ARCHITECTING THE DOCSIS® NETWORK TO OFFER SYMMETRIC 1GBPS SERVICE OVER THE NEXT TWO DECADES

Ayham Al-Banna
ARRIS Group, Inc.

Abstract

The paper analyzes various options to increase the capacity of HFC networks in order to meet the capacity demands over the next two decades. A smooth migration plan is proposed to enable MSOs offering beyond than 1Gbps US service. A High-split prototype system is built and initial results are introduced.

1. INTRODUCTION

The current architecture of Hybrid Fiber Coaxial cable (HFC) networks along with the exponential growth in bandwidth demand are placing the cable Multiple Service Operators (MSOs) at competitive disadvantage as they face capacity limitations. These limitations may preclude the MSOs from satisfying the customers' demands if not properly addressed.

In order for the MSOs to maintain their business and offer more services at faster speeds (e.g., services to business customers, IPTV fans, gamers, etc.), they need to immediately start brainstorming, architecting, and upgrading their networks in ways that will meet the pressing bandwidth demands. This process requires taking smart and gradual steps toward the goal system architecture, which will support beyond than symmetrical 1Gbps service.

Multiple factors need to be considered while going through the system and plant migration: cost, network architecture, spectrum allocation, operational issues, technical challenges, headend equipment (e.g., Converged Cable Access Platform (CCAP) compatible?, servers scale?, etc.), customers Quality of Experience (QoE), etc. The list goes on! Not only do MSOs have to think about the above factors as they prepare their networks for future services, they also need to think thoroughly about the appropriate sequence of steps to take such that an optimal architecture is achieved. The optimal architecture can be defined as a flexible network topology that results in maximum capacity and minimum cost over extended periods of time.

This paper is organized as follows. Section 2 describes the traffic growth trends based on recent real data. Several multiple factors that play heavily in the decision process of network migrations are briefly described in Section 3. Section 4 lists and analyzes the available options to extend the US BW to offer 1Gbps service. A sample plan that offers *smooth* migration steps to result in an optimal network architecture, which offers symmetric 1Gbps architecture and multi-gigabit system in the future, is described in Section 5. Section 6 concludes the paper.

2. RECENT TRENDS IN BW DEMAND

The traffic demand has been growing exponentially for the last 30 years. Different applications and services appeared at different times over the last three decades to ensure that the traffic growth stays on track! Among many, business services, gaming, and IPTV make today's motivation for guaranteed traffic growth for the next few years. The constant traffic growth over the past three decades is shown in Fig. 1, which shows the maximum DS rate per subscriber over cable networks [1]. This curve is sometimes referred to as the Nielsen curve for Cable networks.

Recent data obtained from different MSOs shows similar growth pattern for the average traffic on their networks. In particular, Fig. 2 shows the DS BW Average Cumulative Growth Rate (CAGR) per subscriber for three different MSOs over the past couple of years. Note that the CAGR value for all MSOs is more than 50% per year. Figure 3, on the other hand, depicts the US BW CAGR per subscriber over the past two years for two different MSOs. Observe from the figure that the CAGR averaged over both MSOs results in an US BW growth rate of about 30% per year.

The data in Fig. 2 and Fig. 3 shows that while some MSOs may observe slow growth rate on their networks, other MSOs observe larger growth rates. Additionally, the cumulative traffic growth averaged over all MSOs for the past two years agrees with the traffic growth trend observed for the past thirty years as was shown in Fig. 1.

From Figs. 1 through 3, the average DS and US BW per subscriber CAGR is shown to be >50% and 30%, respectively, for the past thirty years. Therefore, it might be reasonable to assume that the traffic growth will maintain the same trend in the future. In subsequent analyses in this paper, where we focus on the US BW problem in HFC networks, we assume that the US CAGR is at 30% on average.

Given that the US CAGR is at 30%, the question at hand is: when will the current 5-42MHz spectrum be totally consumed and therefore an upgrade of some sort is necessary? The answer to that question not only depends on the US CAGR, but also on the value of the maximum offered subscriber rate (Tmax) today. Between the US CAGR and Tmax values offered today, it will be straightforward to predict when the current US spectrum runs out of capacity, which will be shown later in this section.

The maximum offered rates have been published recently [2]. Table 1 shows DS and US Tmax values currently offered in North America. Note that the table lists Tmax values offered by different industries (Cable and others). Tables 2 and 3, show DS Tmax values offered by different MSOs in Europe. Observe that some European MSOs offer higher rates than their counterparts in North America. In particular, the maximum DS Tmax currently offered in Europe is 360Mbps by Zon Multimedia (See Table 3). The current offering of Zon for DS Tmax and US Tmax shows a constant ratio of 15 between the rates. Therefore, the US Tmax value offered by Zon is assumed to be around 24Mbps. Note that this is close to the 20Mbps US Tmax being offered by Videotron in North America.

One important point to observe from Table 1 is that the maximum Tmax service is offered by Verizon, which is not a cable MSO! Therefore, in addition to customer traffic demand, Table 1 clearly shows the other side of the equation that pushes cable MSOs to add capacity to their networks: Competition!

With the assumptions that the US CAGR is 30% and the current offered US Tmax value is 24Mbps, the next step is to calculate the time when the current US spectrum runs out of capacity. Given a certain US Tmax value per subscriber, some MSOs might consider providing a total capacity of 1.5*Tmax in order to offer service with adequate Quality of Experience (QoE) to their subscribers. Other MSOs might choose other factors that are different from 1.5*Tmax (e.g., 2*Tmax). For the analysis in this paper, we assume that a capacity of 1.5*Tmax is required in order to offer good QoE service for customers with Tmax as the maximum rate per subscriber.

Figure 4 shows the extrapolated growth of US Tmax per subscriber using the above assumptions. Note that the current US spectrum (5-42MHz) capacity is assumed to be around 133Mbps. This is because the total BW of 37MHz may not be completely usable at the highest possible modulation order (some channels can potentially run at QAM256 while others will run at QAM16). Also, strong FEC is assumed for the same reason (some parts of the spectrum are very clean while others are really challenging). The combination of moderate order modulation order (QAM64) and strong FEC (code rate = 0.75) compensates for noisy channels, unusable spectrum, and spectrum that used for services other than data). The total capacity of 133Mbps might be close to what MSOs can achieve in the real-world from the 5-42MHz spectrum. You may notice that this number is a little higher than the more conservative estimates that have been published earlier by the ARRIS' team (the author included) [3], which assumed a total capacity for the 5-42MHz to be around 118Mbps. Upcoming sections in this paper, where comparisons between the capacities of different split options is provided, will refer to the past capacity work and will point out that the estimates might be a little conservative and therefore can be slightly increased. In all cases, the total capacity always depends on the plant condition and MSO's usage plan for the spectrum. Observe, however, that the difference in capacity numbers (15Mbps) due to different assumptions is not significant given the Tmax CAGR growth rate shown earlier.

Observe in Fig. 4 that the current US spectrum runs out of Tmax capacity just before year 2017. This corresponds to service offering of Tmax~90Mbps. Note that 1Gbps US Tmax service will be required around year 2026, if not earlier. One may realize that it not too early to start planning for network architecture updates and migration strategies in order to offer capacities that satisfy the projected traffic demands over the upcoming years.

3. PLAYING FACTORS IN HFC NETWORKS MIGRATION

This section briefly describes the various factors to be taken into consideration while going through the system and plant migration process in order to meet the capacity demands over the next two decades. Not only these elements need to be studied thoroughly, but also the interaction between them needs to be analyzed carefully. The interaction happens because some elements depend on others, where the choice of some elements affects the choice of others. There might be no one ideal solution for all MSOs. However, different MSOs may have different optimal solutions depending on their position from the factors listed below.

3.1. Network Architecture

Both the components composing the network and network topology affect the performance heavily. The number and characteristics of amplifiers, line extenders, bridgers, taps, and other passive devices affect both signal loss and noise. The characteristics of some of these equipment also define the operational BW where signals can be transmitted in the DS or US direction. The type and length of coaxial cables (trunk and drop) affect the signal loss too. The length and type of fiber links as well as the features of the optical transmitter and receiver also affect the performance.

How deep the fiber node in the plant affects the performance. For example, longer cascades results in more attenuation, noise, and worse filters roll-offs, which impair the signals transmitted around band edges. Shorter cascades on the other hand, result in better network performance.

Networks topology needs to be analyzed frequently because the plant topology changes over time as MSOs update their network to expand the capacity of their networks. The change in network topology may affect various customers differently depending on the location of the customer relative to the network update. Specifically, Fig. 4 shows an example of N+5 network topology. After node segmentation and splitting, the network topology becomes as shown in Fig. 5. Note that it is sometimes difficult to balance the number of subscribers between new fiber nodes as apparent from Fig. 5, which affect the capacity per subscriber. Also, the example in Fig. 5 is a good illustration to the node splitting and segmentation process whose output does not guarantee that new nodes have the same cascade length. Figure 5 shows that the resultant nodes possess different lengths (i.e., different number of cascaded amplifiers behind the fiber nodes). Again, this affects the attenuation, noise, and therefore capacity.

The number of cascaded amplifiers behind a fiber node has declined over the years. Some MSOs estimate the current average of their networks to be at N+5 (to N+6)[1]. The current network topologies along with the limited US spectrum (5-42MHz in the USA, 5-65MHz in Europe) place a tight limit on the capacity that can be offered by today's networks and therefore gradual sequential upgrades will be necessary to cover the demand as well as competition over the next two decades!

3.2. Spectrum Allocation

This is a critical topic because it touches many areas. The choice of which split to choose for the US spectrum (mid-split, high-split, top-split) comes as a result of studies of technical feasibility, which analyzes the technical challenges and offered capacity associated with the implementation of each split option. Besides cost, operational aspects are affected depending on the chosen split. For example, affected operational parts include: reclaiming/reallocating analog TV channels, moving DS spectrum, capping DS BW, transition bands (guard bands between DS and US), addressing the Out-Of-Band (OOB) signaling of Set-Top Boxes (STB), etc. This factor (spectrum allocation) is studied in more details in later sections of this paper.

3.3. Operational Issues

Various Operational issues are to be addressed when network migration occurs. Depending on the network architecture and the update to occur, operational aspect that can be affected include: Analog channels reclamation and reassignment, specifying spectrum for DOCSIS and digital channels, addressing STB OOB signaling, DOCSIS and Video management, network maintenance process (depending on equipment being in the headend or in the headend and FN together), network reliability and availability (again, related to equipment being in headend or in headend and FN). Observe that placing more intelligent equipment in the FN introduces higher risk in terms of network availability and reliability. Some of these operational aspects will be addressed in later sections of this paper.

3.4. Technical Challenges

The technical aspects of any solution or proposed network update must be studied thoroughly. The technical study results in recommendations regarding feasibility, cost, capacity estimates, and implementation requirements. For example, the feasibility of certain US spectrum split is a function of the signal attenuation experienced on that split. Another example of how technical studies are important is that understanding the different noise and channel impairments, which exist

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[1] The total number of actives behind a single FN is currently estimated to be around 30.

on different parts of the spectrum and how they can be mitigated via different PHY and MAC technologies, will affect the proposed solution requirements, capacity, efficiency, and cost. A technical evaluation of different capacity-expanding options is included later in this paper, where a migration plan is proposed.

3.5. Headend Equipment

While network topology affects the system performance and offered services, headend equipment also plays a major role into that. The MSOs needs to make sure they specify requirements for products that can scale very well with the projected service offerings. This scale is related to number of channels as well as number of service groups, service group size, servers scale, management and scale of IP addressing scheme (IPv4 & IPv6), etc.

Additionally, not only scale is important, but also the architecture of the headend equipment should be chosen to minimize cost and maximize capacity. Available architectures include Integrated and modular. The MSOs need to make sure they place requirements that result in optimal system architecture in terms of capacity and cost.

On a side note, the Cable industry already started the effort of specifying the scale and requirements of the next generation network architecture, where different requirements were listed in the Converged Cable Access Platform (CCAP) specifications.

3.6. Quality of Experience (QoE)

Quality of Experience is one of the most challenging topics to be addressed. The problem with this topic is that it deals with the customer's perception about the service. The MSO has to collect various system and traffic parameters in order to analyze how the service offering is rated in the customer's eye. The MSOs normally works with system vendors on developing different algorithms and performance metrics that measure the satisfaction of the customers. In this kind of analysis, good questions to be addressed include: For how many seconds can the subscriber wait for a webpage to download? What is the webpage size that the customer is trying to download? How often is he online? How often does he jump between pages while online? What about games latency? What is the pattern of the traffic of a certain game? Does that apply to all games? Does statistical multiplexing help? If so, how does it interact with the number of bonded channels?, etc. The list can go forever!

In order to make sure that the customer has good QoE, the MSOs also need to understand how networks availability affects QoE. Additionally, the effect of the FN size, SG size, offered Tmax needs to be analyzed and understood. Then, the MSO may need to work with system vendors to create algorithms that manage latency and service flows priorities to result in best potential customer QoE.

3.7. Cost

This is the most important factor to consider when planning networks migrations. It is a function of all of the above factors. The goal of network migration is to offer adequate capacity at minimum cost. In many scenarios, the MSOs use the cost per unit of BW as a metric to decide between different proposed solutions. The cost of a certain proposal should take into consideration the investment protection provided by different solutions. It is instructive here to mention that backward compatibility can offer large cost savings, for most of the time, as it capitalizes on using the established base. In many cases, the savings exceed the added cost and complexity which occur when requiring that the new solution be backward compatible with the existing technology.

