DOCSIS 3.1: Scaling Broadband Cable to Gigabit Speeds

Belal Hamzeh, Mehmet Toy, Yunhui Fu, and James Martin

ABSTRACT

The cable industry has recently released the DOCSIS® 3.1 specifications which are the fifth generation of the DOCSIS family of specifications. In this article, we introduce the building blocks of DOCSIS 3.1 and highlight the specific capabilities that will help broadband cable systems scale to support gigabit-per- second network speeds. While this article is a tutorial on DOCSIS 3.1, an important objective is to engage and motivate the academic community to participate in research related to emerging DOCSIS-based cable systems. We identify a set of open issues that represent challenges and opportunities for academic researchers to explore.

INTRODUCTION

In the United States, cable companies serve about 50 million broadband access subscribers, 40 percent more than DSL and fiber subscribers.[1] A major reason for this trend is due to the continued evolution of cable technology. Current cable networks are based on the Data-Over-Cable System Interface Specification (DOCSIS) version 3.0 (DOCSIS 3.0) [1]. Cable Television Laboratories, Inc. (CableLabs), the research and development organization for multiple system operators (we refer to this simply as network operators), has recently released an update to DOCSIS, referred to as the DOCSIS 3.1 specifications [2, 3].

Figure 1 illustrates a modern broadband cable network that applies to both DOCSIS 3.0 and 3.1 systems. Hybrid fiber coaxial (HFC) systems are designed to push content over fiber with the fiber terminating as close to end users as possible. A cable modem termination system (CMTS) interacts with cable modems (CMs) over the coaxial cable. The CMTS resides in the head-end that houses network operator facilities while the CM resides at the subscriber's home residence or business. A subscriber is likely to have multiple devices that consume traditional broadcast video such as televisions and digital video recorders and that use broadband data service such as IP delivered video content and Internet applications. The DOCSIS standard specifies the media access control (MAC) and the physical (PHY) layer procedures.

The network operator's Operational Support System (OSS) contains, among other capabilities, various necessary services including Dynamic Host Configuration Protocol (DHCP), a configuration file and software download server for CMs, a Network Time Protocol server, and a certificate revocation server. The combined functionality of these servers allow for the proper connection and operation of the CMs with the DOCSIS network.

DOCSIS 3.1 was developed to provide subscribers with service speeds up to 10 Gb/s downstream and up to 1 Gb/s upstream. The most significant area of change provided by DOCSIS 3.1 involves spectrum access at the physical layer. Motivating application directions for DOCSIS 3.1 might include:
- Higher video quality such as 4K
- Higher levels of on-demand video
- Network operator provided digital video recorder services;
- Backhaul network service to support cellular operator WiFi offloading;
- Emerging applications enabled by advances in virtual environments, cloud computing, and machine-to-machine communications.

The central focus of this tutorial article is to explore how future cable systems based on DOCSIS 3.1 specifications will scale to support gigabit-per-second network speeds. We introduce the building blocks of modern cable systems provided by the current DOCSIS 3.0 specifications. We highlight DOCSIS 3.1 extensions and present open issues and challenges. An important objective of this article is to identify research issues related to emerging DOCSIS-based cable systems.

This tutorial article is organized as follows. The next section provides a brief overview of the DOCSIS 3.0. Next, we DOCSIS 3.1 enhancements, paying particular attention to modulation and coding profile management and to active queue management (AQM). We highlight specific challenges and identify several research questions. We conclude the article with a brief summary.

DOCSIS BACKGROUND

The DOCSIS 3.1 specifications define the fifth generation of high-speed data-over-cable systems and is part of the DOCSIS family of specifications developed by CableLabs. It builds upon the previous generations of DOCSIS specifications commonly referred to as the DOCSIS 3.0 and earlier specifica-

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[1] http://www.leichtman-research.com/press/081514release.html.

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The coaxial medium provides in excess of 3 GHz of usable bandwidth (in ideal signal-to-noise conditions). Frequency division multiplexing is used to isolate bandwidth for downstream (CMTS to CM) and upstream (CM to CMTS) communications. In current DOCSIS 3.0 systems, downstream communications assumes 6 MHz (8 MHz in Europe) channels which are located in the frequency range between 108 MHz and 870 MHz (and optionally 1002 MHz). Most of the spectrum is allocated for traditional broadcast video. Some downstream channels are allocated to support Internet access. Downstream channels can achieve, assuming 256 quadrature amplitude modulation (QAM), data rates of 42 Mb/s per 6 MHz channel. The CMTS uses asynchronous time division multiplexing to share downstream bandwidth between multiple end-stations. In DOCSIS 3.0 systems, packets sent over the downstream channel are segmented based on a 188 byte MPEG frame format that includes 4 bytes of header and a 184 byte payload. The use of MPEG frames facilitates multiplexing the coaxial medium for use with both data and broadcast video. The CM rebuilds IP packets that arrive over the downstream channel.

