Next Generation HFC:

The Looming Impacts of DOCSIS® 3.1 and EPON over Coax (EPoC)

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

John Ulm
Fellow of Technical Staff
ARRIS
john.ulm@arrisi.com

Mike Emmendorfer
Sr. Dir., Solutions, Architecture & Strategy
ARRIS
Mike.Emmendorfer@arrisi.com

Rob Howald
Fellow of Technical Staff
Formerly of ARRIS

Rob Thompson
Systems Engineer
RJTJ Consulting
robsuet@gmail.com

Abstract

The most seismic change in over a decade is now happening to the cable industry. This is the development of the new DOCSIS® *3.1 specifications and the IEEE 802.3bn EPON over Coax (EPoC) specification. While both are still work in progress, it is important for the industry to understand both these technologies now. A lot of questions are being raised:*

Can cable compete with GPON over today's HFC? What about 10G EPON? Are D3.1 and EPoC complementary or competing technologies? Why would an operator use one or the other? Are there changes required to the HFC to make these work? What path should an operator take to maximize the gain from these technologies? Do D3.1 & EPoC obsolete CCAP? If not, what are the impacts on CCAP architecture? Can these technologies operate in a modular or distributed remote architecture? How does an operator manage the transition strategy?

The authors, who are involved in both the D3.1 & EPoC spec development, will lead the operator thru this maze. A tutorial is provided on both D3.1 and EPoC. The previous questions are then explored in detail.

Disclaimer: DOCSIS® *3.1 and IEEE 802.3bn EPoC specifications are both under development and subject to change. The following are the views of the authors and do not represent decisions or positions of either CableLabs or IEEE 802.3.*

DOCSIS® 3.1 & EPoC Overview

The DOCSIS® 3.0 specification was released back in 2006 and has served the cable industry well. Initial 3.0 cable modems supported 3 or 4 bonded channels. That has grown to where cable modem roadmaps are showing 24 or 32 bonded channels. As it aged, industry experts started discussing what will be the next leap forward for cable technology. In an industry first, a multi-vendor team published a paper [CABLESHOW2012] in meticulous detail that became a blueprint for next generation HFC. This effort helped lead to the DOCSIS® 3.1 effort being kicked off.

In parallel to this, other folks were looking at how they might extend EPON technology over HFC. Since EPON is part of IEEE 802.3 Working Group, this led to a study group that subsequently became Task Force P802.3bn EPON over Coax, or EPoC for short.

Since the cable industry is a fairly tight knit group, many of the same vendors and MSOs starting working on both efforts. That includes the authors of this paper. Now that both efforts are substantially far along, this paper will take a detailed look at both and compare & contrast these new next generation HFC technologies for cable operators.

DOCSIS® 3.1 Key Objectives

DOCSIS® 3.1 (D3.1) is the fifth generation of cable modem specification being developed by CableLabs. While it is ambitious incorporating new technologies, it still provides operators with backwards compatible operation. The key objectives for D3.1 were laid out in [SCHMITT2012] from SCTE Cable-Tec Expo last fall. These are:

- Efficient support for 10+ Gbps downstream, 1+ Gbps upstream
- Significant cost per bit reduction relative to DOCSIS® 3.0
- Adaptation to different amounts of spectrum and plant conditions
- Effective DOCSIS® migration strategy
- Operates on existing HFC networks and actives

The higher capacities will come from both new technologies and new spectrum. The technologies include changing from single-carrier QAM technology to multi-carrier OFDM plus incorporating LDPC, a new Forward Error Correction (FEC) for DOCSIS®. This pair will allow D3.1 to initially operate up to 4096-QAM capacities downstream and up to 1024-QAM upstream, with even higher modulations possible down the road. Leveraging OFDM, DOCSIS® expects to operate much more efficiently in the roll off region and could be pushed to 1.2GHz over today's installed 1GHz active components. In the future, replacing the faceplates on HFC Taps could allow D3.1 to utilize spectrum up to 1.7GHz in passive N+0 architectures.

Two key D3.1 objectives for cable operators will be the migration strategy and ability to operate over existing HFC networks. With hundreds of millions of DOCSIS® cable modems deployed worldwide, this is a monstrous investment that cable operators need to protect. Similarly, operators need to deploy D3.1 now and have it operate in existing HFC plant. Over time as the HFC is improved with fiber deeper and the home migrates towards a point-of-entry gateway architecture, D3.1 will be able to take advantage with additional capacity gains.

The new D3.1 effort is a global effort with strong support from Cable Europe Labs and Euro operators. The old 6 & 8 MHz channels will give way to a flexible channel width that can vary from 24MHz to 192MHz for a truly worldwide specification.

IEEE 802.3bn EPoC Objectives

The P802.3bn EPON over Coax (EPoC) Task Force is part of the IEEE 802.3 Working Group which is home to both Ethernet and EPON. One of the key tenets of EPoC is that it leverages existing EPON MAC and hence EPON technologies. The goal of this Task Force is to extend EPON reach over a coax infrastructure.

Some of the key EPoC objectives from its project authorization include:

- At least 1 Gbps in 120MHz for baseline conditions at MAC Interface
- Minimal augmentation to EPON MPCP (MAC) Protocol
- Co-exist with legacy HFC services
- Symmetric or Asymmetric data rates

By re-using the EPON MAC, EPoC plans to become part of the greater Ethernet ecosystem and hopefully leverage the scale that comes with Ethernet. Because of the Ethernet heritage, it was important that EPoC be able to offer symmetric data rate services when the available RF spectrum allows.

The initial objective of 1Gbps in 120MHz has since been expanded while maintaining the same spectral efficiency targets to 1.6 Gbps in 192MHz. This keeps EPoC somewhat aligned with D3.1.

The EPoC Task Force is very aware that it must co-exist with legacy services. Since IEEE is an international standards body, this means EPoC must comply with many different scenarios worldwide.

An unwritten EPoC goal is re-use existing EPON technologies where possible. This means the team hopes to re-use existing OLT hardware where possible.

Target Markets

Initially, D3.1 and EPoC appear to be going after very different markets. D3.1 with its emphasis on backwards compatibility expects to start in legacy DOCSIS® systems. EPoC on the other hand should get a footing among operators already deploying EPON and looking to extend it over coax.

Today, existing DOCSIS® systems tend to be mostly residential services with a fast growing business segment. Operators are already heavily invested in DOCSIS® infrastructure and back office and will want D3.1 to be deployed seamlessly into that environment. Many of today's DOCSIS systems are installed on 'classic' HFC plants with N+3 to N+6 architectures. D3.1 must operate well in that environment. However, as future fiber deep architectures evolve, D3.1 will be capable of taking advantage of the improved cable system.

EPoC looks to expand EPON service coverage. It may initially have more focus on services that already use EPON. Operators that have already invested in OLT's will be quite interested in EPoC. An interesting new potential market for EPoC has been the MDU market in the Asia-Pacific region, especially in China and Japan. In this market, EPON fiber drop will be pulled to the apartment building, and then EPoC is used to distribute services throughout the building. Currently China is seeing several different proprietary "Ethernet over Coax" or EOC technologies. EPoC offers the possibility of becoming a 2nd generation standardized EOC technology with Gbps rates. These operators in the emerging markets may not be traditional cable operators.

The three figures below show several reference HFC architectures that EPoC is planning to address. Figure 1 represents a legacy N+5 HFC architecture. The Coax Line Terminal (CLT) contains the OLT function + EPoC PHY and is located in the Head End.

Note that this architecture supports a traditional diplexer system. This is referred to as Frequency Division Duplex (FDD) split where upstream spectrum is below downstream spectrum.

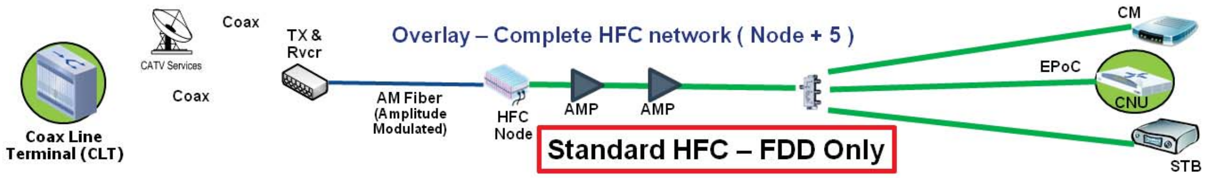

Figure 1 – EPoC in Legacy HFC Architecture

Figure 2 represents the Remote PHY architecture in a legacy N+3 HFC plant. A traditional EPON OLT is located in the Head End and EPON protocol is used over the fiber portion. The EPON wavelengths could be over a dedicated fiber or could be potentially shared fiber with legacy HFC services. A Remote EPoC PHY is located adjacent to the HFC node to drive the coax segments. Note that this is also a FDD system because of the use of existing HFC RF amplifiers.

