Making Room for DOCSIS 3.1 and EPoC – Is your cable plant ready for an OFDM world?

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Abstract

New standards are winding their way through CableLabs and IEEE that will eventually provide cable operators the ability to offer greatly increased data rate capacity to both residential and business customers. DOCSIS® 3.1 and EPoC will usher in a new modulation format for cable MSO's that will help to significantly close the current gap in digital capacity between FTTP and HFC service providers. A major challenge for the success of these next generation technologies is integrating new dedicated bandwidth segments into already constrained RF spectrum. This is particularly true for the upstream where the current 5 to 42 MHz channel allocation is already extremely limited.

Taking full advantage of the efficiencies related to OFDM transport without cannibalizing existing revenue generating RF spectrum will drive new requirements for expanded bandwidth optical and RF components. Although the initial deployment intent of DOCSIS® 3.1 is complete compatibility with the current 1 GHz RF bandwidth, many consider 1.2 GHz to be a logical end point that will maintain the full legacy HFC bandwidth as well as a new 200 MHz sub band for D3.1 or EPoC. Further expansion beyond 1.2 GHz is also a possible consideration for the future, allowing data rates up to 10 Gbps.

This paper will examine the impact of D3.1 and EPoC on current and future access plant components including headend lasers, nodes, and RF actives as well as taps and passives. Network design considerations, operating levels and system performance as the channel loading migrates to include OFDM will also be studied.

INTRODUCTION

Over the past several years' cable MSOs have very successfully launched voice and internet IP services across their HFC networks. DOCSIS QAM has been a large part of this broadband success story. But as competition from Telco and over-builders began to challenge the established cable markets, operators have felt the pressure to increase data rate capacity in order to meet the inevitable comparisons between HFC and fiber to the home (FTTH) networks. The DOCSIS cable standard has also continued to evolve from its early implementation to the current 3.0 standard, offering higher download and upload speeds. But the accelerating growth curve of IP data delivery still threatens to outpace the capacity of traditional DOCSIS transport. The well-publicized Nielsen data rate curves and CAGR plots continue to predict that cable operators will run out of bandwidth in a relatively short time unless some major system changes occur. Node segmentation and analog reclaim have provided breathing room for many operators, extending the available bandwidth to each subscriber. But new challenges to the dominance of cable broadband continue to surface coming from government initiatives, rapidly evolving technology, and the requirements of new business services customers.

THE NEED FOR SPEED

On March 16th 2010 the FCC published the National Broadband Plan[1]. The plan sets forth a number of goals targeting service improvements in both wireline and wireless access. Within the plan objectives are defined timelines to achieve specific download and upload data rate targets. For wireline residential access networks such as HFC cable and fiber to the home the first of these goals includes a minimum of 100 Mbps download and 50 Mbps upload speeds available at an affordable cost to at least 100 million homes in the US by the year 2020. Another goal specifies that every American community should have affordable access to at least 1 Gbps broadband service at institutions such as schools, hospitals, and government buildings. More recently, Julius Genachowski the chairman of the FCC issued a challenge to broadband providers calling for the deployment of gigabit Ethernet service in at least one community in each of the 50 states by 2015.[2]

To meet these growing challenges the IEEE 802.3 Ethernet working group issued a call for interest in November 2011 titled – "Operating the EPON Protocol over Coaxial Distribution Networks". Two months later, the "IEEE 802.3 EPON Protocol over Coax (EPoC) Study Group" was created. In June 2012, CableLabs the non-profit cable industry consortium, initiated a new specification effort to establish the requirements of next generation DOCSIS 3.1.

Downstream data usage rates have been growing at 50% compounded annual rates for several years. If this trend continues the subscriber data capacity needed within the next 10 years will exceed 10 Gbps.

The DOCSIS 3.1 specification will define a new modulation standard for HFC networks with a data rate capacity of 5 Gbps downstream (DS) and up to 1 Gbps upstream (US) while maintaining the current 1 GHz RF bandwidth capabilities of existing cable plant.

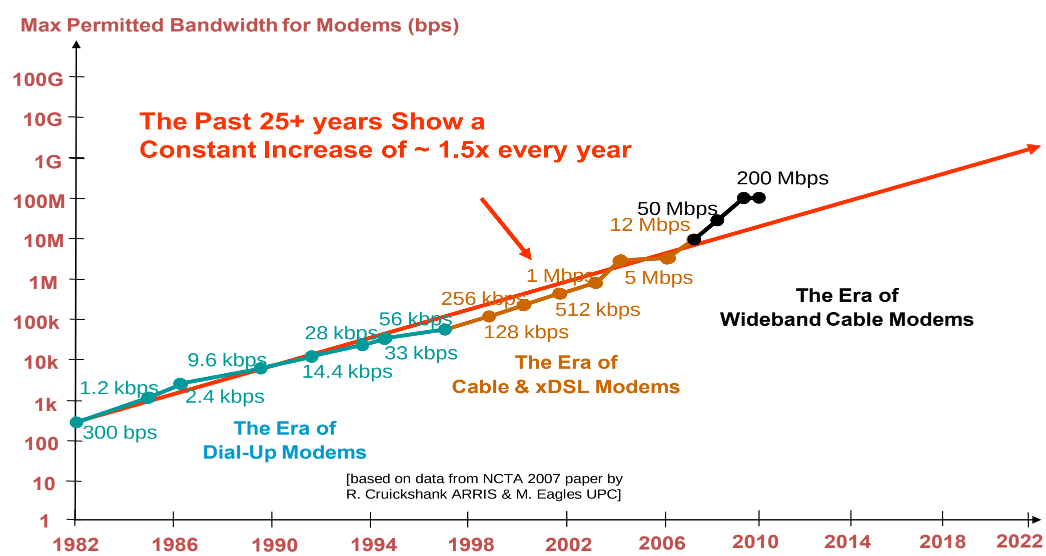

Figure 1 – Nielsen Curve for traffic growth over HFC Networks (3)

The potential for 10 Gbps downstream capacity is achievable with an RF spectrum expansion to approximately 1.5 or 1.7 GHz. Dramatic upstream capacity increases provided by DOCSIS 3.1 will also require significant RF bandwidth changes. High splits of 200 MHz to 400 MHz are still being debated to raise the upstream delivered data capacity to 1 Gbps or higher.

CableLabs has set a target goal to complete the D3.1 specification by year end 2013. Potentially this would allow modem chip sets to be developed and initially introduced as early as 2014 with CPE deployments following in 2015. The IEEE EPOC working group has also been meeting since the beginning of the year along with a number of ad hoc groups that are focused on specific PHY and MAC layer portions of the standard. The estimated timeline to complete the EPOC specification is currently late 2014 or early 2015. The large gap between specification delivery timelines of the two organizations is due to the differences in their respective charters. CableLabs is primarily accountable to its cable operator membership and only creates specifications for the MSO community. IEEE is an international standards organization that must obtain consensus across a wide range of users in many countries.

DOCSIS 3.1 and EPoC Development Goals

A primary goal of both the DOCSIS 3.1 and EPoC specification efforts is the capability to deliver spectrum efficient gigabit data rates. [(4)] To achieve this one of the first considerations is the selection of a modulation format. With a pre-existing transport network and limitations on the usable RF frequency bandwidth, the modulation format (channel width, modulation order, single carrier, multi-carrier, etc.) is the only dimension available to significantly increase the efficiency of the coaxial access link. Both working groups quickly focused on Orthogonal Frequency Division Multiplexing (OFDM) as the successor to single carrier QAM. OFDM is a multi-carrier format with each sub carrier modulated using higher order QAMs.

