Covid-19 Learnings

All Roads Lead To DOCSIS® 4.0 Technology

A Technical Paper prepared for SCTE•ISBE by

Jeff Finkelstein
Chief Access Scientist
Cox Communications
6305-B Peachtree Dunwoody Rd, Atlanta, GA 30328
+1 404.269.5955
Jeff.Finkelstein@cox.com

Tom Cloonan
CTO – Network Solutions
CommScope
2400 Ogden Ave, Suite 180, Lisle, IL 60532
+1 630.281.3050
Tom.Cloonan@commscope.com

Doug Jones
Principal Architect
CableLabs®
858 Coal Creek Circle
+1 303.661.9100
D.Jones@cablelabs.com

Table of Contents

Title **Page Number**

List of Figures

Title **Page Number**

List of Tables

Title **Page Number**

1. Introduction

My most used quote for 2020 so far can be summed up in one of my Bubbie's (Yiddish for grandmother) favorite sayings, which is as follows: *Der Mentsh tracht un Gott lacht.* Which is roughly translated as "Man plans and God laughs".

Despite our plan of intents, plan of records, short-range plans, and long-range plans, the World was caught by surprise with the current events impacting us. We have seen our carefully laid plans cast aside as we have all scrambled to meet user demands resulting from mass isolation to curb the spread of an unseen enemy. For many of us we have experienced 18-24 months of utilization growth in a 3-month window from March to June 2020. Thankfully we are fortunate to have deployed spare capacity and use a data transmission protocol that has handled the new demands very well.

With ubiquitous stay-at-home orders being issued throughout the world in the March and April timeframe, a new era and social experiment had begun. It has created conditions that had never before been witnessed on the planet in the modern era; it would stress many areas of society, including medical resources, human relations, business operations, educational institutions, entertainment and sports, politics and elections, food distribution, travel, supply chains, and much more.

There has been and will be much written about causes and effects of the current World condition. In this paper we will examine learnings we have gathered so far during this unparalleled journey focusing on the cable network and DOCSIS technology in particular.

2. Background

A key segment of society that was undoubtedly surprised and, in some cases, strained by these rapid changes was the high-speed data broadband infrastructure that makes up an important portion of the Internet. With more people staying at home and working at home than ever before, the COVID-19 pandemic introduced rapid and profound changes to the high-speed data infrastructure.

In the DOCSIS networks operated by MSOs, these changes were felt almost instantaneously in both the upstream and downstream data paths within HFC plants. It is accurate to state that no traffic engineers within the Cable Industry (or any Industry for that matter) had ever anticipated the potential need for stressful traffic engineering models simulating bandwidth consumptions that might result from the arrival of a worldwide epidemic that would drive a majority of the subscriber base into their homes for 24 hours a day and for many months at a time.

The surprising and unexpected arrival of these incredible conditions created an intense traffic load, and this load could have easily overloaded the DOCSIS network and rendered the infrastructure (and the Internet) useless at a time when "work-at-home" and the ability to connect to others on-line became a necessity for society.

However, the DOCSIS infrastructure and the Internet held up quite well to these unexpected stresses. Granted, there were some growing pains and problematic issues that required emergency actions for correction, but many of these issues were rapidly resolved with CMTS/CM configuration changes and/or channel augmentations. The Cable Industry was able to successfully respond to this sudden onslaught of traffic. But the issues that were encountered by this sudden bandwidth surge were likely exposing an Achilles Heel that will need to be addressed in the near future.

3. Traffic Engineering Model

It may be instructive to explore some typical traffic engineering models that may have been being used by MSOs in February 2020 prior to the arrival of the COVID-19 pandemic. Within these models, the authors will make use of a "QoE-based Traffic Engineering Formula" defined in [1], which is given by:

$$\text{Required Bandwidth Capacity} = N_{sub}*T_{avg} + K*T_{max} \qquad (1)$$

where:

- N_{sub} is the number of subscribers in the Service Group
- T_{avg} is the Average Bandwidth Consumption of a single subscriber (during the busy hour)
- T_{max} is the maximum Bandwidth offered in the Service Level Agreements
- K is the QoE coefficient, which is a value typically between 0.8 and 1.5 (larger values yield better Quality of Experience); K=1.2 is the value used in this paper.

Let us consider a "typical" HFC network in February of 2020 that might have been architected for a N_{sub}=250-subscriber Service Group with the following assumptions:

- Downstream T_{max} = 1000 Mbps
- Downstream T_{avg} = 2.5 Mbps
- Downstream T_{avg} CAGR of 26%
- Upstream T_{max} = 30 Mbps
- Upstream T_{avg} = 0.175 Mbps
- Upstream T_{avg} CAGR of 26%

Using these assumptions, the following Traffic Engineering rules are observed:

- "Typical" High-Speed Data Downstream Traffic Engineering in February of 2020
  - 32 x 6 MHz 256QAM SC-QAM Channels @ 36 Mbps per channel
    - 32*(36 Mbps) = 1152 Mbps Capacity
  - 1 x 192 MHz 1024QAM OFDM Channel @ usable spectral efficiency of 10 bps/Hz
    - (192 MHz)*(10 bps/Hz) = 1920 Mbps Capacity
  - Total Downstream Bandwidth Capacity

    - 1152 Mbps + 1920 Mbps = 3072 Mbps
  - Busy-hour Downstream Average Bandwidth Consumption per Subscriber = 2.5 Mbps
  - Number of Subscribers in a Typical Service Group = 250 Subscribers
  - Average Busy-hour Downstream Bandwidth Consumption (T_{avg}) in a Typical Service Group
    - 250*(2.5 Mbps) = 625 Mbps
  - "Headroom" Downstream Bandwidth (to support traffic bursts) in a Typical Service Group
    - 3072 Mbps – 625 Mbps = 2447 Mbps
  - Maximum Supportable Downstream SLA Throughput (T_{max}) calculated using the "QoE-based Traffic Engineering formula with a K of 1.2" = Headroom/K = 2447 Mbps/1.2 = 2040 Mbps
  - Maximum Downstream Life-span of existing HFC Plant (without changes) using the "QoE-based Traffic Engineering formula with a K of 1.2 and Downstream T_{avg} CAGR of 26%" and T_{max} of 1000 Mbps"
    - log[(3072 Mbps-1.2*1000 Mbps)/625 Mbps]/log[1.26] = 4.75 years
- "Typical" High-Speed Data Upstream Traffic Engineering in February of 2020
  - 3 x 6.4 MHz 64QAM ATDMA Channels @ 25 Mbps per channel
    - 3*(25 Mbps) = 75 Mbps Capacity
  - 1 x 3.2 MHz 64QAM ATDMA Channels @ 12.5 Mbps per channel
  - 1 x 9.6 MHz OFDMA Channels @ usable spectral efficiency of 8 bps/Hz
    - (9.6 MHz)*(8 bps/Hz) = 76.8 Mbps Capacity
  - Total Upstream Bandwidth Capacity
    - 75 Mbps + 12.5 Mbps + 76.8 Mbps = 164.3 Mbps
  - Busy-hour Upstream Average Bandwidth Consumption per Subscriber = 0.175 Mbps
  - Number of Subscribers in a Typical Service Group = 250 Subscribers
  - Average Busy-hour Upstream Bandwidth Consumption (T_{avg}) in a Typical Service Group
    - 250*(0.175 Mbps) = 43.75 Mbps
  - "Headroom" Upstream Bandwidth (to support traffic bursts) in a Typical Service Group

