EXAMINING HFC AND DFC (DIGITAL FIBER COAX) ACCESS ARCHITECTURES

AN EXAMINATION OF THE ALL-IP NEXT GENERATION – CABLE ACCESS NETWORK

SCTE Cable-TEC Expo

Atlanta, GA

November 14-17, 2011

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1. INTRODUCTION

This paper will cover two (2) fiber to the node (FTTN) network architecture classes for Cable. The first part of the paper will review the existing Cable FTTN network architecture class, called Hybrid Fiber Coax (HFC). The HFC architecture class supports only a Centralized Access Layer Architecture, whereby the access layer equipment is located at the MSO facility; the outside plant (OSP) is transparent, not containing intelligent network elements, and the customer premise equipment has intelligent systems for data processing. The HFC portion of the network contain the headend optical network elements performing media conversion, connecting the access layer systems in the facility and the optical node in the OSP. The HFC optical node performs simple media conversion in both directions or digital-to-analog conversion in the upstream. The optical node interfaces with the coax network. HFC is really a simple media conversion technology that enables the intelligence to be located at the bookends of the network, such as the MSO facility and the customer location. The headend optics and the outside plant elements in the HFC network remain relatively simple, but remarkably flexible. HFC supports changes in technologies at the bookends, while even supporting legacy and cutting edge new access layer technologies simultaneously.

In the future we need to consider the possibility of moving the IP/Ethernet transport past the HE/Hub locations to the node. We will examine what we are referring to as a new class of cable architecture called Digital Fiber Coax (DFC). The use of DFC may augment the existing HFC media conversion class of architecture that has been deployed for about two decades. We are suggesting that there are really two different Fiber to the Node (FTTN) architecture classes for Cable Networks. These will utilize FTTN and coax as the last mile media, but this is where the similarities will stop.

To simply summarize, the Two Different Cable FTTN network architecture classes are:

1. **HFC is a "Media or Digital Conversion Architecture"**
2. **DFC is a "PHY or MAC/PHY Processing Architecture"**

What is Hybrid Fiber Coax (HFC) (a refresher)

- HFC is a media conversion or digital conversion architecture
- HFC may use Media Conversion (Optical-to-Electrical or Electrical-to-Optical)
- HFC may use Digital Conversion (Analog-to-Digital or Digital-to-Analog)
- The network elements include optical transmission systems in the headend to and from the optical node
- HFC is MAC/PHY transparent, allowing different technologies to be supported over time, simultaneously, and during a transition period
- HFC analog return (and forward) is an optical technology that transports RF signals and performs media conversion between the coaxial and fiber network
- HFC digital return is an optical technology using an ADC (analog-to-digital converter) in the HFC optical node to convert analog RF signals to digital format for easier transport

- HFC digital return digitizes an entire spectrum block for optical transport to the digital return receiver where the recovery process takes place
- Optical modulation format schemes (transport clock rate, # bits per sample, data framing, error detection and correction, if any) are vendor specific for digital return

What is Digital Fiber Coax (DFC)

- DFC is a PHY or MAC/PHY processing architecture
- The network elements include optical transmission systems (Aggregation or Access Layer Data Equipment) in the headend to the optical node (called a DFC Node)
- DFC places the MAC/PHY or PHY in the node
- Everything behind the node remains the same (Amplifiers & taps)
- The Optical connection between the Headend and the DFC Node is called Ethernet Narrowcast, e.g. GbE and 10 GbE Ethernet, EPON, GPON, g.709, etc.
- The DFC architecture class defines several optical transport technology options
- The DFC architecture class can use any of several coax technologies
- DFC utilizes optical transport of digital packet streams to carry data (not digitally modulated RF carriers)
- DFC may employ a MAC/PHY or PHY optical termination and may have a MAC/PHY processing, or simply perform PHY processing for the coax technologies
- Ethernet Narrowcast uses standards-based optical transport such as Ethernet, PON, etc
- Ethernet Narrowcast optical link is bi-directional
- Ethernet Narrowcast can support transport for other MAC/PHYs or PHYs in the Node (this can be other coax technologies and other access layer technologies)

The paper will reexamine the HFC network architecture class and introduce DFC as an alternative network architecture class for cable. The HFC network architecture class section will review some of the technologies and architectures. As with HFC, Digital Fiber Coax will have several technology options as well as network architectures, which may be used. The paper will cover many of these options that may make up this proposed new class of Cable Architecture. It should be stated that paper is in no way suggesting that the MSOs overlay DFC with their existing HFC. The use of DFC style architectures would likely be viable in only a few applications (very long, low density and very short, high density links), as described in this paper. The MSO will find that the existing HFC and the centralized access layer architecture it uses today is an extremely viable network architecture class. The HFC architecture enables transparency of the OSP and places intelligence only at the bookends. The versatility of HFC facilitated MAC/PHY transitions for over two decades without touching the plant is proof of this.

2. KEY NETWORK ARCHITECTURE DRIVERS

The key network architecture drivers will define the services and technologies that need to be transported across the HFC and DFC network, to determine which approaches may be better suited. The technologies may be similar to enable these services; however the network architecture to implement them may be vastly different between HFC and DFC.

The examination of the next generation cable access network will need to consider the downstream as well as the upstream network. It is critically important to understand the video and data service requirements, service delivery technology, spectrum allocation downstream and upstream, serving area size, and even cable type and distance. All of these drivers may influence the architecture requirements in many different ways. These drivers are the underpinnings of some key questions the industry will need to address that will impact the future network architecture. Some of these questions include:

- How long will analog delivered video need to be supported?
- How long will QAM digital video need to be supported?
- When will “full” IP delivered video services take place?
- How long will cable operators transmit video services using multiple methods to the home, such as analog video, QAM video, DOCSIS/IP video, and perhaps other new methods yet-to-be identified.
- How much spectrum and capacity will each of these transport methods consume at the peak transition periods?
- Where will the new upstream spectrum be placed in the future, if needed?
- What will be the desired upstream data capacity rate? Will 1 Gbps upstream, or higher, ever be needed?
- Is the there a desire to remain under 1 GHz for as long as possible to avoid touching the passives?

These are important questions and drivers that need to be understood when considering the next generation cable access network. Answers to these questions are most critical to long term network planners and architects. The answers to these questions will be determined by each MSO and will likely yield varying results. This paper will not make predictions as to when these drivers may take place. We did however publish another paper in 2011, where we predicted the service capacity and estimated the timing of network change [1]. Additionally, that paper also yielded network architecture drivers for the expansion of the upstream spectrum. The upstream spectrum selection, network topology, and data rate capacity was found to have an impact on the entire network access layer architecture. The conclusions found in that report will guide the network architecture requirements as defined in this paper. The paper also introduced some of the topics in this paper, but these were not examined in detail. The purpose of this paper is a comparison of HFC with a new cable architecture class, which refer to as Digital Fiber Coax (DFC).

2.1. Services and Technologies supported across HFC and/or DFC

Network	Services / Technology
Downstream	
	Analog video
	QAM video
	IP/Data Services
	OOB STB Control Communications
Upstream	
	Proprietary STB Return
	DOCSIS STB Return
	IP/Data Services
	Status Monitoring (assumed only DOCSIS)

Figure 1: Network Architecture Drivers

2.2. Forward Transport

The services and capacity network drivers for the downstream will need to be examined when considering the appropriate technology and architecture. The optical transport drivers listed below capture some of these considerations for the forward network:

- **Optical Transport Drivers**
  - Support for services (analog video, digital video, and IP services)
  - Distance to serving area
  - Number optical wavelengths may be a driver to the network architecture as node service groups on the downstream are smaller
  - Link to meet capacity, performance, operations, & cost targets

It may be assumed that analog video service support may decline over time and may eventually be removed altogether. A decline in the number of analog video channels /services will benefit the HFC optical transport network, allowing greater reach and capacity of the network between the headend transmitter and the node. The existence of analog video as a required technology and service may be a challenge for DFC style architectures.

2.3. Upstream Augmentation Spectrum Selection Impacts

As stated in the introduction of this paper, the future upstream spectrum selection and the service requirements to reach perhaps 1 Gbps upstream data rate will impact the network architecture. This paper will not cover the reasoning behind the architecture drivers for upstream spectrum and capacity drivers to reach 1 Gbps; for that, refer to reference [1]. In a nutshell, the selection of low frequency return, say up to 200 MHz, or even 250 MHz (referred to as "High-split") will yield 1 Gbps of upstream MAC layer throughput; and most important, still support a 500 HHP node. The selection High-split has pros and cons, as do all the spectrum split options.

The main takeaway for High-split is the 500 HHP Service Group (SG) is fine, no need to layer more fiber, especially if return path segmentation is possible [1]. The impact of High-split to HFC and DFC architecture is relevant to this paper, in that a single return transmitter only may be needed for a 500 HHP SG. The HFC Architecture Class will likely meet the requirement, and the HFC optical technology used can be Analog Return. The HFC section below will examine this topic in more detail. The existing HFC optics may support up to 200 MHz of return path spectrum.

The Top-split architecture has an extensive impact on the network access layer. The Top-split spectrum selection will impact both HFC and DFC designs. Top-split architecture will simply drive fiber deeper into the network. This is because of the high insertion loss of coaxial cable and passives at high frequencies (at 1 GHz and above). This loss reduces RF signal levels to the point where node splitting must be done to mitigate thermal noise floor funneling. Another method is the insertion of mid-span reverse amplifiers to boost levels, enabling higher modulation complexity. The selection of the Top-split spectrum range may vary from 900 MHz to 1100 MHz range to perhaps above 1250 MHz to 1550 MHz. Additionally, the Top-split architecture limits the usable data rate, cable type and cable distance [1].

