Over the past two decades, cable television has largely supplanted over-the-air broadcast as a TV distribution medium, at least in most urban and suburban areas. Several years ago, enterprising companies concluded that they could leverage the extremely wide bandwidth of cable TV systems required to deliver broadcast-quality television as a high-speed conduit for broadband data communications. This led to the birth of the cable modem.

Early cable-modem equipment was vendor proprietary, so interoperability between different vendors’ products was largely nonexistent. To promote interoperability, Cable Labs (the cable TV industry research arm) developed the Data Over Cable Service Interface Specification (DOCSIS), an IP-centric, point-to-multipoint standard that quickly replaced the proprietary solutions that preceded it. DOCSIS has now become the accepted cable standard.

Although it’s successful, DOCSIS 1.0 is a data-only specification, with no support for voice or other latency-sensitive multimedia applications. The newly released DOCSIS 1.1 remedies this with quality-of-service (QoS) support for proper handling and delivery of multimedia and voice applications. DOCSIS has thus provided a standards-based way to deliver a rich variety of data types across cable TV systems.

Many areas still exist, however, that don’t have cable TV service. To fill these gaps, other carriers are fielding fixed-wireless broadband networks. The attraction that wireless technology holds for carriers is its ability to reach tens of thousands of subscribers. Although it was intended for coaxial networks, many manufacturers of fixed-wireless communications equipment have found that they can effectively leverage the DOCSIS standard for the wireless environment, provided that they understand and compensate for the unique qualities and sometimes hostile environment of radio-frequency communications.

With the necessary wireless enhancements, DOCSIS 1.1 is destined to play an important role in the delivery of high-quality multimedia across fixed-wireless communications networks.

With this approach, we can take advantage of all the DOCSIS technology modules that exist in the market today, allowing the wireless platform to migrate toward emerging services such as Internet protocol multicasting and voice over IP (VoIP). In this article, we describe the state of current technologies that have made fixed-wireless access a viable and compelling choice. We also discuss some emerging technologies that will bring exciting new fixed-wireless services and capabilities into homes and small businesses in the near future. Fixed-wireless spans a significant portion of the spectrum from ultrahigh frequency (UHF) to unlicensed bands to multichannel–multipoint distribution service (MMDS), 3.5 GHz, and low multipoint distribution service (LMDS) at frequencies up to 40 GHz. Here, we primarily concentrate on bands under 11 GHz, including the 3.5-GHz band.

What is DOCSIS?

DOCSIS is based on the transport of IP packets, and it has reserved protocol data units (PDUs) to support asynchronous transfer mode (ATM) transmissions. It’s a demand-assignment media access control (MAC) protocol. DOCSIS inherits various properties from Packet Reservation Multiple Access (PRMA) and Distributed Queuing Request Update Multiple Access (DQUMA) and has provisions for QoS guarantees. We can use its reser-
DOCSIS 1.1 builds on DOCSIS 1.0 and adds new features that are necessary for applications that require special treatment from the network. DOCSIS 1.1 has additional features, which let the operator offer ATM-like services, such as

- QoS guarantees for data and voice–video applications, service flows, classifiers, scheduling types, and dynamic-service establishment;
- fragmentation, which segments large packets, simplifying bandwidth allocation for constant bit rate (CBR) type services;
- concatenation, which bundles multiple small packets to increase throughput;
- security enhancements such as Baseline Privacy Plus, which builds on the Baseline Privacy available in DOCSIS 1.0 and provides authentication as well as in-line Data Encryption Standard encryption and decryption;
- encryption support for multicast signaling;
- payload header suppression, which suppresses unnecessary Ethernet and IP header information for improved bandwidth use; and
- VoIP support.

Thus, the key additions are

- multiple service-class support,
- dynamic-service establishment,
- support for real-time services, and
- cryptographic modem authentication.

