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Product Status	Obsolete
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Core Processor	-
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RAM Size	-
Peripherals	-
Connectivity	-
Speed	-
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Introduction

Cable modem termination systems (CMTSs) can report a variety of operating parameters to the end user. For example, CMTSs that use Broadcom® BCM3137, BCM3138, or BCM3140 or Texas Instruments® TNETC4522 series upstream burst receivers can provide an "upstream SNR" estimate. This function is a very useful tool, but it has resulted in much confusion. It is not unusual for a cable company's network operations center (NOC) staff to report an alarm condition when the reported upstream signal-to-noise ratio (SNR) of the CMTS drops below a defined threshold. A headend technician follows up by checking the upstream RF performance with a spectrum analyzer or similar test equipment, only to find that everything appears normal.

Data personnel in the NOC insist there must be a problem, while outside plant technicians see nothing amiss on their test equipment. What is going on here?

The discrepancy occurs from a lack of understanding about just what the CMTS upstream SNR estimate is—and what it is not.

Further confusion comes from the fact that cable modems and digital set-top boxes (STBs) can provide digitally modulated signal operating parameters such as RF signal level and SNR. These are downstream parameters at the customer premises, not upstream parameters as is sometimes incorrectly assumed. In addition, test equipment used by cable operators to characterize digitally modulated signals can measure downstream—and in some cases upstream—modulation error ratio (MER). Some of these instruments call this parameter SNR.

Also, because of the time-shared nature of the upstream, most of today's CMTSs can measure parameters on a per-*channel* basis or a per-*cable-modem* basis. Per-channel measurements provide an average of all cable modems or simply a snapshot of the most recently active cable modem(s). It is important to distinguish which type of measurement is presented.

This paper provides a background on several signal quality metrics applicable to CMTS and cable network operation and how they relate to overall performance. The CMTS upstream SNR and cable modem or STB downstream SNR estimates are explained. Noise, as discussed in this paper and unless defined otherwise, refers to *additive white Gaussian noise* (AWGN), or simply *white noise*, also known as thermal noise. Interference such as narrowband ingress and burst or impulse noise is usually treated separately.

First, what the CMTS upstream SNR estimate is not: the SNR estimate from a cable modem or CMTS is *not* the same thing as the carrier-to-noise ratio (CNR) that one measures with a spectrum analyzer.

Here is what the upstream SNR estimate is: an operating parameter provided by the upstream burst receiver used in DOCSIS® CMTSs. Similar information for downstream signals is provided by the quadrature amplitude modulation (QAM) receiver in a cable modem or STB. The SNR estimate, which is derived after the data is demodulated, is more accurately called receive modulation error ratio (RxMER), a term recently defined in the DOCSIS MIB. RxMER includes the effects of the cable network downstream or upstream noise floor, in-channel frequency response (including amplitude tilt and ripple, group delay variation, and micro-reflections), oscillator phase noise, receiver imperfections, and all other impairments that affect the receive symbol constellation. Because it measures the end-to-end performance of the communications link, RxMER is useful for tracking long-term system performance trends.

Interestingly, it is not unusual to have a reported low downstream or upstream RxMER number, yet find the measured CNR and signal levels to be just fine. Why? Because one or more impairments that cannot be seen on a spectrum analyzer—poor in-channel frequency response, including group delay variation and micro-reflections, and even upstream data collisions—may be the cause of the low reported RxMER.

This paper discusses the terms listed in Table 1.

Table 1: Terminology for Various SNR Ratio Concepts

Abbreviation	Term	Definition	Units
CNR (or C/N)	Carrier-to-noise ratio	The ratio of carrier or signal power to the white-noise power in a specified bandwidth, as measured on an RF spectrum analyzer or similar equipment.	dB
C/N_0	Carrier-to-noise - density ratio	The ratio of carrier or signal power to white-noise spectral density.	dB-Hz
CNIR (or C/(N+I))	Carrier-to-noise-plus-interference ratio	The ratio of carrier or signal power to the total noise power (including white noise and interference) in a specified bandwidth, as measured on an RF spectrum analyzer or similar equipment.	dB
E_S/N_0	Energy-per-symbol to noise-density ratio	In digital modulation, the ratio of the average energy of a QAM symbol to the white-noise spectral density.	dB
EVM	Error vector magnitude	The ratio of RMS constellation error magnitude to peak constellation symbol magnitude.	Percent
MER	Modulation error ratio	The ratio of average signal constellation power to average constellation error power.	dB
RxMER	Receive modulation error ratio	The MER as measured in a digital receiver after demodulation, with or without adaptive equalization.	dB
SNR (or S/N)	Signal-to-noise ratio	(a) A general measurement of the ratio of signal power to noise power. (b) In a specific context, a measurement of the ratio of signal power to noise power made at baseband before modulation or after detection or demodulation.	dB
TxMER	Transmit modulation error ratio	The MER produced by a transmitter under test, as measured by an ideal test receiver.	dB

CNR and SNR from a Telecommunications Industry Perspective

Some of the confusion mentioned in the introduction arises from the fact that in the world of telecommunications outside the cable industry, the terms SNR and CNR are often used interchangeably. According to Roger L. Freeman's *Telecommunications Transmission Handbook*, "The signal-to-noise ratio expresses in decibels the amount by which a signal level exceeds its corresponding noise." Another reference, Tektronix's *Measuring Noise in Video Systems*, says "In the most general case, SNR is expressed as the ratio of RMS (root mean square) signal level, S_{RMS}, to the RMS noise, N_{RMS}, (SNR = S_{RMS}/N_{RMS})." [Eq. 1]

Both of the previous SNR definitions can easily be applied to RF CNR measurements (after all, a carrier is a "signal") as well as baseband SNR measurements (baseband video and audio are "signals," too). If the specific measurement is not clearly defined, it is difficult to know whether SNR refers to a baseband or RF parameter. This paper distinguishes between SNR and CNR. In the subsequent sections, each term is defined and explained, and the distinction is illustrated following usage in the cable industry.