The key takeaway for this paper will be an understanding that the architecture impact of Top-split will drive additional fiber, perhaps FTTLA; and this will drive more return path transmitters. If Top-split drives FTTLA, this could be 30 times the number of nodes or optical transmitters in a 500 HHP serving group, compared with a single upstream transmitter for High-split. The Top-split spectrum selection forces the MSO to deploy more fiber and upstream nodes in every service group. The Top-split architecture impact is smaller size service groups per “return” optical transmitter, however downstream capacity is not required to be dedicated to these smaller size service groups. In fact, the downstream service group size could remain at 500 HHP or 250 HHP per downstream optical service group, however with Top-split the upstream optical service group could be 64 HHP to 16 HHP to achieve 1 Gbps upstream. In other words, Top-split may require 8 to 32 upstream optical transmitters per 500 HHP service group; this is a lot of return transmitters. The HFC optical transport would allocate point-to-point connections, however DFC could share these upstream transmitters. This information may influence the selection of HFC or DFC in the future, among other drivers. The use of DFC may be viable for Top-split because of the required number of upstream node/optical transmitters per service group. This is discussed in more detail in the HFC and DFC sections.

3. HIGH-LEVEL DATA NETWORK REFERENCE ARCHITECTURE

There are two types of data access layer architectures, Centralized and Distributed. First, we will consider the DOCSIS CMTS, Edge QAM, EPON OLT, and Ethernet Switch/Router comprising the access layer network elements of a cable service provider network. These intelligent network elements support 100s, 1000s, or even 10s of 1000s of customer devices. The access layer provides intelligent network connectivity to end-users Customer Edge devices such as Cable Modems, Embedded Multimedia Terminal Adapter (EMTAs), Home Gateways, Set-top Boxes, ONUs, and switch/routers.

In addition to the intelligent network elements within the access layer, there may also be basic network equipment that is between the access layer and the customer edge as described above. The basic network equipment in between theses bookend devices simply extends the reach of the network and/or performs media conversion, and these basic devices are transparent to the data network. In the HFC portion of the network, basic network equipment types may include the Head Optical Transmission gear, Optical Nodes, RF Amplifiers, and Passives.

The section will describe Centralized and Distributed Access Layer architectures and this will be the location of the access layer network elements. If all intelligent network elements of the access layer reside in the MSO facility like a headend or hub, then this type of system will be called a Centralized Access Layer Architecture. However if any of the intelligent network elements of the access layer are located in the outside plant or MDU location, then this type of system will be referred to as Distributed Access Layer Architecture. The placement of the access layer equipment will greatly influence the architecture. The core purpose of this paper will be to describe the options and trade-offs of the HFC – A Centralized Access Layer Architecture; and DFC – A Distributed Access Layer Architecture.

The figure below describes an example of a layered data network architecture for cable; it should be noted that not all operators will use this model. It could be dependent on several factors, including size of the MSO, desire to converge layers of the network and functions of the platforms. The “Access Layer” elements and the “Customer Edge” elements (or CPE) are shown with the interface of the access layer to an aggregation layer.

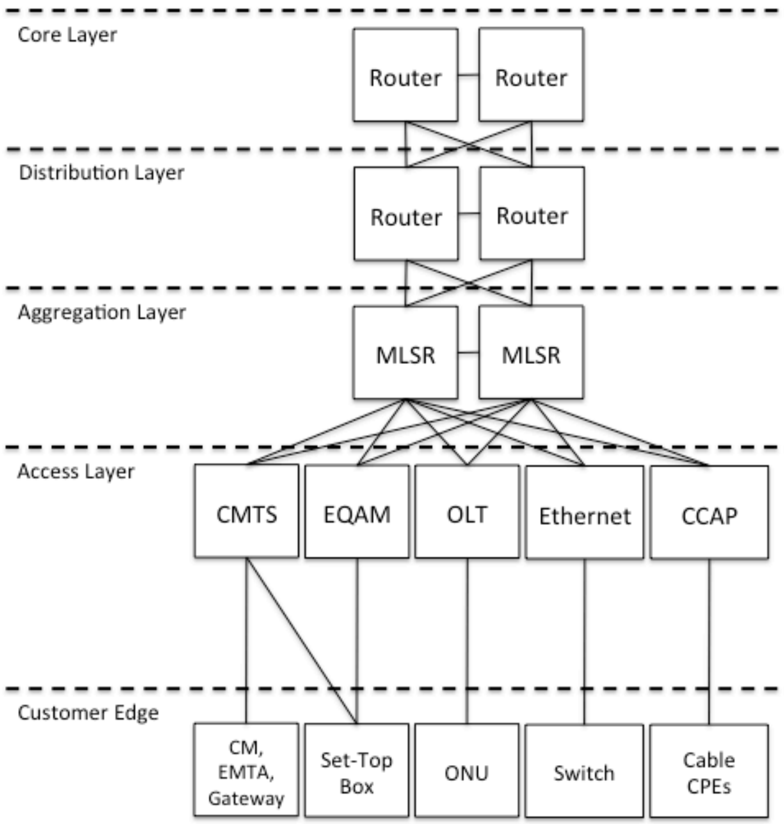

FIGURE 2: CABLE'S DATA NETWORK REFERENCE ARCHITECTURE

3.1. Centralized Access Layer Architecture

The centralized access layer architecture allows customer aggregation functions to reside in the headend or hub locations and the customer edge. This is where the intelligence data processing elements at the end-user locations, like home, apartment, and business reside. Placing the intelligence at the bookends allows the OSP such as nodes to be relativity simple devices and the network is in many ways transparent. The HFC Class of architecture only enables a Centralized Access Layer approach.

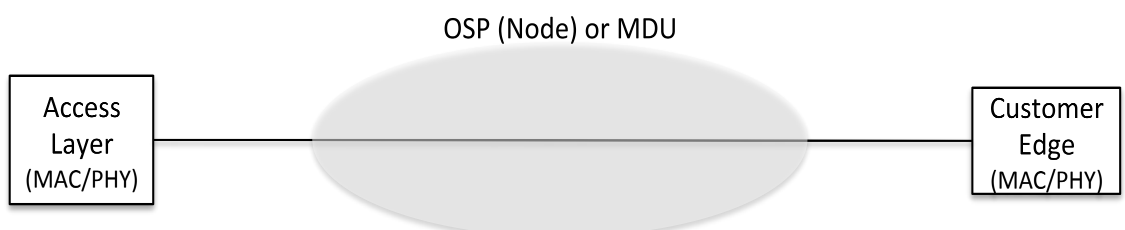

FIGURE 3: CENTRALIZED ACCESS LAYER REFERENCE ARCHITECTURE

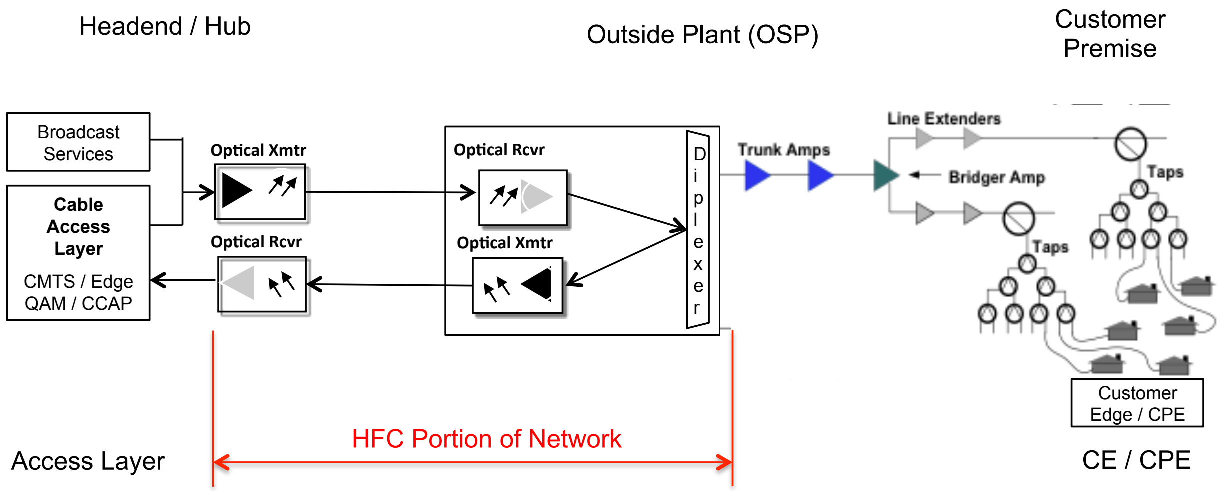

FIGURE 4: CENTRALIZED ACCESS LAYER OVER HFC

In figure 3 is an illustration of an access layer network element over a transparent Outside Plant (OSP) to the customer edge / CPE. In figure 4, the HFC portion of the network is illustrated.

3.2. Distributed Access Layer Architecture

There is another Cable FTTN network architecture class that is not an HFC architecture or technology. This will extend the IP/Ethernet delivery network beyond the hub location to the node (or even MDU) where PHY layer or MAC/PHY layer processing would occur. "Distributed Network Access Layer Architecture" is when PHY layer or MAC/PHY layer processing takes place outside the headend or central office facility; this processing would take place the Node, Cabinet, or Basement of MDU. This is Digital Fiber Coax.

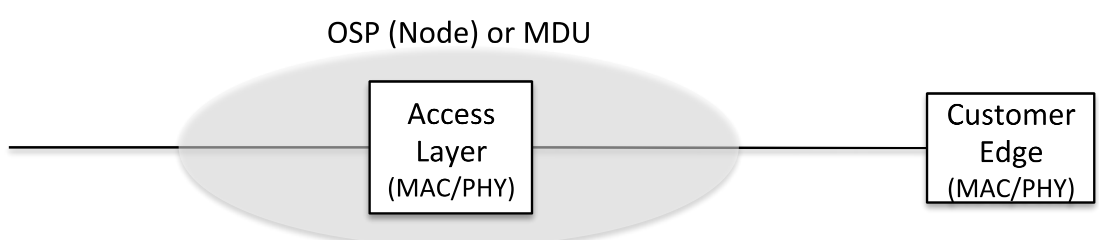

FIGURE 5: DISTRIBUTED ACCESS LAYER REFERENCE ARCHITECTURE

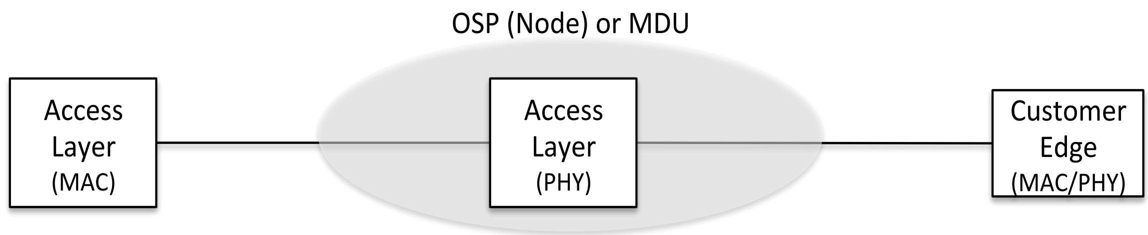

FIGURE 6: PARTIAL DISTRIBUTED ACCESS LAYER REFERENCE ARCHITECTURE

In figure 5 is an illustration of an access layer network element that is Distributed in the OSP or MDU basement location; this moves the access layer closer to the customer edge / CPE. This architecture does not use the HFC optical network, however it will use the coaxial cable network, going through amplifiers and passives. In other words, the HFC RF optical architecture is not used, but HFC components can be used. In figure 6, a portion of the access layer is placed in the outside plant or MDU basement; again the HFC optical architecture is not necessarily used, although it could be, if desired.

