAM with LDPC

UPSTREAM DOCSIS NG				
OFDMA with LDPC				
Function	Attribute	Parameter	Value	Measurement / Comment
Modulation				
	Channel Band	37 MHz	37	
	QAM level	1024 QAM	10	bits per symbol
	Subcarrier size	25 kHz	0.25	
	total number of subcarriers used		1440	
Error Correction Technology				
	LDPC code rate	5/6 inner code	0.833	
	BCH	99% outer code	0.99	
	Total FEC		0.825	
PHY Overhead				
	Pilots and PAPR reduction pilots	2.2%	0.97778	
	Occupied Spectrum in Channlel Band	97.3%	0.9730	
	Guard Interval and Symbol Shaping	10.2%	0.898	
	Total burst overhead (PHY)		0.854	
Total PHY Only Bandwidth Efficiency			7.047	Bps/Hz
MAC and Signaling Overhead				
	MAC header overhead		0.9659	
	Ranging and contention slots	5%	0.9500	Arbitrary 5%, depends on mapper
	Other MAC overheads	1%	0.9900	Depends on MAC
	Total MAC & signalling		0.9084	
Total MAC and PHY Bandwidth Efficiency			6.402	Bps/Hz

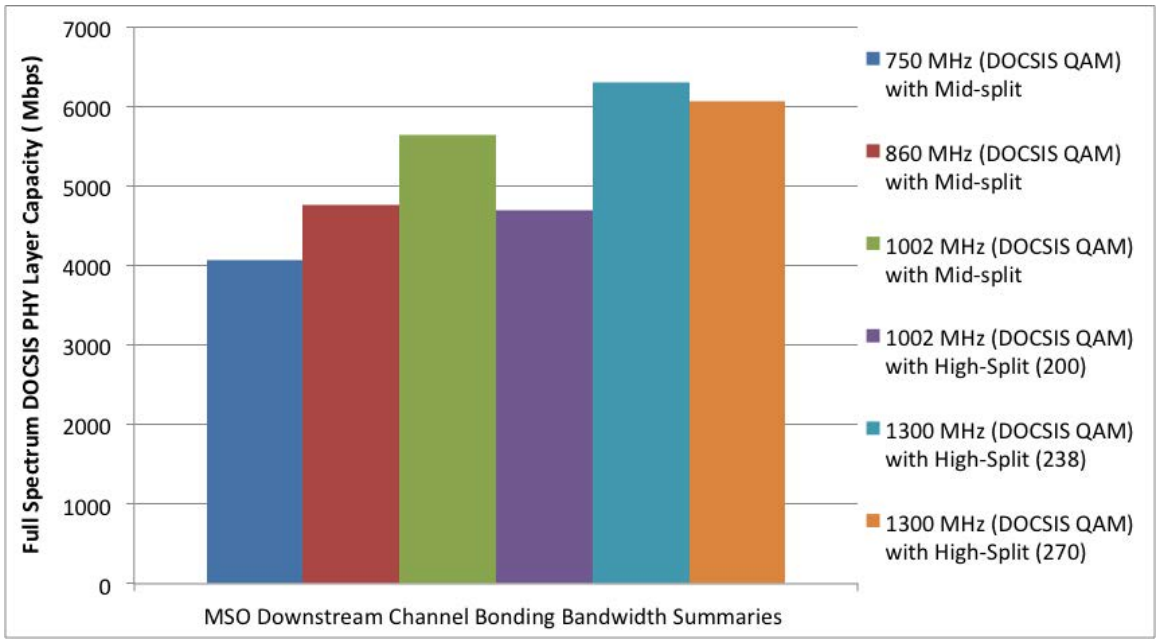


Figure 52 – 256 SC-QAM RS Codes PHY

9.5 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.

Table 35 provides capacity projections considering the upstream spectrum split and the use of DOCSIS Single Carrier QAM using 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 such as 1300 MHz as well as other spectrum options for the upstream. This table will calculate the estimated downstream PHY layer capacity using several spectrum options with limits of 256-QAM though higher modulations are possible.

Figure 52 shows different downstream spectrum allocations as well as the removal of upstream spectrum from the downstream. The downstream network capacity is illustrated using DOCSIS 256 SC-QAM Reed-Solomon Codes PHY or DOCSIS 1024-QAM OFDM LDPC capacity assuming full spectrum.

9.6 Upstream Capacity

The upstream capacity measurements are more complicated and not as straightforward as the downstream capacity projections. In the Figure 53, many of the spectrum split options were evaluated considering several PHY layer options and modulation schemes within each spectrum split.

These are some key assumptions about the upstream capacity estimates:

Table 35 – 256 SC-QAM RS PHY or 1024-QAM OFDM LDPC Full Spectrum Capacity

Split Type	MSO Downstream Channel Bonding Bandwidth Summaries	Total Downstream Spectrum Available	DOCSIS QAM Usable Data Rate Per MHz 256 QAM)	DOCSIS OFDM Usable Data Rate Per MHz (Assuming 1024 QAM OFDM w/ LDPC)	Total Capacity Data Rate Usable (Mbps)
Downstream Capacity with Sub-split (5-42 MHz)	750 MHz (DOCSIS QAM) with Sub-split	696	6.328	7.313	4404
	750 MHz DOCSIS OFDM OFDM w/ LDPC with Sub-split	696	6.328	7.313	5090
	860 MHz (DOCSIS QAM) with Sub-split	806	6.328	7.313	5100
	860 MHz DOCSIS OFDM OFDM w/ LDPC with Sub-split	806	6.328	7.313	5894
	1002 MHz (DOCSIS QAM) with Sub-split	948	6.328	7.313	5999
	1002 MHz DOCSIS OFDM OFDM w/ LDPC with Sub-split	948	6.328	7.313	6933
Downstream Capacity with Mid-split	1002 MHz (DOCSIS QAM) with Mid-split	897	6.328	7.313	5676
	1002 MHz DOCSIS OFDM OFDM w/ LDPC with Mid-split	897	6.328	7.313	6560
Downstream Capacity with High-Split (238)	1050 MHz (DOCSIS QAM) with High-Split (238)	750	6.328	7.313	4746
	1050 MHz DOCSIS OFDM OFDM w/ LDPC with High-Split (238)	750	6.328	7.313	5485
	1300 MHz (DOCSIS QAM) with High-Split (238)	1000	6.328	7.313	6328
	1300 MHz DOCSIS OFDM OFDM w/ LDPC with High-Split (238)	1000	6.328	7.313	7313
Downstream Capacity with Top-split (900-1125)	750 MHz (DOCSIS QAM) with Top-split (900-1050)	696	6.328	7.313	4404
	750 MHz DOCSIS OFDM OFDM w/ LDPC with Top-split (900-1050)	696	6.328	7.313	5090
Downstream Capacity with Top-split (1250-1750)	1002 MHz (DOCSIS QAM) with Top-split (1250-1750)	948	6.328	7.313	5999
	1002 MHz DOCSIS OFDM OFDM w/ LDPC with Top-split (1250-1750)	948	6.328	7.313	6933

- Sub-split and/or Mid-split channel bonding spectrum was counted in capacity summaries with any new spectrum split (Figure 54 does illustrate Top-split spectrum options and the capacity. Note that Sub-split and Mid-split are add to these options)
- Included in the analysis are PHY layer efficiency estimates as well as MAC layer efficiency estimates. This will be labeled in each model

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-bonding group. This will allow for previous, current, and future investments made by the cable operator to be applied to a larger and larger bandwidth pipe or overall upstream capacity.

If backwards compatibility were not assumed, the spectrum options would have to allocate spectrum for

Sub-split Upstream Assumptions:	
37	Sub-split Upstream (5-42 MHz)
-2	Assumed 2 MHz at the roll off (40-42 MHz) is not usable
-5	Assumed 5 MHz to 10 MHz not usable
-2	Set aside Legacy STBs
-2	Set aside Legacy Status Monitoring
-3.2	Assume 3.2 MHz Channel for DOCSIS Legacy using QAM16
22.8	**Possible Spectrum for Upstream Channel Bonding**
22.4	MHz assumed for upstream DOCSIS Single Carrier QAM

Figure 53 – Sub-split Assumptions

DOCSIS QAM and separate capacity for any successor technology, resulting in a lower capacity throughput for the same spectrum allocation. This would compress the duration of time that the same spectrum may be viable to meet the needs of the MSO.

9.6.1 Achieving 1 Gbps Symmetrical Services and Beyond with DOCSIS 3.0

A major interest of the cable operators is the understanding of the architecture requirements for each spectrum split option to achieve 1 Gbps MAC layer performance. The migration strategy to reach 1 Gbps may be of interest as well, so that an operator can make incremental investment if desired to meet the capacity needs over time, this is sort of a pay as you grow approach.

We have modeled the MAC layer capacity estimates for each node service group size starting at 500 HHP and splitting the service group size in half until reaching 16 HHP, equivalent of fiber to the last active (FTTLA). The model assumes .625 PIII distribution cable with the largest span of 1000 feet in the architecture calculations as shown in Figure 54.

The upstream capacity measurements found in Figure 54 compares various spectrum splits using DOCSIS single carrier QAM with Reed Solomon with a maximum of 256-QAM. The spectrum splits found in the table include Sub-split, Mid-split, High-split (238), High-split (500), Top-split (900-11125) with Sub-split, Top-split (1250-1700) with Sub-split, Top-split (2000-3000)

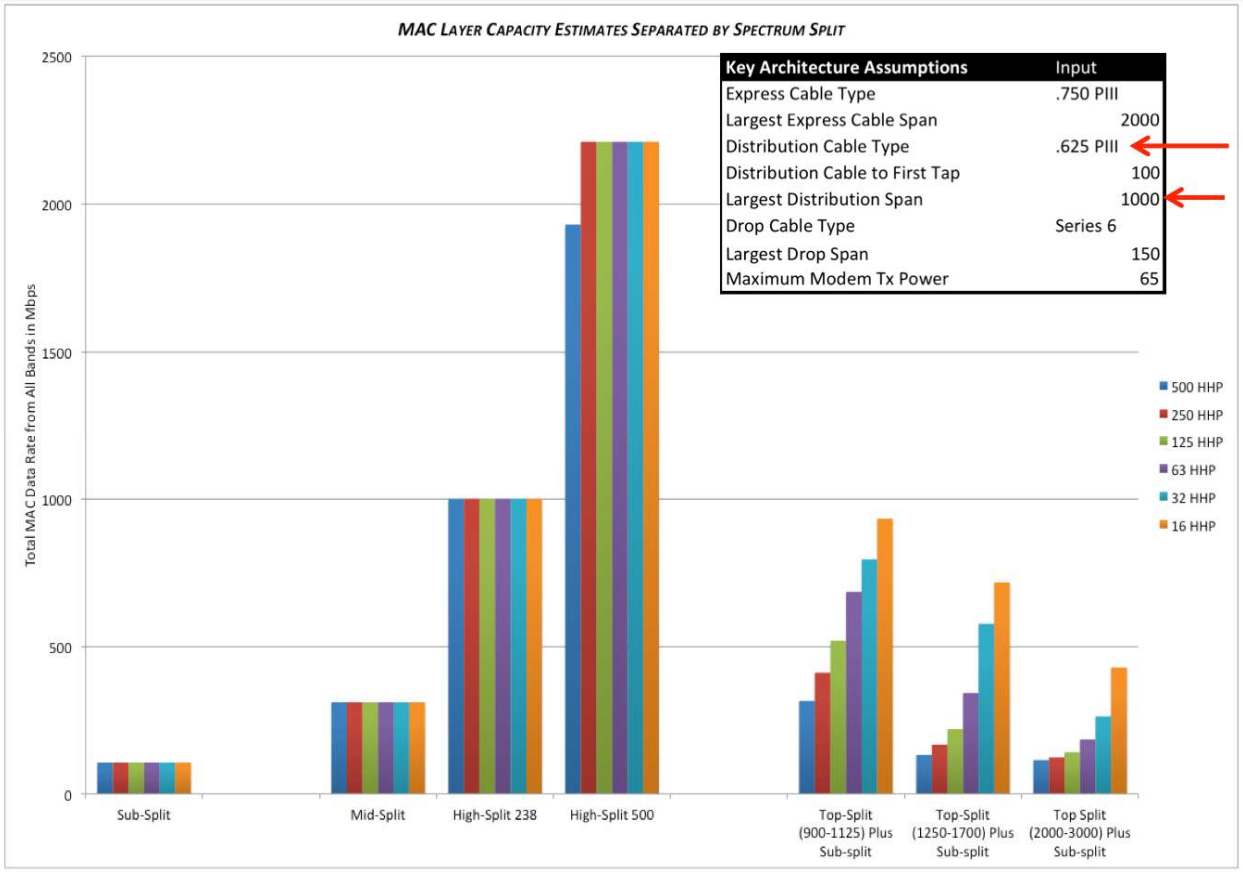


Figure 54 – Upstream D3.0 MAC Layer Capacity Estimates over Dist. Cable .625 PIII at 1000'

with Sub-split.

The various spectrum splits, along with the overhead contributed from the current DOCSIS PHY, the MAC, the use of SC-QAM and the highest possible modulation type, are examined in Figure 54 to determine the Total MAC Channel Bond Capacity Usable. Traffic engineering and capacity planning should consider the headroom needed for peak periods.

Similar to the examination of the downstream capacity projections above, the upstream use of a new error correction technology such as LDPC will allow high order modulations to be used, thus increasing capacity compared to Reed-Solomon based systems. Higher order modulations will also mean less spectrum required for a desired data rate.

The actual gain for the upstream across an HFC network will need to be determined in the real-world deployments. All upstream capacity is limited to 256-QAM, all though higher order modulation may be possible under certain conditions. Figure 54 through Figure 56 are meant to show the vast difference in capacity and network architecture with upstream spectrum just for having different distribution cable and span of this section of the network. It is this layer of the cable network that is vastly different among MSOs and even within MSOs.

Figure 55 represents cable rebuilds or new builds after the year 2005. Figure 56 represents the Mid 1990s – 2004 Rebuild. Again maximum 256-QAM limitations are assumed as well other assumptions defined in the paper.

A ***major*** finding is that Top-split

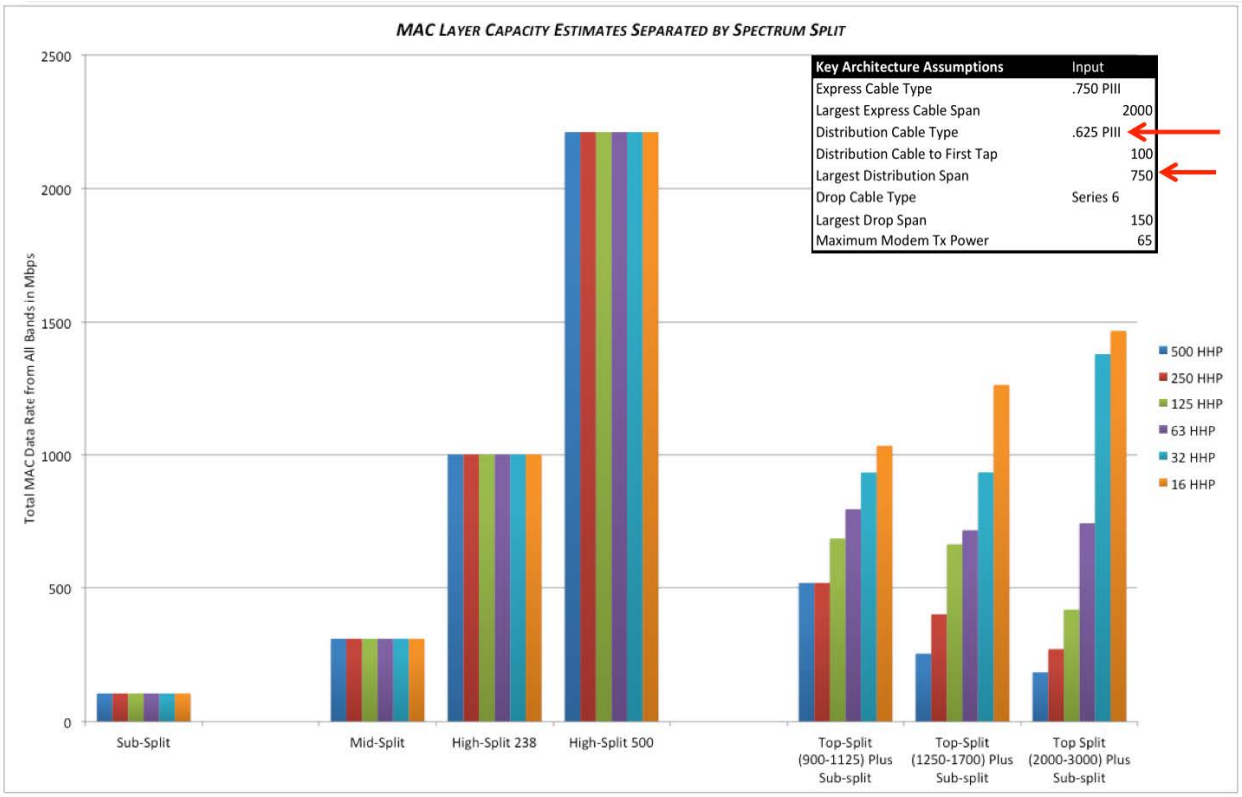


Figure 55 – Upstream D3.0 MAC Layer Capacity Estimates over Dist. Cable .625 PIII at 750′

options require Fiber to the Last Active (~16 HHP) and the placement of a node at each location to maximize the spectrum capacity. However, all Top-split options even if combined with the existing Sub-split will not reach the capacity any of the High-split option. If these two Top-split options are not combined with Sub and Mid-split achieving 1 Gbps MAC Layer performance is not possible, given the assumptions described in this analysis, .625 PIII at 1000 foot spans to last tap and other assumptions.

Another ***major*** finding is that even, given the assumption of the widely deployed cable architecture using .500 PIII distribution cable with 750 foot spans to the last tap, none of the Top-split with Sub-split reaches 1 Gbps with current DOCSIS PHY as shown in Figure 56. Only Top-split with .625 PIII at 750 foot spans to last tap will meet or exceed the 1 Gbps capacity.

Another 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 in different cable types and distance to the subscriber was a critical finding.

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.

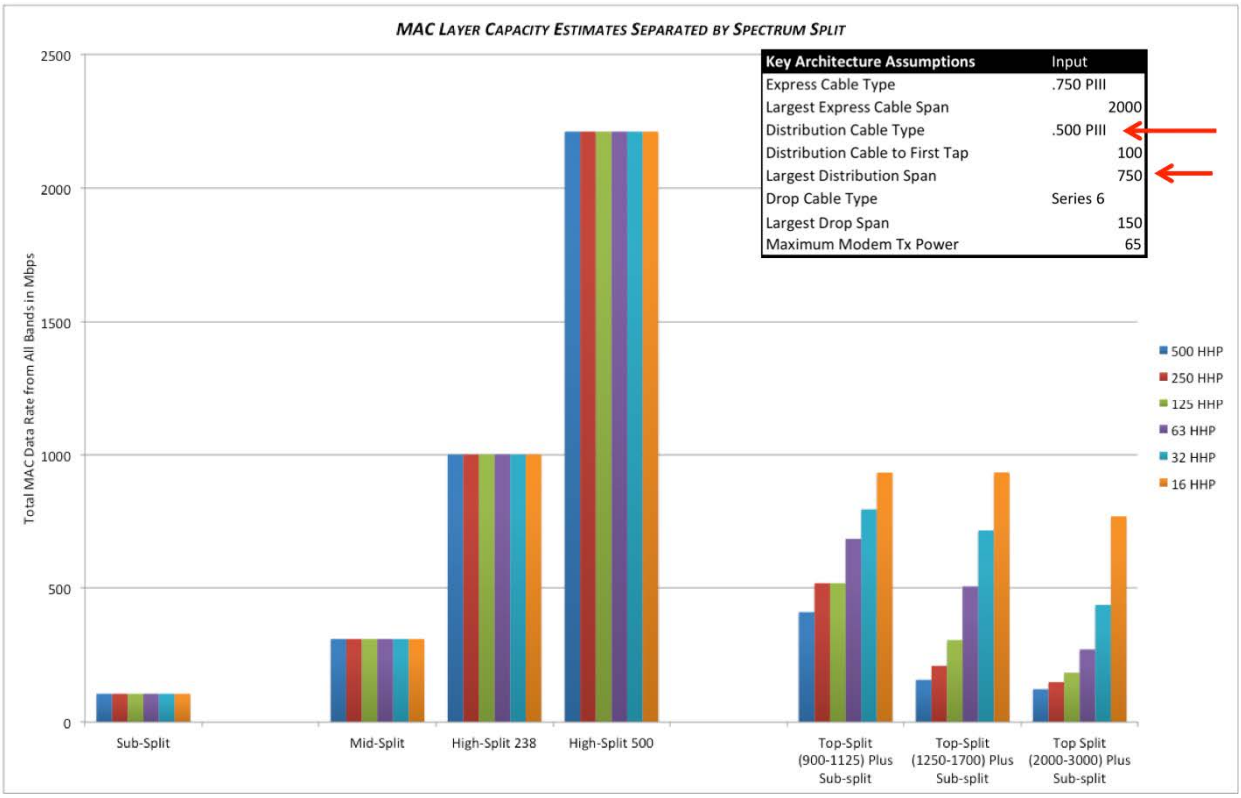


Figure 56 – Upstream D3.0 MAC Layer Capacity Estimates over Dist Cable .500 PIII at 750′

9.6.2 DOCSIS NG Network Capacity Estimates Upstream

We have modeled the network architecture using several HFC coaxial network topologies using DOCSIS 3.0, however in this section DOCSIS NG will be compared. This section will provide a summary of the key methods and measurements to estimate sizing for DOCSIS NG.