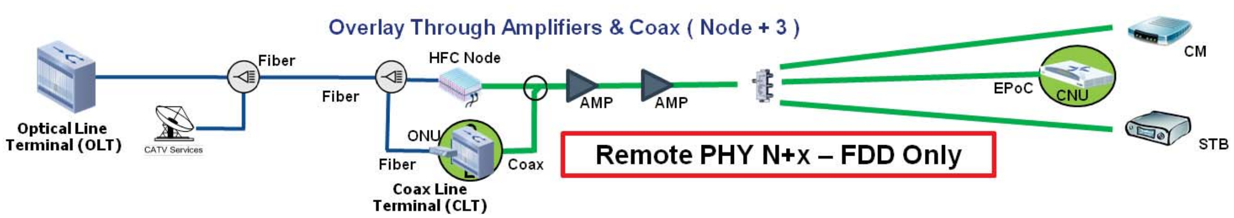

Figure 2 – EPoC in Remote PHY Architecture, Active Plant

Figure 3 represents the Remote PHY architecture with a passive cable plant. A traditional EPON OLT is still located in the Head End and EPON protocol is used over the fiber portion. The Remote EPoC PHY is now located in an MDU adjacent to the HFC node, or as a module in a node in an N+0 architecture. In this system, there are no longer any active components on the coax segment. EPoC supports either an FDD system or a Time Division Duplex (TDD) system in this architecture. For a TDD system, the upstream and downstream share the same spectrum. This is most likely above existing HFC services (e.g. >1GHz).

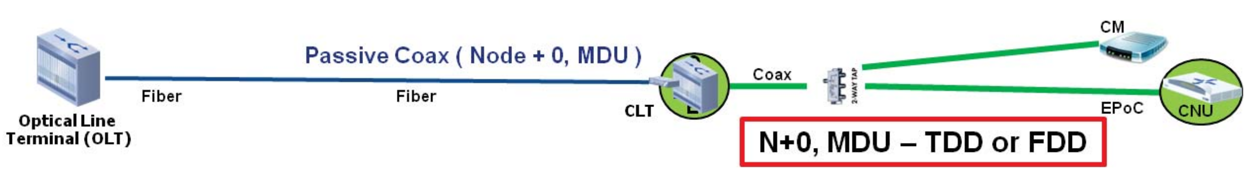

Figure 3 – EPoC in Passive Plant, N+0 or MDU

DOCSIS® 3.1 & EPoC – Common Elements

D3.1 and EPoC share many things in common. Both have to operate over the same legacy HFC plant conditions. As such, both teams shared in the development of a common set of channel models that align with probable deployment scenarios. Since they are both operating over the same physical layer, they have both selected the same advanced technology – OFDM, Higher Order QAM, and LDPC. Let's take a closer look at these components.

Channel Model

The channel model is a critical part of the specification development effort for both DOCSIS® 3.1 and EPoC. Many aspects of the channel model have been carried over from previous versions of DOCSIS®, while others were derived from measured results presented during committee deliberations. The benefit of agreed upon channel model characteristics are in setting boundaries for specification development, simulation, and evaluation.

The channel model covers many impairments including linear distortion, noise, nonlinear distortion, impulse/burst noise, and interference. Multiple HFC architectures have also been considered including N+0, N+3, and N+6, as well as a variety of optical links in both the forward and return paths including digital, FP, and DFB return optics. Considering all the factors above has led to limit and typical values for the list of relevant channel impairments to provide sufficient information for the system design parameters.

Considerations:

Since DOCSIS®3.1 HFC supports backwards compatibility and likely spans a broader range of cascades with a greater variety of optical links than EPoC, the expected variation in channel model parameters is greatest, which should drive specification development efforts accordingly. One such development is the large number of supported modulation levels, which range from QPSK to 16,384-QAM in the downstream. Contrast with an MDU-dominated market, where the likely N+0 architecture for EPoC and the expected variation in noise and nonlinear distortion will be low.

There is still moderate to high potential for linear distortion and ingress impairments for both DOCSIS®3.1 and EPoC systems, which can enter the network via defects in the coaxial segment. Defects can include loose, damaged or corroded connectors, cables, and passive devices. Therefore, both specifications should have adequate digital signal processing (DSP) tools to mitigate the effects of these impairments, like equalization, forward error correction, and interleaving.

Equalization adapts to varying linear distortion and cancels its effects, while forward error correction and interleaving mitigate burst error events via coding and bit shuffling.

The table below summarizes the sensitivity both protocols have to these various channel model parameters.

Sensitivity to Channel Parameters	D3.1	EPoC in MDU
Noise	High	Low
Nonlinear Distortion	High	Low
Linear Distortion	High	Medium
Impulse Noise	High	Medium
Burst Noise	High	Medium
Interference	High	Medium

Table 1 – Channel Model: Sensitivity to various Parameters

Characterization & Maintenance:

Network usage and maintenance go hand-in-hand. The ability to monitor use or loading is vital to maintaining performance at levels in which customers become accustomed. Ideally performance is maintained or improved without the customer ever being aware that it is occurring. Tools have been developed to quantify plant health and assess roll-out of higher capacity signaling.

DOCSIS® Proactive Network Maintenance, now called InGeNeOs®, has produced guidelines that encourage this practice through the use of tools like equalization coefficient analysis. Impairment identification and localization within the network are vital features. Trends in service impacting impairments can be detected, isolated, and minimized prior to degrading customer service to a point at which it is detectable by the customer.

Maintenance window testing allows for exploration of enhanced signaling viability while minimizing impact to subscribers. MSOs can use this technology to trial-run improvements, like more efficient signaling, prior to incorporating into their production plant. Use of more efficient, yet more sensitive, signaling can identify weaknesses to address in the network, which can be identified during a maintenance window. With these weaknesses addressed, rolling out more efficient signaling like, 1024-QAM or higher, become significantly easier and more likely successful long term.

Spectrum Evolution

Operators today support an active HFC plant, typically with 3 to 6 amplifiers (i.e. N+3 to N+6). This is a Frequency Division Duplex (FDD) topology where upstream spectrum is below downstream spectrum and separated by a diplexer. Typical upstream splits found today include 42MHz in North America and 65MHz in Europe. The high end of the downstream spectrum can vary quite a bit from plant to plant and is often one of the following: 550, 750, 870 or 1002MHz.

While Next Generation (NG) technologies will need to work in existing spectrum, eventually operates will try to expand capacity through new spectrum. This new downstream spectrum might be found by extending the high end. This can be done by operating in the roll-off region or by upgrading the plant as shown in the figure below. This could enable 5-7 Gbps downstream capacities in existing HFC plants, with 200Mbps upstream capacity.

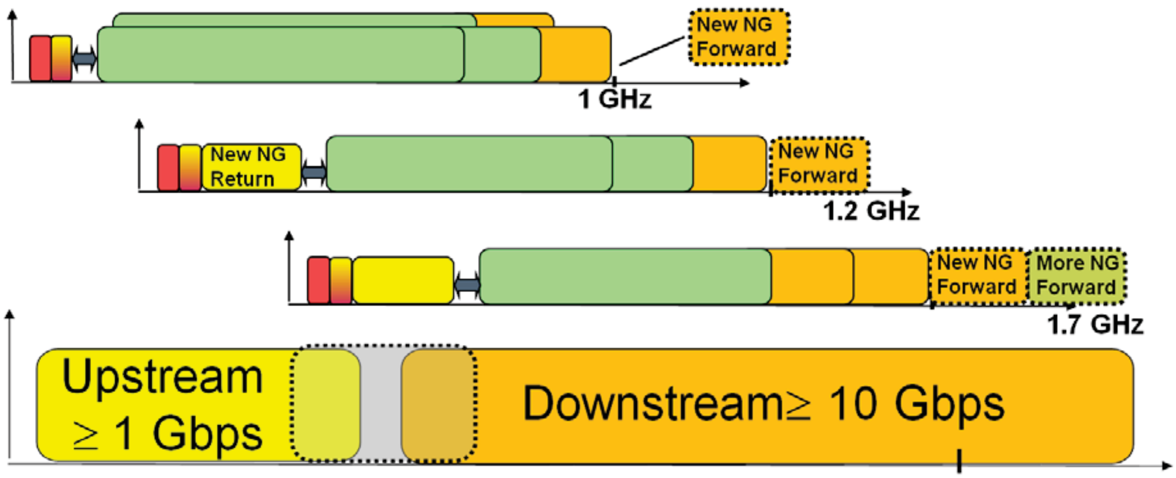

Figure 4 – HFC Spectrum Evolution

The upstream evolution takes place by first extending to mid-split, and subsequently an extension beyond this labeled "New NG Return." The idea is that the 85 MHz mid-split is available in current DOCSIS® 3.0 and HFC technology today, and offers a very long window of upstream lifespan and data rate growth to the 400 Mbps threshold.