CNR and SNR from a Cable Industry Perspective

Modern Cable Television Technology, 2nd Ed., states, "Carrier-to-noise ratio (*C/N*) is defined as follows:

$$C/N(\text{dB}) \equiv 10\log(c/n) \qquad \text{[Eq. 2]}$$

where *c* and *n* are the scalar power levels of the carrier and noise, respectively."[1]

When measuring CNR on a spectrum analyzer with thermal noise underlying the carrier, one actually is measuring not C/N but, more precisely, (C + N)/N = 1 + C/N. This distinction is not normally a concern unless the CNR is very low—say, single-digit decibel (dB) values, as we will see later.[2]

The cable industry has long used CNR and SNR to represent quite different measurement parameters, one in the RF domain (Figure 1) and the other in the baseband domain (Figure 2 on page 5). CNR is applied to the transmitted over-the-cable RF waveform, whereas SNR refers to the video and audio signal prior to modulation for broadcast, or after demodulation of the RF waveform at the receiver.

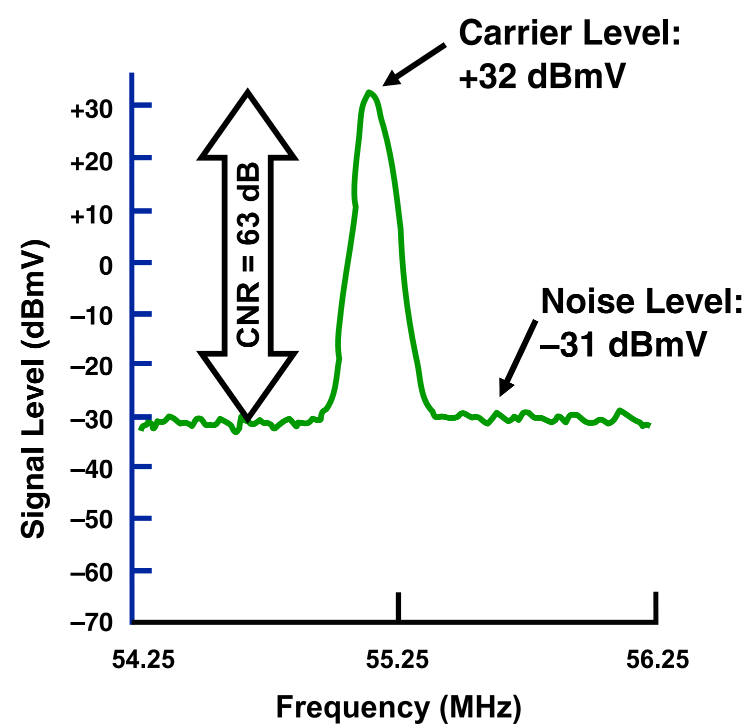

Figure 1: RF CNR Measurement (As Detected in the Test Equipment Resolution Bandwidth)

1. In this paper, all logarithms are base 10.
2. The expression 1 + C/N uses power quantities, not dB; that is, we are not adding 1 dB to C/N.

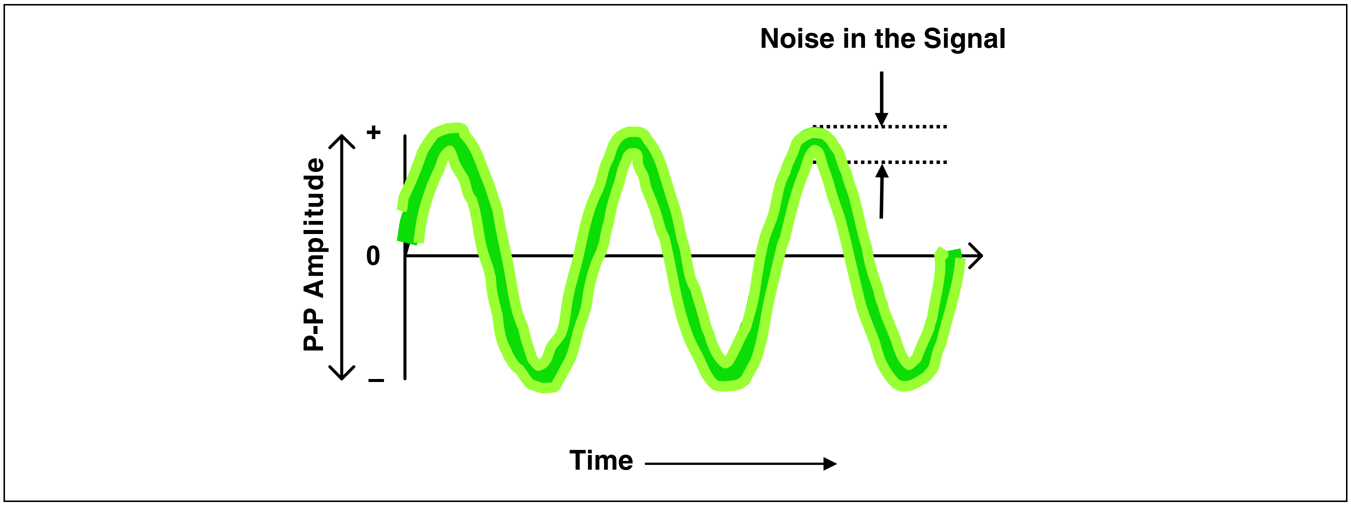

Figure 2: Baseband SNR Measurement

Analog Video CNR in Cable Networks

Consider CNR, which is generally accepted to be a predetection measurement—that is, one made at RF. When only analog TV channels were carried on cable networks, CNR was understood to be the difference, in decibels, between the amplitude of a TV channel visual carrier[3] and the root mean square (RMS) amplitude of system noise in a specified noise power bandwidth. In this application, noise power bandwidth is normally specified as the modulation bandwidth, which is approximately equal to the bandwidth of the baseband modulating signal. It is common practice to express power in terms of RMS voltage across a nominal resistance. For example, *NCTA Recommended Practices for Measurements on Cable Television Systems* defines 0 dBmV (decibels referenced to one millivolt) as the power of a signal of 1 millivolt RMS in 75 ohms, or 13.33 nanowatts = –48.75 dBm.

According to the Federal Communications Commission's (FCC's) cable regulations in §76.609 (e), system noise is the "total noise power present over a 4 MHz band centered within the cable television channel." This latter definition is applicable only to analog National Television System Committee (NTSC) TV channel CNR measurements, and defines the approximate bandwidth of the baseband video that modulates the channel visual carrier.