The multiple service-class support makes it possible to define more than one kind of network access for a wireless modem. We can browse with predefined network settings and, at the same time, use the modem to make voice calls. This wasn’t possible under DOCSIS 1.0 because there wasn’t enough detail in the specification to support multiple service classes in a vendor-independent way.

Dynamic-service establishment offers a way to supply valuable services on demand. For example, on a VoIP telephone, the system would reserve bandwidth only when we place a call.

The real-time support provides a consistent...
way to support time-critical applications. For example, in a VoIP application, it’s possible to define how much delay and jitter the system can tolerate. Because the time-critical services are much more valuable than normal Internet service provider services, making sure that a modem is authenticated correctly becomes important. DOCSIS 1.1 defines a cryptographic way to reliably identify modems.

The situations that require DOCSIS 1.1 support are

- A mixture of transaction-processing or real-time traffic (both of which are sensitive to latencies), with low-priority Web browsing and bulk file transfer on a user-by-user basis. For example, DOCSIS 1.1 would let a user’s business-related data be set at a higher priority than casual Web browsing. In general, situations like this require multiple service IDs (SIDs) stored within each modem—a defining characteristic of DOCSIS 1.1.

- Integrated enterprise backbones, combining data traffic, teleconferencing, and telephony over a single channel. DOCSIS 1.1 enables so-called network “policy management” decisions.

- A mixture of protocols that require short transit times to avoid protocol timeouts and retransmissions when intermingled with bulk traffic.

**DOCSIS operation**

DOCSIS 1.1 protocol has six services that support differing QoS requirements when different organizations share channel bandwidth and want to apportion costs through service-level agreements (SLAs). CBR services are one example of this type of tiered bandwidth-allocation application.

To support QoS, DOCSIS defines six QoS services:

- unsolicited grant service (UGS),
- unsolicited grant service with activity detection (UGS-AD),
- real-time polling service (rtPS),
- non-real-time polling service (nrtPS),
- best-effort service, and
- committed information rate (CIR) service.

Table 1 shows the QoS parameters, access modes, and applications for using these services.

The headend, (an oblique base station), must provide fixed-size data grants at periodic intervals to the UGS flows. However, the reserved bandwidth may be wasted when a corresponding UGS flow is inactive. For the UGS-AD flows, the headend employs an activity-detection algorithm to examine the flow state. Once a flow changes from an active to an inactive state, the headend reverts to provide periodic request polling.

The system polls rtPS and nrtPS flows through the periodic request polling. However, the nrtPS flows receive few request polling opportunities during network congestion, while the rtPS flows are polled regardless of network load.

For the best-effort service, a station must use a normal-reservation or immediate-access mode to gain upstream bandwidth. Vendors can define a CIR service in many different ways. For example, using the nrtPS service with a reserved minimum traffic rate could configure it. To meet the QoS requirements, the headend must adopt an admission control mechanism and an algorithm for scheduling among the different services to reduce
QoS violation probability. Each QoS flow exactly matches one QoS service.

If a station has special bandwidth requirements not specified in the QoS profile, it can dynamically request a service by sending a dynamic service addition request (DSA-REQ) message to the headend. Moreover, after the system establishes a QoS flow, the payload header suppression mechanism can be adopted to efficiently use the bandwidth by replacing the repetitive portion of the payload headers with a payload header index.

DOCSIS has become an International Telecommunications Union-Telecommunications (ITU-T) standard, and various standards bodies have widely simulated and tested it. Moreover, it has been designed for scalability to large customer deployments. It has built-in security, authentication, and management functions. Finally, it can work with different physical layers—for example, single carrier quadrature amplitude modulation and multicarrier orthogonal frequency division multiplexing (OFDM).

