



**VIRTUAL EXPERIENCE
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Measuring DOCSIS 3.1 & 4.0 Capacity: It “HERTZ”!

An Operational Practice prepared for SCTE by

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1. Introduction

In the late 1990s, when the only number after the DOCSIS (Data Over Cable Service Specification) acronym was “1.0,” measuring capacity and throughput, i.e., speeds, was a straightforward matter, limited to one channel in each direction: 40 Mbps Downstream and 10 Mbps Upstream. Now, with DOCSIS 3.1 and 4.0, we can bond multiple channels to support amazing multi-gigabit upstream and downstream speeds – enabling network capabilities that will benefit broadband consumption categories spanning the Internet of Things (IoT) and virtual reality, interactive video conferencing, health care and remote learning, among others.

However, with advanced performance comes advanced complexity, and that’s especially true with respect to how we measure broadband capacity and throughput. This is especially noteworthy as underlying technologies become more deliberately dynamic, able to shift from one carrier or subcarrier to another, when connectivity becomes impaired or is more optimal in an adjacent or nearby spectral location. Measuring capacity and throughput in today’s advanced stages of DOCSIS is trickier and more complicated because each bonded channel’s frequency and modulation type can vary, based on spectrum availability and HFC network reliability.

This paper will address the new challenges in capacity and throughput measurements. It will examine how one operator measures capacity now, versus how those measurements are made or will be made, in more dynamic spectral configurations. It will also explore the capacity measurement methods and requirements for Full Duplex (FDX) and Extended Spectrum DOCSIS (ESD) techniques.

2. The Increasing Complexity of Capacity Management

2.1. Spectrum Range and Capabilities

Coaxial Cable lives on spectrum frequencies (measured in Hertz) located between 5 MHz and a range of upper boundaries (750 MHz, 1 GHz, 1.2 GHz, and future 3 GHz configurations are envisioned.) Figure 1 shows a capacity and services timeline for the cable industry, dating from the pioneering systems of the late 1940s, to today’s growing service mix of voice, video, data and beyond. Capacity-wise, in the 1960s, the maximum frequency reached on coax was 240 MHz; now, cable systems operate at 1218 MHz (1.2 GHz) and beyond. The spectrum is traditionally divided into 6 MHz channels, a now-vestigial segmentation associated with analog television signals. In the beginning, there were three networks carried on three channels: ABC, CBS and NBC. After that, the name of the game was capacity expansion, to transmit dozens of analog TV channels one way, downstream, to homes.

In the 1990s, and coincident with return path / reverse spectrum activation, cable modems were introduced, in part to replace dial-up telephone connections to what was then a very new world wide web. It was those cable modems, and the broadband connections they enabled, that gave rise to so many “broadband native” video streaming, online shopping, and all things done over Internet Protocol (IP) connections. In the 2018 timeframe, for instance, over-the-top (OTT) video, social media services and online gaming drove substantial growth in broadband consumption and catalyzed our industry of connectivity providers to advance our capacity, throughput, and latency. Now, DOCSIS 3.1 enables multi-gigabit broadband speeds over cable spectrum upto 5 Gbps and can combine multiple 6 MHz channels into one large bond, which is what enables multi-Gig services. DOCSIS 4.0 further increases the downstream RF frequency range by using two methods: Full Duplex DOCSIS (FDX) and Expanded Spectrum DOCSIS (ESD). Newer Orthogonal Frequency Division Multiple Access (OFDMA) techniques

designed to accompany the rollout of FDX, ESD and DOCSIS 4.0-based components will provide additional bandwidth up to 10 Gbps. OFDMA will also advance how we measure overall throughput and capacity, which will be discussed later.