At some point in the architecture migration, the new phase of upstream to achieve 1 Gbps can be introduced. This will likely be at least 200MHz upstream split. At this time, enough downstream spectrum may be recovered to accommodate a loss in spectrum to upstream use. Otherwise, this may be the point to extend downstream spectrum. The latter appears to be the more likely scenario, due to the likely slow withdrawal of legacy services and the need therefore to simulcast, burdening downstream spectrum. Initially, the extension may simply be excess bandwidth above 1 GHz such as 1.2 GHz before evolving to a broader chunk of bandwidth exploitation above 1 GHz if necessary. Current thinking is that 1.7GHz is a feasible downstream limit operating within existing component housing with a faceplate change.

This provides HFC with a roadmap to greater than 10Gbps capacity in the downstream stream with more than 1Gbps in the upstream.

Core Technology – OFDM, LDPC

The two key core technologies being incorporated by both D3.1 and EPoC is OFDM – Orthogonal Freq Division Multiplexing; and LDPC – Low Density Parity Check FEC.

OFDM is a widely adopted technology that is already extensively used in both wireless communications (e.g. LTE) and Home networking (e.g. MoCA). Some of the key attributes of OFDM is that it enables extra wide channels while being able to adapt to varying spectrum and plant conditions. As next generation technologies look to multi-gigabit rates, the legacy 6 and 8 MHz channels are no longer sufficient. With OFDM, both D3.1 and EPoC have settled on a 192MHz wide downstream channel.

Why OFDM?

Optimizes Channel Capacity
In particular with varying frequency response, multipath, and hostile interference channels

Granular spectrum allocation
Beneficial during band plan and service transitions

Multiple sources of supply and cross-industry investment

Consistency with **other standards** and cable network extensions (Home LAN, wireless, EPoC)

OFDM + LDPC to Layer 1 as IP is to Layer 3 – likely final RF step (little more capacity worth exploiting)

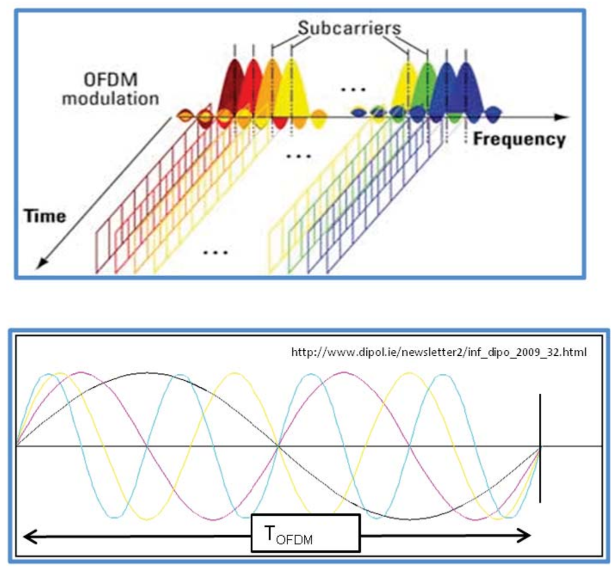

Figure 5 – The Role of OFDM

Another key feature of OFDM is that subcarriers can be selectively turned off. This means the OFDM channel could be fit into smaller spectrum as low as 24MHz. Or chunks of the spectrum could be nulled out so it can fit around legacy services. The ability to change the bit loading per subcarrier or even turn off individual subcarriers give OFDM significant noise resiliency.

All this flexibility makes OFDM a perfect choice to operate and adapt to whatever spectrum and plant conditions are available. And by using OFDM, the cable industry can leverage the large pool of OFDM expertise worldwide.

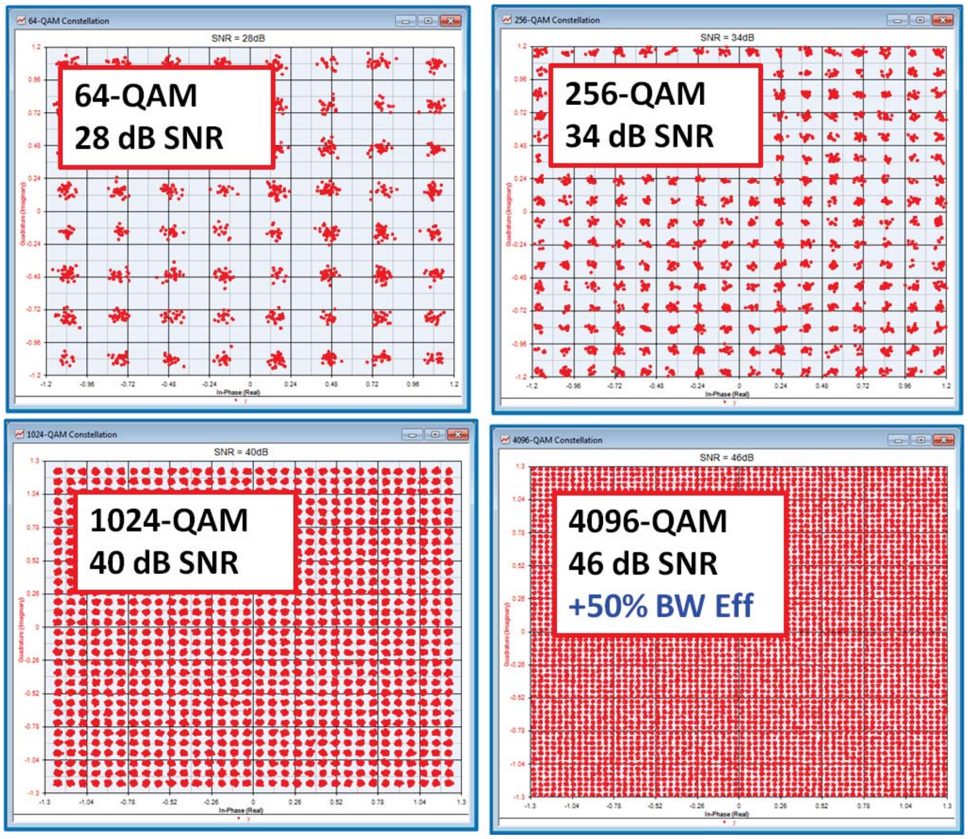

Figure 6 – Modulations and Required SNR (Un-coded)

Today's cable systems implement a maximum modulation format of 256-QAM (8 bps/Hz) downstream and 64-QAM (6 bps/Hz) upstream. Through architecture evolutions (deeper fiber) and technology improvements (optical & RF fidelity, DFB return lasers) cable has already gone through major rounds of improving bandwidth efficiency. Both D3.1 and EPoC look to push well past these modulation formats to support at least 4096-QAM in the downstream and 1024-QAM in the upstream. The figure above gives a visual as to the increased complexity. The additional SNR requirements (un-coded) are shown as well. The bottom line is that the industry is hoping to achieve a 50% gain by going from 256-QAM to 4096-QAM in the downstream. Similar gains will be seen in the upstream.

With the LDPC FEC included, the SNRs required for each QAM format above are aligned with the 90% code rate curves shown in Figure 7 taken from [HOWALD2013].

A common end-of-line HFC cascade performance requirement for digital channels is a 42 dB SNR with digital channels typically set 6 dB below analog channels. Given that 256-QAM requires 34 dB (1e-8) without coding, and up to 4 dB less than this by DOCSIS® specification with a J.83 Annex B error mitigation subsystem included, it is apparent why today's networks are very successful with 256-QAM.