The adoption of higher modulation formats in DOCSIS NG will increase b/s/Hz. A key finding is the use of DOCSIS 3.0 Single Carrier Reed Solomon verse OFDM using LDPC may allow two (2) orders of modulation increase. In Figure 57, DOCSIS 3.0 verse DOCSIS NG Modulation C/N and Capacity Estimates this summarize the major benefits of moving to DOCSIS NG.

Figure 57 illustrates that the use of Reed Solomon and LDPC with different code rates will have different b/s/Hz using the same modulation format. The major takeaway from the table is the use of a stronger error correction code will allow LDPC to operate in the same carrier to noise environment as Reed Solomon but LDPC may use two orders of modulation higher.

The table uses red arrows to illustrate the corresponding Reed Solomon modulation and C/N to the OFDMA LDPC modulation format, which shares the same C/N dB. The table will show that in the same modulation format Reed Solomon will have more b/s/Hz than LDPC and this is due to a higher code rate percentage applied to LDPC. The percentage of gain is measured using the SC Reed Solomon data rate for a given modulation and the used of two order of modulation increase using LDPC.

For example, in the table SC Reed Solomon b/s/Hz of QPSK is measured against OFDMA LDPC using 16-QAM, the percentage of gain in b/s/Hz 89%. As

Modulation and Error Correction Comparison						MSO C/N Target	Desired Data Rate and Spectrum Requirements (Mbps and MHz)				
Modulation	SC Reed-Solomon MAC Layer Capacity Per MHz	Reed Solomon C/N Target (dB)	OFDMA MAC Layer Capacity Per MHz	LDPC C/N Target (dB)	Percentage of b/s/Hz Improvement of LDPC over RS	DOCSIS NG LDPC Operator Desired C/N Target (dB)	100	500	1000	2000	2500
QPSK	1.229	10	1.280	4	N/A	14	78	391	781	1562	1953
8-QAM	2.029	13	1.921	7	N/A	17	52	260	521	1041	1302
16-QAM	2.457	16	2.561	10	108%	20	39	195	391	781	976
32-QAM	3.071	19	3.201	13	58%	23	31	156	312	625	781
64-QAM	3.686	22	3.841	16	56%	26	26	130	260	521	651
128-QAM	4.300	25	4.481	19	46%	29	22	112	223	446	558
256-QAM	4.914	28	5.121	22	39%	32	20	98	195	391	488
512-QAM	5.528	31	5.762	25	34%	35	17	87	174	347	434
1024-QAM	6.143	34	6.402	28	30%	38	16	78	156	312	391
2048-QAM	6.757	37	7.042	31	27%	41	14	71	142	284	355
4096-QAM	7.371	40	7.682	34	25%	44	13	65	130	260	325
All Mbps/MHz with the PHY Layer and MAC Layer Overhead Removed						MSO Adjustable	MHz Required for Channel Bonding assuming all Spectrum Operates at OFDMA MAC Layer				

- Single Carrier Reed-Solomon MAC Layer Capacity with 86 % Coded
- OFDMA calculations use LDPC with 5/6 coded to achieve a 6 dB Target to Operate 2 Orders of Modulation Increase over RS
- DOCSIS NG LDPC Operator Desired C/N Target is set at 10 dB above LDPC and aimed to suggest a value that if met a desired modulation may be used
- All values are estimates and may vary based on vendor implementation and operator networks, some conditions may require different C/N targets
- All Values assume BER of 10^-8
- Percentage of b/s/Hz Improvement of LDPC over RS column is a sssuming a 2 Order Modulation Increase, note these share the same dB target

Figure 57 – DOCSIS 3.0 versus DOCSIS NG Modulation C/N and Capacity Estimates

expected the percentage of gain will decrease as modulation increases, for example moving from 256-QAM to 1024-QAM is a smaller gain, than moving than the doubling of QPSK to 16-QAM.

The table estimates the use of OFDMA and the MAC layer bit rate in a given modulation as explained in the paper. The table calculated several desired MAC layer throughput capacities from 100 Mbps, 500 Mbps, 1,000 Mbps, 2,000 Mbps, and 2,500 Mbps and using the OFDMA estimated MAC layer data rate a required spectrum calculation and corresponding modulation format are aligned.

The MSO may require less upstream spectrum if a high modulation format may be used. The table illustrates a proposed Operator Desired C/N target for each Modulation format using LDPC, please note that the higher the modulation form the higher the C/N requirements but the lower percentage of gain in b/s/Hz.

Table 36 – DOCSIS NG Modulation and C/N Performance Targets

Modulation Type	Uncoded Theoretical C/N dB	LDPC 5/6 Coded C/N dB	Operator Margin is Desired C/N Target
QPSK	16	4	14
8-QAM	19	7	17
16-QAM	22	10	20
32-QAM	25	13	23
64-QAM	28	16	26
128-QAM	31	19	29
256-QAM	34	22	32
512-QAM	37	25	35
1024-QAM	40	28	38
2048-QAM	43	31	41
4096-QAM	46	34	44

Theoretical SNRs Uncoded with BER of 10^-8
Practical C/N is chosen to give 10 dB headroom
Operator Margin above LDPC 5/6 coded

In the past, our industry may have used The “Operating Margin” (OM) or Operator Desired carrier to noise target to be 6 dB above the theoretical uncoded C/N for a given BER, usually between 10E-6 or 10E-8, without any Forward Error Correction (FEC). The 6 dB of margin typically assumed a 500 HHP case; that is, for “Node +5” (or so), involving up to 30 return path RF amplifiers.

In the future perhaps we need to change the method by which we estimates the “Operating Margin” (OM) and perhaps we need to estimate the operating margin from the coded rate used for a given system and then add the Operating Margin, for the analysis below we used 10 dB above the LDPC dB value.

About the “Operating Margin” (OM) parameter, this is a variable (in dB) to account for the performance changes in the HFC return path system due to temperature variation and setup accuracy of the outside plant. This mainly involves RF level changes due to hardline and drop cable loss changes, Tap loss change, and RF Amplifier/Node Return RF drive path (Hybrid) gain changes, and Node passive loss changes with temperature. It also includes setup level tolerances (due to RF Testpoint accuracy and flatness over frequency) and laser optical power output changes over temperature.

Some of these changes are small or only occur in one place, while others are more significant as they occur at many places and in cascade (e.g., cable segments, RF Amplifiers, and Taps). With many

amplifiers in a 500 HHP distribution sector (up to 30 for Node +5 sector), the number of cascaded Amplifiers is typically a maximum of 6. There typically will be 6 or more Taps used between each amplifier, so these elements contribute significantly.

About 2/3 of the 6 dB OM assumed in the calculation matrix is due to the cable part of the plant. The other 2 dB is due to the "optics" part; mainly for the Return laser. The laser is assumed a high quality uncooled CWDM analog laser, with 2 mW or higher optical output. The OM is added to the "Theoretical C/N" at 10E-6 BER (without encoding) to obtain a "Desired C/N" for determining the highest order modulation type allowed.

In the model that will estimate the use of DOCSIS NG and LDPC, we will use a 10 dB Operating Margin, on top of the coded value, please see Table 36 for the allocation.

In order to estimate the capacity of the different spectrum splits using DOCSIS NG we placed the values of the Operator Margin desired C/N target and the b/s/Hz estimates for DOCSIS NG. The model estimates the system C/N and in this case the model used .500 PIII distribution cable at 750 feet.

Please note the that model estimates that very high modulation format may be used in a 500 HHP node for the low frequency return while the Top-split spectrum selection is only capable of using substantially lower order modulation formats.

As seen in Table 37, 2048 QAM and 1024 QAM are possible in the upstream in a 500 HHP node with assumption defined in this table. This is an illustration of the modern DOCSIS PHY and the ability to maximize spectrum for the operator.

DOCSIS NG capacity is examined in Figure 58 considering several spectrum-split options. Please note the capacity of Sub-split, Mid-split, and the pair of High-split options. The MSOs may choose any of this spectrum split or others depending on the desired capacity. The estimates assume that the entire spectrum uses the highest modulation rate possible for a given spectrum selection.

9.6.3 DOCSIS 3.0 versus DOCSIS NG Side-by-Side Upstream Capacity Estimate

Table 37 – Upstream DOCSIS NG MAC Layer Capacity Estimates over Distribution Cable .500 PIII at 750 Feet

DOCSIS NG System Performance Estimates		Sub-Split	Mid-Split	High-Split 238	High-Split 500	Top-Split (900-1125) Plus Sub-split	Top-Split (1250-1700) Plus Sub-split	Top Split (2000-3000) Plus Sub-split
Upper Frequency	MHz	42	85	238	500	1125	1700	3000
Homes Passed		500	500	500	500	500	500	500
HSD Take Rate		50%	50%	50%	50%	50%	50%	50%
HSD Customers		250	250	250	250	250	250	250
Desired Carrier BW	MHz	6.4	6.4	6.4	6.4	6.4	6.4	6.4
Modulation Type		**2048-QAM**	**2048-QAM**	**1024-QAM**	**1024-QAM**	**8-QAM**	**QPSK**	**QPSK**
Bits/Symbol		11	11	10	10	3	2	2
Number Carriers in Bonding Group		3.5	10.25	33	73	35	22	9
Max Power per Carrier Allowed in Home	dBmV	59.6	54.9	49.8	46.4	49.6	51.6	55.5
Worst Case Path Loss	dB	**29.1**	**30.1**	**33.5**	**41.4**	**65.1**	**73.0**	**76.9**
Maximum Return Amplifier Input	dBmV	30	25	16	5	-16	-21	-21
Actual Return Amplifier Input	dBmV	15	15	15	5	-16	-21	-21
Assumed Noise Figure of Amplifier	dB	7	7	7	7	7	7	7
Return Amplifier C/N (Single Station)	dB	65	65	65	55	35	29	29
Number of Amplifiers in Service Group		30	30	30	30	30	30	30
Return Amplifier C/N (Funneled)	dB	50.4	50.4	50.4	40.4	19.9	14.0	14.0
Optical Return Path Technology		DFB	DFB	DFB	Digital	Digital	Digital	Digital
Assumed Optical C/N	dB	45	45	41	48	48	48	48
System C/N	dB	**43.9**	**43.9**	**40.5**	**39.7**	**19.9**	**14.0**	**14.0**
Desired C/N	dB	41	41	38	38	17	14	14

The paper has examines the downstream and upstream features of DOCSIS NG. The analysis has examined modulation profiles such as using LDPC with increased FEC to obtain a 6 dB gain over Reed Solomon in the same modulation format. Figure 59 examines the low frequency return spectrum options using DOCSIS 3.0 using 64 QAM against DOCSIS NG using the maximum modulation format possible given the assumptions and spectrum selection. Please note the much higher aggregate capacity of the DOCSIS NG system over current DOCSIS.

9.6.4 Summaries for Network Capacity

DOCSIS NG will greatly expand the capacity of the cable network and coupled with backward compatibility utilize spectrum efficiently

Downstream Capacity Expansion

1. DTA's & SDV will provide long term downstream plant capacity expansion
2. Reduced service group size enabling fewer customers to share bandwidth
3. Node segmentation and node splits will continue to be used in a targeted basis
4. Use of highest order modulation and channel bonding to increase throughput
5. Consider DOCSIS NG changes with modern error correction technology that allow the modulation rate to increased, given the same SNR, perhaps as much as two orders. For example, 256-QAM could be increased to 1024-QAM
6. Possible downstream bandwidth expansion along with upstream augmentation

Upstream Capacity Expansion

1. Use of highest order modulation and Channel Bonding to increase throughput

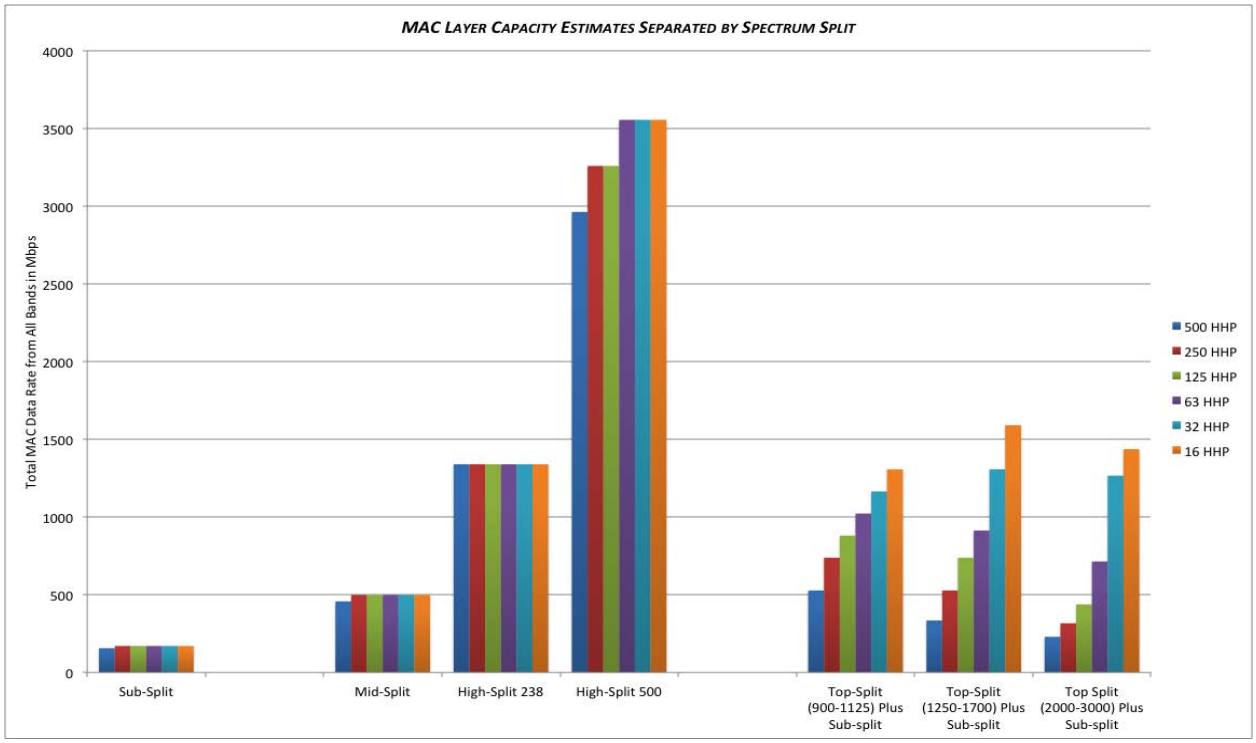


Figure 58 – Upstream DOCSIS NG MAC Layer Capacity Estimates over Dist Cable .500 PIII at 750'

2. Consider DOCSIS NG changes with modern error correction technology that allow the modulation rate to be increased, given the same SNR, perhaps as much as two orders. For example, 64-QAM to 256-QAM and perhaps 256-QAM to 1024-QAM
3. Progressively smaller upstream service groups
4. Ongoing node splits / segmentation
5. These incremental steps should last for a majority of the decade

Upstream augmentation expands upstream spectrum and bandwidth such as conversion to mid-split, high-split, or top-split options.

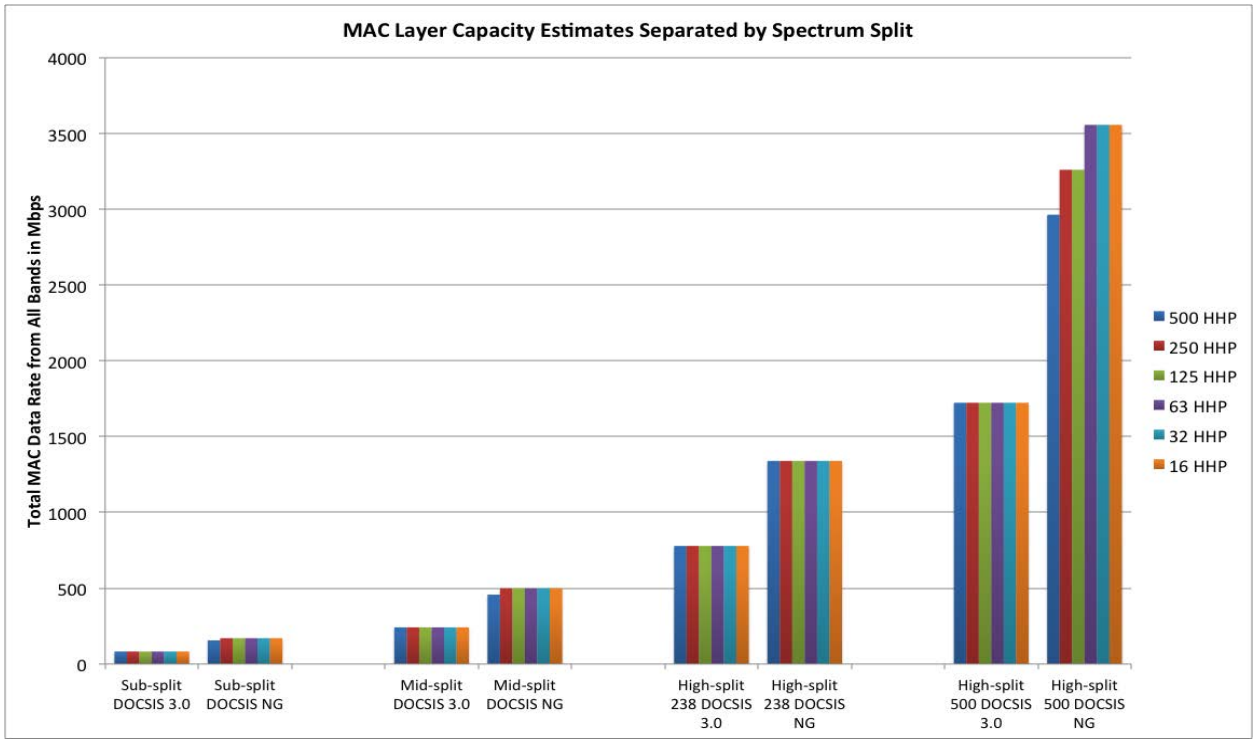


Figure 59 – DOCSIS 3.0 verse DOCSIS NG

10 NETWORK CAPACITY PROJECTION AND MIGRATION STRATEGIES

10.1 Upstream Migration Strategy

10.1.1 Phase 0: Sub-Split and Business as Usual

10.1.1.1 Sub-split Legacy Return Lifespan

Let's put our understanding of upstream data capacities to work in evaluating time-based migration strategies for the HFC upstream. Note that not every capacity number calculated in the paper to this point is represented on a chart in this section. We expect that the reader may have to extrapolate between displayed values in some case to draw conclusions from curves shown for some cases not explicitly plotted.

We introduced a version of an upstream lifespan analysis in Figure 2 of Section 2.6. A more traditional version is shown in Figure 60. Traffic models based on a compound annual growth (CAGR) methodology have been shown to represent historical traffic trends well. However, because of short-term fluctuations, particularly in the upstream, there is a need to engineer ahead of the curve to avoid being unprepared in the case of an unexpected step function in growth (a "Napster" moment).