Upstream channels are 3.2 or 6.4 MHz wide and are located within the frequency range between 5 MHz and 42 MHz (65 MHz in Europe, and optionally 85 MHz in North America). Upstream communications, assuming 64 QAM and a 6.4 MHz channel, can achieve data rates of 30 Mb/s. Additional upstream physical layer operating modes were added in the DOCSIS 2.0 standard. Asynchronous Time Division Multiple Access (ATDMA) and Synchronous Code Division Multiple Access (S-CDMA) to provide communications options that can improve robustness and increase data rates over impaired channels.

In a DOCSIS network, downstream and upstream traffic is classified and managed by service flows. A service flow provides a unidirectional transport of packets over the cable network. Traffic is shaped, policed, and managed based on service quality parameters that were defined for the service flow. A service flow typically includes multiple IP flows. By default, a subscriber is provisioned with two service flows: a downstream service flow that represents all downstream user traffic and an upstream service flow that represents all upstream user traffic. A further example involves a subscriber configuration that supports toll quality IP telephone service and best effort data. This could be provisioned with four service flows: one each for the upstream and downstream VoIP signaling and one each for upstream and downstream aggregate consisting of all the best effort data traffic.

To support higher data rates, DOCSIS 3.0 specifications introduce channel bonding which requires the CMTS to schedule downstream traffic from services flows over potentially more than one channel. A bonding group is an abstraction that represents the group of channels that are available to a service flow. CMs, equipped with multiple tuners and transmitters, are assigned a set of downstream and upstream channels. A common configuration involves 8 bonded downstream channels and 4 bonded upstream channels which can support data rates

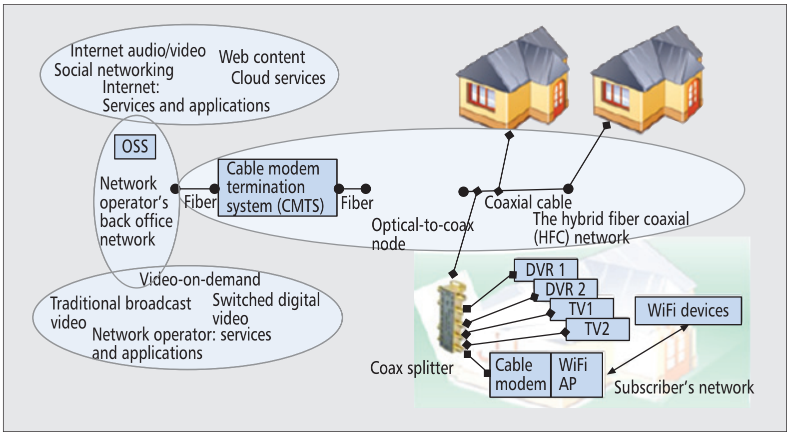

Figure 1. Modern broadband cable network.

up to 320 Mbit/s downstream and 120 Mbit/s upstream. The downstream scheduler, which operates at the CMTS, can allocate bandwidth to service flows from any channel that is in the bonding group assigned to the service flow.

Support for upstream bonding groups is more challenging than downstream due to the request-grant mechanism. Prior to DOCSIS 3.0, a CM was limited to a single outstanding request for bandwidth. This stop-and-wait behavior does not scale to higher speeds. Therefore, DOCSIS 3.0 defined a new request-grant mechanism referred to as continuous concatenation and fragmentation (CCF). CCF allows a CM to send multiple requests for bandwidth concurrently. The CMTS stripes data grants over the set of upstream channels in the service flow's bonding group. A process referred to as segmentation allows the CM to stream data over the bonding group. The CM organizes user data (i.e., packets) into segments which include a sequence number allowing the CMTS to reorder the segments if necessary.