4. REVIEW OF HFC – A CENTRALIZED ACCESS LAYER ARCHITECTURE

The HFC Architecture has been around for nearly two decades and has evolved to include many technologies and architectures. Some of these include analog and digital optical transmission technologies and HFC architectures such as Node+N, Node+0, QAM overlay, full spectrum, RFoG, etc. But regardless of the HFC technology and architecture selected, the function of an HFC class of network remains constant; it has always been a "conversion technology" using analog optical transport (and today digital methods), to join dissimilar media types like fiber and coaxial cable. The HFC architecture being a "conversion technology" allows the outside plant to remain relatively simple and yet extremely flexible to changes in the MAC and PHY layers at the bookends of the network. The HFC architecture is also a "centralized access layer architecture" where all of the MAC/PHY processing takes place at the headend, supporting many customers. In figure 7 is an illustration of the functions of each layer of the network.

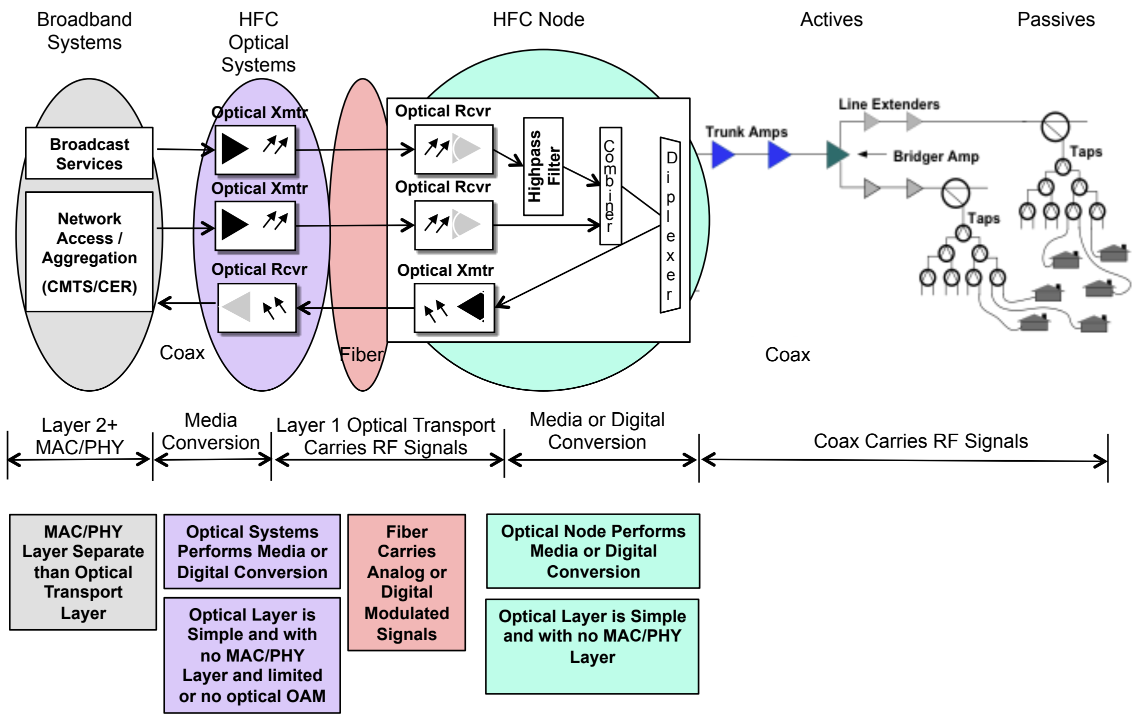

FIGURE 7: HFC A "MEDIA OR DIGITAL CONVERSION ARCHITECTURE"

4.1. HFC Optical Transport Technology Options

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

4.1.1. Overview - Analog Forward path transport

Analog Forward path is currently the only economical method for the transmission of cable signals downstream. The advances in analog forward laser technologies enable transmission of the 54-1002 MHz of spectrum of over 150 channels, each 6 MHz wide. This is approximately 6 Gbps of data capacity assuming the PHY layer transmission utilizing 256 QAM (8 bits per Hz BW efficiency, excluding overhead). The forward path is layer 1 media converter style architecture and the optical transmission may be shared with multiple HFC nodes. There are two network architectures for the forward: Full Spectrum as illustrated in figure 8; and another called QAM Narrowcast Overlay, or simply Narrowcast Overlay, as in figure 9.

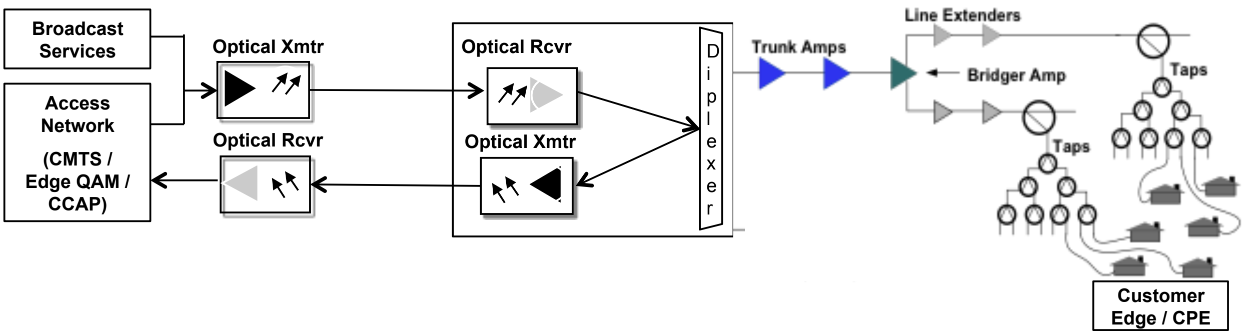

FIGURE 8: HYBRID FIBER COAX (HFC) WITH FULL SPECTRUM AND NODE +N

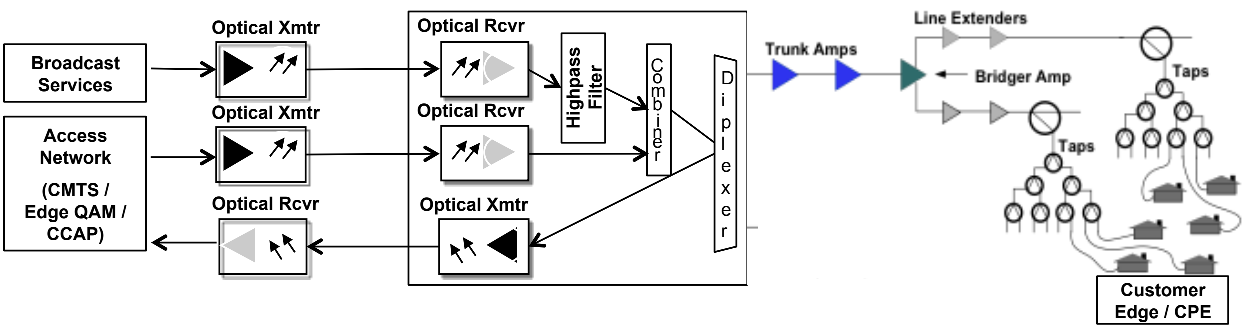

FIGURE 9: HYBRID FIBER COAX (HFC) WITH QAM NARROWCAST OVERLAY AND NODE +N

The MSO serving area between headend and node will be in most cases less than 40 km; therefore this will be easily supported with HFC architecture. The support for extremely long distance to and from the node may be a factor for the HFC. The optical capabilities of HFC simply have lots of dependencies, variables, and trade-offs to determine the HFC optical link distance. We will use round numbers and generalities to discuss some the capabilities of HFC optical transport when considering long distances. So, we will use an example of HFC analog optical transmission of full spectrum, no analog video, and 150 QAM channels, we will assume a 100 km optical reach is achievable in most cases. In a narrowcast overlay architecture, we assume as many as 40 wavelengths / lambdas per fiber, 80 QAMs of narrowcast spectrum, and a reach of approximately 100 km to the node. HFC optical distance will vary based on many factors, including narrowcast channel loading, the number of analog video channels, and many other factors. We could assume greater distance is achievable with HFC Digital Forward, as well as DFC style optical transport, compared with HFC analog forward optics without the use of EDFAs.

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

4.1.2. Overview - Analog Return Path Transport

Analog return path transport is now mostly done with a Distributed Feedback (DFB) laser located in the node housing and an analog receiver located in the headend or hub. Analog return path transport is considered as a viable option for Mid-split, High-split, and Top-split returns. Perhaps supporting short to moderate return path distances of 0-50 km with full spectrum High-split is achievable; at 1550 nm with an EDFA greater distances are possible, as shown in figure 10.

The analog optical return path transport presently supports up to 200 MHz loading; but typically only 5-42 MHz or 5-65 MHz is carried, depending on the distribution diplex filter split. The major benefit with analog optical return is its simplicity and flexibility, when compared with HFC style digital optical transmission. Distance is the chief challenge of analog optical transport. Refer to the figures 10 and 11 below.

