INFINITE DOCSIS

Infinite Ports, Infinite Channels, Infinite Bandwidth and Infinite Opportunity

A Technical Paper prepared for SCTE/ISBE by

John T. Chapman
Fellow & CTO Cable Access
Cisco
170 West Tasman Drive
San Jose, CA 95129
408-526-7651
jchapman@cisco.com

Table of Contents

List of Figures

List of Tables

Title	Page Number

Introduction

In this white paper, together we will both look back over the last twenty years of DOCSIS and look forward to the next twenty years of DOCSIS. As we look at this passage of time before us and time yet to come, we will look at the technology milestones that have been achieved and the ones that still may come to pass. On each milestone, we will assign it a role in its contribution to increasing the bandwidth capacity of the network.

While some technologies happen in isolation, most technologies happen in synergy to each other. For example, the upgrade of the HFC plant to two-way plant provided an opportunity for DOCSIS. DOCSIS in turn drove more plant upgrades. Regardless, we will try to assign each technology part of the credit as we track the downstream and upstream bandwidth of a service group.

This white paper presents the theorem that there are three stages of life to the HFC plant: HFC Classic, Deep Fiber, and Fiber to the Tap (FTTT).

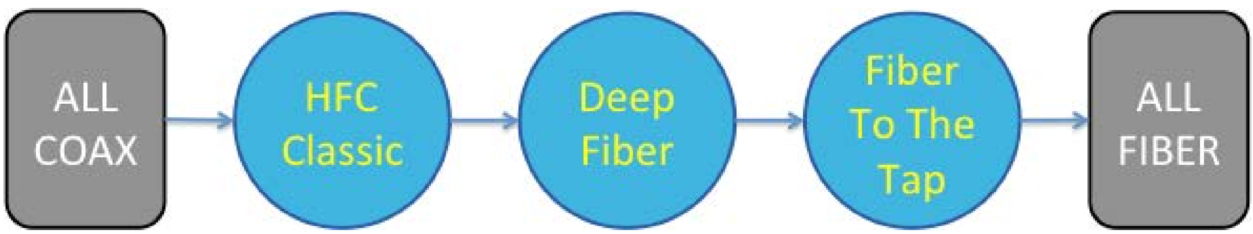

Figure 1 - Three Phases of the HFC Plant

HFC Classic	This is the phase the HFC plant is currently in. It was started in the 1990s when optical nodes where introduced; the plant was segmented into a manageable number of households passed (HHP) per node; the amplifier chain was maintained to a reasonable depth (5 deep was the target); the plant became two-way capable with a frequency division duplex (FDD) spectrum plan.
Deep Fiber	This next phase is starting now in 2016. In deep fiber, all the line amplifiers are removed and optical nodes are placed at the last amp position.
Fiber to the Tap	This is a potential follow-on phase that this white paper suggests. In this final phase, fiber is run to the tap and a small remote PHY device (RPD) converts the fiber to coax for transmission to the home over the existing drop cable.

There are phases of the HFC plant that pre-date "HFC Classic." Those are not relevant to the scope of this white paper as they did not apply to a data over cable scenario. There are phases after FTTT that would involve full fiber solution that we will not cover either.

Phase 1 – HFC Classic

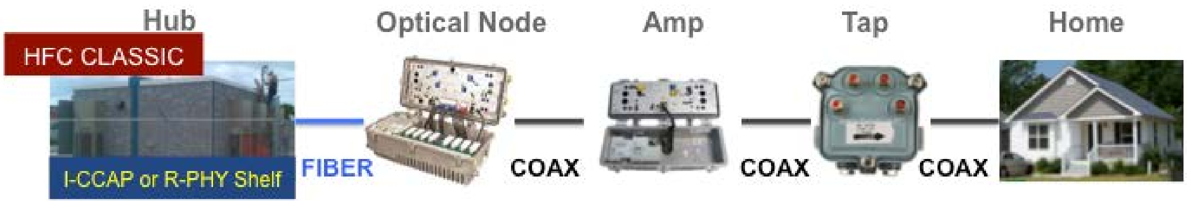

Figure 2 - HFC Classic

The cable plant was originally built in the 1960s as a coax-only, one-way plant that connected a community antenna to multiple homes. The cable plant has come along way since then. The Hybrid Fiber-Coax (HFC) Classic design referenced in this white paper began in the 1990s and was driven by the need to have a more robust HFC plant that could carry data in both the forward and reverse direction. The HFC Classic design has coax-connecting plant transmission in the hub site. This is typically DOCSIS CMTS for data, EQAM for video (Broadcast, SDV and VOD), and OOB signaling. There also used to be analog video retransmission equipment as well.

It is worth recognizing that the first two-way transmission path was the return path needed for control of the set-top box (STB). This is referred to as the Out-Of-Band (OOB) channel and is standardized as SCTE 55-1 [19] and SCTE 55-2 [20]. The OOB channel uses a 1.8 to 2 MHz differentially encoded QPSK carrier. The downstream (DS) is typically located at 75.25 MHz while the upstream (US) carrier is around 8 MHz in the spectrum. The OOB channel works by being low-bandwidth and transmitting at a high power level. Something better is needed for data.

It is also worth recognizing that in the early 1990s, before the introduction of DOCSIS in 1997, it is also worth recognizing that there were a series of proprietary cable modem solutions, such as from LAN City, Motorola, Zenith, and others that lead up to DOCSIS. In fact, LANcity provided much of the DOCSIS IPR license free in the creation of DOCSIS 1.0 [7].

1. DOCSIS 1.0 – In The Beginning

Figure 3 - uBR7246

DOCSIS 1.0 was the start of today's standardized data-over-cable infrastructure. The original specification contained many of the same elements that are still in use today. The downstream is a broadcast Ethernet frame with a DOCSIS header. The upstream is a scheduled upstream. DOCSIS 1.0 offered an equal access service. Traffic to each CM could be identified and rate-shaped.

The downstream specification used a 6 MHz wide carrier in North America and 8 MHz in Europe with 64-QAM or 256-QAM modulation. This provided data rates or 27 Mbps or 38 Mbps respectively. Since initial installations used one channel of 6 MHz, 64-QAM, this will form the baseline we use for the bandwidth growth story in this white paper.

The upstream had a choice of symbol rates, RF bandwidths and QPSK or 16-QAM for modulation. The initial deployed upstream was a QPSK, 1.6 MHz carrier with a throughput of about 2.2 Mbps.

DS baseline: 27 Mbps
US baseline: 2.2 Mbps

2. HFC Plant Rebuilds and Upgrades

One of the big unsung heroes in the whole DOCSIS growth story is the HFC plant itself. The HFC plant was quite happy being a large broadcast plant until the internet came along. The cable operator's desire to create a new revenue stream by offering a high speed Internet service drove the upgrade of the HFC plant to a bidirectional architecture with a "cleaned up" upstream. DOCSIS came about after that because of the desire by the cable operators to standardize the access technology to drive competition and thereby reduce modem pricing.