Since every CM tuned to an upstream channel is a potential sender, controlling access to the upstream channels is considerably more complex than downstream operation. The upstream channel is time division multiplexed with transmission slots referred to as minislots. Permission to transmit data in a block of one or more minislots must be granted to a CM by the upstream schedule which operates at the CMTS. The CMTS grants mini-slot ownership by periodically transmitting Upstream Bandwidth Allocation Map messages, which we refer to as MAP messages, on the downstream channel. In addition to ownership grants, the MAP also typically identifies some minislots as contention slots in which CMs may bid for quantities of future minislots. To minimize collisions in the contention slots, a non-greedy back-off procedure is employed. When a CM has a backlog of upstream packets it may also "piggyback" a request for minislots for the next packet in the current packet.

Quality of Service Mechanisms

Many applications have distinctive network service requirements which in turn requires broadband networks to provide quality of service (QoS) mechanisms. VoIP, online gaming, and video streaming are just a few examples of such applications. Additionally, the migration to an all IP video broadcast

Parameter	Value
Lower Band Edge	Mandatory: 254 MHz Optional: 108 MHz
Upper Band Edge	Mandatory: 1218 MHz Optional: 1794 MHz
Signal Type	OFDM
Subcarrier Spacing	50 kHz, 25 kHz
FFT Time Duration	20 μs (50 kHz subcarriers) 40 μs (25 kHz subcarriers)
FFT Size	50 kHz: 4096 FFT; 3800 Maximum active subcarriers 25 kHz: 8192 FFT; 7600 Maximum active subcarriers
Minimum OFDM Channel Bandwidth	24 MHz
Maximum OFDM Channel Bandwidth	192 MHz
Number of Independently configurable OFDM channels	Minimum of 2
Modulation Type	Mandatory: BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM, 128-QAM, 256-QAM, 512-QAM, 1024-QAM, 2048-QAM, 4096-QAM Optional: 8192-QAM, 16384-QAM

Table 1. Downstream channel parameters.

network makes it critical for the network to provide service guarantees. Each service flow is assigned a scheduling service which is associated with a set of service attributes. For downstream service flows, attributes include traffic priority, traffic shaping parameters (maximum sustained traffic rate and maximum traffic burst), and minimum traffic rate. Because upstream data rates are typically lower than downstream, a set of specific network services have been defined to support application service requirements. As an example, the Unsolicited Grant Service (UGS) is intended to support upstream latency sensitive applications that generate fixed size data packets on a periodic basis, such as Voice over IP. UGS offers fixed size grants (in bytes) on a real-time periodic basis. The default upstream service flow provisioned for each subscriber is treated as a best effort service. The details of the upstream and downstream schedulers are not specified in the DOCSIS specifications and consequently are left for vendor differentiation. Please refer to [1] for further information on DOCSIS services and configuration parameters.

DOCSIS 3.1 System Enhancements

In this section, we provide an overview of the main enhancements provided by the DOCSIS 3.1 specifications. We focus in particular on profile management and AQM.

DOCSIS 3.1 Physical Layer

The DOCSIS 3.1 specifications adopt the use of Orthogonal Frequency Division Multiplexing (OFDM) in the downstream channel and Orthogonal Frequency Division Multiple Access (OFDMA) in the upstream channel. The DOCSIS 3.1 specifications supports 25 kHz and 50 kHz subcarrier spacing options on both channels; the downstream supports channel bandwidths from 24 MHz up to 192 MHz while the upstream channels' bandwidths range from 6.4 MHz to 96 MHz.

The DOCSIS 3.1 specifications extend the range of frequencies that can be used over the coaxial medium. Prior to DOCSIS 3.1 specifications, upstream channels operate in specific band ranges such as 5–42 MHz, 5–65 MHz or 5–85 MHz. The DOCSIS 3.1 specifications introduce two additional bands at 5–117 MHz and 5–204 MHz. Although the use of specific band ranges is typical, for operational reasons a network operator might support other upstream band ranges such as 5-80 MHz by taking advantage of the highly granular channel bandwidths enabled by OFDM signaling. On the downstream, the lower band edge can be as low as 108 MHz (assuming the upstream upper band edge is less than 108 MHz), while the upper band edge can extend up to 1794 MHz.

To maximize the overall spectral efficiency of the system (i.e., to operate as close to the Shannon limit as conditions allow) the DOCSIS 3.1 specifications introduce higher order modulation schemes, with mandatory support up to 4096-QAM on the downstream and 1024-QAM on the upstream. The DOCSIS specifications 3.1 also allow for optional support of 8192-QAM and 16384-QAM on the downstream and 2048-QAM and 4096-QAM on the upstream; this allows the network operator to maximize network capacity and take advantage of signal quality improvements.