        - 164.3 Mbps – 43.75 Mbps = 120.55 Mbps

    - Maximum Supportable Upstream SLA Throughput (T_{max}) calculated using the "QoE-based Traffic Engineering formula with a K of 1.2"

        - Headroom/K = 120.55 Mbps/1.2 = 100 Mbps

    - Maximum Upstream Life-span of existing HFC Plant (without changes) using the "QoE-based Traffic Engineering formula with a K of 1.2 and Upstream T_{avg} CAGR of 26%" and T_{max} of 30 Mbps"

        - log[(164.3 Mbps-1.2*30 Mbps)/43.75Mbps]/ log[1.26] = 4.6 years

Note: The illustrative numbers above do not represent any particular MSO. Different MSOs will have different Traffic Engineering numbers and different Bandwidth Capacity numbers than those shown above.

As can be seen in the example scenarios above, this "typical" MSO in February would have had enough "headroom" in their Downstream Bandwidth Capacity to permit them to operate for another 4.75 years prior to having to consider any type of plant modifications to accommodate the expected Downstream T_{avg} Bandwidth growth rate (resulting from a predicted 26% CAGR that might have existed in February). In addition, this "typical" MSO in February would also have had enough headroom in their Upstream Bandwidth Capacity to permit them to operate for another 4.5 years prior to having to consider any plant modifications to accommodate the expected Upstream T_{avg} Bandwidth growth rate (resulting from a predicted 26% CAGR that might have existed in February). These lifespans are shown by the Bandwidth Requirements curves in Figure 1 and Figure 2 which are based on the QoE-based Traffic Engineering formula of Eq. (1) above.

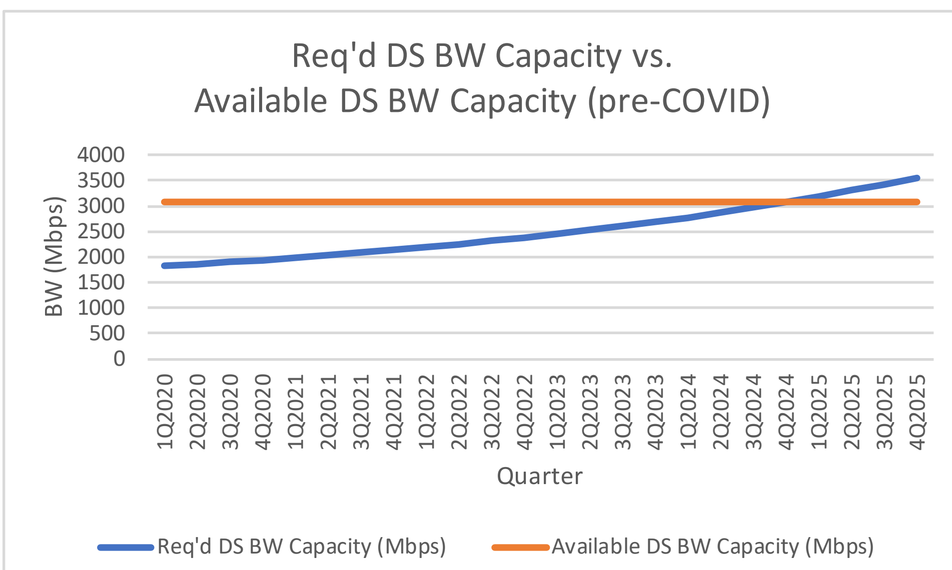

Figure 1 - Required Downstream Bandwidth Capacity vs. Time for "Typical MSO" (pre-COVID-19)

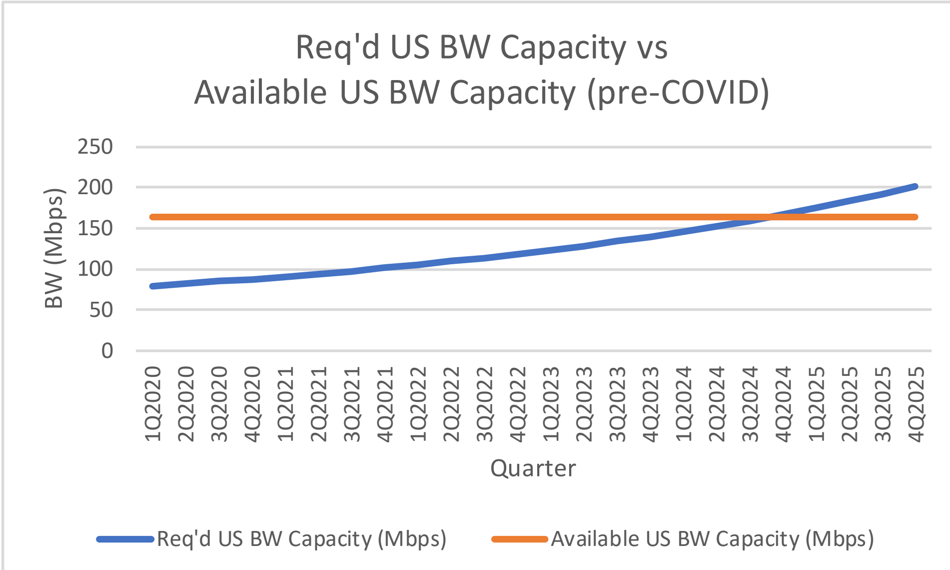

Figure 2 - Required Upstream Bandwidth Capacity vs. Time for “Typical MSO” (pre-COVID-19)

Even without COVID-19, this “typical” MSO would have likely “run out of gas” in their Upstream during the fourth quarter of 2024, and it would have forced the subscribers to live with sub-standard QoE for a while or it would have forced the MSO to utilize one of several options to modify their plant to extend the capacity and life-span of their DOCSIS Upstream services. Many of those possible options for expanding the Available Bandwidth Capacity will be outlined in sections below.