We will use CAGR analysis such as this and Figure 2 as a guideline to understand the most fundamental of drivers for upstream evolution – the need to find more capacity,

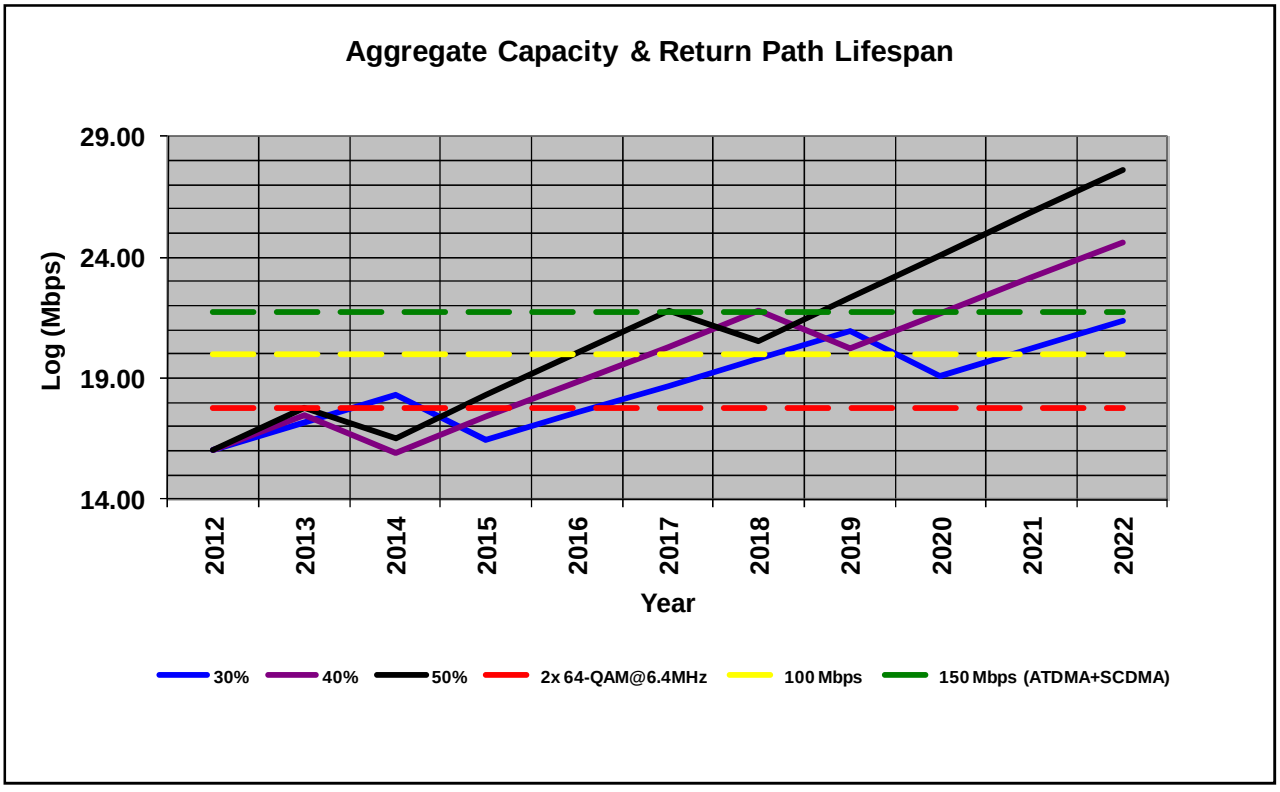


Figure 60 – Upstream CAGR vs. Available Capacity

coupled with a need to deliver competitive service rates, so that the upstream achieves a long and healthy lifespan.

Figure 60 shows this a CAGR approach for the upstream using three different assumptions – 30%, 40% and 50%. The three trajectories, representing a single aggregate service group, are interrupted by two breakpoints over the next ten years.

These represent node and/or service group splits – 3 dB (best case) offsets, or a doubling of average bandwidth per home. Note that the 3 dB is a step straight downward by 3 dB at implementation, so that by the time the next year comes around, some of that has been consumed.

These trajectories are plotted against three different HFC upstream capacity thresholds, using raw physical layer transport rate for simplicity and to remove the ambiguity around overhead of different configurations, packet sizes, and net throughputs. We will use raw transport rate for trajectories and thresholds throughout to simplify apples-to-apples comparisons.

- 60 Mbps – Approximately two 64-QAM DOCSIS channels at 5.2 Msps
- 100 Mbps – Approximate available bit rate in 5-42 MHz with only A-TDMA
- 150 Mbps – Approximately a fully utilized 5-42 MHz using both A-TDMA and S-CDMA

Using these, we can now estimate when various CAGRs exhaust the available upstream. Let's assume 40 Mbps of upstream consumption at peak busy hour – 50% of 80 Mbps of deployed capacity, for example (2x 64-QAM + 16-QAM, all at 6.4 MHz).

Some key conclusions can be drawn from Figure 60. Clearly, a couple of 64-QAM DOCSIS channels get exhausted within a few years without a service group split. While node splits are costly and intrusive, they are well-understood business-as-usual (BAU) activities.

Most important to craft an evolution strategy is to estimate when 5-42 MHz itself gets exhausted, and when a more significant change must be considered. Referring again to Figure 60, note that a single split supports 4-6 years of growth considering 100 Mbps as the 5-42 MHz throughput boundary.

While further node splitting will provide more average bandwidth, the maximum service rate limit also come into play, where 100 Mbps upstream service rates require more total capacity to be achieved. Aside from merely keeping pace with upstream service rate growth, the service rate upstream should be somewhat aligned with 1 Gbps downstream rates from a timing perspective.

Finally, note that with S-CDMA the upstream could last through the decade for a very robust CAGR (40%).

Figure 60 is a useful guide for visualizing growth versus time. In Figure 61, as in Figure 2, we have displayed the same information differently, allowing us to understand the sensitivity of the exhaustion of the 5-42 MHz return path relative to the CAGR assumptions. Note that service group splits are instead represented by dashed traces for the 100 Mbps and 150 Mbps cases.

The three crosshairs on Figure 61 are positioned to help interpret between Figure 60 and Figure 61. For example, note the point at which a 50% CAGR exhausts a 150 Mbps maximum throughput threshold after one split in Figure 60. This occurs 5 years

into the future. We can see this same point represented by the leftmost crosshair in Figure 61. Similarly, we can correlate between the crosshairs at 40% and 30% CAGR on Figure 61 and the corresponding breach of threshold in Figure 60.

We will use the format of Figure 61 in subsequent discussion because of the granularity and clarity it brings in an environment where CAGR tends to have more variation. This variation of CAGR points out why, for network planning decisions, upstream CAGR needs to be considered in the context of an average, long-term CAGR, rather than based on very high or very low periods of growth.

This is particularly true upstream, where there is not a set of knobs and levers at the operator's disposal to manage a spectrum congestion issue as there is in the downstream. In the downstream, while CAGR is consistent and generally higher, but there is more control over service delivery choices to manage spectrum. In the upstream, there is a hard bandwidth cap at 42 MHz in North America, for example, little control over the growth of Internet usage, and limited ability or authority to more actively manage traffic by type. As such, there are not any "easy" answers to creating more upstream capacity in the 42 MHz spectrum.

One area where there is some room to grow is in the low end of the return. A key problem for A-TDMA is its ability to operate efficiently or at all in this region. Some 30-40% of the 5 to 42 MHz return band is polluted by a combination of impulse noise emanating from homes and often times various narrowband interferes managing to get onto the cable in the short wave band.

However, it is the impulse noise that

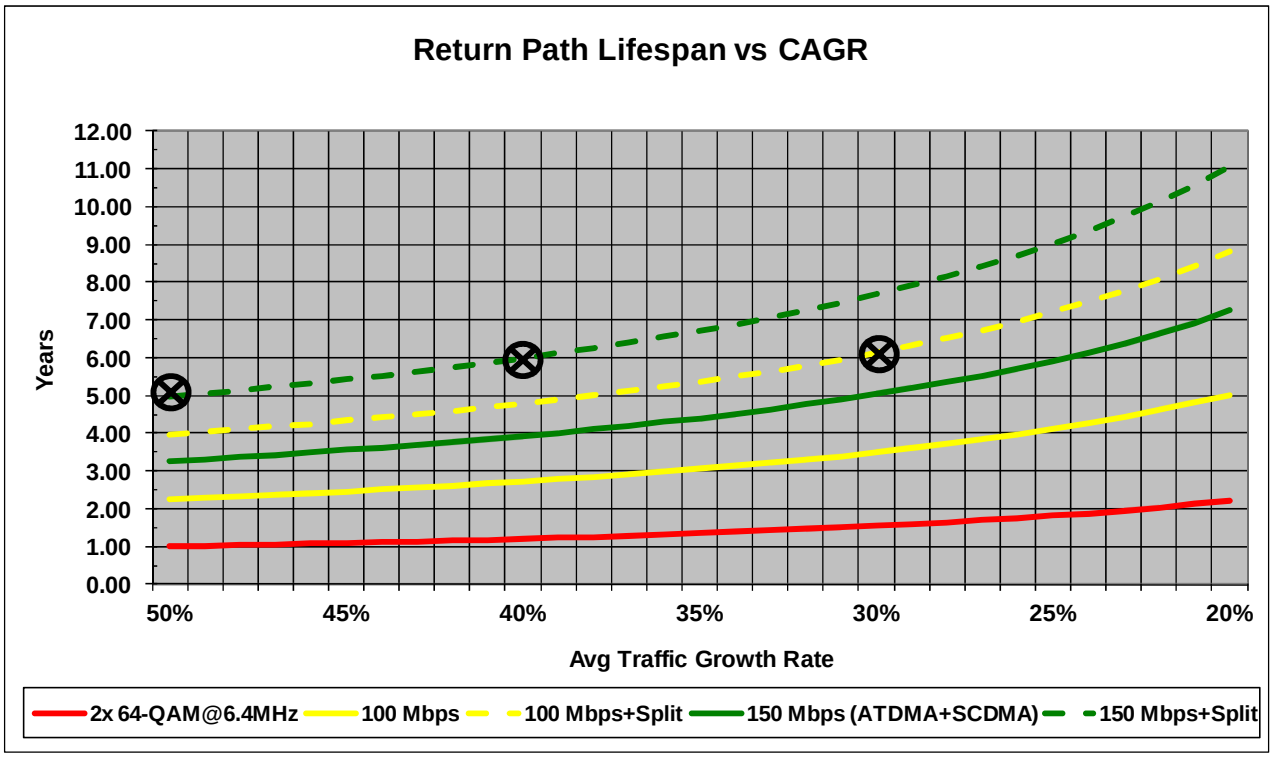


Figure 61 – Lifespan of 5-42 MHz vs CAGR

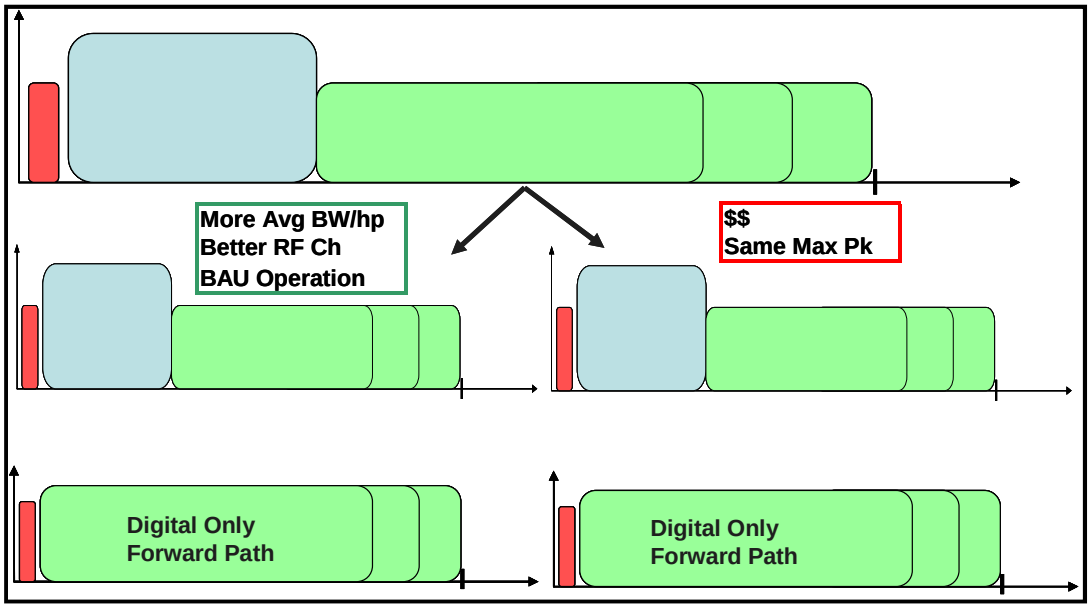


Figure 62 – Serving Group Segmentation

gives A-TDMA the most difficulty, even with powerful Reed-Solomon burst correction employed. To combat this, DOCSIS 2.0 introduced S-CDMA to the standard. By enabling use of the lower portion of the upstream spectrum, the total 5-42 MHz band improves in its total capacity by almost 50%, to about 150 Mbps. We will discussed S-CDMA in Section 7.2, and will use some of the results observed to add to the available capacity in 5-42 MHz to calculate the lifespan of a fully optimized 5-42 MHz.

10.1.1.2 Legacy Relief: Business-As-Usual Node Splitting

The classically deployed tool for improving average bandwidth per user is service group or node splitting. However, this does not enable service rate increases, and splitting nodes in the field runs into diminishing return because of the unbalanced nature of physical architectures.

We observed in Figure 60 and Figure 61 how this lead to a longer lifespan for 5-42 MHz by simply sharing the fixed bandwidth among fewer users. The average bandwidth per user, often a good reflection of user QoE, will increase.

The most natural HFC methods to decreasing the service group size are the removal of combiners at the output of the return optical receivers that combine upstreams into a single port, or the splitting of nodes, either through a segmentable node or pulling fiber deeper.

Figure 62 illustrates this approach from a spectral allocation perspective, identifying also the pros and cons commonly associated with this well-understood tool.

The increased BW/user is an obvious benefit. Another key benefit of this straightforward approach is that, while heavy touch, it is a well-understood "business as usual" operation. In addition, reducing the serving group size can improve the RF channel in two ways.

First, fewer users means a lesser probability of interference and impulse from a troublesome subscriber. While the troublemaker has not gone away, he is now only inflicting his pain on half the number of users. Second, from a system engineering standpoint, the same funneling reduction that increases the probability of not having a troublemaker also reduces any amplifier noise aggregation effect, noticeable when deep RF cascades combine in multiport nodes, for example. All of this can lead to more efficient use of the existing spectrum than had existed prior to the split.

Table 38 – Bandwidth, DOCSIS, and Theory @25 dB SNR

Maximum Capacity for Each Bandwidth

Return Bandwidth	DOCSIS	Maximum Capacity
5-42 MHz	150 Mbps	300 Mbps
5-65 MHz	270 Mbps	500 Mbps
5-85 MHz	360 Mbps	650 Mbps
5-200 MHz	900 Mbps	1.6 Gbps

The primary performance disadvantage of only a segmentation strategy is that 5 to 42 MHz ultimately limits the maximum total bandwidth to around 100 Mbps. Under good conditions, a single 100 Mbps serving group may be all that can be obtained in an A-TDMA only system.

This limits the flexibility of this architecture to provide other services, such as mid-size business service tiers, and to support Nielsen's Law-based peak rate growth. And, peak rate offerings generally are topped out at some scale factor of the total available capacity for practical reasons.

Note that in Figure 62 we have added the "digital only" forward example. As we consume forward band for return applications, techniques that make more efficient use of the forward path also draw more focus. Digital only carriage (DTA deployments) is one of the key tools for extracting more from the downstream as upstream imposes on it, and for adding flexibility to the diplex split used in the architecture.

10.1.1.3 Delivering New DOCSIS Capacity

Because of the known limitations of return spectrum, the expectation that traffic growth in the upstream will continue to compound, and the anticipation that peak service rates will do the same, options to find new capacity are required.

There is consensus that new spectrum must eventually be mined for upstream use. The questions that remain are where do we find it and how much do we need. And, of course, at the core of the discussion, how much new capacity, for how long, and what are the practical implications of implementing such a change.

We will focus on the recommended evolution approach whereby cable maintains a diplex-only architecture for optimum bandwidth efficiency. We view a migration that has as a primary objective the most efficient long-term use of the cable spectrum to ensure the longest lifespan of the architecture, and preferably with the simplicity of implementation that cable enjoys today.

A diplex architecture achieves this. We view the selection of the actual frequency split as something that evolves with time, in

an efficient way, and based on the traffic mix and projected services.

We note that it is possible that extracting the most bandwidth efficiency with flexibility theoretically involves a TDD implementation. However, the obstacles in place to enable TDD in the HFC environment are so great and will be so for so long, that it does not appear to be a sensible plan for typical HFC architectures.

However, with the very long observation window enabled by fiber deep migration and the recommendations made herein, it may at some point become a more practical consideration for cable if the need for increased flexibility of traffic allocation justifies the increase in complexity.

Table 38 illustrates the available DOCSIS transport rate for various low diplex-based frequency split architectures, and the theoretically available channel capacity at the DOCSIS-specified minimum of 25 dB.

While it is impractical to achieve theoretical capacity, the gap has indeed closed over time between practice and theory. This not a negative reflection on DOCSIS 1.0, only a reflection that its PHY basis is 15 years old – a very long time in technology evolution, and a period of extensive advances in communications theory and practice. For DOCSIS NG, we have already introduced the fact that a new FEC added to the PHY mix will enable a major step closer to capacity by enabling higher order profiles over the same SNR.

One simple conclusion of Table 38 is simply the power of the Shannon-defined proportional relationship between capacity and bandwidth for a fixed SNR. Indeed, for high SNR assumptions, capacity is directly proportional to both bandwidth available and SNR expressed in dB – the assumption being very relevant to the cable architecture. This leads to the inescapable conclusion that when discussing new actual upstream capacity, it is first about architecture and bandwidth, and not waveform.

As previously introduced, a straightforward and surprisingly powerful way to exploit new bandwidth and remain compatible with DOCSIS is use of the 85 MHz Mid-Split.

This band edge was wisely chosen to maximize clean low band return without overlapping the FM radio band and potential harmful effects of proximity to that band. Its advantages are numerous. First, however, let's understand what new spectrum means in terms of that fundamental upstream problem – lifespan – that has us so concerned in the first place.

10.1.2 Phase 1: Deploy 85 MHz Mid-Split

10.1.2.1 Capacity and Lifespan

It was shown in Figure 2 how the 85 MHz Mid-Split delivers long-term new capacity to the HFC upstream. Consider **Error! Reference source not found.**, which adds the Mid-Split case to cases observed in Figure 61 for 42 MHz. The gap between the set of 5-42 MHz options and the maximized Mid-Split is readily apparent at 3.5-5.5 years at 30% CAGR, depending on whether S-CDMA is utilized or not.

The transition to Mid-Split pushes the lifespan of the return path to nearly a decade under a 256-QAM maximum assumption – a very comfortable chunk of next generation network planning time. This lifespan time frame is pushed beyond a decade for CAGRs of 35% and below if the Mid-Split is combined with one service group split, as shown in **Error! Reference source not found.**.

Though not apparent in an upstream analysis, it is straightforward to show that a ten-year lifecycle of growth aligns the upstream with what is also achievable in the downstream under similar assumptions about plant segmentation. Aligning these two in terms of physical plant segmentation has operational benefits.

Because of this result observed in **Error! Reference source not found.**, when combined with a service group split, Mid-Split (440 Mbps), in fact, represents a *long-term* solution, not merely an incremental one.

This is a very important, fundamental conclusion to recognize about the 85 MHz Mid-Split architecture, that is often not fully understood. The amount of lifespan afforded by 85 MHz with just a single split is nearly a decade – a technology eternity. If today's observed, low, CAGRs persist, it is even

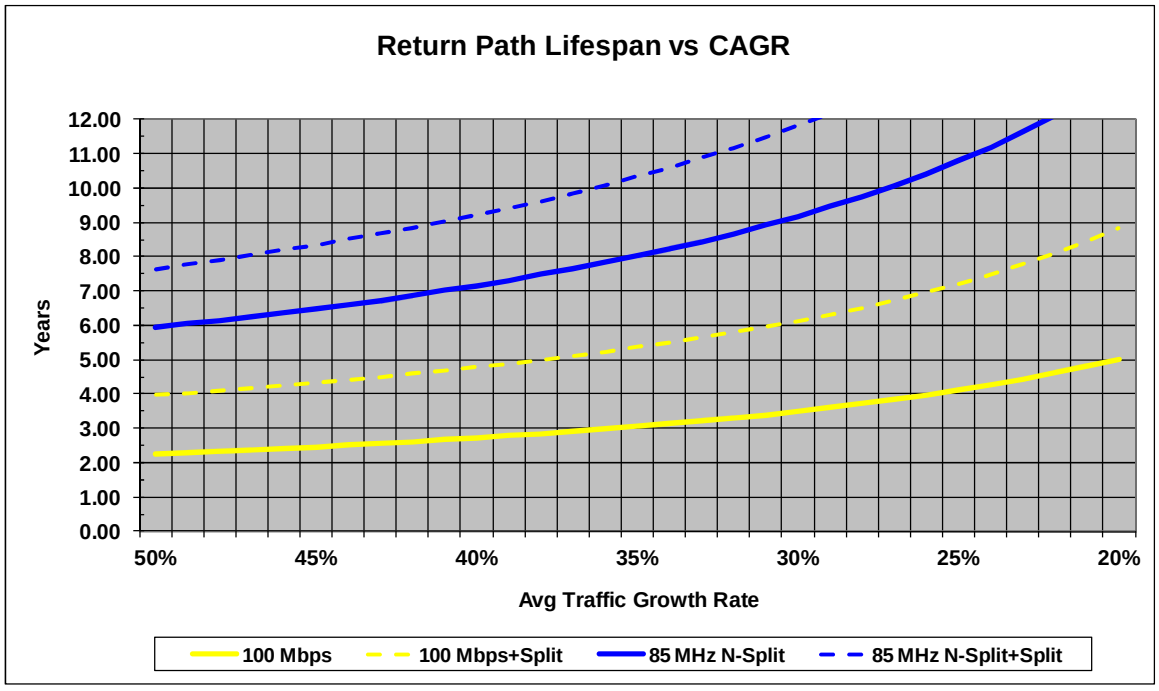


Figure 63 – 85 MHz Mid-Split vs. 42 MHz A-TDMA-Only with Segmentation

longer, and longer still if we assume that modulation profiles extend beyond the 256-QAM examples used for the Mid-Split analysis here. For example, 25% is a three year doubling period, so it offers 50% more lifespan than 40%. Similarly, 1024-QAM, which may become available with LDPC FEC, offers 25% more data capacity, pushing 400 Mbps of 85 MHz throughput to 500 Mbps available for growth.

