On the way to symmetrical 10 Gbps

DOCSIS 4.0 – Pimp my DOCSIS

by Dr. Alexander C. Adams

The internet in its publicly accessible form is celebrating its 25th birthday. Compared to the span of a human life this corresponds to an age when childhood and adolescence should have been concluded and when the most erratic behaviors from those puberty days should have been mitigated. Perfect conditioning for a life dedicated to work and family. An old students' song titled "O quae mutatio rerum" (Oh, how things change) poses the Latin way of introducing the becoming academic to the course of human events. A good time therefore to look upon the achieved and to dare take a glimpse at even bigger and better things to come.

There is justified grounds in the broadband industry for a little pride in the work of the past decades, for the industry was and is one of the main contributors to the developments in communications technology and the overall digitalization of life going along with it. Worldwide, the cable industry counts as one of the main drivers of technical innovation in communications for one good reason: She needs to be! From the get-go she was immersed into a competitive situation with operators of different network architectures. It was perpetual technical innovation that enabled the realization of the technology satisfying the customers' ever-growing demand for bandwidth in up- and downstream over the years. That is an achievement, especially since the point of departure was everything but optimal -- the coaxial networks available where originally not conceptualized for the transmission of broadband data.

A Makeshift-Solution

The so-called "Cable TV Networks" -- in Germany operated by the Federal German Postal Services -- carried predominantly analog signals as a distributed one-way service. These where frequency- and vestigial-sideband-modulated signals transmitting television and radio signals in a spectrum up to 300 MHz, later up to 450 MHz. The application of digital information on these analog lines is principally possible, however, the digital information will still be transported in form of analog electromagnetic waves between the outer and inner conductor of the coaxial cable. In other words, the "digital" information transported across the coaxial part of the plant will always be only "digitalized" information.

When problems rear their ugly heads, engineers excel to their finest hours. The above described problem-setting led to the birth of the DOCSIS-protocol, conceptualized by the US-American CableLabs in Colorado, poured into the globally accepted DOCSIS-Standard by the American Society of Cable Telecommunications Engineers (SCTE). DOCSIS stands for Data-over-Cable-System-Interface-Specifications. One could also describe DOCSIS as a set of specifications for systems transporting broadband data over cable lines that where not really designed to do that on such a scale. The conceptualization of the standard was driven by economic factors, it enabled network operators to offer and market internet services over an existing infrastructure. In the end it is money that makes the world go around.

The DOCSIS-Evolution

DOCSIS defines the traffic regulations for data transport over the coaxial part of an HFC-network. The first version of the standard, DOCSIS 1.0, was introduced in 1997. Quality-of-service parameters were introduced into DOCSIS 1.1 in 2001, mainly for the integration of voice data which needs to get prioritized. DOCSIS 2.0 (2002) and 3.0 (2006) dealt with the problem of increased customer demand in bandwidth, resulting in the adoption of channel bonding into the standard. Channel bonding can be applied in up- and downstream and increases the capacity to and from the customer (refer to Figure 1). All DOCSIS versions up to and including DOCSIS 3.0 are based upon the traditional channelization of the spectrum into 7/8 MHz channels (6 MHz in the USA), using one modulated carrier per channel.