OFDM subcarrier modulation up to 4096 QAM allows 5 Gbps data rates using approximately 500 MHz of RF spectrum. The result is a 35% improvement in bit/Hz efficiency compared to DOCSIS 3.0 transport. The large bit/Hz efficiency increase could be used in place of node segmentation to improve bandwidth per subscriber - potentially at lower cost. Further expansion of data capacity to 10 Gbps will require an extension of the downstream bandwidth to at least 1.5 GHz and possibly higher.

A major goal for the D3.1 spec is the requirement to operate in existing HFC plant architectures. The common assumption is that downstream D3.1 channels will be placed at the upper end of the available frequency bandwidth above the existing broadcast and narrowcast channel lineups. Depending on the age and quality of the network this could include spectrum with higher frequency roll-off tilt, flatness variations, and degraded return loss performance. The spread spectrum nature of OFDM is more robust to these conditions due to the ability to adaptively modulate individual sub carriers.

Upstream goals for D3.1 include CMTS backward compatibility with D3.0 and D2.0 modems. It is also hoped that initial CCAP platforms that are just starting to be delivered will be able to be upgraded to D3.1 through a firmware revision or card change. Nearly 100% of North American cable networks currently use a 42 MHz return bandwidth. To achieve the full 1 Gbps data rate capacity of DOCSIS 3.1 an RF bandwidth of at least 200 MHz is essential. But as stated previously, a goal of D3.1 is that an upgrade is not a requirement for implementation. This maintains existing plant equipment use but limits the immediate impact of D3.1 in the upstream depending on the current US - DS frequency split. The DOCSIS 3.1 working group has also eliminated the idea of doing a top split where upstream spectrum would be placed above the downstream bandwidth.

While EPoC shares many of the same first order target goals as DOCSIS 3.1, a significant difference is that the IEEE standards group specification goal is to provide symmetric and asymmetric full duplex Ethernet transport over coax with no substantive changes to other EPON layers. In this case EPoC would only coexist with HFC. The EPoC transmissions would traverse between an EPON OLT and a coaxial network unit (CNU) modem at the subscriber termination side. In order to achieve symmetric data rates, EPoC transmissions could use either Frequency Domain Division (FDD) or Time Domain Division (TDD). FDD for symmetrical data rates of 2.5 Gbps or more would exceed the available RF spectrum of existing cable networks assuming there were no HFC channels carried on the same system. TDD would solve this problem for networks that plan to overlay HFC with EPoC at 1 Gbps data rates or higher.

<u>Single Carrier vs. Multi-Carrier</u>

DOCSIS 1.0 through the current DOCSIS 3.0 standards have all been based on single carrier QPSK or QAM formats. Single carrier modulation (SCM) uses a fixed, uniform modulation profile. The transmission performance is dependent on the signal to noise characteristics of the channel frequency. With defined channel bandwidths of 6 and 8 MHz, increasing the data capacity is achieved by increasing the QAM modulation order (8 bits/256 QAM, 10 bits/1024 QAM, etc.) of the transported channels or channel bonding. Increasing the modulation order requires an appropriate SNR level maintained across the entire channel(s) bandwidth. Other limitations of SCM are the complexity of bonding multiple channels and the performance degradation impact of noise and discrete interferers within the channel(s).

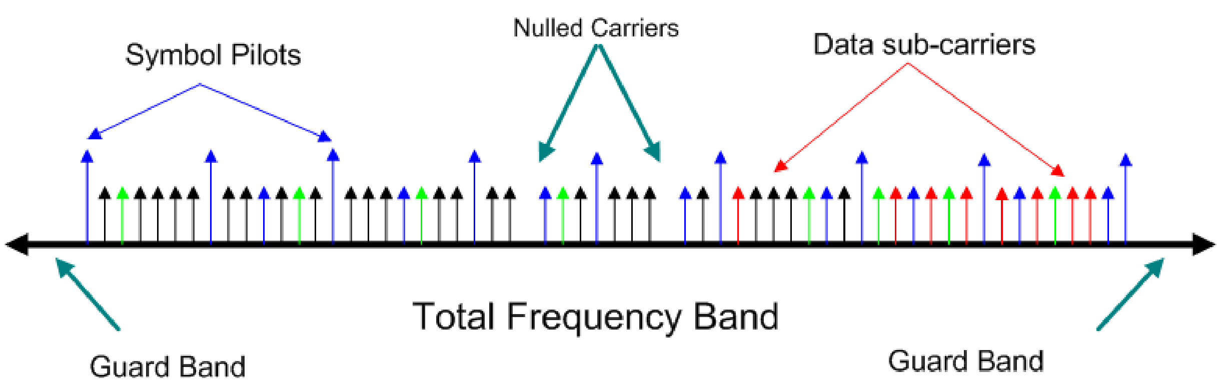

Figure 2 – Representation of OFDM Multi-Carrier Modulation

Multi-carrier modulation uses discrete multiple tones (DMT) spread across a wider frequency bandwidth that does not necessarily have to be a contiguous channel. Orthogonal Frequency Division Multiplexing (OFDM) uses multiple narrow 20 KHz to 50 KHz subcarriers that are each modulated with higher order QAMs. An OFDM FFT block of 192 MHz is the most commonly referenced channel width target for D3.1 and EPoC. DOCSIS 3.1 has further defined a minimum sub block channel size of 24 MHz. The 24 MHz minimum channel size was selected in order to have a common bandwidth allocation for DOCSIS and Euro DOCSIS. Since 24 MHz is a common denominator for both DOCSIS 6 MHz channels and Euro DOCSIS 8 MHz channels. Table 1 details the raw and estimated delivered data capacity for a 192 MHz FFT block and the various modulation formats that could be transported. An overhead efficiency factor of 30% was used in the data rate calculations below (Table 1). Estimates of this efficiency factor range anywhere from 20 to 35% depending on the source. The data capacity for other channel widths can be approximated as multiples of 24/192 MHz assuming the remaining sub-carriers have been nulled out.

OFDM DS Data Rate Capacity

QAM	Bits/symbol	FFT Block Sym rate (Msps)	Block size (MHz)	Raw Capacity (Mbps)	Efficiency (estimate)	Delivered Capacity (Mbps)
64	6	192	192	1152.00	0.7	806.40
256	8	192	192	1536.00	0.7	1075.20
1024	10	192	192	1920.00	0.7	1344.00
4096	12	192	192	2304.00	0.7	1612.80

Table 1 – Downstream Capacity Calculations for D3.1 OFDM

An advantage of OFDM is that the subcarrier modulation order can be varied across the channel to compensate for differences in SNR with frequency as shown in Figure 3. This feature allows OFDM to operate in links where the frequency gain response is not uniform due to passive losses or RF active performance. Individual subcarriers can also be nulled out in the case of discrete interfering signals. This allows OFDM to provide higher throughput than single carrier QAM under non ideal link conditions.

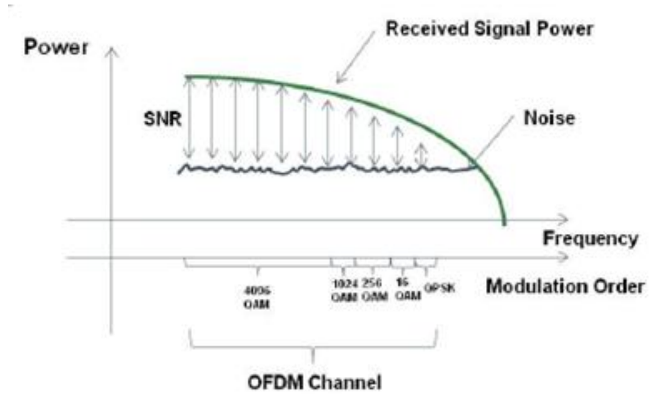

Figure 3 – Example of Adaptive Modulation Order for D3.1 OFDM

OFDM is less complex than MAC layer channel bonding, allowing easier scaling to higher data rates. OFDM is also more resilient to micro reflections, impulse noise, and ingress. In addition to these benefits, both the D3.1 and EPoC specification working groups are planning to also change the current forward error correction (FEC) scheme. Earlier versions of DOCSIS have all used Reed-Solomon FEC coding. In the early 1990's newer turbo FEC codes were developed that demonstrated improved efficiency in high noise channel environments. The discovery of turbo codes led researchers to look for other lower complexity coding solutions. These efforts resulted in the rediscovery of LDPC codes, first proposed by Robert Gallager[5] in his 1960 doctoral dissertation. Low Density Parity Check (LDPC) codes provide FEC solutions that are even closer to the Shannon capacity limit than any previous code. The improved spectral efficiency allows higher order QAM transmission at SNR levels that are 7 to 10 dB lower than achievable with traditional Reed-Solomon coding. Therefore, with LDPC the SNR needed to transport 1024 QAM is approximately equivalent to the DOCSIS 3.0 SNR for 256 QAM. Figure 4 shows a simulation of SNR values for different modulation orders and FEC levels.