The window of time to observe trends in traffic, applications, services, and technology, coupled with the runway for managing down legacy in an all-IP transition, is a very meaningful strategy component considering the low risk associated with implementation.

Even under an acceleration of CAGR, the architecture supports 100 Mbps services and an attractive long-term lifespan. A common traffic engineering assumption is to evaluate an increased CAGR resulting from the exploding number of devices looking for access to the upstream, using similar models for average application bandwidth of the access. The net effect for equivalent QoE is the potential requirement to adjust the oversubscription model.

In **Error! Reference source not found.**, we adjust this traffic engineering parameter by a factor of two to account for the increasing number of simultaneous users (devices) looking to access the upstream. Despite this acceleration, the Mid-Split architecture still achieves a decade of lifespan under two segmentations for common CAGR ranges.

Considering that a downstream CAGR analysis typically requires two splits over this same time period, there is the added opportunity to take advantage of this added lifespan to the upstream as well if necessary.

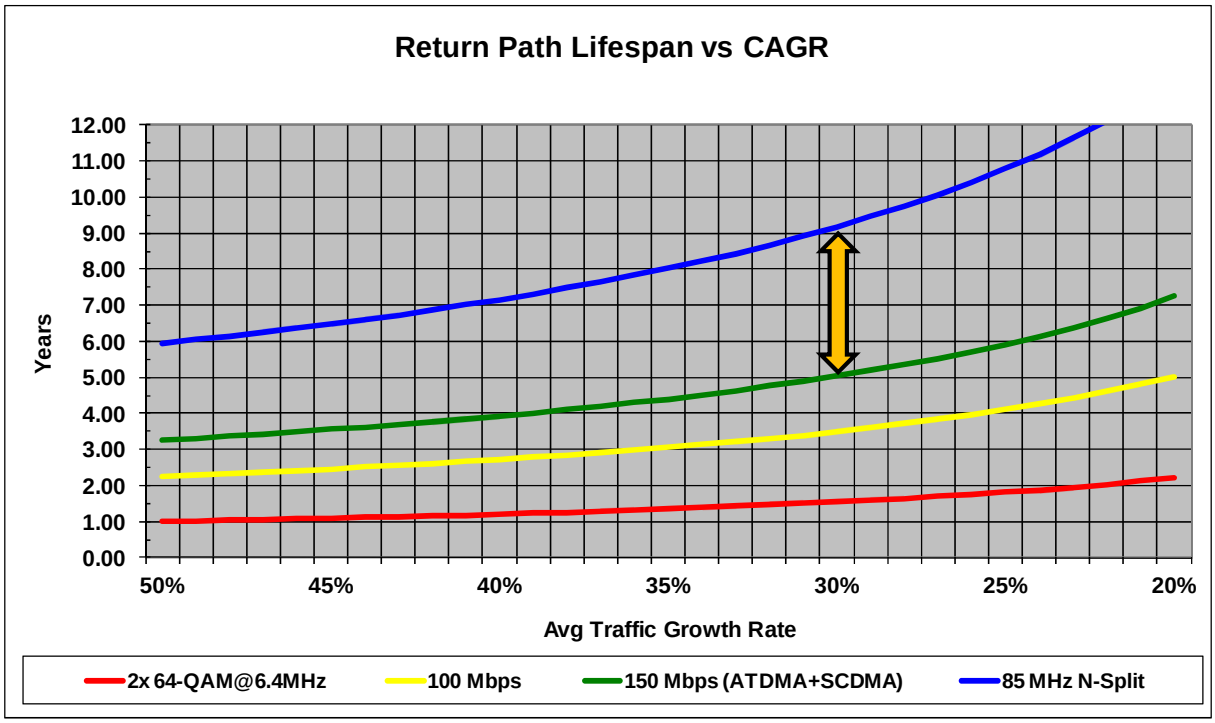


Figure 64 – 85 MHz Mid-Split Years of Growth vs. 5-42 MHz Use

The 85 MHz spectrum approach is

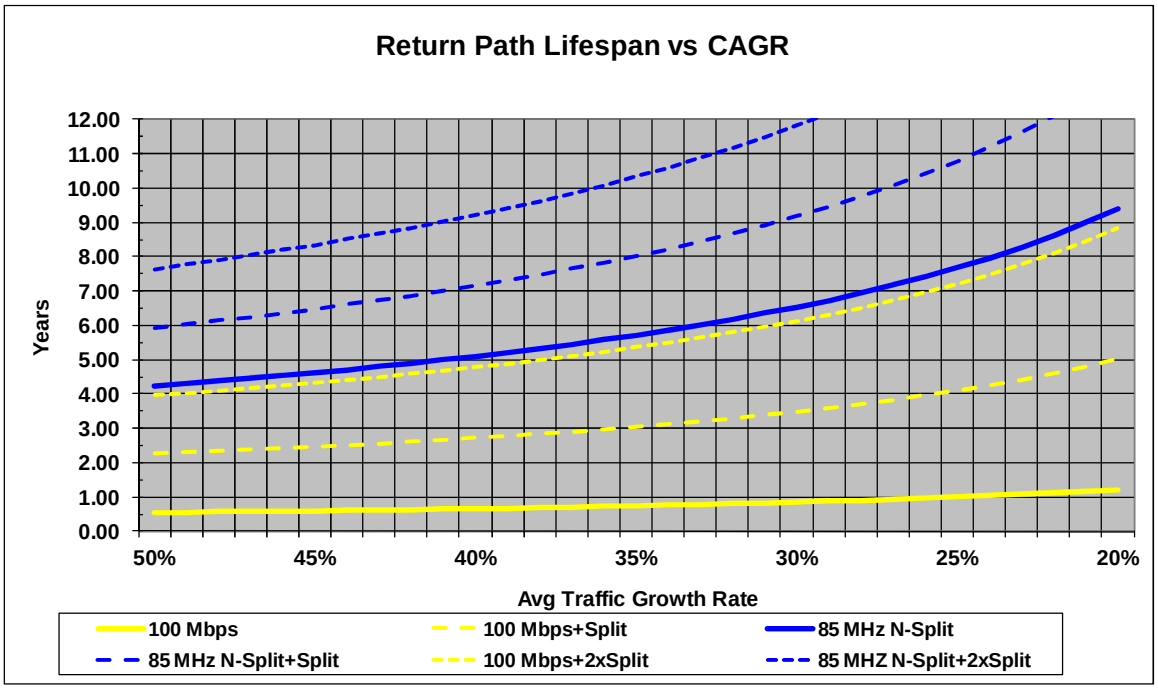


Figure 65 – Upstream Lifespan for Accelerated Usage Patterns

10.1.2.2 Architecture

We observed the clear relationship between available bandwidth and upstream capacity in Table 38. Unfortunately, there simply are no "easy" answers to adding new, real upstream capacity (as opposed to virtual, node splitting).

However, the 85 MHz Mid-Split looks to be the most compelling option in the near term in terms of implementation ease, availability, risk, compatibility, lifespan, and the strength of the value proposition, additional components of which are described in Section 2.1. We have seen in **Error! Reference source not found.** and **Error! Reference source not found.** and **Error! Reference source not found.**, that it also has perhaps unexpectedly powerful benefits.

diagrammed in Figure 66. Also shown is the combined case of the Mid-Split and a node split – clearly these are complementary tools.

This architecture has many very valuable and compelling advantages including the most important one of enabling a long upstream lifespan, while supporting key service expectations around data rate.

We summarize the 85 MHz Mid-Split benefits below:

- More than doubles the spectrum available, and more triple the available capacity compared to the use of 5-42 MHz today

- A decade of life OR MORE of upstream growth under aggressive assumptions for traffic growth using only an assumption of 256-QAM

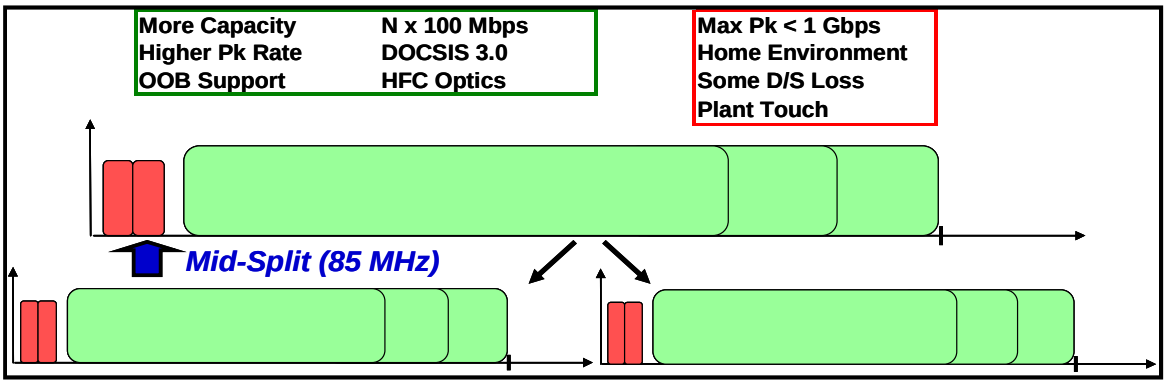


Figure 66 – Step 1: New Return Above the Old Return

- Accommodates multiple 100 Mbps peak rates. Accommodates higher peak rates if desired such as 150 Mbps or 200 Mbps. These may be important to run an effective 1 Gbps DOCSIS downstream service.

- Compatibility with DOCSIS 3.0. Current specification call out support of this extended spectrum. Equipment exists and has been proven for this band.

- Compatibility with standard downstream OOB carriers (70-130 MHz). Thus, no STB CPE using standard OOB is stranded (or at least the vast, vast majority, will not). Over time, as this older population of CPE is removed as part of an all-IP transition, even more flexibility for how to manage return spectrum become available.

- Can be implemented over standard HFC RF and linear optical returns, as well as digital returns. Products exist today for both.

- The new spectrum from 42-85 MHz tends to be cleaner, with less interference and impulse noise, and overall well behaved. This follows the characteristic of the current return that gets cleaner towards the higher end of the band.

- The Mid-Split architecture remains in the low-loss end of the HFC band. Combined with clean spectrum, the DOCSIS 3.0 implementation should have little if any differences, and any updated PHY approaches have the opportunity for even more bandwidth efficient modulation profiles.

- Entails minimal encroachment into the downstream bandwidth as a matter of capacity, and is even less significant when considered in the context of reclaiming the analog spectrum. In this case, it is basically the loss of one 6 MHz slot from a program count perspective – nine lost slots to cover the guard band

- Has similar cable loss versus frequency properties as legacy band – important for understanding CPE implications

- Very low risk, Proven in the field on a fully loaded upstream carrying 64-QAM and 256-QAM. Field trials using standard DFB lasers over typical link length and optical receivers have proven performance.

Note that the proven performance and link characterization for the Mid-Split architecture was discussed in detail in Section 7.1.2, where 256-QAM deployments for upstream were described

A few drawbacks are often cited for the Mid-Split, typically around cost and deployment obstacles. The primary concern is the need to touch actives throughout the plant. It is thus an imperative an upgrade activity be coupled with a segmentation operation and preferably with the ability to enable a Phase 2 of the evolution without requiring the same heavy touch.

Many potential solutions are available to ensure that an elegant transition from 85 MHz to a wider bandwidth in the future can be achieved. Unfortunately, as was originally stated for the upstream, there is no simple solution to more return spectrum.

Recognizing the intrusiveness of the work at hand to modify the frequency split, is commonly observed that the level of touch to the plant means that the "big" step to the 200+ MHz approach should be made.

However, in consulting with operators and suppliers, it is clear that the legacy CPE still requiring the downstream OOB channel for communications must be accommodated. The dynamics associated with this obstacle were detailed in Section 3.3.5. Also, the ability to absorb that amount of loss in the downstream is not tolerable at this phase of the IP migration, which currently might best be described as the "IP Simulcast Bubble" phase of evolution. Therefore, we recommend a phased approach.

Two key items must be recognized in implementing the change. First, it is intrusive, but it is also very low tech, very low risk, available and standardized today. Indeed, it has been proven in existing equipment. Second there is a perception that "just" going to 85 MHz with the effort involved is not enough.

In fact, as shown in the analysis of 85 MHz Mid-Split capacity and lifespan, this is not a band-aid, incremental upgrade, but one that delivers a powerful value proposition in the long term runway it enables, all the while maintaining the fundamental diplex architecture and simplicity of using the low-loss end of the spectrum for the return path.

The deployment challenge often arises out of concern for the home environment when an 85 MHz CM is installed. We described these dynamics in Section 3 and discussed strategies to deal with the challenge. For example, an installation may need to include a blocking filter for some STB CPE. Obviously, the risk here drops considerably if analog channels are removed, or if a Home Gateway architecture is adopted as part of an IP video transition. This is important to characterize and develop a sound operational model for, but is certainly not a technology challenge.

And, in Sections 2.6 we outlined the argument around the limitation often stated that that 85 MHz cannot achieve 1 Gbps of upstream. As was observed in Figure 2, with the time window made available by an Mid-Split upgrade, an extension of the Mid-Split is poised to deliver this capability when necessary and after legacy obstacles have had an opportunity to be addressed. The capacity requirements for residential 1 Gbps of capacity or service rate project well into the next decade on a CAGR basis.

10.1.2.3 Summary – Mid-split Migration Strategy

We recommend an 85 MHz Mid-Split upgrade for a near-term phase of spectrum expansion. Given the lifespan it will be shown to support over CAGRs much more aggressive than are observed today, the 85 MHz Mid-Split should be viewed as a long-term solution and not a temporary fix.

Key benefits are summarized as follows:

1. More than doubles the spectrum and triple the available capacity, providing a path to a decade of life OR MORE of upstream growth
2. Accommodates multiple 100 Mbps peak rates and higher.
3. Compatible with DOCSIS 3.0
4. Compatible with standard downstream OOB carriers (70-130 MHz)
5. Can be implemented over HFC RF and linear optical returns, as well as digital returns.
6. Cleaner spectrum from 42-85 MHz tends to be cleaner
7. Maintains use of the low-loss end of the HFC band. Any updated PHY approaches have the opportunity more bandwidth efficient modulation profiles, and CPE Tx power remains manageable.
8. Entails minimal encroachment into the downstream bandwidth as a matter of capacity
9. Very low risk, proven in the field on a fully loaded upstream carrying 64-QAM and 256-QAM using standard DFB lasers.

While we refer to Mid-Split as "Phase 1", it is a possibility that such a step becomes essentially a "forever" step from a business planning standpoint, on the way to some other long-term approach as greater than ten years of HFC migration is traversed.

Nonetheless, given the projected objectives for the upstream as we see them today, ensuring a path to 1 Gbps in the upstream within the context of HFC tools and technologies is a good long-term objective and a necessary part of long term planning.

Thus, a smooth transition plan beyond Mid-Split requires thinking through the aspects of the Phase 1 implementation that clears the way for this point in the distant future when 1 Gbps becomes a requirement. In this way, the best of multiple key objectives is achieved – many comforting years of immediately available lifespan, support for a long transition window of legacy services, and a strategy for effectively dealing with the continuous traffic growth to come with new bandwidth on-demand.

10.1.3 Phase 2: Deploy High-split – Enabling Gigabit Plus

10.1.3.1 High-Split Extension

Though there are many benefits to an 85 MHz extension, one aspect that cannot be accomplished is support of the 1 Gbps capacity or service rate. This is the case within the parameters of DOCSIS use of the band (360 Mbps), and also the case considering theoretical capacity under DOCSIS SNR assumptions of 25 dB (650 Mbps).

Interestingly, a theoretical 1 Gbps within the 85 MHz Mid-Split architecture would require a 38 dB return path SNR. While well above the DOCSIS requirement, this is, in fact, a relatively easily achievable optical link SNR today using modern DFB transmitters or digital returns. In addition, we can expect higher order modulation profiles enabled at lower SNRs because of the new FEC anticipated – such as 1024-QAM. This would increase data capacity by 25% over 256-QAM and 67% over 64-QAM.

In practice, a manageable operating dynamic range must be considered, as must the other factors that contribute to SNR degradation – RF cascade, user interference, CMTS receivers, and upstream combining, for example. And, though this may be

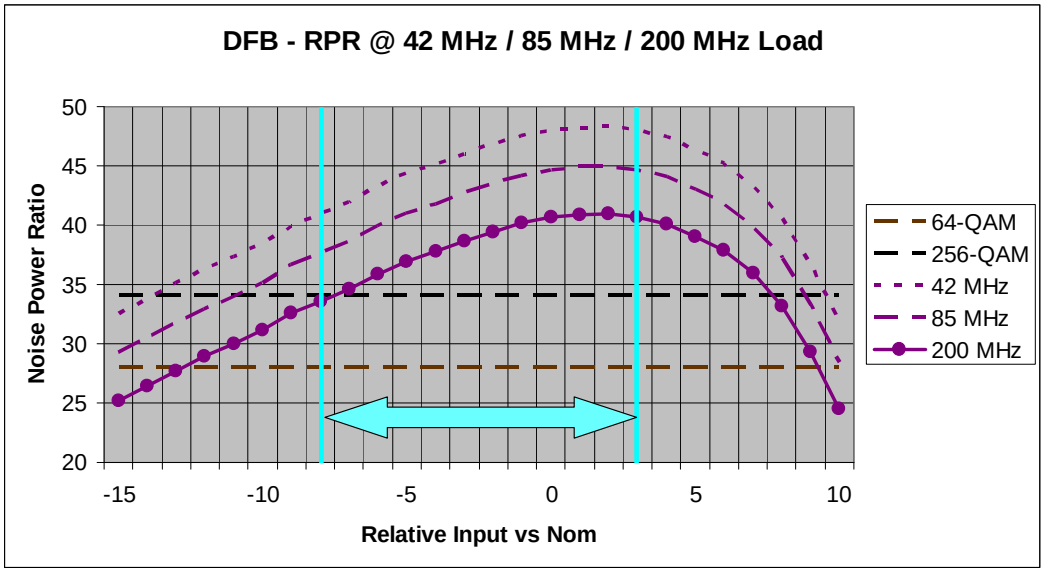


Figure 67 – Bandwidth Loading Effect, 42/85/200 MHz

possible in principle, there is likely to be legacy constraints to having the entire band available for a new, capacity-capable PHY to reach 1 Gbps.

However, this fact does point out that we are entering a new realm of possibilities on the return. Now, with de-combined Headends, 85 MHz of spectrum, modern HFC optics, and new CMTS receivers, and eventually new FEC, many new dB are becoming available toward theoretical capacity and lifespan.

As Table 38 points out, 1 Gbps requires that split to move up to about the 200 MHz range under DOCSIS upstream SNR constraints. 200 MHz is in fact well over 1 Gbps of theoretical capacity, but we assume DOCSIS remains in use for 5-85 MHz, and that the 85-200 MHz region is exploited more aggressively. With new modulation profiles enabled by new FEC, less than 200 MHz will be required, as has been previously discussed.

DOCSIS' maximum profile today (64-QAM@6.4 MHz) itself filling the band out to 200 MHz falls short of 1 Gbps. With 256-QAM, this would no longer be the case. In the case of using split technologies (5-85 MHz of DOCSIS and 85-200 MHz of something else), a shortcoming that could come into play is the inability of that architecture, or at least the added complexity, of supporting 1 Gbps of peak service rate across potentially different systems.

10.1.3.2 Supported by HFC Optics

An attractive advantage of a diplex-based return of 200 MHz or higher is the ability to use analog return optics. However, the additional bandwidth comes with a power loading SNR loss associated with driving a fixed total power into the laser over a wider bandwidth.