The bandwidth needed for DOCSIS required that the plant be continually segmented into smaller and smaller pieces.

Each time the HFC plant is segmented, two or more optical nodes replace one optical node. The connectivity from the optical nodes to the CMTS is engineered to use the least amount of CMTS ports but still supply enough bandwidth for the subscribers. As such, multiple DS and US paths can be combined together to create one DOCSIS service group (SG). Each SG will have some number of DS and US channels and carriers that determines the bandwidth of that group.

The initial DOCSIS CMTS was the Cisco uBR7246 that featured one SG per line card. Each SG had one downstream port and 6 upstream ports. The reason for the 6 upstream ports was to segment the upstream noise instead of it being additive, thereby allowing a higher order modulation to be used. Multiple fiber nodes where often combined onto each upstream port which meant even more fiber nodes shared a downstream port. This worked because the initial market penetration of cable modems was 1-2.

Today's plant is typically 500 HHP per optical node. This can vary in practice from 2000 HHP on old plant to 350 HHP on the newest plant. SG port combinations are described as 1 DS port by N US ports. Typical SGs today in North America are 1x2 and 1x1. There are still many 1x4 SG internationally. 1x2 is the most common configuration because many nodes use a digitized return path called baseband digital return (BDR) that supports two return paths.

HHP can be thought of as a capacity metric. The number of HHP times market penetration determines the number of CMs that share the bandwidth of a SG. For example, with 12000 HHP per DS and 2% market penetration, 240 CMs shared 27 Mbps. On today's plant, with 500 HHP on a DS and 50% market penetration, 250 CM would share 1.2 Gbps for DOCSIS 3.0.

For the bandwidth metrics in this white paper, we will give the credit to the segmentation of the HFC plant for moving from 1x6 ports to 1x1 ports, from 12K HHP in the DS to 500 HHP in the DS, and from 2000 HHP in the US per port to 500 HHP per port.

- DS SG Initial: 2000 HHP per US port * 6 US ports per SG = 12,000 HHP
- DS SG Today: 500 HHP
- DS ratio: 12,000 / 500 = 24x

- US SG Initial: 2000 HHP per US port
- US SG Today (for 1x1): 500 HHP, 1x1 SG

- US ratio: 2000 HHP per port / 500 HHP = 4x

DS Bandwidth Multiplier: 24x
US Bandwidth Multiplier: 4x

3. DOCSIS 1.1, 2.0 & 3.0

DOCSIS 1.1 added quality of service (QoS) that enabled deterministic control of jitter and latency thereby enabling the addition of voice over IP (VoIP) as a service. Around this time, the quality improvements in the HFC plant enabled the MSOs to begin using 256 QAM modulation on the downstream and 16 QAM in a 3.2 MHz channel on the upstream. These modulations were supported by DOCSIS 1.0 but not used till now. The data rates were now 38 Mbps in the DS and 9 Mbps in the upstream.

DOCSIS 2.0 enhanced the downstream by adding an algorithm for load balancing CMs across multiple DS. The CMs were still single-channel but the plant capacity increased by having more channels. The DS capacity of the plant increased to about 4 DS QAM channels thanks to silicon density. The upstream also received the same load-balancing capability. The upstream channel allocation also increased to 4 channels due to silicon densities.

DOCSIS 2.0 also introduced new upstream capabilities. One was SCDMA (Synchronous Code Division Multiple Access) that did not get widely deployed and was eventually abandoned. The other was ATDMA (Advanced Time Division Multiple Access) that increased the upstream modulation to 64-QAM and the RF bandwidth to 6.4 MHz resulting in a useable throughput of 25 Mbps per US channel.

DOCSIS 3.0 introduced bonding which was a more efficient way of using multiple channels. In this phase, the CMs also became multiple channel. Note that for a 4x4 ch group, the plant capacity does not increase but is more efficient. The peak rate that a CM could offer, however, increased considerably. There are several variations of channelized CMs. The two popular ones are an 8x4 ch CM and a 32x8 ch CM. Due to the US plant limitations of 42 MHz, there was only spectral room for 4 US channels to be deployed.

The US story is actually a bit more complicated. Most operators are deploying 4 channels of 64-QAM, so three channels at 6.4 MHz and one channel at 3.2 MHz. These are located between 20 MHz and 42 MHz. Then there is an additional channel that is used for DOCSIS 1.1 CMs that is 3.2 MHz and 16-QAM. DSG (DOCSIS STB Gateway) will share that channel or use one more additional channel at QPSK. The total of all these channels works out to about 100 Mbps.

- DS ratio: 32 ch / 1 ch * 38 Mbps / 27 Mbps = 45x
- US ratio: 4 ch / 1 ch * 25 Mbps / 2.2 Mbps = 45x

DS Bandwidth Multiplier: 45x
US Bandwidth Multiplier: 45x

4. Accumulated Bandwidth Growth for HFC Classic

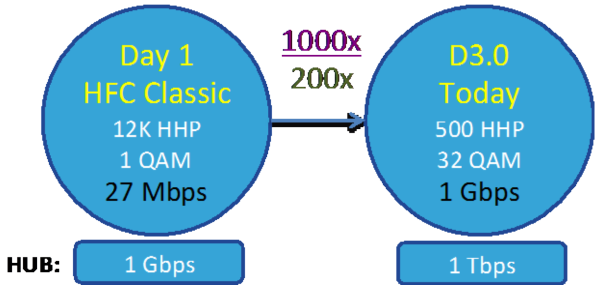

Figure 4 - HFC Classic Data Capacity

For HFC Classic, we started with the early DOCSIS 1.0 CMTS on barely upgraded plant with a small market penetration. We then followed the path of DOCSIS 1.1, 2.0, and 3.0. We upgraded the plant and watched the CM silicon density increase and the HFC plant continue to segment. The journey went from one QAM channel on 12,000 HHP plant to today where some plants have thirty-two channels of QAM at 500 HHP.

- DS Ratio: 24 x 45 = 1081x `= 1000x
- US Ratio: 4 x 45 = 182 ~= 200x

To get an idea of the impact the increased subscriber bandwidth has on a hub site, we can calculate the number of DOCSIS SG and multiply by the bandwidth per SG. Assuming a large hub of 400,000K HHP:

- Hub Day One: 400,000 HHP / 12,000 HHP per SG * 27 Mbps per SG ~= 1 Gbps
- Hub Today: 400,000 HHP / 500 HHP per SG * 1.2 Gbps per SG ~= 1 Tbps

Due to aggregation in the Ethernet network between the nodes and the hub, this bandwidth could be less. However, to interconnect these hubs, the number of 10 GE equivalent ports could be 2.5x more. See [8] for a more detailed explanation of the Ethernet access network. To keep it simple, we will baseline on one times the aggregate SG bandwidth.