3.8. Next Steps & Sequence of Steps

There are many network topology options to consider when it comes to the plant migration. These options include: utilizing the available spectrum efficiently, expand the US spectrum, introduce new techniques for better spectral efficiency (like more efficient Forward Error Correction (FEC)), introduce new robust and more efficient PHY technologies (like Orthogonal Frequency Division Multiplexing (OFDM)), require backward compatibility for added enhancements, Go deeper with fiber, etc.

The decision of choosing particular options and the sequence of implementing the options depend on all of the above factors that need to be analyzed thoroughly. In particular, the available options listed above need to be evaluated technically, operationally, and financially. The purpose of this paper, in the next few sections, is to analyze these proposals from the technical point view to provide recommendations to the MSOs as they brainstorm about their network. The technical analysis will provide implications regarding the cost of different solutions. Some options will also be evaluated from the operational point view.

4. OPTIONS TO ACHIEVE 1GBPS IN THE UPSTREAM

This section lists and analyzes the different options, from which the MSOs can choose when planning networks updates in order to produce the goal network architecture. Along with the analysis, technical and operational challenges that may appear throughout the migration process will be exposed and addressed.

4.1. Utilizing the Available BW Efficiently

The utilization of the current 5-42MHz spectrum is far from efficient. In particular, there are portions of the spectrum that are not used at all, while other parts are used inefficiently such that the obtained capacity is way less than what can be potentially offered by that part of the spectrum.

The DOCSIS3.0 has many tools and features in order to help the MSOs achieve the best capacity out of their US spectrum [4] [5] [6] [12]. Some of these parameters include:

- Multiple access technologies (e.g., Advanced Time Division Multiple Access (ATDMA) and Synchronous Code Division Multiple Access (SCDMA)). SCDMA can be very helpful in fighting impulse noise in the lower part of the 5-42MHz spectrum.
- Center frequency selection
- Symbol rate range (0.16 – 5.12 Msymbol/sec)
- Modulation orders (QPSK, 8QAM, 16QAM, 32QAM, or 64QAM)
- Reed-Solomon Forward Error Correction (RS-FEC) to correct up to 16 bytes
- Codeword size selection
- 24-tap pre-equalization
- Long preambles up to 1536 bits
- Ability to adjust to longer/more powerful Preambles
- Proprietary noise mitigation techniques
    - Ex: Ingress Noise Cancellation
- ATDMA Interleaving…
- SCDMA Interleaving
- SCDMA de-spreading
- SCDMA spreading
- SCDMA Trellis Coded Modulation (TCM)
- SCDMA Maximum Scheduled Codes (MSC) feature
- SCDMA Selective Active Codes (SAC) feature
- Channel bonding (MAC layer feature used for PHY layer noise mitigation)
- & Many Many others (Last Codeword Shortened (LCS), max burst size,

scramble seed, differential encoding, etc.)

Detailed analysis of utilizing the above tools and optimizing the spectrum usage can be found in [4] [5] [6]. The abundance of parameters and the flexibility in choosing their values makes it a challenge to optimize them to result in the best spectral efficiency. Therefore, automated tools can be used to measure the different types of noise and also search the solution space of all the parameters and choose the optimal ones that result in the best spectral efficiency. For example, Fig.7 shows that the spectrum can have different types of noise in different portions. Therefore, the automated algorithm shown in Fig. 7 captures the noise in the channel and specifies the best modulation profile and channel parameters that result in the best spectral efficiency. Any automated algorithm needs to have the flexibility to specify constraints for the optimal solution. This is highly desired especially if the MSO does not want to use certain parameters or want to specify certain range for specific parameters. An example of that is shown in Fig. 8, where the algorithm can accept multiple constraints and then searches the constrained solution space to find the optimal parameters that result in the best spectral efficiency.

4.2. Segmenting and Splitting Nodes

Examples of node splits and segmentations were provided in previous sections. The process of node split and segmentation helps in many ways:

- Less Noise funneling as a result of reducing the number of subscribers per node or service group. Lower noise translates to higher SNR and therefore increased capacity.
- Less attenuation because: the deeper the node is, the shorter the coaxial cable becomes, and therefore less signal attenuation is introduced. The lower attenuation translates to higher SNR and therefore increased capacity.
- More average capacity per subscriber. This comes as a natural result of reducing the number of subscribers per node or service group.
- Less contention for BW. Again, this is a natural result of reducing the number of subscribers per node or service group. The reduction in BW contention makes the assumption of requiring 1.5Tmax (or 2Tmax) of capacity to offer Tmax service more reasonable.

Since node splits and segmentations offer all of the above benefits and increased capacity, one may think of performing this process infinitely as demand increases. This, in fact, can be a good approach! However, the cost of node splits rise exponentially every times they are to be performed because the number of resultant nodes doubles after every node split operation. Therefore, there will be a time, when performing the next node split operation will cost more than changing the US spectrum split or laying fibers all the way to the homes or and therefore the natural step after those many node split operations becomes Fiber To The Home (FTTH). This will then make the most reasonable decision from cost point view and also offers multiple times of capacity that may actually be needed by that time.

4.3. Adding More US Spectrum

At some point in the future, the MSOs will need to add more US spectrum to their networks to provide enough capacity to meet the traffic demands. Adding more US spectrum can take many forms: mid-split (5-85MHz), High-split (5-200MHz, 5-238MHz, 5-300MHz, etc.), and top-split (placing US spectrum above the current DS BW). This is shown in Fig. 9 and Fig. 10.

The above splits can be classified into two categories: diplex category (mid-split and high-split), and triplex category (top-split). In particular, in the diplex category, there is only one transition band in the spectrum which separates the US spectrum below the transition band and the DS spectrum above the transition band as shown in Fig. 9. The triplex category, on the other hand, contains two transition bands separating the US and DS spectra as shown in Fig. 10. Specifically, in the triplex architecture, the lower part of the spectrum is used by US traffic, which is followed by the first transition band that is followed by the DS spectrum. The second transition band sits above the DS spectrum and separates it from the US spectrum at the top.

In order for the MSOs to have enough capacity to offer 1Gbps Tmax service and beyond, they will need to move to either high-split or top-split as a goal architecture. This is because mid-split does not offer enough capacity and also MSOs may choose to move from sub-split to high-split directly (instead of going through mid-split) in order to save on the cost of plan upgrade. In particular, the move from sub-split to high-split directly avoids the need to touch the plan multiple times. Other MSOs, however, might choose to go through the mid-split step in order to avoid addressing the OOB STB signaling issue for few years, which allows them to phase out these STBs before moving to high-split architecture.

There are multiple advantages and disadvantage for both the top-split and high-split options. Some of the advantages of the top-split option are:

1. It does not interfere with the OOB STB signaling (frequency range is 70-130MHz).
2. The DS spectrum layout does not need to change. No video channels are affected.

On the other hand, there are several disadvantages for the top-split option including:

1. High signal attenuation, which results in reduced total capacity and inefficient spectrum usage (analysis shown later).
2. More expensive than the high-split option [3].
3. Requires two transition bands which translate to wasted capacity.
4. Requires large bandwidth for the top transition band. In general, the bandwidth of the transition band depends on the frequency of the band. Since the top transition band occurs at high frequency, the transition band bandwidth will be large and this translates to more wasted capacity.
5. Places a cap on the growth of DS spectrum. Once the US spectrum is placed on the top of the DS spectrum, there will be no room to expand the BW of the DS spectrum. Any future growth for the DS will be very challenging because it has to be on the top of the US spectrum and therefore results in these exact disadvantages of wasted capacity (if that option is ever feasible).
6. Requires high modem transmit power for reliable transmission (still at lower capacity).
7. Requires changing all actives to introduce the second transition band.

The high-split architecture, on the other hand, has various advantages including:

1. Offers the highest system capacity (analysis shown later).
2. Less signal attenuation.
3. Single transition band is required.
4. The transition band is narrow because it happens at low frequency.
5. Offers the cheapest solution [3].
6. Does not place a limit on the growth of the DS spectrum.

7. Leverages some of the existing HFC components like laser transmitters and receivers as some of them do support the high-split BW.
8. Offers some backward compatibility because the current DOCSIS3.0 specifications have the US DOCSIS defined from 5-85MHz. This capability already exists in the hardware of various CMTS and modem equipment.

Some of the disadvantages of the high-split option are:

1. It interferes with the OOB STB signaling.
3. It affects the layout of the DS spectrum because the bottom part of the DS spectrum is chewed by the new US spectrum. Some modifications to the DS spectrum layout and channel assignments need to occur.
2. Requires changing all actives to move the current transition band to a higher frequency.

As mentioned above, one of the challenges introduced by the high-split architecture is addressing the OOB STB signaling scheme. There are different scenarios for addressing this issue including:

1. Some MSOs do not have this issue because they have IP or DOCSIS STBs deployed as opposed to legacy STBs which require the signaling in the frequency range 70-130MHz.
2. Phase-out legacy STBs out of the plant. Some MSOs use 9 years as turn-over time for their STBs. Therefore, if the MSOs plan to move to the high-split option in the future and start planning accordingly, the legacy STB problem may not be an issue. The MSOs still have at least 5 years before they need to make any change with the spectrum from a Tmax perspective. This was illustrated in Fig. 4, where the offered Tmax capacity by the current 5-42MHz spectrum runs out of steam around 2017, when the MSO can offer about 90Mbps (assuming that a required channel capacity of 1.5Tmax to offer Tmax service). Note, however, that if the MSOs assume 2Tmax capacity is needed to offer Tmax service, the 5-42MHz spectrum will be consumed (from Tmax point view) one year elarier, namely in 2016, enabling the MSOs to offer Tmax service of ~70Mbps by then. The date, when the capacity of the 5-42MHz spectrum is consumed, can be pushed further in the future if spectrum is used more efficiently via optimizing modulations profiles parameters (shown in earlier sections) and introducing DOCSIS enhancements (will be explained in later sections).
3. Use up-conversion and down-conversion techniques to move the STB signals to higher frequencies beyond the high-split limit. Several approaches are available to perform this, where each approach has its own advantages and disadvantages. The discussion of these solutions is outside the scope of this paper.

Extensive analysis has been done by the ARRIS' team (the author included) to compare different split options from cost and capacity point view [3]. The detailed analysis in [3] is summarized here for convenience. This analysis shows that the high-split option is the most economical solution that offers the highest capacity.

The assumptions used in this analysis are kind of conservative because it was assumed that parts of the spectrum are completely unusable (which may not be the case in most plants). Also, the analysis defines the capacity to be the available DOCSIS3.0 bonding capacity offered by the spectrum. In other words, the analysis does not assume channels used for legacy devices or spectrum monitoring to be part of the available capacity. Specifically, only 22.4MHz was assumed to generate the capacity numbers for the 5-42MHz spectrum. This was rationalized by the different items listed in Table 4. Others assumptions used for this analysis are shown in Tables 5 and 6, while the analysis results are shown in Fig. 11. As mentioned earlier, these numbers can be slightly increased because the assumptions were a little conservative. However, this may not change the course of actions that the MSOs need to do to augment their networks because the difference is insignificant compared to the CAGR of US Tmax.

As can be seen from the above analysis, the high-split option makes the best potential choice for the US spectrum as MSOs plan to upgrade their networks to offer adequate capacity for the required Tmax offerings. Therefore, ARRIS has built a high-split prototype system to mimic the example real-world N+3 network architecture shown in Fig. 12. The real prototype setup is show in Fig. 13. In Fig. 13, all of the active HFC components are ARRIS-made and modified and support 200MHz high-split operation.

The purpose of this effort is to characterize the system and identify any potential limitations or hurdles that may appear as a result of transmitting US signals using the high-split system. The ultimate goal of this experiment is to develop and propose solutions to any identified challenges well before the time of real network migration has come. System analysis for the high-split setup in Fig. 13 has already started. Fig. 14 shows an initial Noise Power Ratio (NPR) curve measured at early stages of the experiment. Further analyses and experiments are still pending and the obtained results will be shared in future papers.

4.4. Introducing PHY Enhancements (Higher Order Modulations) for Better Spectral Efficiency

Introducing higher order modulation options for US transmissions can be a smart move to increase the offered capacity. Currently, the US part of DOCSIS3.0 can support up to QAM64 (or QAM128 with Trellis Coded Modulation (TCM)). Introducing higher order modulations like QAM256, QAM1024, and QAM4096[2] can help in achieving higher spectral efficiencies if/when the plants can support them. For the above modulation orders, QAM256 offers 33% more spectral efficiency than QAM64. QAM1024 offers 25% more capacity than QAM256, and QAM4096 offers 20% more capacity than QAM1024.

As mentioned earlier, node splits and segmentations can result in reduced signal attenuation and noise funneling. Both of these result in higher SNR values that enable the operation of higher order modulation profiles. DOCSIS3.0 noise mitigation toolkit can also help enable the use of higher order modulation orders. Additionally, the next two sections will explain few enhancements that can be added to the DOCSIS, which result in SNR gains that can enable the operation of high order modulation orders.