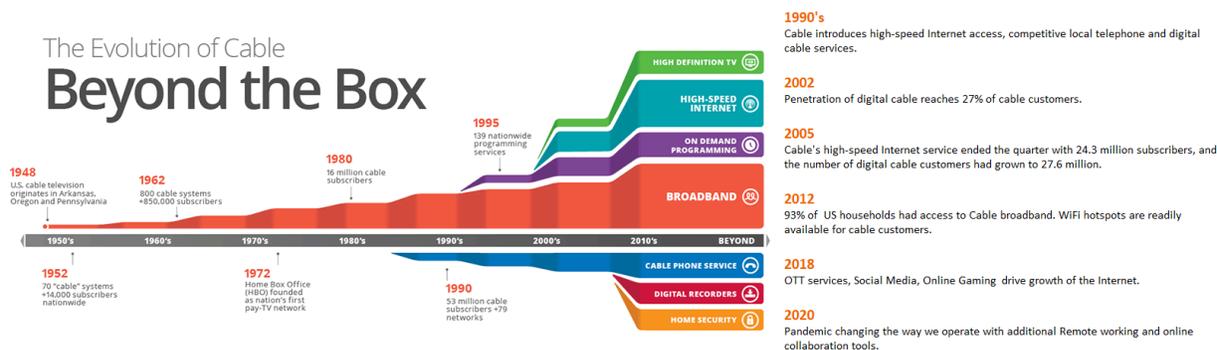


Figure 1 – Evolution of Cable (CCTA)

2.1.1. Coaxial Cable and the Frequency Landscape

Even though fiber is faster than cable capacity wise, coaxial cable is the faraway winner, in terms of capacity to cost ratio – the fire hose to the drinking straw, relative to telco twisted-pair. That said, coaxial does carry its own nuances. The upstream signal path in particular is perpetually nuanced by signal/noise that can overlap with downstream frequencies -- especially as the upstream path is eventually widened to accommodate mid-split, high-split and other upper spectral boundaries beyond the traditional top of 42 MHz.

Expanding the upstream band also allows a buffer for noise reduction and allocates more spectrum for higher speeds -- with frequencies ranging between 5 MHz - 396 MHz (from between 5 MHz – 42 MHz), while the downstream could reach up to 1.8 GHz or 3 GHz, depending on the use of Full Duplex DOCSIS (FDX) or Extended Spectrum DOCSIS (ESD.) Current industry plans to increase the upper boundary of the downstream spectrum to 1.2 GHz allows FDX to play a major role in simultaneous bidirectional transmissions on a signal carrier.

One view of a spectrum progression is shown in Figure 2, below. The top line illustrates a traditional 750 MHz configuration, with a 5-42 MHz return path. Below it, in yellow, the downstream spectrum above 750 MHz is illustrated as potentially usable for downstream transmissions, and the upstream is widened to a mid-split from 5 MHz – 85 MHz. The third line illustrates a high-split return path, from 5 MHz – 204 MHz, guard band between 204-258 MHz, and a combination of video, VOD, DOCSIS 3.0, DOCSIS 3.1, and reserved/unused bandwidth above 1 GHz. The fourth line, with the cutout detail below it, shows an ultimate spectral allocation with simultaneous bidirectional traffic moving between 300 MHz and 644 MHz. In that zone, traditional digital video, VOD and some DOCSIS traffic moves over the same carriers at the same time as FDX and DOCSIS 4.0 traffic. Clearly, as spectral configurations grow and shift to accommodate the ceaseless growth of broadband consumption, our mechanisms for measuring capacity must adapt and grow as well.