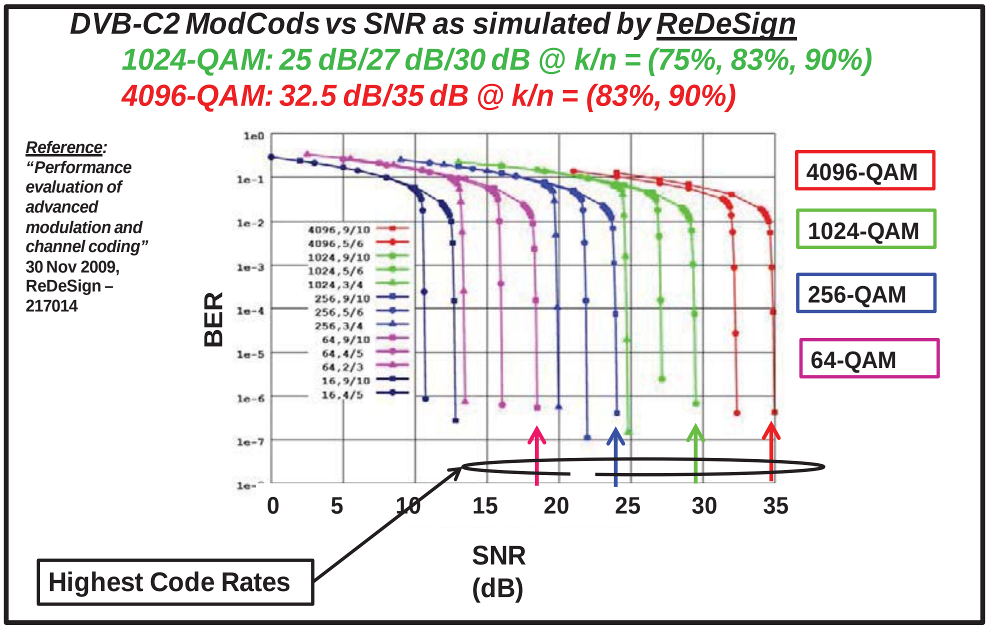

Figure 7 – M-QAM vs. SNR with LDPC

However, even just considering HFC SNRs, the 1e-8 SNRs required of 2048-QAM (43 dB) and 4096-QAM (46 dB) clearly indicate extra "help" is necessary to achieve these with robustness. That help comes in the form of a new Forward Error Correction (FEC) called Low Density Parity Check (LDPC). LDPC theory has been around for decades, but has just recently been able to be implemented cost effectively. LDPC now lets us operate within a few tenths of a dB from Shannon's Limit as shown in Figure 8. The net is that it gains us almost 3 dB compared to J.83 Annex B and almost 6 dB with J.83 Annex A. This new FEC technology will be leveraged by both D3.1 and EPoC.

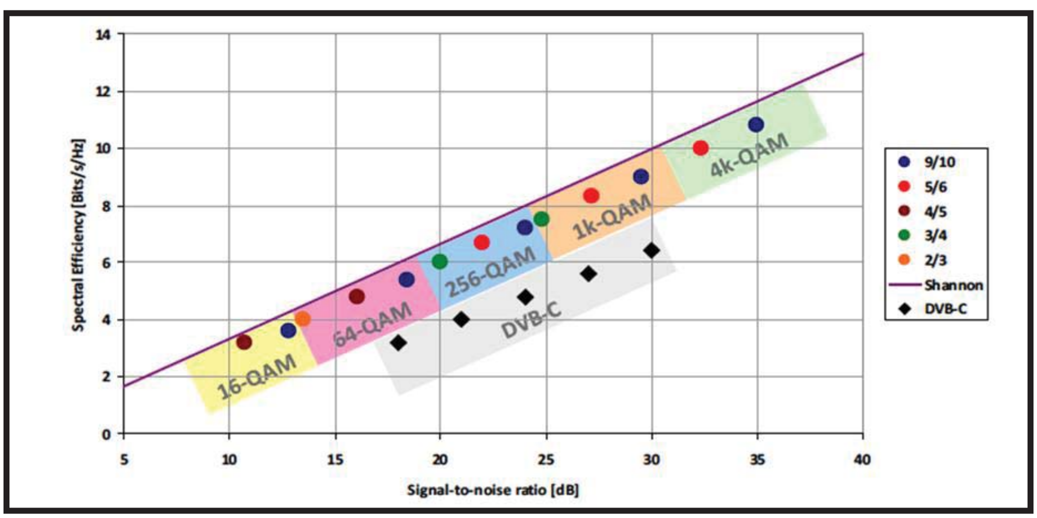

Figure 8 - DVB-C2 LDPC FEC vs. Shannon Theory

Just how hard is the FEC working? Consider the noisy, 1024-QAM and 4096-QAM constellations shown in Figure 9 from [HOWALD2013]. Assuming the poor MER primarily due to AWGN, both of these would be comfortable decoded essentially error-free by the FEC.

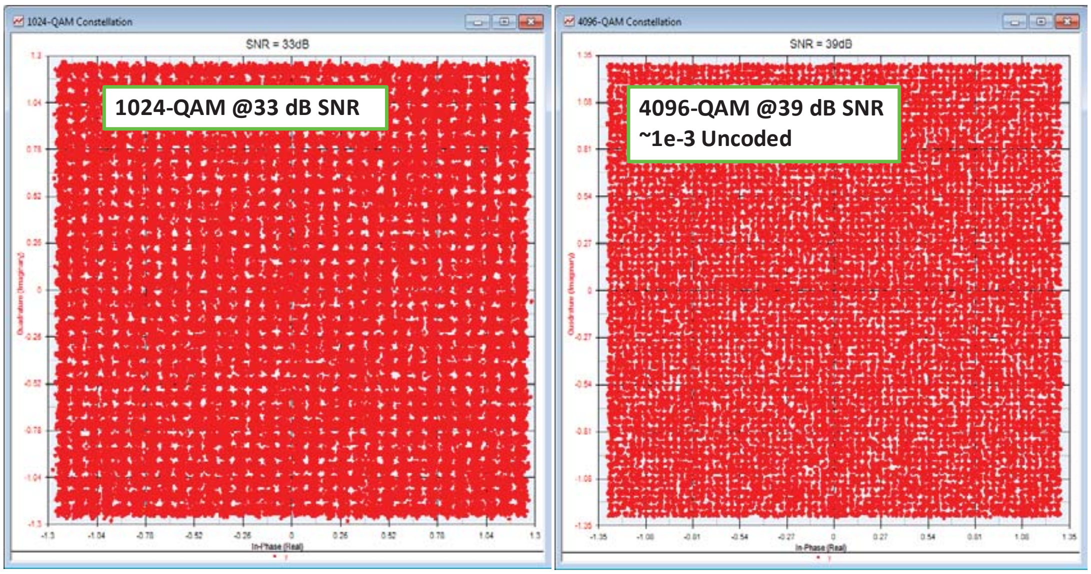

Figure 9 – LDPC FEC Can Work Wonders on Noisy QAM

DOCSIS® 3.1 & EPoC – Key Differences

While the previous section highlights some of the commonality between D3.1 and EPoC, the two have some substantial differences that are highlighted below.

TDD HFC Architecture

DOCSIS® has its roots in legacy HFC plants that are fundamentally FDD diplexer architecture. D3.1 only supports FDD operation. While EPoC plans to operate over legacy HFC in a FDD mode, EPoC is also supporting a TDD mode for passive plants. Note – EPoC can still operate in FDD mode on a passive plant as well.

With a TDD mode, EPoC is hoping to exploit new markets such as the MDU market in the Asia-Pacific region. Some of these markets may have insufficient upstream spectrum available in the lower RF frequencies. TDD allows the upstream to share spectrum with the downstream in higher frequency ranges, such as above 1GHz. This might give an operator more flexibility with variable traffic asymmetry.

The EPoC Task Force has received significant interest in TDD from the Chinese market and multiple meetings have been held to solicit their requirements. The EPoC TF has formed a separate Sub-task team to create a TDD variant of the EPoC specification. Focus is being applied to both FDD *AND* TDD solutions in parallel. This has led to some technical differences between FDD and TDD. For example, they will be using different FEC codes because of different channel environments.