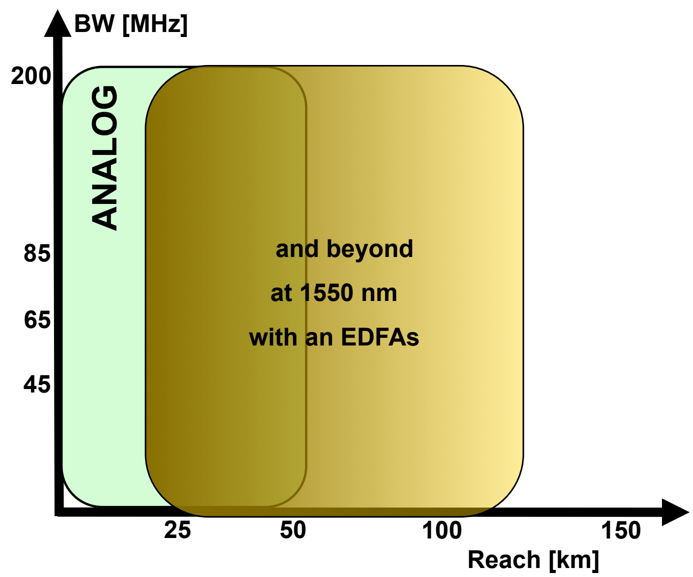

FIGURE 10: RETURN ANALOG OPTICAL BANDWDITH AND REACH

Pros

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

Cons

There are drawbacks to using analog optics. Analog DFB's have demanding setup procedures. RF levels at the optical receiver are dependent on optical modulation index and the received optical power level. This means that each link must be set up carefully to produce the desired RF output at the receiver (when the expected RF level is present at the input of the transmitter). Any change in the optical link budget will have a dramatic impact on the output RF level at the receiver, unless receivers with link gain control are used. Also, as with any analog technology, the performance of the link is distance dependent. The longer the link, the lower the input to the receiver, which delivers a lower C/N performance. The practical distance over which an operator can expect to deliver 256QAM payload on analog return optics is limited.

Assessment

The analog return transmitter will work well for the low and high frequency return. Analog return path options should be available for the higher frequency return options at 900-1050 MHz and 1200-1500 MHz. However the cost vs. performance at these frequencies when compared to digital alternatives may make them less attractive. There will be distance limitations and EDFAs will impact the overall system performance noise budgets. The distance of 0-50 km are reasonable and longer distance would be supported with an EDFA.

4.1.3. Overview – Digital Return Path

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

The parameters of Analog to Digital Conversion will need to be considered when determining the Digital Return optical transport requirements. There are two important factors in the A-to-D conversion, 1) Sampling Rate and 2) Bit Resolution (number of bits of resolution).

- **Sampling Rate**
  - Inverse of the time interval of which samples of the analog signal are taken
    - Referred to as Samples per Second or Sampling Frequency
  - Nyquist Sampling Theorem governs the minimum sampling rate
    - Minimum sampling frequency must be at least twice the frequency width of the signal to be digitized
    - Example: Return band from 5-42MHz must be sampled at 74 MHz (at least) For practical filter realization, the sampling rate should be at least 10-20% greater)
- **Bit Resolution**
  - Number of bits to represent the amplitude for each sample taken
  - Each bit can be "1" or "0" only, but multiple bits can be strung together as "words" of "n" number of bits
  - Number of amplitude levels can be calculated as 2^n, where "n" is the number of bits of resolution. Example: 8 bits leads to 2^8 = 256 levels

Pros

There are a number of advantages to the digital return approach. The output of the receiver is no longer dependent on optical input power, which allows the operator to make modifications to the optical multiplexing and de-multiplexing without fear of altering RF levels. The link performance is distance independent – same MER (magnitude error ration) for 0 km as for 100 km, and even beyond as the figure below illustrates. The number of wavelengths used is not a factor since on/off keyed digital modulation only requires ~20dB of SNR; thus fiber cross-talk effects do not play a role in limiting performance in access-length links (<160 km)

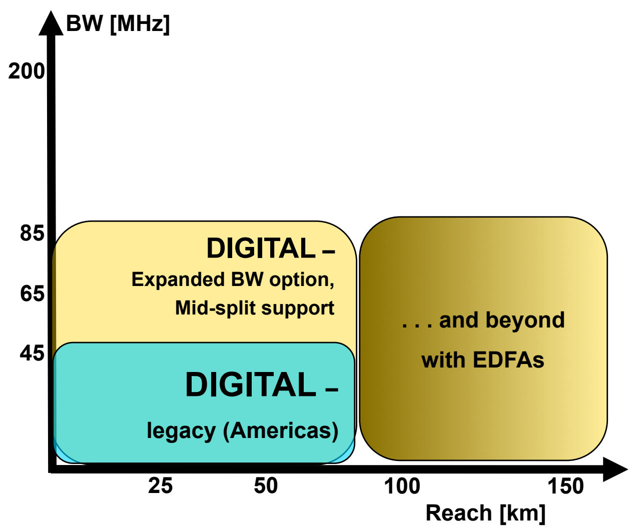

FIGURE 11: RETURN OPTICAL BANDWDITH AND REACH

The RF performance of a Digital Return link is determined by the quality of the digital sampling, rather than the optical input to the receiver; so consistent link performance is obtained regardless of optical budget. The total optical budget capability is dramatically improved since the optical transport is digital. This type of transport is totally agnostic to the type of traffic that flows over it. Multiple traffic classes (status monitoring, set top return, DOCSIS, etc) can be carried simultaneously. The figure 12 below is an illustration of performance and distance when examining the analog and digital optical transport methods.

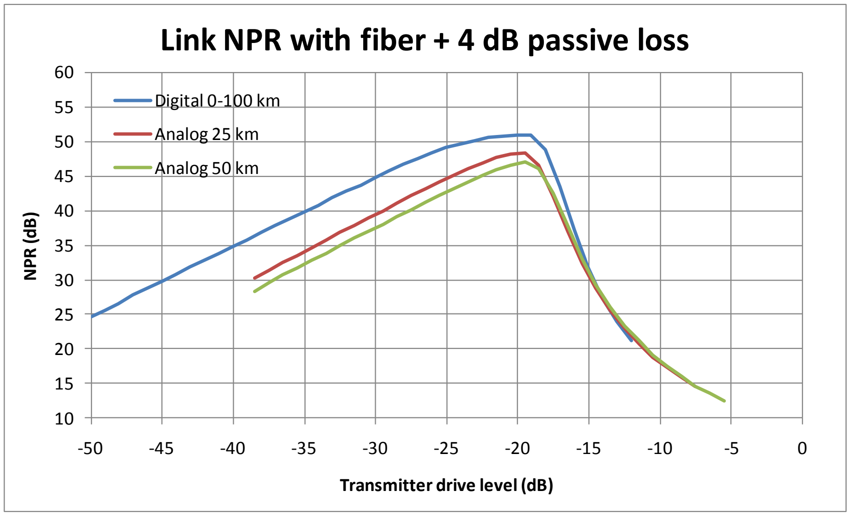

FIGURE 12: ANALOG & DIGITAL RETURN NPR

The Digital Return main drivers are as follow:

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

Cons

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

Another chief drawback to digital return is the Nyquist Sampling Theorem. It requires a minimum sampling rate, fs >2B for a uniformly sampled signal of bandwidth, B Hz. For n-bit resolution, this requires a Transport Clock frequency >2nB. It is assumed that the higher the transport clock, the more costly it is. And with higher clock speed, there is more fiber dispersion, which sets an upper limit on transport rate! This causes some practical limitations as to how high the return spectrum can cost effectively reach when considering digital return. The key points about Nyquist Sampling are captured below. This may be a major driver for the use of analog optics when modest distances are possible; and also a major reason to move away from HFC style architectures to a Digital Fiber Coax (DFC) class of architecture when distance is a challenge.

- **Nyquist Sampling Theorem governs the minimum sampling rate**
  - Minimum sampling frequency must be at least twice the frequency width of the signal to be digitized

- **Nyquist Theorem causes some practical limitations**
  - A 6MHz baseband signal requires a sampling frequency of 12MHz minimum
  - A 42MHz return band requires 84MHz minimum (at least)
  - To digitize the entire forward band, we would need to sample at 1.1GHz (550MHz system) to 2.0GHz (1GHz system)

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

  - **Example: Digital Return**
    - Typical Return band is 5-42MHz
    - Minimum Sampling frequency is 74 MHz (2*37MHz) (at least for practical filter realization the sampling rate may be at least 10-20% greater)
    - For simple math, we will use 100MHz or 100 Million samples/second
    - Determine the bit resolution will be largely dependent on the SNR required
    - For simple math we will use 10-bit resolution or 10 bits/sample
    - Multiply bit resolution and sampling rate
      - 100 Million samples/second * 10 bits per sample = 1,000,000,000 bits/second
      - Approximately 1 Gb/s required to digitize the return band
    - **Key Summary:**
      - >1 Gbps of optical transport was required to transport the 5-42 MHz of spectrum / data capacity
      - Estimate of 4 Gbps plus of optical transport was required to transport the 5-250 MHz of spectrum / data capacity at 10 bits per sample (490 Million samples/second * 10 bits per sample = 4,900,000,000 bits/second, estimate only)

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

Assessment

It is more difficult and therefore more costly to manufacture digital return products. This may be a driver to use Analog DFB products for the new return applications. The selection of digital return products may be driven by distance and performance requirements. Another driver to move to digital return will be when there is near cost parity with DFB; today this is the case with the 5-42 MHz optical transport systems. This may be the case in the future with the new spectrum returns. The main challenge of digital return is the Nyquist Sampling Theorem governs; and when distance, performance, and the desire for high spectrum capacity upstream, these together may be the drivers to consider Digital Fiber Coax (DFC) as described later in this paper for the return path.

4.2. Review of HFC Network Architecture Options

HFC has several technologies for optical transmission and architectures. These include analog optical transport and digital return. An HFC architecture that uses a pair of optical forward connections to the same service group is called QAM Narrowcast Overlay.

4.2.1. Full Spectrum Forward Architecture

This is an example of full spectrum forward architecture where a single transmitter is used to send the entire spectrum to a node or node service group. This allows a single laser to support broadcast and narrowcast services. This approach is used extensively.