The FCC does not actually use the term CNR in the rules. §76.605 (a)(7) states "The ratio of RF visual signal level to system noise shall...not be less than 43 decibels." That definition is more or less in line with the general definition of SNR, although it is understood in this specific instance to mean CNR. Even though the FCC's cable rules mandate a minimum CNR of 43 dB, good engineering practice targets end-of-line analog TV channel CNR in the 46 to 49 dB range. More on this topic appears later in this paper.

3. Visual carrier amplitude is the RMS amplitude of the synchronizing peak or "sync." This amplitude corresponds to the visual carrier's peak envelope power (PEP).

Analog Video SNR in Cable Networks

What about SNR? SNR is, in cable industry vernacular, a premodulation (at the transmitter or modulator) or postdetection (at the receiver) measurement—one made on a baseband signal such as video or audio. The previously mentioned Tektronix application note says: "In video applications, however, it is the effective power of the noise relative to the nominal luminance level that is the greater concern." It goes on to define video SNR in decibels as:

$$SNR = 20\log(L_{NOMINAL}/N_{RMS}) \qquad \text{[Eq. 3]}$$

where $L_{NOMINAL}$ has a value of 714 millivolts peak-to-peak (100 IRE units) for NTSC or 700 mV peak to peak for PAL. These luminance values do not include sync.

Equation 3 simply states that baseband video SNR is the ratio of the peak-to-peak video signal, excluding sync, to the noise within that video signal. The noise is measured in a bandwidth defined by a combination of low-pass, high-pass, and weighting filters. These filters limit the measured noise to a bandwidth that is roughly the same as the video signal and may be used to remove certain low-frequency noise from the measurement. Weighting filters are used to simulate the eye's response to noise in the TV picture. Various standards such as RS-170A, RS-250B, and NTC-7 specify the characteristics of filters that are used in baseband video SNR measurements.

To recap: CNR is a predetection measurement performed on RF signals. It is the difference, in decibels, between carrier power and noise power in the RF transport path only—for instance, a coaxial cable distribution network or a stand-alone device such as an upconverter or headend signal processor. As such, CNR is ideal for characterizing network or individual device impairments. SNR, when applied to analog video or audio signals, is a premodulation or postdetection measurement performed at baseband. It is equal to the ratio of the peak-to-peak baseband signal to the noise within that signal (refer to Figure 1 on page 4). SNR includes noise in the original signal—say, noise in the video from a TV studio camera—as well as noise contributions from the transmitter or modulator, transport path, receiver, and demodulator. It is ideal for characterizing end-to-end performance—the overall picture quality seen by the end user, in the case of baseband video SNR.

Discrete Versus Modulated Signals and Carrier-to-Noise Density Ratio

A measurement that is closely related to CNR is carrier-to-noise-density ratio (C/N_0), defined as the ratio of carrier or signal power (in watts) to the underlying white-noise power spectral density (in watts/Hz). Noise power spectral density N_0 is the noise power in a 1 Hz bandwidth—that is, watts per Hz. Because of the impracticality of making a 1 Hz bandwidth noise power measurement, noise power spectral density is usually measured in a larger, more convenient bandwidth—the test equipment resolution bandwidth (RBW)—or, to be more precise, the equivalent noise bandwidth of the RBW filter. The measured value in watts is then divided by the test equipment resolution bandwidth in Hz, which yields the power (in watts) in a 1 Hz bandwidth. If the noise power measurement is in dBmV, subtract 10log(RBW in Hz) from the measured value to get the 1 Hz bandwidth equivalent, also in dBmV.

Taking the ratio of units shows that C/N_0 has units of Hz:

$$\frac{C\ (\text{watts})}{N_0\ (\text{watts/Hz})} = C/N_0(Hz) \qquad \text{[Eq. 4]}$$

Downstream Digitally Modulated Signal CNR — An Example

Assume that a cable network has been designed to provide a downstream end-of-line CNR of 46 dB with +15 dBmV subscriber tap levels for analog TV channels, and a downstream 64-QAM DOCSIS digitally modulated signal is carried at –10 dBc. Thus the digital channel power of the 64-QAM signal at the tap spigot will be +5 dBmV, or 10 dB lower than the +15 dBmV analog TV channel levels. What is the 64-QAM signal CNR? It is *not* 36 dB, as one might first assume.

Because analog TV channel CNR is 46 dB at the tap spigot, the noise-floor amplitude N_{NTSC} for the analog channels is +15 dBmV – 46 dB = –31 dBmV (4 MHz noise power bandwidth for analog NTSC TV channels). To determine the 64-QAM signal CNR, we have to first calculate what the noise-floor amplitude is for that QAM signal, based on a noise power bandwidth equal to its symbol rate. For DOCSIS 64-QAM signals, the symbol rate is 5.056941 Msym/sec, so the noise power bandwidth is 5.06 MHz (refer to Table 2). From this, we can calculate the noise-floor amplitude $N_{64\text{-}QAM}$ for the QAM signal with the equation:

$$N_{64\text{-}QAM} = N_{NTSC} + [10\log(5.06/4)] = -29.98 \text{ dBmV} \qquad \text{[Eq. 8]}$$

The 64-QAM signal CNR is +5 dBmV – (–29.98 dBmV) = 34.98 dB.

The CNR of the digitally modulated signal is degraded by more than the 10-dB reduction in signal level because the wider noise bandwidth in the digital signal case allows more AWGN through to the demodulator.

E_S/N_0 and CNR of a Digitally Modulated Signal

E_S/N_0 is the most prevalent parameter used in digital communications to represent the SNR of a signal. It is defined as the ratio of the average energy E_S per QAM symbol to the noise power spectral density N_0 with the noise assumed white. It is a unitless ratio and is normally expressed in dB. Energy per symbol is equal to the average power—that is, the energy in 1 second—of the signal divided by the number of symbols in 1 second.

How can we reconcile E_S/N_0 with CNR? If we multiply the numerator and denominator by the symbol rate R_S, we get:

$$\frac{Es}{N_0} = \frac{E_s R_s}{N_0 R_s} = \frac{\textit{Signal Power}}{\textit{Noise Power in Symbol Rate Bandwidth}} = CNR \qquad \text{[Eq. 9]}$$

(assuming no synchronous code-division multiple access [S-CDMA] spreading, which we discuss later). This equation tells us why the measurement of CNR for digitally modulated signals typically uses the noise power bandwidth equal to the symbol rate: It results in CNR being equal to E_S/N_0.