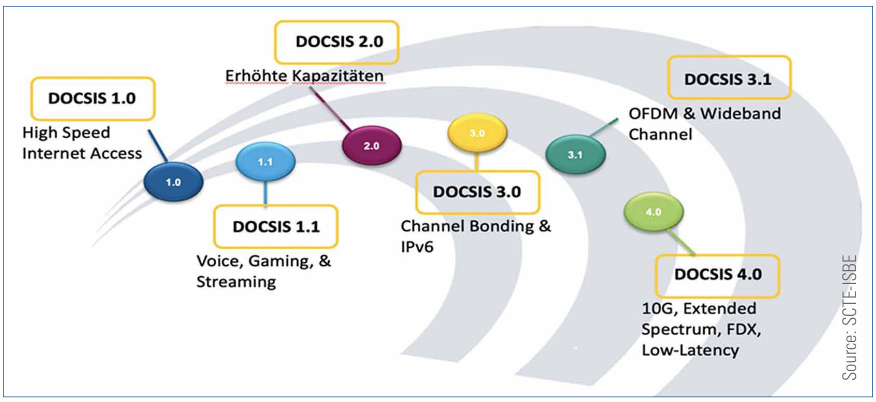

Figure 1: DOCSIS Evolution

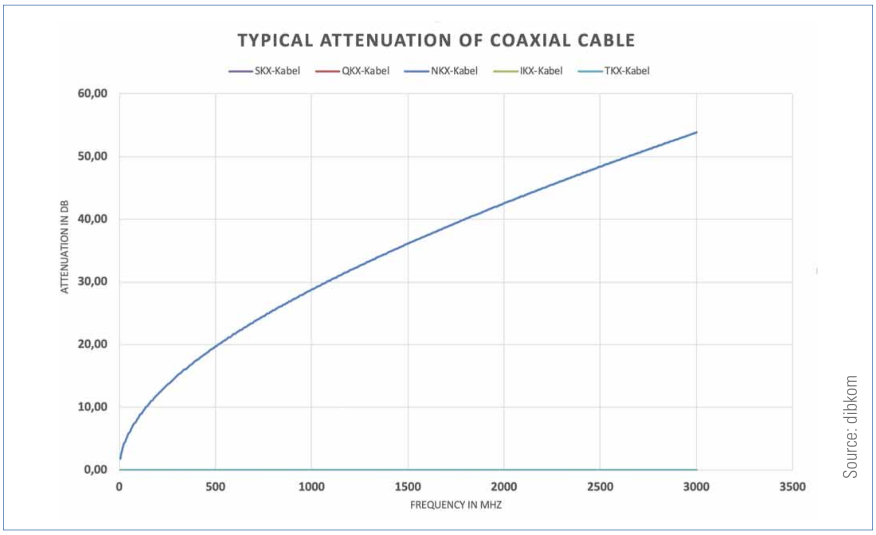

Figure 2: Typical attenuation of a coax-line, approximated F(f)=A*SQRT(f)

A Fresh Technological Approach

DOCSIS 3.1 (2015) broke with this tradition and a completely new approach was applied to cable. Other than its older siblings, DOCSIS 3.1 relies on Orthogonal-Frequency-Division-Multiplexing (OFDM) as a modulation technique, next to the Quadrature-Amplitude-Modulation (QAM) already known from previous versions of DOCSIS. DOCSIS 3.1 OFDM-Channels are not based on traditional channelization. They can be flexibly configured to be up to 96 MHz wide in the upstream and up to 192 MHz in the downstream, using not one single carrier, but thousands of narrowband subcarriers within the channel. Each subcarrier can carry its own individual QAM on a modulation order optimized for the conditions the signal will encounter on the way to its destination. OFDM in combination with a new error correction approach named Low-Density-Parity-Check (LDPC) working close to the physical Shannon Limit forms a solid basis for the DOCSIS 3.1 protocol and improves the spectral efficiency of the system by up to 50 percent. Using the full capacities of the DOCSIS 3.1-standard, data rates of up to 10 Gbps in the downstream and 1 Gbps in the upstream are possible. It is remarkable in this context that the version number 3.1 suggests that DOCSIS 3.1 differs from its older brother DOCSIS 3.0 only in a few updates. Indeed, that is not the case. In fact, DOCSIS 3.1 is very different. It introduces what essentially is a second PHY-layer on top of the existing DOCSIS 3.0 PHY and works hand-in-hand with it.

The DOCSIS-family is fertile, it is subject to steady reproduction, as it seems. The youngest child in this family is DOCSIS 4.0, the standard was introduced by CableLabs earlier this year. This version is based on the OFDM-technology introduced into cable networks with DOCSIS 3.1. DOCSIS 4.0 contains several specifications, such as Full-Duplex DOCSIS (FDX), a special application of DOCSIS 3.1-technology enabling the bi-directional use of the spectrum between 108 MHz and 684 MHz to push networks closer to delivering symmetrical data rates to and from the customer's premise. Bi-directional signaling comes with its own set of complications, which will be described a few paragraphs further down. Additionally, the latest version of DOCSIS extends the spectrum to 1.794 GHz, reduces latency in the network and places a strong emphasis on system security issues.

