MANAGING THE EVOLUTION TO DOCSIS® 3.1

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A TECHNICAL MIGRATION PLAN FOR LONG-TERM SUCCESS

AYHAM AL-BANNA, DISTINGUISHED SYSTEMS ENGINEER
& ARCHITECT, CTO OFFICE

TABLE OF CONTENTS

INTRODUCTION

There are multiple objectives that DOCSIS® 3.1 strives to achieve including: efficient support of 10+ Gbps of downstream and 1+ Gbps of upstream capacity; a significant cost per bit reduction relative to a DOCSIS 3.0 based solution; adaptation to different amounts of spectrum and plant conditions; operation on existing HFC networks and plant equipment; support for improved energy efficiency features; and an effective migration strategy that maximizes investment protection. While DOCSIS 3.1 equipment is still in the development and testing phase, service providers have already begun developing migration strategies to ensure that their networks are ready to take advantage of these new features when they become available.

This paper reviews the advanced features of DOCSIS 3.1 that increase network capacity, and then presents a technical network migration process that helps service providers prepare for the DOCSIS 3.1 era. In it, we discuss the steps that service providers can take to:

- Ensure that existing spectrum is being used efficiently
- Make new spectrum available for DOCSIS 3.1
- Leverage the system densities of CCAP solutions to expand network capacity
- Activate DOCSIS 3.1 features using available and new upstream and downstream spectrum
- Support network evolution with advanced optical technologies
- Utilize best practices to reduce noise and maximize the capacity of DOCSIS 3.1 systems

ADVANCED FEATURES THAT INCREASE NETWORK CAPACITY

The arrival of DOCSIS 3.1 offers great potential for increased capacities. This is mainly due to the fact that the new specifications utilize multiple cutting-edge technologies and features to yield higher throughputs. These technologies cover multiple aspects in the PHY and MAC layers and also introduce the “convergence layer” which is a sub-layer connecting the PHY and MAC layers. The core improvement in the PHY layer is the introduction of Orthogonal Frequency Division Multiplexing (OFDM) as a transmission technology and Low Density Parity Check (LDPC) codes as an error correction technology. MAC layer strengths and enhancements include backward compatibility and bonding with legacy channels, high resolution time stamps, and a decreased skew budget. The introduction of the convergence layer offers multiple benefits such as hierarchy Quality of Service (QoS) and support for multiple downstream modulation profiles. Note that support for backward compatibility and bonding with legacy channels avoids the simulcast tax that occurs when the same service is delivered via multiple PHY technologies.

DEALING WITH DENSITY

There are several technologies being proposed and developed to allow in excess of 20X service group density to be supported using the same head end rack space and power consumption characteristics over the next few years. On top of I-CCAP increases in density brought about through continued platform development, Techniques such as Remote PHY, remote CCAP, remote PMD and advanced digital optics along with advanced cloud and SDN based element management systems all provide potential solutions to wide variety of potential constraints that forward thinking planners must take into consideration. These topics are explored in more detail in later white papers in this series

A TECHNICAL NETWORK MIGRATION STRATEGY TO GUIDE DOCSIS 3.1 DEPLOYMENT

Due to the abundance of options and features from which service providers can choose [1], planning for DOCSIS 3.1 deployment can be both confusing and challenging. This section proposes a migration plan that evolves the networks from where they are at today to a state beyond the DOCSIS 3.1 time-frame. The plan is composed of multiple phases such that service providers can choose the appropriate phase and it's timing to align with their unique network configurations, service goals, and budgets. The multi-phase migration plan is described below.

- **PHASE 0:** Use the Available Spectrum Efficiently
- **PHASE 1:** Node Segmentations and Splits
- **PHASE 2:** Expand Systems With CCAP System Densities
- **PHASE 3:** Add More Capacity With DOCSIS® 3.1 Features
  - ***CATEGORY 1:*** Use DOCSIS 3.1 with existing spectrum
    - Higher order modulations
    - New FEC (LDPC)
    - New PHY (OFDM)
  - ***CATEGORY 2:*** Expand the US spectrum using High split as goal architecture
    - Mid-Split (85 MHz) as intermediate step
    - High-Split (204 MHz, 300 MHz, other)
  - ***CATEGORY 3:*** Expand the DS spectrum beyond 1 GHz (i.e., 1.218 GHz or 1.794 GHz)
- **PHASE 4:** unleash the Capacity of HFC Networks
  - Unleash frequency range limitations – RFoG
  - Unleash SNR – digital optics
- **PHASE 5:** FTTH Using EPON or Next Generation DOCSIS (Bandwidth Shared By Service Group)
- **PHASE 6:** FTTH Using Arrayed Waveguide Gratings (Point-To-Point Optical Ethernet)

It is important to note that phases 0-5 above can all share the same spectrum, while phase 6 is based on dedicated subscriber bandwidth. In addition, categories 1-3 of phase 3 can be performed in any order (or concurrently) depending on the service provider's needs and preferences.