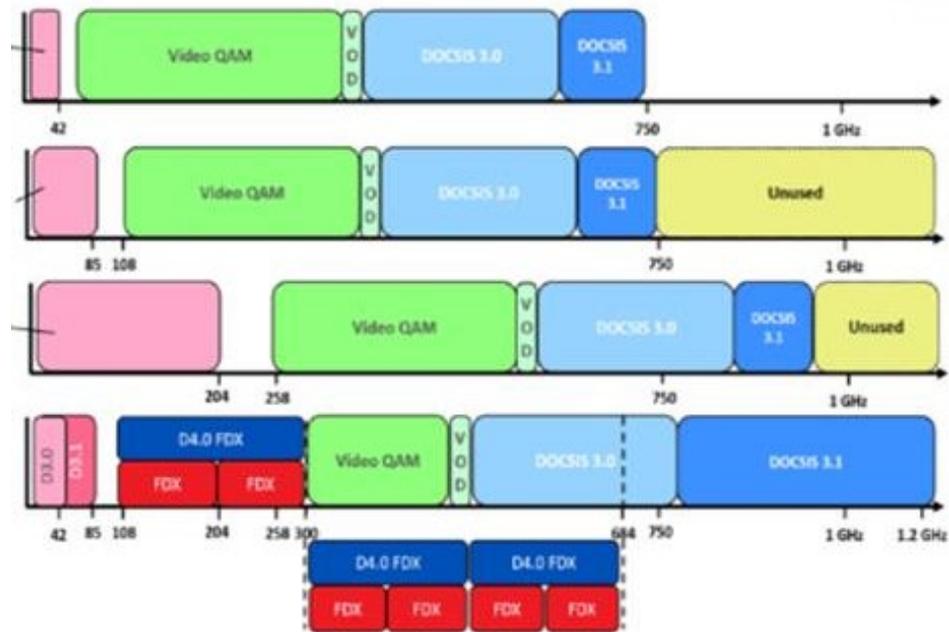


Figure 2 – HFC Spectrum

2.1.2. Hybrid Fiber Coax (HFC) Plant Issues

Attenuation, or the loss of signal strength, is a factor when measuring network capacity. The outside hardline coaxial cables typically attenuate at a rate of 2.4 dB/100 ft at 1.8 GHz, and 3 dB/100 ft at 3 GHz. By contrast, drop cables connecting to homes, and in-home RJ-6 cables, can attenuate at a rate of 12 dB/100 ft at 3 GHz. In general, the older the cable, the less it can carry, in terms of higher frequencies and long distances. In some cases, taps, amplifiers and nodes will need to be replaced to support an upper spectral boundary of 1.8 GHz. In other cases, the amplifiers could be replaced with fiber deeper nodes (such as to achieve N+1 or N+0 amplifier configurations).

2.2. Upstream and Downstream Frequencies

2.2.1. Upstream Boundaries

The upstream frequency band from 5 MHz to 42 MHz typically carries 4 Single-Carrier Quadrature Amplitude Modulators (SC-QAMs) that can deliver an aggregate 100 Mbps. Implementing an upstream mid-split to 85 MHz increases the aggregate capacity to 8 SC-QAM channels, which can deliver up to 200 Mbps that are usable by D3.1 modems.

2.2.2. MAC Layer vs. Physical Layer Capacity

One measurable difference between the Media Access Control (MAC) Layer and the Physical (PHY) Layer is the DOCSIS overhead. The Profile Management Application (PMA), which was developed by Comcast in 2019, and consequently shared with the industry, is vital for generating the D3.1 profiles for OFDM channels. In a capacity measurement context, PMA enhances part of the overhead efficiency to increase the usable bandwidth by ~15%, on average, based on a mix of modem types. The dynamic changes in the profile range between 10% to 25% in improvement. Table 1 is a PMA example using 6.4 MHz channels, where profile 271, when dynamically experiencing changes such as improved plant conditions/reduced noise, or a reduction of the number of connected modems, will proactively shift to profile 251, thus gaining an additional 5 Mbps of capacity.

Table 1 – Profile Management Application (PMA) example

Profile Template for 6.4 MHz Channels				
251	256	261	266	271
25.6 Mbps 64-QAM short: 97/2, burst=5 long: 247/4 snr at 1% uccw = 22.8 dB	24.5 Mbps 64-QAM short: 91/5, burst=5 long: 239/8 snr at 1% uccw = 22.1 dB	23.3 Mbps 64-QAM short: 105/10, burst=6 long: 229/13 snr at 1% uccw = 21.2 dB	22.5 Mbps 64-QAM short: 99/13, burst=6 long: 223/16 snr at 1% uccw = 20.5 dB	20.7 Mbps 64-QAM short: 99/13, burst=6 long: 121/16 snr at 1% uccw = 20.3 dB

Based on the table 1 we observe ~9% improvement for Profile 266, ~12.5% for Profile 261, ~18% for Profile 256 and up to ~24% improvement for profile 251. In actual deployments we have observed ~15% improvement on average when PMA has been deployed in the field.

2.2.3. Frequency Bands, Modulation and Spectrum Allocation

One current approach in capacity is to increase the HFC spectrum to 1.2 GHz, allowing FDX combined with D3.0 and D3.1 channels to achieve a D4.0 bandwidth supply of up to 4.2 Gbps for the US and 7.6 Gbps for the DS. The modulation and spectrum enhancements intrinsic to FDX and ESD will allow even higher Multi-Gig services. This is depicted in Figure 3.