Single or Multiple Profiles

During the development of both D3.1 and EPoC, Dave Urban of Comcast provided significant details on the cable modem SNR distribution across 20 million cable modems. One of his representative figures is shown below.

Today, all existing DOCSIS® cable modems operate at the lowest common denominator, i.e. 256-QAM. With the improved LDPC FEC, this could get bumped up to 512-QAM, or maybe 1024-QAM on better plants. Urban's results show that most modems are well beyond this lowest common point. In fact, the vast majority of modems may be able to operate at 2048-QAM or even 4096-QAM with the new OFDM and LDPC technologies.

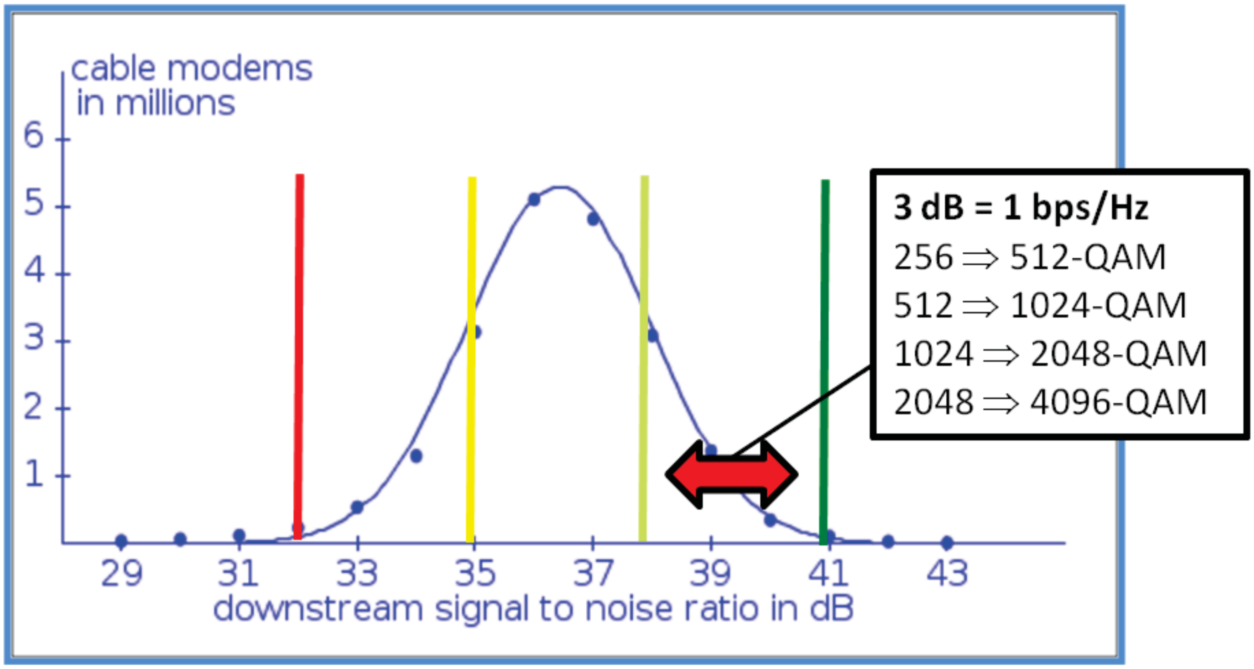

Figure 10 – Cable Modem SNR Distribution (courtesy of Comcast)

Additional data was provided in [HOWALD2012a, HOWALD2012B]. The figure below maps the potential modulations levels across various RF Input levels and HFC CCN delivered. This example shows that the HFC might actually support beyond 4096-QAM in the future. This will require some changes such as fiber deeper, digital optics and home gateways with a single point of entry. This figure shows 5 potential profiles in that scenario.

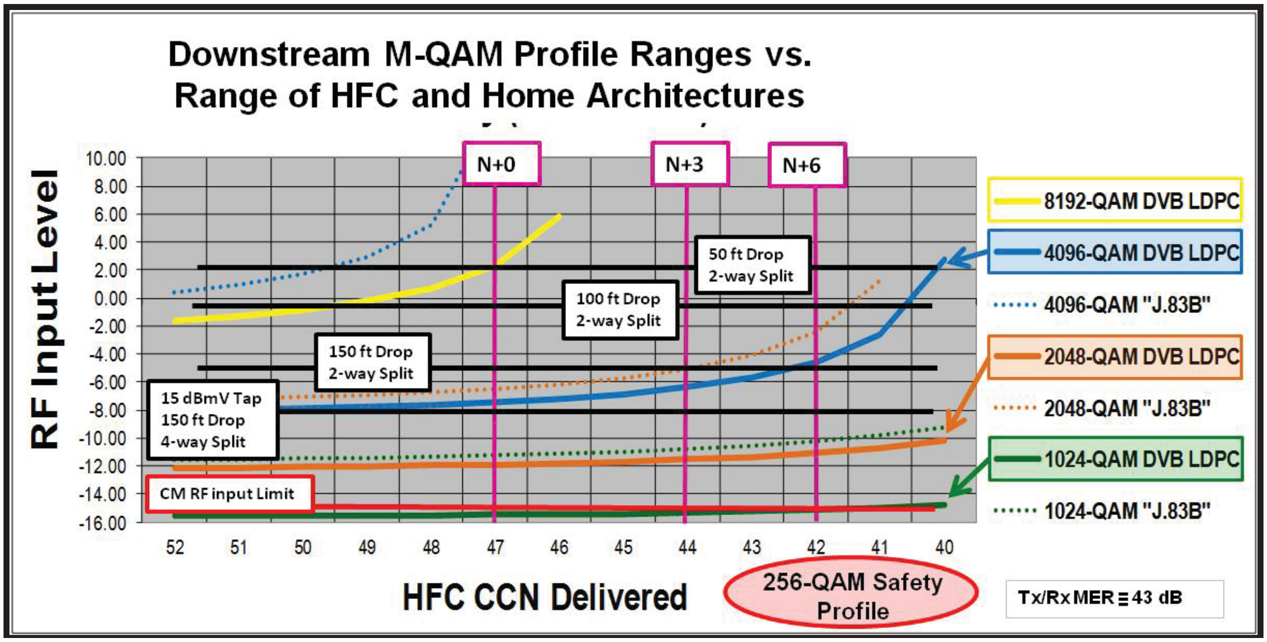

Figure 11 – RF Levels vs. CCN: Rational for Multiple Profiles

With this input, D3.1 adopted support for Multiple Modulation Profiles (MMP). Initial modem support will be for four profiles but the spec hopes to allow for future expansion of more profiles if needed. With this capability, the average downstream bit loading might be closer to 11-12 bits per hertz rather than 8-9 bits/Hz. Some scenarios could see up to a 33% gain from using MMP.

Introducing MMP has other potential uses. An extremely robust profile could be created for use with problem modems in the field. This opens up a channel of communication that would not have been there in the past. This provides improved installation and maintenance. This may also keep some subscribers operational at a minimal level after their modems have experienced some plant change (either inside home or on external plant), reducing customer outages.

MMP does introduce complications. Most notable is that the downstream pipe may vary in bandwidth capacity depending on the instantaneous traffic load. This will create potential timing and QoS issues with the MAC. The D3.1 MAC has the flexibility to deal with these. EPoC uses the EPON MAC exactly as is, so MMP creates significant timing challenges. Currently, EPoC FDD is only planning to support a single profile; while EPoC TDD is planning MMP support. This is another significant difference between EPoC FDD and TDD operation.

OFDM, OFDMA Channels

EPoC supports a single 192MHz OFDM downstream channel and a single 192MHz OFDMA upstream channel.

D3.1 initially plans to support two 192MHz OFDM downstream channels and a pair of 96MHz OFDMA upstream channels. More channels can be supported in the future.

Having two separate smaller OFDMA upstream channels can allow one OFDMA channel to be optimized for robust operation (e.g. below 20MHz) while the other OFDMA channel is optimized for maximum throughput in the cleaner spectrum.

Backwards Compatibility

In addition to the OFDM/OFDMA channels mentioned above, DOCSIS® 3.1 will maintain backwards compatibility with previous DOCSIS® systems. To achieve this, D3.1 modems will contain 24 downstream channels and 8 upstream channels that are compatible with legacy 3.0 channels. This is important to allow D3.1 capable modems to be deployed NOW into existing 3.0 systems with full capabilities, and then later turn on the D3.1 capabilities.