4.5. Introducing PHY Enhancements (New PHY) for Better Spectral Efficiency

Enhancements to the DOCSIS standard can go beyond offering higher order modulations. Adding modern transmission technologies to DOCSIS toolkit can increase the spectral efficiency. For example, the multi-carrier Orthogonal Frequency Division Multiplexing (OFDM) technology is one of the common PHY techniques used in many of the modern applications including the

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[2] These are even-order modulations. Odd modulation orders can be proposed too for higher granularity.

European standard Digital Video Broadcast standard (DVB-C2) [7].

OFDM can be implemented efficiently using the Fast Fourier Transform (FFT) algorithm. Therefore, it requires less chip resources when compared to other transmission technologies with comparable noise immunity, which is one attractive feature that enabled OFDM to be used by different applications. OFDM is also known to have good immunity to various types of noise and channel impairments, which is enabled by the use of subcarriers that also results in long symbol duration, which helps the performance in the presence of impulse noise. The good noise immunity is another attractive feature of OFDM. The proposal to use OFDM (to be exact, Orthogonal Frequency Division Multiple Access (OFDMA)) for US DOCSIS is not a new concept in this paper. In particular, the author analyzed the performance of multi-carrier signals in the presence of HFC noise in 2009 [8] and also proposed the use of OFDM technology for US transmissions in DOCSIS back in 2010 [9].

This section analyzes the gain obtained from using OFDM for US transmissions in DOCSIS networks. The gain obviously depends on the assumptions and input parameters to the model. The analysis assumes an Additive White Gaussian Noise (AWGN) channel. Therefore, the analysis shown here is not an extensive or comprehensive analysis but only shows the gain obtained for one example scenario. More detailed analysis for the benefits of using multi-carrier signals can be found in [9]. Fig. 15 shows capacity estimates for an US single carrier DOCSIS signal and Fig. 16 shows an analysis for the capacity of 200MHz high-split system that uses OFDM. Comparing the results in Fig. 16 to those in Fig. 15, the gain resulting from using OFDM instead of Single carrier is about 2.6% or 0.129 bps/Hz of capacity improvement.

Observe that the increased capacity obtained from introducing OFDM as a new PHY technology for US transmissions is 2.6% when calculated at QAM256. Note that this value is highly dependent on the choice of the OFDM parameters, particularly the cyclic prefix code length and the preamble-to-burst-length ratio. The above improvement at QAM256 is equivalent to an additional 0.214 bits, which translates to 0.63dB of SNR gain. Although the gain may not be very large, some MSOs may choose to use OFDM for US transmissions in order to utilize the US spectrum in the most efficient way and also to use the noise and impairment immunity of OFDM to provide reliable transmissions in harsh plant conditions. In fact, the gain provided by the use OFDM can increase significantly when other parameters are used and also when different noise types (other than AWGN) and channel impairments exist on the channel [9].

Apart from the insignificant capacity improvement provided by OFDM when used with US DOCSIS transmissions shown in the above example, there are many benefits that can be drawn from using OFDM for US DOCSIS including:

1. Backward compatibility with US Channel Bonding: The MSOs can consider bonding across two different PHY technologies and therefore achieve the best possible spectrum utilization. This concept was originally introduced in [9].
2. Easy coexistence and smooth migration: The ability to turn on/off OFDM subcarriers makes it straightforward to accommodate legacy channels within the BW used for the new technology. The reader may be referred to [9] for more details.
3. Low Cost and Optimized Implementation [9]: The OFDM is based on the efficient FFT algorithm and is believed to result in simpler

implementation, which translates to lower cost.

4. Robust to noise and channel impairments: the OFDM is one of the most powerful PHY technologies in terms of its ability to fight different noise types and also mitigate interference [8] [10]. In fact, OFDM is used for wireless channels which are more challenging than the DOCSIS US channels because of multipath fading.
5. More Efficient US Bandwidth Utilization: the analysis above shows that OFDM can result in better spectral efficiency. The analysis assumed AWGN channel, where the results showed minor gain. The gain can be much larger when different noise scenarios and channel impairments exist on the plant [8] [9].
6. Load-Balancing: MSOs can choose to load-balance the traffic on the US between two different PHY technologies. This concept was originally introduced in [9] and also helps with backward compatibility.

One *potential* drawback of OFDM is increased latency. This can appear if the subcarriers width is selected to be very small, which results in increased symbol duration and therefore extended latency. If the subcarriers width is chosen in such a way that the OFDM symbols durations are similar or shorter than the SCDMA symbol durations used in DOCSIS, there will be no extra latency.

4.6. Introducing PHY Enhancements (New FEC) for Better Spectral Efficiency

Another enhancement that can be added to DOCSIS, which results in highly efficient spectral efficiency, is the use of modern Forwarded Error Correction Techniques (FEC). For example, Low Density parity Check (LDPC) codes are known to be much more efficient that the traditional Reed-Solomon codes (RS) codes that are currently being used in DOCSIS. The LDPC scheme was invented many years ago (in 1960's) by Gallager who, at the time, was working on his PhD thesis in MIT on this topic [11]. The LDPC error correction scheme was abandoned for many years because of its implementation complexity that needs high processing power. Recently, LDPC codes have been used in many applications including the DVB-C2 standard [7], which was enabled by the advances in processing platforms.

In order to evaluate the gain offered by the LDPC coding scheme, computer simulations were performed for a QAM signal with un-concatenated Reed Solomon (RS) to represent the current DOCSIS signals [12]. The results of these computer simulations (packet size = 250Bytes) are plotted in Fig. 17 along with other performance numbers for QAM LDPC FEC that are obtained from the published DVB-C2 standard [7]. Note that the above simulated numbers for RS FEC are close to the numbers derived from the J.83 Annex A, where RS FEC and not concatenated RS (RS with convolutional codes) [13] is used, and also similar to the DOCSIS US signals that use vanilla RS FEC. If comparison is to be made against concatenated RS FEC, one will find that the gain achieved by adding LDPC FEC is less because concatenated RS FEC performs better than vanilla RS FEC. Vanilla RS FEC was used in this analysis because it is what currently being used in DODCSIS US transmissions.

Observe that the gains in the QAM256 for the three plotted data points are 4.4dB, 5.1dB, and 7dB, depending on the code rate. Similarly, the gain ranges between 4.2dB and 5.5dB for the QAM64 case depending on the code rate. Therefore, the *average* gain between the LDPC numbers (from DVB-C2) and the RS S numbers (simulated DOCSIS RS FEC) is found to be 5.5dB and 4.85dB for the

QAM256 and QAM64 modulations, respectively. These average SNR gains of 5.5dB or 4.85dB translate to 1.83 bits and 1.62 bits of capacity improvement, respectively.

The above analysis used the *average* SNR gain obtained from using LDPC (the gain is function of the code rate). Therefore, one can be extra conservative and assumes a minimum gain or generous and assumes maximum gain depending on code rate usage on the target network. This paper uses the average gain in the analysis as a reasonable assumption.

4.7. Protecting the Established Base via Backward Compatibility and/or Coexistence

Backward compatibility and coexistence are critical tools to attain investment protection for the established base. As mentioned above in the new PHY proposal, backward compatibility and coexistence can be achieved easily using the OFDM PHY technology if selected as a new PHY for future DOCSIS US transmissions. Several aspects of backward compatible features are offered by OFDM: backward compatibility with US channel bonding across different PHYs, coexistence via the ability to turn on/off subcarriers of OFDM, and load balancing between the legacy and new PHY channels [9].

4.8. Going Deep with Fiber

FTTH is still way in the future! With the current offered capacities and the various available options for MSOs to augment their networks to result in increased capacity, there will be so many years before the MSOs will need to go down the FTTH path.

In fact, gradual migration steps that the MSOs do normally get them smoothly toward FTTH. For example, node splits and segmentations process gets the node closer to the subscribers' homes, which makes it easy and more economical to jump to FTTH at some point in the future. By then, the required capacity will be high (multi-gigabits) and the move to the FTTH will come in the right time. This is one of the beauties of cable networks that they offer the opportunity for timely investments, where spent money and resources are actually used. This is opposed to investing in FTTH, where a large amount of money and resource is spent to offer capacities that are not needed yet.

4.9. Capacity Analysis Summary

This section summarizes the capacity analyses that were introduced in previous sections of this paper. We will start with the analysis from section 4.3, where expanding the US spectrum was proposed. We will use the estimates from that section [3]. Assuming QAM256, the net offered capacity by 200MHz high-split was found to be 855.6Mbps, while the net offered capacity by 238MHz high-split was found to be 999.5Mbps (1Gbps).

Section 4.6 showed an average SNR gain of up to 5.5dB using LDPC alone for the QAM256 case. Additionally, section 4.5 showed additional SNR gain of 0.63dB as a result of using OFDM. Therefore, the total gain introduced by using OFDM and LDPC, compared to the current US DOCIS technology, can be 6.13dB. This gain is equivalent to 2.04 bits. Therefore, the capacity of the 200MHz and 238MHz high-split systems will be as follows:

1. 200MHz High-split: 855.6/(200-5) = 4.3877 bps/Hz. Adding 2.04 bits will increase the above spectral efficiency (calculated at QAM256) to: 4.3877*(8+2.04)/8= 5.51bps/Hz (net capacity is 1.073Gbps).
2. 238MHz High-split: 999.5/(238-5) = 4.2897 bps/Hz. Adding 2.04 bits will increase the above spectral efficiency (calculated at QAM256) to:

4.2897*(8+2.04)/8= 5.38 bps/Hz (net capacity is 1.254 Gbps).

Assume that reduction in noise and signal attenuation that results from multiple node splits and segmentations, as well as optimizations of modulations and channel parameters, result in conservative gain estimate of 3dB (equivalent to one additional bit). Therefore, the capacity of the 200MHz and 238MHz high-split systems is increased as follows:

1. 200MHz-High-split: 5.51*(10.04+1)/10.04 = 6.05bps/Hz (net capacity is 1.18 Gbps).
2. 238MHz-High-split: 5.38*(10.04+1)/10.04 = 5.92bps/Hz (net capacity is 1.378 Gbps).

Since the offered channel capacity is well above 1Gbps in both of the above high-split architecture, one may argue that 200MHz high-split (with offered capacity of 1.18Gbps) is enough to offer a service with Tmax= 1Gbps. Although we assumed earlier that MSOs might choose to require 1.5Tmax of channel capacity to offer a Tmax service, one may suggest that a channel capacity of 15% more than the 1Gbps Tmax value is enough. The rationale behind that is that:

1. After so many node splits and segmentations, the number of subscribers per service groups drops exponentially. This reduces the chances that two subscribers will ask for BW at the same time.
2. When the Tmax value is really large (Tmax = 1Gbps), US bursts from subscribers consume very little time and therefore contention drops significantly. In particular, data transmissions from any single subscriber may not take an extended period of time and therefore will not likely affect other customers that are about to transmit their content. It is, therefore, likely that all customers attain the desired Tmax rates for their service.

Some MSOs may choose to be more cautious and decide to use 238MHz high-split option as a target US spectrum. After all, it is expected that either of the high-split options 200MHz (net capacity of 1.18Gbps) or 238MHz (net capacity of 1.254Gbps) will be able to offer a service with Tmax=1Gbps and beyond.

5. SAMPLE MIGRATION PLAN TO REALIZE SYMMETRIC 1GBPS SYSTEM AND BEYOND!

DOCSIS scales very well! It offers just-in-time steps for plant upgrades, where money and resources that are spent will actually be used. This is opposed to investing in FTTH before it is needed; following that path may lead to a large amount of money and resource being spent to offer capacities and capabilities that are not needed yet.

This section proposes smooth migration steps that MSOs might consider taking when upgrading their networks as they move into the future. These steps offer just-in-time investments that are necessary to offer the needed capacity that meets traffic demands. A natural consequence of these gradual steps is that they will likely occur over many years, with the end goal of migrating to a FTTH architecture when it is truly required. By migrating to FTTH at the right time, this approach will avoid upfront investments that will not be actually used until much later. Based on traffic engineering studies, the need for a FTTH architecture appears to be needed only when traffic demands require much more bandwidth than is provided by DOCSIS or DOCSIS variants. This condition appears to be many years down the road, so the economics of the upgrade process to FTTH can probably be deferred until that time.

As explained earlier, there are many steps and options to take in the process of network migration. One proposed sequence of these steps is given below:

1. **Step 0: Use the available spectrum efficiently.** Section 4.1 addressed this topic. For more details, refer to [4] [5] [6].

2. **Step 1: Node segmentations and splits.** This was covered in Section 4.2.

3. **Step 2: Add more BW.** This is divided into two categories:
    a. **CATEGORY 1 of STEP 2: Expand the US spectrum using High split as goal architecture.** This can be done in a single step to save on upgrade costs or via passing through Mid-split to gain more time to avoid the OOB legacy STB signaling problem. This topic was covered in Section 4.3.
    b. **CATEGORY 2 of STEP 2: Enhancements to DOCSIS.**
        i. <u>Higher order modulations</u>. This is viable because less noise and attenuation as a result of multiple noise segmentations / splits as well as other DOCSIS enhancements mentioned below. Section 4.4 covered this topic.
        ii. <u>New FEC (e.g., LDPC)</u>. This provides several dBs of SNR gain over RS. Section 4.6 addressed this topic.
        iii. <u>New PHY (e.g., OFDM)</u>. OFDM is an easy to implement technology that is robust against different types of noise. Section 4.5 covered this subject. For more details, refer to [9] [10]. Note that a new PHY may not be required because the capacity gain may be marginal as shown earlier. However, if MSOs would like to get the most out of the plant and use noise-robust technology, OFDM makes a good choice.
        iv. <u>Backward Compatibility</u>. This is a key item to maintain the increased offered capacity. Example is bonding across new and legacy channels. This was covered in Section 4.7. For more details, refer to [9].
    c. **NOTE:** The above categories of step 2 (items a & b) can be done in any order or even concurrently. This is a key feature to this proposal. In fact, some MSOs may choose not to go beyond category 1 if they think that it provides enough capacity. Others may jump to category 2 as it may line up better with the timing of their plans to expand the US spectrum. Others may go to both options concurrently (or consecutively) with a bold move to get the most capacity out of the plant.