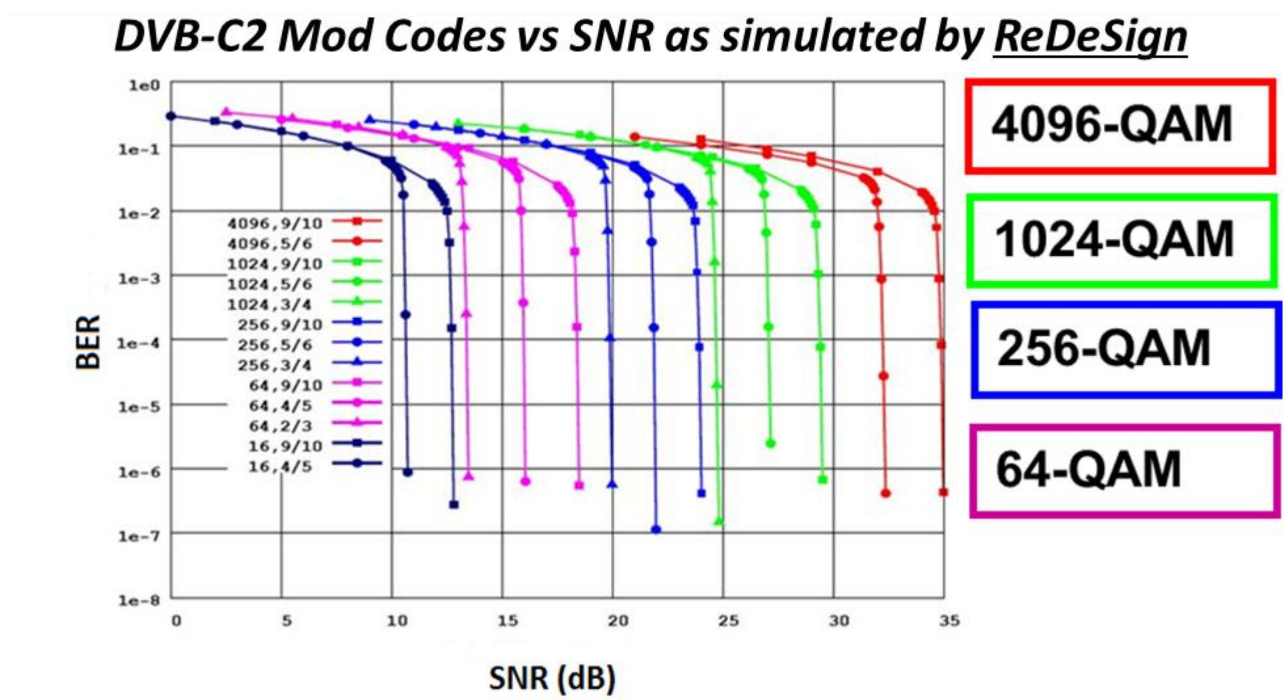

Figure 4 – SNR for OFDM with LDPC Forward Error Correction [6]

The efficiency of OFDM combined with LDPC FEC alleviates the need for higher CNR performance optics and RF actives when compared to single carrier 1024 QAM channels. A 1K OFDM channel should be able to maintain the same -6 dB from virtual level derate used today for downstream 256 QAM channels. This should allow systems that need to carry analog plus QAM channel loads to potentially add DOCSIS 3.1 or EPoC channels as long as the total RF input drive level to the transmitter is maintained. The SNR requirements for higher order modulation OFDM channels are still within the range of typical HFC networks but will have reduced margin against the normal range of network and seasonal variations. In this case the 4K OFDM channels could still be carried on legacy access links at the same -6 dB derate as existing QAM channels with the assumption that the modulation order and peak data rates would be backed off to areas of the network with lower SNR values. Changing the derate to -3 dB or higher as an example would buy back most of the lost margin for 4K OFDM transport but the increased power load could push the laser transmitter or RF amplifier into compression degrading the performance of the entire serving area link. More investigation is needed once the working groups have completed their spec definition efforts to determine the worst case loading conditions and the active device peak power performance that will be needed.

Discrete non time varying interferers could disrupt OFDM subcarriers that fall on the same frequency. In most cases these subcarriers can be nulled out with very little impact to the overall data rate of the OFDM block. In the case of mixed analog video channel loading with OFDM the concern is the number of CTB beats that will impact the D3.1 subcarriers. For a 192 MHz block of OFDM subcarriers, only 2% to 5% will be impacted by CTB beats generated from a 79 analog channel load. As the analog carriers are reclaimed this becomes less of a problem. A reduction from 79 analog channels to 60 channels results in a 6 dB reduction in CTB. Interleaver coding may also help reduce the impact of distortion beats such as CTB and CSO generated by analog carriers. Interleavers are typically used in multi-carrier wireless applications to mitigate selective signal fading by distributing the transmitted bit-stream across a wider range of frequencies rather than concentrating the bits on a narrow band of subcarriers. CTB beats are predictive based on the channel relationships of the analog carriers allowing interleaver algorithms to minimize the loss of critical parts of the bit-stream. The eventual transition to all digital loading by reclaiming the remaining analog video channels will completely eliminate the issue of CTB impairments.

OFDM in the Upstream

The legacy upstream bandwidth allocation is much more constricted than the downstream with less than 37 MHz available in most North American systems today. It is also anticipated that cable operators will maintain the current D2.0 and D3.0 channels for a considerable time, consuming a large portion of the limited clean spectrum in the 15 to 42 MHz bandwidth segment. The HFC upstream environment contains many more local sources of potential interference than the downstream. The SNR levels received from each subscribers' home has a wide distribution resulting from varying loss budgets depending on the tap position along the access coax path, ingress levels, and in-home wiring losses. To counter the dynamic nature of the upstream a variation of OFDM has been selected for subscriber premise equipment. Orthogonal Frequency Division Multiple Access (OFDMA) provides a combination of frequency domain and time domain multiple access by assigning different numbers of subcarriers to different users as shown in Figure 5 below. In addition to providing the same robustness to ingress and impulse noise as OFDM, OFDMA also enables adaptive modulation for every individual user. The modulation order can be dialed back to optimize throughput for subscribers with poor SNR values without affecting the upload speed of other customers on the same link.

The target FFT block size for upstream OFDMA is 96 MHz with a minimum sub-block size of 24 MHz consistent with downstream OFDM. The capability to null out subcarriers potentially allows DOCSIS 3.1 to fit in whatever bandwidth is allocated although at a proportionally reduced data capacity. Table 2 details the expected data capacity based on the smallest sub-block size and the range of modulation orders that are most likely to be supported.