Now let us consider the profound bandwidth usage changes that occurred in the mid-to-late March timeframe in most MSOs and let us explore their impact on the curves and DOCSIS lifespans of Figure 1 and Figure 2.

The bandwidth activities of post-COVID-19 “stay-at-home” subscribers are very different from the activities of subscribers prior to the arrival of COVID-19; in both the upstream and downstream direction, and during the day and at night. In a matter of a few days while “stay-at-home” was becoming the norm, the bandwidth demands increased more rapidly than ever seen before.

Reported Downstream Bandwidth consumption (T_{avg}) during the evening busy-hour timeframe increased by 12-25% at different MSOs. Upstream Bandwidth consumption (T_{avg}) during the evening busy-hour timeframe increased by 20-50% at different MSOs. Most of this night-time bandwidth growth was driven by a combination of more video streaming, video-conference work meetings, social networking traffic, and gaming traffic (both playing and viewing). In the Upstream, it also included an increase in TCP ACKs associated with the Downstream packets.

Reported Downstream Bandwidth consumption (T_{avg}) during the mid-day timeframe increased by 26-86% at different MSOs and reported Upstream Bandwidth consumption (T_{avg}) during the mid-day timeframe increased by 30-150% at different MSOs. Most of this day-time bandwidth growth was driven by a combination of video-conference work meetings, videoconferencing for remote education, social networking traffic, and gaming traffic (both playing and viewing). In the Upstream, it also included an increase in TCP ACKs associated with the Downstream packets.

Examples changes with US operators from the NCTA web page are shown in Figure 3 and Figure 4.

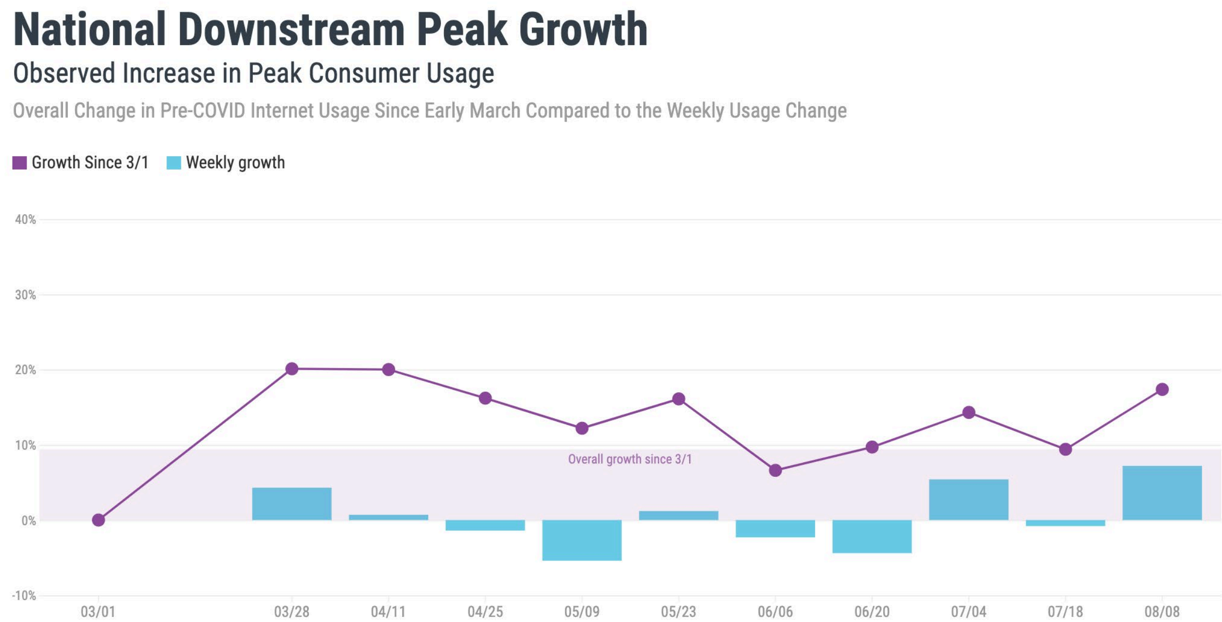

Figure 3 – Example Downstream Bandwidth Changes as "Stay-At-Home" was Rolled Out

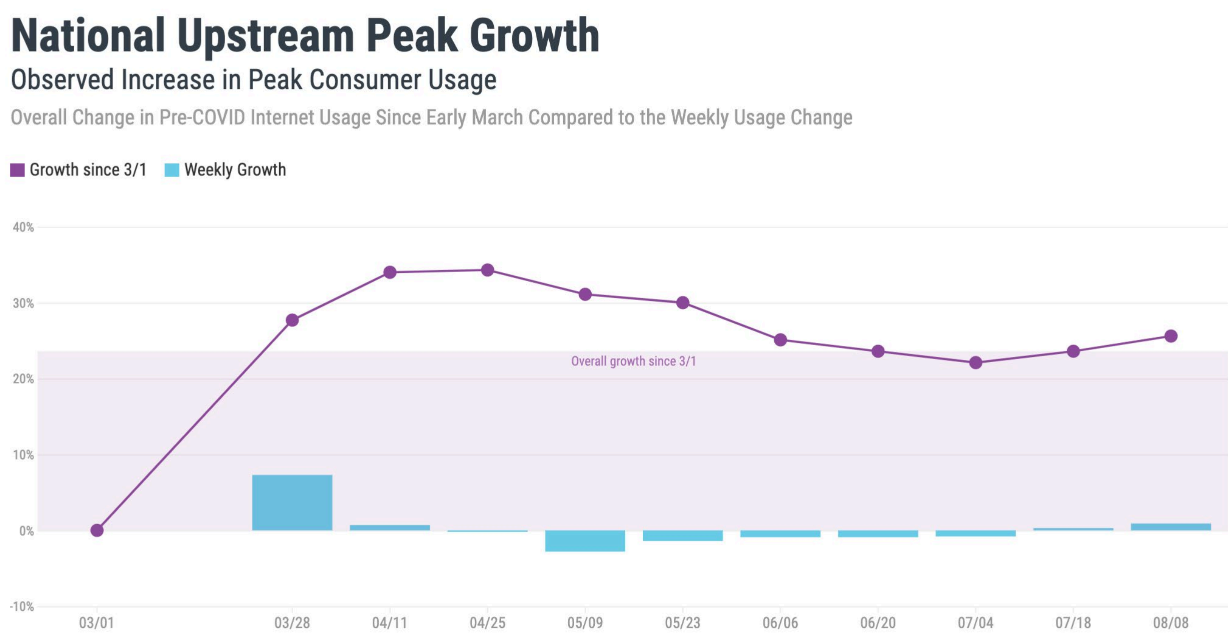

Figure 4 – Example Upstream Bandwidth Changes as "Stay-At-Home" was Rolled Out

In the figures above, the busy-hour bandwidth (at night) still exceeds the mid-day bandwidth, so the busy-hour bandwidth characteristics will still stress the DOCSIS system and define the ultimate Bandwidth Capacity Requirements (as they did in the past prior to COVID-19).

