



# Advanced Physical Layer Technologies for High-Speed Data Over Cable

## Introduction

Since its introduction in the 1990s, Data Over Cable Service Interface Specification (DOCSIS<sup>®</sup>) has emerged as the leading standard for high-speed data transmission over cable networks. DOCSIS 2.0 is the latest addition to the DOCSIS family. DOCSIS 2.0 adds an improved upstream channel physical (PHY) layer. Downstream functionality remains largely unchanged, retaining 64- and 256-QAM (quadrature amplitude modulation) capability.

This paper highlights the major differences between DOCSIS 2.0 and earlier versions, and discusses advantages of deploying the advanced PHY technology available today. This paper summarizes numerous field and lab tests that demonstrate how cable modem termination systems (CMTSs) and cable modems using advanced PHY silicon perform in the presence of impairments. Also discussed is the fact that a number of advanced PHY features benefit existing DOCSIS 1.0 and 1.1 cable modems. Many advanced PHY functions – for instance, ingress cancellation – occur in the CMTS and are modem agnostic. That means it is not necessary to replace older modems with new DOCSIS 2.0 modems to reap some of the benefits of advanced PHY.

## DOCSIS Background

DOCSIS 1.0 provided the cable industry with standards-based interoperability, which means *certified* cable modems from multiple vendors work with *qualified* CMTSs from multiple vendors. DOCSIS 1.1 added a number of features, including quality of service (QoS), more robust scheduling, packet classification, and other enhancements that facilitate voice services.

DOCSIS 1.0 and 1.1, collectively known as DOCSIS 1.x, support two downstream modulation formats: 64-QAM and 256-QAM. This is summarized in Table 1.

**Table 1.** DOCSIS Downstream Modulation Formats and Data Rates

Modulation Format	Channel Bandwidth, MHz	Symbol Rate, Msym/sec	Raw Data Rate, Mbps	Nominal Data Rate, Mbps
64-QAM (DOCSIS)	6	5.056941	30.34	~27
256-QAM (DOCSIS)	6	5.360537	42.88	~38
64-QAM (Euro-DOCSIS)	8	6.952	41.71	~37
256-QAM (Euro-DOCSIS)	8	6.952	55.62	~50

DOCSIS 1.x supports several upstream data rates, ranging from a low of 320 kbps to a high of 10.24 Mbps. It also supports two modulation formats – quadrature phase shift keying (QPSK) and 16-QAM – as well as five upstream radio frequency (RF) channel bandwidths. See Table 2.

**Table 2.** DOCSIS 1.x Upstream Modulation Formats and Data Rates

Channel Bandwidth, MHz	Symbol Rate, Ksym/sec	QPSK Raw Data Rate, Mbps	QPSK Nominal Data Rate, Mbps	16-QAM Raw Data Rate, Mbps	16-QAM Nominal Data Rate, Mbps
0.200	160	0.32	~0.3	0.64	~0.6
0.400	320	0.64	~0.6	1.28	~1.2
0.800	640	1.28	~1.2	2.56	~2.4
1.6	1280	2.56	~2.4	5.12	~4.8
3.2	2560	5.12	~4.6	10.24	~9.0

DOCSIS 1.1 added some enhancement to upstream data transmission robustness with eight-tap adaptive equalization. Adaptive equalization is performed in the modem using pre-equalization. The CMTS sends equalization coefficients to the modem, and the transmitted upstream signal is “pre-distorted” or pre-equalized with a response that is the approximate inverse of the actual channel response.

DOCSIS 2.0 brought the cable industry higher upstream per-channel data throughput, increasing the maximum to as much as 30.72 Mbps. DOCSIS 2.0 supports 64-QAM in the upstream – plus 8-QAM and 32-QAM – and optionally supports 128-QAM trellis coded modulation (TCM) encoded modulations for synchronous code division multiple access (S-CDMA) channels.

### Summary of Key DOCSIS 2.0 Features

- 30.72 Mbps maximum upstream per-channel data throughput in a 6.4 MHz bandwidth channel
- Added upstream 8-QAM, 32-QAM, 64-QAM, and 128-QAM TCM
- Improved forward error correction (FEC)
- Programmable byte interleaving
- Adaptive equalization extended to 24 taps

### Additional Features in Cisco Advanced PHY-Equipped CMTS Upstream Receivers

- Direct sampling (digital burst receivers)
- Ingress cancellation

The increased per-channel data throughput available with DOCSIS 2.0 technology is accomplished using higher orders of modulation and greater RF channel bandwidth. Higher orders of modulation require more robust data transmission. This is especially true in the often hostile reverse path RF spectrum used in most cable networks. To facilitate more robust upstream data transmission, DOCSIS 2.0 introduced *advanced PHY*.

### What is Advanced PHY?

Advanced PHY, or advanced physical layer, is a suite of CMTS and cable modem upstream performance enhancements that enable higher orders of modulation and increased throughput. The advanced PHY umbrella includes better adaptive equalization, burst acquisition, and FEC compared to DOCSIS 1.x. Also included are programmable byte interleaving and ingress cancellation. As well, the upstream burst receiver silicon used in advanced PHY-equipped CMTSs incorporates a digital receiver, allowing lower implementation margin.

## Advanced PHY Performance Concepts

*Implementation margin* is the difference, in decibels (dB), between theoretical and real-world performance in an additive white Gaussian noise (AWGN) environment. For example, assume the theoretical carrier-to-noise ratio (C/N) to achieve  $1.0 \times 10^{-6}$  bit error rate (BER) with a given type of upstream data signal is 21 dB. In practice, a CMTS with an analog upstream receiver comprising a tuner – local oscillator, mixer, various filters, and gain stages – and first-generation burst receiver silicon might actually need, say, 25 dB C/N to get  $1.0 \times 10^{-6}$  BER. In this example, the implementation margin is 4 dB. That is, the upstream data signal's real-world C/N performance needs to be 4 dB better than theory to achieve a given BER.

*Processing gain* is the performance improvement, in dB, that occurs when using techniques such as FEC or ingress cancellation. Consider an example in which ingress cancellation is turned off. Under this scenario, a carrier-to-interference ratio (C/I) of 21 dB might yield  $1.0 \times 10^{-6}$  BER. Assume that turning ingress cancellation on allows the same  $1.0 \times 10^{-6}$  BER when the C/I is only 11 dB. The processing gain in this example is 10 dB.

## Advanced PHY Improvements

Among the upstream PHY improvements are increased symbol rates, higher-order modulation formats, and the previously mentioned better adaptive equalization, burst acquisition, FEC, and programmable byte interleaving. DOCSIS 2.0 PHY incorporates two multiplexing techniques: advanced time-division multiple access (A-TDMA) and S-CDMA. Both technologies provide additional upstream capacity and improved robustness over DOCSIS 1.x upstream PHY.

A-TDMA is a direct evolution of DOCSIS 1.x PHY, which uses TDMA multiplexing. S-CDMA is a form of multiplexing that allows multiple modems to transmit simultaneously through the use of different subsets of a 128 orthogonal code set. A-TDMA and S-CDMA provide the same maximum data throughput, although one may perform better than the other under specific operating conditions.

## Increased Upstream Capacity

DOCSIS 2.0 provides a 50-percent increase in spectral efficiency and 300-percent increase in the throughput of a single RF channel compared to DOCSIS 1.x. The new upstream PHY supports a raw data throughput of up to 30.72 Mbps via a single 6.4 MHz bandwidth digitally modulated signal. Under DOCSIS 1.x, the maximum data throughput was 10.24 Mbps in a 3.2 MHz channel bandwidth.

These enhancements increase the network capacity and improve statistical multiplexing performance, thus reducing the cost per bit for the service provider. Requirements for more symmetric throughput are being driven by services and applications such as voice over IP (VoIP), videoconferencing, peer-to-peer networking, and gaming. DOCSIS 2.0 with its greater per-channel upstream throughput supports this trend with higher-order modulation formats and increased upstream channel RF bandwidth.

## Increased Transmission Robustness

Accommodating higher-order modulation formats in the often hostile upstream RF spectrum requires more robust data transmission. Advanced PHY technology facilitates enhanced transmission robustness to deal with impairments such as AWGN, impulse, and burst noise.

## Better Adaptive Equalization

DOCSIS 2.0 supports a symbol (T)-spaced adaptive equalizer structure with 24 taps, compared to 8 taps in DOCSIS 1.1. This allows operation in the presence of more severe multipath and micro-reflections, and accommodates operation near band edges where group delay is usually a problem. 24-tap adaptive equalization also works well in situations where cumulative group delay occurs in lengthy amplifier cascades.

## Improved Burst Acquisition

Carrier and timing lock, power estimates, equalizer training, and constellation phase lock are all done simultaneously. This allows shorter preambles and reduces protocol overhead.

## Better FEC

DOCSIS 1.x provides for the correction of up to 10 errored bytes per Reed Solomon (RS) block ( $T = 10$ ) with no interleaving, whereas DOCSIS 2.0 allows correction of up to 16 bytes per RS block ( $T = 16$ ) with programmable interleaving. Upstream programmable byte interleaving allows the FEC to work more effectively when errors are created by impulse or burst noise.

## Ingress Cancellation

Although not specifically a requirement of DOCSIS 2.0, all advanced PHY silicon vendors have incorporated some form of ingress cancellation technology into their upstream receiver chips, further enhancing upstream data-transmission robustness. Ingress cancellation technology digitally removes in-channel impairments such as ingress and common path distortion (CPD).

## Outside Plant Performance

DOCSIS 2.0 and advanced PHY do not require changes to the cable network itself; nor do they imply relaxed network performance requirements. Although advanced PHY technologies are intended to improve upstream data-transmission robustness, the cable network must still meet assumed downstream and upstream RF channel transmission characteristics in the DOCSIS 2.0 Radio Frequency Interface Specification for maximum reliability and data throughput. DOCSIS upstream performance parameters are listed in Table 3.

**Table 3.** DOCSIS 2.0 Assumed Upstream RF Channel Transmission Characteristics

Parameter	Value
Frequency range	5 to 42 MHz edge to edge
Transit delay from the most distant cable modem to the nearest cable modem or CMTS	Less than or equal to 0.800 millisecond (typically much less)
Carrier-to-interference plus ingress (the sum of noise, distortion, CPD, and cross-modulation and the sum of discrete and broadband ingress signals, impulse noise excluded) ratio	Not less than 25 dB
Carrier hum modulation	Not greater than $-23$ dBc (7.0 percent)
Burst noise	Not longer than 10 microseconds at a 1 kHz average rate for most cases
Amplitude ripple 5–42 MHz	0.5 dB/MHz
Group delay ripple 5–42 MHz	200 nanoseconds/MHz
Micro-reflections – single echo	$-10$ dBc at less than or equal to 0.5 microsecond $-20$ dBc at less than or equal to 1.0 microsecond $-30$ dBc at greater than 1.0 microsecond
Seasonal and diurnal reverse gain (loss) variation	Not greater than 14 dB minimum to maximum

The minimum upstream carrier-to-noise, carrier-to-ingress, and carrier-to-interference ratios of DOCSIS 2.0 are 25 dB, the same as DOCSIS 1.0 and 1.1. With the exception of seasonal and diurnal reverse gain (loss) variation, the remaining parameters are unchanged, too. The improved upstream data-transmission robustness of DOCSIS 2.0 is intended to support the higher-order modulation formats – not serve as a bandage for poorly maintained cable networks.

## Comparing DOCSIS 1.x PHY and DOCSIS 2.0 Advanced PHY

DOCSIS 1.x upstream PHY uses a frequency division multiple access (FDMA)/TDMA burst multiplexing technique. FDMA accommodates simultaneous operation of multiple RF channels on different frequencies. TDMA allows multiple cable modems to share the same individual RF channel by allocating each cable modem its own time slot in which to transmit. TDMA is carried over in DOCSIS 2.0, with numerous enhancements. The specification also adds S-CDMA multiplexing, allowing multiple modems to transmit in the same time slot. Table 4 summarizes the main upstream PHY parameters in DOCSIS 1.x and 2.0.