EPoC offers no backwards compatibility with legacy HFC system. EPoC does have a goal to re-use existing OLT if possible.

Key MAC Differences

Since D3.1 and EPoC are leveraging similar PHY technologies, this leaves the MAC as a key distinguishing feature between the two protocols.

Channel Bonding

DOCSIS® 3.0 introduced the concept of channel bonding integrated into the DOCSIS® MAC. Channel Bonding creates a single virtual channel to the higher layers that is distributed across multiple PHY channels. Initial 3.0 modems bonded 3-4 channels, and this has grown over time to bonding of 24 or more 3.0 channels.

In D3.1, the MAC will support bonding across all combinations of OFDM and legacy QAM channels. In the downstream, a D3.1 modem can start by bonding just 24 legacy 3.0 channels in existing system. As spectrum is made available, the D3.1 modem can bond between the 24 legacy 3.0 channels and its OFDM channels. Later once the 3.0 channels have been retired, the 3.1 modem can bond between just the OFDM channels. Upstream bonding supports a mix of legacy ATDMA &/or SCDMA channels with the newer OFDMA. Bonding may actually be more critical in the upstream where RF spectrum is extremely scarce and is mostly filled with legacy DOCSIS® channels.

Bonding also provides a migration path for higher data rates in the future. Future D3.1 modem generations might support 4 or even 8 OFDM channels, providing operators a path to a modem with 10Gbps or higher. Theoretically, DOCSIS® is unbounded and does not define a Maximum Capacity.

EPoC is a PHY standard and re-uses the existing 802.3 EPON MAC, which does NOT support channel bonding. IEEE 802 protocols allows for link aggregation at a higher layer. This relies on a hashing algorithm to spread packets across multiple channels, and comes with its own inefficiencies. A general rule is that the network might only achieve 70% utilization. Also, this hashing approach prevents a single flow from using anything more than a single channel. Link aggregation might be useful in the backbone or core, but becomes less useful for an access network where a single device may try to burst at line rate.

Not only will EPoC be limited to a single OFDM channel downstream and a single OFDMA channel upstream, the 10G EPON system has other limitations. It turns out that the "10G EPON" system only nets 8.7Gbps after accounting for its FEC overhead.

Service Group Size

The DOCSIS® MAC was designed from its inception with a Service Flow structure that is capable of enabling operators to provide a wide variety of different services with vastly different requirements. Because early DOCSIS® systems contained 1000's of homes passed per Service Group (SG), the CMTS were designed to handle 10,000's of Service Flows in a chassis. D3.1 maintains this ability to scale to large numbers of subscribers per SG with a large amount of Service Flows to meet operator's needs.

Existing EPON systems have designed to typically support 16-32 ONU per SG. They could be pushed to 256 ONU per SG but that could introduce over issues with the scheduler and/or LLID availability. LLID is the EPON equivalent of Service Flow. Not only do ONUs tend to support fewer LLIDs than DOCSIS® modems support Service Flows, a typical OLT might support only 1K-2K LLIDs total, a fraction of the number of Service Flows that a CMTS supports today.

All this means that EPoC may be limited to very small SG sizes, while D3.1 can support a much wider range of Service Group scenarios.

QoS

In addition to the service flow vs. LLID discussion above, there are other QoS differences between the DOCSIS® and EPoC/EPON systems.

DOCSIS® 2.0 introduced the concept of a two dimensional scheduler for S-CDMA. One dimension was time and the other dimension was code. This allowed for extremely efficient upstream utilization. In D3.1, this two dimensional scheduler can now be easily applied to OFDMA with one dimension in time and the other dimension in frequency. Thus, D3.1 will continue to leverage advances in DOCSIS® QoS over the last decade.

The EPON MAC on the other hand uses a much simpler one dimensional scheduler that is only aware of time. The EPoC PHY requires that it maintains this model to the EPON MAC. This means that the EPoC PHY must bend over backwards to accommodate the MAC timing with no changes. Not only does it not get to use the advantages of a two dimensional scheduler, but additional inefficiencies get added to align with the EPON MAC timing.

Since DOCSIS® fully defines its QoS architecture; it has the ability to enhance it. A new QoS enhancement being added to D3.1 is Hierarchical QoS (H-QoS). This provides a multi-layer scheme that will enhance and enable new services. As one example, a higher QoS layer may be applying QoS per Service Class while the lower QoS is applying per Service Flow. This will become more important as operators look to implement IP Video and Business Services. H-QoS allows the operator to isolate these different Service Classes down a single shared pipe.

The EPON MAC does NOT define QoS or how it's implemented. CableLabs has provided a system spec called DOCSIS® Provisioning over EPON (DPoE) to help fill this gap. However, OLTs have a much more limited QoS capability than today's CMTS. For more advanced features like H-QoS, the EPON system would need to rely on the B-RAS device, an enhanced router further up in the network.

HFC Plant – Distance Limitations

From the beginning of DOCSIS®, its MAC protocol was designed to operate at distances up to 100 miles or 160km. D3.1 continues to support these extended distances. These distances are independent of the number of subscribers per Serving Group as well. DOCSIS® operates over these distances with no changes to the operator's HFC infrastructure.

EPON systems today are typically limited to 32 or fewer subscribers on a 20km or 12.5 mile fiber link. While PON systems with more subscribers are possible, this must be done with a corresponding decrease in the fiber link length to accommodate additional loss due to the extra optical splitters that must be added. The EPON MAC also has restrictions around latency requirements such as a 1 msec Round Trip Time (RTT). This will also potentially limit the distance an EPoC system can cover. While these latency requirements might be exceeded, it comes at the cost of reduced capacity and increased service delays.

CCAP or Remote PHY Architectures?

CCAP products are being deployed today and will become widespread over the next several years. A key consideration needs to be the migration strategy and investment protection. Since D3.1 is providing DOCSIS® backwards compatibility, it will fit seamlessly into the CCAP architecture. In fact, some CCAP products may allow portions of D3.1 to be implemented as a soft upgrade to existing hardware.

Another key aspect of migrating D3.1 into the CCAP architecture is that it keeps ALL services, including legacy MPEG Video, through a single RF port. This becomes more important as the mix of legacy MPEG video (i.e. VOD, SDV, digital broadcast) with DOCSIS® continues to change over time. Again, this is another soft upgrade inside the CCAP products. Putting D3.1 inside CCAP also keeps the existing Fiber Nodes as PHY-agnostic devices.

Since EPoC is based on EPON technology, it does not fit naturally in today's CMTS or CCAP products. In fact for most N.A. operators, EPoC will be deployed as a Remote PHY technology. This means the operator will require the installation of new gear: an OLT at their head end site and overlay an EPON network on top of their existing fiber links. Then at the node, the operator is required to install the Remote EPoC PHY. All of this radical change is needed on day one. In addition to this, the operator still needs to maintain and manage of all its legacy MPEG video equipment (VOD, SDV, digital broadcast) and existing DOCSIS® service tiers, even existing fiber nodes must stay.

As it turns out, D3.1 can also support Remote architectures, but it is not needed on day one and does not need to be deployed everywhere. For example, an operator that wants to deploy Remote architectures only in highly competitive or congested markets could surgically roll out a Remote CCAP with D3.1 integrated. The market needs determine when to roll out the Remote architecture, not the technology.

Operator's Perspective – Which do you choose?

With a lot at stake as operators plan their next generation HFC architectures; let's take a look at some additional considerations to the key differences that were just highlighted.

Investment Protection

With tremendous investments in DOCSIS® modems and CCAP products continuing to grow over the next several years, cable operators need an effective migration story that protects their investments. Because of this, DOCSIS® 3.0 backwards compatibility becomes the linchpin in a migration story and perhaps the most important consideration for cable operators to choose their next generation HFC architecture. This means that cable operators will have no stranded capital with D3.1.

It is important to note that D3.1 modems operate day one with *zero* plant infrastructure change. This can delay or avoid major plant investments. D3.1 will also leverage existing DOCSIS® back office infrastructure for additional savings compared to EPoC. It is expected that Moore's Law will help to make D3.1 cost effective over time, just as 3.0 modems came down a steep price reduction curve after its initial introduction.