For our "typical" MSO scenario (post-COVID-19), let us assume that they experienced the following T_{avg} BW growth spurts on their networks when "stay-at-home" rules were initiated:

- Downstream T_{avg} Bandwidth step function increase in 2Q2020 = 25%
- Upstream T_{avg} Bandwidth step function increase in 2Q2020 = 50%

It is assumed (and hoped) that there will come a time in different localities when "stay-at-home" orders will begin to be relaxed. At that point in time, it is expected that some workers will begin to return to work at the office. However, the success of the "work-at-home" model during 2020 may push many companies to consider allowing more of their employees to continue working at home even after the "stay-at-home" orders are relaxed. We will create models for our "typical" MSO which assume that 25% of the "stay-at-home" workers will return to the office in 3Q'2020 and another 25% of the "stay-at-home" workers will return to the office in 1Q'2021. Note: These percentages may be accomplished by rotating different employees into the office at different times to reduce the density of employees in the office and reduce the likelihood of COVID-19 transmissions).

After the two phases of employees returning to work, we are assuming that 50% of the "stay-at-home" workers will continue to work at home moving into the future. As a result, it will leave the Bandwidth requirements higher in the long-term; even after COVID-19 has returned the world back to the "new normal." These "new normal" Bandwidth requirements will thus be higher than they would have been had COVID-19 never existed.

The resultant modified Bandwidth Requirements curves (post-COVID-19) are shown in Figure 5 and Figure 6. Within these figures, we have assumed that the network conditions have not changed (other than the step functions resulting from COVID-19).

We are still assuming an N_{sub}=250-subscriber Service Group with the following assumptions:

- Downstream T_{max} = 1000 Mbps
- Downstream T_{avg} = 2.5 Mbps
- Downstream T_{avg} CAGR of 26%
- Upstream T_{max} = 30 Mbps
- Upstream T_{avg} = 0.175 Mbps
- Upstream T_{avg} CAGR of 26%

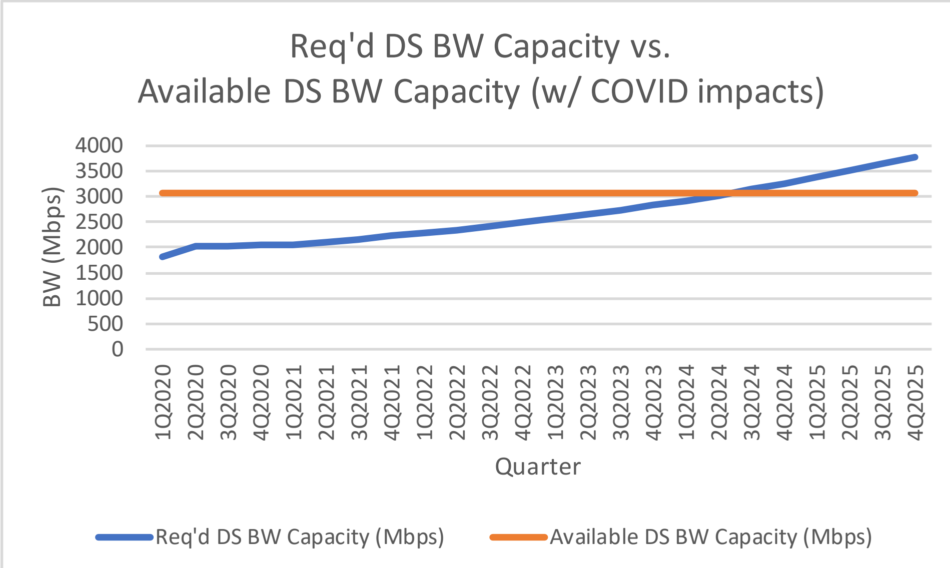

Figure 5 – Required Downstream Bandwidth Capacity vs. Time for "Typical MSO" (post-COVID-19)

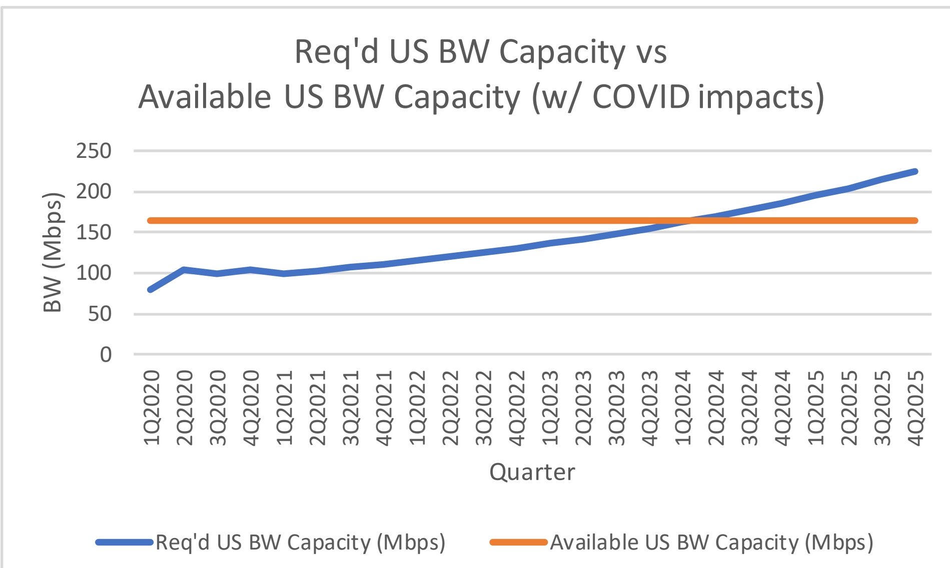

Figure 6 – Required Upstream Bandwidth Capacity vs. Time for "Typical MSO" (post-COVID-19)

Comparing both Figure 1 to Figure 5 and Figure 2 to Figure 6, it is clear that COVID-19 may play a large role in DOCSIS network evolution going forward. It may force MSOs to make network transitions sooner than they had originally planned - even if the Downstream T_{avg} CAGRs and Upstream T_{avg} CAGRs do not increase. The large bandwidth "step function" up resulting from "stay-at-home" actions and the smaller bandwidth "step functions" down resulting from limited "return-to-work" actions leads to these transitions.