**Table 4.** Upstream PHY Parameters

Property	DOCSIS 1.x	DOCSIS 2.0 A-TDMA	S-CDMA
Multiplexing technique	FDMA/TDMA	FDMA/TDMA	FDMA/S-CDMA
Symbol rates (ksym/sec)	160, 320, 640, 1280, 2560	160, 320, 640, 1280, 2560, 5120	1280, 2560, 5120
Modulation types	QPSK, 16-QAM	QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM	QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM, 128-QAM (trellis-coded modulation [TCM] only)
Raw spectral efficiency (bits/sym)	2 and 4	2 to 6	1 to 6
FEC	RS (T = 1 to 10)	RS (T = 1 to 16)	RS (T = 1 to 16), TCM
Equalizer	8 tap	24 tap	24 tap
Byte block interleaving	No	Yes	No
S-CDMA framing	No	No	Yes
Bit rate (Mbps)	0.32 to 10.24	0.32 to 30.72	2.56 to 30.72

### A-TDMA

A-TDMA is a direct extension of the DOCSIS 1.x upstream PHY. The same FDMA/TDMA mechanism is used with an improved PHY toolbox:

- The modulation types can be QPSK, 8-QAM, 16-QAM, 32-QAM, and 64-QAM. This allows spectral efficiency 50-percent higher than in DOCSIS 1.x for increased aggregate throughput.
- A symbol rate of 5120 ksym/sec was added. This allows a 2x increase of the symbol rate in a single channel and overall 3x increase in the bit rate (when used with 64-QAM) compared to DOCSIS 1.x.
- A block byte interleaver was added. The byte interleaver allows spreading bursty error events among various RS code words, thus increasing the robustness to impulse and burst noise. The byte interleaver is the only new block in A-TDMA mode.
- The size of the transmit equalizer was extended to 24 taps, necessary because of the higher symbol rate and higher linear distortion sensitivity of 64-QAM. A CMTS employing A-TDMA will have a 24-tap receive equalizer, which may be used on a burst-by-burst basis. While maximum pre-equalization is enabled when both the CMTS and cable modem have a matching number of taps, DOCSIS 1.x and 2.0 modems alike can benefit from performance gains because of the improved CMTS burst acquisition capability. A higher-order receive equalizer enhances performance in a single-ended fashion.
- The preamble consists of QPSK symbols (regardless of the payload modulation type). The power of the preamble symbols is either approximately equal to the payload power or is approximately 2.5 dB higher. The high-power preamble allows better estimation of the burst parameters.
- The spurious requirements were tightened to match the lower noise floor required for 64-QAM.
- The minislot size can be reduced to 6.25 microseconds ( $M = 0$ ) to reduce capacity loss related to minislot granularity.

## S-CDMA

S-CDMA actually uses the FDMA/TDMA/S-CDMA burst multiplexing technique. This allows multiple cable modems to transmit simultaneously. The underlying modulation format for each modem is QAM.

S-CDMA includes all the features of A-TDMA with the following differences:

- S-CDMA offers a spreading mechanism.
- S-CDMA offers a framing mechanism that establishes the time and code domain access.
- S-CDMA (optionally) offers support for 128-QAM with TCM; however, the maximum data throughput remains the same as for 64-QAM.
- Close synchronization, to within a few nanoseconds, is required between downstream and upstream symbol rates.

## Performance in the Presence of Impairments

### Noise

Impulse or burst noise is a common impairment in cable networks. It consists of short, but powerful bursts of random noise. Common sources of impulse or burst noise include automobile ignitions, neon signs, power-line switching transients, arc welders, electronic switches and thermostats, home electrical appliances (mixers, can openers, vacuum cleaners, etc.), and static from lightning. Impulse noise typically consists of impulses with a duration of 1 to 10 microseconds ( $\mu\text{sec}$ ), and rates up to a few kilohertz (kHz). Burst noise consists of bursts with a duration up to 100  $\mu\text{sec}$ , and rates up to a few hertz. Because the underlying upstream channel modulation is QAM, A-TDMA and S-CDMA have very similar AWGN performance, assuming comparable data rates.

Narrowband interference is another common impairment in cable networks, especially at the lower frequencies in the upstream spectrum. Narrowband interference is commonly divided into two categories:

- Narrowband ingress from over-the-air radio transmissions such as citizens band (CB) radio, amateur (“ham”) radio, and shortwave broadcasting
- Intermodulation distortion products such as CPD, which is created from intermixing of downstream channels in nonlinearities in the hybrid fiber/coax (HFC) network

The typical bandwidth of individual narrowband interference is less than about 20 kHz. However, the power of the interfering signal can be similar to that of the DOCSIS signal. Ingress cancellation is a tool that can be employed here.

### A-TDMA Tools to Combat Impulse or Burst Noise

A-TDMA mode includes several tools to combat impulse and burst noise:

- FEC – The first tool is RS FEC encoding. This involves the transmission of additional data (overhead) that allows correction of byte errors.
- Byte interleaving – The byte interleaver can spread data over the transmission time. If a portion of that data is corrupted by a burst or impulse, the errors appear spread apart when de-interleaved at the CMTS, allowing FEC to work more effectively.

### S-CDMA Tools to Combat Impulse or Burst Noise

S-CDMA time spreading is another tool to deal with certain types of impulse and burst noise. The S-CDMA scheme has two main tools to mitigate impulse and burst noise:

- The time spreading allows reducing the effective C/N of noise bursts that are shorter than the spreading interval.
- S-CDMA framing and subframing spread bytes over multiple RS code words, in a similar manner to byte interleaving in A-TDMA.

Both S-CDMA and A-TDMA provide a set of tools to combat impulse or burst noise. S-CDMA tools are more efficient for the case of low power and relatively short impulses. A-TDMA is less sensitive to impulse power. Burst tolerance in A-TDMA and S-CDMA is comparable when the size of the byte interleaver and S-CDMA frames are similar.

## **Advanced PHY Implementation in the Cisco 5x20S and 5x20U Broadband Processing Engines and in Cisco uBR7200 Series MC16U, MC16X, MC28U, and MC28X Broadband Processing Engines**

Cisco® 5x20S and 5x20U Broadband Processing Engines (BPEs) for the Cisco uBR10012 Universal Broadband Router were designed to provide high port density – 5 downstream and 20 upstream connections per line card; integrated upconverters; a sophisticated RF feature set including advanced PHY; and next-generation A-TDMA capabilities.

The Cisco uBR7200 Series MC16U and MC16X BPEs for the Cisco uBR7246VXR Universal Broadband Router provide one downstream and six upstream connections per line card. The Cisco uBR7200 Series MC28U and MC28X provide two downstream and eight upstream connections per line card. Both the Cisco uBR7200 Series MC16U and MC28U feature integrated upconverters, a sophisticated RF feature set including advanced PHY, and next-generation A-TDMA capabilities. The Cisco uBR7200 Series MC16X and MC28X BPEs do not include an integrated upconverter, but are otherwise identical to the Cisco uBR7200 Series MC16U and MC28U BPEs.

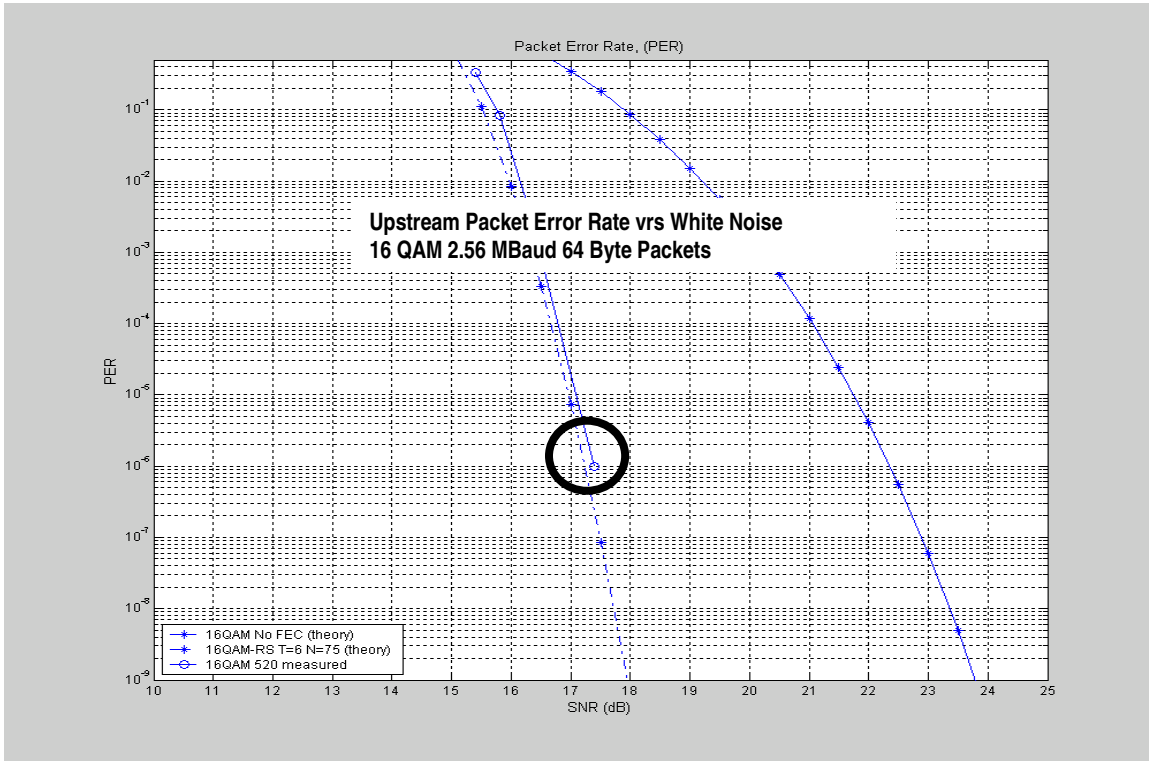
### **Second-Generation Upstream Receivers**

The latest generation of CMTS upstream receivers feature a digital implementation, which eliminates in-channel impairments such as tuner noise and pass-band ripple. Digital burst receivers offer many other benefits, including:

- Reduced receiver circuit complexity to a filter and amplifier stage connected to a high-performance analog-to-digital (A/D) converter per upstream port
- Dynamic interference cancellation is available using advanced-signal-processing algorithms; ingress waveforms are detected and digitally removed prior to final detection
- Improved receiver power accuracy through digital calibration across the full upstream spectrum of all upstream channels
- Full channel selectivity in high-performance digital signal processing algorithms
- Enhanced equalizer performance through an increased number of taps

Figure 1 illustrates typical upstream packet error rate (PER) versus C/N for available digital burst receivers. The graph shows three curves. The far-right curve is theoretical performance with FEC off. The two curves that are close together near the center of the graph show theoretical and measured performance with FEC on.

**Figure 1**  
Packet Error Rate Versus C/N



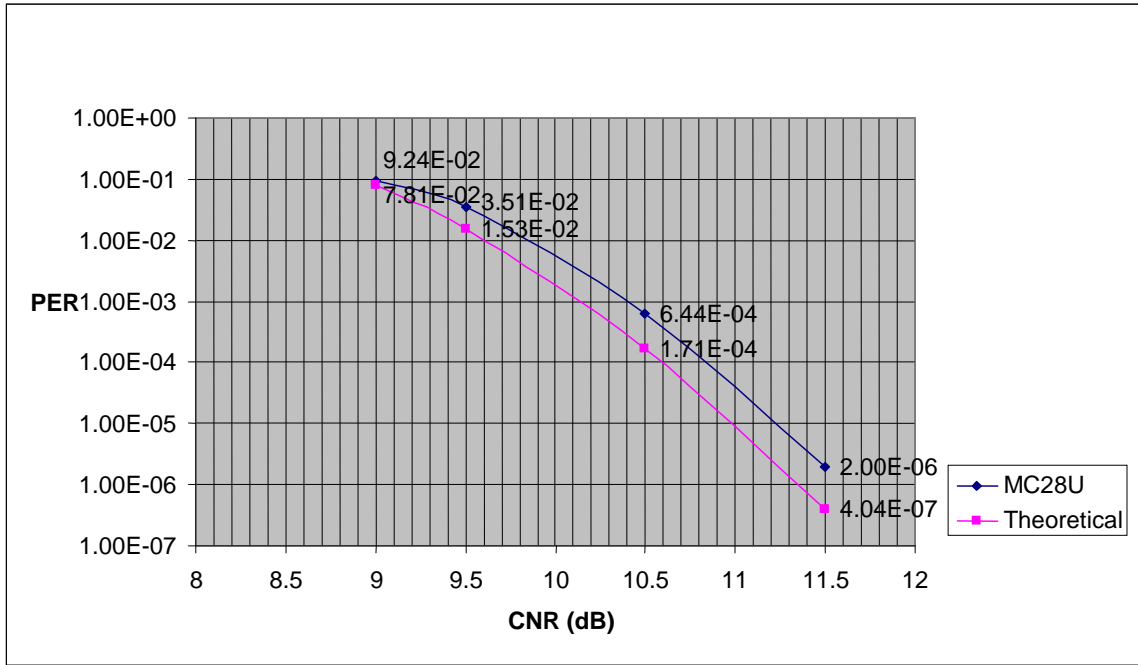
Digital burst receiver technology is supported on Cisco 5x20S and 5x20U BPEs, as well as Cisco uBR7200 Series MC16U, MC16X, MC28U, and MC28X BPEs.