Figure 67 compares 200 MHz optical link performance, fully loaded, to 85 MHz and 42 MHz cases. As previously, the lines representing 64-QAM and 256-QAM are SNRs representing theoretical BER without the use of error correction. The power loading loss is easily predictable, as simply the dB relationship among total bandwidths. For the optical link at least, using typical

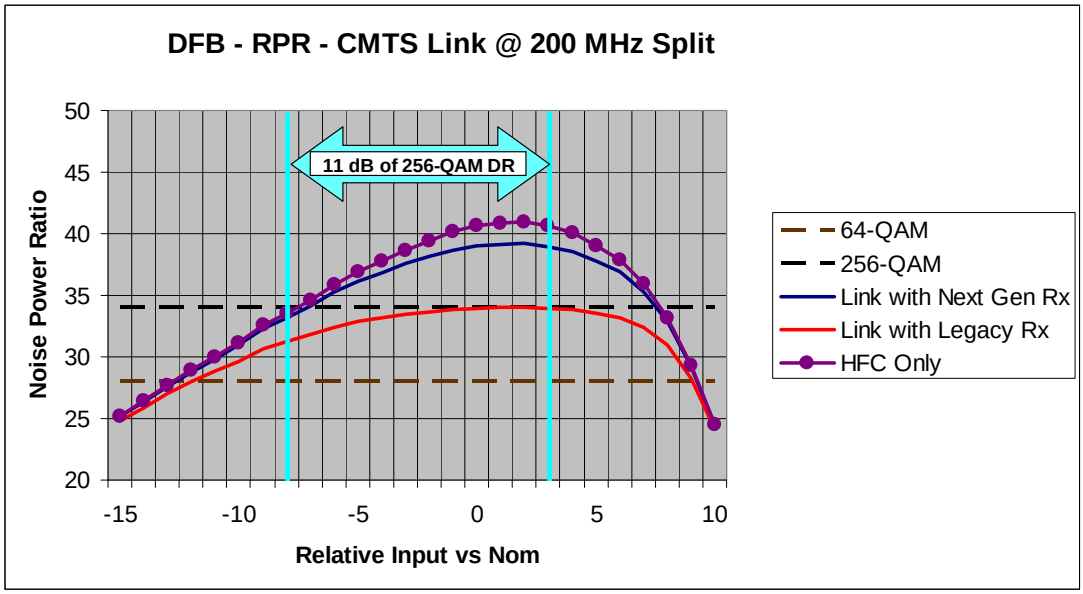


Figure 68 – Projected 256-QAM Dynamic Range Over 200 MHz Split

performance delivered by an analog DFB link, 10-11 dB of dynamic range exists across the HFC optics – a reasonable margin to accommodate alignment, drift, and plant behaviors, but borderline itself for robust, wide-scale roll-out, particularly given degradations that the link will inherent from the rest of the plant.

A comparison of the link using equivalent legacy CMTS receiver performance and modern, lower-noise receivers, is shown in Figure 68. Figure 68 helps to make the point noted in the beginning of this section. The minimum SNR limit assumed for DOCSIS is itself a very dated, and unfortunately conservative and constraining with respect to available capacity.

We now can observe in Figure 68 how the combined effect of the evolution of cost effective, high quality return optics coupled with low noise DOCSIS receivers is opening up new possibilities for extracting capacity from more capable upstream spectrum over wider band.

Based on Figure 68, the full low diplex migration approach has the flexibility of being supported over currently available linear optics. Note once again that we also observed DWDM lasers operating in Figure 20 over high split with NPR performance slightly better than the 1310 nm projection showed here under different link assumptions. This once again shows that today's HFC linear optics is at, or on the verge of, compliant performance for bandwidth efficient profiles over high-split, even without considering new FEC.

Furthermore, High-Splits that exceed current return path optical bandwidth, such as 300-400 MHz, could, in principle, be delivered over linear optics as well. The optics used would simply instead be forward path lasers, which would obviously be high performance.

The preferred, long-term, architectural direction for the long term is a solution based

on digital transport over fiber to the node, such as Ethernet or EPON protocol based, to the node, and RF transport over coax. However, an approach based on a low diplex expansion does not require this architecture to operate, offering flexibility to the operator during the difficult transition phase of the network.

When such an architecture is available, the benefits of removing linear optical noise and distortion from the access link budget have very powerful capacity benefits to a low diplex, whose SNR performance is typically set by the optics.

10.1.3.3 Spectrum Evolution

If 85 MHz Mid-Split is a "natural" extension of the Sub-Split (42 MHz) for long-term growth, then a "natural" extension of Mid-Split for long-term peak rate support and FTTH competiveness is the 200-300 MHz High-Split. This concept is diagrammed in Figure 69, along with a summary of the pros and cons.

Unlike Mid-Split, a high split can achieve the 1 Gbps rate foreseen as possibly the next threshold in the upstream after 100 Mbps. And, in doing so, it does not suffer the very high RF attenuations that the alternatives that rely on frequencies above the forward band do. The exact upper band edge is a function of modulation profile, which again is tied to architecture and FEC.

This translates into more cost-effective CPE. As we have seen, implementation of today's HFC optics is possible, as modern HFC optics is based on 5-200 MHz and 5-300 MHz RF hybrids. And, to reiterate, this architecture, too, would benefit from any migration in the plant that relies on digital fiber delivery and RF carried only in native form on the coaxial leg of the plant.

By maintaining fundamentally a diplex architecture, there is still but one guard band in the architecture, preserving use efficiency. Lastly, at the low end of the HFC spectrum, there would not necessarily be a compelling reason to require an OFDM system, unlike other portions of the band.

The channel quality would not necessarily demand a multi-carrier waveform, and it would have modest advantages at best in a clean channel environment anticipated. Extensions that further empower DOCSIS become more reasonable to consider without a fundamental change in the waveform used, silicon architecture, specification, or new technology learning curves.

At the same time, because the linear optical return architecture anticipates a broadband, noise-like signal, the addition of OFDM channels, even wideband, can be carried within the linear optical architecture as well if the high split band evolves to

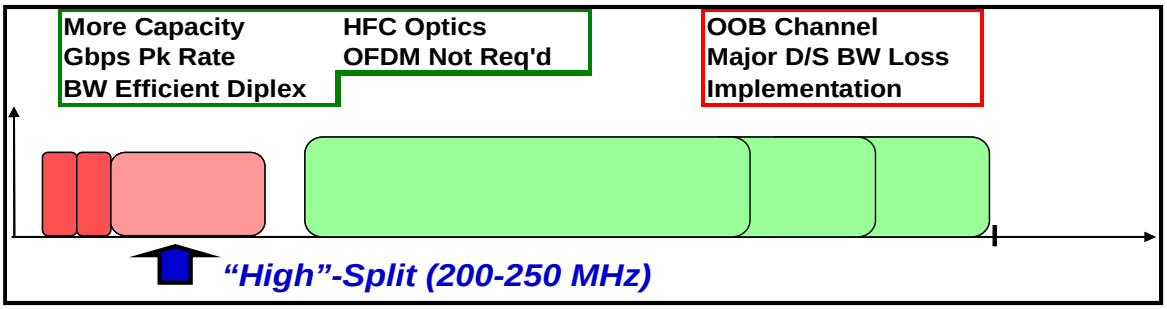


Figure 69 – High-Split Concept, Pros and Cons

include multi-carrier formats. Again, in comparison to other alternatives, this is an added degree of implementation flexibility.

The loss of the OOB downstream channel is an important consideration. However, the logic of this approach is that by the time it becomes necessary – again, likely at least 10 years down the road – the MSO has had ample opportunity to retire through natural attrition or actively manage down legacy STB relying on this OOB channel.

Again, knowing what steps are in place and coming over time, decisions can be made about handling legacy STB either through DSG or Home Gateways associated with an IPV transition.

10.1.3.4 Notable Obstacles

Unlike Mid-Split, High-Split is now a major imposition on downstream spectrum. However, it is expected that downstream spectrum will also undergo expansion over time as traffic in both directions continues to grow. There is already potential spectrum to be mined above the top end of the forward path in many cases, and it is anticipated that if the upstream is to continue to move "up" with high-split, there may be a need also to offset the loss of downstream spectrum by extending downstream as well beyond its current limitations.

By appending new spectrum to the end of the current downstream, this approach to exploiting new coaxial bandwidth is able to maintain a single diplex architecture. This concept is shown in Figure 70.

While this presents a potential solution from a capacity perspective, from a CPE perspective there are important limitations associated with legacy equipment. As the "Simulcast Bubble" winds down at the back end of this decade, models suggest that those savings will be able to compensate for the expansion of upstream into a high-split architecture.

However, under an assumption of persistent CAGR and a continued evolution of HD into even higher resolution formats, such savings will over time once again give way to spectrum management of a new phase of services growth. The window of savings, however, is an important component of a transition that includes the possibility of extending the forward spectrum. We will elaborate on the forward aspects in subsequent section.

10.1.3.5 High-Split Extension – Timing and Implications

The time frames required for a high-split migration are a key element of the strategy because of the intrusive nature of this magnitude of change, and the idea that we may wish to include as part of a transition plan the creation of new forward bandwidth. We touched on the expected timing of 1 Gbps solution in Section 2.6.

Even should the access network be evolved to enable a high-split in the 200-300 MHz band on-demand, such as putting the

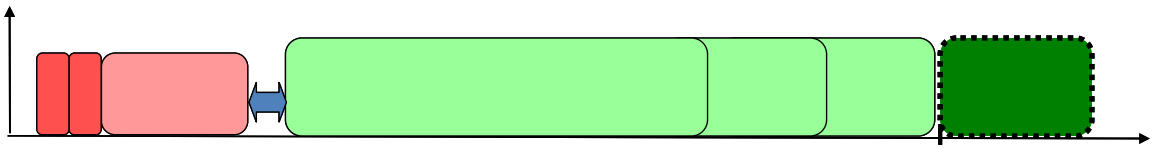


Figure 70 – Possible "Offset" Band Compensating for High Split

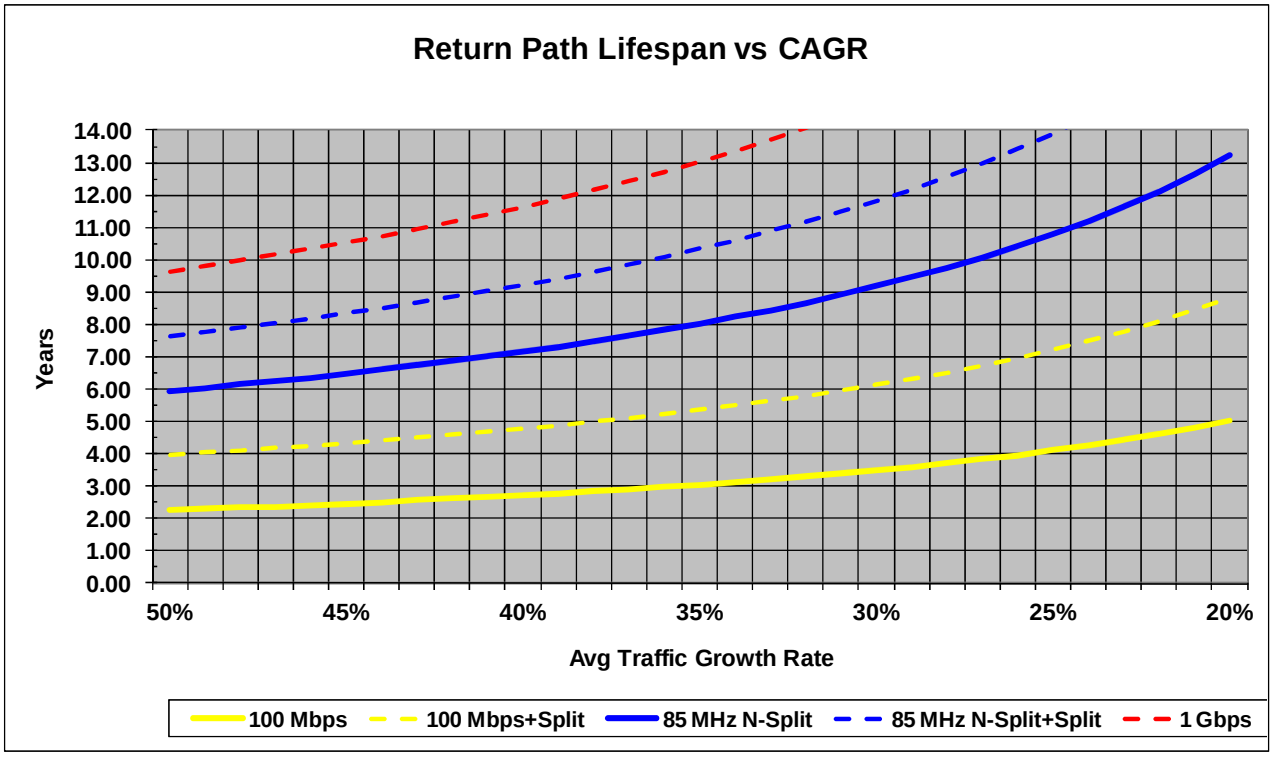


Figure 71 – Relative Lifespan and the Benefits of 1 Gbps

capability in when 85 MHz is deployed, the move to a high split has large impacts on the forward spectrum and return path transport that must be planned.

It is therefore important to get an idea of when we might need it. There are consumption and market pressure components of that, but let's view it in an apples-to-apples way with the prior analysis of the 85 MHz capability for extending return path lifespan. What does a Gbps of capacity imply for long-term traffic growth?

The answer to this question can be examined in Figure 71. It is an excellent illustration of how compounding works and the need to consider what it means if played out over the long term. It shows three threshold cases – 100 Mbps (A-TDMA only), 85 MHz Mid-Split and 1 Gbps (also with a split included).

Zeroing in on the gap between 85 MHz Mid-Split and 1 Gbps at 35% CAGR, we see that there exists about 2.5 years of additional growth after about 10.5 years of lifespan. When we think of "1 Gbps," this intuitively seems odd. Again, this is simply how compounding works. If we base analysis and decisions on the continuance of a compounding behavior paradigm, then the mathematical basis is quite straightforward.

With CAGR behavior, it takes many YOY (year-over-year) periods to grow from. For example, the 40 Mbps of upstream used by a service group today service today to the 440 Mbps that can be delivered by Mid-Split. That number, as Figure 68 shows, is 10.3 years of compounding at 35%. However, once there, the subsequent annual steps sizes are now quite large. That is the nature of compounding, resulting in what seem like small extra lifespan.

10.1.4 Summary

The spectrum migration shown and described above is repeated in Figure 72 and Figure 73. The role of the upstream migration phases in the larger picture of HFC spectrum evolution and the transition to an All-IP end-to-end system is shown in Figure 74 and Figure 75.

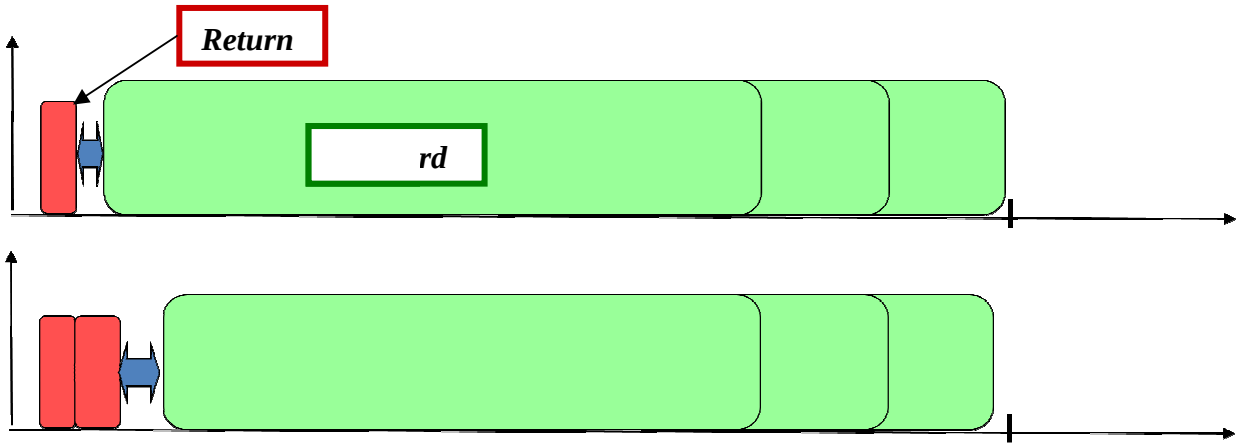


Figure 72 – Phase 1: 85 MHz Mid-Split

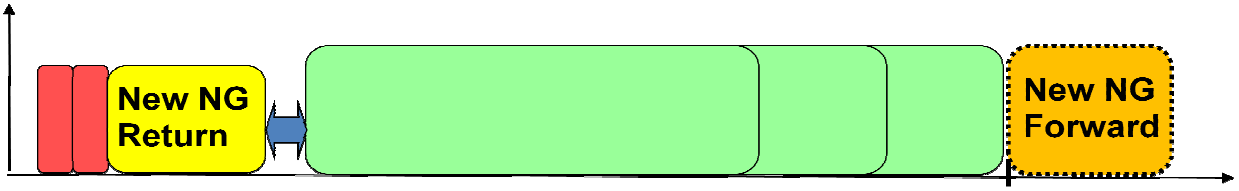


Figure 73 – Phase 2: 200+ MHz High-Split and Possible Relief Band Forward

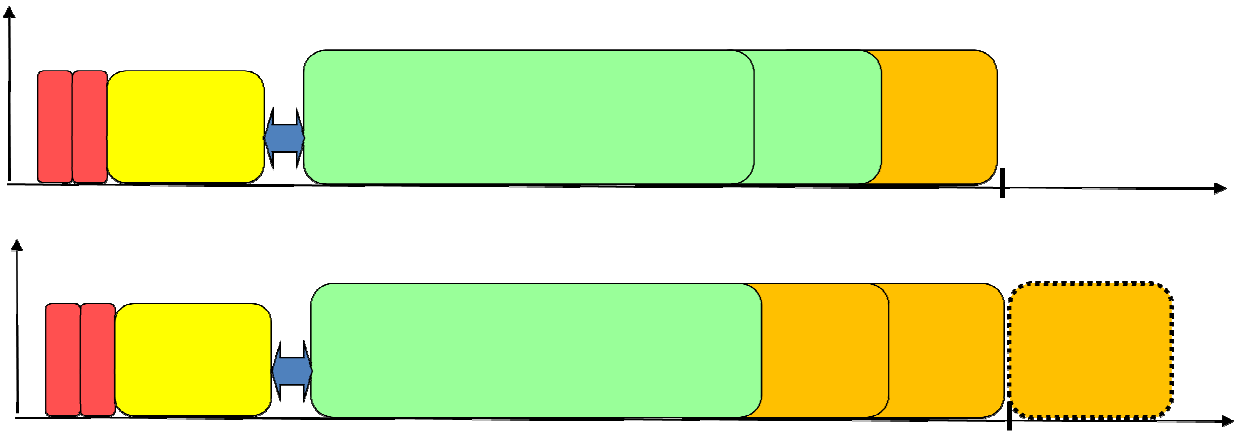


Figure 74 – IP Transition in Progress – Legacy Roll-Back

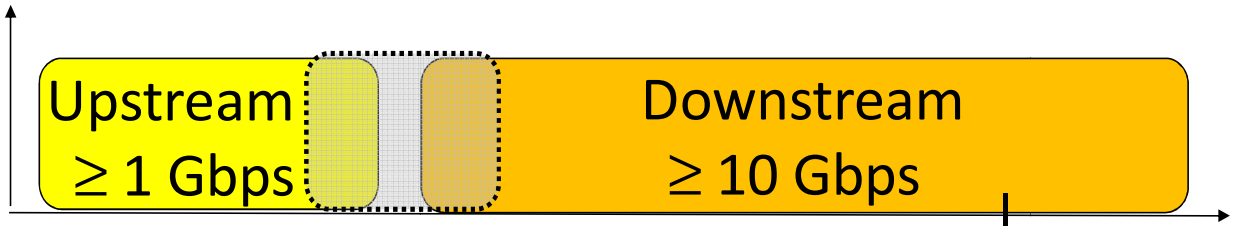


Figure 75 – Final State of All-IP Transition

Flexible/Selectable Diplex, Advanced PHY, Digital Transport-Based HFC Architecture, N+Small/N+0

10.2 Downstream Migration Strategy

10.2.1 Capacity and Lifespan Implications of IP Growth

Every individual HFC plant has evolved on an as-needed basis, and of course under CAPEX budget constraints that inherently come with a network of fixed assets expected to last a long time. As a result, HFC networks in North America have a range of top-end forward path bandwidths.

Typically, however, plant bandwidth is 750 MHz, 870 MHz, or 1 GHz – more so that former two. Absolute bandwidth is obviously important, but fortunately multiple additional tools are available to help manage downstream service growth, such as digital television (DTV), increasingly efficient DTV compression, more bandwidth efficient modulation formats, and switched digital video platforms (SDV). These are all complementary and are in addition to common network segmentation.

As cable advanced video services and data services have grown, however, it has become clear that powerful new dynamics are working against cable operators, and towards a capacity bottleneck in the downstream. The result has been a renewed interest in finding new spectrum, which to a first order directly translates to increased network capacity. Being aware that coaxial cable is not limited to any of the forward band limitations mentioned above, operators are exploring how to access what today is unexploited spectrum above these defined forward bands. There are no technology obstacles to its use, but significant legacy service, network, and equipment implications.

We have discussed in detail the capacity available in DOCSIS and DOCSIS NG as evolution phases take place. However, we have not discussed them in the context of the *available* HFC spectrum. While new DOCSIS capacity is powerful and important, most of the downstream spectrum today is locked down for video services. Finding new DOCSIS spectrum is a major challenge in the normal HFC band, and it is years away before we can exploit the extended bands. We can illustrate quite easily why finding new HFC capacity has become so important and difficult. Consider Figure 76.