It can be seen in Figure 5 that the impact of the COVID-19 step functions would force Downstream network modifications for this "typical" MSO to occur in 2Q2024 instead of 4Q2024. And it can be seen in Figure 6 that the impact of the COVID-19 step functions would force Upstream networks modification for this "typical" MSO to occur in 2Q2024 instead of 4Q2024

This "typical" MSO may not represent the situations at all MSOs. Many MSOs have smaller Service Groups with less than 250 subscribers. And many MSOs also have allotted more Bandwidth Capacity to DOCSIS networks. For example, European MSOs typically have 65 MHz of spectrum dedicated to the Upstream, which gives them much more Upstream Bandwidth Capacity and a longer lifespan on their Upstream. And some MSOs throughout the world have already begun to transition to 85 MHz Mid-Splits. As a result of this additional "headroom" (in the form of extra Bandwidth Capacity), many of these MSOs were able to easily absorb the bandwidth surge that occurred during the "stay-at-home" orders, and they therefore saw little or no problems on their Upstream DOCSIS systems when COVID-19 hit.

4. Early Learnings

DOCSIS technology has handled the dramatic increase in usage very well. Both work-at-home and schooling-at-home created a large step-function in demand where operators have seen 18 months of growth in the first 3 months of isolation. In fact, with the effort to flatten the curve everything became focused in the home including work, school, entertainment, gaming, and new areas including exercise, tele-health, remote-library (book) access, video calls, etc. Just about everything migrated to the home broadband connection.

Why did DOCSIS broadband hold up so well? Starting from the ground up, the coaxial cable used for DOCSIS broadband is a superior medium from which more capacity keeps being mined. Coaxial cable supports much higher speeds than the twisted pairs used for telephone DSL service and even early fiber optic point-to-multipoint protocols. Starting with the DOCSIS 3.1 specifications in 2016, the coaxial cable supported higher speeds than a fiber optic network running GPON technology (gigabit passive optical network). The recent DOCSIS 4.0 specifications position cable-based broadband to rival 10 gigabit PON technologies using the existing coaxial cables in place today. This bandwidth can be realized in that at one point the coaxial cable carried hundreds of cable TV channels, which over the past decade have been migrated to broadband and entertainment migrating to IPTV.

Beyond the cable, DOCSIS technology has been optimized for orderly traffic flow. It has evolved to become a point-to-multipoint network that supports large amounts of capacity; and the network efficiently schedules the use of that capacity among users to meet service demand and provide quality of experience. The work first started in 1996 with collaboration among suppliers and operators to unify cable broadband technologies. Back then there were over a dozen proprietary systems which created a fragmented market and more importantly prohibited the retail availability of cable modems. The original goal was to unify around a single specification that brought together best-of-breed technologies. Without going into details, though very interesting, the effort was successful.

A huge benefit to unifying around a single set of specifications was getting the supplier community to focus their efforts on making DOCSIS technology the best-in-class service it has become today. The technical details include the physical layer (PHY), the media access control (MAC) layer, the security layer (SEC), operating system support (OSSI), and more. Over the next 20 years the innovations continued including advancements in silicon for better digital signal processing allowing even higher speeds and larger capacity to be realized.

The result is coupling an outstanding medium, i.e. coaxial cable, and very focused technology development to create the DOCSIS cable broadband as we know it today, with gigabit services possible anywhere there is a cable system. The DOCSIS 4.0 specifications support multigigabit symmetric service which will be the service offerings of this decade as that technology becomes available.

Both capacity and usage are instrumented in the DOCSIS network. There is a deep knowledge of how the network is performing both from a capacity and performance perspective on a day-to-day basis. The goal is to stay ahead of growth and the DOCSIS network has multiple levers to pull to increase capacity. Operators are always increasing capacity by one of two methods: adding more spectrum or segmenting the network so available spectrum is applied to fewer users.

The focus of DOCSIS 4.0 technology is increasing upstream capacity to as much as 6 Gbps. The operator has flexible options for upstream capacity, and along the way the downstream can be increased to as much as 10 Gbps.

Speaking to the upstream in North America, the vast majority of the coaxial cable is operated with a low-split (42 MHz) and typically has less capacity than the downstream. Low-split is a hold-over from the days of analog television channels and cable-ready TV sets (both of which are rapidly going the way of the do-do bird, if not already there). Low-split allowed the old Channel 2 to be carried on the coaxial cable starting at 54 MHz. The old analog Channel 2 has generally been replaced by digital TV carriers and IPTV, so the reasons for low-split are becoming few and far between.

DOCSIS equipment is very resilient, and for low-split operation it would encourage operators to experiment with these recommendations to get more upstream capacity. Next we discuss some strategies.

Removing large guard-band between carriers as it is not needed. The DOCSIS specifications are written such that RF channels can be directly adjacent to each other. In discussions with operators during the time of COVID-19, we have seen situations where the upstream DOCSIS carriers have large guard-bands between them as shown in Figure 7 below.

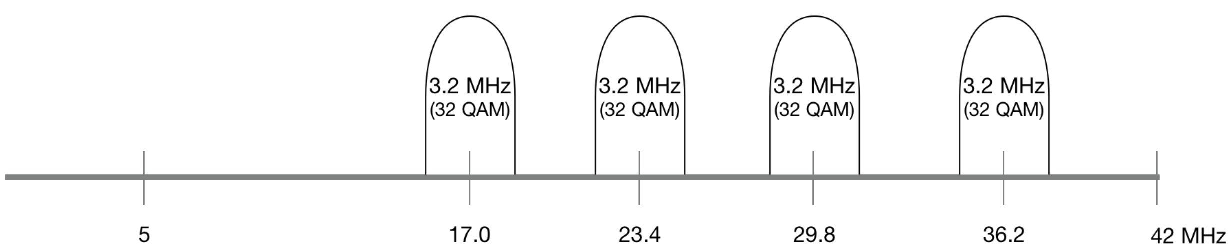

Figure 7 – Large Guard Bands Between Upstream Channels

These spaces between any DOCSIS carriers (upstream or downstream) have been found to not be needed; the carriers may be directly adjacent to each other on each side with minimal guard-band. There is a potential to use as little as 100 KHz spacing between ATDMA carriers. However, as you place a carrier near the roll-off starting at 42 MHz it is best to leave around a 500 KHz guard-band from 41.5 MHz to 42 MHz to avoid non-linearities related to amplifier cascades.