The plan starts with phase '0' to indicate the 'free' cost of this step. It is important to utilize the available spectrum on current networks efficiently. In particular, optimizing the channel and modulation profile parameters by taking network noise and conditions into consideration can significantly increase performance and recover unutilized resources. DOCSIS 3.0 already contains many noise mitigation techniques and numerous channel and profile configurable parameters that can be exploited to yield higher throughputs. Some of the above tools and parameters include:

- Multiple access technologies such as Advanced Time Division Multiple Access (ATDMA) and Synchronous Code Division Multiple Access (SCDMA), where SCDMA helps in fighting impulse noise in the lower part of the spectrum
- Center frequency selection, symbol rate range, different modulation orders
- Reed-Solomon Forward Error Correction (RS-FEC) to correct up to 16 bytes, Codeword size selection
- 24-tap pre-equalization
- Long preambles, ability to adjust to longer/more powerful preambles
- Proprietary noise mitigation techniques (e.g., Ingress Noise Cancellation), ATDMA Interleaving
- SCDMA Interleaving, de-spreading, spreading, Trellis Coded Modulation (TCM), Maximum Scheduled Codes (MSC) feature, Selectable Active Codes (SAC) feature
- Many others, such as Last Codeword Shortened (LCS), max burst size, scramble seed, and differential encoding

Phase 1 concurs with the common practice of node splits performed regularly by MSOs to reduce the service group size in order to offer higher average subscriber bandwidth and reduce noise funneling. Node split and segmentation will remain a useful tool for many years to come because the number of nodes is still manageable, which leads to moderate-cost node split process. In addition, the user average bandwidth is still low enough such that the time duration before another node split is needed can be long enough to result in a reasonable return on investment.

Phase 2 recommends the use of high-capacity devices (i.e., CCAP), which can offer significant reductions in cost, space, and power consumption. This will enable service providers to save rack space and power while supporting converged services and faster speeds to more customers.

Figure 1: E6000 Converged Edge Router (CER)

Phase 3 is related to the deployment of DOCSIS 3.1 equipment, where higher throughputs can be obtained via high modulation orders, noise-robust Orthogonal Frequency Division Multiplexing (OFDM) [2] [3] [4], LDPC, and extending the downstream and upstream frequency ranges. Note that DOCSIS 3.1 service does not have to be deployed in a single step but can be implemented over multiple phases (or categories) as shown in the proposed migration plan. These categories can be executed concurrently, sequentially, or in any order that fits the service provider's plans, networks, and budget.

The ability of OFDM to exclude or mute subcarriers will enable seamless deployment of DOCSIS 3.1 service where "holes" within the OFDM signals are created to accommodate legacy channels [4]. The potential capacity gain that can be offered by DOCSIS 3.1 systems when compared to DOCSIS 3.0 systems is provided in tables 1 and 2 for the downstream and upstream directions, respectively.

The top part of Table 1 shows capacity improvements of DOCSIS 3.1 (D3.1) over the maximum frequency range supported by DOCSIS 3.0 (D3.0), where the gain can reach up to 22% assuming an MSO SNR operating margin of 2 dB, DOCSIS 3.1 DS 8K FFT, and DOCSIS 3.0 downstream spectral efficiency of 6.33 bps/Hz (assuming QAM256, 0.90 FEC (RS/TCM), Annex B symbol shaping, etc.). The bottom part of the same table shows improvements with network upgrades via extending the downstream spectrum beyond what is supported by the DOCSIS 3.0 specifications offering a gain of 129%. Table 1 assumes DOCSIS 3.1 OFDM/LDPC efficiency of 7.7038 bps/Hz (CP, pilots, PLC, NCP, symbol shaping, LDPC, BCH, etc.).