Figure 76 projects two cases of IP traffic growth, modeled after the well-travelled Nielsen's Law approach to user bandwidth trends. In this case, it is taken in the aggregate, representing, for example, one service group or perhaps one node.

It assumes that eight DOCSIS downstream service this population today. This is represented on the y-axis, shown on a logarithmic scale because that is the nature of compounding growth. The axis is quite simple to translate in dB – 100 Mbps is 20 dB, 1 Gbps is 30 dB, and 10 Gbps is 40 dB. For eight DOCSIS channels (always using the transport rate in this example, since we are not quantifying service tiers), this works out to 25 dB as a starting point.

The trajectories proceed at 50% Compound Annual Growth Rate (CAGR), interrupted by service group segmentations (such as node splits). In this example, a simple, perfect split (in half) is performed mid-decade. A second, perhaps final, segmentation is done at the end of the decade that resembles an N+0 from a service group size perspective (40 hhp), although it is immaterial to the analysis whether there would physically need to be an amplifier in some particular plant geographies. We use N+0, as we subsequently discuss the implication this has for spectrum planning and capacity exploitation.

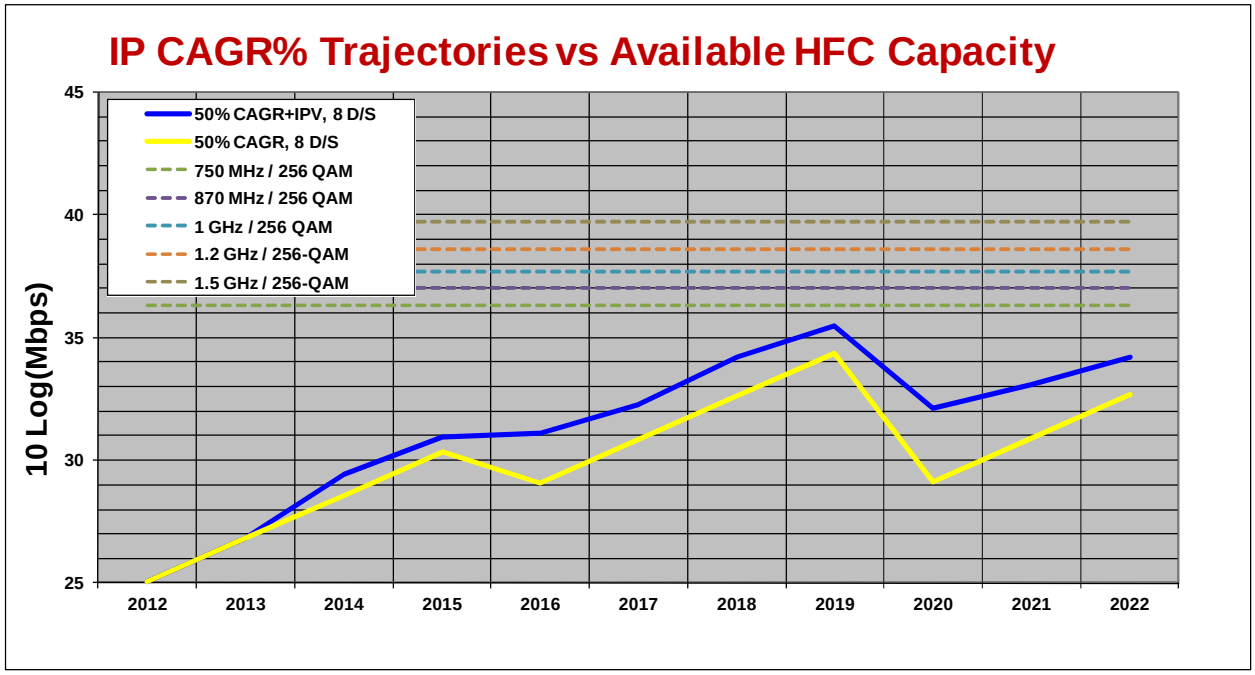


Figure 76 – HFC Downstream Capacity, IP Traffic Growth, and Segmentation

Finally, there are two trajectories because in one case we add dedicated IP Video channels to to IP traffic growth, in addition to the 50% CAGR itself. There is somewhat a philosophical discussion to be had about whether managed IP Video is the new engine of 50% growth (like OTT has been for years), or if CAGR plows ahead in addition to shifting the current video service onto the DOCSIS platform.

Here, the assumption is that blocks of DOCSIS carriers are added every other year beginning in 2014 – first four channels, then 8 channels, then 8 channels for a total of 20. It is a separate analysis how 20 DOCSIS slots represents an assumed video line-up that we will not go into here, but this has been analyzed and written about in many industry papers over the past 4 years.

Five thresholds are shown, consistent with five different assumptions of network bandwidth. In every case, it is assumed that the return bandwidth has been extended to 85 MHz, and the first forward channel is therefore in 109 MHz. It is also assumed, in the extended bandwidth cases of 1.2 GHz and 1.5 GHz, that 256-QAM can be supported.

This is a reasonable assumption – in fact minimally necessary to make turning that band on worth the effort – but obviously unproven at this point. Lastly, each of these thresholds can be incremented by about 1 dB (more) by making the assumption that 1024-QAM replaces 256-QAM (10 Log (10/8)). It was decided not to clutter this figure with those minor increments. But, as discussed, for DOCSIS NG, 1024-QAM downstream and up to 4096-QAM downstream are anticipated modulation profiles, with an objective for total downstream bandwidth of 10 Gbps (which is simply 40 dB in Figure 76 and Figure 77, however it is accomplished).

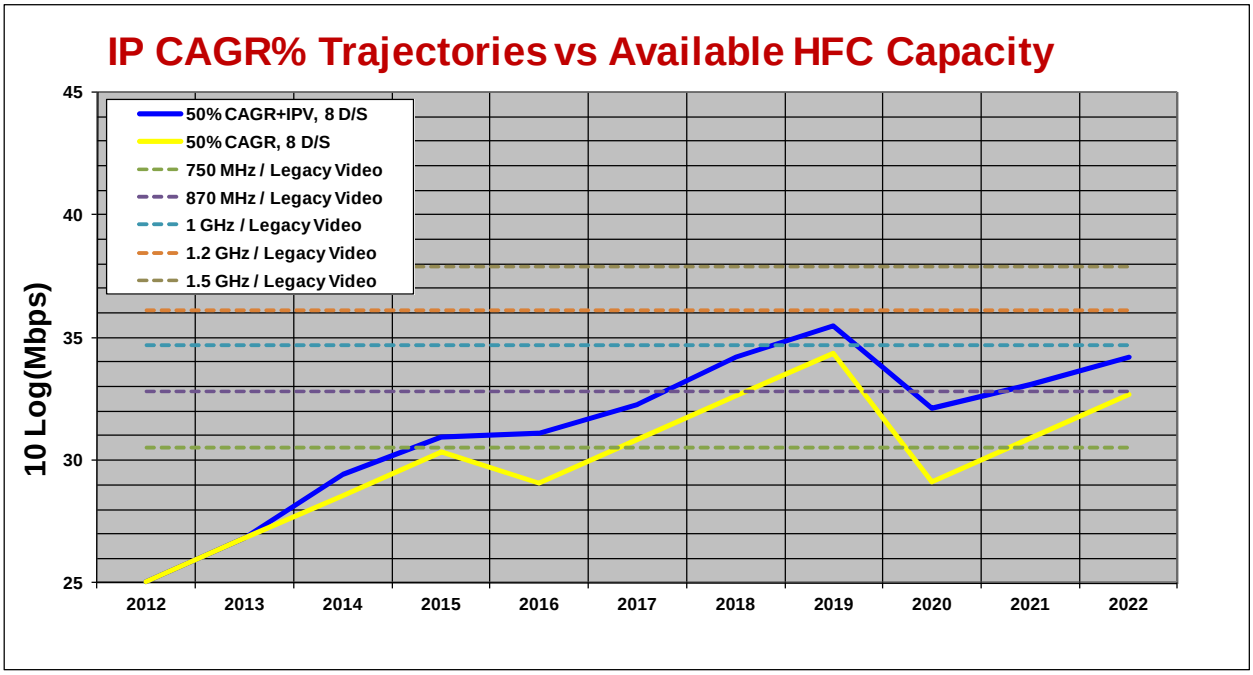


Figure 77 – Capacity, Traffic Growth, and Segmentation – Video Services Added

The thresholds are still based on the assumption of 6 MHz slots of 256-QAM, so represent "current" spectral usage efficiencies, and as such are conservative in that sense. The thresholds, thus, represent the integer number of 256-QAM slots, aggregated to a total based on 40 Mbps/per slot.

An obvious conclusion from Figure 76 would be that the HFC network is in fine shape to take on an extended period of aggressive growth. The network appears not threatened until (projecting to the right) the 2023-2024 time frame, worst case. Of course, there is something seriously missing from this analysis – current services.

Now consider Figure 77.

Figure 77 takes into account that most of the HFC spectrum is not available for new IP growth today. In fact, for most operators, have very little or no "free" spectrum to put new DOCSIS carriers in. When they need new ones, they shuffle other things around and use the tolls above to make it happen. This is much easier said than done as more spectrum, not less, is being consumed with the increasingly competitive environment around HD programming.

The programming line-up above assumes the following:

- Broadcast SD: 100 programs (10 slots)
- Broadcast HD: 40 programs (10 slots)
- SDV 24 slots: This increases the total programming to SD~300 and HD~150
- VOD 4 slots
- No Analog

Clearly, this is not particularly aggressive. First, it is assumed that there are no analog carriers – everyone's long term goal, but executed on by only a few. Also,

not all operators are using SDV to this degree, the VOD count is modest, and objectives for HD are for 200-300 programs (not to be confused with "titles"). Finally, there is a real possibility that upstream congestion will require that this band be extended beyond 85 MHz, up to the 200 MHz range or beyond. This would significantly impose on available capacity.

And the result? A 750 MHz is in immediate danger without a service group split, and an 870 MHz network is not far behind. In all cases that do not go above 1 GHz, the "N+0" phase is required before the end of the decade to manage the growth.

The extra runway offered above 1 GHz is apparent – relatively modest for an extra 200 MHz (but this would offset a 200 MHz return at least), and substantial for a 1.5 GHz extension. In the context of the evolution of video services, then Figure 76 can be viewed as the capacities available when the full IP Video transition is complete, and no legacy analog or MPEG-2 TS based video services exist.

As such, they are not "phony" capacities – they merely represent the available capacity, under today's limitations of technology, at the point in time when the legacy service set is fully retired. In this sense, then, they are very valuable thresholds for guiding plant migration and bandwidth management.

A final note on the Figure 76 thresholds is to note that 1 GHz of ideal 1024-QAM bandwidth, at 10 bits/s/Hz efficiency, adds up mathematically to 10 Gbps. We almost achieved this only considering 256-QAM @ 1.5 GHz, and clearly would have done so under a 1024-QAM assumption (one more dB on added to this threshold).

This order of magnitude is important relative to competitive PON deployments. With respect to subscribers served, the PON port is shared by 32 or 64 subscribers. With cable, the access leg is shared by one node port as a minimum, or more generally one complete node. Today, a typical single node average is about 500 homes passed, and this is headed downward. At N+0, it will reside likely in the 20-50 HHP range. For cable then, the subscriber base sharing a 10 Gbps-capable node will be similar to 10 Gbps PON networks in the downstream.

10.2.2 Making Room for Gbps Upstream with New Downstream

Moving to the 85 MHz Mid-Split adds 43 MHz of return bandwidth, doing so at the expense of modest imposition on forward bandwidth. When factoring in the new guard band, possibly nine or ten forward path slots in the traditional analog band are eliminated. Mathematically, converting these channels to digital allows them to all fit into one slot.

As such, as analog reclamation continues, this forward loss does not represent a major capacity concern. The primary operational concern is that the nature of the channels in this region. They are often a basic service tier, and therefore cannot simply be transitioned into the digital tier and off of the analog tier, practically or contractually in some cases, as perhaps some of the longer tail of the analog service could.

Instead, some channel re-mapping and/or more aggressive deployment of digital adaptors would be required. In any case, given the powerful set of tools available to provide downstream capacity, 85 MHz does not present significant imposition on the forward bandwidth in terms of capacity loss.

In the case of a 200 MHz extension, however, this is no longer the case. Cable

operators generally use all of their spectrum, and a changed such as high-split, even if it phased in, will call for some significant impacts to the downstream services line-up.

The issue is magnified further when considering that while we are looking to extract downstream capacity and give it to the upstream, the downstream itself continues to see rapid CAGR – more rapid and consistent that the upstream. This amount of lost downstream capacity will have to be replaced, and, in fact, capacity above today's available forward capacity will have to grow over time. 1 GHz worth of 256-QAM slots today adds up to about 6.3 Gbps of total transport capacity, and 7.9 Gbps by enabling 1024-QAM. A 300 MHz starting frequency for the downstream removes about 1.6 Gbps – too big to ignore. That means we must find new downstream bandwidth. In Section 4.5 to 4.7, we identified performance of spectrum above 1 GHz for upstream use, and argued that the obstacles to effectively using the band for upstream make it much more suitable for extending the downstream. Here, we elaborate on this possibility and the potential new data capacity available.

So, where would new bandwidth come from above today's forward band? Virtually any new (actually new, not reseller) plant equipment purchased today will be of the 1 GHz variety. This is clearly at odds with trying to use bandwidth above 1 GHz. Industry discussion around enabling new bandwidth is along three fronts:

(1) What bandwidth do 1 GHz devices actually have? We observed "1 GHz" Taps for out-of-band performance in Section 4.5. Because there is always design margin, is there " free," but unguaranteed, spectrum to exploit? Some operators already place channels above the "official" downstream bandwidth, perhaps at a lower modulation order for robustness, which indicates that there is obviously exploitable capacity in some cases.

It can be shown that some of the friendliest taps in the field have about 20% of imperfect excess bandwidth to mine before difficult to manage roll-off kicks in. Field testing of this grade of tap has been extensively performed. In live plant conditions, a typical tap cascade of nominal coaxial spacing showed useable bandwidth to 1160 MHz with high efficiency for wideband (50 MHz) single carrier QAM [1]. Not all deployed taps will have this amount of useful bandwidth. Of course, the best way to mine bandwidth in such difficult conditions would entail a different modulation approach, and this is particularly the case where discussion of multi-carrier modulation (OFDM) is often introduced for cable networks. Aside from the flexible use of spectrum it allows in periods of transition, and through its use of narrow QAM subcarriers, OFDM would more effectively extract bandwidth, and make more bandwidth able to be exploited.

(2) Some suppliers have developed a 1.5 GHz tap product line. However, there is not very much new build activity, so the market for such products has not grown. Extended bandwidth is also available for some taps already in the field by "simply" swapping out faceplates. This is very intrusive and time-consuming, but of course it is also much *less* intrusive and much *less* time consuming than a full tap swap-out.

Some suppliers have developed this technology specifically for existing plant (versus new build which could, in principle, purchase 1.5 GHz taps). The "swap out" approach yields taps with a specified bandwidth to 1.7 GHz. There is more bandwidth than the 1.5 GHz taps, but it

comes at the expense of minor degradation in other specifications. However, field testing has been encouraging that these taps extend bandwidth to at least 1.6 GHz [1].

(3) Full tap swap outs for models that increase bandwidth to up to 3 GHz (or use in new builds). This, of course, is a very intrusive plant modification.

It is important to note that suppliers have not yet developed node or amplifier platforms, at least not in volume scale, that extend beyond 1 GHz. There are no technology reasons this could not be done, although there are likely major redesigns involved in most cases right down to the housing, circuit boards, and connectors.

This is viewed as unlikely to take place for RF amplifier platforms, but perhaps not so for nodes. As N+0 is potentially a logical "end state" for an HFC architecture, the ROI picture is somewhat clearer to make for equipment manufacturers. In addition, nodes have undergone generally more R&D investment than RF platforms have, as they have kept up with the optical technology evolution.

Many fielded RF platforms have not changed very much since they were originally designed, and have been had their bandwidth limits continuously pushed. It is unclear how many new MHz are easily available, and the range of RF platforms is much larger.

This limitation on the bandwidth of the RF amplifier is important in the context of accessing new bandwidth and understanding the enabling architectures to do so. We will elaborate and quantify aspects of this in subsequent sections.

10.2.3 Excess Bandwidth Calculations on the Passive Plant

The first place to look for more downstream spectrum is simply in the band that continues directly above today's forward path band edge. While this was shown to be a difficult band for an upstream service to efficiently and cost effectively support, it is much easier to consider as much for the downstream.

The downstream channel is already very linear, has a very high SNR, and these features of the access equipment are shared by the homes passed common to a piece of equipment in the plant. And, fortuitously, in many 1 GHz tap models there is that significant "free" bandwidth available.

Figure 78 shows the frequency response on the "through" port of the particular 1 GHz tap described in the field trials above that yielded an 1160 MHz net useful band edge. This port would be in series with other taps on the way to a connected home. The response on the tapped port also has essentially parasitic, low-loss properties over the first 200 MHz above 1 GHz.

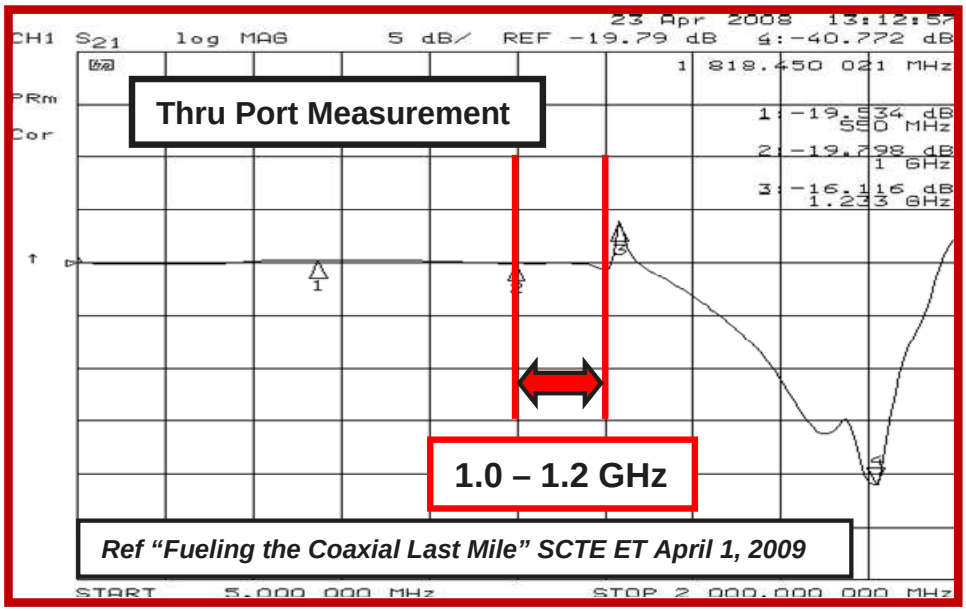


Figure 78 – 1 GHz Tap Frequency Response, "Thru"

Though not as perfectly flat, it creates no significant distortion burden to RF signals in the band, and in particular when considering that a new generation of OFDM technology will almost certainly be created to operate in that regions, and if so will run an adaptive bit loading algorithm.

The same is the case for some families of 750 MHz taps (available bandwidth exists above 750 MHz) and 870 MHz taps (available bandwidth exists above 870 MHz).

The amount of useful bandwidth and loss properties are vendor dependent, but cable operators already often use slots above these limits. Conveniently, as Figure 78 shows, the amount of available new bandwidth simply trickling over the top of the band is virtually the same the amount of bandwidth that would be removed from the forward by a 200 MHz high-split architecture.

With the support of the supplier community, CableLabs has undertaken an investigation to statistically quantify this excess bandwidth across Tap models and manufacturers so that operators can better understand in their specific plants what useful bandwidth is available, and how that changes with time with shorter cascades.

An important item to re-emphasize is that there is no guard band involved when this spectrum is operated as only a downstream extension, as there would necessarily be if upstream were to be deployed in this band. This "replacement" bandwidth amount provides adequate spectrum to facilitate new downstream capacity.

The ability to fully exploit this bandwidth in the passive plant obviously depends heavily on the band coverage of the actives themselves and the depth of the cascade. Clearly, this is where shortening cascades and "N+small" continue to payoff for HFC evolution.

The tapped port, of course, also contributes to the frequency response, and a sample of this port on the same 1 GHz tap

model (2-port, 20 dB) is shown in Figure 79. The response on the tapped port also has essentially parasitic, low-loss properties over the first 200 MHz above 1 GHz.

Though not perfectly flat, it creates no significant burden to RF signals in the band, and in particular when considering a new generation of modem technology, such as multi-carrier. The same is the case for some families of 750 MHz taps (available bandwidth exists above 750 MHz) and 870 MHz taps (available bandwidth exists above 870 MHz).

It is clearly evident that the band between 1.0 GHz and 1.2 GHz is not flat, having about 2 dB of what can best be described as a broadband ripple in the response.