**RF Performance: PER vs. AWGN**

One way to characterize the effectiveness of digital burst receiver technology and its implementation margin performance is to measure PER versus C/N, and compare the results to theoretical curves.

Figure 2 shows measured performance (blue line) of the Cisco uBR7200 Series MC28U BPE implementation margin compared to theoretical performance (purple line) with QPSK. Note that measured performance of the line card's digital receiver is within 0.5 dB of theoretical performance, an indication of the very low implementation margin of advanced PHY-equipped CMTS upstream burst receivers.

**Figure 2**  
Cisco uBR7200 Series MC28U BPE PER Versus C/N (QPSK)



Similar measured implementation margin performance is seen in Figure 3 with 16-QAM (blue line), and is within 0.5 dB of theoretical performance (purple line).

**Figure 3**

Cisco uBR7200 Series MC28U BPE PER Versus C/N (16-QAM)

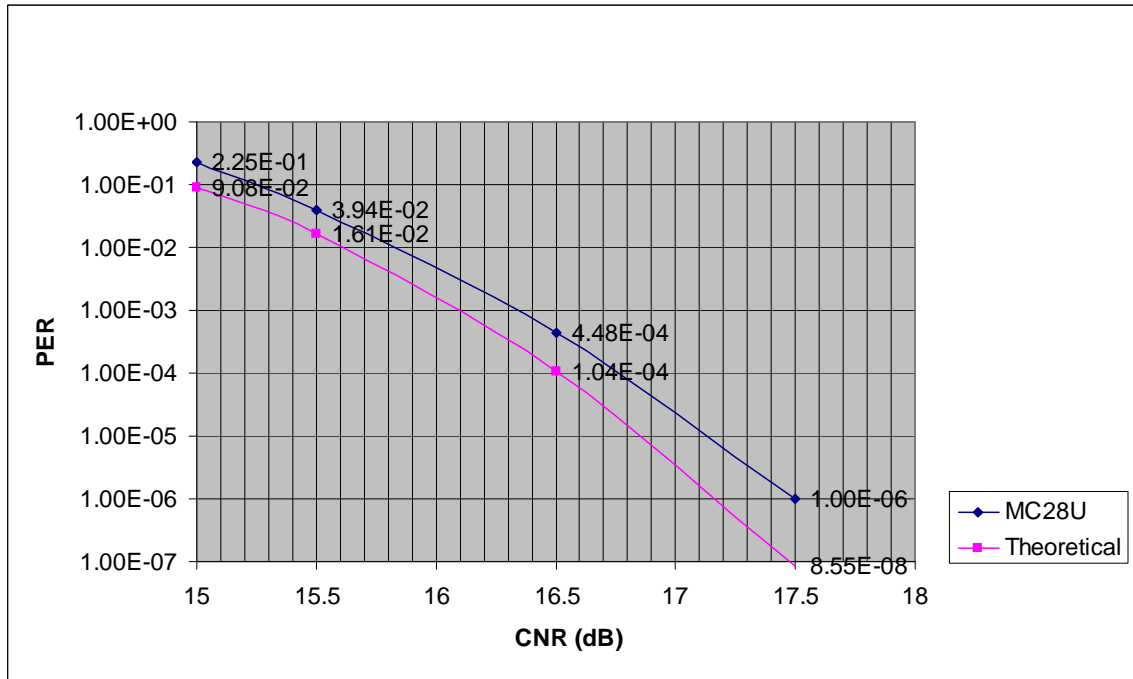
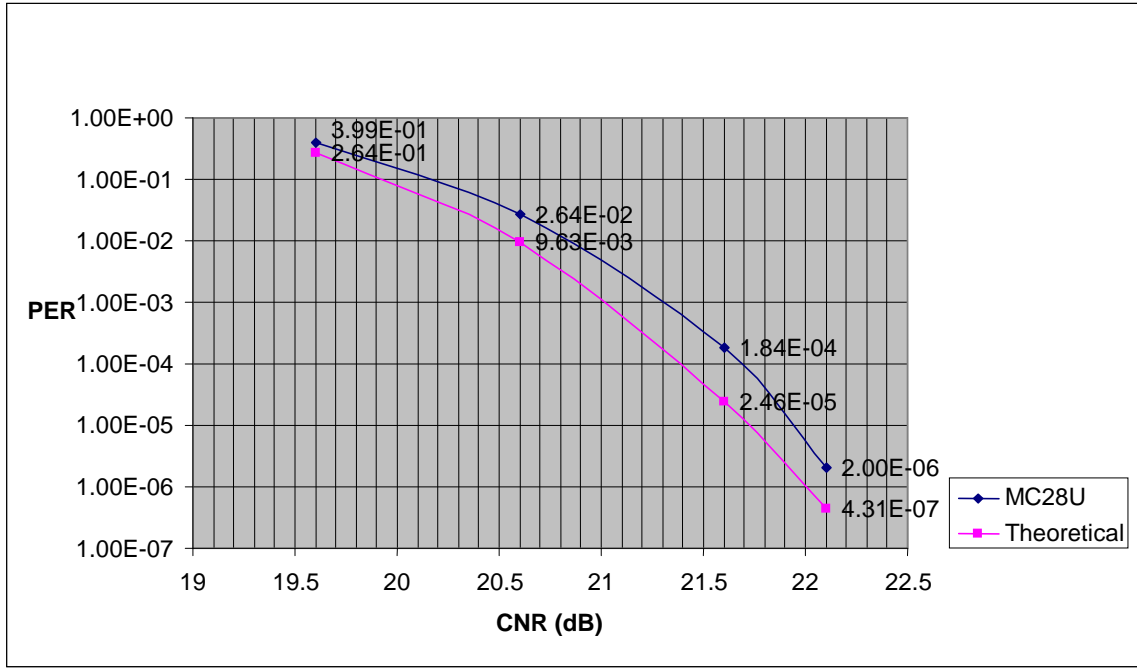


Figure 4 shows that 64-QAM (blue line) benefits from the reduced implementation margin of the CMTS's upstream digital receiver, which is also within 0.5 dB of theoretical performance (purple line).

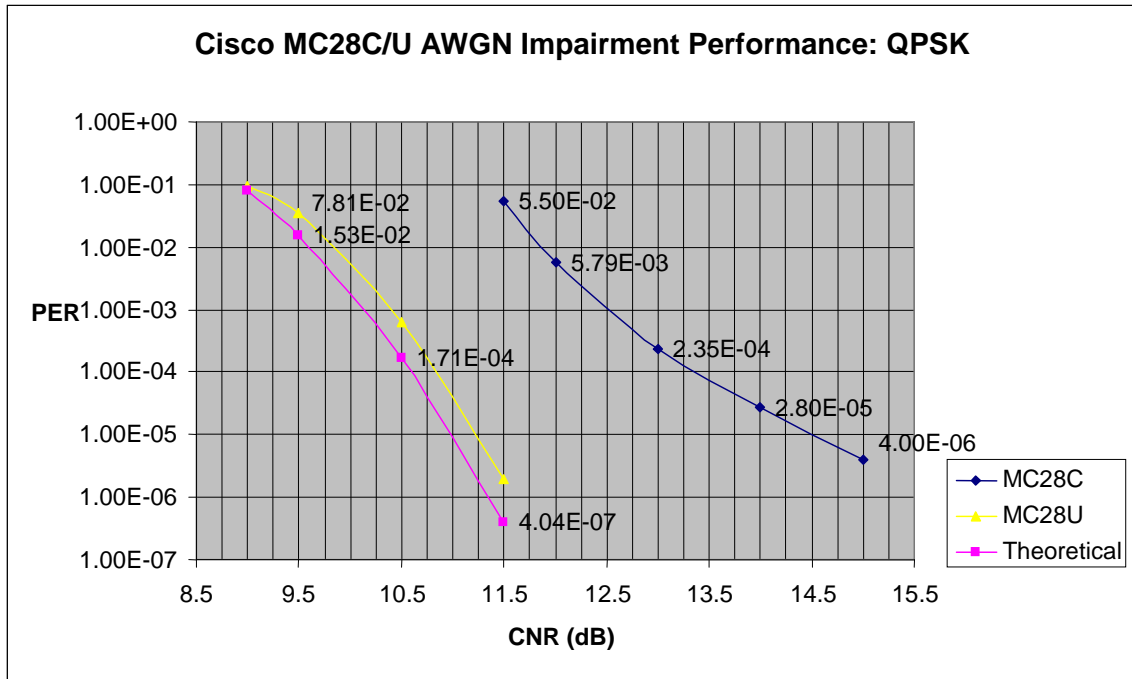
**Figure 4**

Cisco uBR7200 Series MC28U BPE PER Versus C/N



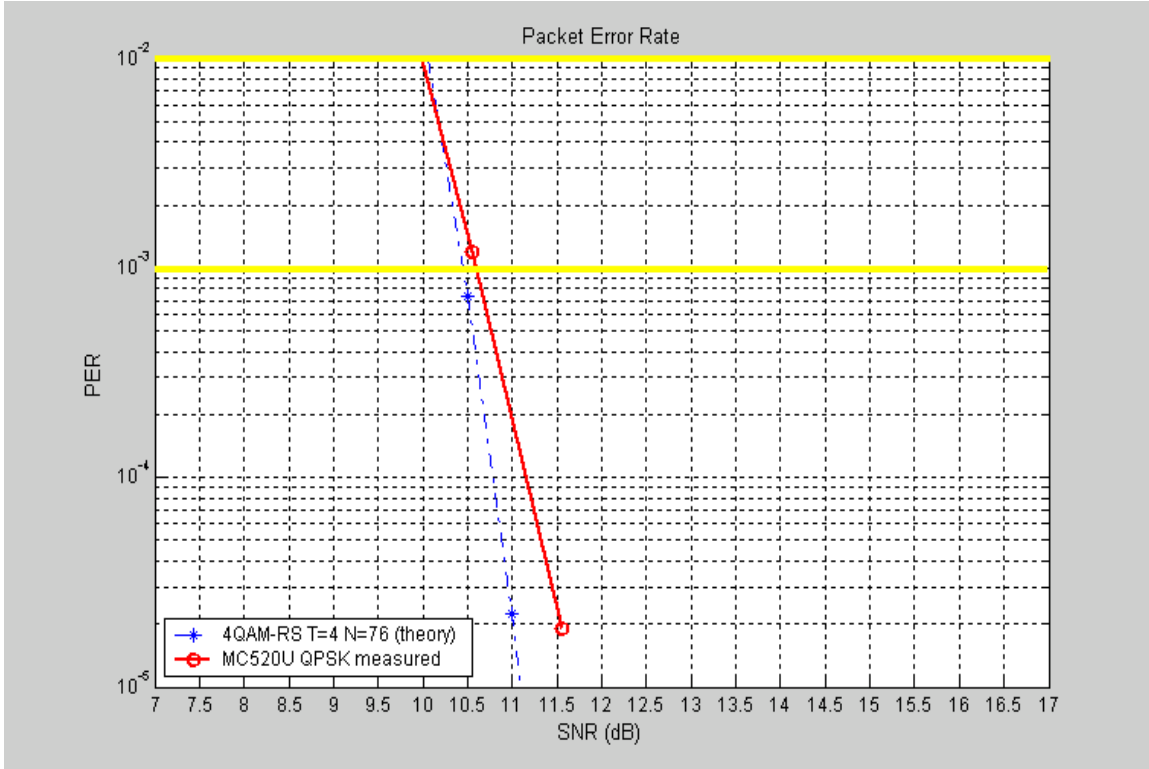
Earlier cards such as the Cisco MC16C and MC28C Universal Broadband Router line cards use analog upstream receiver circuitry. The blue line on the right side of Figure 5 shows measured performance of the MC28C line card's upstream analog receiver circuit with QPSK. Compare the earlier generation line card's implementation margin to that of the Cisco uBR7200 Series MC28U BPE's digital receiver (yellow line) versus theoretical performance (purple line). Similar implementation margin performance improvement occurs with 16-QAM.