Far from Immortal … but still Kicking and Packing a Punch

From the get-go, DOCSIS has been a project to "buy network operators time" and that stays true to this very day. A complex issue has become more complex over the years, but DOCSIS remains a project that enables network operators worldwide to use the existing coaxial infrastructure between the RemotePHY-node and the customer without suffering from economic or competitive disadvantages. As long as technology and protocols are available to provide data rates to and from the customer's premise that in the medium run meet the demands, their implementation will in most cases be more cost-efficient than the large-scale deployment of fiber to the premise. Fiber is the transmission medium of the future and HFC-network operators too are driving it deeper into their footprints, but the existing coaxial footprints hold an invaluable advantage: They are largely paid off and they are readily available. On top they have redeemed themselves as far as their robustness and flexibility is concerned. DOCSIS was originally conceptualized in the 1990s to prolong the life-expectancy of coax-networks by about ten years. After a quarter century of relentless data-pumping the approach might be considered successful. Like most things in the universe, DOCSIS is far from immortal, but it is still kicking and packing quite a punch.

DOCSIS 4.0 – Pimp my DOCSIS 3.1

So, while network engineers across the planet are still heavily involved with the throws of DOCSIS 3.1 and DAA deployment, DOCSIS 4.0 hatches out of its egg. DOCSIS 4.0 aggregates refinements of and additions to the DOCSIS 3.1 standard and adds some important functions such as low-latency- and refined security-specifications. The targeted data rates are 10 Gbps in the downstream and 6 Gbps in the upstream. Essentially, DOCSIS 4.0 follows an approach that could be described as "Pimp-my-DOCSIS 3.1" under consideration of the technological boundary conditions of the coming years. DOCSIS 4.0 constitutes a compromise in an argumentation between large US-network operators on how to best realize symmetrical 10 Gbps. One side favors Full-Duplex DOCSIS, the other Extended Spectrum DOCSIS. Hence, DOCSIS 4.0 contains both approaches

– the classic compromise. Symmetrical 10 Gbps data rates indicate that by any means more data per unit time will be flowing up- and downstream compared to the present, posing the question on how to make it reality. Either the available spectrum used in up- and downstream gets extended to make room for more modulated data content, or the classic differentiation between up- and downstream spectrum is being reconsidered and simultaneous data traffic within the same spectrum at the same time is made possible. Both approaches increase the data throughput of the system, both have their own set of complications.

Extended-Spectrum DOCSIS

Extending the spectrum on coax to a certain extend collides with the physics of the cable itself. Coaxial cable is a low-pass device, meaning it attenuates higher frequencies stronger than lower ones. Figure 2 illustrates this principle, showing the typical attenuation of a coaxial cable in decibels (dB) across frequency for a spectrum of 862 MHz. The attenuation in dB rises approximately with the square root of frequency, the tilt-levels in the line-amplifiers are set to compensate for this increased attenuation with rising frequency. The attenuation at 1.8 GHz is about 40 percent higher than it is at 1 GHz. Active and passive equipment needs to be designed to support this higher portion of the spectrum. Higher attenuation at higher frequencies can be overcome with increased amplifier output levels, again resulting in higher distortion levels of linear and nonlinear types. These factors need to be considered in the standard.

DOCSIS 4.0 contains Extended-Spectrum DOCSIS, taking the downstream up to 1.794 GHz in the spectrum. Now, DOCSIS 3.1 already contained the option to extend the downstream this far, but globally the large network operators were much more in favor of the more popular 1.214 GHz downstream option in DOCSIS 3.1 when it came to the implementation of the technology in the field. Also, by far not all vendors designed their DOCSIS 3.1 equipment to support the extended downstream at that point in time. But the idea bears potential indeed, since 1.794 GHz is not supposed to be the last upgrade in spectrum. Currently technical approaches are being discussed to push the spectrum out to 3 GHz, even 6.4 GHz, within the framework set by the DOCSIS 4.0 specifications. Figure 3 is taken from a Commscope Research Paper, illustrating this idea. According to Figure 3, this approach would eventually increase the data throughput by 35 Gbps compared to an all-out DOCSIS 3.1 system driven to 1.794 GHz. The future sounds promising.