Table 1 and Table 2 summarize the downstream and upstream channel parameters. The tables indicates that 4096 or 8192 point Fast Fourier Transform (FFT) is used for downstream and that 2048 or 4096 point FFT is used for upstream. To further enhance spectral efficiency, forward error correction based on low density parity check (LDPC) coding is applied along with interleaving of code words in time and in frequency prior to transmission in both downstream and upstream.

Proactive Network Maintenance — The DOCSIS 3.1 specifications provide enhanced diagnostic tools and statistics monitoring and reporting for proactive network maintenance (PNM). The statistics and measurements are collected at the CMs and the CMTSs distributed within the network. The goal for PNM is to rapidly and accurately characterize, maintain and troubleshoot the upstream and downstream cable plant. Information such as mean error rates per subcarrier, noise power, and forward error correction statistics analyzed over large timescales can be used by the network operator to proactively identify potential performance issues and respond accordingly.

The measurements for PNM are in-service measurements, which mean they are transparent to the end-user without disruption of service.

The PNM functionality provides the network operator with a centralized view of the complete network health and can help predict network faults before they cause a service disruption. The collected measurements and statistics enable the network operator to have embedded functionalities including network analyzers, spectrum analyzers, vector signal analyzers in addition to various functionalities provided by the collected metrics. A detailed description of the collected measurements and statistics is provided in [3].

DOCSIS 3.1 MAC Layer

In this section we summarize the main MAC layer functional extensions introduced with DOCSIS 3.1 specifications.

Profile Management — By using OFDM/OFDMA, DOCSIS 3.1 systems can vary the modulation details over all subcarriers, effectively optimizing the transmission to account for different channel conditions observed by different CMs. In its simplest form, a profile defines a set of subcarriers and associated modulation orders that are assigned to a CM. On the downstream, a CM is required to support 4 profiles for live traffic and 1 test profile for each OFDM channel. For upstream, a CM is must support at least 2 profiles for each OFDMA channel. Profiles are assigned on a per CM basis, thus CMs will be able to operate using the highest modulation order possible according to the signal-to-noise ratio (SNR) of the channel (or profile-assigned subcarriers). Profiles are channel dependent but independent of service groups. For example, if a CM is operating with two downstream channels, the profiles for each channel can be set independently. This can potentially increase system efficiency. This is in contrast to previous versions of the DOCSIS specifications where CMs were required to use the same profile (or modulation order) within the same service group.

Figure 2 illustrates the use of five downstream channels along with four profiles (referred to as Profiles A, B, C, and D). The downstream scheduler must be "channel aware" in that it determines which profile should be used for each transmission. Channel quality information is periodically sent by the CMs to the CMTS. The CMTS selects the best burst profile for a CM based on current channel conditions and on the set of profiles available to the CM. Over longer time scales, the CMTS can update the set of profiles available at a CM. The specification indicates that Profile A will offer a robust configuration through the use of relatively low bit loading to ensure all CMs can receive it. This profile will be used by the CMs for initialization and to carry broadcast MAC management messages. A test profile will be used to check whether a CM can receive a certain profile before the profile is assigned to the CM and live traffic sent on it. The methodology to select the profile configuration, which profiles to assign to a CM, and when to switch between profiles is not specified in the DOCSIS 3.1 specification. As with scheduling, this functionality is meant to be vendor specific.

For upstream, the CMTS specifies the specific channel as well as the specific burst profile that a CM should use for a particular grant.

Parameters	Value
Frequency ranges	5–42 MHz 5–65 MHz 5–85 MHz 5–117 MHz 5–204 MHz
Signal Type	OFDMA
Subcarrier Spacing	50 kHz, 25 kHz
FFT Time Duration	20 ms (50 kHz subcarriers) 40 ms (25 kHz subcarriers)
FFT Size	50 kHz: 2048 FFT; 1900 Maximum active subcarriers 25 kHz: 4096 FFT; 3800 Maximum active subcarriers
Minimum OFDMA Occupied Bandwidth	6 MHz for 25 kHz subcarrier spacing 10 MHz for 50 kHz subcarrier spacing
Maximum OFDMA Channel Bandwidth	96 MHz
Number of Independently configurable OFDMA channels	Minimum of 2
Modulation Type	Mandatory: BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM, 128-QAM, 256-QAM, 512-QAM, 1024-QAM Optional: 2048-QAM, 4096-QAM

Table 2. Upstream channel parameters.