**Figure 5**  
Implementation Margin Performance Comparison



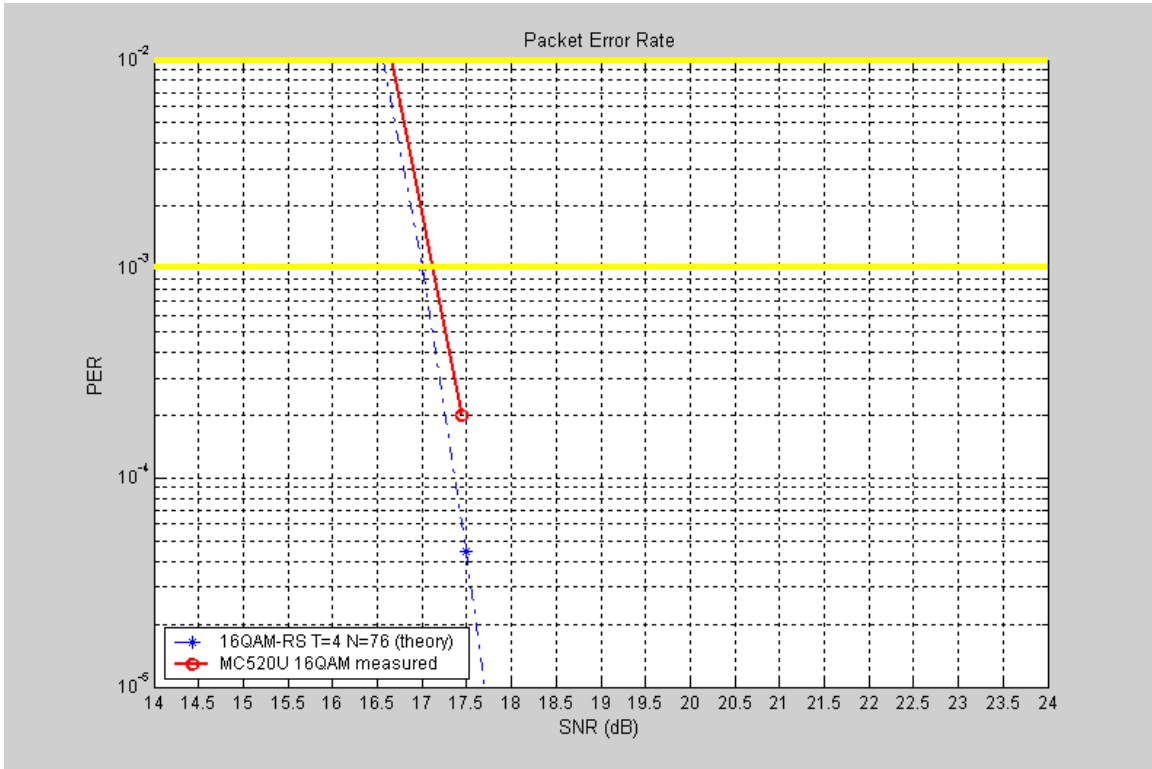
Cisco 5x20S and 5x20U BPEs upstream implementation margin performance also is within 0.5 dB of theory for QPSK, 16-QAM and 64-QAM, as shown in Figures 6–8.

**Figure 6**  
Cisco 5x20S and 5x20U BPE PER Versus C/N (QPSK)

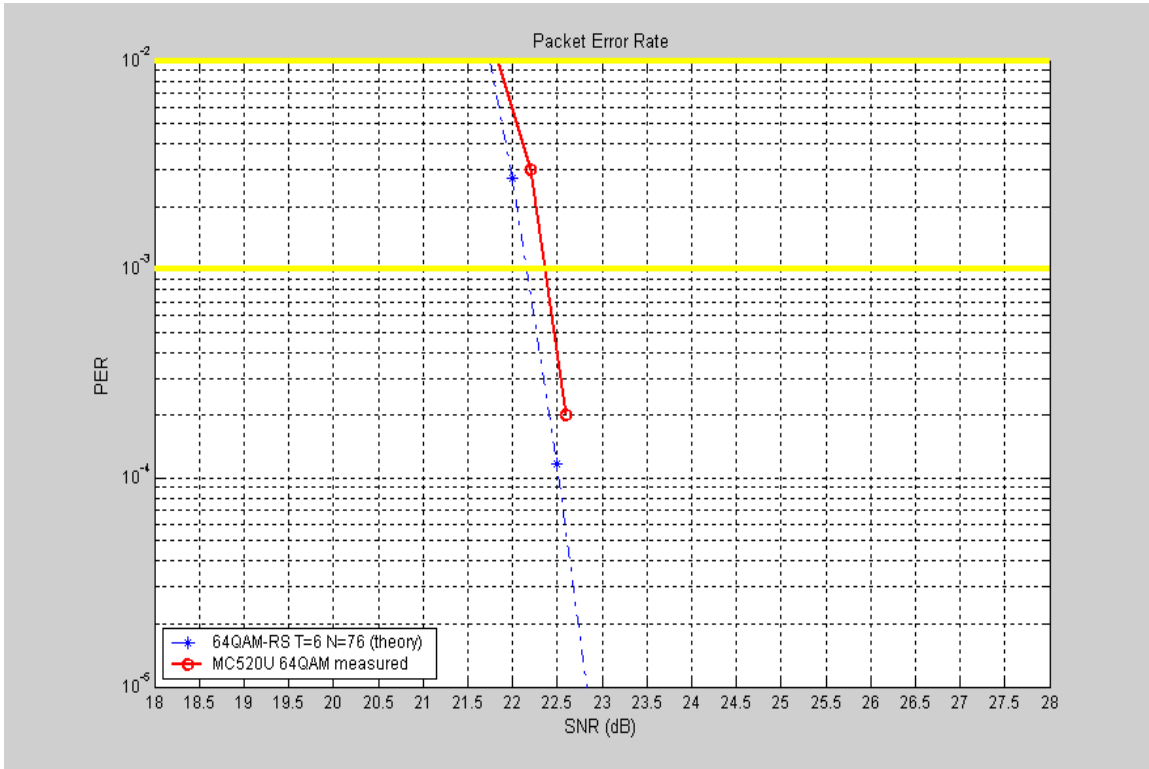


**Figure 7**

Cisco 5x20S and 5x20U BPE PER Versus C/N (16-QAM)



**Figure 8**  
Cisco 5x20S and 5x20U BPE PER Versus C/N (64-QAM)



### Cisco uBR7200 Series MC16U and MC28U BPE Ingress Cancellation

The Cisco uBR7200 Series MC16U, MC16X, MC28U, and MC28X BPEs use Broadcom’s BCM3138 digital burst receiver. The 3138 series receiver incorporates ingress cancellation technology that suppresses in-channel impairments and is transparent to DOCSIS. Using ingress cancellation, error-free demodulation in the presence of multiple in-channel ingress signals with total power higher than the desired signal power is possible.

### Cisco 5x20S and 5x20U BPE Ingress Cancellation

The Cisco 5x20S and 5x20U BPEs use Texas Instruments™ TNETC4522 digital burst receiver. The 4522 series receiver incorporates ingress cancellation technology that suppresses impairments and is transparent to DOCSIS. Using ingress cancellation, error-free demodulation in the presence of multiple in-channel ingress signals with total power higher than the desired signal power is possible.

### Ingress Cancellation Test

Table 5 summarizes the results of measurements of C/I versus PER for the Broadcom BCM3138. The test procedure used was the CableLabs® optional PHY22B ingress cancellation test. Test conditions included the use of 64-byte packets, AWGN C/N at values shown in the table, and a single in-channel continuous wave (CW) carrier. A negative C/I value indicates the interfering signal power was higher than the desired signal power. In the measurement conditions shown, the packet error rate remained less than 0.5 percent.

**Table 5.** Ingress Cancellation Test Results

Modulation type	QPSK	16-QAM	64-QAM
Symbol rate	1.28 Msym/sec	2.56 Msym/sec	5.12 Msym/sec
C/N (AWGN)	20 dB	25 dB	30 dB
Cisco uBR7200 Series MC16U and MC28U C/I	-20.2 dB	-18.2 dB	-10.7 dB

With QPSK at 20 dB C/N (AWGN), the in-channel interfering carrier is 20.2 dB *higher* than the amplitude of the data carrier and the PER is <0.5 percent. Even 64-QAM at 30 dB C/N yields <0.5 percent PER when the in-channel interfering carrier is 10.7 dB *higher* than the data carrier.

Table 6 summarizes the results of measurements performed by Texas Instruments on the TNETC4522. Negative C/I ratios indicate that the interfering signal power was higher than the desired signal power. The upstream signal was configured for 2.56 Msym/sec, and the interference was an in-channel CW carrier.

**Table 6.** Texas Instruments' TNETC4522 Measured Performance

Test Number	Burst Length in Bytes	Preamble Symbols	Modulation	FEC	C/I @ PER = 1 percent
1	1549	64	QPSK	T = 0	-6.67
	1535	64	QPSK	T = 0, K = 220	-6.67
2	1562	64	16-QAM	T = 0	-1.0
	1540	64	16-QAM	T = 8, K = 220	-1.8
3	1575	64	16-QAM	T = 0	15.0
	1551	64	16-QAM	T = 10, K = 218	-2.7

### Adaptive Equalization

Adaptive equalization is a method to digitally compensate for certain signal transmission impairments such as in-channel amplitude ripple or tilt. Adaptive equalization creates the equivalent of a digital filter, which has a response approximately equal to the inverse of the channel's actual frequency response. When upstream adaptive equalization is used, the cable modem pre-equalizes the transmitted signal.

DOCSIS 1.1 and 2.0 specify pre-equalization in the cable modem (most DOCSIS 1.0 modems do not support adaptive equalization). DOCSIS 1.1 modems support a symbol (T)-spaced equalization structure with 8 taps. DOCSIS 2.0 modems support a symbol (T)-spaced equalization structure with 24 taps. The 24-tap adaptive equalization in DOCSIS 2.0 allows operation in the presence of more severe multipath and micro-reflections. It accommodates operation near upstream band edges where diplex filter-related group delay is usually a problem, and is more effective in situations where cumulative group delay occurs in lengthy amplifier cascades.

During the cable modem ranging process, the CMTS upstream burst receiver measures linear distortion in the received signal. The CMTS sends equalization coefficients to the cable modems in a ranging response (RNG-RSP) message. The equalization coefficients are used by the modems to configure transmit pre-equalization in the upstream signal.

The example in Figure 9 illustrates a 6.4 MHz bandwidth 64-QAM upstream digitally modulated signal at a center frequency of 48 MHz, well into the diplex filter roll-off area. This figure shows the signal as it appears at a CMTS upstream input in a lab setup. The severe in-channel tilt is from the modem's internal low pass filter, rather than amplifier or node diplex filters. Single modem throughput was about 17 Mbps, but correctable FEC errors were incrementing about 7000 codewords per second (232 bytes per codeword). The CMTS's upstream signal-to-noise ratio (SNR) estimate – similar to modulation error ratio (MER) – was 23 dB.