Practical QAM CNR Measurements

Figure 6 shows an example of measuring downstream digitally modulated signal CNR and E_S/N_0 using a spectrum analyzer marker noise function, which measures noise power in a 1 Hz bandwidth. The carrier is centered on the screen, and the marker noise function is activated. Make a note of the indicated marker noise amplitude of the digitally modulated signal (–80.70 dBmV in the left display), and then tune the analyzer to a frequency that allows measurement of the noise floor of the cable network. The right display shows a noise-floor amplitude of –95.82 dBmV. The difference between the two measurements is the approximate CNR and E_S/N_0, in this case about 15 dB.

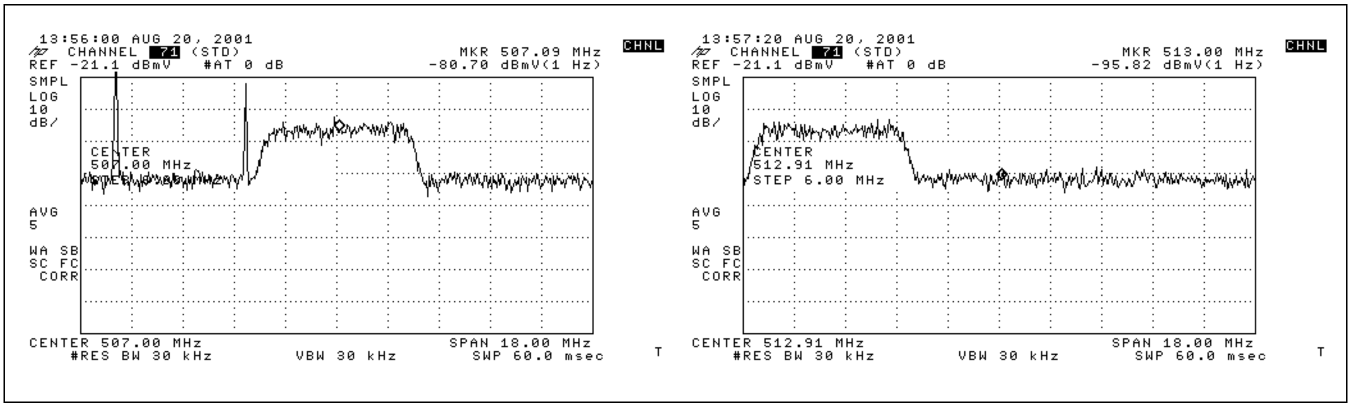

Figure 6: Digitally Modulated Signal CNR (This Example Shows an Approximate CNR of 15 dB.)

For best accuracy, noise should be measured using sample detection, which is typically employed by a spectrum analyzer marker noise function. Marker noise measurements usually encompass a range of frequency samples, starting from the marker and going plus or minus a small number of points out of the total available in the analyzer trace, so proper placement of the marker away from the carrier is important for accuracy. Refer to the analyzer documentation.

Signal and Noise Measurements on a Spectrum Analyzer

A few practical tips are worth noting when measuring modulated signals and noise on a spectrum analyzer.[6]

- Ensure that the spectrum analyzer uses sample detection when measuring noise or noise-like signals. If log/peak detection is used, a detector correction factor (typically 2.5 dB—consult the spectrum analyzer documentation) needs to be applied to the measurement result. Of course, if the signal and noise have the same statistics (Gaussian or nearly so), the same correction factor will be added to both the signal and noise measurements, and the correction will cancel out when measuring the CNR.

6. For a thorough treatment of this subject, refer to Agilent Application Note 1303, "Spectrum Analyzer Measurements and Noise: Measuring Noise and Noise-like Digital Communications Signals with a Spectrum Analyzer."

- Be sure that the signal being measured (the information signal itself or the system noise, which is also a "signal") is at least 10 dB above the noise floor of the spectrum analyzer.[7] Sometimes, a low-noise preamplifier must be added at the spectrum analyzer input, or a test point with greater signal amplitude must be found. If measurement of a signal with very low CNR cannot be avoided, the offset caused by the analyzer noise floor can be subtracted from the raw measurement in order to correct the power readings. Figure 8 in the next section gives the applicable noise-floor correction. Care should be taken when subtracting nearly equal noise power measurements (for example, System noise + Analyzer noise floor – estimated analyzer noise floor), because the result may become zero or negative because of measurement uncertainties. In that case, more smoothing of the measurements may be needed.
- Correct the measurement to account for the ratio of the resolution bandwidth to the noise bandwidth of the analyzer. The RBW is normally expressed as the –3 dB bandwidth of the RBW filter. The equivalent noise bandwidth of the RBW filter is typically 6 to 13 percent wider than its –3 dB bandwidth, requiring a 0.25 to 0.5 dB correction, respectively, to the measurement. Consult the analyzer documentation for the exact values.

More on the Effect of Noise Floor on CNR and Power Measurements

As mentioned earlier, measuring a signal with very low CNR requires a correction to back out the noise underlying the signal. Let's look more closely at the effect of underlying noise on the measurement of CNR, or, in general, the difference between S/N and (S+N)/N. Figure 7, which shows a close-up view of a band-limited digitally modulated signal with a CNR value of only 4 dB, illustrates the effect. The blue trace, S + N, is observed on a spectrum analyzer. The underlying signal S without the noise N is shown in red in the figure; it would not be visible on the spectrum analyzer because noise is always present in a real system. The top of the blue haystack is about 1.5 dB above the top of the red haystack, showing the measurement error (S+N)/S caused by the noise-floor contribution.

7. Temporarily disconnect the spectrum analyzer RF input. The displayed noise should drop at least 10 dB. If it does not, a significant portion of the displayed noise is the test equipment noise floor adding to the cable system noise floor.