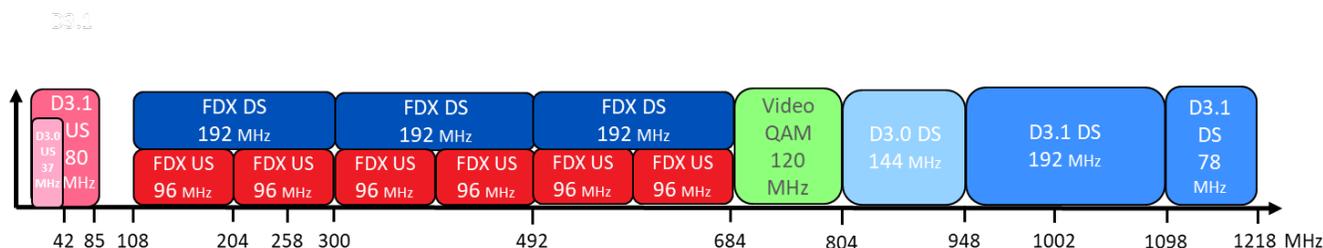


Figure 3 – D4.0 FDX HFC Spectrum

2.3. Multi-Gig Services That Will Likely Impact Capacity Measurements

Demand for higher speeds is increasing, as it has since the very onset of cable modems and broadband connections, in the mid-1990s. The current amount of bandwidth consumed per device is continuously

on the rise. Many applications and services are likely to require multi-Gig speeds, such as those within the Internet of Things (IoT), Virtual Reality (VR), Augmented Realty (AR), cloud gaming and streaming. Further discussion of these anticipated growth engines is out of scope for this paper, other than to note that anything that impacts the demand for network capacity must be considered and modeled, to the extent possible, when measuring throughput and capacity.

Downstream speed tiers reaching 1 Gbps using D3.1 are expected to expand to 10 Gbps with D4.0, which will yield ample bandwidth that can be applied to both foreseen and unforeseen applications.

2.4. Capacity Measurement Methods

As mentioned previously, in the “good old days” of early DOCSIS networks, with static channel widths and fixed modulation mechanisms (variations on QAM, from 64-QAM to 256 QAM in the downstream, and QPSK in the upstream), it was reasonably straightforward to predict capacity readings: The modulation rate on a particular channel width yielded a specific number of bits/Megabits per second.

As our broadband networks continued to advance and were deliberately engineered to stay ahead of consumer and business demand, the “simple math” of capacity measurement became part of a far more complex assessment. Now, multiple channel widths and a wider range of advanced modulation makes capacity measurement a trickier proposition.

2.4.1. Capacity Measurement Methods for OFDM Carriers

Currently, and because OFDM channels are primarily available on the downstream signal path, we have been collecting the percent utilization values reported by the CMTS based on demand. For SC-QAM, D3.1 modems can access both SC-QAM channels and OFDM, so they benefit from measurably higher throughput.

When high speeds are required for certain applications, or to run a speed test, the DOCSIS 3.1 modem can utilize both SC-QAM and OFDM spectrum. Since there is no means to determine the combined throughput between the two metrics, the actual available capacity can be determined based on the available capacity -- after deducting the 98th percentile SC-QAM used bandwidth from the total capacity, to remove anomalies, as well as the 98th percentile OFDM utilization. This is achieved by converting it to bandwidth based on the most prevalent profile used during a designated polling hour, then deducting that amount from the capacity of that profile. The sum of these two provides the available bandwidth during peak hours – in a sense, an erlang for broadband capacity. This matters to ensure that we plan for augments and have enough capacity to support our advertised speeds. This will be discussed later.

2.4.2. Orthogonal Frequency-Division Multiplexing (OFDM)

Combining multiple 6 MHz channels into one larger band (192 MHz) avoids Inter-Symbol Interference (ISI) and improves Signal-to-Noise ratio (SNR), which impacts capacity measurement in a beneficial (to capacity) way. OFDM traffic combined within SC-QAM channels provides an ample amount of BW to allow multi-Gig transmissions.