**Figure 9**

Upstream Signal Before Adaptive Equalization

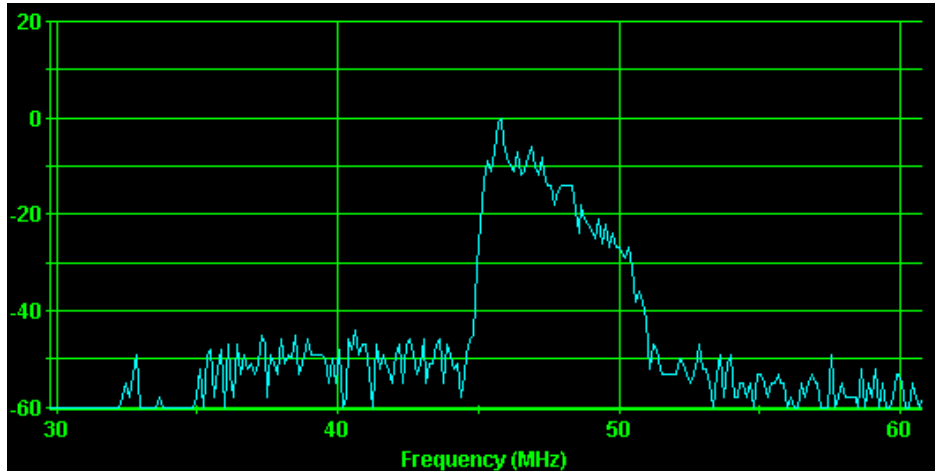
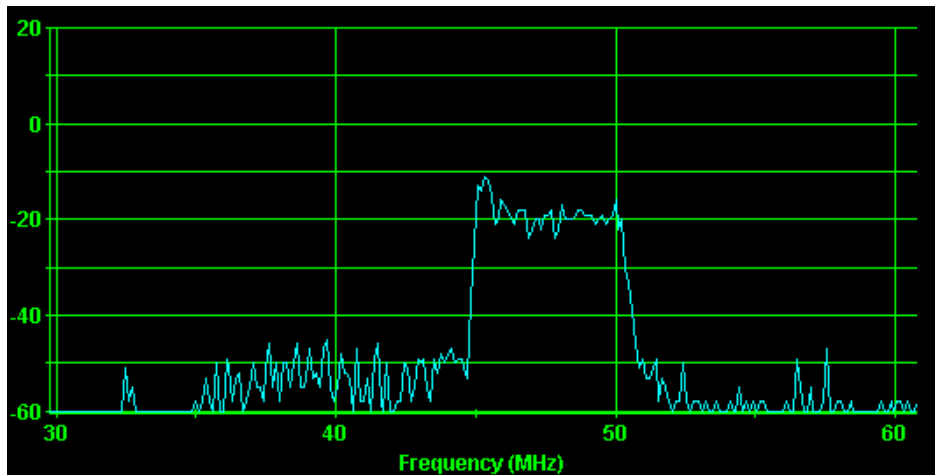


Figure 10 shows the same signal at the CMTS upstream input after adaptive equalization in the cable modem was turned on. The cable modem's pre-equalization was able to compensate for nearly all of the in-channel tilt. There were no correctable FEC errors and the CMTS's upstream SNR estimate increased to 36+ dB.

**Figure 10**

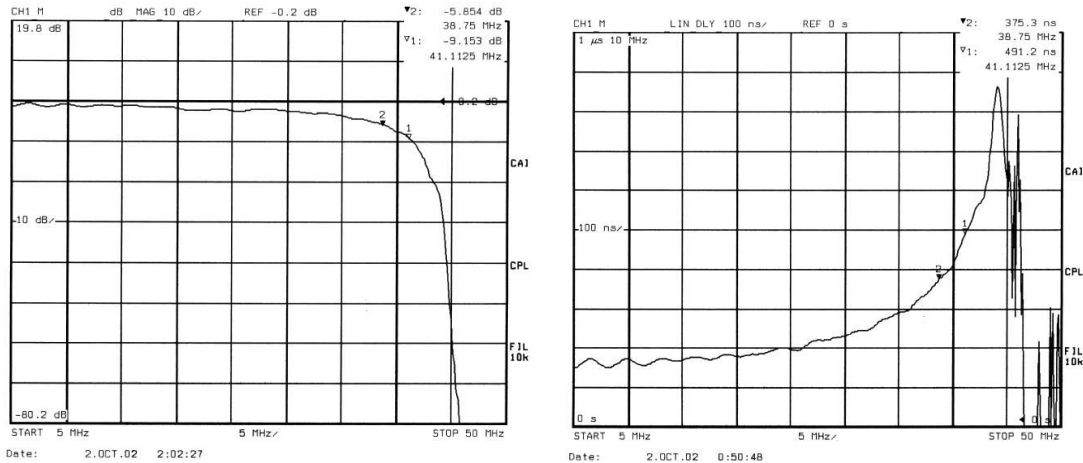
Upstream Signal After Adaptive Equalization



The two screen shots in Figure 11 show vector network analyzer measurements of the upper edge of a cable network upstream spectrum. Frequency response rolloff (left screen shot) and group delay (right screen shot) are evident near the band edge. With DOCSIS 1.1's eight-tap adaptive equalization, only a 1.6 MHz bandwidth QPSK signal could be carried in this part of the spectrum. DOCSIS 2.0's 24-tap adaptive equalization allowed a 3.2 MHz wide 16-QAM signal in the same place, with less than  $1.0 \times 10^{-8}$  BER.

**Figure 11**

Vector Analyzer Measurements



### Additional Tools

Cisco has implemented advanced spectrum management algorithms that automatically adjust key parameters. Criteria including C/N, SNR, and FEC errors can be selected by the cable operator to initiate parameter changes.

- Frequency – Available channels are continuously monitored for noise-free performance. If noise impairments are detected at the operating frequency, the cable modems are directed to a new frequency.
- Modulation – Decreasing the constellation size, for example from 16-QAM to QPSK, increases the power transmitted in each symbol, improving immunity to noise impairments.
- Symbol rate – Decreasing the symbol rate increases the transmission time for each symbol, improving immunity to short-duration impulse noise.

Ingress cancellation and other advanced PHY features in the Cisco 5x20S and 5x20U BPEs and Cisco uBR7200 Series MC16U, MC16X, MC28U, and MC28X BPEs can in many instances minimize or eliminate the need for frequency hopping or modulation changes.

Cisco advanced PHY-equipped line cards report upstream C/N when spectrum groups are assigned and is before ingress cancellation is applied. Reported upstream SNR is after ingress cancellation has been applied.

### Advanced PHY Performance Verification

Testing at several sites was done to evaluate advanced PHY and ingress cancellation features available in the Cisco 5x20S and 5x20U BPEs and Cisco uBR7200 Series MC16U, MC16X, MC28U, and MC28X BPEs. Ingress, noise, and impairments from an operating cable network or from signal sources simulating a cable network were used to quantify the performance of advanced PHY robustness features. Dropped ping packets were used as an indicator of C/I thresholds. A spectrum analyzer was used to measure C/I and C/N. Multiple modes of the analyzer were used, including zero-span (time domain) and frequency domain. The testing and results are explained in the following sections.

### Cisco uBR7200 Series MC28U BPE

At the Society of Cable Telecommunications Engineers Cable-Tec Expo 2004, Cisco demonstrated the operation of the Cisco uBR7200 Series MC28U BPE's advanced PHY in the presence of real-world impairments. Figure 12 shows multiple carriers across the upstream spectrum.

Each carrier is actually two closely spaced carriers from a pair of Viewsonics multicarrier generators combined through a backwards two-way splitter. The combined not-quite-identical frequency carriers results in the equivalent of amplitude modulation. Note that the fifth interfering carrier is nearly in the middle of the cable modem upstream data signal, and even with this level of in-channel interference there was no packet loss.

**Figure 12**  
Cisco uBR7200 Series MC28U BPE In-Channel Interference: AM Carrier

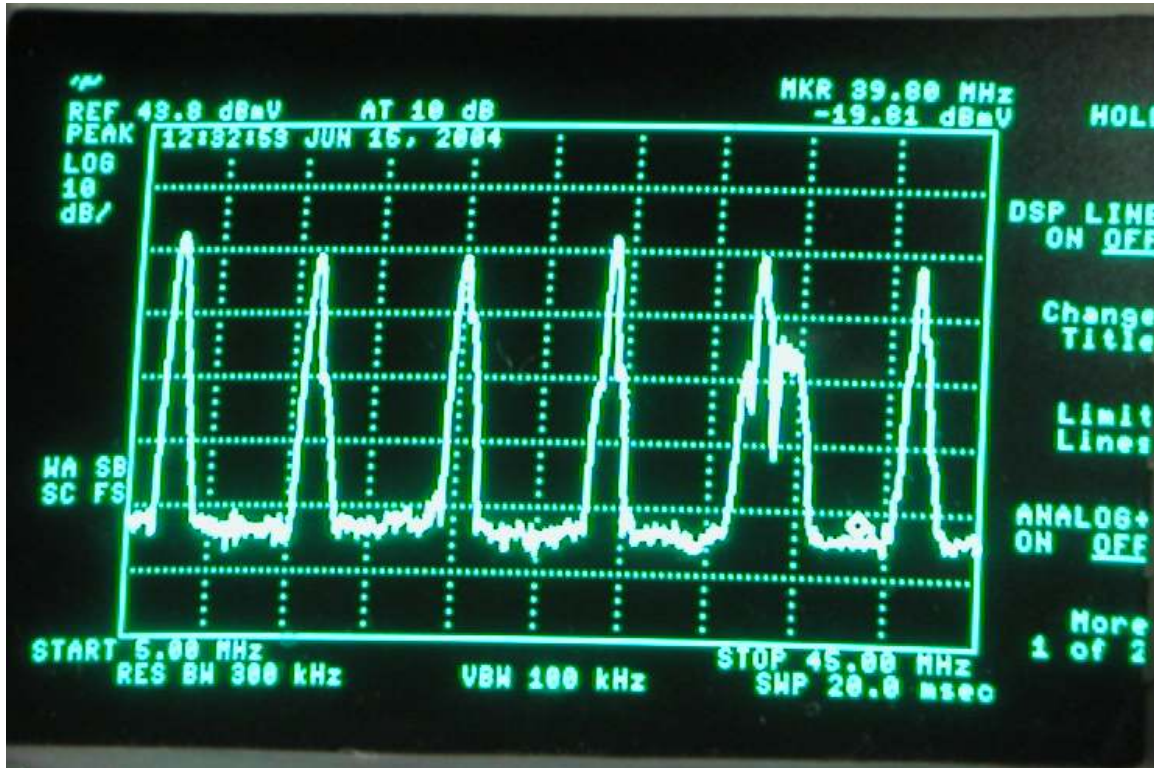
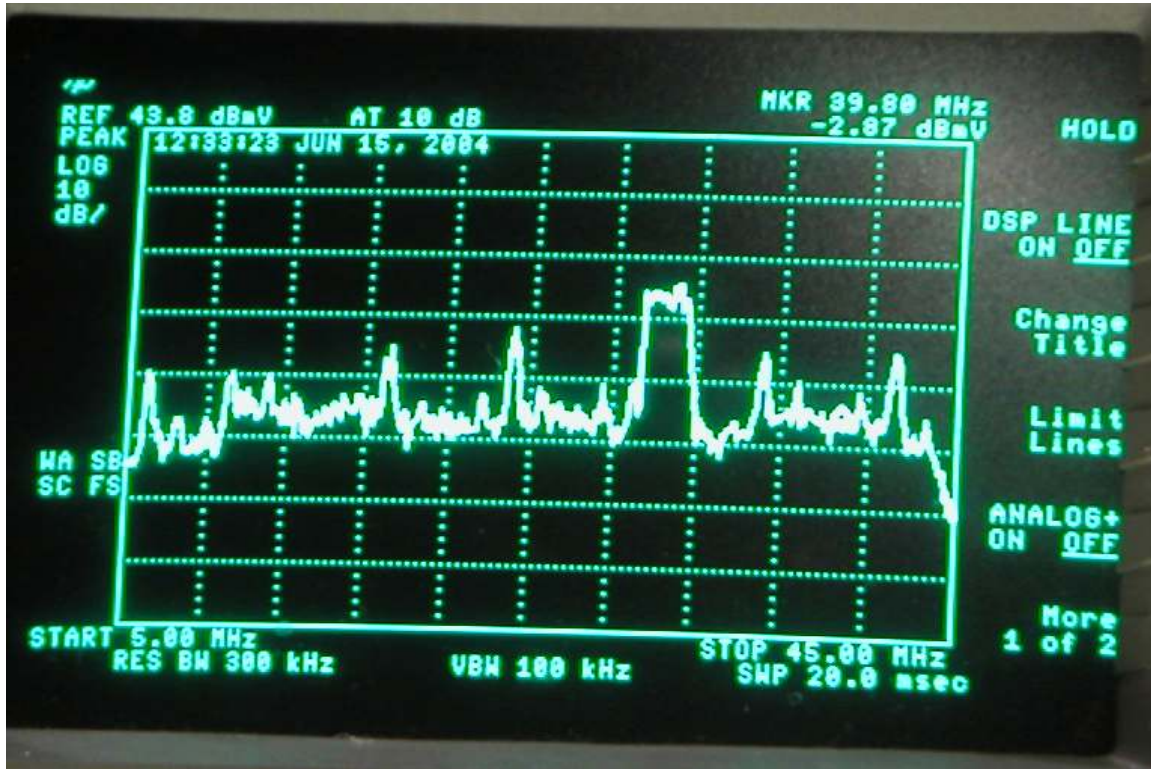


Figure 13 shows CPD, which was generated by connecting the local cable company’s downstream feed to a diode circuit. The CPD appears as beat clusters every 6 MHz across the upstream spectrum. One of the CPD beat clusters is underneath the cable modem upstream data carrier signal. There was no packet loss.