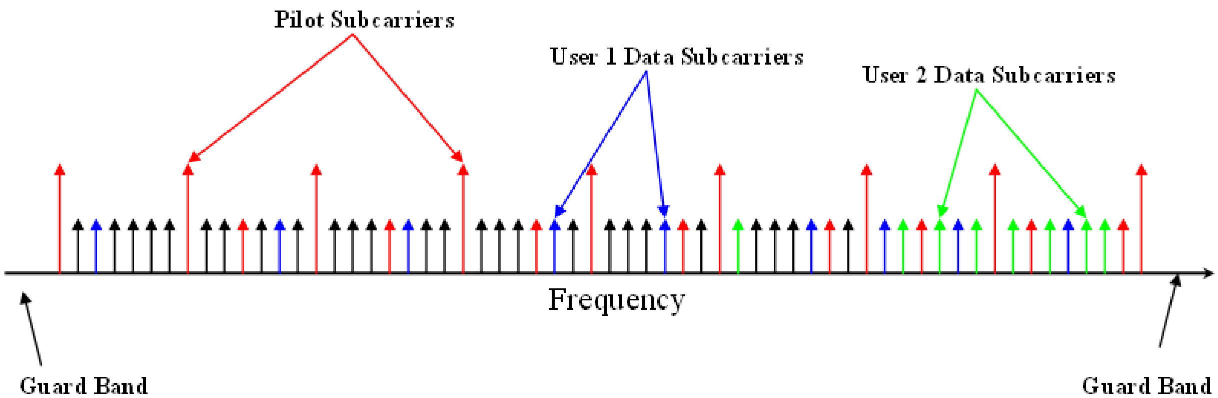

Figure 5 – Example of Multi-user Subcarrier Assignments with OFDMA

OFDM US Data Rate Capacity

QAM	Bits/symbol	FFT Block Sym rate (Msps)	Sub-block size (MHz)	Raw Capacity (Mbps)	Efficiency (estimate)	Delivered Capacity (Mbps)
64	6	96	24	144.00	0.7	100.80
256	8	96	24	192.00	0.7	134.40
1024	10	96	24	240.00	0.7	168.00

Table 2 – Upstream Capacity Calculations for D3.1 OFDM

The upstream DOCSIS 3.1 data rate target of 1 Gbps can be easily achieved using two US FFT blocks of 1024 QAM modulated OFDMA subcarriers. This equates to 192 MHz of upstream RF spectrum. It is anticipated that the working group final upstream allocation for D3.1 will specify a minimum of 200 MHz bandwidth.

Finding room for D3.1 in the current 5 to 42 MHz return path bandwidth is virtually impossible without a mid split expansion. Most cable systems today are using two DOCSIS 3.0 channels (6.4 MHz) and one DOCSIS 2.0 channel (3.2 MHz) to meet existing voice and data rate tier demands. Many operators expect to add a third DOCSIS 3.0 channel within the next year or two. Even with an OFDMA channel minimum sub-block size of 24 MHz there is not enough RF bandwidth available to accommodate D3.1 and maintain the legacy DOCSIS channels. Migrating to an 85 MHz mid split would provide the needed growth room to effectively plan upstream capacity without extensive node segmentation.

INTRODUCING D3.1 INTO LEGACY HFC NETWORKS

When it becomes available, the first applications of DOCSIS 3.1 in legacy 750 MHz to 1 GHz systems will be to raise delivered DS data rate tiers without making any physical changes to the existing HFC plant equipment. The next sections of this paper will review the advantages and limitations of deploying D3.1 in current BW networks. Following sections of the paper will detail the considerations necessary to take full advantage of the data capacity potential of this next generation modulation scheme.

Limitations of the No Touch Approach

HFC networks today are a mix of 750 MHz, 870 MHz, and 1 GHz RF access plants reflecting the system design targets of the individual cable operator. RF bandwidth extensions, analog reclaim, switched digital video, and various digital compression techniques have allowed MSOs to expand the content offerings and IP services they provide while at the same time extending the lifetime of their existing network. Node segmentation provides operators with a minimally disruptive method to significantly increase the delivered bandwidth per subscriber. The cost of the initial primary node segmentation is typically estimated at $20,000 since the majority of the expenses are usually limited to material costs rather than new fiber deployments. [7] By comparison, subsequent node split costs can increase almost exponentially due to fiber construction expenses and when calculated based on the fixed number of subscribers served by a particular node. The appeal of DOCSIS 3.1 in this situation is the potential to increase data capacity per subscriber without doing additional node splitting.

It is expected that data rate growth will continue to be asymmetrical with download speed requirements increasing at a significantly faster rate than upload speeds. Downstream RF bandwidth continues to be under pressure today due to the steady increase of HD programming, the popularity of on-demand streaming, and the rapid growth of IP everything. Many MSOs continue to support a large number of analog video channel offerings due to the large CPE conversion cost of migrating to all digital all at once. Others feel that analog is still a positive differentiator to customers comparing cable with competitive satellite and PON providers. Every MSO expects to migrate to all digital carriage at some point in the future, but the projected timelines vary per operator from within the next 12 months to nearly ten years out. Finding open RF bandwidth is already a challenge in most cable operator networks. Reclaiming channels in order to deploy DOCSIS 3.1 without major disruption to the existing physical plant will take careful planning.

In legacy brownfield networks active element gain, tilt, and spacing along the coaxial access path has been set to optimize the bandwidth and cascade depth reach of the system. For 870 MHz systems and particularly for 750 MHz systems with analog plus QAM channel loads, there are only a limited number of open channels available. In most cases, adding a new OFDM channel block on these networks can only be accomplished by reclaiming RF spectrum from the existing analog or digital portions of the channel map.

In the case of 1 GHz networks, few if any are fully loaded today. DOCSIS 3.1 could take full advantage of this available channel space. In many designs, systems with longer amplifier cascades have a buildup of cable and passive losses along with response flatness issues at the high end of the spectrum preventing acceptable BER / MER performance. OFDM could help these 1 GHz system operators to reclaim this lost bandwidth as illustrated previously in Figure 3.

A new OFDM channel block can be placed anywhere in the downstream spectrum but the most likely location for these subcarriers will be above the existing broadcast and narrowcast channel loading but within the upper band edge of the system. The robustness of OFDM will allow operators to reclaim previously unusable channel space at the upper limit of this RF spectrum. The data capacity increase due to this legacy no touch scenario will be limited only by the amount of bandwidth that is dedicated to DOCSIS 3.1 modulation.

Similarly, the current 5 to 42 MHz return bandwidth that dominates in all North American cable MSO networks is already rapidly approaching its capacity limit. DOCSIS 3.0 and node segmentation have kept cable operators just ahead of the curve but the existing RF bandwidth limits the upstream to just under 100 Mbps using QAM 64 modulation. Low frequency ingress and impulse noise further reduce the usable portion of this narrow allocated spectrum. Many cable systems today load the upstream with two 6.4 MHz DOCSIS 3.0 channels and one 3.2 MHz DOCSIS 2.0 channel. This covers their highest advertised data rate tier plus VoIP phone service but leaves very little spectrum for a new D3.1 sub band. Transitioning to higher order modulation would only provide a short lived incremental increase in capacity.

Extending the Life of the Brownfield HFC Network

The compound annual growth rate of upstream data usage commonly reported at 10 to 12% is consistently lower compared to downstream rates. In spite of this lower growth rate and the benefits of node segmentation the current upstream band cannot meet anticipated forward looking capacity requirements due to the limited 5 to 42 MHz RF return bandwidth. Even with DOCSIS 3.0 channel bonding the peak data rate is restricted to roughly 100 Mbps.

To truly extend the life of the upstream plant and reduce the urgency of node splitting, an increase in the allocated RF bandwidth is needed. As a result, many system operators are now planning 85 MHz mid split trials in 2013. The 85 MHz mid split or commonly referenced "N-split" return bandwidth allocation was defined as part of the DOCSIS 3.0 standard. The shift to 85 MHz would nearly triple the amount of clean spectrum available in the return band with only a small reduction in the forward path bandwidth.