CMs use a profile denoted as IUC 13 for initialization and then can be assigned to a different profile with higher bit loading for live traffic. A second upstream profile may be assigned to the CM for test purposes or for live traffic.

Downstream multicast supports the use of multiple profiles. The CMTS should attempt to conserve bandwidth by selecting the highest bandwidth profile common to the CMs that are members of the multicast group. If this is not possible, or if a CM requests to join a session but does not support the current session profile, the CMTS can either move all CMs in the session to a lower bandwidth profile or it can replicate the multicast on multiple profiles.

Active Queue Management (AQM) — Bufferbloat in access networks has received significant attention recently [4]. Bufferbloat is caused by network equipment that is provisioned and configured with large unmanaged buffer queues. Its effects are persistently large queue levels that in turn lead to large and sustained packet latency. Active Queue Management (AQM) has long been considered a solution to bufferbloat. Controlled Delay (CoDel) and Proportional Integral controller Enhanced (PIE) are two recently proposed AQM algorithms that address Random Early Detection (RED) issues [5, 6]. Both are delay-based as they proactively drop packets to maintain an average packet queue delay that is less than a configured latency

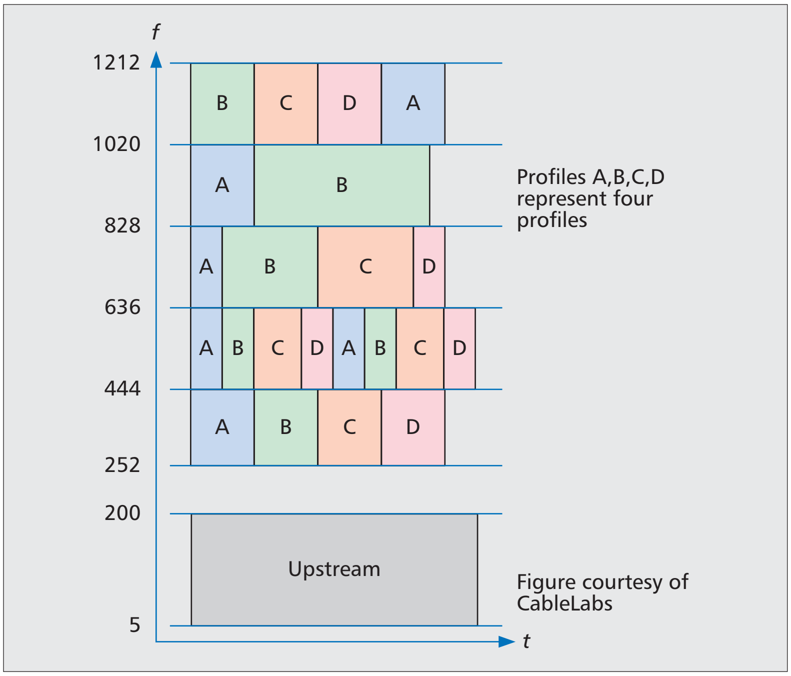

Figure 2. DOCSIS spectrum management.

target. The DOCSIS 3.1 specification requires AQM turned on by default for both downstream and upstream service flows. Further, the CM must support PIE AQM on a per-upstream service flow basis. For downstream, the CMTS is required to support a published AQM. Presumably this will be PIE or CoDel.

The DOCSIS 3.1 specifications introduce other MAC enhancements which we briefly describe below. A complete description of the enhancements is available in [2]. Hierarchical QoS (HQoS) adds an aggregate service flow abstraction allowing an intermediary level of scheduling located between aggregates of service flows and bonding groups. The concept is similar to class-based queueing where different groups of flows (perhaps organized by organization or type of traffic) is allocated a percentage of available bandwidth [7]. Scheduling within one class has no effect on flows that are scheduled within a different class. An energy management mode specifically targeting CMs uses OFDM downstream channels. The CM supports multiple levels of CM functionality and operation, with each level offering reduced capabilities but with lower power requirements. A new DOCSIS Timing Protocol allows CMs to maintain time synchronization with the CMTS within 3000 nanoseconds.

Deployment Discussion

The DOCSIS 3.1 specification is backwards compatible with DOCSIS 3.0 (or earlier) specifications, where a DOCSIS 3.1 CMTS must interoperate seamlessly with DOCSIS 3.0, DOCSIS 2.0 and DOCSIS 1.1 CMs and a DOCSIS 3.1 CM must interoperate seamlessly with a DOCSIS 3.0 CMTS. The CMTS is required to support time and frequency multiplexing of OFDMA and Single Carrier QAM signals (DOCSIS 3.0 signaling) on the upstream. Depending on the scheduling methodology used by the CMTS, DOCSIS 3.1 and DOCSIS 3.0 signaling can be frequency division, time division or time and frequency division multiplexed which provides the highest efficiency in spectrum utilization.