2.4.3. Orthogonal Frequency-Division Multiple Access (OFDMA)

OFDMA uses time slot and frequency allocation for D3.1 modems and higher. Each modem will be given a time slot or group of subcarriers to send the data. Excellent coverage of the topic of OFDMA for

upstream capacity gains can be found in the 2020 SCTE Expo paper titled “Field Experiences with US OFDMA and Using US Profile Management.” As well, substantial detail about improvements to the upstream signal path are expected as part of this year’s Fall Technical Program. For those reasons, we will say only that from a capacity management perspective, the inclusion of OFDMA adds another layer of complexity to the capacity measurement task.

It represents an active area of exploration.

2.5. Tools and Methods to Measure Utilization

Currently, we measure capacity by regularly polling the CMTS for network activity from channels modulated with SC-QAM, as well as channels or bonded channels modulated with OFDM. In the case of the upstream signal path, the four SC-QAM channels are polled every five minutes, and the results aggregated. The total value for those four channels is then adapted from a daily or weekly view, depending on report type, and the last two percent removed, to get to a 98th percentile reading. The top 2% is removed as a countermeasure against network anomalies.

2.5.1. Cable Modem Consumption

Measuring hourly consumption in bytes per service flow at the cable modem level helps in identifying “top talkers” and the contribution during peak hours. Peak hours are based on the highest consumption of the averaged top 20 hours per month. Figure 4 shows the US and DS speed tier consumption at peak hours by service type. Modem consumption by speed tier is crucial to evaluate the growth and projection for multi-Gig speeds.

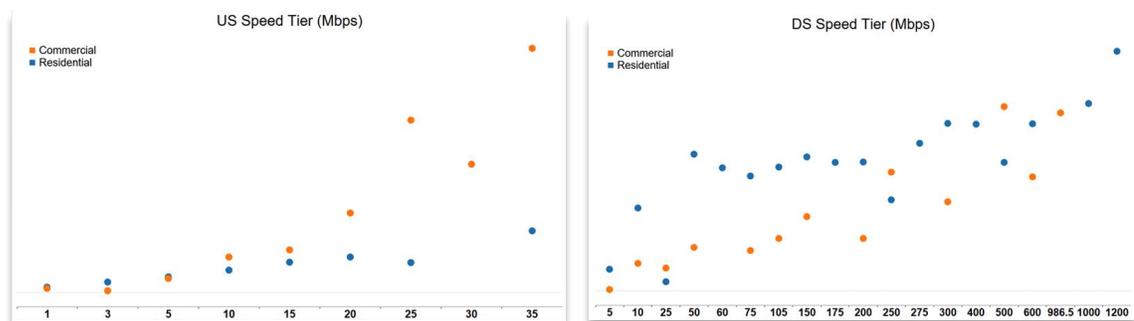


Figure 4 – BW Consumption During Peak Hours by Speed Tier

2.5.2. Traffic Aggregation and Concurrency

Aggregating hourly consumption during the top-twenty hours per month, per modem, at the CMTS Service Group (SG) and CMTS Bonding Group (BG), provides the behavior by demographics and shows any heavy usage by SG and BG. This method helps in better augmentation approaches and predictive analysis. It also aids in capacity measurements.

2.5.3. Reporting Frequencies and Metrics Needed

We use the iCMTS/vCMTS pollers to collect the average 5-minute polls, daily, over a month period, to calculate the 98th percentile values. The reported values are based on daily, weekly, and Monthly periods at a SG/BG level.

The metrics collected are as follows:

- In-bps, out-bps converted into percent utilization
- Up-channel utilization
- OFDM percent utilization
- OFDMA percent utilization
- PMA profiles and capacity
- Interfaces' speeds

Cable modem pollers provide the following metrics:

- Cable modem type
- Bootfile specifications
- CMTS mapping
- SNR, MER

Additional metrics collected are:

- HHP per node, per zip code
- Node-to-CMTS mapping

The combination of these metrics is utilized to address network augmentations, forecasting, and DOCSIS 4.0 capacity.

2.5.4. Future of Measurements

More trials and higher D4.0 penetration will be needed, in addition to methods to report on FDX. Profile types by interface are necessary to collect 5 minutes utilization for OFDM/A.