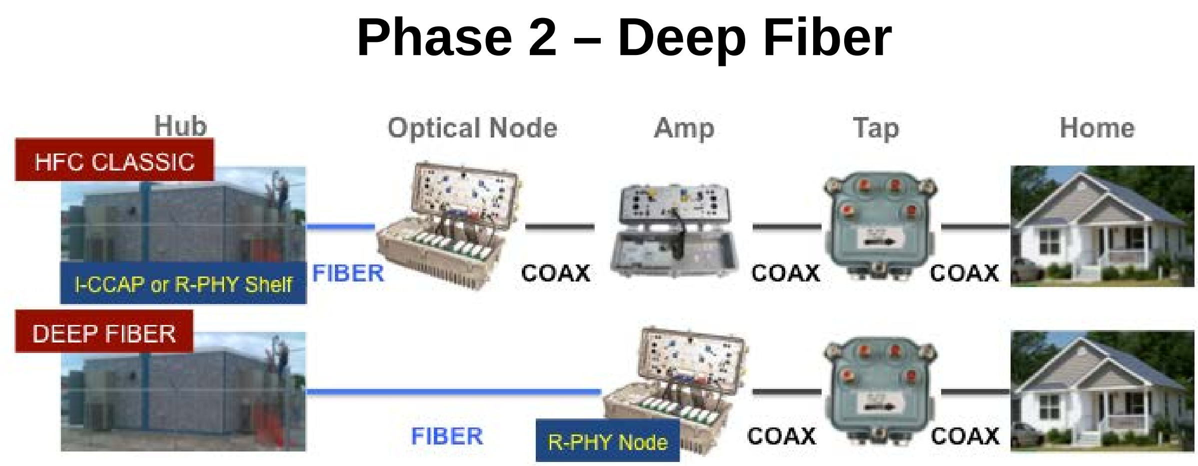

Figure 5 - Deep Fiber

The cable industry is about to embark on the next big phase of HFC evolution referred to as Deep Fiber [8] [9] [10] [11]. The goal is to eliminate all amplifiers and rebuild the plant using optical nodes. Sometimes old amplifier locations can become the new node locations. Sometimes Deep Fiber requires a complete redesign of the access network that will clean up incremental growth over years and will minimize the number of optical nodes.

A notable characteristic of a deep fiber design is that the node directly drives passive coax. This opens up the bandwidth of the coax to more possibilities as we will see in the next few sections.

5. Node+0

The general concept of HFC plant segmentation is to assign a small geographical area, say 500 HHP to a node. Amplifier cascades were used to keep the RF levels at a sufficient level for the RF signal to reach the home.

In a complete Deep Fiber deployment, all amplifiers are removed. In theory, a node is placed at the location of the last amplifier. In practice, cable segments can be redesigned and/or node are placed at new locations so that the number of nodes can be minimized. Depending upon the size of the old node location, the old optical node may get replaced by up to 10 to 15 new nodes.

If these nodes are directly connected to a CCAP (Converged Cable Access Platform), then the bandwidth capacity also increases by 10x to 20x. If instead the nodes are digitally combined before being connected to a DOCSIS SG, then the multiplication effect will be less. This analysis will take the lower end of the node expansion, which is 10x, and then assume each node is connected separately to the CMTS.

DS Bandwidth Multiplier: 10x
US Bandwidth Multiplier: 10x

6. Remote PHY – SNR Contribution

Remote PHY is a complementary technology to Deep Fiber. Remote PHY removes the CCAP PHY from the CCAP and into either the optical node or into a RF Shelf at the hub site. The PHY circuit that is relocated is referred to as a Remote PHY Device (RPD). The remaining CCAP Core can be located at the hub, moved to the head end, or even virtualized into a server environment and put into a data center. [3] [4]

Remote PHY solves a scaling problem. The SG density of a CCAP is determined by how many RF ports the CCAP has. With Deep Fiber creating 10x the number of optical nodes, there is a need for 10x the number of service groups (SG) which typically means 10x the number of CCAP chassis. Ten times the number of chassis generally will not fit into the same hub site. Remote PHY allows this problem to be solved in several ways. First, now that there are no RF ports, the chassis can just be made to support more SGs so maybe only 2x to 4x the chassis are needed. The other solution is to relocate the CCAP core chassis to the head end where there will be more room.

By moving the DOCSIS PHY to the node from the hub, the DOCSIS QAM and OFDM signals no longer need to traverse the optical path. This can add a four to five dB to the SNR which should be good for one or two orders of modulation (1 to 1.5 bps/Hz). For example, this could increase a 1024-QAM signal (10 bits/symbol) to 2048-QAM (11 bits per symbol).

- DS: 11 bits per Hz / 10 bits per Hz = 1.1x = +10%
- US: 10 bits per Hz / 9 bits per Hz = 1.1x ~= +10%

DS Bandwidth Multiplier: +10%
US Bandwidth Multiplier: +10%

7. Remote PHY – Segmentation

The initial vision of a RPD in a node is an RPD with a port count of 1x1 ports or 1x2 ports. The RPD would interface with the amplifiers and ports on the node. Here's the thing. Most nodes have four bidirectional ports. That means that the plant that is connected to the node is four separate segments. The forward path output of the RPD would be split across the four node ports. In the return path direction, if the RPD had two input ports, then two node ports would be combined and connected to one RPD port.

Ideally, the RPD becomes a single-chip implementation. So why not just build a denser chip with more ports? What not build a 4x4 port RPD where each port of the RPD directly connects to a port on the optical node? This, of course, is segmentation within the node, and is an old trick.

In the previous analysis, we left HFC classic with a 1x1 port configuration. Deep Fiber with remote PHY with segmentation will take it up to 4x4 ports. The bandwidth ratio in both the DS and US directions would be 4x.

DS Bandwidth Multiplier: 4x
US Bandwidth Multiplier: 4x

8. DOCSIS 3.1 & 1.2 GHz

DOCSIS 3.1 will be deployed on both the HFC Classic and the Deep Fiber plant. So will the earlier versions of DOCSIS, for that matter. In the context of this white paper, the role out of DOCSIS 3.1 will occur in the same timeframe as the rollout of Deep Fiber so they are lumped into the same timeframe.