4. **Step 3: FTTH.** way in the future. Natural step after many node segmentations/splits, which will enable MSOs to offer multi-gigabit service in DS and US. This was covered in section 4.8.

6. CONCLUSIONS

The paper studied different options available to the MSOs as they brainstorm to augment their networks for added capacity. The paper proposed using the current spectrum efficiently, performing node segmentations/splits, adding more US spectrum (Mid-Split/High-Split), and adding enhancements to DOCSIS (Higher order modulations/LDPC/OFDMA/Backward Compatibility for added features). A proposed sequence of gradual migration steps was included, which is deemed to carry the MSOs deep into the future with adequate offered capacity according to the provided analysis.

Since the high-split architecture was shown to make the best technical option for US transmissions, a description a high-split prototype system built by ARRIS was included in the paper. The prototype is aimed at studying and analyzing any potential challenges with the high-split proposal, which enables vendors to offer solutions for any problems or issues well before any mass deployment. Initial results for the prototype system were provided. Future papers are planned to share the results as more experiments are done and data is collected.

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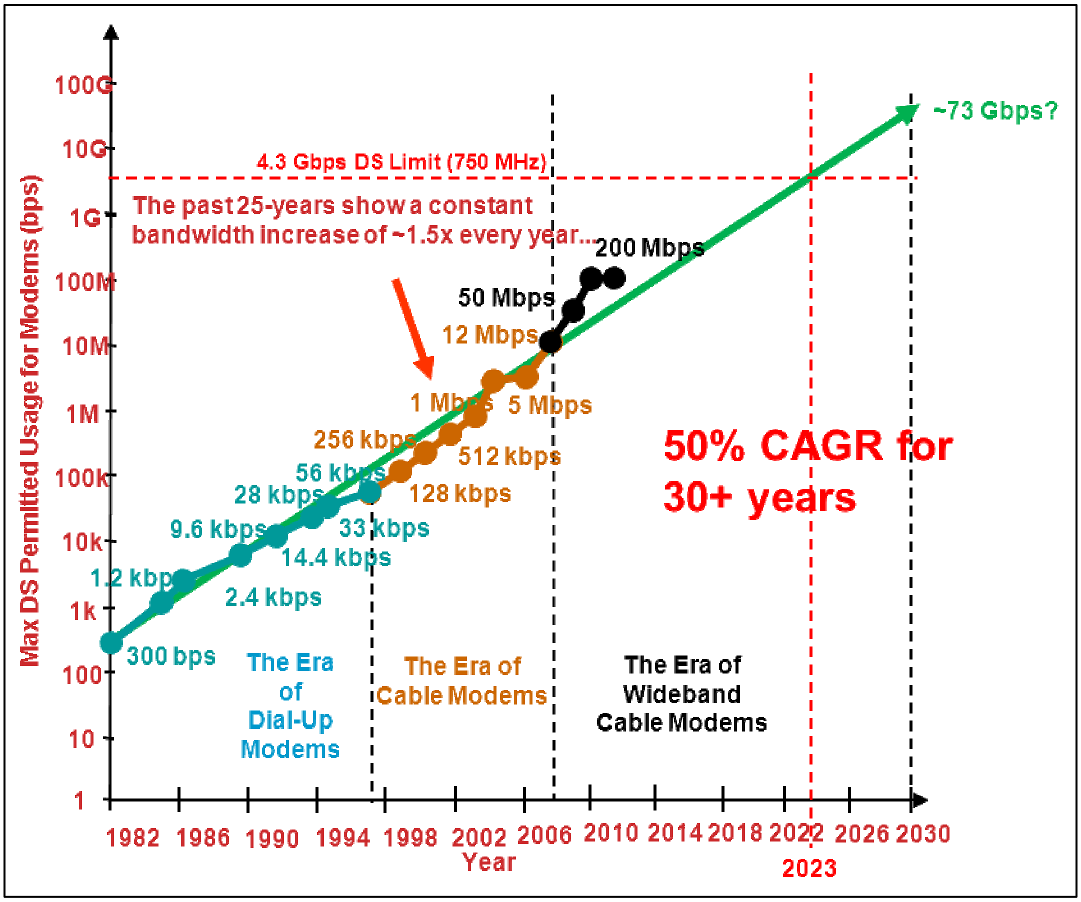


Fig. 1. The Nielson Curve for traffic growth over cable networks (Max. DS Usage/subscriber)

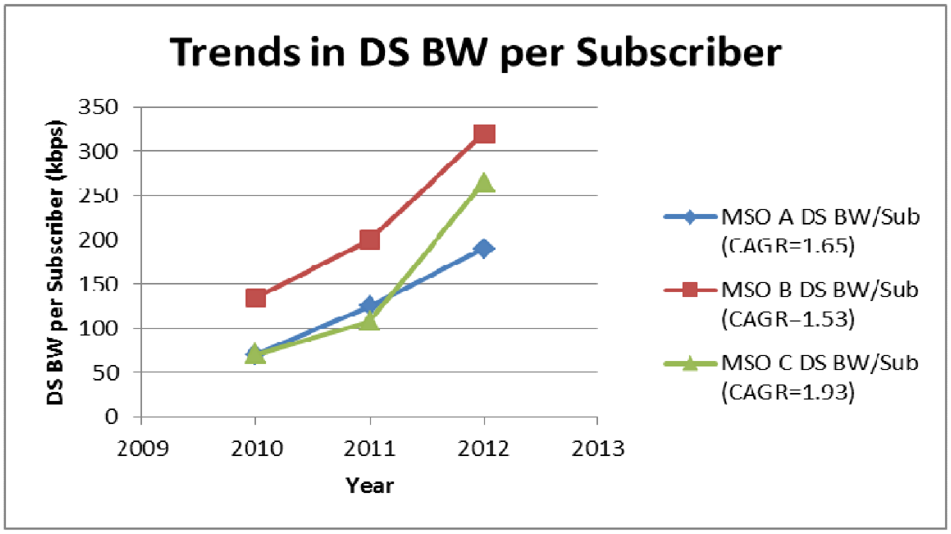


Fig. 2. CAGR of average DS BW per subscriber for three different MSOs over the past two years (>50% DS CAGR on average)

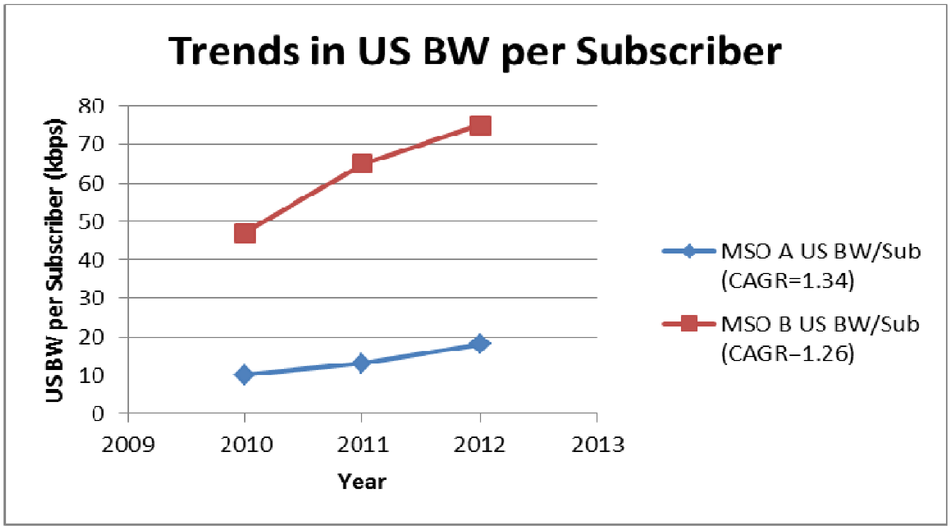


Fig. 3. CAGR of average US BW per subscriber for two different MSOs over the past two years (~30% US CAGR on average)

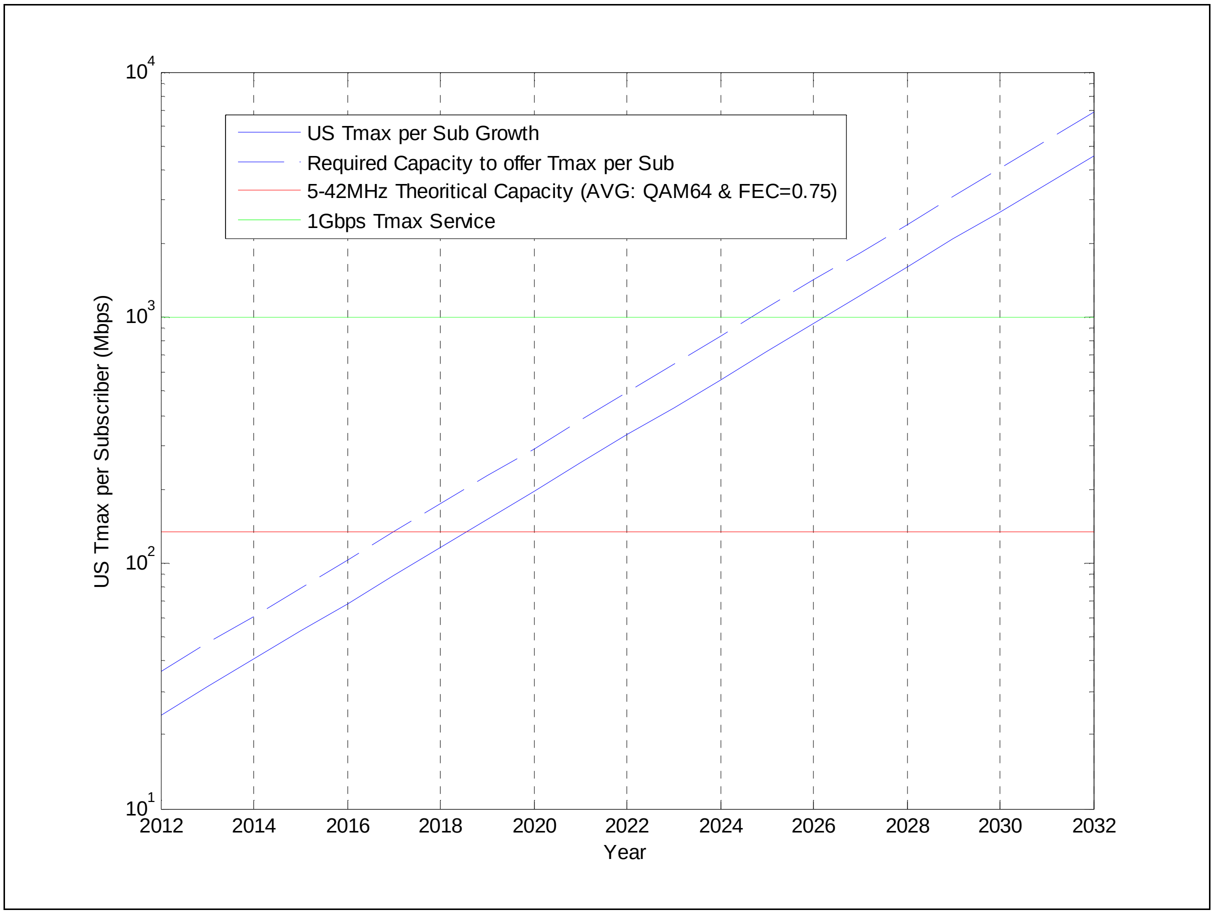


Fig. 4. US Tmax per subscriber growth over the next two decades (assuming CAGR = 30% & starting Tmax = 24Mbps per Subscriber in 2012)

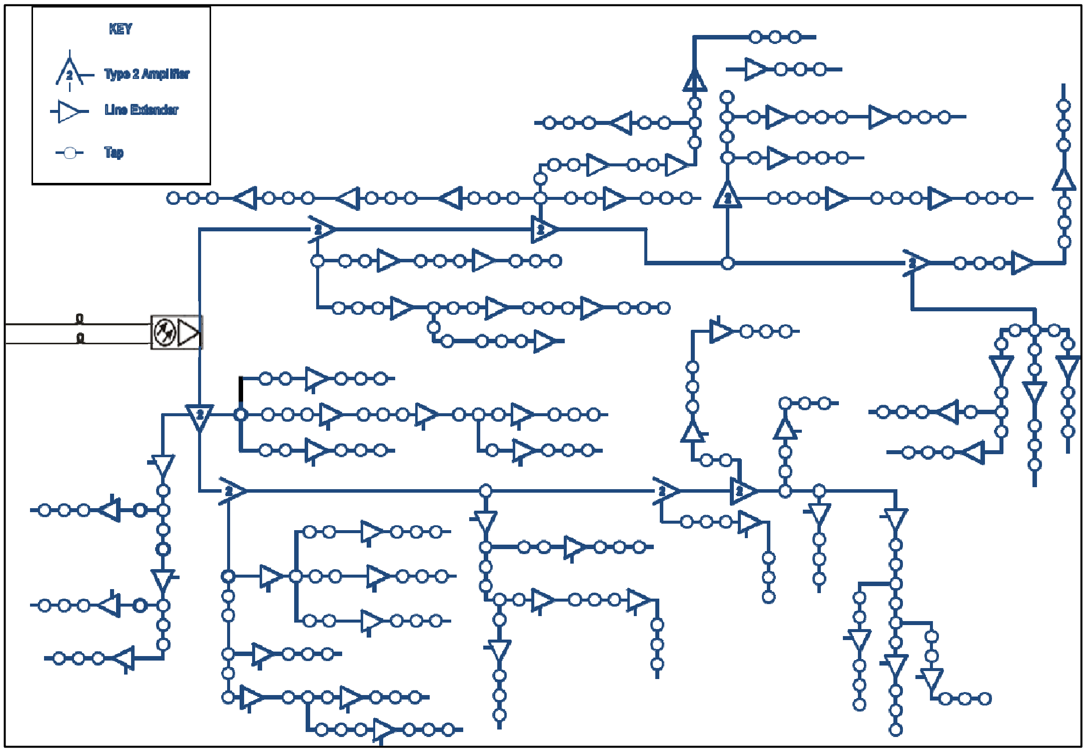


Fig. 5. Example of N+5 Network topology.