2.6. DOCSIS 4.0, Full Duplex DOCSIS (FDX) and Extended Spectrum DOCSIS (ESD)

2.6.1. Boundaries of D3.1

DOCSIS 3.1 modems max out at 1.2 GHz, where one (relatively large) OFDM channel could be utilized. This sets the downstream speed at 2 Gbps and the upstream speed at 300 Mbps (and potentially 600 Mbps where OFDM/A is applicable.)

2.6.2. Bandwidth Boundaries and CM Populations (D2, D3,...)

Currently, our network, like that of most operators, operates a range of cable modems, some based on DOCSIS 3.0 and others on DOCSIS 3.1. Currently, most of our footprint uses D3.0-based CMs, with the rollout of D3.1-based modems poised to shift the balance in a reasonably swift fashion. To fully and efficiently utilize an advanced, future-state network. outfitted with OFDM/A and FDX/ESD, and to benefit from the additional BW, that same trajectory will be required, to shift the balance again, from D3.1-based CMs to D4.0-based CPE.

Plus, because the maximum capacity of D2.0 is limited to 40 Mbps DS and 30 Mbps US, modems based on that DOCSIS version will ultimately need to be replaced.

For D3.0-based modems, the number of DS SC-QAM channels varies from 8 to 32, resulting in a capacity range from 320Mbps to 1.2 Gbps. Similarly, US capacity ranges from 30 Mbps to 120 Mbps. This is summarized in Table 4, below.

Table 2 – Modem Types and Bandwidth

Modem Type	Max. Speed	SC-QAM Bonding	OFDM/A Capable?
D2.0	40 Mbps DS 30 Mbps US	1 DS 1 US	NO
D3.0	1 Gbps DS 120 Mbps US	8 DS 4 US	NO
D3.1	10 Gbps DS 1 Gbps US	32 DS 8 US	YES
D4.0	10 Gbps DS 6 Gbps US	44 DS 8 US	YES

2.6.3. Differences between D3.1 and D4.0

A very important reason why measuring broadband capacity is sometimes an “It Hertz” proposition can be seen in Figure 5, below, which shows spectrum ranges and modem capabilities. The expansion of spectrum frequency is the only means to obtain additional throughput:

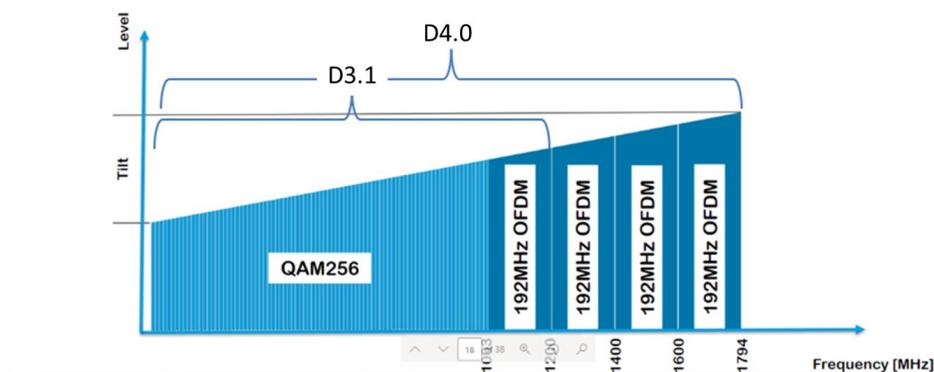


Figure 5 – Frequency Expansion

DOCSIS 3.1 can function at a maximum frequency of 1.2 GHz, with OFDM channels, while DOCSIS 4.0 can utilize higher spectrum up to 1.8 GHz, thus combining multiple OFDM channels to reach multi-Gig speeds.

2.6.4. Why is D4.0 needed?

Higher speeds, like 10 Gbps downstream and 6 Gbps upstream, are only possible with DOCSIS 4.0, also known as Full Duplex DOCSIS (FDX). This will coincide with plans by operators to drive optical fiber deeper into their networks, go higher spectrally, and/or to provide sufficient capacity to the Remote PHY Devices (RPDs).

Although this paper didn't go into substantial detail, it is worth repeating that more bandwidth, wider spectrum, and higher efficiency (lower latency and faster speeds) will be required to meet the demand for known and unknown broadband services and service categories (e.g. IoT, the "metaverse," and so on.)