The various generations of video technology deployed in operators' networks define the required video transmission formats over the network. In the extreme case an operator may have to broadcast traditional video channel in multiple forms such as analog, digitally using MPEG2 in both standard and high definition formats, and in IP format for DOCSIS capable set-top boxes. As network operators migrate their access network to all IP (including video), the amount of duplicate broadcasts that has to be maintained is greatly reduced. For example, once an operator decides to no longer support analog, there is no longer the need to have commonly viewed content broadcast in both analog and digital formats. Further, network operators might need to broadcast the same content over a 6 MHz channel as well as over an OFDM channel. The transition from analog video, to digital video to IP video is happening but at different rates depending on the number of legacy devices deployed in the network. Once beyond this migration period, emerging DOCSIS systems will greatly increase the spectral efficiency of the coaxial medium.

Emerging Issues

There are many areas related to the DOCSIS 3.1 specifications that are fertile for innovative research. We briefly identify several examples.

DOCSIS 3.1 Scheduling — The DOCSIS specifications purposely do not address specific scheduling techniques for either the downstream or the upstream. We expect that some form of channel aware scheduling will be supported by a CMTS. The following simple downstream example is meant to illustrate the concept. We consider two subscribers that have the same service plan in a DOCSIS 3.1 network. Assume that one subscriber is poorly connected and is assigned a profile that is optimized to mitigate low signal-to-noise level. The second subscriber is well connected and is assigned a profile that can achieve high data rates over the channel. If these are the only two flows in the network and all packets are the same size, simple round robin downstream scheduling at the CMTS will allocate bandwidth such that the throughput achieved by both flows will be the same (this is referred to as max-min fair allocation [8]). Unfortunately, this underutilizes spectrum capacity. An alternative allocation strategy referred to as 'max throughput' would favor the better connected flow but might starve the poorly connected subscriber. This scheduling complexity has been well studied in wireless networks. A widely accepted compromise is proportional fair scheduling that applies a slight bias towards the better connected subscriber but ensures the poorly connected subscriber also receives a share of available bandwidth [9].

High Bandwidth Applications and Issues — It is well known that TCP has issues in certain network environments. Well studied examples include TCP over wireless and TCP over high speed networks. TCP over cable also has been studied. In fact much of the early research in cable networks focused on TCP issues [10, 11]. Better performing DOCSIS upstream support along with more robust TCP implementations have addressed these early concerns. However, DOCSIS 3.1 systems that offer gigabit-per-second data rates over networks that involve new delay-based AQM mechanisms will require further study to better understand and engineer future deployments.

Wireless Last Hop — Broadband access is likely to involve wireless as the last hop network. A natural evolution for cable networks is to extend services over wireless networks.

Ethernet over DOCSIS — Extending carrier grade Ethernet over DOCSIS is an open issue. The challenge is matching the precise timing and quality required by Ethernet to available DOCSIS profiles and service qualities.

Autonomic Capabilities — Network fault characterization based on PNM measurements and statistics. This can be viewed as a "big data" problem where software needs to analyze large amounts of information searching for early signs of errors, faults, network performance issues, and subscriber quality of experience issues.

Innovative Economic Models — If current tiered pricing models are scaled to support gigabit per second data rate services, the top tiers (i.e. tiers that offer the highest service rates) might not be widely used due to the high cost. New economic models are required.

Virtualization and Software Defined Networking — In the future, cable systems involving virtualizations of CM and CMTS functionality are likely as this can simplify equipment and reduce equipment cost. Further simplification of equipment and automation of provisioning are also expected with applications of Software Defined Network (SDN) concept to DOCSIS systems.

Conclusions

The DOCSIS 3.1 specifications define a flexible and highly extensible technology that is capable of meeting the growing capacity requirements of broadband networks. The main enhancements include more flexible and efficient use of coaxial spectrum. These capabilities will allow broadband cable to scale to gigabit speeds. The more challenging issue might be related to economics. Innovative applications and network services must synergistically evolve to ensure appropriate economic factors are in place so that gigabit-per-second broadband access services see wide usage.

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Biographies

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