Although DOCSIS is designed to carry IP packets, it can be part of an access network that has, for example, an ATM backbone. The MAC protocol on the shared-medium portion of an access network need not have the same packet format as on the backbone network. Also, we can’t translate the QoS guarantees on the backbone network directly to the shared medium portion just because the network protocol is the same. As long as the mapping exists between the backbone network QoS parameters and the DOCSIS QoS parameters, we can achieve an end-to-end guarantee of the QoS parameters in a statistical sense. In other words, the assumption that we need an ATM MAC to satisfy ATM QoS guarantees in an end-to-end manner is incorrect. QoS guarantees are the mechanism with which we satisfy SLAs statistically. Through the QoS mechanisms it possesses, the DOCSIS protocol can satisfy customer SLAs.

Radio-frequency impairments

Before discussing what modifications DOCSIS requires in order for us to use it in wireless applications, let’s review what impairments a radio-frequency communications link must contend with. As with any communications link, the key figure is the signal-to-noise ratio (SNR), also known as the carrier-to-noise ratio (CNR). The greater the signal (short of overloading, of course) and the less noise (and distortion products) the better. Unfortunately, several radio-frequency phenomena work to reduce the signal and increase noise, which isn’t the direction we want to go.

One of the most significant challenges, particularly for the MMDS bands, is multipath. Unlike the situation in a cable environment, radio propagation in free space is 3D. The signal will be reflected by buildings, aircraft, and any structures or surfaces that are large in relation to the signal’s wavelength. The receiver will pick up the main signal (the direct-path signal) and those that arrived on various other, longer reflected paths (see Figure 1). Because of the difference in arrival times for the various path lengths, these other signals can either add to or detract from the main signal’s amplitude. In a worst-case scenario, they can be 180 degrees out of phase and thus cancel each other out completely (see Figures 2 and 3).

Yet another impediment is frequency offset. In an ideal world, both the receiver and transmitter would be tuned to precisely the same frequency. In practice, there will usually be slight offsets between the two. Crystal drift (due to temperature sensitivities, for example) can create frequency shifts. Crystal aging produces more long-term frequency variation.

Wide ranges of interference problems exist that can occur in a radio-frequency environment. This interference can come from the communications system (known as self-jamming) or from other sys-
tems. One form of self-jamming occurs when the subscriber’s transmissions interfere with the receiver section. Another type of self-jamming is caused by other system users. Examples of interference from other systems include the harmonics of broadcast systems or portable devices as well as the intermodulation products of several transmitters.

A radio-frequency system can create interference for other systems. To keep this under control, the FCC requires that a transmitter’s spurious emissions at a 3-MHz offset (from the designed transmitter frequency) be no greater than $-60 \text{ dBc}$ (decibels down from the carrier frequency).

**Modifications required for wireless applications**

When designing wireless systems, engineers must consider the major assumptions made by DOCSIS with respect to the upstream and downstream channels’ performance. For downstream performance, the CNR in a cable TV downstream 6-MHz channel shouldn’t be less than 35 dB, while the typical multipath (microreflections in the cable) shouldn’t be greater than 1.5 ms. The carrier-frequency offset between a headend modulator and the customer premises equipment (CPE) demodulator is negligible, but the receive power level at the CPE is relatively fixed. Upstream performance assumptions include an SNR in the cable upstream channel (including ingress noise) of greater than 25 dB and a typical multipath of less than 1.5 ms. The carrier-frequency offset is negligible, and the receive power level at the Universal Mobile Telecommunications System (UMTS) remains constant.

Broadband wireless-network characteristics differ from cable deployments in some key areas. Regarding downstream performance, there’s a limited SNR that’s mainly determined by the transmit level, antenna gain, distance, link budget, and the receiver-noise figure. Narrowband and burst interference exists from other transmitters (harmonics and intermodulation of personal communication system [PCS], analog–mobile phone system [AMPS], TV, radar, and so on) as do interferences from cochannels and reused frequencies. Multipath can be higher than 5 ms. A higher carrier-frequency offset may exist between the modulators and demodulators, along with a higher dynamic range and more fading, which we must accommodate.