10.2.3.1 Excess Bandwidth SNR Model

In order to calculate the capacity associated with this "extra" bandwidth, we must numerically model this frequency response. This is easily accomplished for parasitic-type roll-offs, more so even that with classic RF filter responses such as diplexers.

We can, in fact, fit the attenuation response to some fundamental filter shapes and use those to calculate attenuation. And, by proxy, SNR for a fixed transmit power. In this case, the roll-off response can be fairly well represented by scaled versions of a 5th order Butterworth response, as shown in Figure 80.

Here, the thru attenuation (blue) of approximately 10 dB across the 1-2 GHz band, as well as the roughly 20 dB of attenuation over 600 MHz represented by the port (red), is represented. Note that increasing stop-band attenuation typically means correspondingly poor *return loss*, which is an RF reflection mechanism – a mechanism already part of DOCSIS, and that has become very sophisticated with DOCSIS 3.0. Of course, if a multi-carrier PHY is adopted in this band, it too is robust to this distortion, but through different means, such as use of a cyclic prefix.

Filter roll-off regions also typically correspond with regions of high group delay variation – another challenge taken on by the 24-Tap equalizer. For A-TDMA, however, there are limits to how successful the equalizer can be with combined micro-reflection, amplitude response, and group delay distortion.

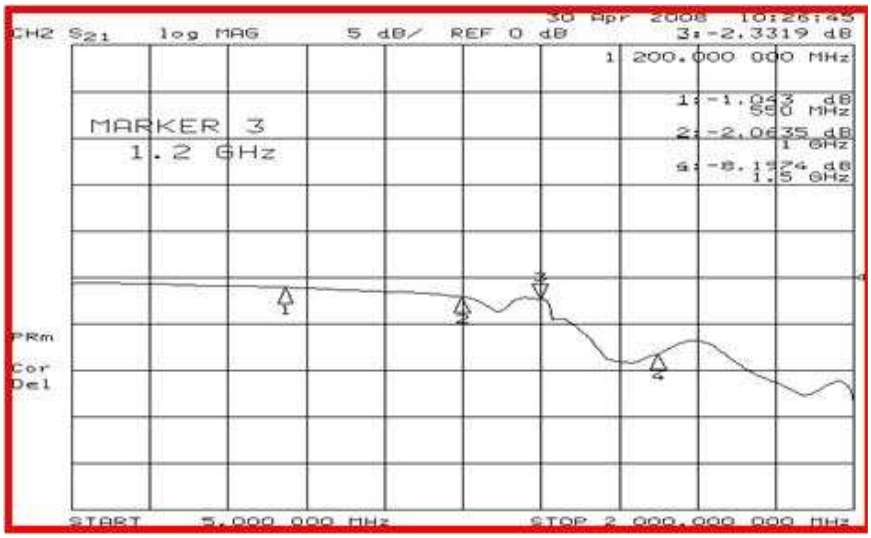


Figure 79 – 1 GHz Tap Frequency Response, Tapped Port to Home

Performance has been shown to be far, far beyond the conditions called out in DOCSIS specifications. Nonetheless, multi-carrier evolutions to the PHY minimize the

potential concerns over operating in these regions as well. System parameters (subchannel widths, cyclic prefix guard times) can be used very effectively to overcome these obstacles where the channel performance degrades.

Consider the two narrowest bandwidth curves of Figure 80. These represent the composite frequency response of an N+0 cascade of five taps (N+5T, pink) or ten taps (N+10T, brown), and an accompanying length of coax governed by a typical attenuation model.

A subscriber at the end of a ten tap run will of course see nine thru responses and a tapped port (and quite possibly an active that would need to support this band or bypass it), and this response is represented by the brown curve. The pink curve represents a five tap scenario, which is a more typical run of taps between actives.

These attenuation curves for a cascade of taps, plus interconnecting coaxial runs, can be used to quantify the attenuation profile, and, given a transmit power profile (is it tilted or not), the SNR delivered from the network for a given power, and thus the capacity available as a function of new spectrum. We can thus see the efficiency with which this new part of the band delivers capacity.

10.2.3.2 Capacity Derived from Excess Spectrum

Figure 81 quantifies available capacity, assuming an HFC forward digital band starting SNR of 45 dB at 1 GHz in the HFC plant and using the frequency response of Figure 80. An HFC downstream link at the output of a node would be expected to deliver at least 51 dB of SNR as a common objective in the analog band, leaving the digital band 6 dB removed from that performance.

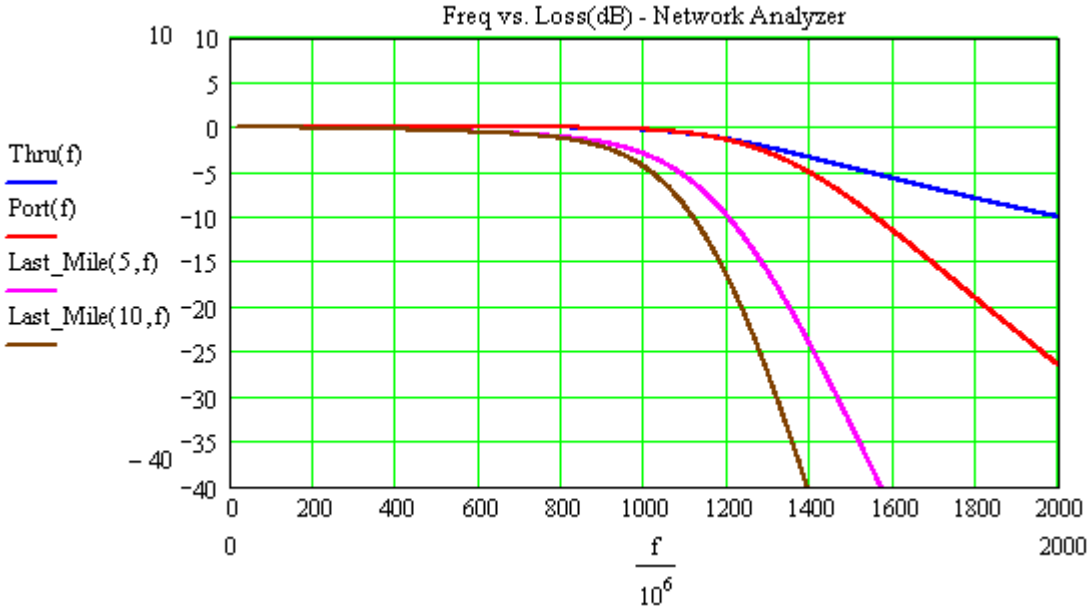


Figure 80 – Modeled Tap + Coax Performance

Thus, this represents an N+0 case ideally, but could also reasonably apply to a short cascade that includes RF amplifiers that pass this band with a flat response as long as there are not more than 5 taps in the series (the 10 Tap case is not shown in Figure 81). It also conservatively assumes a flat transmit response, and, while increasing in frequency, calculates the resulting capacity as this band edge moves to the right.

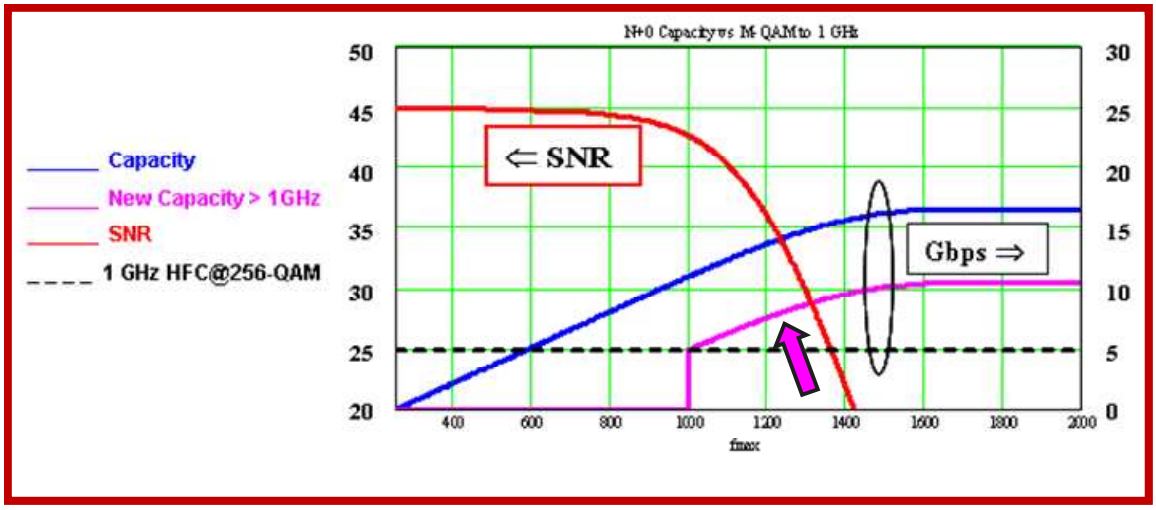


Figure 81 – N+0 Capacity vs. M-QAM to 1GHz

It is reasonable that an uptilt may be applied to compensate for the cable effect at least, but this would amount only to about 3 dB from one band edge to the other. Today's RF outputs are already tilted so as an extension of the payload this could be inherent.

The curves in Figure 81 show a full forward band throughput of 256-QAM , along with the theoretical capacity in Gbps (blue, right vertical axis), for a given maximum upper edge of the band shown on the x-axis. These capacities are shown along with the SNR vs. frequency delivered from a 5-tap cascade made up of taps such as that shown in Figure 78, and one coupled port from the same as shown in Figure 79.

The final trace (pink) recognizes the 256-QAM legacy spectrum as a given, already occupied bloc, and above that identifies new theoretical capacity potentially that can be exploited above 1 GHz in the passive segment as a function of the maximum upper frequency used.

Clearly, within the first 200 MHz above 1 GHz, more than a Gbps of capacity can be extracted. Also apparent is how much latent capacity still exists as the cascades shrink and open up new RF bandwidth potential, considering that 256-QAM is today's maximum modulation profile.

Of course, the expectation of 1024-QAM and perhaps even higher order modulations [1] are expected with the help of new FEC, allowing the "actual" to get closer to the capacity curve. Figure 81 also indicates that beyond 1.4 GHz there is diminishing return on new capacity as attenuation begins to take its toll on SNR.

For high SNR, such as those used in Figure 81, capacity is directly proportional to both bandwidth and SNR expressed in dB

with very small error, a relationship observable in Figure 81.

10.2.3.3 Multicarrier Modulation Optimizes Channel Efficiency

Multicarrier techniques(OFDM)have made it possible to work through seriously impaired frequency response characteristics with high performance. As we observed in Section 7.3 “OFDMA, OFDM & LDPC”, the use of narrow subcarriers vastly simplifies the equalization function, and simultaneously provides the ability to consider each subcarrier independently in terms of the bandwidth efficiency of the modulation profile it can support on a dynamic basis.

Implementing multi-carrier technology for cable is a potentially attractive way to make use of the extended bandwidth of the coax, and because of this is a fundamental recommendation for the DOCSIS NG PHY. Much like xDSL before it, cable can leverage the powerful capabilities of OFDM techniques to most effectively use the current media, and this becomes more important as the use of the spectrum changes over time.

10.2.3.4 Excess Capacity Summary

In summary, here are plenty of available bits per second left to be exploited on the coax. It is expected that the DOCSIS NG PHY, using LDPC for most efficient use of SNR, and OFDM for most efficient use of unpredictable and changing bandwidth, will close the gap considerably on theoretical capacity over the HFC network. The most straightforward way to access this bandwidth is by continuing to migrate to fiber deeper, with a likely end state landing at an N+0 architecture of passive coax, and perhaps for practical purposes in some case N+1 or N+2.

Other useful elements of the migration include new RF technologies, such as GaN amplifiers that deliver more power at equivalent distortion performance can be used in multiple ways to enable this capacity to be accessed – allowing more economical deployment of N+0 long term (more hhp/node), using the additional RF drive capability to drive the new forward spectrum, or taking advantage of analog reclamation to deliver broadband performance based on QAM-only performance requirements.

Lastly, the same architectural option that delivers more capacity from the plant (N+0), bringing the last active and CPE closer together, works also from the receive end of the downstream link. Tied closely to optimal use of new spectrum is the ability to implement a point-of-entry (POE) home gateway architecture long-term.

This approach abstracts the HFC plant from inside the home, terminates downstream PHYs, delivers the bandwidth within the home on an IP network, and rids the access plant of having to overcome uncontrollable in-home losses and architectures.

10.2.4 Architectures for More Excess Bandwidth in The Passive Plant

As comforting as it might be that some plant segments already have some useable bandwidth above the specified top end of the equipment – used in some cases already for legacy extension – Figure 81 obviously behaves asymptotically because of the limitations of existing equipment. In the case evaluated above, it is due to the ultimate limitations of the 1 GHz Taps used in the analysis.

If this limitation could be addressed, then the blue and pink curves shown in Figure 81 would continue to climb, providing access to more capacity, and with only the inherent coaxial attenuation contribution to shaping of the frequency response.

While there is little appetite for the intrusive nature and cost of exchanging all Taps in the plant, an elegant solution to freeing up more very useful spectrum is one that allows more spectrum without a wholesale cut-out of the existing Taps.

Tap models, such as those developed by Javelin, Inc., that allow for only a faceplate change of the existing Tap housing have been on the market to support this concept for some models of Taps in the field.

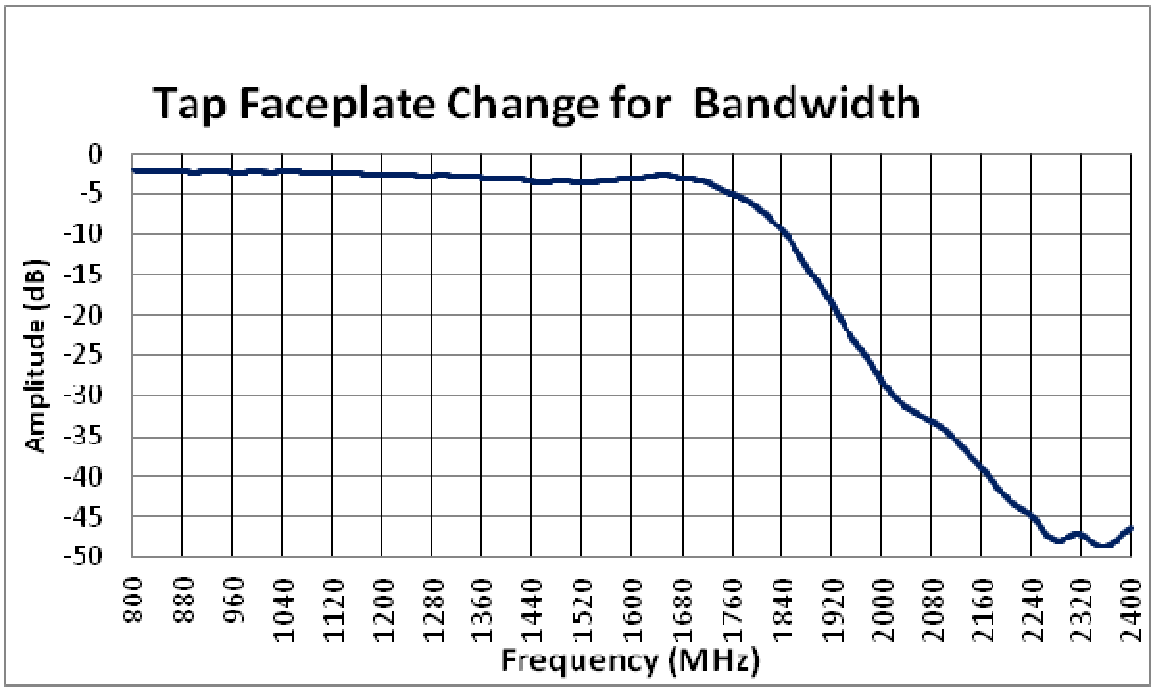


Figure 82 – Modifying Taps to Increase Bandwidth on the Passive Plant

This is a much more simplified and time-efficient process for a field technician, and thus potentially a manageable option to operators looking for the sweet spot of "quick fix" versus bandwidth extraction. Wholesale change-outs can extend the Tap bandwidth to almost 3 GHz.

Figure 82 shows a frequency response of a sample Tap that has had its faceplate removed for the purpose of having the bandwidth extended.

Figure 82 shows a well-behaved passive response to 1.7 GHz. It is straightforward to

estimate the additional capacity this provides using Figure 81. The first 200 MHz of spectrum added slightly less than 3 GHz of new capacity to the forward path. The additional 500 MHz shown in Figure 82 under the same assumption increases the total new capacity available to a little more than 10 Gbps theoretically.

This is a compelling number, as it immediately brings to mind the ability of the properly architected and engineered HFC plant to deliver GEPON-like speeds to its subscribers, without the need to build fiber-to-the-home. Indeed, as pointed out in [1], exploiting all of the available coaxial plant instead of just the legacy spectrum allows HFC to be directly competitive with FTTH rates and services.

Even more simply, using just 1024-QAM, or one order of full modulation profile increase above 256-QAM (not full capacity), we need about 1.2 GHz of spectrum to aggregate to 10 Gbps of transport. Cable is not far from having the tools in place to achieve this already, and new LDPC FEC will make this actually quite simple to achieve.

Figure 83 shows a snapshot of the signal quality measured through an RF leg in the field made up of Taps of the type shown in Figure 82, transmitted *from* the end of a typical 150 ft drop cable (i.e. though passive, a measurement in the upstream direction).

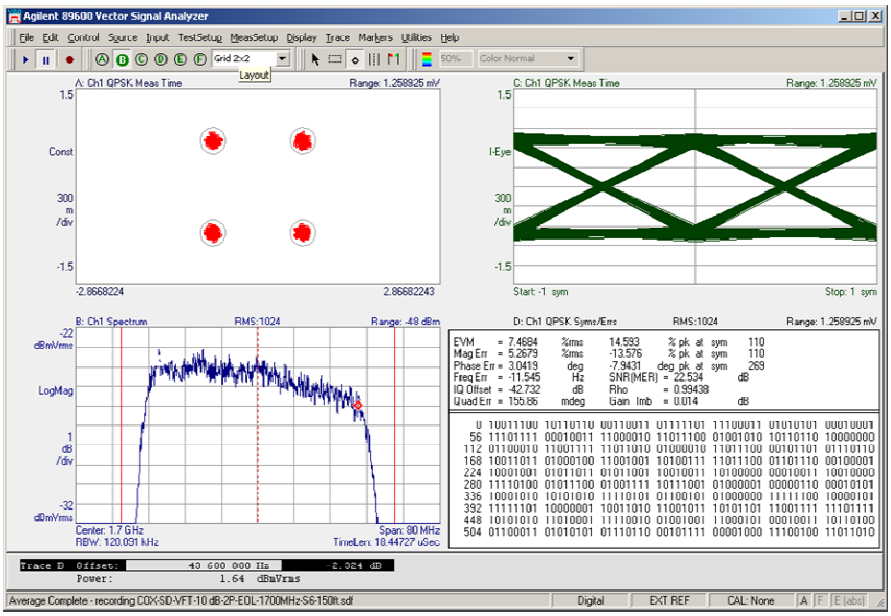


Figure 83 – Wideband (50 Msps) Characterization on Extended Tap BW

There is some obvious droop at the band edge of this unequalized signal, with the drop cable contribution a primary culprit, but it is nonetheless easily corrected. The most important characteristic of Figure 83 has nothing to do with frequency response, but instead with the measured link loss from the end of the drop to the measurement station, sitting at the point where it would represent the first active in an N+0.

This is where "top split" architectures struggle to effective for return path applications. They must overcome in the 60 dB range – potentially worse when considering in-home variations – all tied simply to the relative attenuation characteristics of the low diplex band versus above 1 GHz.

The extended bandwidth taps relieve some of this through loss, but the impact on new CPE is significant in terms of generating broadband, linear, high RF outputs to

overcome the loss and enable bandwidth efficient link budgets.

10.2.5 Summary

Many "1 GHz" Taps have significant, useable excess bandwidth above 1 GHz, although this is not guaranteed by specification. A practical cutoff point for family of Taps with the behavior shown in Figure 78 and Figure 79 for a 5-TAP cascade is between 1.16 GHz and 1.22 GHz.

It is expected that the same can be said above 750 MHz for "750 MHz" Taps and above 870 MHz for "870 MHz" Taps. However, because performance above 1 GHz is unspecified, different TAP models from different vendors are likely to vary in performance.

Faceplate replacement Taps represent a less-intrusive bandwidth extension option for the passive plant than 100% Tap replacement, and yield significant excess capacity.

The primary system issue is simply the RF loss entailed at these frequencies, and for this reason this capacity is most easily accessed for downstream use. The downstream channel already operates to 1 GHz, is highly linear across multiple octaves, delivers very high SNR for QAM, and is designed for broadband high power cost effectively to many users.

Each level of investment in bandwidth corresponds, as expected, to increased intrusiveness and operational expense. For some Tap models, there is virtually free bandwidth on the passive plant to at least 160 MHz above 1 GHz.

With the intrusiveness of a tap faceplate change, there is at least 700 MHz of new bandwidth made available. Finally, if all TAPs are completely replaced, bandwidth out to 2.75 GHz is freed up.