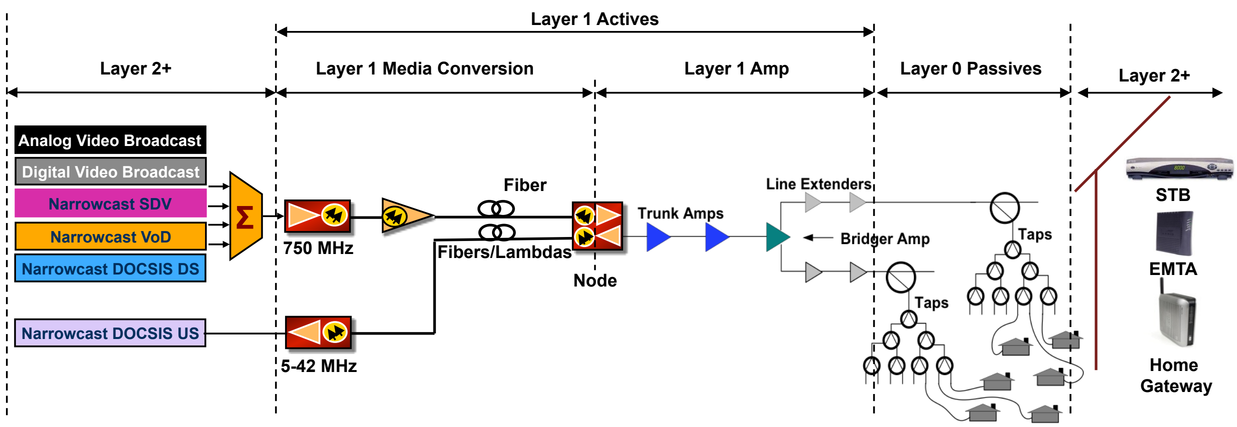

FIGURE 13: FULL SPECTRUM FORWARD ARCHITECTURE

4.2.2. QAM Narrowcast Overlay Forward Architecture

The Narrowcast overlay architecture has been used since perhaps the late 1990s; the main driver for the use of this HFC architecture is to allow the broadcast optics to be shared by a larger pool of customers. The narrowcast overlay optics could be shared by a smaller group of nodes or even dedicated to a single node.

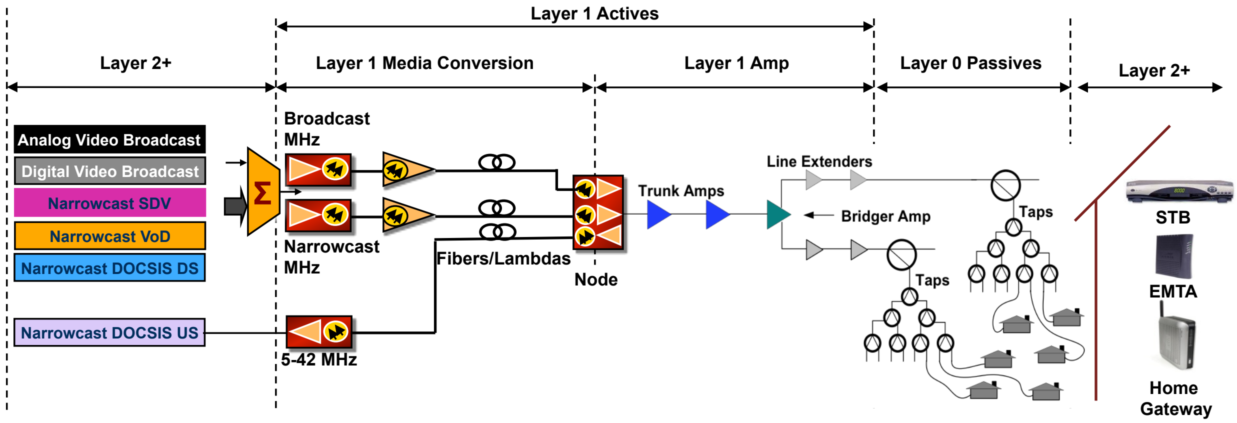

FIGURE 14: QAM NARROWCAST OVERLAY FORWARD ARCHITECTURE

4.2.3. Analog Return Architecture

The analog architecture will use a single spectrum range, say 5-200 MHz upstream, and this will utilize a single fiber or lambda.

4.2.4. Digital Return Architecture

The digital architecture may use two spectrum ranges, say 5-42 MHz upstream, and using 2:1 Time Division Multiplexing, place two 5-42 MHz RF signal bands on a single fiber or lambda. This is an added benefit of the architecture of digital return; double the capacity using a single fiber or lambda.

4.2.5. RFoG – Radio Frequency over Glass Architecture

The use of RFoG is a type of HFC class of technology that has a different architecture. This extends fiber to the premise (FTTP) and uses HFC style optics; this is why RFoG is part of HFC. This is HFC in an FTTP Architecture.

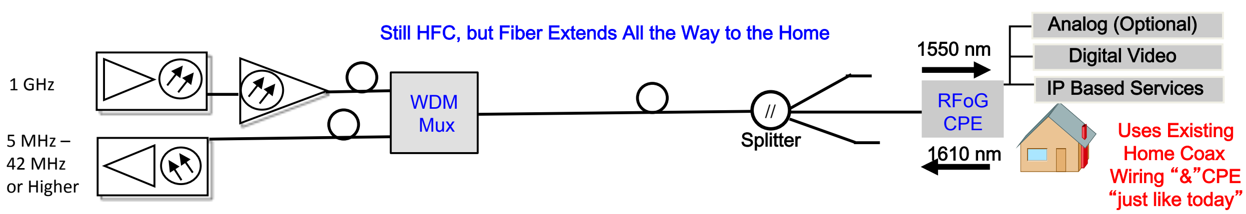

FIGURE 15: RF OVER GLASS ARCHITECTURE

4.3. Review of MAC/PHY Layer Technologies over HFC

The diversity, flexibility, and versatility of the MAC/PHY layer technologies over the HFC are one of the most significant benefits. The past, current and future MAC/PHY technologies have been and will be supported simultaneously over HFC. Improvements in MAC/PHY technologies have been possible because HFC is a transparent media conversion or digital conversion technology. Not placing the MAC/PHY in the OSP has been proven to be beneficial, allowing the MSO to utilize new technology advancements to provide new services, maximize capacity, and improve cost savings; all without touching the HFC optical transport and HFC nodes.

4.4. Conclusions for HFC as a Centralized Access Layer Architecture

The HFC architecture has proven to be a valuable asset for the MSO. It has enabled the evolution to next generation access layer technologies while avoiding changes to the HFC layer of the network. The exception is adding spectrum and capacity. Examples of HFC's versatility include support for analog video systems, digital video systems, EQAMs, UEQ, SDV, CBR voice systems, pre-DOCSIS data systems, DOCSIS 1.0, 1.1, 2.0, 3.0 and so on. This entire multi decade transition did not fundamentally change the HFC architecture. HFC remained simple and carried the next generation data technology through it transparently; these are clear examples of its flexibility.

Additionally, HFC may have carried all of these technologies simultaneously to support a seamless migration to the next generation; a clear example of versatility! The evolution of the cable network primarily is achieved by changing the bookends and not the plumbing in-between. It is hard to imagine the impact if the outside plant, such as optical transmission and nodes, needed to be changed to support each next generation MAC/PHY technology that came along over the last 20 years.

The use of analog return provides more upstream spectrum, although there are distance limitations, this optical transport will meet the needs of most MSO networks. The use of analog optical transmission will carry the industry far into the future and meet the bandwidth and data capacity targets for the upstream [1].

The use of A-to-D and D-to-A and the Nyquist Sampling Theorem, which governs the use of digital optical transmission for HFC, will likely hit practical limits. Considering the services that the MSO will want to offer such as higher upstream data rates, the spectrum may reach over 200 MHz for the low frequency return; and if top-split is selected the spectrum band will need to be wider, perhaps 300 MHz. The use of 250 MHz return spectrum would enable 1 Gbps of RF data MAC capacity, let's say using DOCSIS. The optical link when using HFC Digital Return would have to be over a 4 Gbps optical transmission link, to carry 1 Gbps of actual customer traffic. The use of HFC digital forward will require an 11 Gbps link for up to 550 MHz of spectrum., This will be a challenge for the deployment of such an optical technology for several factors, the main one being that the use of 550 MHz is not full spectrum. The use of digital HFC optics will be possible but optical transmission requirements will increase at a very high rate because of the use of ADC/DAC technology. Nyquist requirements are the main challenge; and the use of Digital Fiber Coax (DFC), as describe in the next section, will seek to solve some of these challenges. Again, the use of HFC with digital return has benefits for the return and to solve distance challenges, among other factors listed above.

As stated in section 2 of this paper, the network performance when using High-split will allow service group size to remain as they are today; perhaps a 500 HHP node with 30 amplifiers in every node service group. High-split will not force smaller service groups and more fiber spending in the OSP, allowing those resources for revenue generation investment. The use of High-split and HFC will be a great choice for the future, the main reason being the simple and transparent ability to carry the next generation data technology. These are clear examples of its versatility. The current HFC forward capacity is 6 Gbps and the current upstream is cable of 200 MHz, and approaches 1 Gbps. The capacity and the distance of HFC networks will meet the needs of the MSO for many years to come.

Network	Services / Technology	Supported With HFC
Downstream		
	Analog video	YES
	QAM video	YES
	IP/Data Services	YES
	OOB STB Communications	YES
Upstream		
	Proprietary STB Return	YES
	DOCSIS STB Return	YES
	IP/Data Services	YES
	Status Monitoring (assumed only DOCSIS)	YES

FIGURE 16: KEY NETWORK ARCHITECTURE DRIVERS SUPPORTED BY HFC

5. INTRODUCTION TO DFC (DIGITAL FIBER COAX) – A DISTRIBUTED ACCESS LAYER ARCHITECTURE

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

The Digital Fiber Coax Architecture is a network class, which differs from HFC in that MAC/PHY or just PHY processing is distributed in the outside plant (node) or MDU. The DFC architecture also uses "purely digital" optical transport technologies such as standardized Ethernet, PON, or other transport methods providing optical capacity to and from the node. The industry may determine to call this class of architecture something else, but the functions, technology choices and architectures are different than HFC. Figure 17 is a high-level architecture of DFC and in this illustration a MAC/PHY are both located in the DFC node and Ethernet Narrowcast connecting Aggregation Layer and the DFC Node may use PON or Ethernet. There are other illustrations of DFC architectures and technologies in this section.