Cable system operators initiating mid split band shifts have in almost every case already moved to all-digital QAM transport. An 85 MHz return band will allow cable operators to maintain existing DOCSIS 2.0 and 3.0 CPE while also providing over 40 MHz of bandwidth for a new D3.1 upstream sub-band.

The mid-split migration will require changes to the diplex filters and return path gain stages located in the node and amplifier E-pac modules. Addressing downstream bandwidth improvements at the same time as the mid split migration would provide a one touch opportunity to extend the data capacity of both downstream and upstream. For 750 and 870 MHz systems this could be as straightforward as changing out the E-pac with a 1 GHz capable version. The major equipment manufacturers have all consolidated their laser, node, and RF amplifier product offerings to 1 GHz designs that drop into existing housings. With the proper padding and equalization these 1 GHz actives can maintain legacy 750 and 870 MHz system performance and provide a future migration path when additional frequency bandwidth is needed.

Increasing the upstream bandwidth beyond 85 MHz could have significant design and cost impacts to legacy brownfield HFC networks. The final determination of a high split frequency plan for DOCSIS 3.1 is still being debated by the CableLabs D3.1 working group. The upstream high split band edge is expected be specified at or near 200 MHz with an appropriately narrow guard band between US and DS that balances the potential impact to CPE cost against a significant reduction in the number of revenue generating DS channels.

GOING BEYOND 1 GHz NETWORKS

The main drivers for increasing the HFC RF plant frequency bandwidth beyond the current 1 GHz DOCSIS 3.0 spec limit are expanding upstream data capacity and at the same time preserving the total existing downstream bandwidth. In order to reach the 10 Gbps target goal of DOCSIS 3.1 or EPoC a total RF bandwidth exceeding the current 946 MHz allocated to downstream channels in a 1 GHz RF plant is required. When combined with the bandwidth needed to maintain legacy broadcast and narrowcast video, phone, and D3.0 data services the total RF spectrum estimates range from 1.5 GHz to 1.7 GHz. A second driver also related to DOCSIS 3.1 is the potential expansion of the upstream to 200 MHz in order to achieve the target goal of 1 Gbps data rates. The only way to accommodate 200 MHz of new return path spectrum is to cannibalize downstream bandwidth. To preserve the current downstream bandwidth most cable operators prefer to shift the downstream upper band edge to 1.2 GHz.

Developers of new HFC plant equipment are already at work planning designs that will support the eventual introduction of DOCSIS 3.1 including extended bandwidth optical and RF plant actives. Whenever outside plant changes are considered the impact on new builds is much different than migrating an existing system where amplifier spacing's, powering, and signal distribution have been pre-determined. The following sections will detail the various changes and challenges of expanding the HFC plant beyond 1 GHz. Since the DOCSIS 3.1 and EPoC working groups have adopted OFDM transport over coax as the central anchor point for their respective efforts, the principles discussed in these next sections are applicable to both technologies.

Extending the Coaxial Network Bandwidth

The first elements that need to be considered for any outside plant migration are the coaxial and RF passive devices. Trunk, access, and drop coax attenuation versus frequency data is readily available from the manufacturers. Figure 6 shows estimated levels and coaxial loss budget information for a simplified N+3 downstream design extended to 1.2 GHz.

Taps and passives with 1 GHz bandwidth have been available for several years and are now ubiquitous across every MSO network. The main line insertion loss and tap port loss of these devices is well behaved across the specified bandwidth making performance estimates easier to generate.

Above 1 GHz the tap port attenuation and thru loss tilt increases substantially with increasing frequency. Cascaded insertion losses from a typical 5 to 7 tap string combined with highly tilted tap port loss further reduce end of line signal levels by an additional 4 to 6 dB at 1.2 GHz. Figures 7 and 8 show examples of the main line insertion loss, return loss, and tap port response for a 1 GHz 14 dB tap plotted from 1 MHz to 1.5 GHz. While the claimed advantages of OFDM modulated channels make it feasible to operate in this imperfect frequency response portion of the spectrum, the high cascade loss budget may overwhelm the available signal level beyond the first few taps in the string.

The example of Figure 6 also illustrates the challenges that many cable operators encounter even with a 1 GHz network deployment. The end of line modem input levels for 1 GHz and higher in this model are at the lower limit of the specified range for most CPE devices. Additional losses due to plant seasonality variations, in-home issues due to customer wiring, etc. will further decrease the received signal levels below the threshold.

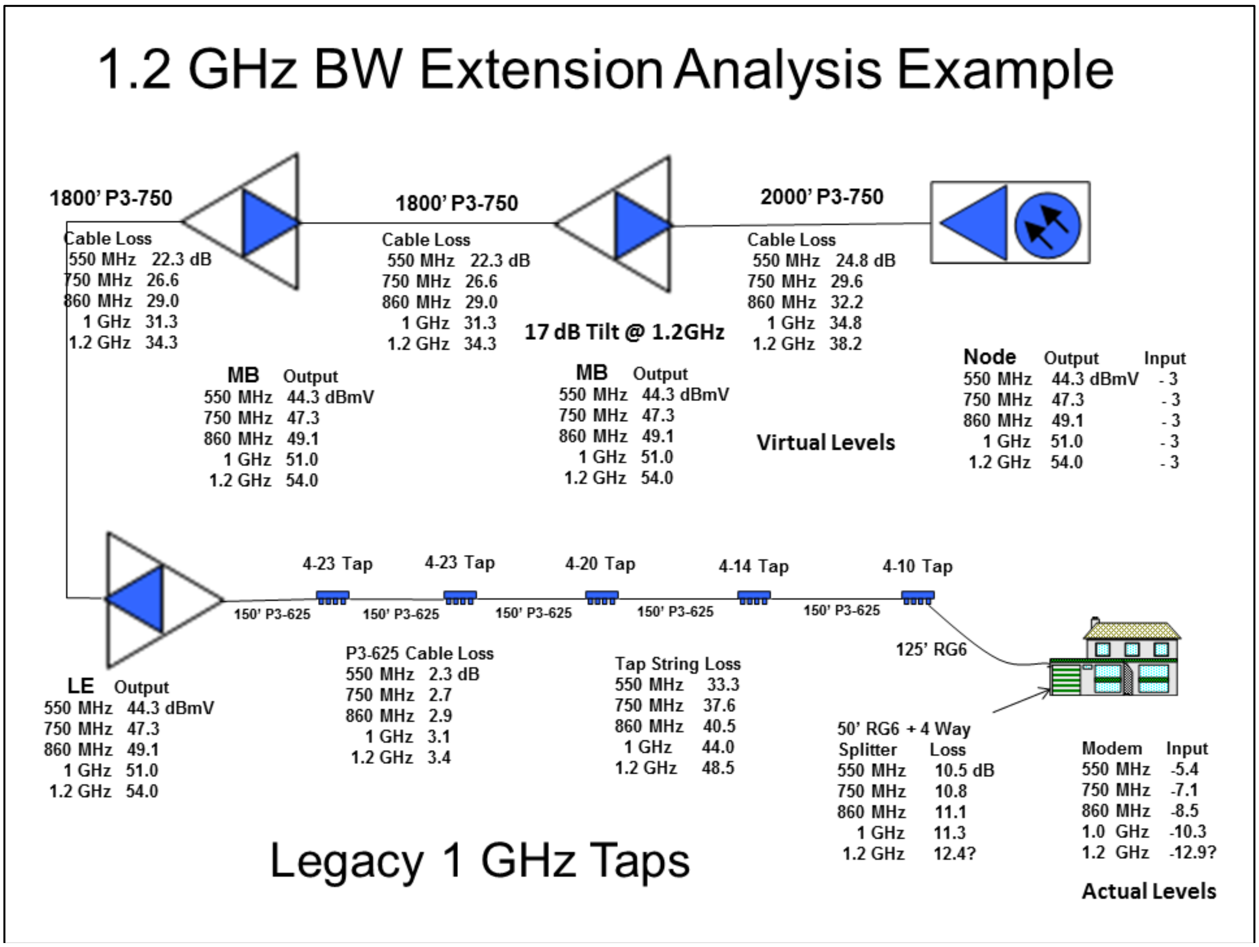

Figure 6 – Design Example of a 1.2 GHz Bandwidth Expansion

Extended bandwidth taps and passives are beginning to appear on the market in response to interest in expanding above 1 GHz. In most cases these devices simply provide a more controlled flatness and return loss response up to 1.2 GHz but insertion losses are not improved. New innovations have demonstrated performance capability up to 1.8 GHz. These devices have also shown improved insertion loss performance compared to legacy 1 GHz passives which could be used to gain back 1 to 2 dB of SNR margin or compensate for other losses in an existing 1 GHz network.