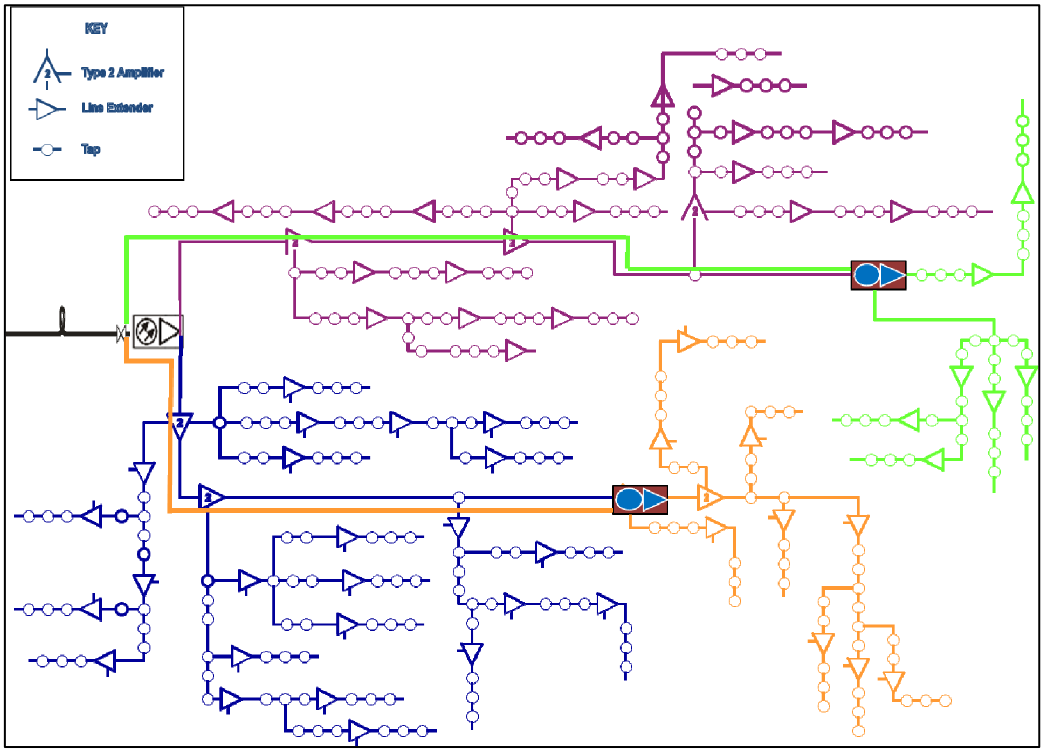
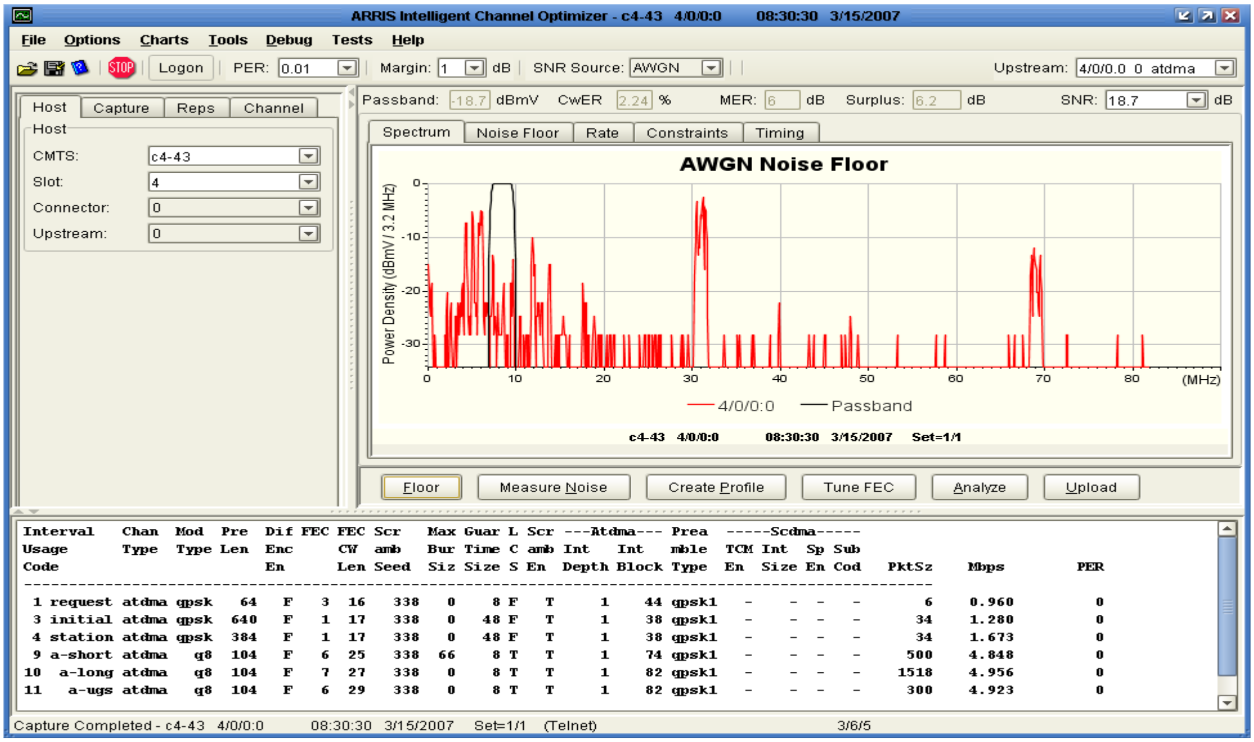


Fig. 6. Segmenting and Splitting the FN in the network example shown in Fig. 5.



PER: 0.01
Margin: 1 dB
SNR Source: AWGN
Upstream: 4/0/0.0 0 atdma

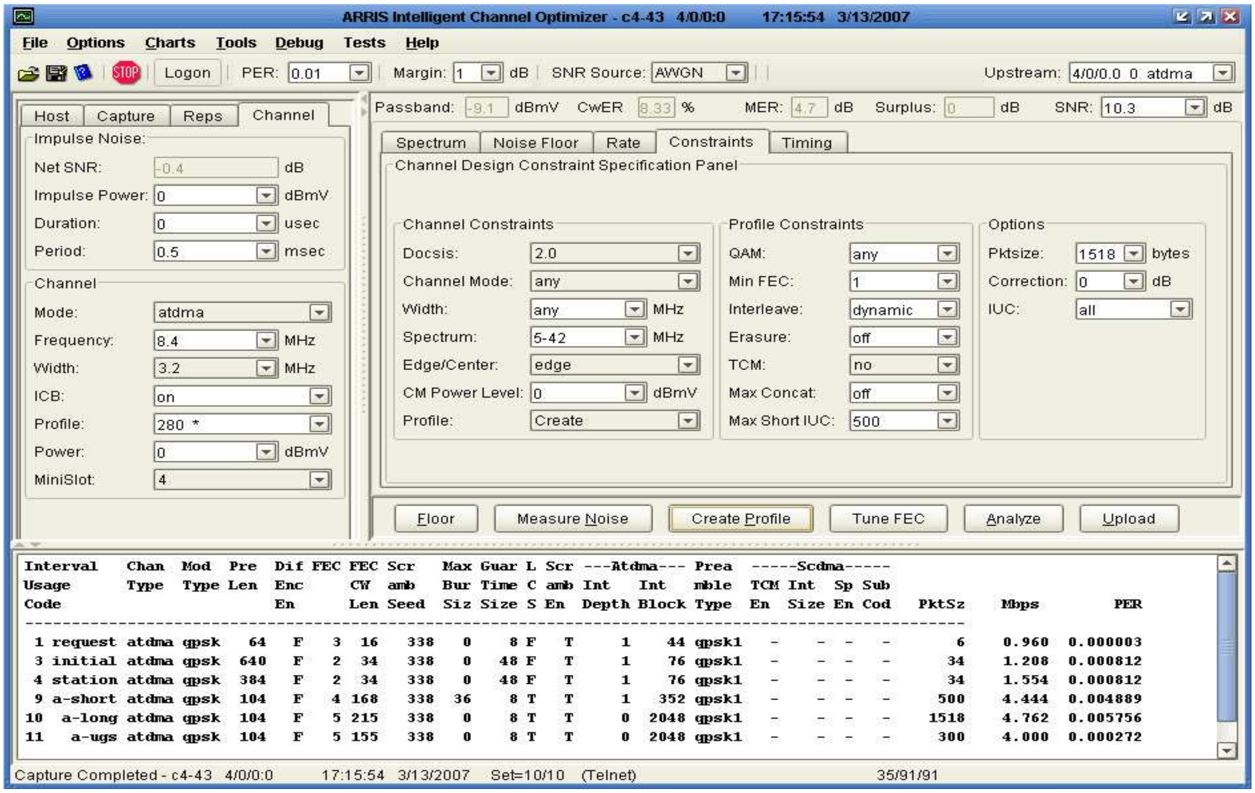
Passband: -18.7 dBmV
CwER 2.24 %
MER: 6 dB
Surplus: 6.2 dB
SNR: 18.7 dB

Host
CMTS: c4-43
Slot: 4
Connector: 0
Upstream: 0

```
Interval    Chan  Mod  Pre  Dif FEC FEC Scr    Max Guar L Scr ---Atdma--- Prea   -----Scdma-----
Usage       Type  Type Len  Enc      CW  amb   Bur Time C amb Int    Int  mble   TCM Int  Sp Sub
Code                        En      Len Seed   Siz Size S En  Depth Block Type   En  Size En Cod   PktSz    Mbps       PER
----------------------------------------------------------------------------------------------------------
 1 request atdma qpsk   64   F   3  16   338   0    8 F   T     1    44 qpsk1   -    -  -   -       6    0.960       0
 3 initial atdma qpsk  640   F   1  17   338   0   48 F   T     1    38 qpsk1   -    -  -   -      34    1.280       0
 4 station atdma qpsk  384   F   1  17   338   0   48 F   T     1    38 qpsk1   -    -  -   -      34    1.673       0
 9 a-short atdma   q8  104   F   6  25   338  66    8 T   T     1    74 qpsk1   -    -  -   -     500    4.848       0
10  a-long atdma   q8  104   F   7  27   338   0    8 T   T     1    82 qpsk1   -    -  -   -    1518    4.956       0
11   a-ugs atdma   q8  104   F   6  29   338   0    8 T   T     1    82 qpsk1   -    -  -   -     300    4.923       0
```

Capture Completed - c4-43 4/0/0:0 08:30:30 3/15/2007 Set=1/1 (Telnet) 3/6/5

Fig. 7. Automation of optimizing the upstream modulation profile and channel parameters (choosing the best parameters for the noise that exists on the plant)



PER: 0.01
Margin: 1 dB
SNR Source: AWGN
Upstream: 4/0/0.0 0 atdma

Passband: -9.1 dBmV
CwER 8.33 %
MER: 4.7 dB
Surplus: 0 dB
SNR: 10.3 dB

Impulse Noise:
Net SNR: -0.4 dB
Impulse Power: 0 dBmV
Duration: 0 usec
Period: 0.5 msec

Channel
Mode: atdma
Frequency: 8.4 MHz
Width: 3.2 MHz
ICB: on
Profile: 280 *
Power: 0 dBmV
MiniSlot: 4

Channel Design Constraint Specification Panel

Channel Constraints
Docsis: 2.0
Channel Mode: any
Width: any MHz
Spectrum: 5-42 MHz
Edge/Center: edge
CM Power Level: 0 dBmV
Profile: Create

Profile Constraints
QAM: any
Min FEC: 1
Interleave: dynamic
Erasure: off
TCM: no
Max Concat: off
Max Short IUC: 500