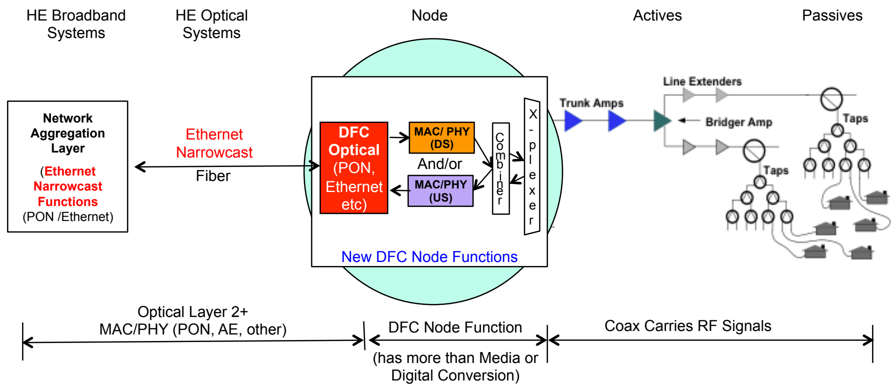

FIGURE 17: DIGITAL FIBER COAX A "MAC/PHY PROCESSING ARCHITECTURE"

What is Digital Fiber Coax (DFC)

- DFC is a PHY or MAC/PHY processing architecture
- The network elements include optical transmission systems (Aggregation or Access Layer Data Equipment) in the headend to the optical node (called a DFC Node)
- DFC places the MAC/PHY or PHY in the node
- Everything behind the node remains the same (Amplifiers & taps)
- The Optical connection between the Headend and the DFC Node is called Ethernet Narrowcast, e.g. GbE and 10 GbE Ethernet, EPON, GPON, g.709, etc.
- The DFC architecture class defines several optical transport technology options
- The DFC architecture class can use any of several coax technologies
- DFC utilizes optical transport of digital packet streams to carry data (not digitally modulated RF carriers)
- DFC may employ a MAC/PHY or PHY optical termination and may have a MAC/PHY processing, or simply perform PHY processing for the coax technologies
- Ethernet Narrowcast uses standards-based optical transport such as Ethernet, PON, etc
- Ethernet Narrowcast optical link is bi-directional
- Ethernet Narrowcast can support transport for other MAC/PHYs or PHYs in the Node (this can be other coax technologies and other access layer technologies)

Key Architecture Attributes of Digital Fiber Coax (DFC)

- DFC is a New Architecture Class for Cable
- Deployment may be instead of or in conjunction with HFC
- Combines the Data Network Access/Aggregation Layer with the Optical Node
- Increases the intelligence of the Optical Distribution Layer between Headend and Node,; this is the Ethernet Narrowcast link, which will use standard Ethernet OAM
- The Optical Layer does not perform media conversion or carry RF signals
- DFC places the Coaxial MAC/PHY or simply PHY in the Node in either one or both directions
- DFC supports Node +N or Node +0 Architectures (in fact the Amps and passives are not changed because of using DFC)

- DFC is a Network Architecture Class; thus Operators & System Vendors may select different Architecture and Technologies.

DFC Technologies for Optical Transport (called Ethernet Narrowcast)

- 1 GbE Optical Ethernet
- 10 GbE Optical Ethernet
- 1G EPON
- 10G EPON
- GPON
- XG-PON
- G.709
- Others

DFC Technologies for RF Coax MAC/PHY

- Analog Video
- Edge QAM
- DOCSIS
- Ethernet over Coax – HPNA 3.1
- Ethernet over Coax – HomePlug AV
- Ethernet over Coax – G.hn
- Ethernet over Coax – MoCA
- Ethernet over Coax – HiNOC
- Ethernet PON over Coax (EPOC)
- Others coax

As described in the following sections there are many technologies and architectures that could all be categorized as the class of architecture we define as Digital Fiber Coax (DFC). Since it is clear that the functions of DFC are not similar to HFC, the industry should consider specifically naming this class of architecture. As illustrated in figure 18, this is an example of a DFC Architecture placing the RF MAC/PHY technology in the node, while using PON or Ethernet as the "Ethernet Narrowcast" technology. When the MAC/PHY is placed in the DFC node it may interface with the Network Aggregation Layer, like a 10G Ethernet switch or PON OLT. As seen in figure 19, within the DFC architecture it permits the PHY sub-systems to be located a long distance from the MAC sub-systems. The PHY sub-system may be a node or MDU gateway and the MAC sub-system is the other half of the access layer and may be placed in the headend.

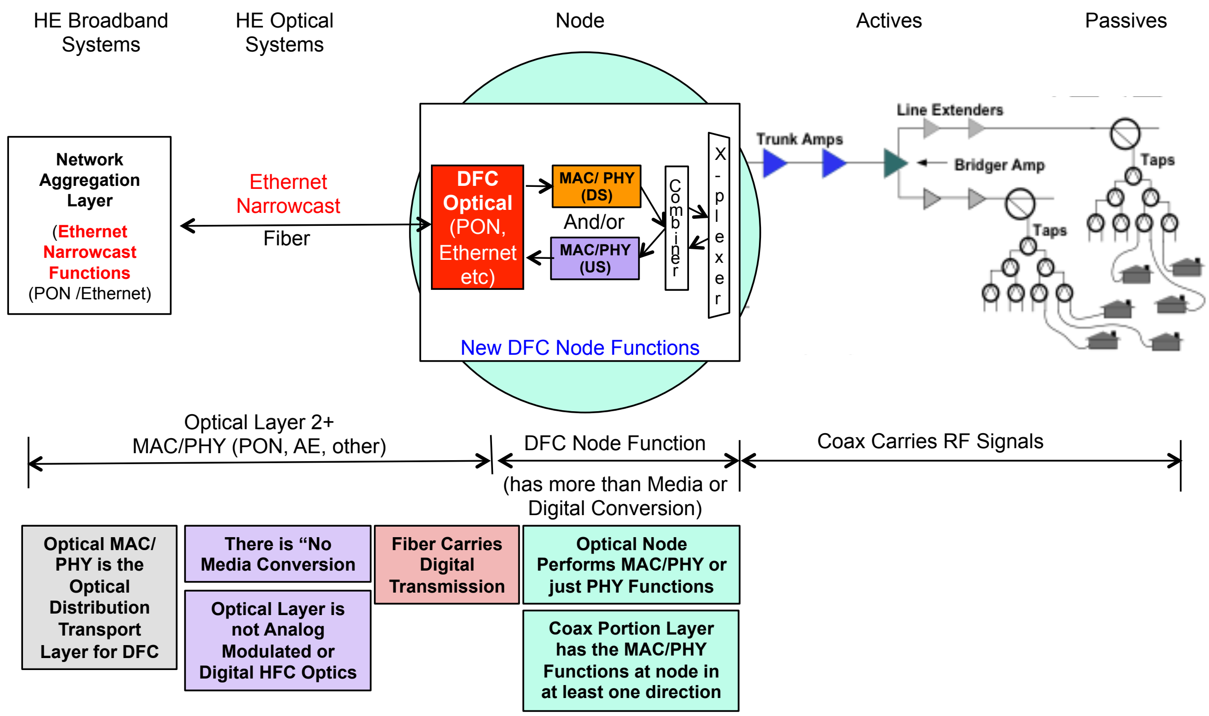

FIGURE 18: DIGITAL FIBER COAX A "MAC/PHY PROCESSING ARCHITECTURE"

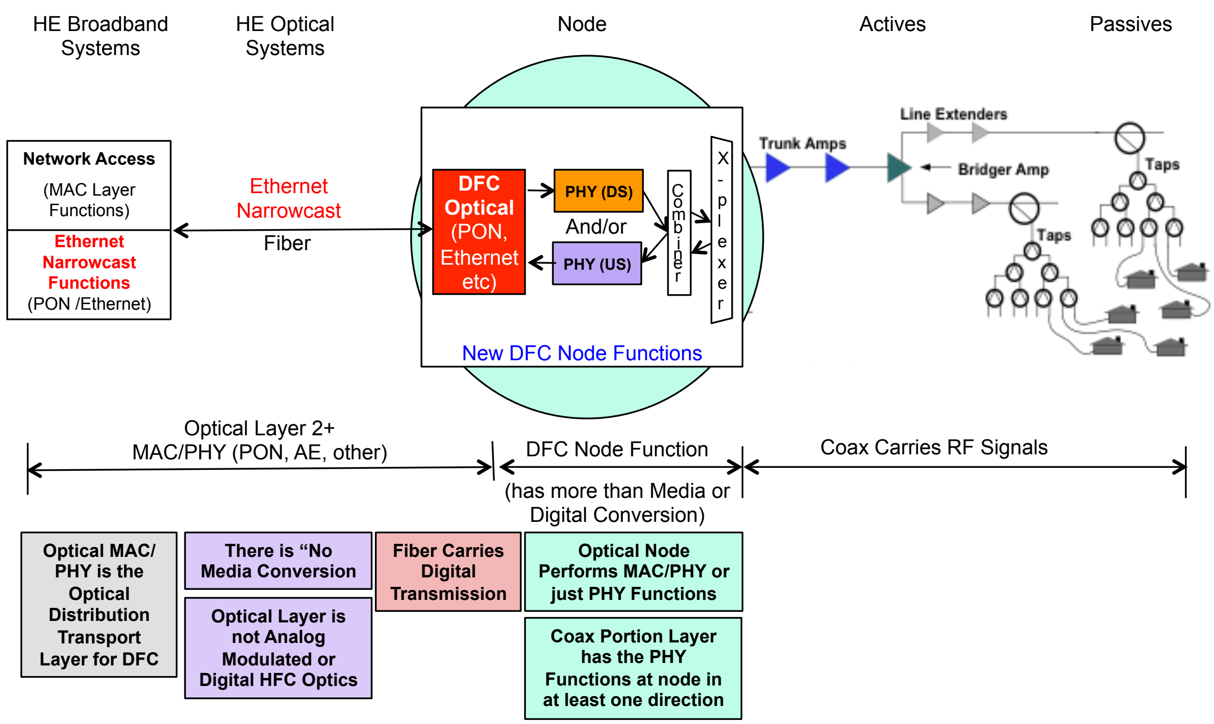

FIGURE 19: DIGITAL FIBER COAX A "PHY PROCESSING ARCHITECTURE"

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

As shown in figure 20, this illustrates an example of Digital Fiber Coax Class of Network Architecture using CMTS as the coax technology and PON or Active Ethernet as the optical transport to the node. The illustration is a node but could be an MDU. Additionally any optical technology or coaxial data technology could be employed, as discussed in detail below.