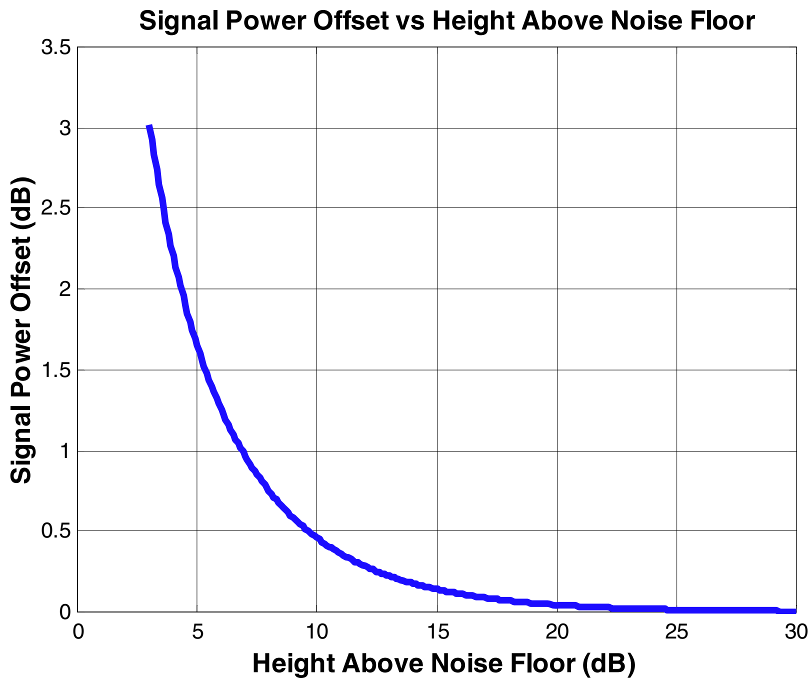

Figure 8: Signal Power Measurement Correction Relative to Noise Floor

Returning to the example in Figure 7, the height of the haystack above the noise as seen on the spectrum analyzer will be:

$$\begin{aligned} \text{haystack\_height\_dB} &= 10\log(1 + 10^{\text{true\_CNR\_dB}/10}) \\ &= 10\log(1 + 10^{4/10}) \\ &= 5.45 \text{ dB} \end{aligned} \qquad \text{[Eq. 17]}$$

and, reversing [Eq. 17], the true CNR follows:

$$\begin{aligned} \text{true\_CNR\_dB} &= 10\log(10^{\text{haystack\_height\_dB}/10} - 1) \\ &= 10\log(10^{5.45/10} - 1) \\ &= 4 \text{ dB} \end{aligned} \qquad \text{[Eq. 18]}$$

In summary: In the example in Figure 7, measuring a signal with a very low CNR of 4 dB requires subtracting 1.5 dB from the haystack-height CNR reading in order to back out the noise underlying the signal. To measure the CNR of normal QAM signals with CNR greater than about 15 dB, such a correction is not necessary. For measurement of system noise power that is less than 10 dB above the spectrum analyzer noise floor, a correction from Figure 8 is required to back out the analyzer noise-floor contribution.

CNR at the CMTS Upstream Input Port

In most cases, the CNRs for all modems at a given CMTS upstream port are identical, or nearly so. Cable modem upstream transmit levels are managed by the CMTS ranging process to provide the same receive

Carrier-to-Noise-Plus-Interference Ratio

Often we need to make a distinction between the underlying thermal noise floor, which is flat, and narrowband interference, which appears as spectral lines or narrow humps on a spectrum analyzer display. In that case, we use the term "carrier-to-noise-plus-interference ratio" (CNIR). In DOCSIS, the CMTS upstream receive CNIR is defined in the MIB as the ratio of the expected commanded received signal power to the noise-plus-interference in the channel. Both the digitally modulated signal power and noise-plus-interference power are referenced to the same point—the CMTS input. The expected commanded received signal power is the power of an upstream burst that has been correctly adjusted by the CMTS ranging process. The noise-plus-interference power is the total power measured when no desired signal is present, that is, during quiet times on the upstream, when only the unwanted noise and interference are present. Note that one reason for not including narrowband interference with white noise when measuring CNR is that devices such as ingress cancellers can reduce the effect of narrowband ingress, whereas white noise cannot be similarly mitigated.

Digitally Modulated Signals and Baseband SNR

RF CNR is fairly straightforward for digitally modulated signals. But what about baseband SNR? Rather than using our previous definition of baseband video or audio SNR, we must look for a different way to measure baseband data SNR.

Views of a QAM Waveform

For further insight, consider the DOCSIS 256-QAM downstream signal shown in Figure 9. In (a), we see the familiar haystack spectrum of a QAM signal. Its shape is flat on the top, except for implementation imperfections and measurement noise, and, in this example, the channel has inserted some slight amplitude ripple and tilt as well. The height of the spectrum above the noise floor is 45 dB, which is the CNR and E_S/N_0 value. Its width at the –3 dB point is equal to the symbol rate R_S = 5.36 MHz. Its sides are shaped by the transmit filter, with excess bandwidth equal to 12 percent; that is, the signal occupies 12 percent more bandwidth than an ideal brick-wall signal of the same symbol rate, because of the roll-off region. (As a quick check, 6 MHz occupied bandwidth ÷ 5.36 MHz symbol rate = 1.12.)

the histogram or probability density function (PDF) of the I or Q component of the QAM signal. The QAM signal approaches a Gaussian distribution, shown as a dotted red line, although the QAM distribution bulges more and has limited tails compared to the reference Gaussian distribution, which has the same standard deviation (signal level) as the QAM signal.

Baseband SNR could be defined as the ratio of the average power in the complex baseband (I and Q) signal to the average noise power in the symbol rate bandwidth. However, this definition would just replace RF CNR with an equivalent complex baseband CNR, because it does not include demodulation of the signal. For a digital SNR, we wish to measure the QAM signal after demodulation all the way down to its received constellation symbols. That is where RxMER comes in.

The SNR of a Demodulated Digital Signal: RxMER

The solution is to define a new quantity to represent the SNR of a digital baseband signal: receive modulation error ratio. RxMER is defined as the ratio of average constellation symbol power to average constellation error power, expressed in dB. As we will see, RxMER looks at the demodulated complex baseband constellation symbols and measures their quality. The RxMER measurement gives the near “bottom line” status of the communications link, because it is these demodulated symbols that will go on to produce correct bits, or bit errors, at the receiver output after processing by the forward error correction (FEC) decoder.