In a design’s upstream portion, broadband wireless designers normally encounter a limited SNR, which is mainly determined by the CPE transmit power, antenna gains, narrowband and burst interference rates, and multipath values. The carrier-frequency offset between the headend modulator and CPE demodulator can be up to 50 kHz. Receive power level at the base station may fade by more than 20 dB. There’s a high dynamic range requirement from the propagation path losses.

The different characteristics of the wireless network relative to the cable TV network indicate that the DOCSIS standard, as is, will limit large-scale broadband wireless deployment unless we modify it at both the MAC and physical layers.
The modifications reflected are for the close-line-of-sight (CLOS) and next-generation non-line-of-sight (NLOS) system.

The physical-layer scheme should be robust enough to enable reliable operation over a wireless network. Designs should address the SNR and multipath requirements in particular.

For the upstream channel, DOCSIS uses quadrature phase shift keying (QPSK) or 16-bit quadrature amplitude modulation (16-QAM) techniques. System designers can set either modulation scheme during equipment configuration settings. DOCSIS specifies five upstream symbol rates—160, 320, 640, 1,280, and 2,560 ksym/s (kilosymbols per second). Designers can use the lower symbol rates to increase the robustness against multipath because it has less impact on lower symbol rates than it does on higher symbol rates. The upstream must be capable of power compensation.

The downstream direction also needs additional robustness. For the downstream, DOCSIS specifies 256- and 64-QAM, giving high data rates but also yielding brittleness in the challenging radio-frequency environment. We can’t use 256-QAM in a wireless application, and for 64-QAM, DOCSIS specifies a single symbol rate of 5.056 Msymbols/s. Designers can make the system more tolerant with additional, more robust QAM constellations (QPSK and 16-QAM) and lower symbol rates. Adding lower symbol rates on the downstream, together with a more powerful (approximately 10 ms) equalizer, will provide the required multipath robustness in the downstream.

In addition to the single-carrier approach that QPSK or QAM offer, the multicarrier OFDM approach is another way to provide a more robust physical layer. Because of its multicarrier properties, OFDM has greater immunity to multipath interference. Another method of defeating multipath is antenna diversity; incorporating this technology on the receive side of the wireless modem termination system (WMTS) will produce higher reliability. Advances in antenna technologies represent a key enabler for NLOS operations. Two principal techniques that are emerging include multiple-in-multiple-out (MIMO) processing and beam steering.

MIMO technology implies diversity at the transmitter’s output and the receiver radios’ input at both the base station and subscriber transverters. At the transmitter, the data signal is multiplexed at the base station onto two or more transmission paths feeding into individual antennas. (The details of antenna diversity are beyond the scope of this article.) The NLOS systems will incorporate some of these features. The cost of antenna diversity at the base station isn’t a burden because it can be allocated across the entire distributed base. The increase in cost is unappealing to the system operators at the CPE notwithstanding the increase in the available downlink capacity.

An important requirement for the wireless product in the near future is being able to operate the CPE in a NLOS environment through obstructions such as trees, buildings, and walls. Current wireless products can handle CLOS operations, in which operation is possible even with partial obstruction through one or two trees (see Figure 4). The CLOS transverter is typically mounted on the rooftop, possibly on a pole, to achieve sufficient height to clear local obstacles. Long-range operation up to 28 miles is possible with this configuration. These products are based on the physical layer adopting the single-carrier QAM scheme.

In the near future, complete NLOS operations will be possible using outdoor transverters and indoor modems, due to emerging technologies based on the physical layer adopting multicarrier OFDM. Users will typically install the outdoor unit on a building’s eaves or sidewall, pointing in the base station’s general direction (see Figure 5). NLOS outdoor unit equipment will be able to receive extremely weak signals in the presence of significant multipath reflections arising from foliage and buildings. The key advantage to this solution is that it allows quick installation. Because an installer can implement the transverter by standing on the ground or using a stepladder, the ultimate result is cheaper truck rolls. The typical operating range for this configuration is one to three miles, which implies a microcellular deployment.