DOCSIS 3.1 replaced the QAM DS, ATDMA US of DOCSIS 3.0 with an OFDM (Orthogonal Frequency Division Multiplexing) DS and an OFDMA (Orthogonal Frequency Division Multiple Access) US. OFDM did not really increase the bandwidth per bit directly, but the new LDPC (Low Density Parity Check) FEC (forward error correction) added about 5 dB equivalent noise immunity which is good for almost two more bits per Hertz which is two orders increase in modulation. As a result, the DS modulation can be effectively increased from 256-QAM to 1024-QAM. The downstream OFDM channel is 192 MHz which is equivalent in RF bandwidth to thirty-two 6 MHz channels (or twenty-four 8 MHz channels).

DOCSIS 3.1 profile management on the downstream and upstream allows different modulations to be used for different groups of cable modems. [1] CMs at the end of a five-amplifier cascade may only work with 1024-QAM in the downstream, but the CMs right after the node or the first amp may work at 4096-QAM. For the sake of our calculations, we can give DOCSIS 3.1 profiles credit for moving the average modulation to say 2048-QAM from 1024-QAM.

DOCSIS 3.1 also increased the downstream upper band edge from 1004 MHz to 1218 MHz. This does require the installation of new optical nodes with the higher frequency output. These higher-frequency bands may only be available on deep fiber systems unless nodes and amps are both upgraded.

For DS bandwidth metrics:

- A 192 MHz, OFDM channel with 4096-QAM, 8K subcarriers, ~20% overhead, is 1.89 Gbps.
- A 192 MHz, OFDM channel with 2048-QAM, 8K subcarriers, ~20% overhead, is 1.73 Gbps.
- A 192 MHz spectrum of thirty-two, 6 MHz channels, 256-QAM, 38 Mbps, is 1.21 Gbps.
- DS Bandwidth multiplier is 1.73/1.21 -1 ~= +40% (for D3.1 FEC and profiles)

So how long will it be until there is full spectrum DOCSIS? Let's think about this. Analog video – something many said would never get displaced – has mostly been turned off. Digital video is still very much on the plant. However, there is a clear shift to Video-over-IP, and there may be some operators in new parts of their plant who will have a complete Video-over-IP with no classic MPEG video-over-QAM within three to five years.

So a bandwidth analysis should assume full spectrum DOCSIS from 108 MHz to 1218 MHz. Operators will retain at least 8 QAM channels and maybe up to 32 QAM channels for DOCSIS 3.1. For this analysis, we will assume predominantly OFDM deployment. The SNR may not be as strong above 1004 MHz as it is below, so lets assume the average modulation above 1004 MHz is one order of modulation less, which would be 2048-QAM. That means the modulation might start at 4096-QAM at 1004 MHz and reduce to 1024-QAM at 1.2 GHz.

We will also assume that the combination of D3.1 LDPC, D3.1 OFDM with Profile, and the ten percent boost from R-PHY get us to 4096-QAM in the DS and 1024-QAM in the upstream.

- (1218 – 1004 MHz) * (1.73 Gbps per 192 MHz for 2048-QAM OFDM) +
  (1004 – 108 MHz) * (1.89 Gbps per 192 MHz for 4096-QAM OFDM) = 10.7 Gbps

The previous bandwidth for DOCSIS 3.0 with 32 channels was 1.21 Gbps. We also have to credit Remote PHY it's ten percent. (Hey, the accountants do this to my budget all the time).

- DS Ratio: 10.7 Gbps / 1.21 Gbps / 1.1 = 8x

DOCSIS 3.0 defined an upstream migration plan. [2] Options included (described as US Max frequency // DS Min frequency)

- Low-Split: 42 MHz // 54 MHz.
- Mid-Split: 85 MHz // 108 MHz
- High-Split: 204 MHz // 258 MHz

DOCSIS 3.0 systems have continued to ship with low-split. DOCSIS 3.1 systems need room to deploy an OFDM return path and the current candidate is a mid-split system with OFDMA from 42 MHz to 85 MHz.

In this scenario, the US calculations play out in a similar manner to the downstream. Below 42 MHz is assumed to stay as DOCSIS 3.0 CMs and earlier. The aggregate bandwidth assigned to below 42 MHz is 100 Mbps. The US FEC can be credited with two orders of modulation increase and we will give profiles credit for one order of modulation increase on average and Remote PHY one order of modulation. So the average modulation effectively increases from 64-QAM to 1024-QAM.

- D3.0: 4 ATDMA channels below 42 MHz = 100 Mbps
- D3.1: (88 MHz – 42 MHz) * (0.78 Gbps per 96 MHz at 1024-QAM) + 100 Mbps = 473 Mbps
- US Ratio for D3.1 and 85 MHz: 473 Mbps / 100 Mbps / 1.1 = 4.3x

As before, I wanted to show a complete DOCSIS 3.1 calculation for later reference, but I also need to show the impact of Remote PHY separately for the model, so the ten percent is divided back out.

DS Bandwidth Multiplier: 8x
US Bandwidth Multiplier: 4.3x

9. FDX DOCSIS

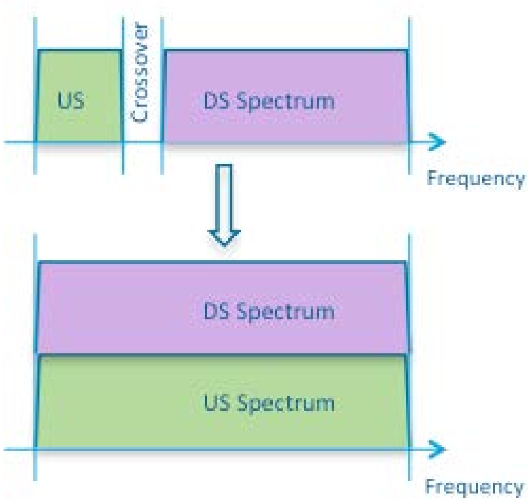

Figure 6 - FDX DOCSIS Spectrum

Full Duplex DOCSIS is an exciting new technology that will forever change the face of the HFC plant. FDX has not been standardized as of the creation of this white paper. A proposal for FDX described from the same author as this paper can be found in [5] and [6].

In today's HFC spectrum, as shown in Figure 6, the HFC plant is run as Frequency Division Duplex (FDD). That means that one block of frequencies is used for the downstream forward path (54 to 1004 GHz) and another block of frequencies is used for the upstream return path (5-42 MHz).

In FDX, some or all of the spectrum is used for both directions. On passive coax, energy can travel simultaneously in opposite directions. Analog telephones have always operated with this principle. When the signal requires amplification, the forward and reverse paths must be isolated. To keep the design manageable, FDX works best on a deep fiber, N+0 plant, where each plant segment connected to each leg of the optical node is passive.

Here is how we propose to make FDX work:

1. We echo cancel at the CMTS PHY.
2. We measure and sort CMs into interference groups (IG) and IGs into transmission groups (TG).
3. We use FDD (and/or TDD) within a TG so that those CMs do not interfere with each other. All broadcast is handled separately.
4. We overlap TGs in frequency and time so that 100 percent of the spectrum and 100 percent of the timeline are used for both DS and US.