Equalized and Unequalized RxMER

Returning to Figure 9, we see in part (d) the received QAM constellation before equalization. Although the CNR on the spectrum display is 45 dB, the channel imperfections have caused the constellation to exhibit an RxMER value of only 26 dB. After the adaptive equalizer compensates for the channel response, the RxMER is restored to 45 dB, as shown in part (e) of Figure 9. This discussion shows that when we discuss RxMER, it is important to specify whether we are talking about the equalized or unequalized value.

Figure 10 shows a diagnostics page screen capture from a residential cable modem.[8] The indicated signal-to-noise ratio is 36 dB (circled). Most cable modems provide an equalized RxMER measurement of the downstream 64- or 256-QAM digitally modulated signal. For the example in Figure 10, a QAM analyzer provided a nearly identical equalized MER measurement of the cable modem received 256-QAM signal (35 dB).

8. Many DOCSIS cable modems allow viewing the diagnostics page on the computer connected to the modem. To access the diagnostics page on modems that support this function, type **http://192.168.100.**1 in the browser address or URL window.

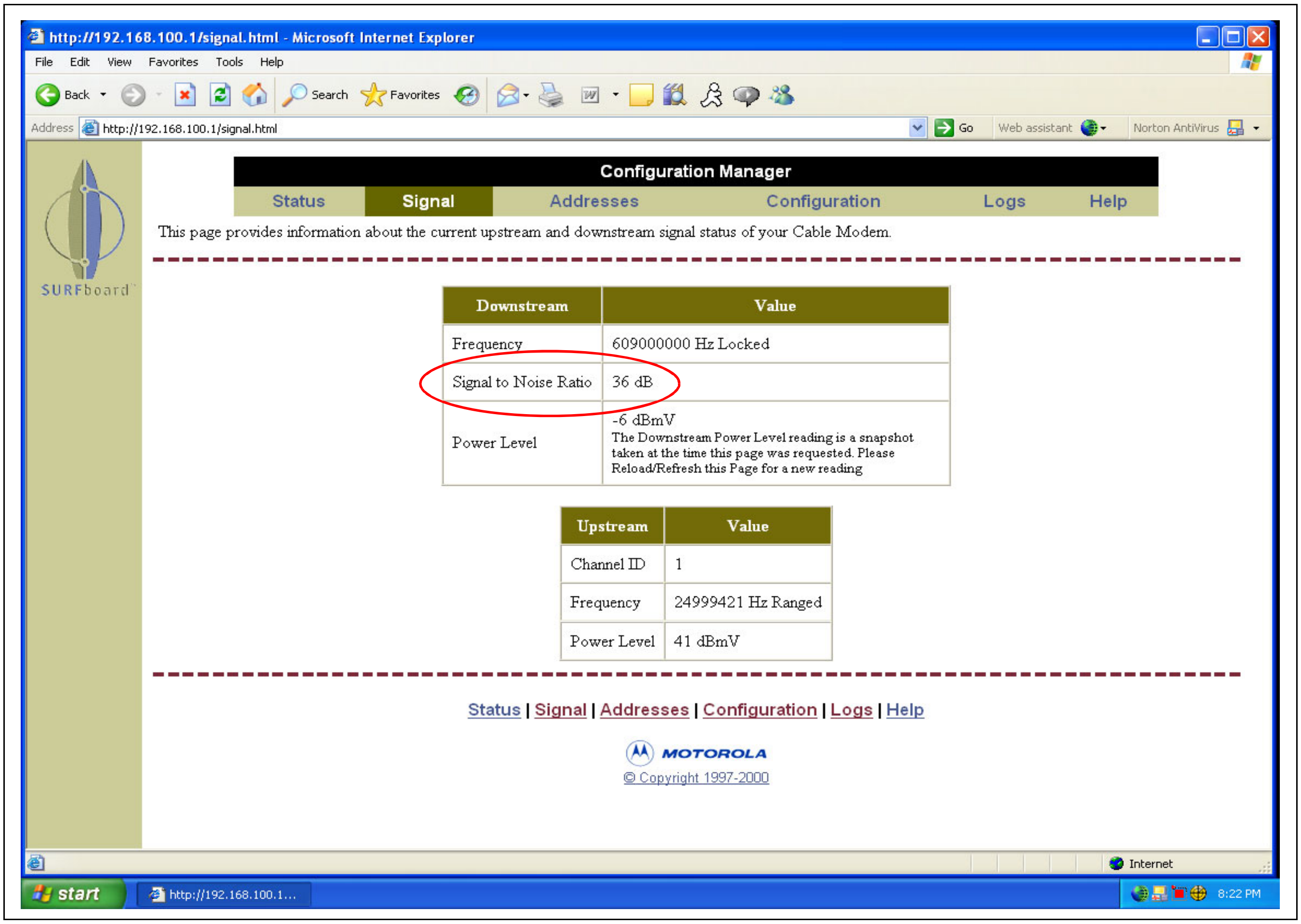

Figure 10: Cable Modem Diagnostics Screen Showing Downstream Equalized SNR (RxMER)

RxMER Measurement in a Digital Receiver

Before further discussing RxMER, we consider how a digital receiver is implemented, and how RxMER is measured. Figure 11 is a generalized block diagram of a digital QAM receiver. The receiver may reside in the CMTS, in which case it receives time-division multiple access (TDMA) or S-CDMA upstream bursts; or it may reside in a cable modem or set-top box (STB), in which case it receives a continuous stream of downstream digital data. The RF signal from the cable plant enters at the left of the diagram, and is processed by analog and digital front-end components that perform tuning, automatic gain control, channel selection, analog-to-digital conversion, and related functions. The square-root Nyquist filter has a response “matched” to the symbol or S-CDMA chip (a “chip” is a bit in the pseudorandom spreading code used in S-CDMA, as explained later). An adaptive equalizer compensates for channel response effects, including group delay variation, amplitude slope or ripple, and microreflections. An ingress canceller is normally included in a CMTS burst receiver to remove in-channel narrowband interference. Acquisition and tracking loops provide estimates of frequency, phase, and symbol timing, allowing the receiver to lock to the incoming signal. In the CMTS burst receiver, preamble symbols are used as a reference to aid in the acquisition and tracking of each upstream burst. In the case of S-CDMA, the chips are despread. The received QAM symbol, or soft decision, is passed to the slicer, which selects the nearest ideal symbol, or hard decision, from the QAM constellation. The decisions are passed to the Trellis decoder, descrambler, deinterleaver, Reed-Solomon (RS) FEC decoder and MPEG deframer, and on to the MAC layer, which assembles and outputs received packets to the user.