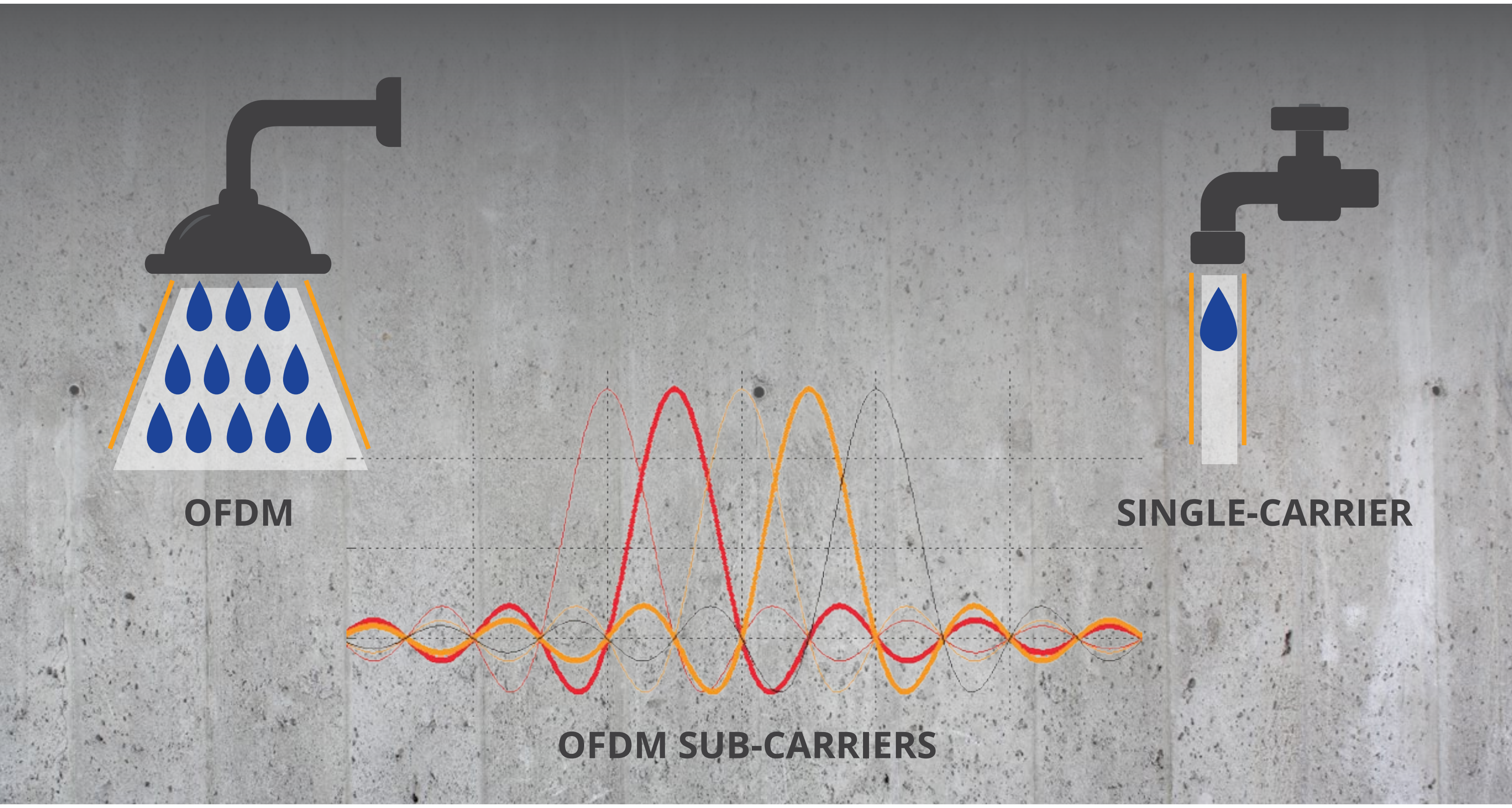

Figure 2: OFDM as an example of multi-carrier systems

The top part of Table 2 shows capacity improvements over the maximum frequency range supported by DOCSIS 3.0 (D3.0), where the gain can reach up to 79%. The bottom part of the same table shows improvements with network upgrade via extending the upstream spectrum beyond what is supported by the DOCSIS 3.0 specifications offering a gain of gain of 779%. Table 2 assumes an MSO SNR operating margin of 2 dB, DOCSIS 3.0 upstream spectral efficiency of 4.15 bps/Hz, assuming QAM64, no FEC (high SNR), and 25% symbol shaping. Additionally, the Table 2 assumes DOCSIS 3.1 4K US FFT block size with OFDMA/LDPC spectral efficiency of 7.359 bps/Hz (CP, pilots, symbol shaping, etc.). Future papers will provide more detailed analysis regarding capacity numbers shown in Tables 1 and 2.