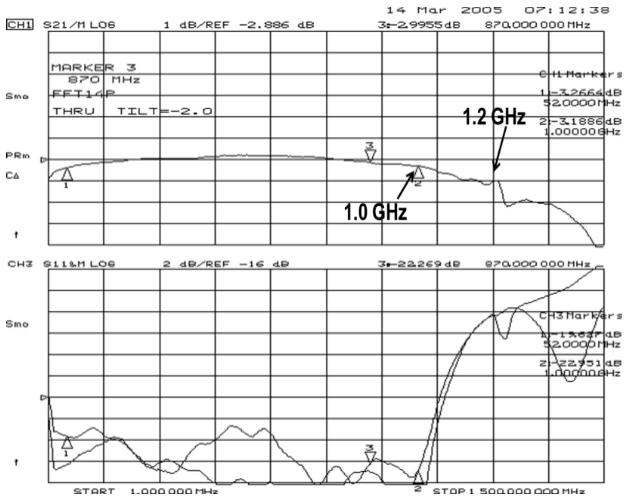

Figure 7 - 14 dB 1GHz Tap Thru Loss and RTN Loss

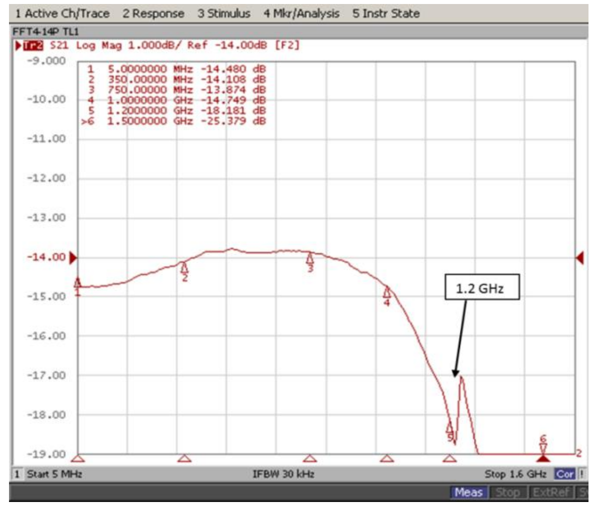

Figure 8 – 14 dB 1GHz Tap Port Loss

Optical Headend Laser Transmitters

Every optical transmitter intended for use in HFC downstream access links today is designed with a DFB laser at its core. These lasers have been linearized either by pre-distortion techniques or through the use of an on chip or external modulator. The RF bandwidth response of the lasers and modulators used in HFC applications are typically 3 GHz or higher. The actual usable bandwidth is determined by the RF amplifier driver stages at the input to the laser or the various laser package parasitics that limit or disturb the broadband frequency response. All laser transmitters capable of analog video loading should also be able to transport OFDM channel blocks.

HFC analog lasers have a fixed optical modulation index (OMI) typically in the range of 22% to 26% for a 1 GHz transmitter. Increasing the loading by 200 MHz decreases the OMI per channel. The effect of this added loading on CNR is a reduction of 0.6 dB per channel. This assumes there is no change in the upstream bandwidth. The reduced C/N could be minimized if the total loading on the laser was only shifted in frequency and kept constant at a 1 GHz level. This scenario would occur if the upstream was expanded to a 200 MHz high split and the 1 GHz downstream loading was merely shifted up to 1.2 GHz.

Creating optical headend laser transmitters that provide a 1.2 GHz flat RF response is a relatively straightforward task of modifying the RF driver stages to assure that they have the bandwidth and linear output capability to drive the laser or modulator. Transmitters designed for this extended bandwidth have already been displayed by a number of vendors. Distortion performance measurements for these extended bandwidth devices is still somewhat variable depending on the equipment used and skill of the vendor.

DOCSIS 3.1 and EPoC modulation format specifications are still in development so signal generation and test equipment availability is still a few years away. Most the specialized QAM generation and test equipment for cable applications on the market today is limited to 1 GHz total bandwidth with the exception of a few high end lab grade instruments. Digital channel loading above 1 GHz can be simulated by the use of noise blocks or by up converting a band of lower frequency QAM carriers. These methods allow basic noise power ratio measurements with the appropriate channel filters. MER and BER testing is possible using up converted QAM channels. The upconverter phase noise is especially critical to making these digital measurements accurately.

Laser transmitters with bandwidths higher than 1.2 GHz are also possible. Many manufacturers have created versions covering various frequency bandwidths up to 3 GHz in order to support satellite and military applications. The drawback for analog lasers as the RF bandwidth becomes wideband is the reduction in carrier to noise which will ultimately restrict the maximum link reach of the system.

Nodes and Actives

Increasing the bandwidth and channel load has the highest impact on the RF active components in the system. Output power level, gain, power consumption, thermal dissipation, path isolation, and numerous other design considerations must be addressed. A primary driver for all network migrations is backward compatibility with the existing deployed network. This places additional pressure on the performance of the expanded BW actives since key factors such as DC power, mechanical housing size, and input / output levels are set by the prior legacy design.

In order to migrate an existing system to a 1.2 GHz network, RF gain and output levels must be increased to maintain legacy 1 GHz performance and overcome the higher cable loss budget at 1.2 GHz. Expanding the channel loading to 1.2 GHz effectively extends the current 14 dB RF amplifier output tilt line common for 1 GHz systems to 17 dB. The added loading increases the output level requirement for the node and each amplifier by 3 dB. The design example diagram in Figure 6 shows the digital channel power (virtual) needed for each station in the cascade. The higher output at 1.2 GHz and raised tilt level increases the power load of the digital channels by approximately 3.5 dB. This will increase the CIN distortion generated by the digital channels which primarily impact the channels in the lower part of the frequency band.

GaAs technology power doubled gain blocks are not capable of supporting the higher output levels needed for 1.2 GHz channel loading. Initial testing using Gallium Nitride (GaN) devices which have been introduced in a number of node and amplifier platforms over the past three years show adequate performance, assuming the digital derate remains at -6 dB referenced to the virtual analog level, but with very little excess margin. The advantage of GaN is its improved output power capability. This is achieved primarily as a result of dramatically reduced thermal resistance compared to GaAs allowing higher output power without increased die temperatures. Another key difference is the higher voltage capability of GaN. GaN amplifier technology was initially developed for high voltage operation applications such as satellite transponders and terrestrial base stations. Cable amplifiers have been designed for 24 volt operation since the first silicon hybrids introduced in the early 1970's. Modified higher voltage power supplies would provide the potential for additional output capability.