Options
Pktsize: 1518 bytes
Correction: 0 dB
IUC: all

```
Interval    Chan  Mod  Pre  Dif FEC FEC Scr    Max Guar L Scr ---Atdma--- Prea   -----Scdma-----
Usage       Type  Type Len  Enc      CW  amb   Bur Time C amb Int    Int  mble   TCM Int  Sp Sub
Code                        En      Len Seed   Siz Size S En  Depth Block Type   En  Size En Cod   PktSz    Mbps       PER
------------------------------------------------------------------------------------------------------------
 1 request atdma qpsk   64   F   3  16   338   0    8 F   T     1    44 qpsk1   -    -  -   -       6    0.960  0.000003
 3 initial atdma qpsk  640   F   2  34   338   0   48 F   T     1    76 qpsk1   -    -  -   -      34    1.208  0.000812
 4 station atdma qpsk  384   F   2  34   338   0   48 F   T     1    76 qpsk1   -    -  -   -      34    1.554  0.000812
 9 a-short atdma qpsk  104   F   4 168   338  36    8 T   T     1   352 qpsk1   -    -  -   -     500    4.444  0.004889
10  a-long atdma qpsk  104   F   5 215   338   0    8 T   T     0  2048 qpsk1   -    -  -   -    1518    4.762  0.005756
11   a-ugs atdma qpsk  104   F   5 155   338   0    8 T   T     0  2048 qpsk1   -    -  -   -     300    4.000  0.000272
```

Capture Completed - c4-43 4/0/0:0 17:15:54 3/13/2007 Set=10/10 (Telnet) 35/91/91

Fig. 8. Automation of optimizing the upstream modulation profile and channel parameters (specifying constraints)

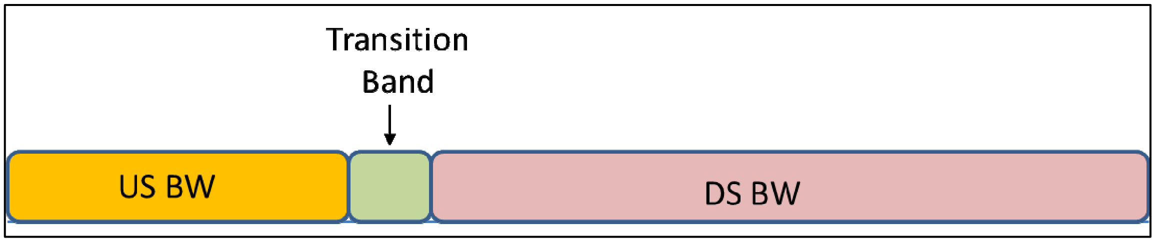


Fig. 9. Mid-Split and High-Split options for US spectrum usage

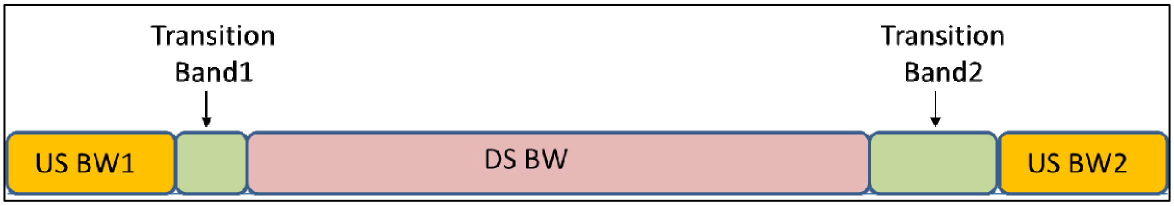
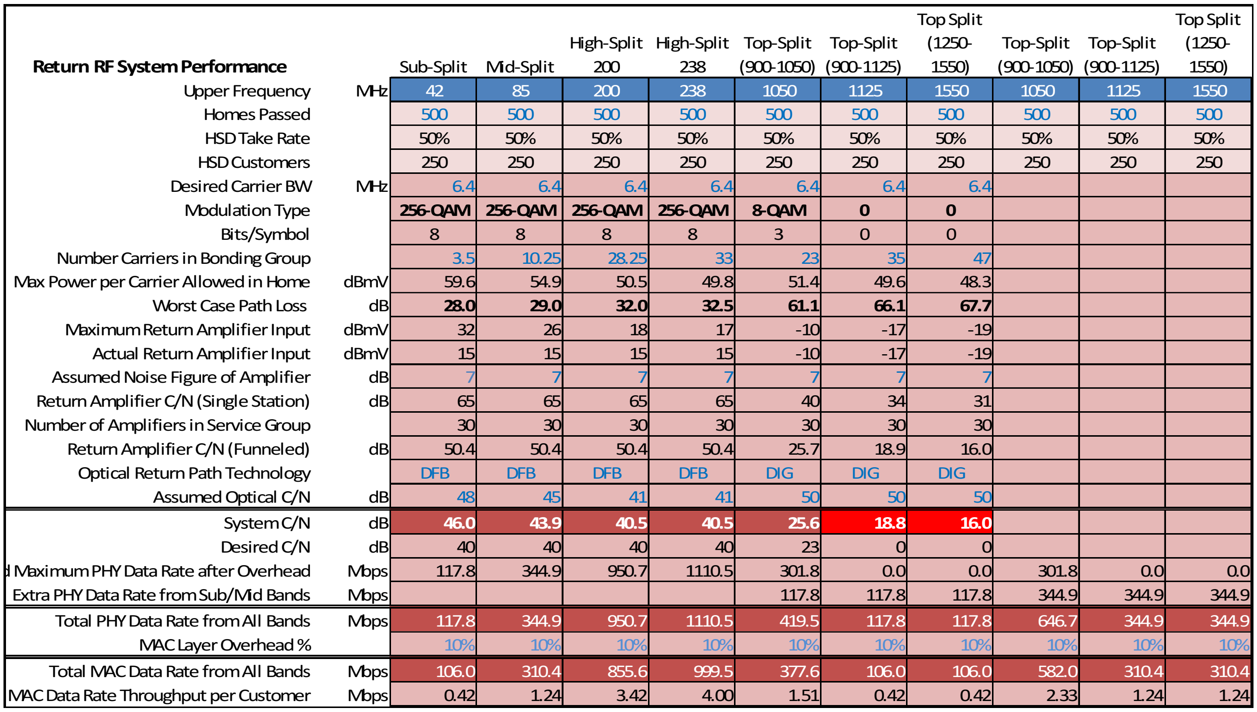


Fig. 10. Top-Split option for US spectrum usage



Return RF System Performance		Sub-Split	Mid-Split	High-Split 200	High-Split 238	Top-Split (900-1050)	Top-Split (900-1125)	Top Split (1250-1550)	Top-Split (900-1050)	Top-Split (900-1125)	Top Split (1250-1550)
Upper Frequency	MHz	42	85	200	238	1050	1125	1550	1050	1125	1550
Homes Passed		500	500	500	500	500	500	500	500	500	500
HSD Take Rate		50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
HSD Customers		250	250	250	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**	**256-QAM**	**8-QAM**	**0**	**0**			
Bits/Symbol		8	8	8	8	3	0	0			
Number Carriers in Bonding Group		3.5	10.25	28.25	33	23	35	47			
Max Power per Carrier Allowed in Home	dBmV	59.6	54.9	50.5	49.8	51.4	49.6	48.3			
Worst Case Path Loss	dB	**28.0**	**29.0**	**32.0**	**32.5**	**61.1**	**66.1**	**67.7**			
Maximum Return Amplifier Input	dBmV	32	26	18	17	-10	-17	-19			
Actual Return Amplifier Input	dBmV	15	15	15	15	-10	-17	-19			
Assumed Noise Figure of Amplifier	dB	7	7	7	7	7	7	7			
Return Amplifier C/N (Single Station)	dB	65	65	65	65	40	34	31			
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	50.4	25.7	18.9	16.0			
Optical Return Path Technology		DFB	DFB	DFB	DFB	DIG	DIG	DIG			
Assumed Optical C/N	dB	48	45	41	41	50	50	50			
System C/N	dB	**46.0**	**43.9**	**40.5**	**40.5**	**25.6**	**18.8**	**16.0**			
Desired C/N	dB	40	40	40	40	23	0	0			
Maximum PHY Data Rate after Overhead	Mbps	117.8	344.9	950.7	1110.5	301.8	0.0	0.0	301.8	0.0	0.0
Extra PHY Data Rate from Sub/Mid Bands	Mbps					117.8	117.8	117.8	344.9	344.9	344.9
Total PHY Data Rate from All Bands	Mbps	117.8	344.9	950.7	1110.5	419.5	117.8	117.8	646.7	344.9	344.9
MAC Layer Overhead %		10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Total MAC Data Rate from All Bands	Mbps	106.0	310.4	855.6	999.5	377.6	106.0	106.0	582.0	310.4	310.4
MAC Data Rate Throughput per Customer	Mbps	0.42	1.24	3.42	4.00	1.51	0.42	0.42	2.33	1.24	1.24

Fig. 11. Analysis of different split options for the US spectrum in DOCSIS networks [3]

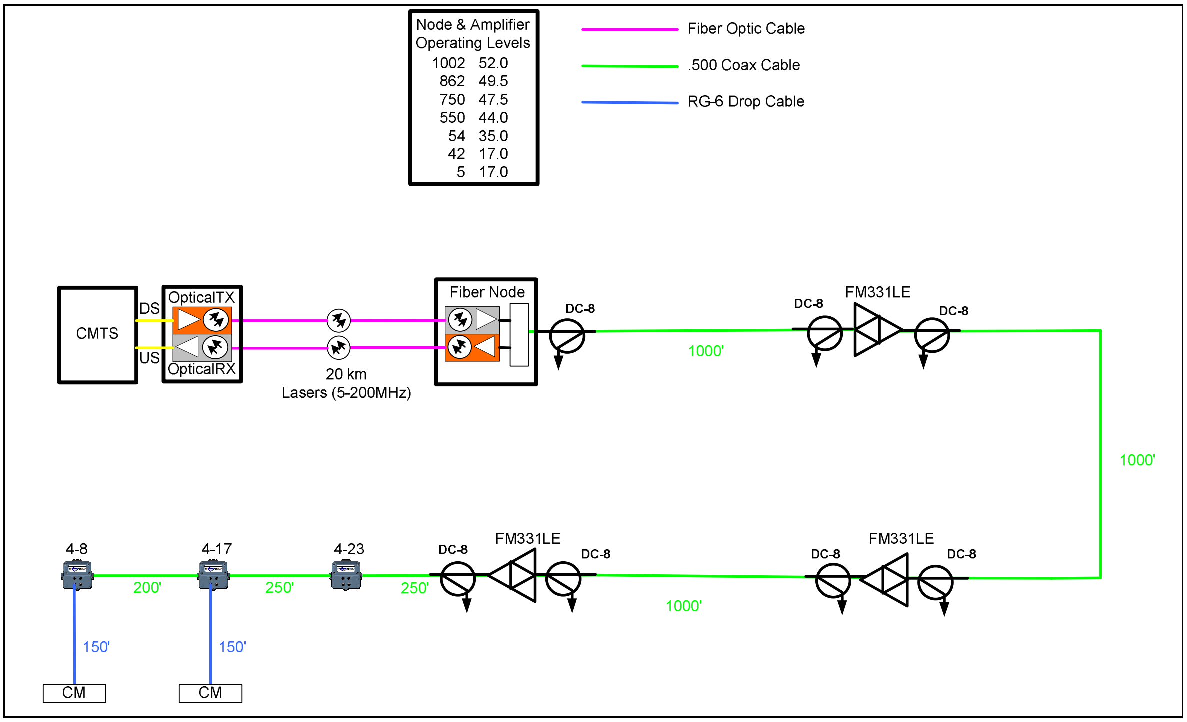


Fig. 12. Example setup for Real-world N+3 network architecture

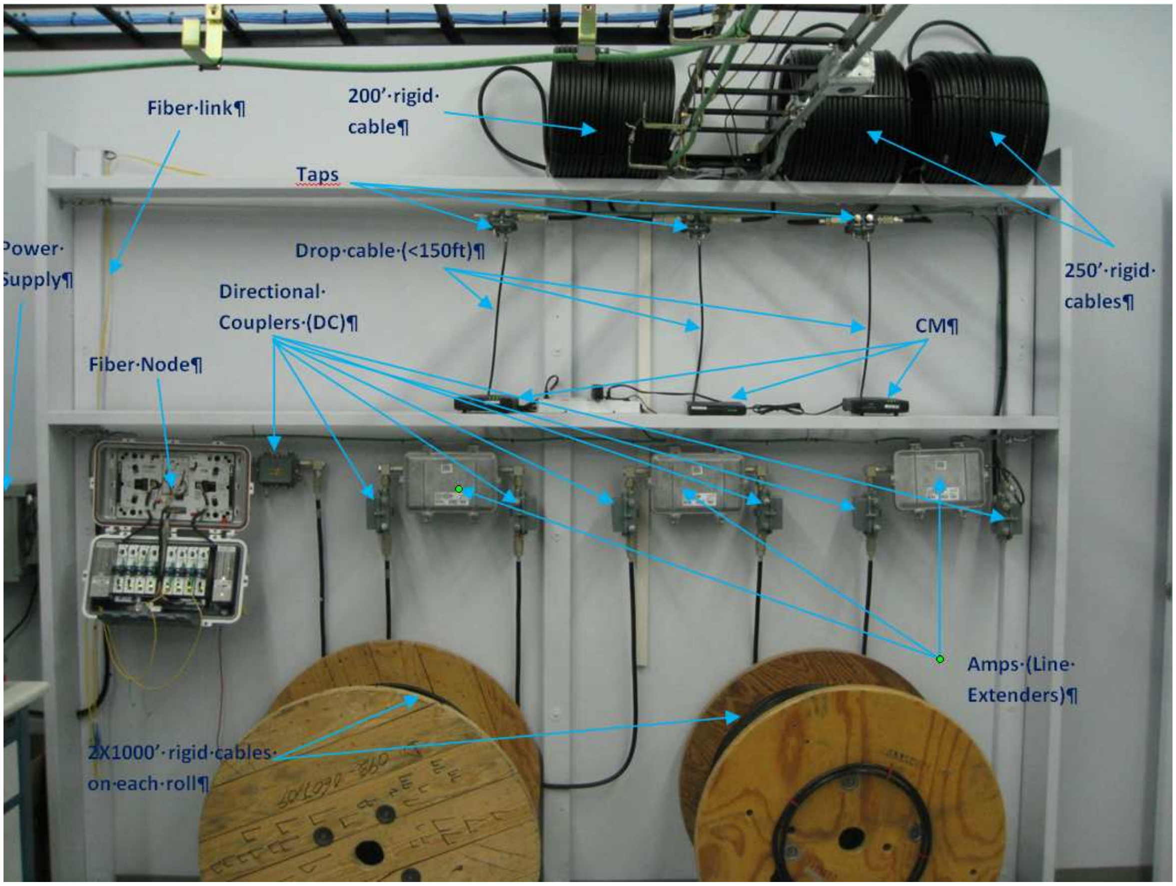


Fig. 13. ARRIS Implementation of high-split prototype architecture network to mimic the setup in Fig. 12 (laser Tx/Rx in the headend is not shown in the figure).