Note that the analyses in Tables 1 and 2 were performed for SNR distributions for all customer devices on an N+6 network with AM optics. The gain values increase when the SNR distribution is assumed for gateway devices only that are after one splitter in the home network. The numbers further improve as the MSO moves to digital optics and smaller cascades. Finally, the use of smaller MSO SNR operating margin can lead to higher potential gain.

DS Spectrum (MHz)	D3.1 DS Throughput (Gbps)	MAX D3.0 DS Throughput (Gbps)	Gain %
108-1002	6.89	5.66	22
108-1794	12.99	5.66	129

Table 1. Potential downstream capacity gain offered by DOCSIS 3.1 over DOCSIS 3.0

US Spectrum (MHz)	D3.1 US Throughput (Gbps)	D3.0 US Throughput (Gbps)	Gain %
5-85	0.59	0.33	79
5-204	1.46	0.33	342
5-396	2.9	0.33	779

Table 2. Potential upstream capacity gain offered by DOCSIS 3.1 over DOCSIS 3.0

Phase 4 is an anchor phase that occurs with or after DOCSIS 3.1 deployment (phase 3). This phase can unleash the capacity of DOCSIS networks via different techniques. One method is to deploy RF over Glass (RFoG) technology over HFC networks to offer very high data rates enabled by the unconstrained non-overlapping downstream and upstream spectra while avoiding the replacement of deployed DOCSIS equipment (cable modems and CMTSs). DOCSIS 3.1 together with RFoG can offer unprecedented downstream and upstream speeds for many years to come while offering equipment investment protection [5]. Another method to unleash the capacity in phase 4 is the use of digital optics instead of analog optics. Analog optics can be the limiting factor of HFC network performance when reaching its maximum capacity because analog optics have limited SNR values. Digital optics, on the other hand, can offer several benefits including very high SNR values, performance that is independent of distance or spectral loading, support for more wavelengths, simpler operations, and the ability to capitalize on the pricing of Ethernet optics. The higher SNRs values that are offered by digital optics will further increase the value of D3.1. Different distributed architecture implementations can offer the digital optics that includes remote PHY and remote CCAP.

1 GHz RF over Glass (RFoG) System at 32 HHP Per Optical Segment

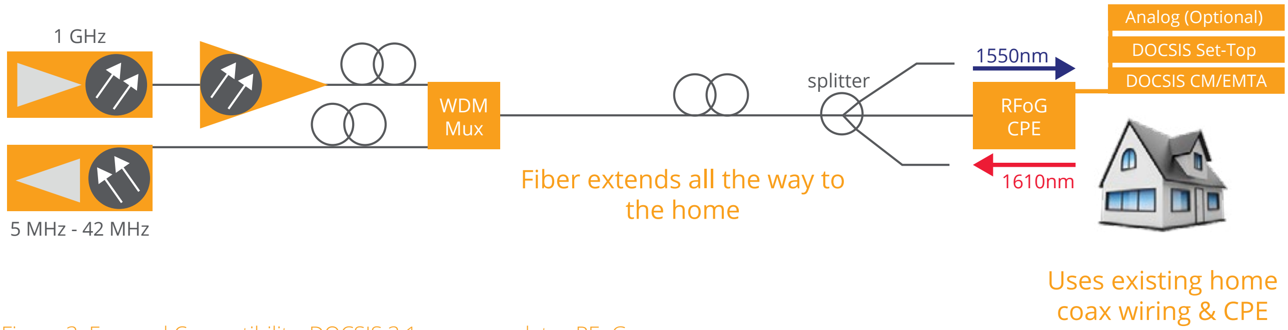

Figure 3: Forward Compatibility: DOCSIS 3.1 accommodates RFoG

Phases 5 and 6 provide network evolution through the use of advanced fiber-based technologies. Some MSOs may decide to skip phase 5 and jump straight to phase 6 as they may be able to utilize the large capacities offered by the different methods in phase 4 for extended periods of time. Phase 6 offers very high dedicated throughputs to subscribers to enable the transmission of rates needed by applications such as holograms, machine-to-machine applications, etc.