The next evolution of a NLOS product is an integrated unit that is deployed indoors and includes both the transverter and modem. Again, vendors will use similar emerging technologies as in the

Figure 4. CLOS operation is typical of the wireless products currently available. For CLOS operation, there must be a clear line-of-sight path between the base station antenna and customer’s antenna (although partial obstruction by one or two trees shouldn’t be a problem).
prior evolution that will allow NLOS operation. In this case, NLOS implies first-wall penetration, where principally only multipath exists. Another key technological development with this solution is a highly integrated approach in the design of both the transverter and modem to yield a cost-effective, compact product. Because of its compactness and NLOS capability, the consumer will install the CPE, avoiding the need for truck rolls. The operating range for this product is approximately 1 to 1.5 miles, which requires a picocell deployment.

Adaptive modulation

Adaptive modulation is another key technology that’s critical to both CLOS and NLOS operations. Adaptive modulation involves automatically choosing the appropriate modulation level based on local signal-to-noise conditions at each subscriber. If the SNR is high, then the system automatically chooses the highest modulation level, such as 64- or 16-QAM, which provides high spectral efficiency and hence high data rates in a given channel. (For example, 16- and 64-QAM yield efficiencies as high as 3 and 5 b/s/Hz (bits per second per hertz) for pure data transfer, respectively.) If the SNR is low, then the system chooses QPSK. The advantage of this approach is that it’s performed on a noninterference basis. That is, subscribers select the best modulation for their local condition without affecting other users in the service area.

With adaptive modulation, the burden and risk of designing the optimal network up front is essentially removed from the cell planner. The cell planner simply designs the network assuming that it only implements QPSK. The system then automatically balances the network using adaptive modulation. With this approach, the network’s overall capacity can effectively double over a similar area operating QPSK only. Increasing spectral efficiency to this extent lets the service provider derive more revenue from the same spectral resource, which in turn provides a much healthier business plan—that is, an accelerated return on investment.

The system must support adaptive modulation in both the downstream and upstream direction to realize the full benefit. Therefore, the underlying physical layer that is implemented in the modem design at both the base station and subscriber site must switch automatically from one modulation level to another on a packet-by-packet basis. This implies that the site requires a form of burst receiver, or a derivative thereof, at both ends. The technology exists today for upstream adaptive modulation, while technologies are currently being developed to support downstream adaptive modulation. The same techniques also apply to adaptive forward error correction.

MAC modification

As we previously discussed, the proposed MAC interface is based on an IP-centric MAC, as contained in DOCSIS 1.1 specifications—DOCSIS radio-frequency interface (RFI) specification SP-RFIv1.1-I06-001215—and is designed to support all existing and known future IP-based services, working in frequency bands from 2 to 11 GHz and in OFDM environments.

The wireless modifications and extensions to DOCSIS 1.1 will provide the additional level of robustness required in a typical wireless environment. Here are the highlights of the extensions and modifications to DOCSIS 1.1:

- Considering the large number of possible downstream schemes, automatic channel acquisition will be maintained by periodically transmitting downstream channel descriptor (DCD) messages over the downstream channels. These messages let the user acquire the information regarding all the applicable downstream channels—that is, channels serving the user’s and neighboring sectors.
- Upstream channel descriptor (UCD) messages will be modified to define the OFDM and MIMO parameters.
- The priorities scheme will be used for an optimized selection of downstream and upstream channels, based on both system-wide load balancing and per-modem, channel-dependent performance.
- A modified allocation scheme will enable a flexible allocation for OFDM and MIMO physical
layers, including allocation for multiple modems on the same OFDM symbol or on parallel MIMO channels, limited bandwidth allocation for improved link budget, and flexible use of the MIMO bandwidth.

- Bidirectional adaptive modulation will enable more efficient and flexible use of the available channels. With the limited availability of MMDS channels, we don’t want to use different channels for different physical-layer schemes. Using different physical-layer schemes on the same channel is more efficient and the allocation between the physical-layer schemes is more flexible and dynamic.