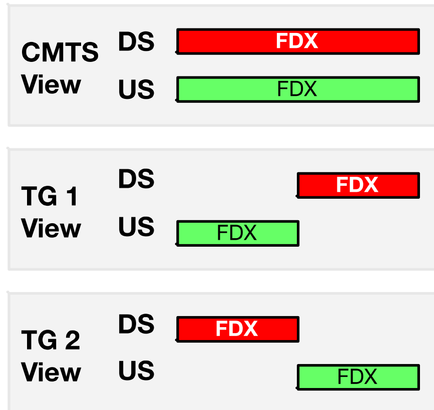

Figure 7 - FDX TGs

The downstream bandwidth multiplier for FDX results from the fact that the downstream does not get diminished when increasing the US bandwidth. For example, on a 204 MHz return system, instead of the downstream spectrum starting at 258 MHz, it could start at 108 MHz or even 54 MHz. In the model in this white paper, the downstream is already starting at 108 MHz. We will assume that below 108 MHz is for DOCSIS 3.0 and DOCSIS 3.1 non-FDX. Thus, for the model, the downstream bandwidth multiplier is 1x. For the other two cases, the increase in bandwidth efficiency is:

- (1218 – 108) / (1218 – 258) – 1 = 16%
- (1218 – 54) / (1218 – 258) – 1 = 21%

The upstream bandwidth multiplier for FDX depends upon how many OFDMA channels can be made to work, which is unknown at this time. Note that the OFDMA channel count is with respect to the CMTS, not the CM. Just to be fair, the calculations assume that the average modulation decreases as the spectrum usage increases. Here are the values from the CCAP perspective:

For a Baseline from D3.0: 100 Mbps

- 204 MHz return, 2 OFDMA, 1024-QAM, 20% OH ➔ 1.5 Gbps, 15x
- 600 MHz return, 6 OFDMA, 512-QAM, 20% OH ➔ 4 Gbps, 40x
- 800 MHz return, 8 OFDMA, 256-QAM, 20% OH ➔ 5 Gbps, 50x

For a Baseline from D3.1: 473 Mbps

- 204 MHz return, 2 OFDMA, 1024-QAM, 20% OH ➔ 1.5 Gbps, ~3x
- 600 MHz return, 6 OFDMA, 512-QAM, 20% OH ➔ 4 Gbps, ~8.4x
- 800 MHz return, 8 OFDMA, 256-QAM, 20% OH ➔ 5 Gbps, ~10.5x

For this model, we will pick the DOCSIS 3.1 600 MHz return as our baseline.

DS Bandwidth Multiplier: 1x
US Bandwidth Multiplier: 8.4x

10. Accumulated Bandwidth Growth for Deep Fiber

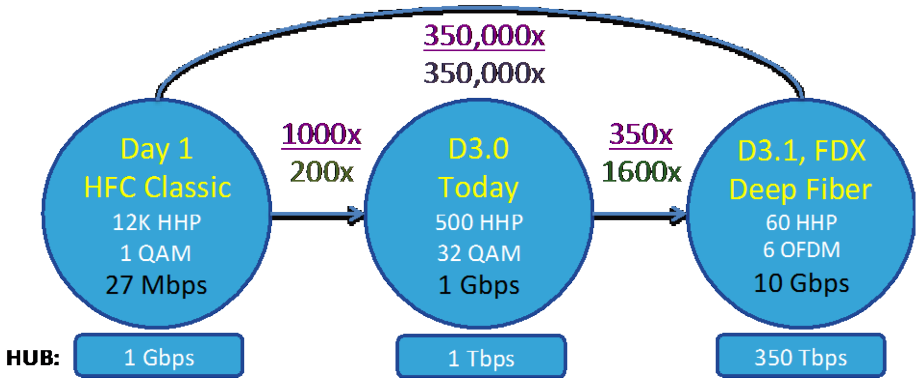

Figure 8 - Deep Fiber Data Capacity

For deep fiber, the number of nodes and DOCSIS Service Groups expanded by 10x. Remote PHY silicon add the possibility of another bonus 4x segmentation. By eliminating the analog optical path, Remote PHY increased throughput by about 10%. DOCSIS 3.1 dramatically increased the DS and US bandwidth. Full Duplex finished off the party by upping the upstream bandwidth by another 8.4x

- DS Ratio: 10 * 1.1 * 4 * 8 * 1 = 354 ~= 350x
- US Ratio: 10 * 1.1 * 4 * 4.3 * 8.4 = 1600x

The increase from Day 1 is:

- DS Ratio: 1000 * 350 = 350,000x
- US Ratio: 200 * 1600x = 320,000x ~= 350,000x

The data capacity of a 400,000 HHP Hub would be:

- DS Capacity: 400,000 HHP per hub / 12.5 HHP per SG * 10.7 Gbps per SG = 350 Tbps
- US Capacity: 400,000 HHP per hub / 12.5 HHP per SG * 4 Gbps per SG = 128 Tbps