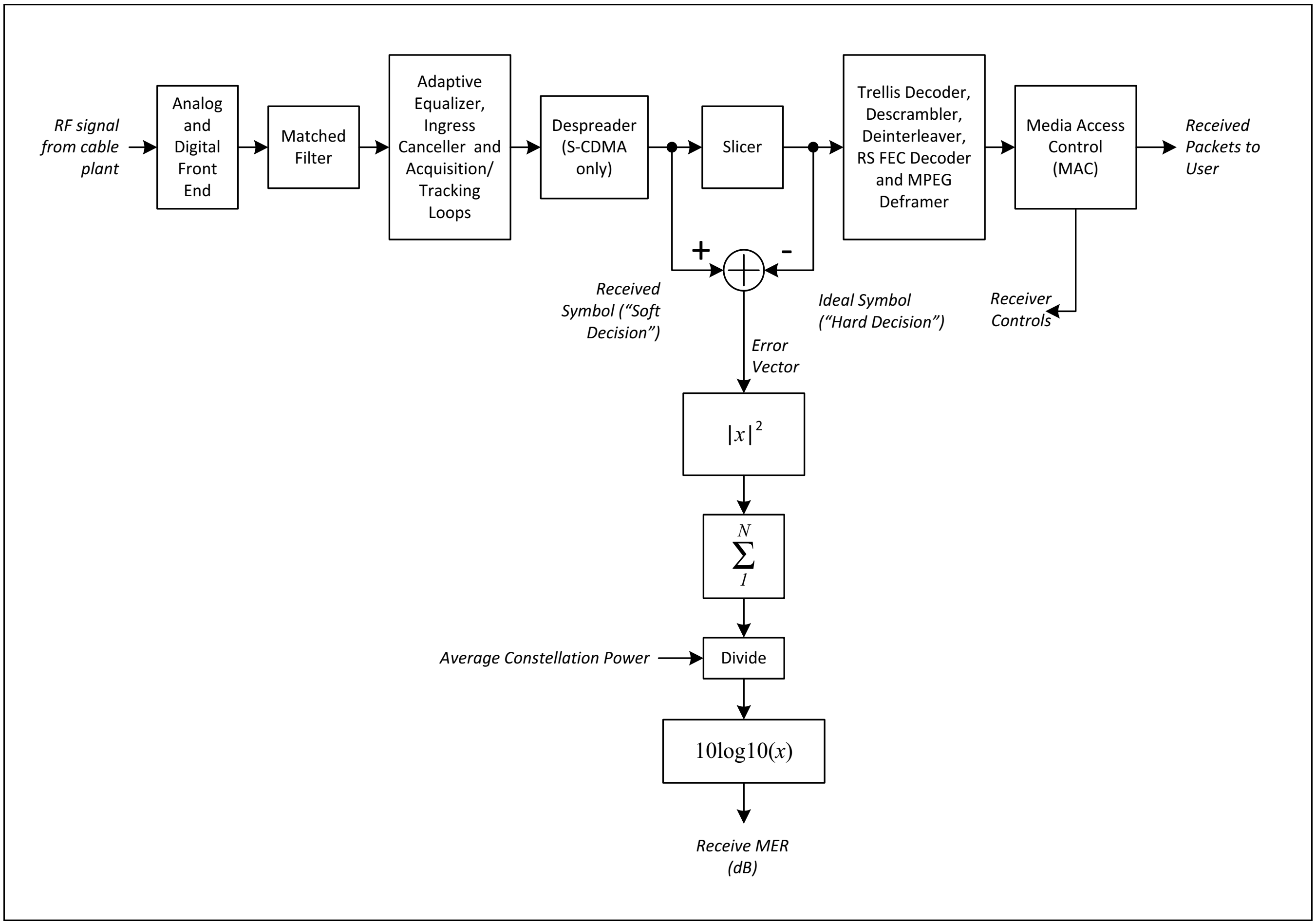

Figure 11: Block Diagram of Generalized Digital QAM Receiver, Showing Computation of Receive MER

Table 4: Valid MER Measurement Ranges

Modulation Format	Lower E_S/N_0 Threshold	Upper E_S/N_0 Threshold
QPSK	7–10 dB	40–45 dB
16 QAM	15–18 dB	40–45 dB
64 QAM	22–24 dB	40–45 dB
256 QAM	28–30 dB	40–45 dB

Good engineering practice suggests keeping RxMER in an operational system at least 3 to 6 dB or more above the lower E_S/N_0 threshold.[10] This guideline will accommodate numerous factors that can affect operating headroom, including temperature-related signal-level variations in the coaxial plant, amplifier and optoelectronics misalignment, and imperfect calibration of test equipment. The lower E_S/N_0 threshold can be thought of as an "MER failure threshold" of sorts, that is, when unequalized RxMER approaches the lower E_S/N_0 threshold, the channel may become unusable with the current modulation. Possible workarounds include switching to a lower order of modulation, using adaptive equalization, or identifying and repairing what is causing the low RxMER in the first place.

Transmit MER

Although this paper is mainly concerned with RxMER, transmit MER (TxMER) is also of interest. TxMER is defined as the MER produced by a transmitter under test, as measured by an ideal test receiver. In a real test, the receiver is, of course, not ideal and will introduce its own degradations to MER measurement. The receiver contribution, if small (a few dB) and accurately measurable, can be used to correct the TxMER measurement. In addition, DOCSIS provides the following method for removing the effects of the frequency response of a test receiver on a TxMER measurement. First a near-ideal test transmitter is connected to the test receiver, and the receiver equalizer coefficients are allowed to converge in order to compensate for the frequency response of the test bed. The receive equalizer is then frozen, and the transmitter under test is connected in place of the test transmitter. The MER reading taken from the test receiver is the unequalized TxMER measurement. The test receiver is again allowed to adapt its equalizer coefficients, and the resulting MER reading is the equalized TxMER measurement.