Figure 13

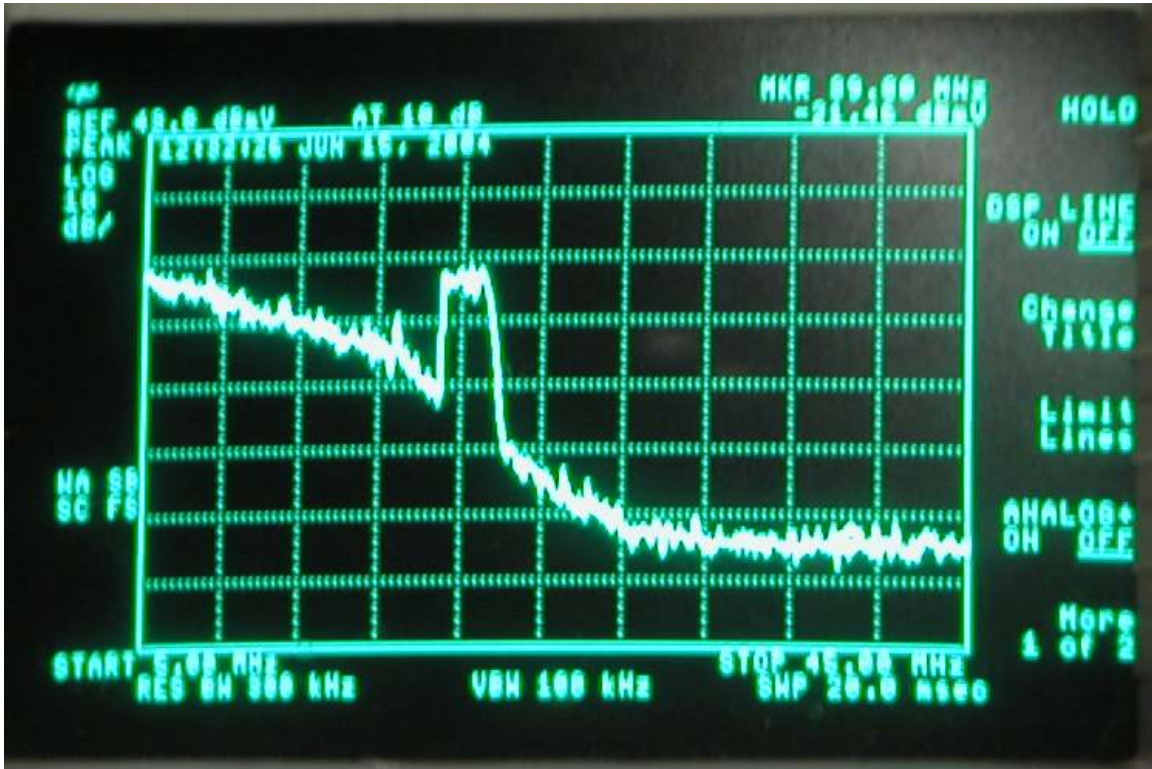
Cisco uBR7200 Series MC28U BPE In-Channel Interference: CPD



The example in Figure 14 has the cable modem data carrier located on a sloped noise floor. The noise was from a Hewlett-Packard noise generator. While ingress cancellation is not intended to help with a situation like this, the Cisco uBR7200 Series MC28U BPE's digital front end can operate at lower C/N than legacy CMTS equipment because of the reduced implementation margin. Here, too, there was no packet loss.

Figure 14

Cisco uBR7200 Series MC28U BPE In-Channel Interference: Degraded CNR



Cisco Broadband Troubleshooter (CBT) provides spectrum analyzer functionality that can be viewed anywhere there is an Internet connection. Figure 15 illustrates the same CMTS upstream spectrum displays as Figures 12–14.

Figure 15

Cisco Broadband Troubleshooter

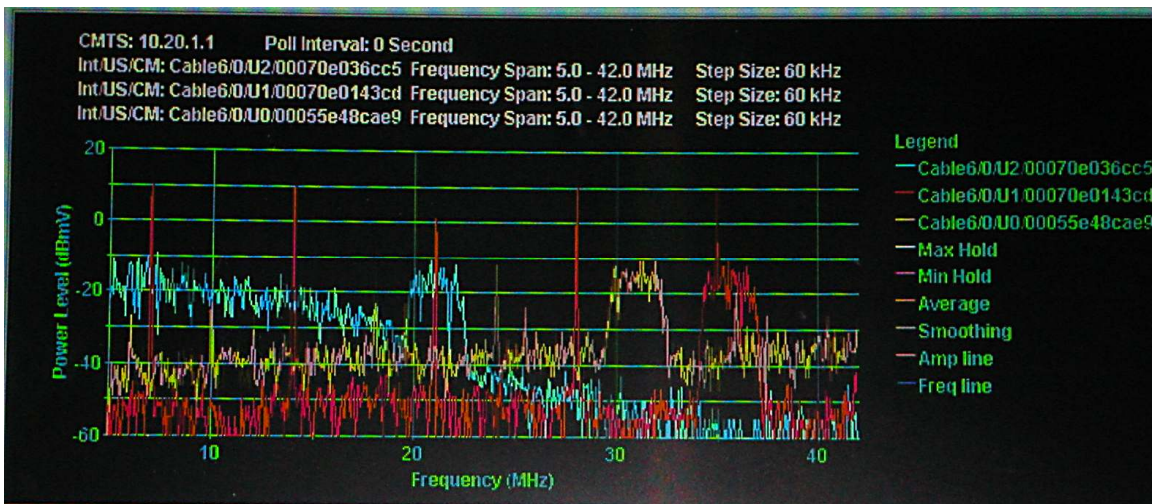
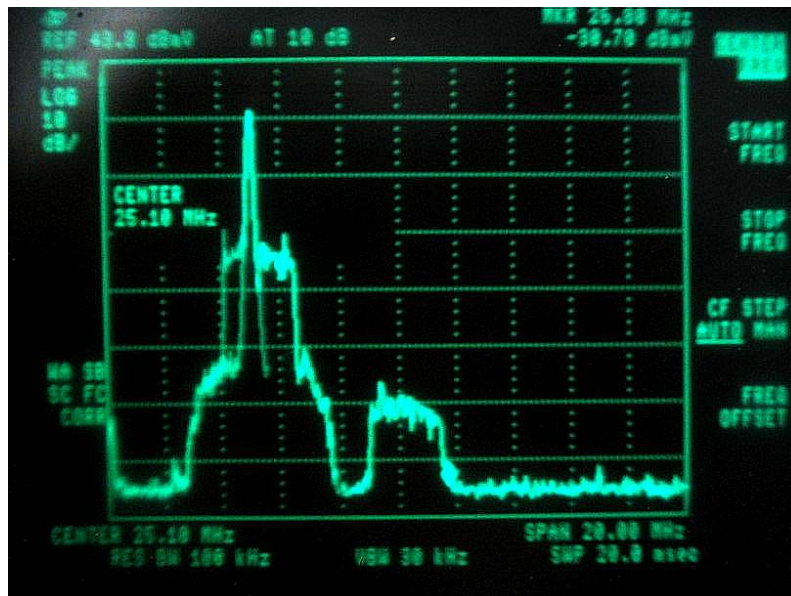


Figure 16 shows an unusual example of upstream interference at a customer site in Europe, where the Cisco uBR7200 Series MC28U was undergoing evaluation. A 3.2 MHz bandwidth 16-QAM signal has been placed on top of an S-CDMA signal, and a CW carrier injected in the middle of the channel. There was no packet loss in the 16-QAM signal.

**Figure 16**

Cisco uBR7200 Series MC28U BPE Performance at Customer Site



## Cisco 5x20S BPE

### Test Site 1: Asia

One of the first locations to test the advanced PHY features of the Cisco 5x20S BPE was a customer site in Asia. Figure 17 shows a CW carrier inserted directly under a 3.2-MHz bandwidth 16-QAM cable-modem signal centered at 31.6 MHz. After compensation for analyzer resolution bandwidth (RBW) settings, the C/I was measured at 14.3 dB. There was no perceived degradation in cable modem performance.

**Figure 17**  
CW Carrier Test

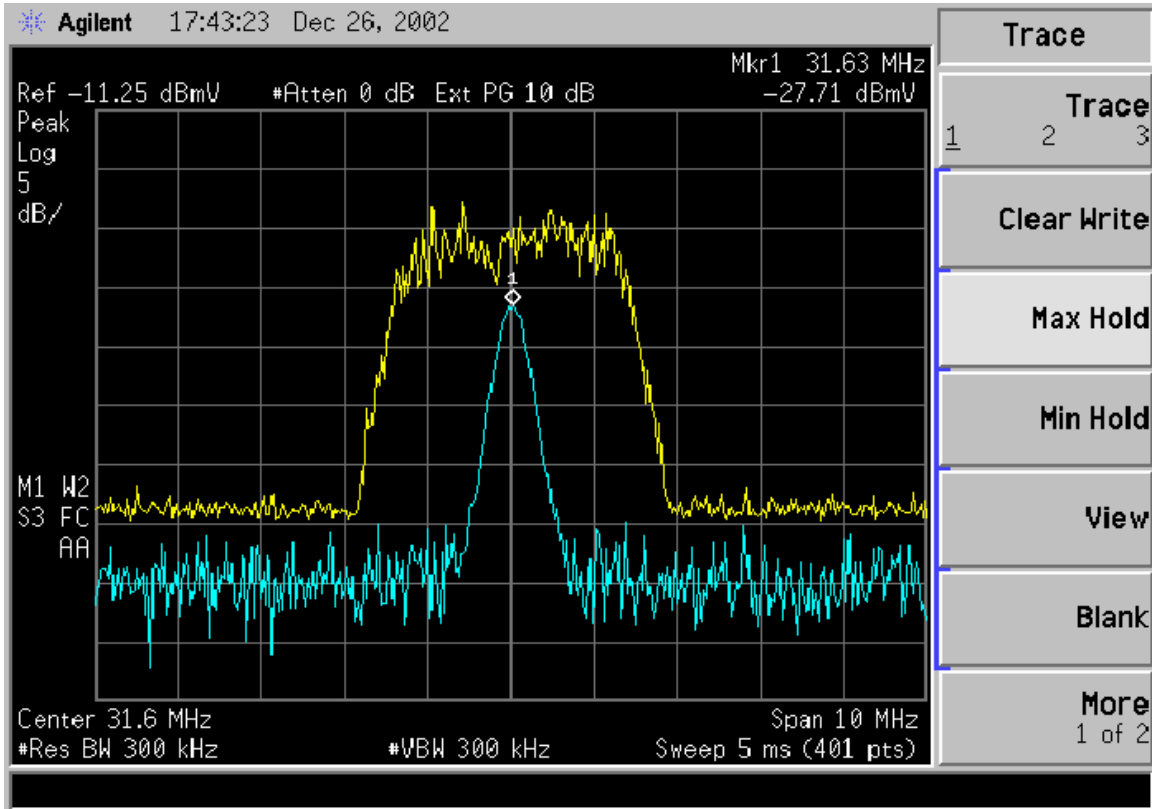
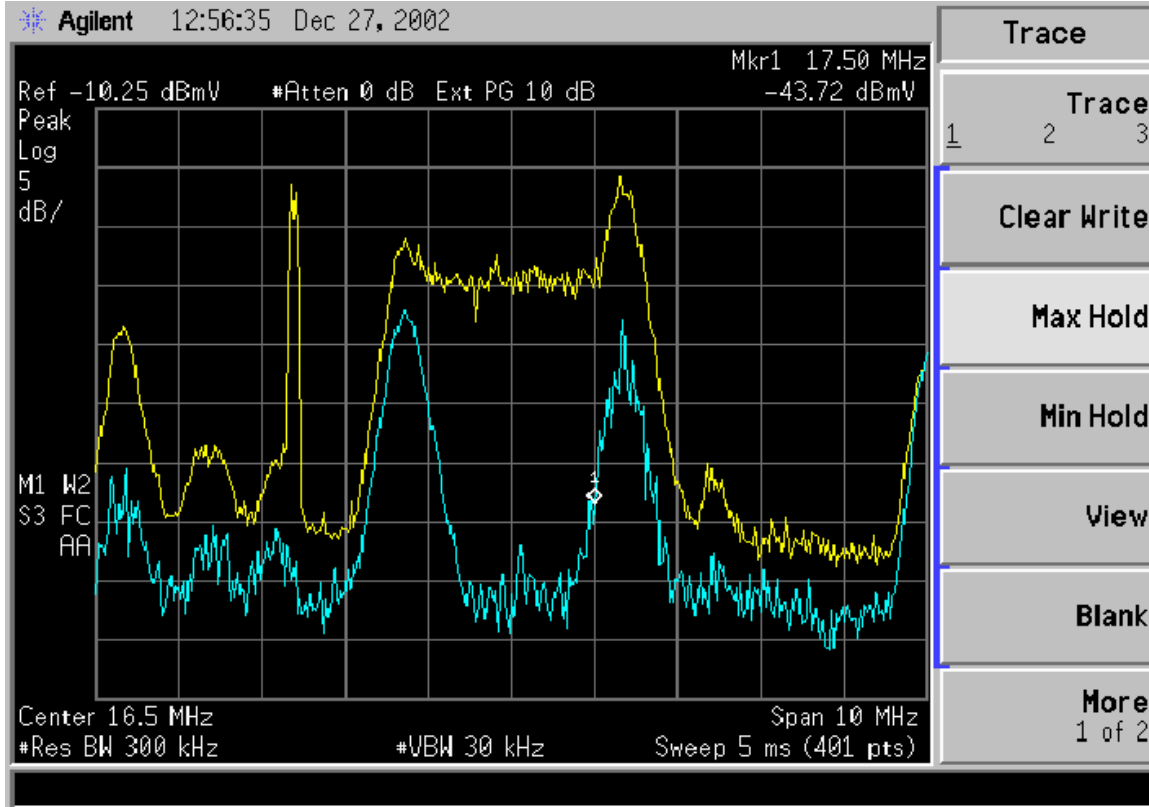