Increasing modulation order to 64 QAM for the legacy upstream DOCSIS carriers. The DOCSIS QAM technology is quite resilient, and the recommendation is to increase carriers to 64 QAM modulation, widen the carriers to use available spectrum, and remove the guard-band between the carriers. As shown in Figure 8 below, the moves should be done stepwise to confirm proper operation.

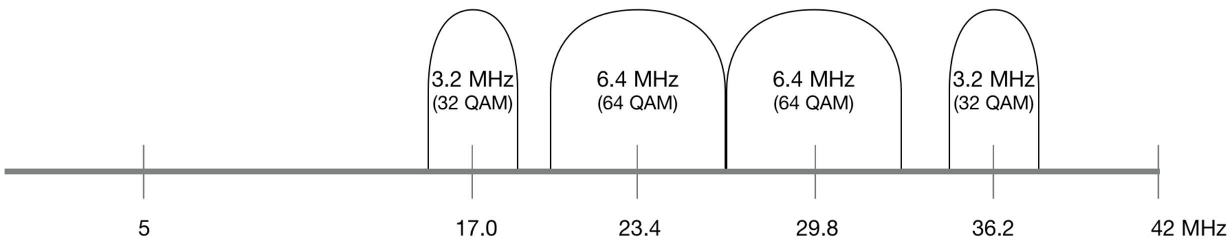

Figure 8 – Increasing Channel Width To Increase Upstream Capacity

Figure 9 shows using all available spectrum, which could include widening all upstream carriers and abutting those carriers.

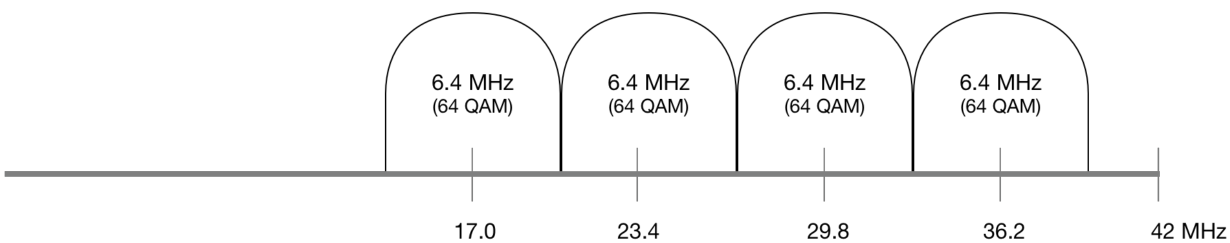

Figure 9 – Maximizing Upstream Capacity With Wide Upstream Channels and Small Guard Bands

As an additional step, try one or more additional carriers, up high or down low as shown in Figure 10. Operators have been successful at adding new carriers, which is a testament to maintaining the plant more diligently over the last decade. The DOCSIS technology has many options for optimizing channel layout and is not the same as even a decade ago. The digital transceivers have increased in sensitivity and capabilities to enable optionality not thought of even 5 years ago.

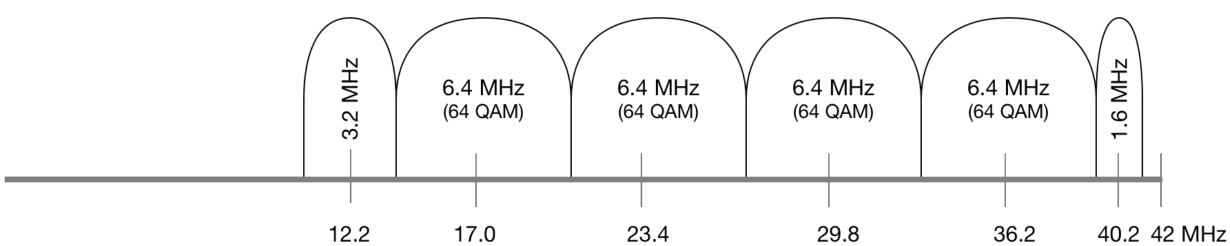

Figure 10 – Adding Additional Upstream Channels

Homes passed decreased which lowers the effect of noise funneling at low frequencies. Cascades have shortened which lessens the impact of group delay close to the diplex filter cut-off frequency. Operators have been successfully running narrow carriers (typically with lower order modulation) both down to 10 MHz and closer to the diplex filter.

Next steps include:

- Allocating more spectrum to DOCSIS broadband, specifically in the upstream which has implications on the downstream
- Migrating to DOCSIS 3.1 technology that includes OFDMA in the upstream and new modulation orders up to 1024 QAM (Theoretically may be up to 4096 QAM)

The DOCSIS 3.1 specifications define three upstream spectrum options that include a top end of the spectrum at 1,218 MHz and are in use around the world, as shown in Figure 11

- Euro-split (65 MHz)
- Mid-split (85 MHz)
- High-split (204 MHz)

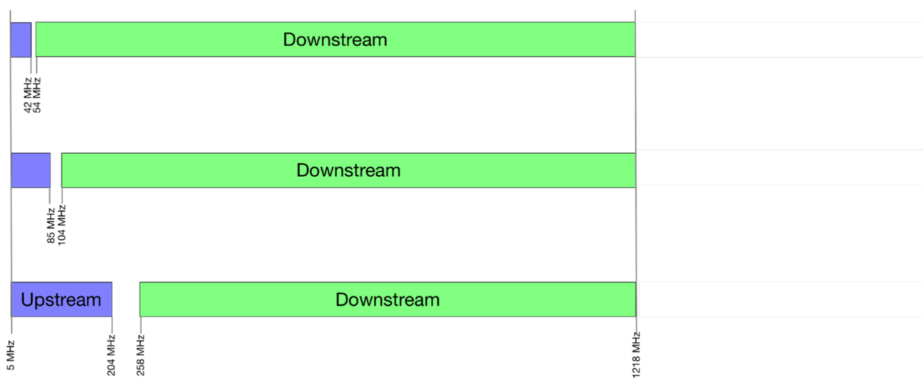

Figure 11 – DOCSIS 3.1 Upstream Spectrum Options

The DOCSIS 4.0 specifications include additional upstream spectrum options:

- 204 MHz
- 300 MHz
- 396 MHz
- 492 MHz
- 684 MHz

And the DOCSIS 4.0 specification includes operating the coax up to 1794 MHz, as shown in Figure 12.