D3.1 backwards compatibility allows a critical mass of D3.1 CPE devices to be deployed before the operator ever needs to light up their first D3.1 OFDM channel.

While EPoC maintains EPON compatibility, this only helps for operators who already have a substantial investment in OLT technology.

EPoC Taxes – Spectrum, IP Simulcast

As operators look to deploy new services using either D3.1 or EPoC, a major question that needs to get answered is how much additional spectrum do I need for that service? Then the operator needs to go and find that much spectrum. In this respect, EPoC has some extra "taxes" imposed that are not applicable to D3.1.

The EPoC Spectrum Tax is best shown through an example. Suppose the operator is offering services today over 24 bonded 3.0 channels. This is roughly 900 Mbps of capacity. Now the operator wants to introduce a new service with twice that capacity. With EPoC, this would require deploying the full 192MHz OFDM channel on day one to achieve 1.8 Gbps. This is shown on the left side of the figure below.

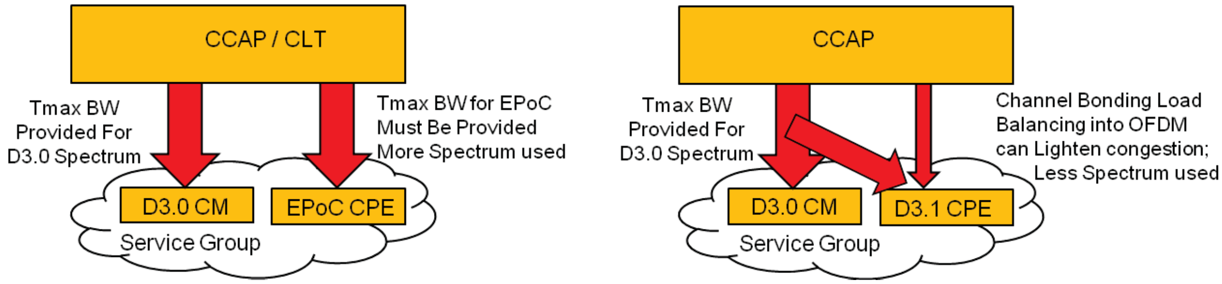

Figure 12 – Spectrum Tax

Since D3.1 can bond with 3.0 channels, the operator only needs to deploy a 96MHz OFDM channel to add 900 Mbps to its existing 900 Mbps 3.0 bandwidth. This is shown on the right in the figure above. Note that the D3.1 spectrum usage is half the EPoC spectrum needs. As D3.1 usage grows, the operator has the flexibility to increase the OFDM spectrum usage or to optionally reduce the 3.0 spectrum usage.

Hence, the EPoC system requires an additional 96MHz of spectrum to offer the max service tier. This is referred to as the Spectrum Tax.

The next tax considered is the IP Simulcast Tax. IP Video will be an extremely important service for next generation HFC technologies. Multicast technologies will be used to effectively 'broadcast' IP video programs to multiple subscribers. These services will be available to existing DOCSIS® devices.

With EPoC, the entire IP video lineup will need to be replicated down the EPoC channel in addition to the legacy DOCSIS®. This can be seen on the left in the figure below. This means that the IP video lineup must be simulcast between both. Meanwhile, D3.1 can retrieve the entire IP video lineup over its 3.0 capable channels. This means that there is no unneeded duplication of IP video content. This is shown on the right.

The IP Simulcast Tax actually applies to all multicast applications. IP video is just the highest bandwidth multicast application of interest today.

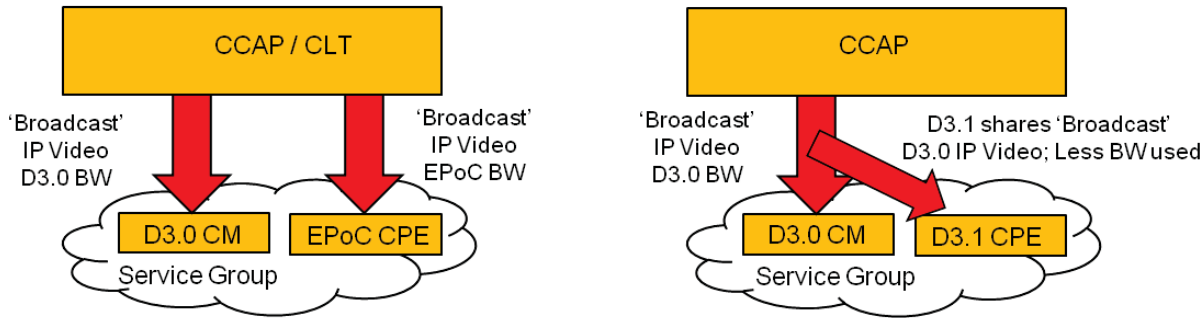

Figure 13 – IP Simulcast Tax

As can be seen above, the D3.1 Backward Compatibility features avoids the Spectrum Taxes and allows operators to make the most efficient use of their precious spectrum resources.

Spectrum Evolution & HFC Migration Strategies

A key consideration for cable operators is their HFC migration strategy and how do they expect to free spectrum? With most all HFC architectures being active plants with amplifiers in the path, this requires an FDD topology on day one. Over time, fiber will be pushed deeper, but it may be a long time, *if ever*, that the amplifiers are totally removed and it becomes a completely passive plant.

Once an operator has obtained a passive cable plant, does it make sense to switch over to a TDD topology? FDD vs. TDD considerations were explored in detail in [CABLESHOW2012]. There are significant challenges with having TDD CPE devices transmit at the very high RF frequencies, such as >1GHz. The cable loss at those frequencies requires significant TX power for TDD CPE products or they suffer significantly less throughput capability. It also almost forces operators to deploy home gateway architectures from a coaxial loss standpoint, and also recognizing that splitters in the home are not likely to have pass bands above 1 GHz.

The recommendation from that paper is that cable operators should continue with an FDD topology. As more downstream spectrum is harvested at the upper end, the upstream split can be moved up accordingly. The initial D3.1 specification will support at least a 200MHz upstream split. As the downstream grows to 1.7GHz, it is conceivable that the upstream spectrum grows to 400MHz, allowing the downstream to start at 500MHz.

In addition to FDD/TDD topology considerations, operators also need to consider distance requirements for their next gen HFC. Will the EPoC technology have the reach to satisfy all of their market needs? If operators want to migrate to a Remote architecture, then standard DWDM Ethernet makes more sense than an EPON based approach.

Service Tier Offerings

Another consideration for operators is the maximum service tier that they can offer with their next gen HFC technology. As discussed previously, EPoC suffers from the Spectrum Tax. That means that given the same amount of spectrum, D3.1 can offer higher service tiers than EPoC as it can also leverage almost an additional1 Gbps of downstream bandwidth from the 3.0 channels.

In the upstream direction where available spectrum is much scarcer, EPoC is severely challenged. With the DOCSIS® upstream scheduler controlling both D3.1 OFDMA and 3.0 ATDMA/S-CDMA channels, it has the flexibility to allow D3.1 subscribers to utilize the entire upstream spectrum. This could be as high as a *250 Mbps* burst rate on a 5-42MHz plant. Meanwhile, EPoC might have to work around four 3.0 channels, 6.4MHz each, that are in the prime spectrum. EPoC might only be able to burst at *50 Mbps*.

Looking at maximum downstream capacity, EPoC might support a downstream rate of *1.4 Gbps* from its single 192MHz OFDM channel. Remember that in an FDD topology, EPoC only supports a single modulation profile that must be used by all modems. Meanwhile D3.1 with its MMP support might support 1.8 Gbps per OFDM downstream channel. This is an aggregate downstream rate of *4.5 Gbps* from its two OFDM channels plus 24 3.0 QAM channels.

Initial D3.1 modems will have almost tripled the capacity of EPoC.

It is also important to consider service rate migration over time. With channel bonding, D3.1 is already set up to support additional OFDM channels. With a 200 MHz upstream split and a 1.2 GHz downstream, D3.1 could support 5 OFDM DS channels for 9 Gbps capacity with an upstream capacity around 1.2 to 1.5 Gbps. Note that this is more throughput, both upstream and down, then today's 10/1 EPON networks. Later with a 1.7 GHz plant, D3.1 could bond 7 or 8 channels to achieve downstream rates in excess of 12 Gbps.

Future D3.1 modems can match or exceed 10/1 EPON.