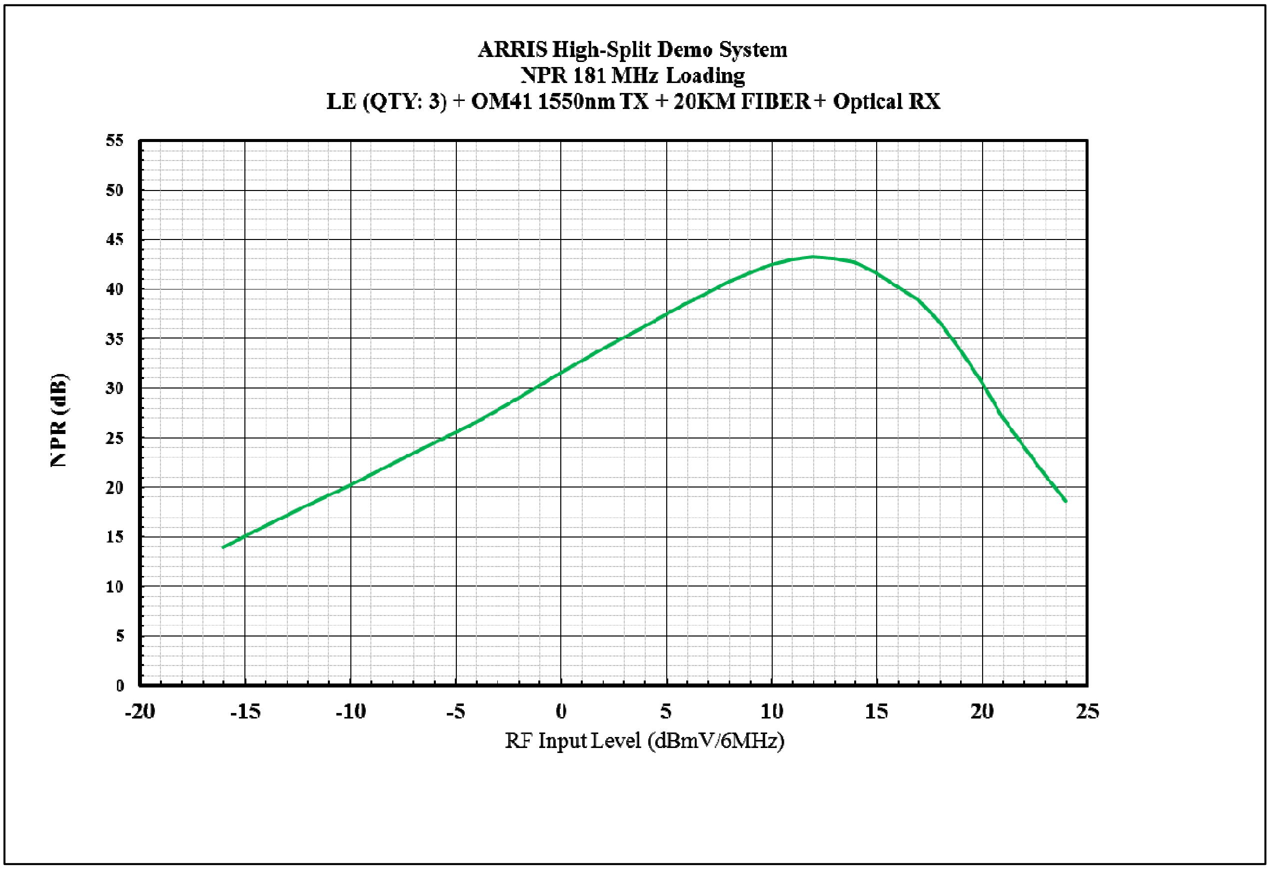
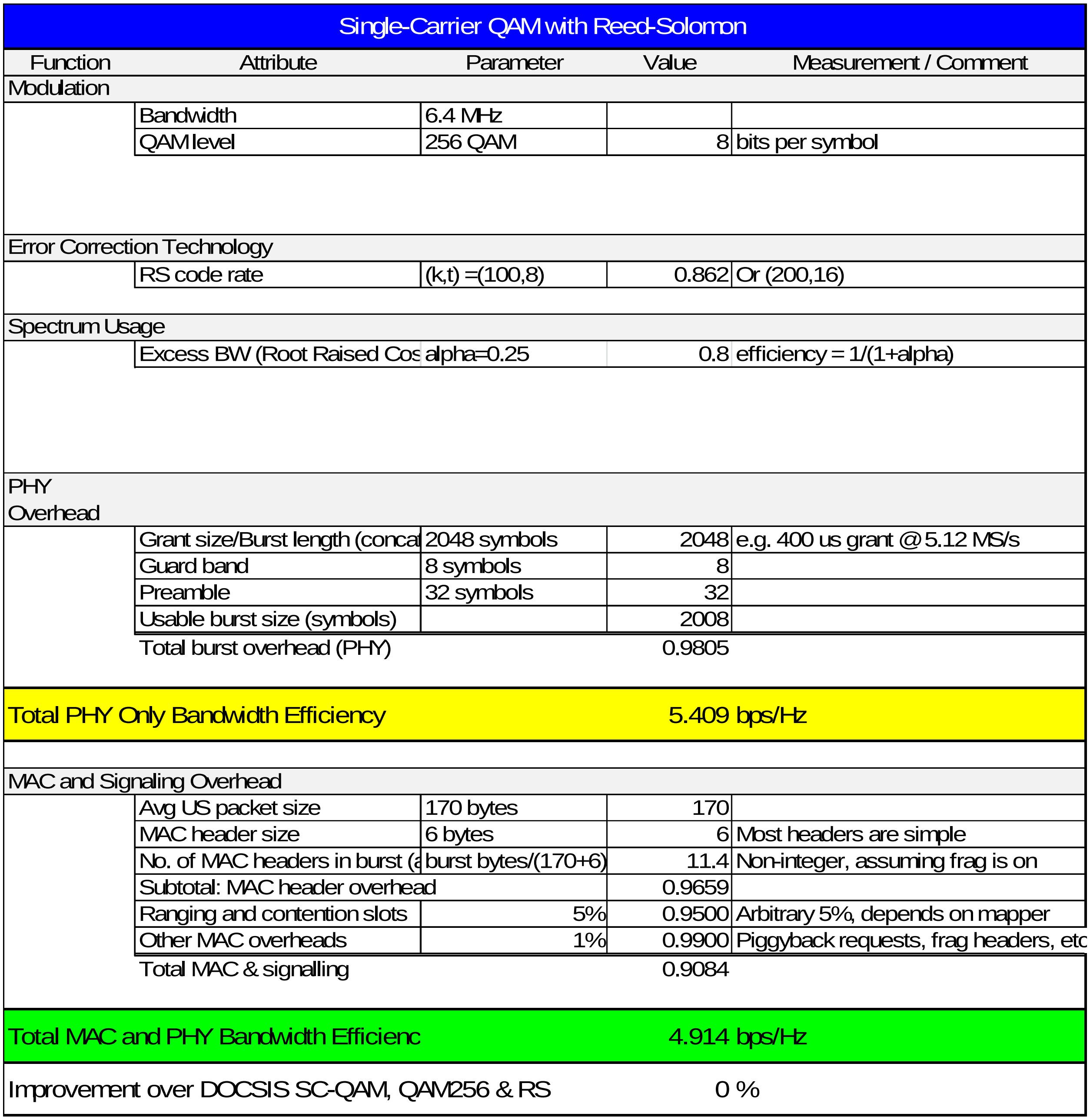


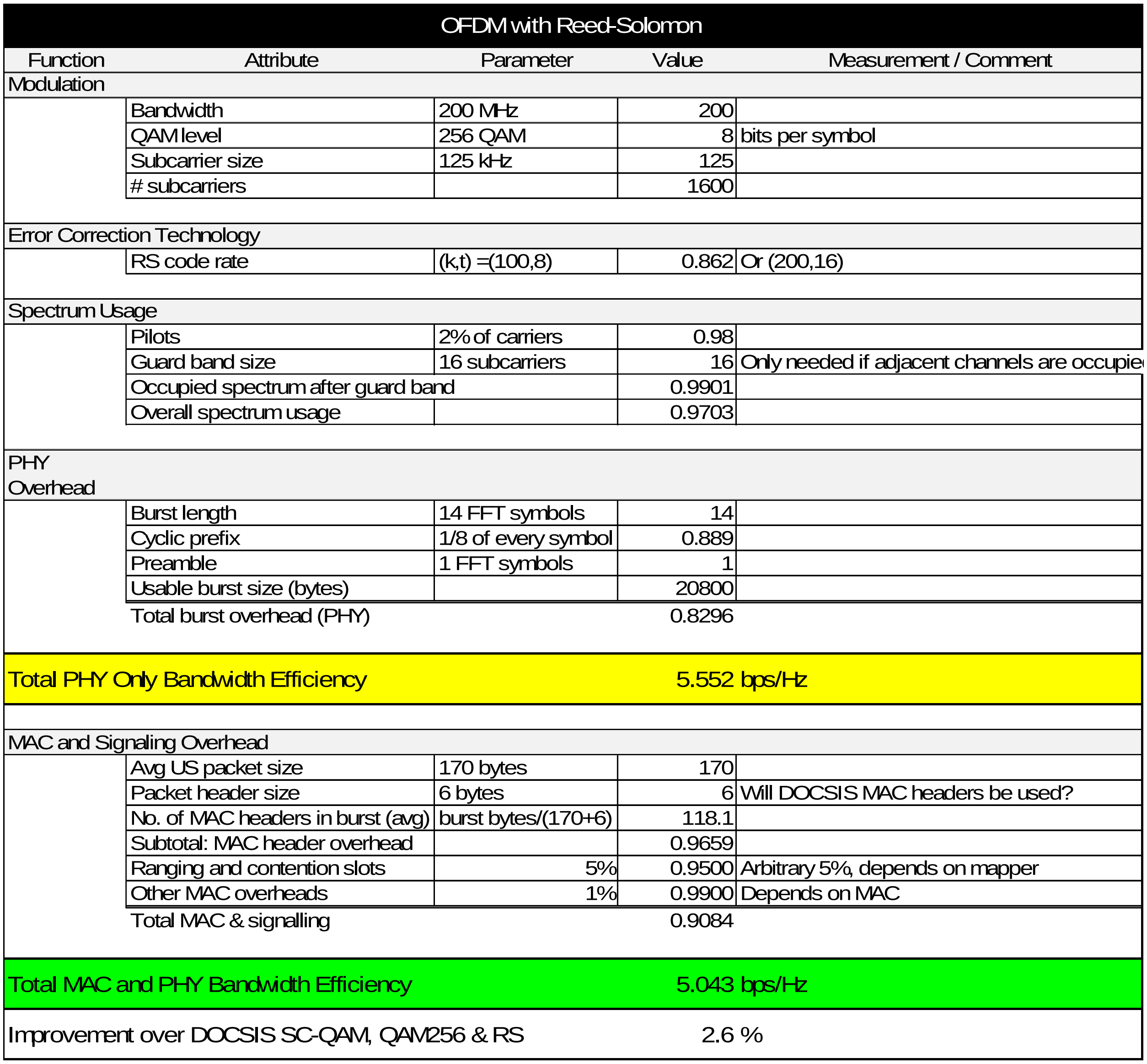
Fig. 14. An initial NPR curve for the plant setup shown in Fig. 13.