In all cases, standard 1 GHz HFC actives do *not* support the extended bands. And, in all cases, the rules governing RF loss versus frequency across the coaxial cable still exist and become the primary link budget obstacles to high order QAM transmission.

10.3 System Implications of HFC Evolution and Extended Bandwidth

There is already some flexibility in existing outdoor plant platforms. Modern nodes are very modular in nature and offer the flexibility to segment by port. Figure 84 shows the type of modularity most modern HFC nodes have today.

While amplifier platforms have seen less evolution than nodes in the past decade, there

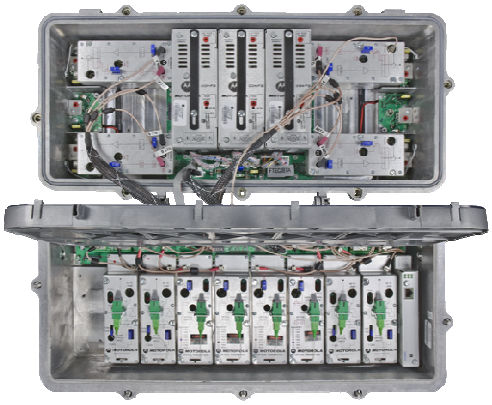


Figure 84 – Modern Node Platforms are Inherently Modular and Increasingly Flexible

has been substantial investment in one area – fielded amplifiers today that can become nodes tomorrow through the swapping of internal plug-ins.

This allows incremental bandwidth improvements as required within the context of the well-understood HFC infrastructure. Some suppliers have developed this capability for their entire RF amplifier portfolio, and it then becomes quite straightforward to envision at least a lower touch evolution to an N+0 deployment built around an existing plant.

Taking the idea of node splitting to it logical conclusion, it ultimately leads to a natural N+0 end-state architecture. It is the final incarnation at which the coaxial cable last mile medium remains, leaving this passive part of the network and infrastructure investment in place.

Now, since these deeper nodes will correspond with adding bandwidth and average bandwidth is about serving group size, practical geography (subscribers don't always tend towards a uniform physical density) may dictate that an active element is still required. And, getting to an N+0 by successively splitting nodes repeatedly until there is nowhere else to go is probably not the most effective way to accomplishing the objective.

Plant geography and diminishing returns on average bandwidth per SG due to imbalance are likely to make this approach and less effective than a managed transition plan, and likely more costly as well.

Note that the march of nodes deeper into the network to N+0 leaves high similarity at the block diagram level to FTTC architectures used in the telco domain. Of course, there are significant differences in signal types on the fiber (at least for now), what is inside the node, and in the electrical medium – copper pair or coaxial. At some point, and possibly within the window of this fiber-deep evolution, the fiber delivery may become more common, leveraging 10 GbE or EPON technologies in both cases.

Table 39 – Total QAM Power with *All* Analog Removed

	Additional QAM Level Available			
	870 MHz		1000 MHz	
Analog-QAM Back-off	870 MHz Uptilt		1000 MHz Uptilt	
	12 dB	14 dB	14 dB	16 dB
-6	2.8 dB	2.5 dB	1.9 dB	1.6 dB
-8	4.2 dB	3.8 dB	2.9 dB	2.5 dB
-10	5.7 dB	5.3 dB	4.2 dB	3.7 dB

10.3.1 Bandwidth and Power Loading

The highest order deployed QAM modulation today is 256-QAM, which delivers a 1e 8 BER at a 34 dB SNR, ignoring coding gain improvements for simplicity. Meanwhile, a modest analog channel requirement is on the order of 45 dB – or 11 dB different.

Some of that large margin is eaten up in the relative signal level back-off, used on the QAM load. Use of 64-QAM levels 10 dB below analog and 256-QAM levels 6 dB below analog are common – and yet still leave significant SNR margin (7 dB and 5 dB in the examples given). These digital offsets can be used as tools in the RF power loading plan, to a degree.

Because of the relationship between analog and digital power and their contribution to the total, when considering analog reclamation, additional power potentially becomes available for QAM signals. This added level means that they could absorb more attenuation from an SNR perspective.

Table 39 shows an example of the theoretically available increase in digital power on the multiplex, given that a fixed total RF output power is required for the mixed multiplex or for an all-digital load.

While this analysis is done for a full digital load, the analysis is easily adaptable to any number of analog carriers. For a small analog carrier count, the difference with "all-QAM" is relatively minor, because the limited set (such as 30) of analog channels are carried at the low end of the band, where their individual powers are smallest under commonly applied RF tilt. An example of stages of analog reclamation is shown in Table 40 for 870 MHz for comparison.

The case of "flat" would represent the change in the forward path multiplex sent across the optical link, while the uptilted cases represent the case out of the node or of

Table 40 – Power Loading Effects of Analog Reclamation - 870 MHz

	Channel Uptilt @ 870 MHz					
	Flat		12 dB		14 dB	
	Delta Ref	QAM Increase	Delta Ref	QAM Increase	Delta Ref	QAM Increase
79 Analog	Ref Load	---	Ref Load	---	Ref Load	---
59 Analog	-0.7	2.5	-1.0	1.5	-0.9	1.5
39 Analog	-1.6	3.5	-1.7	2.5	-1.6	2.0
30 Analog	-2.1	4.0	-2.0	2.5	-1.9	2.5
All Digital	-4.5	4.5	-2.8	3.0	-2.5	2.5

an amplifier where the RF level is tilted to compensate for cable attenuation versus frequency. Typically, it is the optical link which sets HFC SNR, and the RF amplifier cascade that is the dominant contributor to distortions.

What is clear from Table 39 and Table 40 are that the process of analog reclamation offers the potential; for SNR recovery. In the case of beginning with 79 analog slots and migrating to an all digital line-up, there is 4.5 dB of increased digital level available per carrier into the optical transmitter in theory, which can be converted to a better digital SNR.

10.3.2 Extended Bandwidth Loading

If the use of coax is to be extended to frequencies above 1 GHz, power loading will be affected accordingly for non-RF overlay approaches. For the sake of simplicity, we consider two cases:

1) Assume that the applied tilt will be required to extend this band according to the coaxial relationship previously discussed

2) Consider a flat signal band is delivered in the 1-1.5 GHz range, and new technology is burdened with overcoming the limitations of higher attenuation

We will use 1.5 GHz to be consistent with the above discussion on capacity and tap bandwidths. Example cases under these assumptions are shown in Table 41, which illustrates some key points. The starting point is the 1 GHz reference load of sufficient level and performance.

From a power loading standpoint, continuing the tilted response to 1.5 GHz adds a significant power load. However, variations to the tilt approach create a seemingly manageable situation (small dB's) from a power handling standpoint. Hybrids today are typically designed, through their external circuit implementations, to purposely roll-off.

Several 1-1.5 GHz RF loading implementations in Table 41 are relatively non-stressful. If the 1 1.5 GHz band is flat, the additional power load is between 0.4 dB to 3.9 dB. In the situation where the band is extended to 1.5 GHz in conjunction with analog reclamation leaving 30 channels in analog, the increase in total load is limited to 1.2 dB.

In order to maintain a tilted output to 1.5 GHz, an overall digital band de-rate of -10 dB instead of 6 dB keeps the power load hit to less than 4 dB. Given that this may be accompanied by perhaps anN+0 architecture,

Table 41 – Power Loading of Extended Bandwidth

	Analog BW	Digital BW	Digital Derate Relative to Analog (dB)		Digital BW Tilt (dB)		Relative Pwr
	MHz	MHz	550 MHz-1GHz	1-1.5 GHz	550 MHz-1GHz	1-1.5 GHz	dB
Reference	**550**	**450**	**-6**	**Unused**	**14**	**Unused**	**0.0**
Case 1	550	450	-6	-6	14	14	7.4
Case 2	550	450	-10	-10	14	14	3.9
Case 3	550	450	-6	-6	14	0	3.9
Case 4	550	450	-10	-10	14	0	0.9
Case 5	550	450	-6	-15	14	14	2.0
Case 6	265	735	-6	-6	14	14	7.2
Case 7	265	735	-10	-10	14	14	3.3
Case 8	265	735	-6	-6	14	0	1.2
Case 9	265	735	-10	-10	14	0	0.4
Case 10	265	735	-6	-13	14	14	2.2

the 4 dB of power may be available while maintaining sufficient performance because no noise and distortion margin needs to be left for an amplifier cascade. This approach may be more costly in terms of added power, but it is more straightforward to implement a uniform frequency response in a single circuit, than one that tilts part of the band but not another.

A final set of cases that show reasonable loading increase are the 79 channel and 30 channel cases with the tilt maintained, but new derate applied in the 1-1.5 GHz band. To maintain a load increase of <2 dB, an additional 9 dB and 7 dB derate should be applied for 79 and 30 channels, respectively. However, considering the link budgets associated with HFC networks today, dropping the levels this low likely creates a challenge to most efficiently using this band, as this would is then lost SNR and lower capacity.

Summarizing, it appears that various implementation scenarios are eligible for maintaining a reasonable power loading situation while extending the band of the output to 1.5 GHz. This does not account for possible changes in hybrid capability for an extended band. The hybrids themselves have bandwidth up to 1.5 GHz, but the circuits they are designed into are purposefully limiting and optimized for today noise and distortion requirements over legacy bandwidths.

10.3.3 Reduced Cascade Benefits

It is well-understood cable math how shorter cascades result in higher SNR and lower distortion, as the link degradation of adding a relatively short length of fiber is a favorable trade-off with a run of active and passive coaxial plant.

Let's look at a typical example and evaluate this cascade shortening impact. In this case, the link is a 1310 nm link in an N+6 configuration in its original state, and the noise and distortion performance calculated for a 1 GHz multiplex of 79 analog channels.

The link is then modified to an N+0, and the analysis re-run at the same nominal output levels. It was also run for a 4 dB increased output level mode, as the extension to N+0 architectures today may entail a higher output requirement to accommodate the likelihood that the plant geography is not well suited to 100% N+0, and recognizing that the removal of the RF cascade gives distortion margin back that may allow higher output levels. The results of this analysis are shown in Table 42.

Note the emergence of 3-4 dB of additional SNR (CCN or Composite Carrier to Noise). This is independent of any SNR gain due to increasing digital levels that may be possible with analog reclamation per Table 39.

Increasing QAM levels while adding QAM in place of analog is not a fixed dB-per-dB SNR gain, as adding digital channels adds contributors to CCN (composite carrier-to-noise). However, this conversion to CCN also creates a significant drop in CSO and CTB distortions, which are significant impairments for higher order QAM

Table 42 – Performance Effects of N+6 to N+0 Conversion

Performance of 1 GHz Multiplex with 79 Analog			
Parameter	**N+6**	**N+0 (nom)**	**N+0 (high)**
CCN	48	51	51
CSO	56	64	62
CTB	58	70	67

Table 43 – Performance Effects of N+6 to N+0 Conversion

Performance of 1 GHz Multiplex with 30 Analog			
Parameter	N+6	N+0 (nom)	N+0 (high)
CCN	48	52	52
CSO	67	70	70
CTB	68	74	73

performance [1].

Table 43 shows the same parameter set and HFC architecture as used in Table 42, but with an analog channel count of 30. Note the significant improvements in analog beat distortions, as well as the SNR (CCN) behavior. Clearly, the added digital distortion that contributes to CCN is mitigated by the improvements obtained by eliminating the cascade effects.

10.4 Importance of the CPE in the DOCSIS NG Migration Plan

We are proposing that DOCSIS NG have a minimum of two (2) PHYs and a common MAC across these independent PHYs. These PHYs will be at least one of the existing DOCSIS 3.0 upstream PHYs and the downstream PHY. In addition there will be a modern PHY. The placement of DOCSIS NG CPEs in the homes that have both DOCSIS 3.0 and DOCSIS NG PHY provides an evolutionary migration strategy.

This will allow the MSO to use the legacy DOCSIS 3.0 PHYs while the cable operator grows the installed base of DOCSIS NG CPEs in their subscriber homes. At such time there are sufficient numbers of DOCSIS NG CPE deployed, the MSO may allocate a few channels to the new DOCSIS NG PHY.

By supporting legacy and modern PHYs within the same CM, the MSOs can smoothly transition to the modern PHY as the legacy CPEs decrease in numbers.

11 RECOMMENDATIONS

This section summarizes the recommendation of the authors. A more extensive explanation of each decision can be found the in the rest of this white paper.

11.1 Areas of Consensus

Compatibility

The recommendation is to define a backwards compatibility goal that would allow the same spectrum to be used for current DOCSIS CMs and new DOCSIS NG CMs.

In this context, co-existence refers to the concept that DOCSIS NG would use separate spectrum but coexist on the same HFC plant. Backwards compatibility would refer to the sharing of spectrum between current DOCSIS and DOCSIS NG.

One example of this strategy would require a 5 to 42 MHz spectrum to be used for four carriers (or more) of DOCSIS 3.0. At the same time, a DOCSIS NG CM would be able to use the same four channels (or more) plus any additional bandwidth that a new PHY might be able to take advantage of.

Upstream Spectrum

The immediate goal with DOCSIS NG is to get as much throughput as possible in the existing upstream 5 to 42 MHz (5 to 65 MHz) spectrum.

This goal recognizes that it will take time, money, and effort to upgrade the HFC plant. The initial goal will to see how more advanced CMTS and CM technology can extend the life of the current HFC plant.

The short-term recommendation for upstream spectrum is mid-split.

Mid-split can be achieved with today's DOCSIS 3.0 technology. If an HFC plant upgrade strategy could be defined that would allow a cost effective two-stage upgrade, first to mid-split, and then later to high-split, then the advantage of higher data rates can be seen sooner.

Conversely, if downstream spectrum is available, an HFC plant could be upgraded to high-split sooner, but would start by deploying mid-split DOCSIS 3.0 equipment.

The long-term recommendation for upstream spectrum is high-split.

High-split offers the best technical solution that should lead to the highest performance product at the best price. The logistical challenges that high-split encounters are not to be underestimated but they are both solvable and manageable, and significantly less imposing than a “top-split” approach.

Downstream Spectrum

The short term goal is to make use of any and all available tools to manage downstream spectrum congestion, such as analog reclamation, SDV, H.264 and deploy 1 GHz plant equipment whenever possible.

This goal includes an expanded upstream spectrum within the current operating spectrum of the HFC plant.

The long-term goal is to utilize spectrum above 1 GHz, and push towards 1.7 GHz.

Field measurements have shown that the spectrum up to 1.2 GHz is available in the passive RF link. Measurements also show that up to 1.7 GHz is available with modest plant intrusiveness. Spectrum above 1 GHz is unspecified, and inherently more challenging than the standard HFC band and thus should take advantage of advanced modulation techniques such as OFDM.

New US PHY Layer

The recommendation for DOCSIS NG upstream is to add OFDMA with an LDPC FEC.

There is considerable new spectrum with DOCSIS NG that only requires a single modulation. Although ATDMA and SCDMA could be extended, now is a unique time to upgrade the DOCSIS PHY to include the best technology available, which the team feels is OFDMA and LDPC FEC.

New DS PHY Layer

The recommendation for DOCSIS NG downstream is to add OFDM with LDPC FEC.

Using the spectrum above 1 GHz will require an advanced PHY such as OFDM. To minimize the cost impact on CMs, a cap could be placed on the number of QAM channels required. OFDM will also be used below 1 GHz, and likely supplant legacy QAM bandwidth over time.

PAPR

We do not anticipate PAPR issues with multicarrier modulation for the upstream or the downstream when compared with single carrier channel bonded DOCSIS.

It is recognized that PAPR for multi-carrier technologies such as OFDM is worse than a single isolated QAM carrier. However, as the number of SC-QAMs in a given spectrum are increased, multiple SC-QAM and OFDM exhibit similar Gaussian characteristics.

Higher Orders of Modulation

The recommendation is to study the option to define up to 4K QAM for OFDM in both the upstream and downstream.

These new modulations may not be usable today. However, as fiber goes deeper coax runs become shorter, and other possible architectural changes are considered (POE home gateway, digital optics with remote PHY), there may be opportunities to use higher orders of modulation. The DOCSIS NG PHY will define these options.

SCDMA Support in a DOCSIS NG CM

The recommendation is to not require SCDMA in a DOCSIS NG CM that employs OFDMA

It is generally agreed that OFDMA with LDPC will be able to replace the role that SCDMA and ATDMA perform today. Thus, in a DOCSIS NG CM, SCDMA would be redundant.

US MAC Layer Baseline

The recommendation is to use the SCDMA MAC functionality as a basis for designing the OFDMA MAC layer.

The SCDMA MAC layer is very similar to the ATDMA MAC layer that has allowed upstream scheduling and QOS services to be near seamless between the two current modulations. This structure is to be extended over OFDM so that the new PHY has a less impact on the rest of the DOCSIS system.

11.2 Areas of Further Study

Some of these decisions require additional information. Some of these decisions have most of the required information and just lack consensus.

High-Split Cross-Over Frequencies

Further study is required to determine the upper frequency of the high-split upstream spectrum and the lower frequency of the downstream spectrum.

At this time, we are not sure the right choice of upstream band edge to achieve 1 Gbps throughput with satisfactory coverage and robustness. This will depend upon the base modulation chosen, FEC overhead, and if there are any areas of spectrum that cannot be used. There will likely be a reference configuration that will pass 1 Gbps and other configurations that will run slower or faster.

There may even be a set of frequencies that matches a 1.0 GHz HFC plant, and a different set of frequencies that matches up to a 1.7 GHz HFC Plant.

There may also be the ability to configure the cross-over frequency in the HFC plant so that it can be changed over time with shifts in traffic patterns. Similar flexibility in the CM could also be considered.

ATDMA in the Upstream

Further study is required to determine how may ATDMA channels a CM and a CMTS should support in the upstream.

Many cable operators are already deploying three full-width carriers or four carriers of mixed widths between 20 MHz and 42 MHz. In order to fully utilize a 5 to 42 MHz spectrum, a DOCSIS NG CM would need to support these channels, so four is the minimum. Newer DOCSIS 3.0 CMs promise 8 upstream channels. It depends upon the market penetration of these CMs as to the impact on backwards compatibility.

Some networks may have migrated to an 85 MHz mid-split before any DOCSIS NG CMs are available, and these would then be A-TDMA channels. Timing of such activity might define minimum channel requirements for the NG CM.

The CMTS may need more QAM channels than the CM. The CMTS needs to have a spare ATDMA channel to support DSG. It also needs to have an ATMDA channel running at a lower rate to support DOCSIS 1.1 CMs. These may be in addition to the 3-4 channels for DOCSIS 3.0.

SCDMA in the CMTS

Further study is required to determine if SCDMA should be retained.

It is generally agreed that SCDMA does offer better performance below 20 MHz (in North America, higher in other countries with worse plant) than ATDMA. For DOCSIS 3.0, SCDMA may be required to get that extra fourth full-size carrier, and is an important component for maximizing the throughput available in 5-42 MHz band.

Retaining SCDMA in addition to ATDMA and OFDMA potentially adds product cost, development cost, and testing cost. This has to be weighed against any significant market penetration of SCDMA prior to DOCSIS NG being available.

One possible approach is to specify a small number of channels of SCDMA as mandatory and more channels optional. However, an overall objective is to try and get to only one or two PHY technologies in

the CMTS silicon that would imply the elimination of SCDMA.

Early deployment of mid-split would also help negate the need for SCDMA, as that would provide the extra spectrum to relieve the congestion in 5-42 MHz

Advanced FEC for Single Carrier Systems

Further study is required to determine if LDPC FEC functionality should be added to enhance the existing upstream and downstream PHY.

The argument for doing this is that the bulk of new capacity comes from advanced FEC, and existing SC QAM that co-exists on the silicon should benefit from this investment to optimize efficiency in systems that will be operating single carrier mode for many more years. The argument for not doing this is to cap the legacy design and only expand capability with OFDM.

Expansion of Upstream ATDMA Capabilities

Further study is required to determine if ATDMA functionality should be extended with wider channels, more channels, higher order modulation formats, and improved alpha.

The argument for doing this work is that they represent simple extensions of DOCSIS 3.0, and field experience and RF characterization of A-TDMA tools suggests a high probability of success. The argument for not doing this is to cap the legacy design and only expand capability with OFDM, and that an OFDM implementation would be less complex.

Expansion of Downstream QAM Capabilities

Further study is required to determine if downstream QAM functionality, currently defined by ITU-T J.83, should be extended with wider channels and higher order modulation formats.

The argument for doing this work is that they represent simple extensions of DOCSIS 3.0 and field experience and characterization of A-TDMA SC tools suggests a high probability of success. The argument for not doing this is to cap the legacy design and focus on expanding capability only with OFDM, and that an OFDM implementation would be less complex.

US MAC Improvements

Further study is required to determine if any changes not directly related to OFDM are worth pursuing.

Current suggestions include changing the request mechanism from request-based to queue-based, elimination of 16-bit minislots, and not including request slots on each upstream carrier.

Modifications need to be weighed against increases in performance, decrease in cost, and the need for backwards compatibility.

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