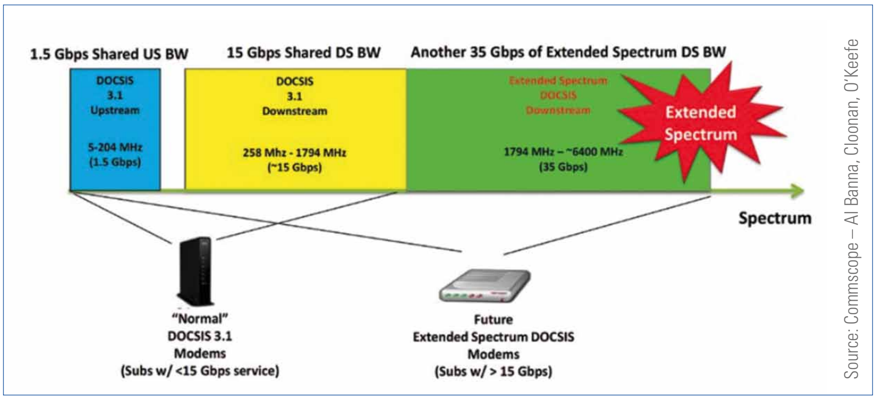

Figure 3: Extended Spectrum DOCSIS

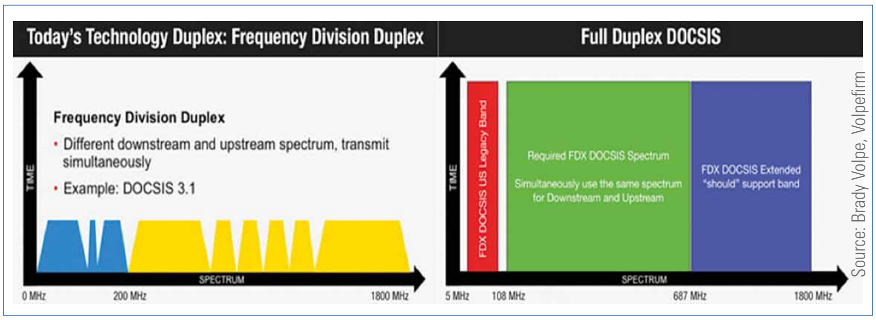

Figure 4: Frequency spectra for "legacy" DOCSIS 3.1 and for FDX

Full-Duplex DOCSIS

Next to Extended-Spectrum DOCSIS, Full-Duplex DOCSIS poses another pillar of the DOCSIS 4.0 standard. Full-Duplex DOCSIS is described in Annex F of the DOCSIS 3.1 standard, which is now taken over into DOCSIS 4.0. This enhancement of DOCSIS 3.1 technology enables theoretical symmetric throughputs of 10 Gbps in up- and downstream, however lately data rates of 10 Gbps downstream and 6 Gbps upstream are considered realizable in the field. For this purpose, the spectrum between 108 MHz and 684 MHz is designated for bi-directional traffic, next to keeping designated regions of spectrum for up- and downstream only. This principle is illustrated in Figure 4. Bi-directional traffic is enabled with complicated procedures requiring a lot of computation per unit time to be able to constantly determine how much up- and downstream transmissions interfere with each other and to then adjust the QAM-modulation orders of the subcarriers accordingly. Additionally, FDX-DOCSIS is based upon a N+0-architecture, meaning no amplifications of the electrical signals are being conducted behind the RemotePHY-nodes.

Signal Interference

The problem with simultaneous transmissions in up- and downstream on the same frequency, or subcarriers very close to each other, is the fact that the signals will interfere significantly in such a scenario. In a system based upon FDX-technology, a modem transmitting on an upstream frequency will most likely annihilate a simultaneous downstream reception on that frequency (or one close to it) at the neighbor's house, especially if the two modems are fed off the same tap. One needs to consider the differences in signal levels between up- and downstream transmissions close to the modem. HFC-networks are conceptualized in a manner accounting for a 50 dB to 60 dB signal attenuation between transmission and reception on the coaxial line. 60 dB corresponds to a power relation of factor 1000. Figure 5 illustrates this concept using water. The 20 m wave on the left side of Figure 5 represents an upstream transmission on a subcarrier frequency, the 2 cm ripple on the right stands for a simultaneous downstream reception on that same subcarrier (or an adjacent one) close by, for example at the neighbor's house introduced above. Since FDX-systems are based upon a part of the spectrum being used simultaneously in both directions, traditional filter-approaches separating up- and downstream cannot be applied to FDX-technology. Hence, the differentiation of up- and downstream traffic needs to be supported by directional couplers. Directional couplers, however, are not working optimally, meaning that a fraction of the upstream transmission's signal energy will leak into the above described downstream reception. The closer modems are located to each other on a trunk-line (C-line), the more profound these interferences arise. Back to the wave-example, only a fraction of the water of the 20 m wave leaking into the 2 cm ripple would result in the probable annihilation of the ripple. This corresponds to a negative signal-to-interference-ratio … more interference than signal power.