BEST PRACTICES FOR MAXIMUM DOCSIS® 3.1 CAPACITY

Different features such as variable bit loading, enabled by DOCSIS 3.1, can result in optimization of the modulation order taking the plant's SNR (on a subcarrier basis) into consideration to yield the maximum possible capacity while avoiding the need for large SNR margins. Therefore, service providers will be able to operate their networks at much smaller SNR margins than they are currently using with DOCSIS 3.0. Low SNR margin is not the only way to increase the capacity of HFC networks using DOCSIS 3.1. In particular, optimizing the various OFDM and LDPC parameters to the plant's noise and channel characteristics is crucial. These parameters, which can be optimally selected to result in maximum capacity, include subcarrier spacing and FFT size, CP size, windowing guard time, preamble pattern, frequency interleaver settings, time interleaver depth, FEC rate and codeword size, variable bit loading modulation profiles, and channel width.

The low SNR margin and high modulation orders enabled by DOCSIS 3.1 lead to a very sensitive operation environment, where healthy networks with high SNR values are required to maintain reliable service. Healthy networks can be achieved when: plant equipment including connectors, amplifiers, taps, and cables are well maintained; loose connections are terminated to reduce noise; aging components such as lasers, amplifiers, and passives are proactively replaced; and automatic network monitoring tools are heavily utilized to observe dynamic network conditions. Following proper installation practices by technicians in the field and inside the homes can also help significantly in reducing noise, interference, and signal attenuation on cable networks.

In addition to the outside plant, there are several home network implications in the DOCSIS 3.1 era that require heightened awareness. Specifically, consumers should take note of how their service is affected when they re-wire their home networks and add/remove new connections within their residences. Consumers may appreciate that the newly-introduced gateway style architecture, where the cable modem is placed at the point of entry of the house or at most after one splitter, leads to best performance. On the other hand, burying the cable modem behind many splitters can result in degraded performance. Consumers must also understand that leaving loose or un-terminated connectors in their homes may affect their service and may also affect their neighbors as they present an entry point for noise and interference in the system.

CONCLUSIONS

As service providers prepare for the DOCSIS 3.1 era and the advanced new features that it brings, they must consider the steps they'll take to prepare and migrate their networks to ensure that they are ready when the time comes for deployment. In this paper, we outlined the advances DOCSIS 3.1 is leveraging to significantly expand network bandwidth. We also offered a phased technical network evolution plan that can help service providers make the most of their available spectrum, unlock new spectrum, take advantage of high-density CCAP solutions, activate new DOCSIS 3.1 features on both existing and new spectrum, and plan for future optical network system enhancements. In addition, we proposed several best practices for creating and maintaining healthy network conditions in support of a DOCSIS 3.1 environment that is more sensitive to noise and interference than its predecessor.

RELATED READINGS

- *Migration Paths to Full CCAP Functionality white paper* The cable industry has begun a multi-year migration toward a common platform for video and data. While CCAP defines a particular architecture, there are numerous ways to reach that converged endpoint. Drawing from the real-life experience that service providers have had to date, this paper recognizes the diversity and ongoing evolution of the headend and existing cable infrastructures; focusing on three paths to full CCAP.
- *DOCSIS 3.1 Plans and Strategies webinar recording* In this 60-minute webcast, sponsored by ARRIS and Cisco and hosted by CED, attendees learn some of the operational and training considerations that need to be looked at ahead of 3.1 deployments. Topics discussed include: An overview of the DOCSIS 3.1 specification, including OFDM, MAC layer, downstream and upstream PHY, and FEC, the transition from DOCSIS 3.0 to 3.1 and the timeline for deployments, and equipment considerations

MEET OUR EXPERT: AYHAM AL-BANNA

When it comes to DOCSIS-based cable access networks, Ayham Al-Banna is at the forefront of innovation and expertise. At ARRIS, his role is to define the architecture and guide the evolution of the company's CCAP and CMTS solutions, and he is the holder of several granted and pending patents in this area. But his influence truly transcends the cable industry. Through his work on the DOCSIS 3.1 PHY committee and its covert predecessor the Advanced MAC PHY committee, Ayham has helped shape this exciting new specification from the very beginning.

And when he's not busy inventing the future, he's sharing his knowledge with his peers at IEEE events and industrial conferences, presenting new ideas to customers to help them architect better cable access networks, and inspiring the minds of tomorrow through his work as an Advisory Council member for Miami University and his adjunct teaching role at several other universities.

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