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 Cos	alpha=0.25	0.8	efficiency = 1/(1+alpha)
PHY Overhead				
	Grant size/Burst length (concat	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 (a	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 Efficienc			4.914	bps/Hz
Improvement over DOCSIS SC-QAM, QAM256 & RS			0	%

Fig. 15. Capacity analysis for Single carrier DOCSIS signal



OFDM with Reed-Solomon

Function	Attribute	Parameter	Value	Measurement / Comment
Modulation				
	Bandwidth	200 MHz	200	
	QAM level	256 QAM	8	bits per symbol
	Subcarrier size	125 kHz	125	
	# subcarriers		1600	
Error Correction Technology				
	RS code rate	(k,t) =(100,8)	0.862	Or (200,16)
Spectrum Usage				
	Pilots	2% of carriers	0.98	
	Guard band size	16 subcarriers	16	Only needed if adjacent channels are occupie
	Occupied spectrum after guard band		0.9901	
	Overall spectrum usage		0.9703	
PHY Overhead				
	Burst length	14 FFT symbols	14	
	Cyclic prefix	1/8 of every symbol	0.889	
	Preamble	1 FFT symbols	1	
	Usable burst size (bytes)		20800	
	Total burst overhead (PHY)		0.8296	
Total PHY Only Bandwidth Efficiency			5.552 bps/Hz	
MAC and Signaling Overhead				
	Avg US packet size	170 bytes	170	
	Packet header size	6 bytes	6	Will DOCSIS MAC headers be used?
	No. of MAC headers in burst (avg)	burst bytes/(170+6)	118.1	
	Subtotal: 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			5.043 bps/Hz	
Improvement over DOCSIS SC-QAM, QAM256 & RS			2.6 %	

Fig. 16. Capacity analysis for OFDM signals when used for DOCSIS US transmissions

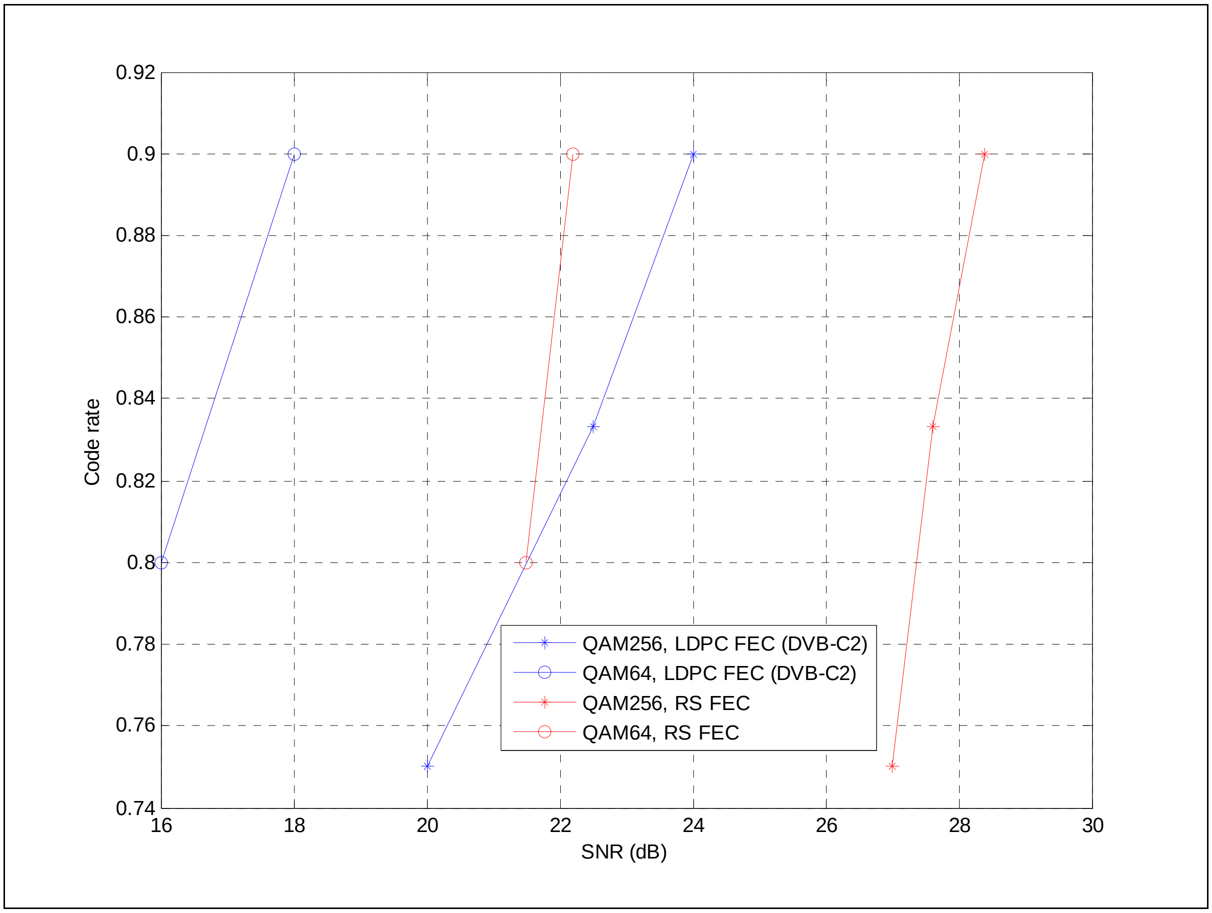
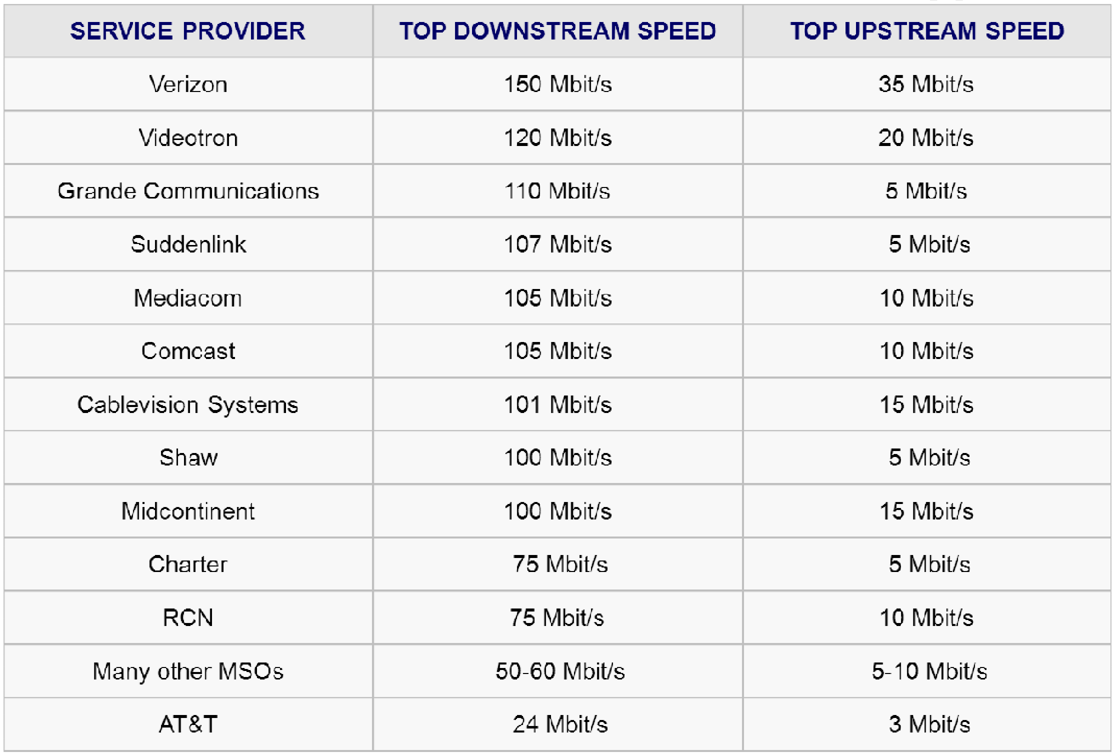


Fig. 17. Comparison between RS FEC (computer simulations) and LDPC FEC (from DVB-C2)

Table 1. Offered DS and US Tmax values in North America [2]



SERVICE PROVIDER	TOP DOWNSTREAM SPEED	TOP UPSTREAM SPEED
Verizon	150 Mbit/s	35 Mbit/s
Videotron	120 Mbit/s	20 Mbit/s
Grande Communications	110 Mbit/s	5 Mbit/s
Suddenlink	107 Mbit/s	5 Mbit/s
Mediacom	105 Mbit/s	10 Mbit/s
Comcast	105 Mbit/s	10 Mbit/s
Cablevision Systems	101 Mbit/s	15 Mbit/s
Shaw	100 Mbit/s	5 Mbit/s
Midcontinent	100 Mbit/s	15 Mbit/s
Charter	75 Mbit/s	5 Mbit/s
RCN	75 Mbit/s	10 Mbit/s
Many other MSOs	50-60 Mbit/s	5-10 Mbit/s
AT&T	24 Mbit/s	3 Mbit/s

Table 2. Offered DS Tmax values in Europe [2]

OPERATOR	MARKET	SPEED
Cable Europa (ONO)	Spain	100 Mbit/s
Cabovisão	Portugal	120 Mbit/s
Canal Digital	Norway	100 Mbit/s
Com Hem	Sweden	200 Mbit/s
Get	Norway	200 Mbit/s
Kabel Baden-Württemberg	Germany	100 Mbit/s
Kabel Deutschland	Germany	100 Mbit/s
Numericable	France	100 Mbit/s
Sanoma Television Welho	Finland	200 Mbit/s
Tele Columbus	Germany	100 Mbit/s
Telenet	Belgium	100 Mbit/s
Liberty Global	—	120 Mbit/s
UPC Austria	Austria	100 Mbit/s

Table 3. Offered DS Tmax values in Europe (Continued) [2]

OPERATOR	MARKET	SPEED
UPC Czech Republic	Czech Republic	100 Mbit/s
Unitymedia	Germany	128 Mbit/s
UPC Hungary	Hungary	120 Mbit/s
UPC Ireland	Ireland	100 Mbit/s
UPC Netherlands	Netherlands	120 Mbit/s
UPC Poland	Poland	120 Mbit/s
UPC Romania	Romania	100 Mbit/s
UPC Slovak Republic	Slovak Republic	120 Mbit/s
UPC Cablecom Switzerland	Switzerland	100 Mbit/s
Virgin Media	U.K.	100 Mbit/s
YouSee	Denmark	50 Mbit/s
Ziggo	Netherlands	120 Mbit/s
ZON Multimedia	Portugal	360 Mbit/s

Table 4. Assumptions about spectrum usage used in analyzing the capacity of 5-42MHz spectrum in [3]

Bandwidth	Description
37	Sup-split Upstream spectrum (5-42MHz)
-2	Assumed 2MHz as roll off (40-42MHz) being unusable
-5	Assumed that the noisy spectrum (5-MHz) to be unusable
-2	Legacy STBs
-2	Legacy Status Monitoring
-3.2	3.2MHz channel for legacy QAM16 DOCSIS
22.8	Possible spectrum for DOCSIS3.0 US channel bonding
22.4	Assumed value for capacity analysis

Table 5. Typical Fiber node assumptions used to compare different split options [3]

Item	Value	Unit
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

Table 6. Express/distribution segments assumptions used to compare different split options [3]

"Express" (untapped) Segment Characterization	Unit	Sub-Split	Mid-Split	High-Split 200	High-Split 238	Top-Split (900-1050)	Top-Split (900-1125)	Top Split (1250-1550)
Upper Frequency	MHz	42	85	200	238	1050	1125	1550
Typical Maximum Cable Loss (Amp to Amp 70 deg F)	dB	6.5	9.2	14.1	14.8	35.7	36.9	43.3
Additional Gain Required for Thermal Control (0 to 140 deg F)	+/-dB	0.5	0.6	1.0	1.0	2.5	2.6	3.0
Total Reverse Amplifier Gain Required	dB	**6.9**	**9.8**	**15.1**	**15.8**	**38.2**	**39.5**	**46.4**
"Distribution" (tapped) Segment Characterization		Sub-Split	Mid-Split	High-Split 200	High-Split 238	Top-Split (900-1050)	Top-Split (900-1125)	Top Split (1250-1550)
Upper Frequency	MHz	42	85	200	238	1050	1125	1550
Worst Case Path Loss	dB	**27.9**	**28.9**	**33.1**	**33.5**	**63.0**	**68.0**	**69.9**
Path Loss from First Tap	dB	*27.9*	*28.9*	*31.0*	*31.0*	*42.2*	*44.6*	*44.8*
Distribution Cable Loss	dB	0.4	0.6	0.9	0.9	2.1	2.2	2.6
Tap Port Loss	dB	21.9	21.9	22.0	22.0	25.4	27.2	24.5
Drop Cable Loss	dB	2.1	2.9	4.6	4.6	10.1	10.4	12.2
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	*24.4*	*26.9*	*33.1*	*33.5*	*63.0*	*68.0*	*69.9*
Distribution Cable Loss	dB	4.0	5.7	8.8	9.2	21.2	22.0	25.8
Tap Insertion Loss	dB	7.9	7.9	9.2	9.2	16.7	18.7	17.9
Tap Port Loss	dB	6.9	6.9	7.0	7.0	10.4	12.2	8.5
Drop Cable Loss	dB	2.1	2.9	4.6	4.6	10.1	10.4	12.2
In Home Passive Loss to Modem	dB	3.5	3.5	3.5	3.5	4.6	4.7	5.5