Sounding

A challenging environment to deliver an optimal data throughput in. For this purpose, the CMTS needs to determine on a very regular basis how much the downstream receptions of all modems on a trunk-line (C-line) are being disturbed by the upstream transmissions of a single modem. Full-Duplex DOCSIS uses the so-called sounding process, graphically illustrated in Figure 6 for the sounding of one modem on a trunk-line. The singer on tap 1 (emoji with circular shaped mouth) sends a special upstream sounding-signal into its upstream. Upon its reception the individual modems on the line report to the CMTS how much their downstream receptions were interfered by that signal. Herein distance is a key factor. The QAM-modulation orders are set accordingly. The lower the order of modulation, the more robust the signal is, but the less information it contains per symbol. Hereunto, the modems on a line are regularly divided into interference groups, also shown in Figure 6. Its complexity and its impressive data throughput capabilities have earned Full-Duplex DOCSIS the nickname "DOCSIS on steroids" in the USA. The US-American network operator Comcast has been undertaking field trials with FDX-technology in Connecticut and Colorado to do stress-tests in a feel-real environment. The first results look promising, so Comcast.

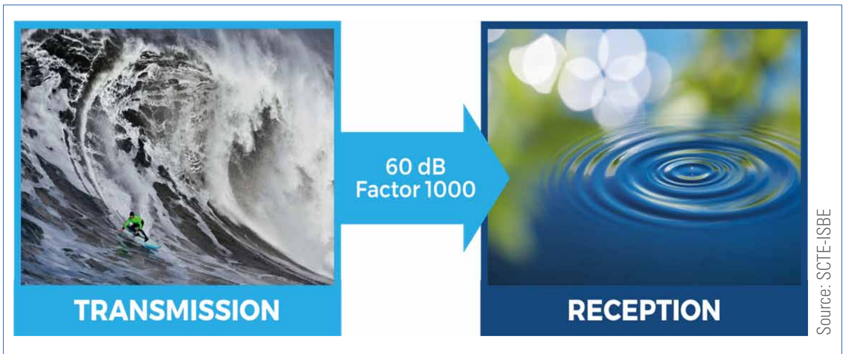

Figure 5: 60 dB difference in signal level illustrated

Low-Latency DOCSIS and Security

Low-Latency DOCSIS (LLD) is another important component of the DOCSIS 4.0-standard. An average latency in a DOCSIS 3.1 network is about 10 ms. Low-Latency DOCSIS reduces this time to 1 ms, which has a significant effect on the quality of video signals and online gaming as well as the processing speeds. Internet data traffic consists of a variety of different types of data streams. Some need a lot of bandwidth and are relatively robust against latency-issues. Others need a lot less bandwidth, but they need to get to the other end quickly. Video-streams or application downloads pose an example for the first type, online gaming signals for the second. Those parents in secret awe at what their offspring can whisk up on a Playstation-controller know the scenario from experience: "Guaranteed I was first and then the internet got stuck." (Annotation by the author: Should your offspring know what industry you apply your profession to, then that's the point when personal re-location becomes your top priority.) Low-latency DOCSIS separates data-streams according to their sensitivity to latency, since some types are more susceptible to it than others. Latency countermeasures are executed only on the data streams that have latency-related issues, increasing and optimizing the overall data rates to take advantage of the full capabilities of the spectrum. LLD-technology can be easily integrated into existing DOCSIS 3.1 systems by means of software upgrades and it is an integral part of DOCSIS 4.0 technology.