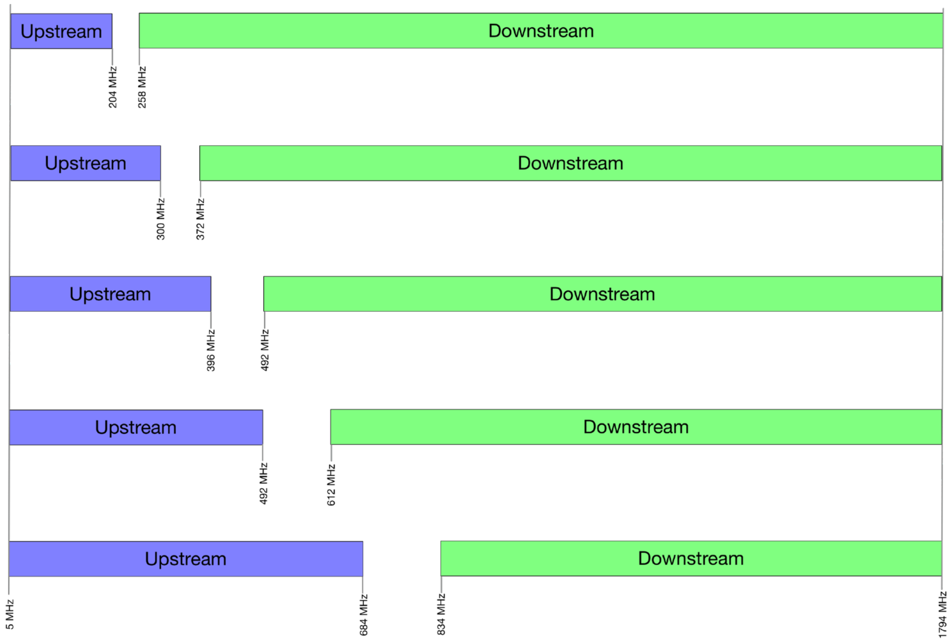

Figure 12 – DOCSIS 4.0 Upstream Spectrum Options

Table 1 shows a comparison of the upstream capacities for these different upstream spectrum options shown in Figure 11 and Figure 12.

Table 1 – Upstream Capacity Comparison

Upstream Frequency (MHz)	Increase in Spectrum	Aggregate Upstream Capacity
42	Not applicable	100 Mbps
85	102%	400 Mbps
204	385%	1.4 Gbps
300	614%	2.3 Gbps
396	842%	3.1 Gbps
492	1,071%	4.0 Gbps
684	1,528%	5.7 Gbps

The capacities above include 4 upstream SC-QAM channels and filling the rest of available spectrum with OFDMA channels (primarily 1024 QAM though your numbers may vary).

There are many options, but operators first have to wrap their heads around allocating more spectrum to the upstream. Which also may mean moving the top end of the downstream to allow for maintaining legacy video and data as increasing the return without changing the forward means less available forward spectrum.

5. More Upstream Means a Few Technology Changes

OFDMA technology, which includes high order modulations up to 1024 QAM technology, which is double the bit density of current upstream 64 QAM technology (10 bits per second per Hz as compared to 6 bits per second per Hz).

The nature of most internet network traffic has changed a lot over the past few decades. Many of the network protocols (at Layer 4 and higher) have become much more intelligent and more adaptive to network congestion. These algorithm use information on network packet loss and network packet delay to determine optimal throughputs that vary as a function of time. These algorithms (for the most part) tend to be very accommodating, backing off their traffic rates at the source whenever congestion is suspected anywhere within their traffic's path through the network. This is true of all of the Layer 4 TCP variants (ex: BIC, CUBIC) that have been developed and deployed in recent history. It is also true of the higher-layer protocols that throttle traffic for UDP-based applications (ex: QUIC). IP Video transport has evolved to now utilize many Adaptive Bit-Rate techniques at higher protocol layer to change the video resolution and the required video bandwidth capacity in response to network congestion. These types of adaptive bandwidth management techniques can be found in both MSO-managed IP video delivery services and OTT IP video delivery services. They can also be found in the video-conferencing solutions (ex: WebEx, Zoom, and Teams) that have become extremely popular for use by work-at-home employees. It was (in part) the ability of these protocols to throttle down their bandwidth usage during times of congestion that helped permit MSOs to survive the sudden bandwidth surge that occurred when the COVID-19 lock-downs first began. That throttling capability, coupled with the innovative scheduling algorithms in DOCSIS CMTSs, ensured that most users could get adequate QoE even in the presence of an incredibly high traffic load generated by their neighbors.

MSOs have taken great steps to increase the reliability of the cable broadband network. With the move to work-at home, network reliability takes front seat. No one wants network issues when on web calls most of the day, or students participating in classes from home. As part of its long-standing proactive network maintenance (PNM) project, CableLabs® has been developing technology and best practices to increase the reliability of the cable network. The SCTE took this effort up in 2017 by creating a PNM working group within its standards program, specifically in the Network Operations Subcommittee (NOS). PNM for the HFC network has taken advantage of the intelligence available in cable network elements such as the CMTS and CM, as well as plant information to determine type, severity, and location of an impairment. The goal is to proactively correct issues before customers are even aware of them. By sifting through huge amounts of data collected from the network, information can be turned into actionable intelligence to increase the reliability of the network and provide a better experience to cable broadband subscribers.

6. Current Activities

As operators became aware of the mass isolation policies and the resulting bandwidth impact on the access network, we needed to respond rapidly. In many cases there was sufficient latent capacity in the network to handle the initial load, particularly in the downstream; but upstream challenges required fast decisions. We are accustomed to a long-term planning cycle of projecting node actions. These actions may include combinations of adding channels for capacity, node segmentation, or physical node splits, and they oftentimes demand forecasting of the bandwidth capacity requirements 6-18 months into the future. As a result of sheltering-in-place, we saw our 18-month forecast occur in a few weeks.

We were fortunate with how resilient the DOCSIS protocol has become, but it does not alleviate the reality of needing to increase spectrum for both upstream and downstream as we progress into the future.

This experience implies that each operator needs to make some difficult decisions quickly. Now that the DOCSIS 4.0 specifications are complete and silicon is being developed for both Extended-Spectrum and Full-Duplex DOCSIS technologies, cable operators need to decide which path to follow. Not necessarily today, but in the near future, as decisions need to be made regarding changing the outside plant to support either direction. Some of those changes may require years of small plant modifications to ultimately support the bandwidth demands of the future.

What we learned from COVID-19 can fill volumes; but the key learning seems to be that even a blind mouse can find a piece of cheese at times. We were very fortunate for the brilliant men and women who developed the DOCSIS infrastructure, as the inherent resiliency of the protocol and products, coupled with the work done in the cable outside plant itself, enabled us to weather the initial storm of a pandemic. However, it is not the time to rest; we need to prepare and prepare rapidly for the next potential event on the horizon.