The major challenge in the migration path to 1.2 GHz or even higher bandwidths is station gain. Increasing the amplifier tilt is necessary to overcome the increased cable and passive losses associated with higher bandwidth operation. Along with higher output capability, increased gain would normally allow amplifiers to hold their current locations when migrating to the higher frequency bandwidth. The difficulty is that existing cable networks have migrated several times over the past 20 years as a result of bandwidth capacity drivers and new technology innovations. In each case the internal circuitry modules or E-pacs have been updated but the strand mount housing has remained in place. The typical internal gain stages in a 1 GHz amplifier today total up to well over 50 dB. Some of this gain is lost to internal filter attenuation, equalization boards, splitters for multiple outputs, test points, and other necessary functions. The additional gain needed for a 1.2 GHz migration to hold locations in a brownfield design is an estimated 4 to 6 dB depending on the increased losses of new interstage components for above 1 GHz operation.

This is further complicated due to the potential expansion of the upstream bandwidth to 200 MHz for D3.1 and EPoC 1 Gbps data capacity improvements which will require an estimated 4 to 5 dB increase in return path gain. The combination of forward and reverse gain increases will make it extremely difficult to maintain path isolation and stability in the current amplifier housings. This makes it unlikely that traditional 6 deep cascade brownfield networks can be migrated beyond 1 GHz without a major re-design effort.

For new build applications, amplifier spacing's can be set to match the achievable stable gain of 1.2 GHz actives.

Upstream Expansion beyond 42 MHz

With a few component changes most deployed amplifiers and nodes can be migrated to an 85 MHz mid split. These changes include the diplex filters and any high pass cut off filters added to the upstream signal path in order to improve path isolation within the amplifier. Depending on the age of the unit, in some cases the return path hybrid may also need to be replaced. It is not advisable to make these changes in the field so the migration process will include swapping out the amplifier E-pac module with one that has been converted and bench tested to assure proper operation. With appropriate care and controls, lab testing has been done demonstrating that it is possible to hot swap these modules lowering the manpower costs and system downtime during the conversion.

In a high split expansion to 200 MHz or above several additional factors will need to be addressed. First among these is the increased coax loss plus high value tap attenuation that impact upstream modem levels reaching the first active. Figure 9 illustrates the cable losses for different upstream bandwidths and shows the estimated modem level reaching the first active amplifier. The modem output in this example is based on the current D3.0 four bonded channel level. Four D3.0 channels represent a roughly equivalent bandwidth to the minimum D3.1 sub-block of 24 MHz.

Higher cable loss tilt between 5 and 200 MHz shown in Figure 9 requires equalization to avoid large variations in modem power levels across the frequency band. Loss variation over temperature will also increase significantly and may require the addition of return path AGC within the cascade amplifiers.

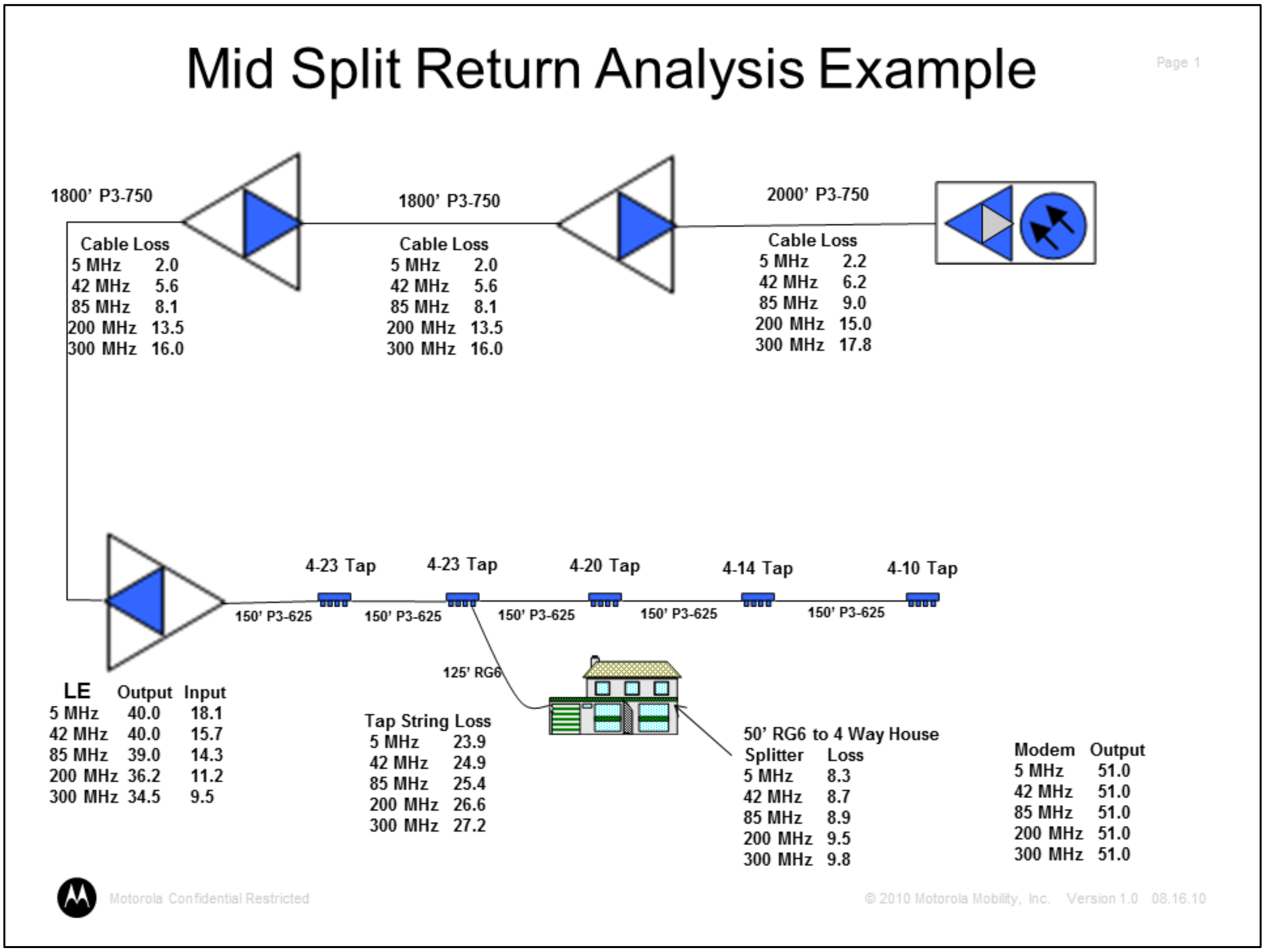

Figure 9 –Design Example for Mid and High Split Upstream Expansions

The SNR delta between D3.0 64-QAM and D3.1 1K-OFDM is 6 to 7 dB. The increase in cable and passives loss as the upstream bandwidth expands to 200 MHz will cause D3.1 channels levels to move closer to the dynamic range noise floor of the upstream laser as shown in Figure 10 unless modem levels are raised higher [(8)]. Since the expected release of the DOCSIS 3.1 specification is still several months away it is unknown what output levels these next generation modems will achieve. This remains a critical issue in the ultimate performance of DOCSIS 3.1.

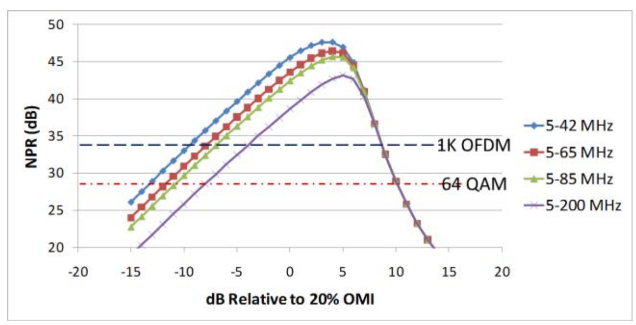

Figure 10 – US NPR for various BW splits

Analog vs. Digital Return

Figure 11 shows measured typical NPR performance of a 2 mw DFB-RPR return of nominal link length. A measured DR system using (post-processed) 10-bits of transport is shown overlaid, in each case using a 65 MHz (European) split.