Global Market – Economies of Scale

At the end of the day, CPE prices are most impacted by the size of the market and economies of scale. D3.1 now offers a truly global solution that all cable operators worldwide can join the bandwagon. There will no longer be separate North American, European & Japanese DOCSIS® markets. D3.1 will be a universal global standard bringing even larger economies of scale & efficiencies.

EPoC on the other hand might struggle with volumes due to the lack of DOCSIS® backwards compatibility and the resulting Spectrum Tax. EPoC must also contend with two different implementations: FDD and TDD that will fracture its market in two. Even if the Chinese EPoC market takes off, this will only benefit TDD devices, leaving FDD devices in the lurch. Even within the TDD & FDD markets, a wide variety of potentially different spectral requirements from different regions could fragment the EPoC markets even further.

Time to Market

There are some additional considerations when looking into EPoC. Another aspect is time to market. D3.1 specification has been on a fast track and is coming together rapidly. It looks to be released some time in 2013. Meanwhile, EPoC continues to struggle with schedule. It is currently on track to be standardized by 2015, and that date is at risk. With EPoC coming late to market and with the lack of backwards compatibility, it will face stiff headwinds to establish significant market share.

CCAP Migration Strategy

From previous discussions, CCAP using D3.1 provides MSOs the best migration strategy for operating in today's HFC plants with minimal changes while providing one access layer platform for all services. It has the flexibility to adapt to changing service mixes in a single platform while provide a growth path for higher data rates with additional bonded channels. Yet this approach allows migration to future Remote architectures in an as needed basis.

Plant Characterization:

Many lessons have been learned over the years of developing DOCSIS® specifications. Backwards compatibility will greatly benefit MSOs by allowing transitional use of proactive maintenance tools while migrating to DOCSIS® 3.1. Driving towards 2nd generation proactive maintenance tools with new hooks put into place in the early stages of DOCSIS® 3.1 development will enable enhancements in diagnostic monitoring to achieve even more than what is done today.

What has limited InGeNeOs® to date is that much of the guidelines were constrained to working within the DOCSIS® infrastructure long after the specifications were developed. These constraints in some ways limited the abilities of the proactive tools. Now, consideration is being given to hooks during the D3.1 developmental stages. With a suite of network testing in mind, the proactive concepts can be extended and used in a much more comprehensive manner. This all leads to more conclusive characterization of the network and better confidence in claims associated with what DOCSIS® 3.1 features that can be supported.

Today, there are no known proactive maintenance tools pertinent to EPoC. So this is an open issue to operators looking to deploy EPoC.

Robust Upstream

As the differences between D3.1 and EPoC are reviewed with a fine tooth comb, there are some additional D3.1 points to consider regarding upstream robustness. D3.1 chose to have two 96MHz upstream channels rather than EPoC's single 192MHz channel. Having the ability to bond two 96MHz OFDMA upstream channels gives operators the flexibility to optimize one for difficult environments (e.g. below 20MHz) and the other for maximum throughput (e.g. clean spectrum).

Next Gen HFC – Conclusion

For any traditional cable operator with a sizable investment in DOCSIS® technologies, selecting D3.1 for its next gen HFC technology over EPoC becomes a slam dunk. The backwards compatibility features are key to enable a migration strategy. Reusing existing 3.0 spectrum, D3.1 can be deployed now in existing systems with absolutely no changes to plant, head end or back office infrastructures. The D3.1 capabilities can then be turned on as needed. EPoC requires plant, head end and back office changes from day one.

Besides solving the near term migration issues, D3.1 provides a path forward that will enable cable to compete head on with 10G EPON. When combined with RFoG, it provides the potential to leapfrog over EPON.

Channel bonding and QoS are two of the most important differentiators between the DOCSIS® MAC and the EPON MAC. Channel bonding between OFDM and legacy 3.0 channels is critical to enabling the backwards compatibility. Bonding enables initial D3.1 modems to offer almost triple the data rate then EPoC. Bonding additional OFDM channels in the future provides the horsepower to match 10G EPON.

D3.1 also plays perfectly into operator's investment into CCAP equipment that will expand tremendously over the next several years. Parts of D3.1 are potentially a soft upgrade to some of these products. With all services, including legacy MPEG video, coming from a single RF port, the operator can easily adjust the mix between the various services. Yet operators still have the flexibility with D3.1 to migrate to a Remote architecture as its market needs dictate. EPoC however might force the Remote PHY architecture from the start, whether operators want it or not.

As operators plan out their HFC migration, D3.1 fits nicely with the FDD topology and a gradual migration of the upstream split on an as needed basis. Operators can maximize usage of existing upstream spectrum before pushing to a mid-split than eventually a 200MHz or higher high split return. EPoC will require significant plant upgrades much sooner; either to support TDD operation or to find sufficient upstream spectrum for FDD due to the Spectrum Tax.

The paper has highlighted a number of other limitations with EPoC. This includes: Spectrum Tax; IP Simulcast Tax, single profile FDD operation, distance limitations, QoS limitations, and reduced upstream flexibility.

On almost every front, D3.1 is the clear winner over EPoC for cable operators with a stake in the DOCSIS® market.

References

1. [HOWALD2013] Howald, Dr. Robert, *Breathing New Lifespan into HFC: Tools, Techniques, and Optimizations,* 2013 Cable Show Spring Technical Forum, Washington, DC, June 10-12.
2. [SCHMITT2012] – "*DOCSIS® 3.1 Project: Key Objectives and Directions*", M. Schmitt, SCTE Cable-Tec Expo, Orlando, Oct 2012
3. [CABLESHOW2012] Chapman, John, Mike Emmendorfer, Dr. Robert Howald, Shaul Shulman, "*Mission Is Possible: An Evolutionary Approach to Gigabit-Class DOCSIS®"*, 2012 Cable Show Technical Sessions, Boston, MA, May 21-23.
4. [HOWALD2012a] Howald, Dr. Robert, "*The Grown-Up Potential of a Teenage PHY",* 2012 Cable Show Spring Technical Forum, Boston, MA, May 21-23.
5. [HOWALD2012b] Howald, Dr. Robert L, *Time on Our Side: Using the Past to Pave the Way Forward*, 2012 Cable Show Spring Technical Forum, May 21-23, Boston, MA.
6. CableLabs, *DOCSIS®* Best Practices and Guidelines; Proactive Network Maintenance Using Pre-Equalization, CM-GL-PNMP-V02-110623, http://www.cablelabs.com/specifications/CM-GL-PNMP-V02-110623.pdf

Appendix – D3.1 v. EPoC Comparison Table

Attribute	Comment
Backward Compatibility	**DOCSIS 3.1 Yes, seamless migration; EPOC No**
Leverage CCAP Investment	**DOCSIS 3.1 Yes, some SW upgrade; EPOC No**
RF port integration for simplified HE operation	**MPEG-TS & D3.1 can share same CCAP RF port; EPoC is an Overlay**
Spectrum plans: FDD / TDD	**D3.1: FDD only; EPoC market split: TDD, FDD**
Multiple Modulation Profiles	**DOCSIS 3.1 Yes; EPoC** TDD Yes, **FDD No**
Spectral Efficiency (FDD)	Same OFDM/LDPC technology, but D3.1 uses multiple modulation profiles for **more bits/sec/Hz**
Bandwidth Expansion	**D3.1 bonding ≥ 10G EPON; EPoC 1x192MHz**
Spectrum + Simulcast Tax	**EPOC needs more spectrum for identical services**
Initial Downstream capacity	**D3.1 ~4.5 Gbps; EPoC ~1.5 Gbps**
42MHz US capacity with 3.0	**D3.1 ~250 Mbps; EPoC ~50 Mbps**
Flexibility of MAC, QoS	**DOCSIS® rich QoS, services; EPON 1D scheduler**
Service Flows, SG Size	**D3.1 large SG, many SF; EPoC very limited SG, SF**
HFC Analog Optics	Both compatible with existing AM HFC Optics
Digital Optics, HE to Node	Both D3.1 and EPoC may operate over Digital Optics
Distributed Access Arch	D3.1 optional as needed; EPoC likely Remote PHY
Spec Control	**D3.1 CableLabs controlled; IEEE: individuals**
Time To Deployment	**D3.1 is on fast track; EPoC languishing**
Overall Costs	EPoC needs OLT + B-RAS for comparable functions CPE delta small due to Moore's Law, Econ. of scale