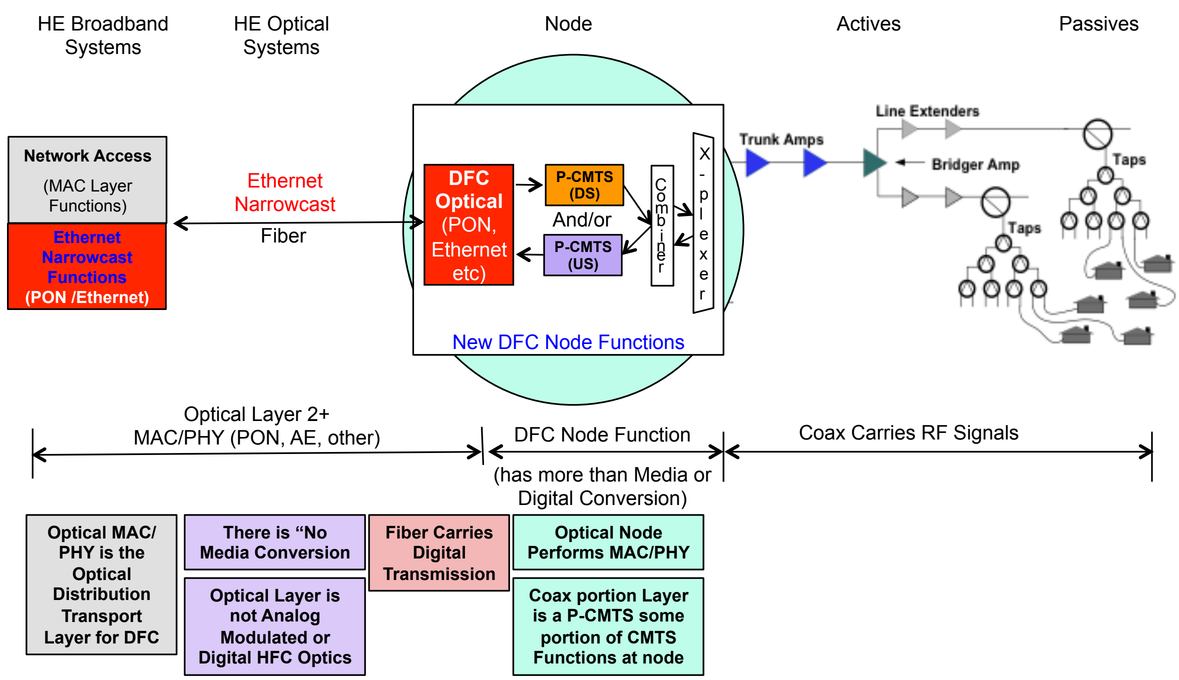

FIGURE 20: DIGITAL FIBER COAX (DFC) WITH DOCSIS TECHNOLOGY AND PHY IN NODE

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

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

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

5.1. Overview - DFC is a New Architecture Class for Cable

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

5.2. DFC – Ethernet Narrowcast – Optical Transport Technology Options

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

5.3. DFC – RF Coax – MAC/PHY Layer Technology Options

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

5.4. DFC Network Architecture Options

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

5.4.1. Examination of HFC and DFC with 10G-EPON and P-CMTS

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

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

The DFC Architecture selected as an example in figure 21 illustrates 10G-EPON as the optical transport, placing the optical MAC/PHY in the optical node; and the second selection uses DOCSIS as the RF technology. The architecture is an upstream only PHY in the node.

Consider then the use of HFC and DFC to support the legacy and new architecture simultaneously; this approach may be referred to as the HFC & DFC Split Access Model, as illustrated in figure 21. HFC is used to support legacy transport technology, services, and most importantly, the centralized access architecture for the downstream such as the very high capacity CMTS/UEQ; the plus side is that the massive and existing downstream optical transport is leveraged. There is no need to place downstream RF MAC or PHYs in the node in most configurations.

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

The DFC style architecture is used for two-way high capacity optical transmission to the node (like 10G Ethernet or 10G-EPON); however, initially this architecture will just consider using the upstream for the expanded coax upstream; see figure 21. The Partitioned CMTS (aka P-CMTS) using upstream only is examined in this paper, however additional downstream capacity could use the existing optical connection and the placement of a future P-CMTS for the downstream could be added later if needed, perhaps over 1 GHz spectrum range.

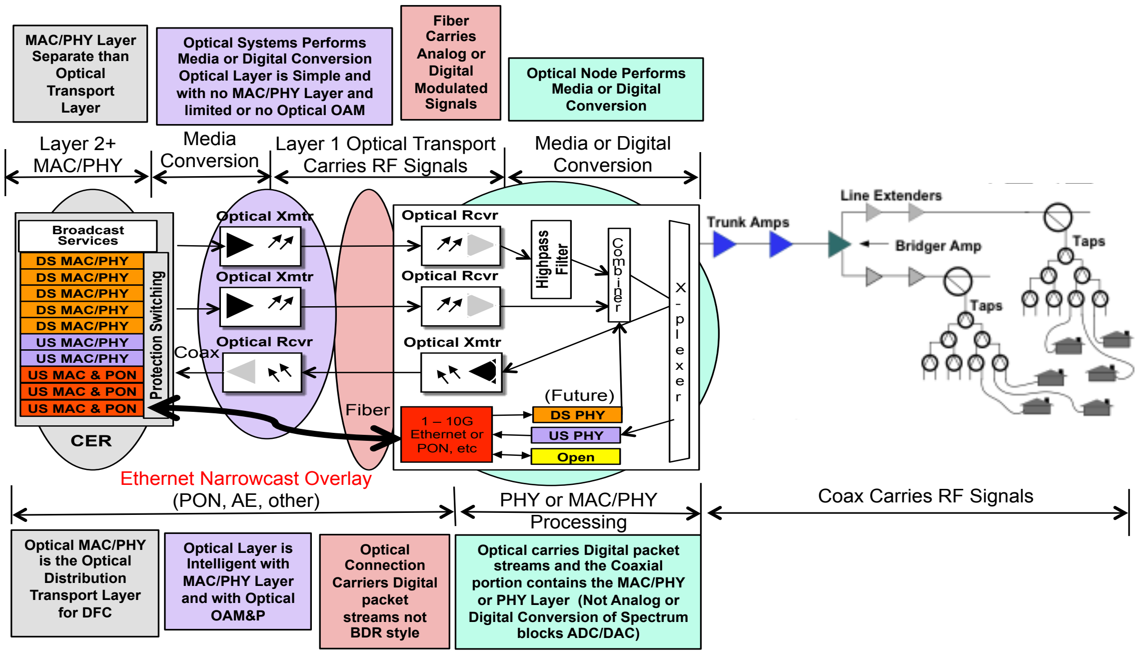

FIGURE 21: HFC & DFC SPLIT ACCESS MODEL

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

Description of P-CMTS (upstream only)

This paper has created a few new labels for cable networking architectures just for use within the paper. Another term that was created in a 2008 whitepaper but perhaps not well known is the Partitioned CMTS (aka a P-CMTS) [2]. The P-CMTS proposes to remote the DOCSIS PHY sub-system from the core CMTS chassis. The primary reason for the P-CMTS is that it can potentially permit the PHY sub-systems to be located a long distance from the MAC sub-systems, such as the node, and use the optical transport options defined above for Digital Fiber Coax to/from the node. The digital packet streams carrying the DOCSIS-encapsulated packets are transmitted across the optical link between the external PHY (node) and the core CMTS chassis.

Pros

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

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

This architecture may be ideal for Top-split Upstream augmentation, as this spectrum selection drives fiber deep, likely to every amplifier, called FTTLA. But the Top-split may drive the need for 15 – 30 times the number of existing nodes to handle the reverse capacity targets of 1 Gbps. The upstream only P-CMTS may be a more compelling approach as this may share the optical upstream when using 10G-EPON. Point to point Ethernet is an option as well.

Cons

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

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

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

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

5.4.2. <u>Examination of DFC with Active Ethernet and QAM in Node</u>

In an effort to illustrate another example of DFC, this will show support for video service from the node. This could also support DOCSIS services in the node as described above. This is an example that DFC can support multiple coaxial MAC/PHY technologies at the same time; it should also be noted that the Ethernet Narrowcast link may support multiple Coaxial MAC/PHY or PHY layer technologies at the same time.

Description of QAM in Node

The technology and architecture of transporting video and even data services using the DFC Ethernet Narrowcast to a QAM Modulator device in the node is a consideration in this DFC style architecture. Again this is not HFC, this is intelligent optical transport to a PHY in the node performing an RF technology; in this case Edge QAM functions are placed in the node.

These QAM modulators may be referred to as IPQAM, IPQAM Gateways, or simply QAM Gateways. The technology uses an IP/Ethernet connection, such as Active Ethernet or EPON, called Ethernet Narrowcast, to connect the node or even MDU. A consideration is the selection of more than one technology in the DFC Node, such as an IPQAM Gateway Node as well as DOCSIS technology. The important takeaway about IPQAM Gateway technology and DOCSIS will be coexistence in DFC, and use the same or different optical connections.

Pros

The placement of an edge QAM in the node has been discussed for years, the architecture driver may be to solve optical distance challenges for long QAM Narrowcast or full digital spectrum links. The placement of a Partitioned CMTS (P-CMTS) would remote the DOCSIS PHY sub-system from the core CMTS chassis, and in this case could provide the additional optical narrowcast downstream channel capacity. Additionally the upstream P-CMTS could be added to this architecture to solve distance and channel capacity concerns.