Figure 18 shows a 3.2 MHz bandwidth 16-QAM cable modem signal that was placed in the lower portion of the upstream spectrum of an operating cable network with ingress present. The center frequency is 16.5 MHz. There was no perceived degradation in cable modem performance.

**Figure 18**  
Live Plant Test



**Note:** The Cisco 5x20U supports all capabilities of the Cisco 5x20S and adds support for Euro-DOCSIS and J-DOCSIS.

**Test Site 2: Europe**

Two test locations in Europe were chosen where customers wanted to deploy the Cisco 5x20S BPE new features to operate 16-QAM in a previously unusable part of the spectrum. Cisco 5x20U BPE supports these capabilities.

A Cisco 5x20S BPE line card and a Cisco uBR905 Cable Access Router were used for the test setup. The Cisco uBR905 upstream signal was combined with the tested node via a two-way splitter. The downstream was attenuated and connected to the cable modem. The spectrum analyzer RBW filter setting of all zero-span pictures for this test was 1 MHz, and the analyzer vertical scale was set to 5 dB/div.

**Results**

The cable modem upstream carrier was intentionally set to a frequency where ingress was especially severe. The approximate C/I was 5 dB, although the ingress amplitude varied considerably during the test.

The results of the test clearly showed that it was possible to successfully operate 16-QAM on the cable network, despite the severity of the ingress in part of the spectrum previously thought to be unusable. Tables 7, 8, 9, and 10 summarize measured performance results.

**Table 7.** Location 1 – Test A

**16-QAM**  
**Center Frequency (fc) = 25 MHz**  
**3.2 MHz**

CMTS Input (dBmV)	C/I (dB)	Ping
13	21	99.99 percent
3 <sup>1</sup>	14	99.95 percent
3 <sup>2</sup>	14	99.98 percent
0	12	100 percent

**Note:** Two tests at 3 dBmV were performed with 1500-byte packets:

1. Standard test of 10,000 packets
2. Longer time period with 255,276 packets

The Cisco 5x20S BPE worked well at a C/I of 12 dB.

**Table 8.** Location 1 – Test B

**QPSK**  
**fc = 13 MHz**  
**3.2 MHz**

CMTS Input (dBmV)	C/I (dB)	Ping
13	20	99.99 percent
8	14	99.98 percent
3	11	99.89 percent

**16-QAM**  
**fc = 13 MHz**  
**1.6 MHz**

CMTS Input (dBmV)	C/I (dB)	Ping
8	14	99.94 percent

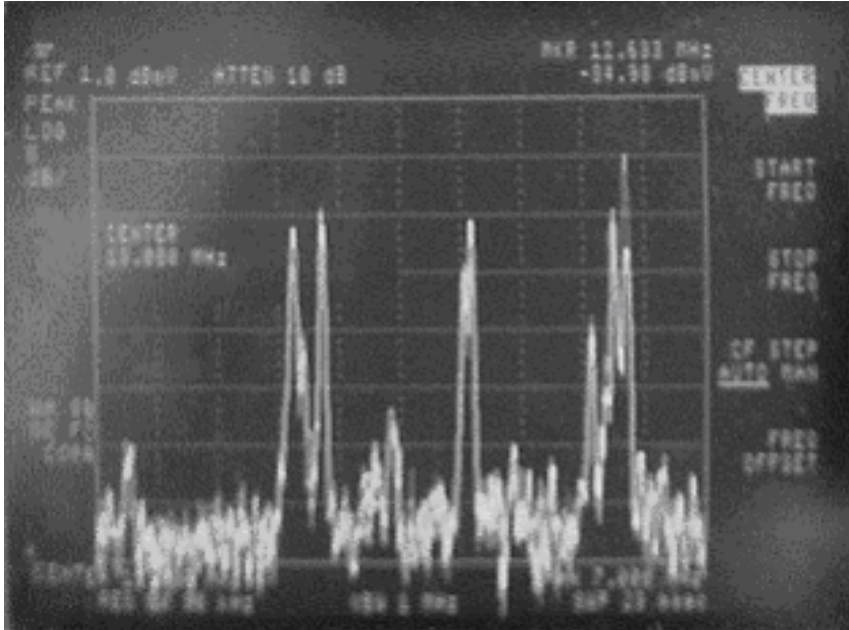
**16-QAM**  
**fc = 13 MHz**  
**3.2 MHz**

CMTS Input (dBmV)	C/I (dB)	Ping
8	12	97.84 percent

Figure 19 shows the selected spectrum with continuous sweep. Figure 20 shows the carrier placed in the spectrum with a 10-second maximum hold.

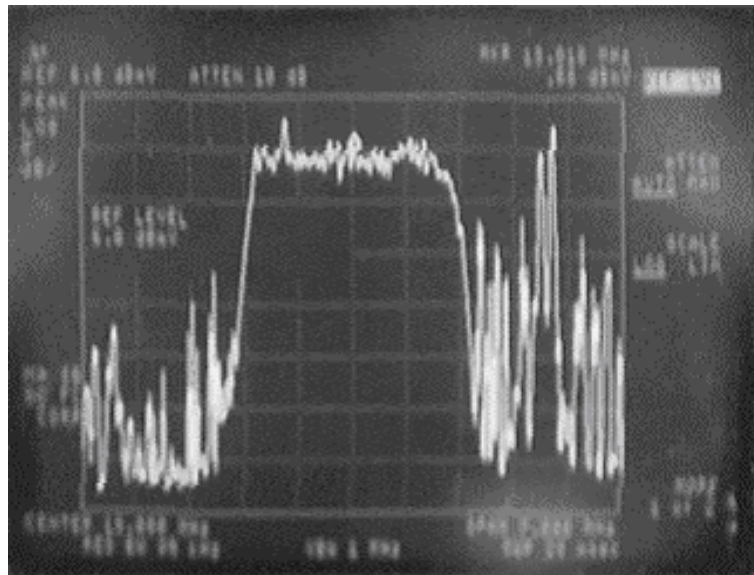
**Figure 19**

Spectrum Analyzer Continuous Sweep



**Figure 20**

Spectrum Analyzer Maximum Hold



**Table 9.** Location 2 – Test A

**QPSK**  
**fc = 18 MHz**  
**3.2 MHz**

CMTS Input (dBmV)	C/I (dB)	Ping
13	5	89.00 percent

Figure 21 displays severe ingress with the spectrum analyzer in maximum hold for 10 seconds.

**Figure 21**

Ingress with Spectrum Analyzer in Maximum Hold for 10 Seconds

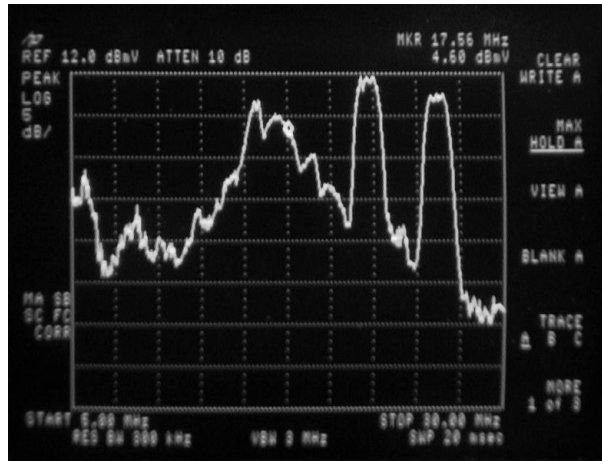
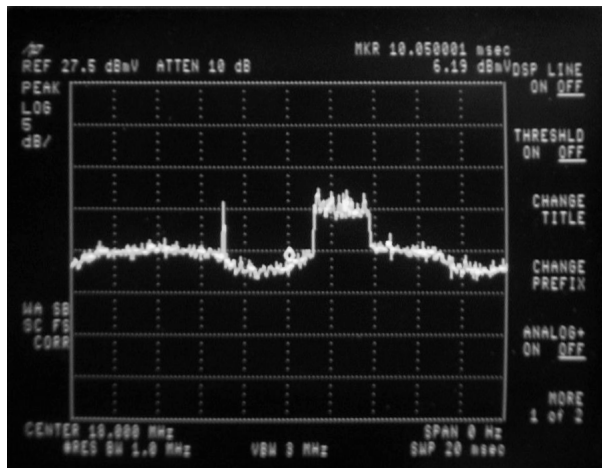


Figure 22 illustrates the C/I ratio of the QPSK signal with a 5 dB/div scale.

**Figure 22**

C/I Ratio of QPSK Signal with 5 dB/div Scale



**Table 10.** Location 2 – Test B

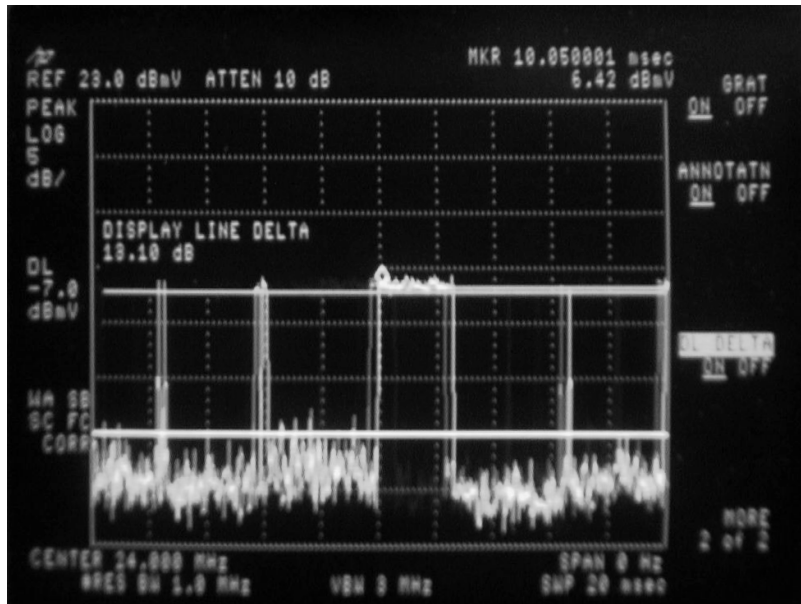
**16-QAM**  
**fc = 24 MHz**  
**3.2 MHz**

CMTS Input (dBmV)	C/I (dB)	Ping
8	15	99.95 percent
3	11	99.89 percent

Figure 23 shows a zero-span trace of the cable modem signal while set for 3 dBmV. The spectrum analyzer RBW is 1 MHz, and the vertical scale is 5 dB/div.