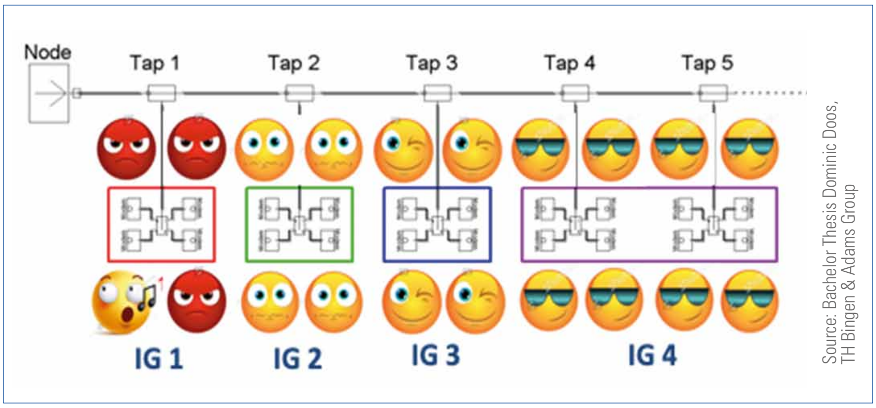

Figure 6: The DOCSIS Sounding-Process

DOCSIS 4.0 places intensified focus on system security against trespassing from the outside. Single algorithms shall not be part of the discussion here, instead a glimpse at the digital ecosystem of the near future will serve as an example for the gauntlet of complexity that is being hurled at the cable industry. We live in a world connected by networks and the trend to more and more complex networks will continue and intensify. Not only the seemingly unquenchable thirst for bandwidth will grow stronger, billions of internet-of-things devices and applications will send information into the upstreams, in combination with the roll-out of the 5G-standard into the field. Those can be industrial applications as well as everyday household items, such as thermostats or the infamous refrigerator ordering its own beer. Such an IoT-thermostat or fridge is connected to the cable modem across a wireless network (WLAN), and from thereon into the network operator's footprint and beyond. A computer- and network-savvy individual could potentially use the thermostat or the clever fridge to hack into the network operator's network, let alone the customer's home network. An approach to the problem is the aggregation of IoT-signals in a specially secured gateway. Securing access to a network under the boundary conditions posed by an internet-of-things environment is a complex endeavor taking high priority, for the process can never be considered concluded. Network operators need to constantly analyze new threats and react to them in their systems.

10G
The Next Great Leap for Broadband

CableLabs 10G-Initiative

DOCSIS 4.0 needs to be seen in conjunction with the 10G-initative by CableLabs and the cable industry, officially introduced in January 2019. 10G can be seen as a quiver of different technologies that in cooperation with each other enable the customer of the future to enjoy what is called a "seamless experience", with 10 Gbps symmetrical data rates. The customer of this not-too-far future lives in the above described complex world, with virtual reality data and innumerous IoT-applications screaming for bandwidth on our networks. The 10G-initiative, next to DOCSIS 4.0 for the coaxial parts of

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Vita

Dr.-Ing. Alexander C. Adams is managing director of Adams Network Engineering, a company of the Adams Group. Alex looks back upon 19 years of experience in the German, European and international cable industry. He is the European representative of SCTE – Society of Cable Telecommunications Engineers (US), as such part of the CableLabs Proactive Network Maintenance Research Group, and Instructor at the Jade University of Applied Science in Wilhelmshaven/Oldenburg, Germany. Alex holds a Bachelor- as well as a Master-of-Science degree in Electrical Engineering from the University of Hawai'i, USA, and a Doctorate degree (Dr.-Ing) from the Technical University of Darmstadt, Germany.

the networks, also included innovative approaches in fiber optic technology, such as coherent optics applications in the access levels of the networks. Traditionally, coherent optics are being used in long-haul optical transmissions, their application to the access level can increase optical throughput significantly.
Covid19 has hit the world's economy like an asteroid. This has had repercussions on the cable industry, but not as dramatically as on many other economic sectors. The numbers of service truck-rolls in the networks are at a high and engineers are feverishly working on the further segmentation and upgrade of the networks to meet the current demand for bandwidth. The social restriction policies have led to a significant proportion of the population working from their home offices, and one thing became apparent: it works! On top of that, the cable industry has proven indispensable. It can be assumed that after the pandemic has died down, a work week with a higher proportion of home office work will prevail, since travel-times and office space are being reduced in this manner. The problem a lot of network operators faced with the sudden hike in video conferences can be located in the upstream. Upstream capacities are being pushed by the numerous video-signals a lot of people are constantly and simultaneously streaming out of their living rooms. Currently, HFC-networks worldwide are allocating more spectrum to the downstream than to the upstream. Symmetric data rates of 10 Gbps would primarily benefit upstream capacities to serve customers' demand. The 10G-initaitive does hit the "Zeitgeist", the spirit of the time. Covid19 also showed that there is still a lot of engineering work laying ahead to get the indispensable fixed-wire cable industry sea-worthy for the technologically stormy years ahead. DOCSIS 4.0 in conjunction with the industry's 10G-initiative places a solid multi-tool into the hands of vendors and operators to do that work on the coaxial parts of their footprints. ■