This DFC application of placing the QAM in the Node to enable digital video and two-way DOCSIS services may allow more channels of both technologies to be used where there are longer optical links where QAM Narrowcast Overlay or Full spectrum will not work.. This is an example of a DFC architecture that may provide more reach and capacity for narrowcast video and data services than otherwise would have been supported with just HFC architecture.

Recall, that the HFC Architecture that used a “Digital Forward” technology would require very high capacity optical connections from the headend to an HFC node where a DAC would be located. The example we covered in the HFC section stated that roughly 550 MHz of spectrum using HFC digital forward would require an optical link of at least 11 Gbps. This would only be a little more than half the spectral capacity of HFC. Using DFC Architecture with the QAM in the Node and even P-CMTS Downstream, the 10 Gigabit Ethernet link could support the entire spectrum band (54 – 1002 MHz, or more) with additional optical capacity for other services. The efficiency and reach of the optical links may have some uses.

Cons

There are cons with this approach, replacing the node and placing intelligence in the OSP. The OSP equipment must operate over a wide temperature range and be immune to weather and AC power line surges. Additional cons would be similar to the P-CMTS approach above. The architecture does not exist in the market and may be considered unproven. Economics are not known.

5.5. Conclusions for DFC as a Distributed Access Layer Architecture

It is fair to say that HFC's use of the term Digital Return could cause confusion with what we are calling Digital Fiber Coax (DFC). It is true that the optical transport of the HFC Digital Return Transmitter uses the same On-Off Keying (OOK) optical modulation as used in DFC. There are some major differences in HFC Digital transmission; this includes the use of proprietary modulation and data framing and clock recovery protocols. The HFC digital return is not standardized; thus these optical links are proprietary. Additionally, the HFC Digital Return or even HFC Digital Forward digitizes the entire spectrum block and uses more optical capacity than the actual data capacity of the spectrum. This is not the case with DFC Ethernet Narrowcast; actual user traffic plus some transport overhead is transmitted across the optical link and will uses substantially less optical capacity than HFC Digital. The consideration of digital forward is not likely feasible in the market place because of the Nyquist rule and the amount of optical capacity required; transporting full spectrum forward is not practically feasible. Thus DFC's use of standardized optics and optical capacity close to the actual traffic used by consumers is a benefit of this architecture.

MSOs using DOCSIS over HFC have benefited from leveraging DOCSIS capacity across many service groups expanding and contracting the service group size at the DOCSIS layer where and when needed. However, a DFC architecture that uses a DOCSIS P-CMTS upstream only technology, placing just the CMTS PHY upstream in the node, may be viable for Top-split applications when attempting to reach 1 Gbps. This is because of the volume of upstream nodes required as Top-split requires the node to be close to the customer. The optical link could use 10 GbE or 10G-EPON to connect several DFC – P-CMTS nodes together. Placing the CMTS functions of any kind or any MAC/PHY or PHY technology may have higher start-up costs and total cost of ownership could be a challenge. Additional concerns of power, cooling and space will need to be explored if remote DOCSIS P-CMTS Upstream is explored as well as other functions. More study is needed to determine the viability of this type of architecture.

There are three applications where a Digital Fiber Coax (DFC) class of architecture may have viability.

1. Fiber count is insufficient
2. Extremely long distance to/from the Node:
3. Top-split as a new return path Spectrum Selection

6. HFC AND DFC EXECUTIVE SUMMARY AND CONCLUSIONS

The HFC network enables centralized access layer architectures and DFC enables distributed access layer architectures. As discussed above, the industry since the 1990s has examined the placement of intelligence in the nodes, like CMTS and since then different parts of the CMTS have been considered for the node. The Edge QAM, PON, and many other technologies have also been considered in a distributed access layer architecture. Placing the intelligence in the node and distributing the architecture may limit future flexibility, and in large part has been avoided by the cable industry.

The HFC architecture has proven to be a valuable asset for the MSO. It has enabled the evolution to next generation access layer technologies while avoiding changes to the HFC layer of the network. This entire multi decade transition from analog video systems, digital video systems, EQAMs, UEQ, SDV, CBR voice systems, pre-DOCSIS data systems, DOCSIS 1.0, 1.1, 2.0, 3.0 did not fundamentally change the HFC architecture. HFC remained simple and carried the next generation data technology through it transparently; these are clear examples of its flexibility.

The HFC may have carried all of these technologies simultaneously to support a seamless migration to the next generation; a clear example of versatility! The evolution of the cable network primarily is achieved by changing the bookends and not the plumbing in-between. It is hard to imagine the impact if the outside plant, such as optical transmission and nodes, needed to be changed to support each next generation MAC/PHY technology that came along over the last 20 years.

The use of DFC may augment the existing HFC media conversion class of architecture that has been deployed for about two decades. We are suggesting that there are really two different Fiber to the Node (FTTN) architecture classes, which utilize coax as the last mile media. To simply summarize the two different cable FTTN network architecture classes and the key deltas between HFC and DFC:

- HFC is a "Media or Digital Conversion Architecture"
- DFC is a "PHY or MAC/PHY Processing Architecture"

HFC Conclusions

1. Architecture remains viable well through this decade and beyond
2. Existing technology, flexibility and versatility to support transport of virtually any new MAC/PHY technology remains a core benefit and value of HFC
3. Optical transport supported with DFB analog lasers and digital return last throughout the decade

4. HFC allows the outside plant to remain simple, just performing media and/or digital conversion (for digital return), thus no MAC or PHY layer processing is required in the node
5. Enables a centralized access layer for economies of scale, reliability of systems, and just in time investment in capacity
6. HFC and High-split is a strong combination if additional spectrum splits are planned
7. HFC is a viable approach for MDU applications
8. It is hard to imagine the impact if the outside plant, such as optical transmission and nodes, needed to be changed to support each next generation MAC/PHY technology that came along over the last 20 years.

Digital Fiber Coax (DFC) Conclusions

1. The DFC architecture class is not a strong competitor to HFC in nearly all cases.
2. The DFC – Distributed Access Architecture includes the risk of: stranding capital, low flexibility and limited versatility, if the PHY is placed out in the Node MSOs are tied to that PHY and MAC technology until the nodes are changed.
3. DFC is a viable approach for MDU applications
4. Fiber count is insufficient
    - The optical capacity of DFC style optics like Optical Ethernet is far superior to HFC analog optics.
    - Fiber starved serving areas where fiber over lash is costly may be an application for DFC style architecture.
5. Extremely long distance to/from the Node:
    - Full Spectrum perhaps exceeding 100 km with 150 digital channels may be an application for DFC style architecture.
    - If Narrowcast optical distances are greater than 100 km, with as many as 40 optical wavelengths and greater than 80 narrowcast channels. this may be an application for DFC style architecture.
    - The use of Digital Forward may solve the distance challenge but will require about 20 Gbps of optical transport capacity for full spectrum (assume Nyquist and 950 MHz channel block), DFC would require less than half (~ 6 Gbps) and is a two-way optical transport.
    - Top-split with Gbps data capacity using HFC analog optics that would require an EDFA may be an application for the DFC class of architecture. Downstream is not a driver for DFC in this case at all.
    - The use of Digital Return may solve the distance challenge for High-split or Top-split but will require about 6 - 8 Gbps of optical transport capacity when digitizing the entire return spectrum (Nyquist rule). DFC would require about 1 Gbps of optical capacity and is two-way optical transport; thus it could be shared.
6. Top-split as a Spectrum Selection

- o If Top-split is selected for new upstream and a high data rate capacity of 1 Gbps is desired, this will require an upstream transmitter serving perhaps 64 to 16 HHP [1]. This will drive the need for lots of "upstream" transmitters from these smaller "upstream" HHP service groups.
- o Top-split drives fiber and lots of upstream transmitters, the volume of optical connections may be an application for DFC class of architecture. An example used in the paper is the use of 10G-EPON to provide upstream transport.
- o Downstream is not a driver for DFC in this case at all.

Essentially, the DFC Architecture Class seeks to solve the challenges cited above with HFC. The placement of the MAC/PHY or PHY in an effort to "Distribute the Access Layer Architecture" will allow standard optical transmission to the Node, called Ethernet Narrowcast. There may be three applications that Digital Fiber Coax (DFC) class of architecture may have viability this may include: fiber count is insufficient in the serving area, extremely long distance to or from the Node, and Top-split upstream augmentation applications to address the volume of upstream transmitters per service group. More study is needed to determine the viability of these types of architectures using DFC.

7. ACKNOWLDEGEMENTS

The authors would like to thank the contributions from ARRIS' Derald "DOC" Cummings, Venk Mutalik, Brent Arnold, Bill Dawson and Marcel Schemmann.

8. REFERENCES

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9. LIST OF ABBREVIATIONS AND ACRONYMS

1 GbE	Gigabit Ethernet
10G-EPON	10 Gigabit Ethernet Passive Optical Network
10GbE	10 gigabit Ethernet
BDR	Broadband Digital Return (also referred to as Digital Return)
DFC	Digital Fiber Coax
DIG	Digital Return Optical Transport (also referred to as BDR)
DOCSIS	Data Over Cable Service Interface Specifications
DSG	DOCSIS Set-top Gateway
EoC	Ethernet over Coax
EPON	Ethernet Passive Optical Network
FTTLA	Fiber to the Last Active

FTTN	Fiber to the Node
GbE	Gigabit Ethernet
Gbps	Gigabits per Second
GPON	Gigabit PON
HFC	Hybrid Fiber Coax
HHP	Households Passed
HPNA	HomePNA Alliance
HSD	High Speed Data
HSD	High-speed Internet
IP	Internet Protocol
IPTV	Internet Protocol TV (video) over IP networks
MAC	Media Access Layer
Mbps	Megabit per Second
MDU	Multiple Dwelling Unit
MoCA	Multimedia over Coax Alliance
MSO	Multiple System Operator
OOB	Out of Band
OSP	Outside Plant
PHY	Physical Layer
QAM	Quadrature Amplitude Modulation
RFoG	RF Over Glass
US	Upstream
VoD	Video on Demand
XG-PON	10G-PON