**Figure 23**

Zero-Span Trace of Cable Modem Signal Set for 3 dBmV



### Test Site 3: North America

The third test site was a customer location in the southeastern United States.

### Test Setup for Packet Loss

The Cisco uBR10012 was configured with the Cisco 5x20S BPE running 16-QAM/3.2 MHz channel width. The Cisco 5x20S BPE was in slot 8/0 with u0, u1, u2, and u3 connected to a live plant. Modems tested included the Toshiba 2200 and Motorola 4200. A 23.25 MHz CW carrier from an Acterna SDA-5000 was the interfering signal. The test began at a C/I of 23 dB and the ratio was decreased to 12 dB.

The test was performed using a command-line interface (CLI) ping command with a packet size of 1518 (Toshiba 1400 packet size), and 500 continuous pings.

Interface 8/0 is a Cisco 5x20S BPE with 423 total modems on 4 upstream ports. Table 11 shows cable modems connected to the Cisco 5x20S BPE under test.

**Table 11.** Cable Modems Connected to Line Card Under Test

Interface	Cable Modem			
	Total	Registered	Unregistered	Offline
Cable8/0/0/U0	175	163	12	11
Cable8/0/0/U1	193	176	17	15
Cable8/0/0/U2	53	51	2	2
Cable8/0/0/U3	1	1	0	0

Table 12 summarizes Cisco 5x20S BPE performance results using Toshiba 2200 and Motorola 4200 cable modems.

**Table 12.** Performance Results

**Toshiba 2200 Cable Modems:**

Measured C/I	CMTS Reported SNR	Comments
23 dB	25 dB	No packet loss/48-ms avg. speed
20 dB	24 dB	1 percent packet loss/47-ms avg. speed
16 dB	22 dB	1 percent packet loss/46-ms avg. speed
12 dB	17 dB	7 percent packet loss/45-ms avg. speed

**Motorola 4200 Cable Modems:**

Measured C/I	CMTS Reported SNR	Comments
23 dB	25 dB	No packet loss/47-ms avg. speed
20 dB	22 dB	1 percent packet loss/47-ms avg. speed
16 dB	21 dB	1 percent packet loss/47-ms avg. speed
12 dB	16 dB	8 percent packet loss/41-ms avg. speed

**Live Plant Test**

Additional 16-QAM/3.2 MHz channel bandwidth tests were performed with ingress and noise coming from the customer’s network. Noise-generating equipment was not used.

On the Cisco 5x20S BPE card with advanced PHY capabilities, including ingress cancellation, CPU utilization of 2 to 3 percent and 3 to 5 percent was observed for non-peak and peak periods, respectively.

All results were verified by the cable customer, and acquired on the Cisco uBR10012 while connected to an operating cable network. Operation for 16-QAM was successful on both the Cisco MC28C line card and the Cisco 5x20S BPE. The Cisco MC28C line card was running 256-QAM downstream/16-QAM upstream and exhibited no upstream packet loss until ~22 dB C/I. The Cisco 5x20S BPE was tested with 16-QAM, achieving <1-percent packet loss at ~20 dB and ~ 16 dB C/I.

**Additional Cisco 5x20S BPE Lab Tests**

An additional set of tests was conducted to quantify the Cisco 5x20S BPE advanced PHY performance configured for 3.2 MHz bandwidth 16-QAM operation. The following results summarize measured performance in a controlled lab environment, set up to closely simulate real-world impairments.

## Test Procedure

1. Measure cable modem transmitted digitally modulated carrier at the CMTS upstream input port; verify 0 dBmV average power level.
2. Apply AWGN such that upstream digitally modulated carrier average power level-to-AWGN ratio is 25 dB.
3. Apply interferers in this configuration (that is, with carrier-to-AWGN at 25 dB).
4. Three cable modems were used in the test, each running 100 packets per second (pps) for 60 seconds, 64-byte packets, with a Smartbits traffic generator.
5. Measure results from 0.05- to 5-percent (sometimes 30-percent) packet loss. Result is packet loss closest to 1 percent when averaging across all three modems.
6. Preliminary testing indicated that the performance of 64-byte versus 1500-byte packets was within 1 dB, so all subsequent tests were performed at 64 bytes.

## Definitions

- $C/I$  is measured with  $C$  = Digitally modulated carrier average power level;  $I$  = Peak power of interferer (except AWGN)
- $f_c$  = Center frequency
- $f_c + 1/2 f_s$  = Digitally modulated carrier center frequency + 1/2 symbol rate offset from  $f_c$

## AWGN Test

Reduce carrier-to-AWGN ratio until 0.5- to 1-percent packet loss is observed.

## Single Carrier Interferer

Reduce  $C/I$  until 0.5- to 1-percent packet loss is observed.

1. CW carrier at  $f_c + 1/2 f_s$
2. Fifty-percent amplitude modulated carrier at  $f_c + 1/2 f_s$
3. One hundred-percent amplitude modulated carrier at  $f_c + 1/2 f_s$

## Dual Carrier Interferers

Reduce  $C/I$  until 0.5- to 1-percent packet loss is observed.

**Note:** Both interfering carriers have identical peak power – the measured result is the peak power of each carrier separately.

1. One hundred-percent AM carrier at 15 Hz (made using two Viewsonics comb generators added together) @  $f_c - 1$  MHz, plus frequency modulated carrier (50-kHz peak deviation) @  $f_c$
2. One hundred-percent AM carrier at 15 Hz (made using two Viewsonics comb generators added together) @  $f_c - 1$  MHz, plus 100-percent AM carrier @  $f_c$

## Common Path Distortion

CPD signal was derived from a standard fiber node high-level output port using a diode circuit as the source of the impairments. The CPD was generated using National Television System Committee (NTSC) standard channelization, using analog channels 2–78 and 96–99. Upstream channel  $f_c = 30$  MHz.

## Results

Measured values represent 0.5- to 1.2-percent average packet loss with FEC enabled. A negative C/I ratio indicates that the interfering signal power was greater than the cable-modem signal power. Table 13 gives results of the test.

**Table 13.** Test Results

Test	Measurement Results
AWGN	16 dB C/N
1 CW carrier at $f_c + 1/2 f_s$	-3 dB C/I
2 50 percent AM at $f_c + 1/2 f_s$	-4 dB C/N
3 100 percent AM Carrier at $f_c + 1/2 f_s$	2 dB C/I
4 Dual Carrier AM	6 dB C/I
5 Dual Carrier AM + FM	2 dB C/I
6 CPD	9 dB C/I

## Summary

Reliable 3.2 MHz bandwidth QPSK and 16-QAM upstream operation have been verified under conditions considered as extreme as when the power of an in-channel interfering carrier exceeds that of the cable modem transmitted signal. Operation in the presence of complex interference comprising multiple carriers, frequency modulated carriers, or CPD has been shown at C/I as low as single digits, and carrier-to-AWGN ratios in the mid-teens. This performance has been further verified in operating cable networks in Asia, Europe, and North America, utilizing parts of the upstream spectrum previously thought unusable.

The advanced PHY in DOCSIS 2.0 provides significantly improved upstream data-transmission robustness compared to DOCSIS 1.x PHY. A-TDMA and ingress cancellation are among the improvements, and they are available today in the Cisco 5x20S and 5x20U BPEs, as well as the Cisco uBR7200 Series MC16U, MC16X, MC28U, and MC28X BPEs. The technology has been proven in both operating cable networks and controlled lab settings, and is fully compatible with DOCSIS 1.x cable modems. Indeed, features such as ingress cancellation will improve the performance of those DOCSIS 1.x modems. Advanced PHY technology has moved beyond theory into real-world deployments.

## References

DOCSIS 1.0 Radio Frequency Interface Specification

<http://www.cablemodem.com/specifications/>

DOCSIS 1.1 Radio Frequency Interface Specification

<http://www.cablemodem.com/specifications/>

DOCSIS 2.0 Radio Frequency Interface Specification

<http://www.cablemodem.com/specifications/>

“DOCSIS 2.0: Wazzup?” Ron Hranac, October 2002 *Communications Technology*

[http://www.ct-magazine.com/archives/ct/1002/1002\\_broadband.html](http://www.ct-magazine.com/archives/ct/1002/1002_broadband.html)

“How to Increase Return Path Availability and Throughput” John Downey, Cisco Systems®

[http://www.cisco.com/en/US/products/hw/cable/ps2209/products\\_white\\_paper09186a00801be4ad.shtml](http://www.cisco.com/en/US/products/hw/cable/ps2209/products_white_paper09186a00801be4ad.shtml)

“More on DOCSIS 2.0,” Ron Hranac, November 2002 *Communications Technology*

[http://www.ct-magazine.com/archives/ct/1102/1102\\_broadband.html](http://www.ct-magazine.com/archives/ct/1102/1102_broadband.html)

“Advanced PHY,” Ron Hranac, April 2005 *Communications Technology*

[http://www.ct-magazine.com/archives/ct/0405/0405\\_broadband.htm](http://www.ct-magazine.com/archives/ct/0405/0405_broadband.htm)

“Optimizing Transmission Parameters in DOCSIS 2.0 with a Digital Upstream Channel Analyzer (DUCA),” Noam Geri and Itay Lusky; Cable Broadband Communications Group, Texas Instruments

**Corporate Headquarters**

Cisco Systems, Inc.  
170 West Tasman Drive  
San Jose, CA 95134-1706  
USA  
www.cisco.com  
Tel: 408 526-4000  
800 553-NETS (6387)  
Fax: 408 526-4100

**European Headquarters**

Cisco Systems International BV  
Haarlerbergpark  
Haarlerbergweg 13-19  
1101 CH Amsterdam  
The Netherlands  
www-europe.cisco.com  
Tel: 31 0 20 357 1000  
Fax: 31 0 20 357 1100

**Americas Headquarters**

Cisco Systems, Inc.  
170 West Tasman Drive  
San Jose, CA 95134-1706  
USA  
www.cisco.com  
Tel: 408 526-7660  
Fax: 408 527-0883

**Asia Pacific Headquarters**

Cisco Systems, Inc.  
168 Robinson Road  
#28-01 Capital Tower  
Singapore 068912  
www.cisco.com  
Tel: +65 6317 7777  
Fax: +65 6317 7799

Cisco Systems has more than 200 offices in the following countries and regions. Addresses, phone numbers, and fax numbers are listed on the **Cisco Website at [www.cisco.com/go/offices](http://www.cisco.com/go/offices).**

Argentina • Australia • Austria • Belgium • Brazil • Bulgaria • Canada • Chile • China PRC • Colombia • Costa Rica  
Croatia • Cyprus • Czech Republic • Denmark • Dubai, UAE • Finland • France • Germany • Greece • Hong Kong SAR  
Hungary • India • Indonesia • Ireland • Israel • Italy • Japan • Korea • Luxembourg • Malaysia • Mexico  
The Netherlands • New Zealand • Norway • Peru • Philippines • Poland • Portugal • Puerto Rico • Romania • Russia  
Saudi Arabia • Scotland • Singapore • Slovakia • Slovenia • South Africa • Spain • Sweden • Switzerland • Taiwan  
Thailand • Turkey • Ukraine • United Kingdom • United States • Venezuela • Vietnam • Zimbabwe

All contents are Copyright © 1992–2005 Cisco Systems, Inc. All rights reserved. Cisco, Cisco Systems, and the Cisco Systems logo are registered trademarks or trademarks of Cisco Systems, Inc. and/or its affiliates in the United States and certain other countries.

CableLabs and DOCSIS are registered trademarks of Cable Television Laboratories Incorporated. Texas Instruments is a trademark of Texas Instruments Incorporated. All other trademarks mentioned in this document or Website are the property of their respective owners. The use of the word partner does not imply a partnership relationship between Cisco and any other company. (0502R)  
JR/LW8741 08/05