- Downstream adaptive modulation is supported by multiple profiles in the DCD message and added feedback information in the ranging-response message. This implements smart algorithms for the downstream profile selection per modem or per SID.

- Upstream adaptive modulation is supported by defining multiple parameters sets that permits using different profile based on both interval usage (as in DOCSIS 1.1) and modems.

- Automatic repeat request (ARQ) is a retransmission protocol that we can implement at the link layer of a wireless system to recover from packet errors. Using ARQ on the downstream and upstream enables reliable data delivery on dynamic fading channels, typical for NLOS and CLOS systems. The ARQ also permits a reduced fading margin and the use of higher throughput physical-layer parameters (QAM level and FEC combinations). Instead of using a more robust scheme, we can use a less robust but higher throughput approach, using the robust scheme only when necessary—for example, for retransmissions. ARQ with adaptive modulation makes the MAC more robust. We won’t use ARQ for real-time services like voice. For data flows that aren’t real time, ARQ can significantly improve performance with minimal complexity and little added cost.

- The modified UCD message and the DCD message support multicell and multisector configurations.

**Standards in industry**

We can’t emphasize enough that standards can lead to lower product costs because we can manufacture the required components in volume. A standardized interface and protocol will ensure that multiple vendors will manufacture the product, which is the key consideration for service providers looking for a second source. Standardized products also ensure interoperability because service providers can mix and match different products in the same environment. Standards are now emerging for the below 11-GHz broadband wireless access (BWA) space. The first generation of systems being deployed in North America use cable-modem derivatives. The two major players in the industry use either a proprietary cable modem derivative or a DOCSIS standard-based wireless system.

Standards groups and consortiums are defining the second generation of wireless modems. The newer NLOS technologies, centered on OFDM, will provide significant capabilities. It’s safe to say that standards will be more critical to the wide acceptance for this next generation of systems.

In terms of standards activity, the Broadband Wireless Internet Forum (which includes companies such as Broadcom, Cisco Systems, Spike, Texas Instruments, Analog Devices, California Amplifier, Vyyo, and Toshiba) have standardized point-to-multipoint systems, which is also based on the DOCSIS 1.1 MAC.

The IEEE 802.16.3 and ITU are two international technical forums that let vendors collectively define a standard for next-generation modems. The 802.16 group faces challenges in the pursuit of a standard from the time-to-market perspective. The Wireless Communication Association International (WCAI) is another forum available to service providers who wish to exercise some influence on the direction of standards activities. The WCA is promoting an interoperable standard called 1Standard. They’re targeting it to be based on an OFDM physical layer and a DOCSIS 1.1-based MAC. WCA’s 1Standard committee is likely to give the IEEE input. The Internet Engineering Task Force, established to address Internet-specific technical problems, also addresses the standards problems because it’s closely related to DOCSIS development, especially in the area of management information bases (MIBs) for the management functions.

For both first- and next-generation systems, it’s critical to leverage existing standards where possible. DOCSIS is the accepted cable standard, and vendors have effectively adopted and implemented it to support BWA products below the 11-GHz range. With this approach, we can take advantage of all the DOCSIS technology modules in the mar-
ket today so the wireless platform can migrate toward emerging services such as VoIP and IP multicasting.

**Conclusion**

The DOCSIS MAC is based on demand-assignment type protocols, including the useful features of PRMA and DQRMA. DOCSIS has provisions for guaranteeing QoS, built-in security, authentication, and management functions. It’s a mature, widely implemented and tested MAC. This makes it an excellent foundation on which to build enhancements that will work well in the wireless environment. We can meet the challenges that the wireless links face by adding enhancements such as extending frequency tolerance, adding more equalization, increasing dynamic range, supporting multiple modulation and symbol rates and by adding new features such as adaptive modulation and coding, ARQ, and antenna diversity. With these advancements, DOCSIS has the potential to be successful in the wireless environment.

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