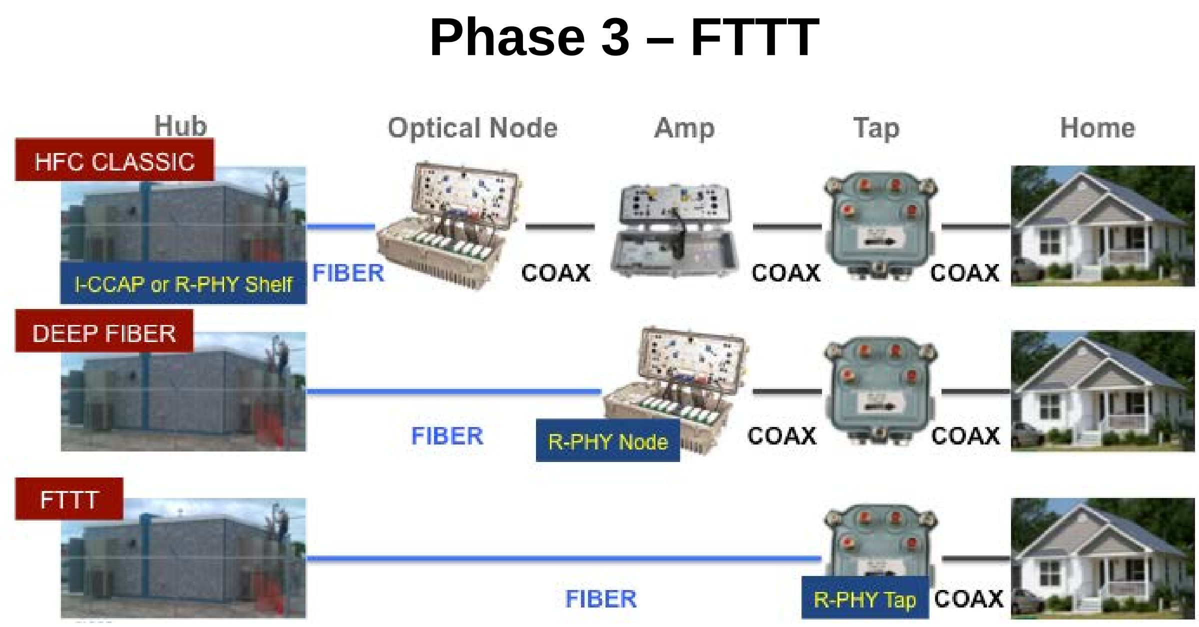

Figure 9 - Fiber to the Tap

11. Fiber to the Tap – DOCSIS to the Door

This next concept is proving to be the most controversial of them all. Perhaps this is true of all good concepts that are just before their time.

In Deep Fiber, the amps are replaced with Optical Nodes. In FTTT, the optical-to-electrical conversion is moved all the way to the tap. The tap is the connectivity point for the drop cable to the home. Typical taps as shown in Figure 10 may have two to eight homes per tap plate.

In this proposed FTTT scenario, the Remote PHY Device from the node would be shrunk down to a single chip implementation and placed into the tap. The design would also have to contain some moderate RF power of about 15 dBmV per tap, enough to get the signal down 50 to 200 feet of coax cable to the home. The design could be reverse-powered from the home or plant-powered, depending on the power policy of the operator.

Figure 10 - Typical Taps

There are several options for a Remote PHY Tap design that differ based upon technology, capacity and cost.

The first is the number of SGs per tap plate. One implementation would be to have a 1x1 (1 DS by 1 US) RPD chip that connects to the splitter and combiners in the tap. However, as silicon densities get denser, it may be possible to do better. 1x2 is a more likely minimum implementation and a full 4x4 for a 4-way tap may soon become possible. With a 4x4 RPD chip, there would be a single 1.2 GHz, 10 Gbps spectrum per household passed. That would be both incredible and technically feasible.

The next is the fiber backhaul technology. The fiber probably originates from an aggregation point located either the original 500 HHP node location or at one of the displaced deep fiber node's locations. The bandwidth of the fiber can match or concentrate the aggregate bandwidth of the tap.

- A FTTT with a 1x2 RPD and FDX would require 10GE
- A FTTT with a 4x4 RPD and FDX would require 10GE, 25GE, or 40GE
- A FTTT with a 8x8 RPD and FDX would require 10GE, 25GE, or 40GE.

The choice for a fiber transport could be either point-to-point or PON. PON has the advantage of less fiber but would not allow the full 10 Gbps per tap. 32 PON legs at 40 Gbps is 1.28 Tbps; that would be very high over subscription of a PON.

Point-to-Point fiber could run at a lower speed and use cheaper optics per fiber, although it would be more optics overall. Point-to-point would match the bandwidth of the tap more efficiently. The choices for point-to-point speeds would be 10 Gbps, 25 Gbps, 40 Gbps, or even 100 Gbps. 25 Gbps is a potential sweet spot as it is an emerging standard that is still single wavelength and the distance is short. There is a very interesting and economical method for installing point-to-point fiber described in [12]. Note that this method requires copper for powering to be included or reverse powering would be required.

A common question on FTTT is why not just run fiber right to the home? Indeed, you could. However, there are several reasons why it may be easier to just do FTTT instead of FTTH

1. It is worth considering the cost of ripping up everyone's front lawn and driveway (for underground service delivery. If there is a conduit there which would allow fiber to be blown in, great. If not, it may be cheaper to just use the FTTT as a fiber to Coax adaptor.
2. Another consideration is the doorbell. The plant rebuild with FTTT as the edge of the rebuild can be done without disturbing the customer. 50 HHP could be upgraded in one day. However, contacting 50 customers, arranging service, doing driveway and lawn digs could all take months.
3. The FTTT uses an RPD that supports not only DOCSIS but also legacy video. Thus, FTTT is compatible with all the equipment in the customer's home. Running fiber to the home usually implies an all IP service which may require upgrading of all the customer's equipment. This is more time and money.

For FTTT work, we will need advances in RPD silicon technology and in Ethernet-Fiber aggregation technology. Both of these seem very feasible.

The deep fiber plant averaged 50 HHP per node in the examples in this paper. The FTTT could be 4 HHP for 1x1/1x2 or 1 HHP for 4x4. Since we already allowed for four-way segmentation of the deep fiber node, with an average of 12.5 HHP per HFC segment, then the bandwidth multiplier drops to 12.5x.

If it is the same or less cost in terms of dollars, time and effort to run fiber to the home, then fiber becomes the natural choice. Either way, the multiplier is the same.

DS Bandwidth Multiplier: 12.5x
US Bandwidth Multiplier: 12.5x

12. Extended Spectrum DOCSIS (ES)

At a basic level, the ability of the HFC plant to operate at higher frequencies has generally been limited by two factors:

1. RF power levels, RF attenuation, the noise floor, signal roll off of the plant components as the frequency increases, all of which result in a lower SNR as the frequency increases;
2. ASIC technologies associated with QAM generation and reception

The ASIC technologies in the CCAP PHY are further defined by two variables – the speed of the logic and the bandwidth of the analog-to-digital converters (ADC) and digital-to-analog converters (DAC). ADC and DAC now comfortably operate at the 1 GHz level with an oversampling clock for better fidelity. Roadmaps from the respective suppliers show that these components could go to 5 GHz, 10 GHz, or even 20 GHz or higher over the next few years.

But what about that RF? As the operating frequency increases, the attenuation of the coax increases. If you assume a constant noise floor and a constant transmit power level (or even with tilt), the SNR will decrease as the frequency increases. It turns out there is a neat trick to be had. With DOCSIS 3.1, we can measure the performance at these higher frequencies and use successively lower modulations at higher frequencies.

Further, if this technology is applied in an FTTT scenario, the attenuation is the result of just the 50 foot to 150 foot coax cable drop into the home. More research will have to be done to see how well extended spectrum DOCSIS fits with a deep fiber installation.

There has been some excellent early research done to date [13]. Suppose you had 6 dB to play with in your output amplifier. If that 6 dB resulted in 6 dB more SNR, then you could increase your order of modulation by a factor of 2. For example, 1024-QAM could be increased to 4096-QAM for a net gain of 20% more throughput. However, the same 6 dB gain could also be used to quadruple the output spectrum. For example, if you had 1 GHz of spectrum, you could now transmit 4 GHz of spectrum, which is a 400% increase in spectrum.