7. Longer-Term Activities

The negative experiences suffered by some MSOs during the COVID-19 bandwidth surge is a harbinger of things to come in the future if MSOs do not continually upgrade their networks to accommodate the ever-growing traffic demands. While Downstream T_{avg} CAGRs may have slowed from 50% to ~26% in recent years, there is still yearly bandwidth growth occurring in both the Downstream and Upstream directions. In addition, there has clearly been some un-planned bandwidth growth resulting from COVID-19 stay-at-home actions.

Competitive threats from 5G and PON providers may also someday force bandwidth wars, and that struggle will undoubtedly lead to a need for much higher bandwidth offerings within subscriber Service Level Agreements. There will likely come a day when the T_{max} of 1 Gbps within the Service Level Agreement of today is replaced by a 2 Gbps (or higher) T_{max} Service Level Agreement in the future. As we have learned in the past, a higher T_{max} means a higher T_{avg}. And increases in either or both of those parameters will produce a need for higher Bandwidth Capacities.

To provide adequate Bandwidth Capacity to support these higher T_{avg} and T_{max} bandwidths, MSOs are already looking at new technologies for the future. These technologies include the tried-and-true action of running with a Fiber Deeper architecture. Whenever permissible, MSOs will likely pull fiber closer to the home as the years pass to reduce customer counts per node. This effectively reduces the N_{sub} value within Service Groups, and it also moves the MSOs closer to their end-game technology, which is possibly a Fiber-To-The-Premise or wireless delivery solution.

As a step towards the 10G Initiative of the future, MSOs are also likely to begin deploying the newly defined DOCSIS 4.0 technologies by the middle of the 2020 decade. This may include Full-Duplex DOCSIS (FDX) technologies (with 1.2 GHz Downstreams and up to 684 MHz Upstreams) or Extended Spectrum DOCSIS (ESD) technologies (with 1.8 GHz Downstreams and up to 684 MHz Upstreams). It is quite possible that many MSOs will find a need to utilize only 300-492 MHz of that available Upstream spectrum (which offers ~2.1-3.6 Gbps of Upstream bandwidth capacity).

MSOs are likely to deploy these DOCSIS 4.0 technologies even before they enable them, because they typically want to deploy gear that will last deep into the future. For many MSOs, DOCSIS 4.0 technologies are planned for use well into the 2030's, so the desire to have the equipment in the field for 10-20 years requires that they begin planning for DOCSIS 4.0 equipment deployments as soon as possible. This also means preparing the outside plant by deploying equipment that can support the spectrum required for the same time period. As an example, if an MSO expects that 10 Gbps SLAs requiring DOCSIS 4.0 technology are required to be enabled by 2032, and if it requires eight years of diligent plant upgrades to permit ubiquitous enablement of DOCSIS 4.0 technology, then DOCSIS 4.0 field deployments in the outside plant would clearly have to begin by 2024.

Since many of these network technologies will be deployed in DAA environments (both Remote PHY and Remote MACPHY), a critical element of those networks is the Converged Interconnection Network (CIN) that provides Ethernet connectivity from the head-end to the node. Today, CIN networks tend to be limited to 10 Gbps Ethernet optics. A Fiber Node supporting two 10 Gbps Service Groups would obviously require more than 10 Gbps of Ethernet capacity. Thus, as bandwidth capacities of DOCSIS 4.0 deployments rise in the future, it is probable that there will be a move to 25 or 50 Gbps Ethernet Optics within the next decade.

If daisy-chaining of nodes becomes popular or if future architectures employ an Ethernet hub near the nodes, then MSOs may also find value in using the newly defined Coherent Optic technologies. These technologies will provide very high bandwidth capacities (>500 Gbps) at a very low cost for the relatively short-hop fiber runs between head-ends and hubs/nodes.

8. Conclusion

There were some great learnings that to date have come out of COVID-19 shelter-in-place orders:

1. You can never have too much fiber or spectrum in your network
2. Leverage existing technologies as long as you can, but not longer
3. Not every node is created equal
4. There is an established order to things, but sometimes it can get mixed up

And most importantly…

5. Serendipity and hope are not a business plan

We were very fortunate as an industry that all of the hard work that went into DOCSIS specifications, silicon, and products, over the past 24 years has shown that the capabilities of the DOCSIS ecosystem are what enabled the cable broadband industry to lead the way providing incredible service during a pandemic. As leaders of the cable industry it is incumbent on us to prepare the way for those that will follow in our footsteps, as we have followed in the footsteps of those that came before us. We must therefore create a series of technologies that will allow cable to continue exceeding the demands of our customers for the next 50+ years.

This implies planning, committing to, and supporting those who are working on and developing these new technologies. Keeping our focus on what our customers need today and in the future will lead each of us to make the right decisions for our companies; this means not getting led down a path that may look shiny today but will tarnish rapidly as the reality of long-tail and support costs kick in.

Now is the time to analyze where our companies and customers are heading, plan for our network transformations, develop resources towards executing our plans, and commit to our vendors for our directional choices. Like anything else in cable, these things take time and now is that time to begin.

In conclusion, we need to **act now**, **be bold**, and **stay true** to our individual directions.

Abbreviations

ACK	acknowledgement
BIC	binary increase congestion
bps	bits per second
CAGR	compound annual growth rate
CIN	converged interconnect network
CM	cable modem
CMTS	cable modem termination system
COVID-19	Coronavirus disease 2019
CUBIC	an enhanced version of BIC
DAA	distributed access architecture
DOCSIS	data over cable service interface specifications
DSL	digital subscriber line
HFC	hybrid fiber-coax
Hz	hertz
IP	Internet Protocol
Gbps	gigabits per second
GPON	gigabit passive optical network
IPTV	Internet Protocol television
ISBE	International Society of Broadband Experts
Mbps	megabits per second
MHz	megahertz
MSO	multiple system operator
OFDMA	orthogonal frequency division multiple access
OTT	over the top
PNM	proactive network maintenance
PON	passive optical network
SC-QAM	single carrier quadrature amplitude modulation
SCTE	Society of Cable Telecommunications Engineers
TCP	transmission control protocol
TV	television
QAM	quadrature amplitude modulation
QoE	quality of experience
QUIC	a general purpose transport layer protocol

Bibliography & References

1. Traffic Engineering in a Fiber Deep Gigabit World, John Ulm and Tom Cloonan, 2017 SCTE Cable-Tec Expo.