3. Conclusion

Measuring network capacity is an activity that is vital to strategic planning, especially as broadband consumption continues to steadily grow. In the earliest days of broadband, such calculations were a relatively straightforward matter related to modulation type and channel width. As network capabilities advanced, however, the very technologies that enabled the advancements simultaneously increased the complexity for capacity planners.

DOCSIS 4.0 traffic, for instance, is especially convoluted – so, from a complexity standpoint, "it Hertz". In addition, the dynamic nature of the Profile Management Application (PMA) introduces additional challenges, in that it is vastly more challenging to count when channel widths and modulation types are hopping around, on the fly, in pursuit of optimal transmission paths. While many of the DOCSIS 3.1 techniques of measuring traffic apply, an aggregation of the OFDM interface metrics is required for DOCSIS 4.0.

Upgrading the network to 1.2 GHz and 1.8 GHz by replacing taps, amplifiers and nodes is a major effort, as is stairstepping D2.0 and D3.0 modems with D3.1 and D4.0 gear. With FDX and ESD on the near-term horizon to further increase the capacity of the access network, it is paramount that we make sure our capacity measurement techniques keep pace.

The good news is, over time, these network improvements will facilitate the periodic measurement of a balanced demand at SC-QAM, and OFDM/A levels combined. Tracking Latency/Jitter and SNR/MER proactively will further eliminate network issues. Along the way, we will need to also consider how to blend WAN, CPU, Memory, and other metrics beyond DOCSIS into the capacity monitoring mix, as all are or will be essential to the overall capacity planner's work.

Abbreviations

AP	Access Point
AR	Augmented Reality
bps	bits per second
BW	Bandwidth
CMTS	Cable Modem Termination System
CPU	Central Processing Unit
D2.0	DOCSIS 2.0
D3.0	DOCSIS 3.0
D3.1	DOCSIS 3.1
D4.0	DOCSIS 4.0
dB	Decibels
DOCSIS	Data Over Cable Service Interface Specification
DS	Downstream
EoHFC	Ethernet over HFC
ESD	Extended Spectrum DOCSIS
FDX	Full Duplex DOCSIS
FEC	Forward Error Correction
GHz	Giga Hertz
Gpbs	Gigabits per second
HD	High Definition
HFC	Hybrid Fiber Coax
Hz	Hertz
IoT	Internet of Things
ISBE	International Society of Broadband Experts
ISI	Inter-Symbol Interference
MAC	Media Access Control
Mbps	Mega Bits per Second
MER	Modulation Error Rate
MHz	Mega Hertz
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	OFDM Access
PMA	Profile Management Application
SC-QAM	Single-Carrier Quadrature Amplitude
SCTE	Society of Cable Telecommunications Engineers
SG	Service Group
SMB	Small Medium Business
SNR	Signal-to-Noise Ratio
US	Upstream
VR	Virtual Reality
WAN	Wide-Area Network

Bibliography & References

CommScope: Extended Frequency Performance of Coaxial Cable

Corning/Broadband SP: Get Ready – ‘Cause here it Comes DOCSIS 4.0 (D. Kozischek, J. Burton)

CCTA: History of Cable

CableLabs: DOCSIS® 4.0 Technology Realizing Multigigabit Symmetric Services (D. Jones)

RF Wireless World: Difference between DOCSIS 3.0 DOCSIS 3.1 and DOCSIS 4.0

QualComm: VR and AR pushing connectivity limits

The Workshop- Mangiante: VR is on the Edge: How to Deliver 360° Videos in Mobile Networks

Google Stadia: Internet usage (<https://support.google.com/stadia/answer/9607891?hl=en#zippy=>)

StreamLabs: Q3 2020 Live Streaming Industry Report (<https://streamlabs.com/>)

ANSI C63.5-2006: American National Standard Electromagnetic Compatibility–Radiated Emission Measurements in Electromagnetic Interference (EMI) Control–Calibration of Antennas (9 kHz to 40 GHz); Institute of Electrical and Electronics Engineers

The ARRL Antenna Book, 20th Ed.; American Radio Relay League

Code of Federal Regulations, Title 47, Part 76

Reflections: Transmission Lines and Antennas, M. Walter Maxwell; American Radio Relay League