Further research suggests that throughputs of up to 50 to 200 Gbps would be achieved [14]. For this white paper, a goal of 100 Gbps will be chosen. 25 Gbps is another interesting operating speed as it matches the new emerging single lambda Ethernet-over-fiber standard [21] and EPON [22].

If a particular design took a spectrum of 10 GHz to send 100 Gbps, that would average out to about 10 bits per Hertz. Generally, the spectrum might start with 12 bits per Hertz with 4096-QAM and end with 8 bits per Hertz with 64-QAM (or even down to QPSK). It will be a race to see which runs out first – the bandwidth of the DAC/ADC or the SNR.

For these RF bandwidths it may make sense to have larger OFDM channels above 1 GHz – maybe 1 GHz per OFDM channel. Better or different FECs could be used as well. Maybe even a coded modulation that can operate in a negative noise floor would be useful.

- DS: Assuming 100 Gbps for ES and 10.7 Gbps from before, the ratio is ~10x.
- US: Assuming 100 Gbps for ES and 4 Gbps from before, the US ratio is ~25x.

DS Bandwidth Multiplier: 10x
US Bandwidth Multiplier: 25x

13. Accumulated Bandwidth Growth for FTTT

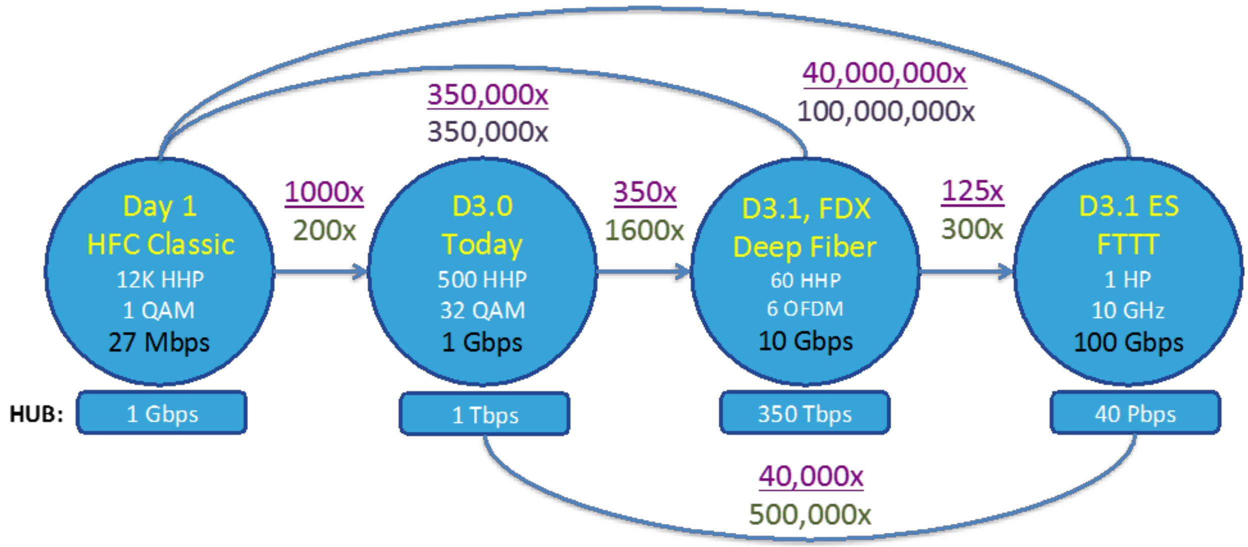

Figure 11 - FTTT Data Capacity

In the possible third phase of the HFC plant upgrade, the RPD that was in the node is shrunk to a single chip with low power RF amplification and is located in the tap. This would be Fiber-to-the-tap and DOCSIS-to-the-Door. This allows the plant to drive all legacy services and should not require upgrade of the drop cable.

The technology evolution in DACs and ADCs allow silicon to drive RF signals above 1 GHz. Depending upon the silicon gymnastics, data rates in the downstream could go to 100 Gbps or higher. This might also be possible from the node, but not at the same high rate.

- DS Ratio: 12.5 * 10 ~= 125x
- US Ratio: 12.5 * 25 ~= 300x

The cumulative ratio from today is:

- DS Ratio: 350 * 125 ~= 40,000x
- US Ratio: 1600 * 300 ~= 500,000x

The cumulative ratio from Day 1 is

- DS Ratio from Day 1: 1000 * 350 * 125 ~= 40,000,000x
- US Ratio from Day 1: 200 * 1600 * 300 ~= 100,000,000x

The base bandwidth of a 400,000 HHP hub would be:

- DS Capacity: 400,000 HHP * 100 Gbps per HHP = 40 Pbps

- US Capacity: 400,000 HHP * 100 Gbps per HHP = 40 Pbps.

Infinite DOCSIS

Table 1 - Summary of Bandwidths

Evolution of DOCSIS Bandwdith

Phase	Technology	DS Gbps	US Gbps	DS HHP	US HHP	DS Ratio	US Ratio	DS Phase	US Phase
HFC	DOCSIS 1.0 Baseline	0.027	0.0022	12000	2000	1	1		
Classic	HFC Rebuild	0.027	0.0022	500	500	24	4		
	D1.1 to D3.0	1.2	0.1	500	500	45	45	1081	182
Deep	Node + 0	1.2	0.1	50	50	10	10		
Fiber	Remote PHY - SNR	1.3	0.11	50	50	1	1		
	Remote PHY - Seg.	1.3	0.11	12.5	12.5	4	4		
	D3.1, 108 to 1.2 GHz	10.7	0.47	12.5	12.5	8	4.3		
	FDX	10.7	4	12.5	12.5	1	8.4	354	1600
FTTT	FTTT	10.7	4	1	1	12.5	12.5		
	ES DOCSIS	100	100	1	1	9.3	25.0	116	313
								44,444,444	90,909,091

Table 1 has a summary of the three phases and the technology that was included in each phase. These are the raw numbers before rounding.

Infinite Opportunity

The calculations so far in this white paper are really for the existing installed base of residential cable modem subscribers. The installed base of cable subscribers represents maybe sixty percent of the households passed in most developed countries. That is impressive. But there are opportunities for so much more.

There are all the people on this planet who are not connected to broadband yet. There are thirty million Americans and four billion people worldwide who do not have broadband. If you consider access to broadband and the Internet as basic a need as electricity, or running water, there is work to be done. There has been some excellent thought put into this at the Broadband Center of Excellence at the University of New Hampshire. [15] [16]

Then there is the next horizon of connectivity – IoT – The Internet of Things. Things refer to machines, sensors and actuators. It can be the temperature sensor in your home or sensors measuring traffic analytics on your local street. There are over four billion devices waiting to be interconnected and some large number of those could be over a cable network. [17] [18]

The opportunity is infinite.