There is link length dependence for the analog link, and the associated wavelength vs. loss dependence. These variables are not drivers of NPR performance for optical fiber lengths within the digital optical link budget of the DR system, as is commonly the case for HFC applications. Nonetheless, this data confirms the general equivalence of a digital return system achieving a full ten bits of performance to nominally performing higher power DFB returns over average HFC link lengths. It is also apparent how both technologies show comfortable margin to the higher order modulation thresholds shown.

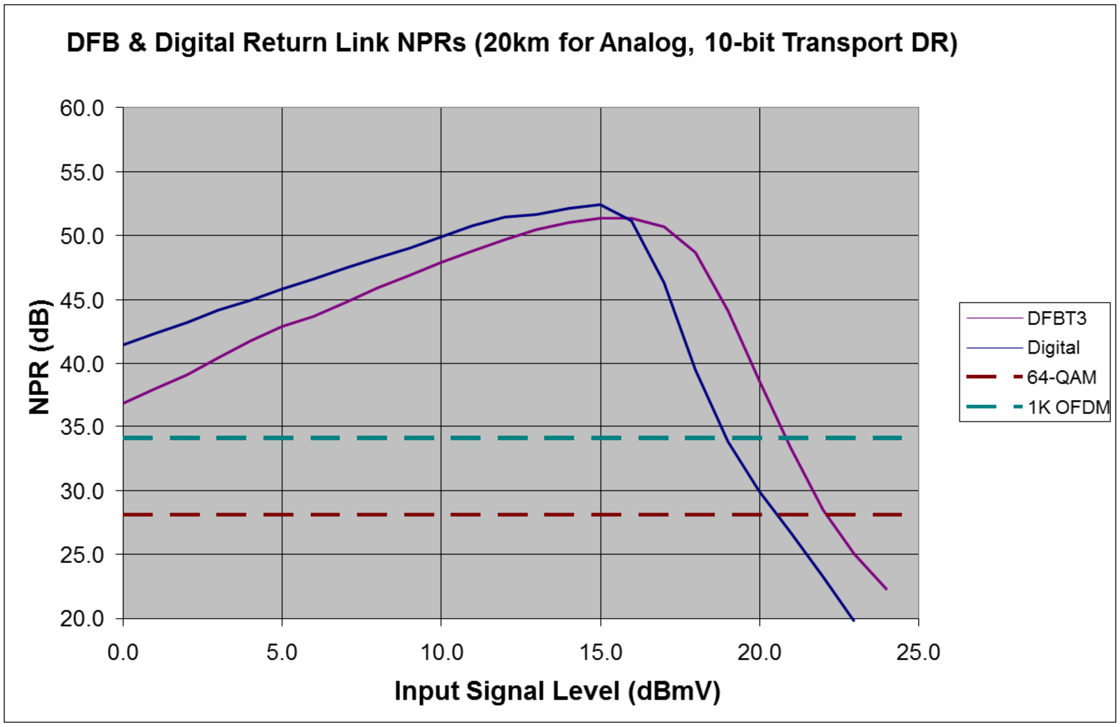

Figure 11 – Typical NPR Performance, Existing DFB and Digital Returns (65 MHz)

Analog return lasers and RF driver stages already accommodate these bandwidth extension options with minimum changes, if any, needed to existing deployed transmitter modules or Hub receivers. For digital return the sampling rate and laser data rate requirements for a typical 2X RF stream transmitter become increasingly difficult and expensive as the bandwidth increases. Table 3 shows the optical line rates resulting from various combinations of A/D resolution and RF upstream bandwidth.

The implication here is that each incremental increase in bandwidth will require a new design iteration replacement of the current DR transmitter / receiver pair. The A/D and laser cost for 200 MHz and higher bandwidth increases dramatically driven by the higher sampling speed and high cost >10 Gbps optics.

Return BW (MHz)	10 bit A/D Sample Rate	12 bit A/D Sample Rate	Laser BW Requirement
5 - 42	1.90 Gbps	2.28 Gbps	2.5 Gbps
5 - 85	3.60 Gbps	4.32 Gbps	4.5 Gbps
5 - 125	5.20 Gbps	6.24 Gbps	8 Gbps
5 - 200	8.40 Gbps	10.08 Gbps	12 Gbps

Table 3 – Digital Return: A/D Resolution, Upstream BW, and Optical Link Bit Rate

CONCLUSIONS

Downstream data rates continue to grow at a 50% compound annual rate and still widely outpace upstream growth. Node splitting is a viable remedy to relieve the increasing data capacity pressures but the cost increases dramatically with each additional layer of segmentation. The introduction of DOCSIS 3.1 in the next two or three years promises to provide cable operators with an alternative tool to incrementally increase data rate capacity to gigabit rates without a major forklift upgrade of the existing HFC plant. The robustness and efficiency of OFDM modulation in conjunction with LDPC coding will enable DOCSIS 3.1 channels to reclaim spectrum that is now impractical to use with prior DOCSIS formats.

The limited spectrum available within the current 5 to 42 MHz return band continues to constrain the peak deliverable data rate and the future ability to effectively use DOCSIS 3.1 to increase upstream capacity when it becomes available. Many cable operators are now planning to trial and potentially deploy 85 MHz mid split systems starting in 2013. To accomplish a mid split migration, the node and amplifier RF modules must be configured with new diplex filters. Migrating to 1 GHz capable downstream modules at the same time as the mid split would achieve a one touch bandwidth capacity expansion that will extend the life of the legacy HFC network for 10 years or more.

HFC frequency extensions beyond 1 GHz are particularly feasible for Greenfield applications. Taps and passive devices allowing future expansion up to 1.7 GHz bandwidth are planned to be available before the end of this year. Optical lasers and GaN amplifier technology has the output capability to support 1.2 GHz networks today and potential optimizations on these devices show promise to further extend bandwidth and reach within a few years. Extending the frequency bandwidth of legacy brownfield networks beyond 1 GHz is going to be much more challenging. The cost of changing every tap faceplate in order to access the higher bandwidth will be the first impediment. Beyond that, the combined gain increases needed for both forward and return signal paths to drive existing 750 MHz spaced housings will require new re-designs to assure path isolation and stability within the node and amplifier. Even then it is not certain that some level of amplifier re-spacing will not be needed.

For the many reasons stated above and detailed in this paper, it appears extremely unlikely that the need for a high split return band and complementary downstream expansion beyond 1.2 GHz will be felt for a considerable number of years. As amplifier cascades significantly shorten and fiber is deployed deeper into the network, the viability of 10 Gbps wideband RF delivery networks will be within the reach of every cable operator.

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Acronyms and Abbreviations

AGC	Automatic Gain Control
CCAP	Converged Cable Access Platform
CIN	Composite Intermodulation Noise
CMTS	Cable Modem Termination System
CNU	Coaxial Network Unit
CPE	Consumer Premise Equipment
DOCSIS	Data over Cable Service Interface Specification
DR	Digital Return
DS	Downstream
EPoC	Ethernet Protocol over Coax
FCC	Federal Communications Commission
FDD	Frequency Domain Division
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FTTH	Fiber to the Home
GaAs	Gallium Arsenide
GaN	Gallium Nitride
Gbps	Gigabit per second
GHz	Gigahertz
HFC	Hybrid Fiber Coax
KHz	Kilohertz
LDPC	Low Density Parity Check
Mbps	Megabits per second
MHz	Megahertz
MSO	Multiple Service Operator
NPR	Noise Power Ratio
OFDM	Orthogonal Frequency Division Multiplex
OHE	Optical Headend
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RPR	Return Path Receiver
SCM	Single Carrier Modulation
SNR	Signal to Noise Ratio
TDD	Time Domain Division
US	Upstream