Conclusion

In 20 years, together we have transformed the HFC plant into broadband network and increased its data capacity by a factor of 1000x, a feat that matches the growth of Ethernet. Yet, when looking at the future technology roadmap, there is 40,000x more to go for a total journey of 40,000,000x from where we started!

How long in time is this? Using the Ethernet rule of thumb of 10x every 7 years, 350x for Deep Fiber to play out would be about 20 years and 40,000x with FTTT would be about 30 years.

This paper suggests even though we are 20 years into the journey of DOCSIS that we easily have 20 more years to go. HFC has staying power for as long as it is needed.

Abbreviations

ADC	Analog to Digital Converter
ATDMA	Advanced Time Division Multiple Access
BDR	Broadband Digital Return
bps	bits per second
cBR	Converged Broadband Router
CCAP	Converged Cable Access Platform
CM	Cable Modem
CMTS	Cable Modem Termination System
DAC	Digital to Analog Converter
DOCSIS	Data Over Cable System Interface Specification
DS	Downstream
DSG	DOCSIS Set-top Gateway
DTTD	DOCSIS To The Door
EQAM	Edge QAM
ES DOCSIS	Extended Spectrum DOCSIS
FEC	Forward Error Correction
FTTT	Fiber To The Tap
HFC	Hybrid Fiber Coax
HHP	Households Passed
IoT	Internet of Things
IP	Internet Protocol
LDPC	Low Density Parity Check
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OOB	Our of Band
PON	Passive Optical Network
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
R-PHY	Remote PHY
RF	Radio Frequency
RPD	Remote PHY Device
SCDMA	Synchronous Code Division Multiple Access
SCTE	Society of Cable and Television Engineers
SDD	Space Division Duplex
SDV	Switched Digital Video
SG	Service Group
SNR	Signal to Noise Ratio
STB	Set-top Box
TDD	Time Division Duplex
uBR	Universal Broadband Router
US	Upstream
VOD	Video on Demand

Bibliography & References

Related Papers by the Same Author

[1] *Managing DOCSIS 3.1 Profiles – Downstream and Upstream*, John T. Chapman, SCTE Cable-Tec Expos, September, 2014

[2] Taking the DOCSIS Upstream to a Gigabit per Second, John T. Chapman, NCTA Spring Technical Forum, May 12, 2010, http://www.nctatechnicalpapers.com/Paper/2010/2010-taking-the-docsis-upstream-to-a-gigabit-per-second

[3] *Remote PHY for Converged DOCSIS, Video and OOB*, John T. Chapman, NCTA Spring Technical Forum, June 10, 2014, http://www.nctatechnicalpapers.com/Paper/2014/2014-remote-phy-for-converged-docsis-video-and-oob

[4] *DOCSIS Remote PHY*, John T. Chapman, SCTE Cable-Tec Expo, October 21, 2013

[5] *Full Duplex DOCSIS*, John T. Chapman & Hang Jin, INTX Spring Technical Forum, May 16, 2016, http://www.nctatechnicalpapers.com/Paper/2016/11-Jin

[6] Interference-Aware Spectrum Resource Scheduling for FDX DOCSIS, John T. Chapman, Hang Jin, Tong Il, SCTE Cable-Tec Expo, Sept 26, 2016

Related References by Other Authors

[7] *Planet Broadband*, History of Cable Modems, pages 34 to 54, Rouzbeh Yassini, Cisco Press, 2004

[8] *Choosing an Optimal Switch Complex for Remote PHY Deployments*, Fernando Villarruel, SCTE Cable-Tec Expo, Sept 26, 2016

[9] *The Fiber Frontier*, Howald, Dr. Robert, INTX Show, Boston, MA, May 16-18, 2016.

[10] *Fueling the Coaxial Last Mile*, Howald, Dr. Robert, SCTE Conference on Emerging Technologies, Washington, DC, April 3, 2009.

[11] *Growth Architectures: Built to Last, Built to Launch*, Cable Show Spring Technical Forum, Howald, Dr. Robert, Los Angeles, CA, Apr 29-May 1, 2014.

[12] *Tomorrowland: Customers, Services, Networks*, Howald, Dr. Robert L and Robert Thompson, SCTE Cable-Tec Expo, Denver, CO, September 22-25, 2014.Deep Fiber Solutions, http://deepfibersolutions.com

[13] *Shannon's Limits Applied To Cable Networks Above 1 GHz*, Tom Williams, Greg White, Alberto Campos, CableLabs, October, 2014, http://www.cablelabs.com/wp-content/uploads/2016/02/Shannons_Limits_Applied_To_Cable_Networks_Above_1GHZ-October2014.pdf

[14] *Using DOCSIS to Meet the Larger Bandwidth Demand of the 2020 Decade and Beyond*, Tom Cloonan, Ayham Al-Banna, Frank O'Keeffe, INTX Spring Technical Forum, May 16, 2016,

[15] Broadband Center of Excellence, University of New Hampshire, http://www.unh.edu/broadband/

[16] *Broadband 2020: Achieving Ubiquity*, Broadband Center of Excellence, Dr. Rouzbeh Yassini, Nov 2013, http://www.unh.edu/broadband/sites/www.unh.edu.broadband/files/media/pdf-general/bcoe_broadband_2020_final.pdf

[17] *Broadband 2030: The Networked Future*, Broadband Center of Excellence, Dr. Rouzbeh Yassini, December 2013, http://www.unh.edu/broadband/sites/www.unh.edu.broadband/files/media/pdf-general/bcoe_broadband_2030_final.pdf

[18] *Impact of IoT (Internet of Things) on Cable MSOs*, Amit Singh, SCTE Cable-Tec Expo, Sept 26, 2016

Related Industry Specifications

[19] *SCTE 55-1 2009, Digital Broadband Delivery System: Out of Band Transport Part 1: Mode A*, SCTE, http://www.scte.org/documents/pdf/standards/SCTE%2055-1%202009.pdf

[20] *SCTE 55-2 2008, Digital Broadband Delivery System: Out of Band Transport Part 2: Mode B*, SCTE, http://www.scte.org/documents/pdf/standards/ANSI_SCTE%2055-2%202008.pdf

[21] *25 Gb/s Ethernet Over Single Mode Fiber Call for Interest Consensus*, D. Lewis, K. Tamura and P. Jones, in IEEE Plenary Meeting, Dallas, Texas, 2015.

[22] *IEEE 802.3 Industry Connections Feasibility Assessment for the Next Generation of EPON*, IEEE 802.3 WG, March 13, 2015, http://www.ieee802.org/3/ad_hoc/ngepon/ng_epon_report.pdf