Factors Affecting MER Measurement

Because MER is a digital computation performed on digital quantities in the receiver, it is by nature extremely accurate in itself. However, the measured value can be affected by many things. As a result, MER may not accurately reflect the CNR or E_S/N_0 at the input to the receiver.

- *Statistical variation*: The number of samples N over which the MER (or RxMER) is averaged affects the reliability of the measurement. For independent samples, the standard deviation of a measurement is in general proportional to $1/\sqrt{N}$, so, for example, averaging over 10,000 samples will result in 10 times smaller standard deviation of the MER measurement than using 100 samples. A smaller standard deviation means the MER measurement will appear more stable. Conversely, taking fewer samples can also offer advantages. In a sense, the number of samples N provides a

10. Many cable operators use the following unequalized MER (RxMER) values as minimum acceptable operational values: QPSK ~18 dB; 16-QAM ~24 dB; 64-QAM ~27 dB; and 256-QAM ~31 dB.

control analogous to the video averaging function on a spectrum analyzer. A smaller number of symbols allows the observation of transients in the MER measurement, which can highlight the effects of burst noise, distortion, clipping, and pulsed ingress.

- *Unequal occurrence of symbols*: The average constellation power is a known constant for each constellation, such as 64-QAM or 256-QAM, and does not need to be computed. Some MER implementations nevertheless compute the average constellation power by taking the complex magnitude-squared of the received ideal symbols and averaging it over a given number of captured symbols *N*. For large *N*, this works fine and approaches the average constellation power. However, if the MER measurement is performed over just a few symbols (for example, $N < 100$), the result may be unreliable because, in some cases, many large QAM symbols (near the outer edges of the constellation) will happen to be transmitted, and in other cases, many small QAM symbols (in close to the origin, or center of the constellation) may happen to be transmitted.
- *Nonlinear effects*: Nonlinearities in the signal path, including laser clipping and amplifier compression, can affect outer constellation points more severely than inner points. As an example, in one return-path system with nonlinearities present,[11] the equalized RxMER (24-tap equalizer) of a QPSK signal was measured at 38.0 dB, a level that seemed to promise good margin for higher orders of modulation. However, with 16-QAM, the equalized RxMER was 31.9 dB, and with 256-QAM, the equalized RxMER was 30.2 dB. Hence, when measuring MER, it is important to measure the same constellation that will be used for transmitting data. It is also important to capture a large enough data sample to ensure that all symbols occur with equal likelihood.
- *Linkage of carrier loop bandwidth to capture length*: Some MER measurement equipment does not have an explicit carrier tracking loop. Instead, a block of *N* received symbols is captured and averaged. The averaging produces an effective carrier tracking loop with equivalent one-sided noise bandwidth $BL = R_S/2N$, where R_s is the symbol rate. To achieve the DOCSIS specification value of BL = 50 kHz, for example, would require $N = 54$ symbols at $R_s = 5.36$ MHz. As mentioned previously, measuring MER over such a small number of symbols can give unreliable results.
- *Implementation-loss MER ceiling*: Even if the input E_S/N_0 is very high, the MER reading will saturate at a value reflecting the implementation loss of the receiver. The receiver contributes noise to the MER measurement because of front-end noise figure; imperfect time, frequency, or phase tracking; round-off effects; imperfect equalization; etc. For example, it is unusual in a 256-QAM receiver for the MER measurement to go much above 40 to 45 dB, even when there is no noise at the receiver input, as mentioned previously in the description of Table 4.
- *Symbol-error MER floor*: The slicer produces the hard decision by taking the soft decision and finding the nearest ideal constellation point. If the wrong constellation point is chosen, a symbol error occurs. The error vector magnitude then indicates the distance to the nearest symbol point, which may be closer than the correct symbol, meaning that the error will seem smaller than it really is, and the MER will seem better than its true value. As a general rule, the MER measurement is not valid when the input E_S/N_0 is below the point that produces roughly a 1-percent symbol error rate (before trellis or FEC decoding), as mentioned previously in the description of Table 4.
- *Analog front-end noise*: The analog front end of the receiver contributes thermal noise and possibly spurious products, effectively raising the noise floor of the system and lowering the RxMER relative to the CNR measurement. This effect is most pronounced at low RF input levels.
- *Phase noise*: Phase noise is a slowly varying random phase in the received signal. The analog tuner is a primary contributor of phase noise in the receiver. The carrier phase tracking loop in the receiver

11. Reported by Cooper, et al. in a paper presented at SCTE Cable-Tec Expo 2006.

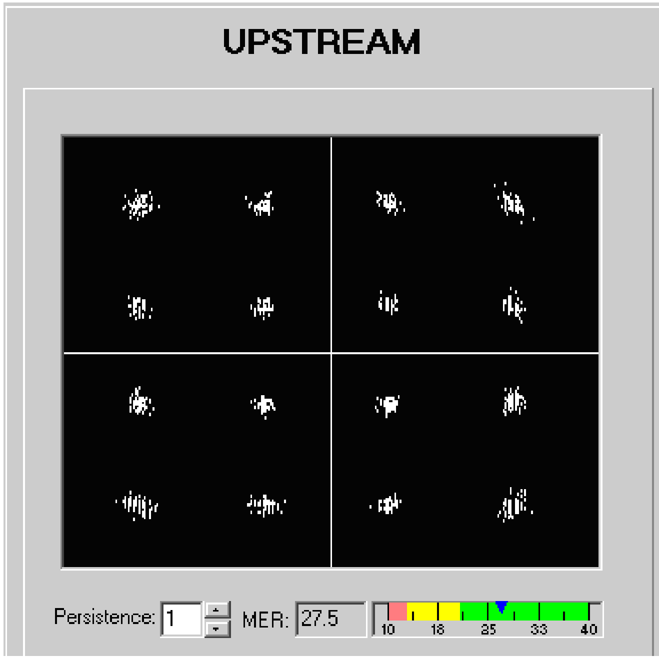

Figure 17: Unimpaired 16-QAM Digitally Modulated Signal; the Unequalized MER Is 27.5 dB. (Courtesy Filtronic-Sigtek)

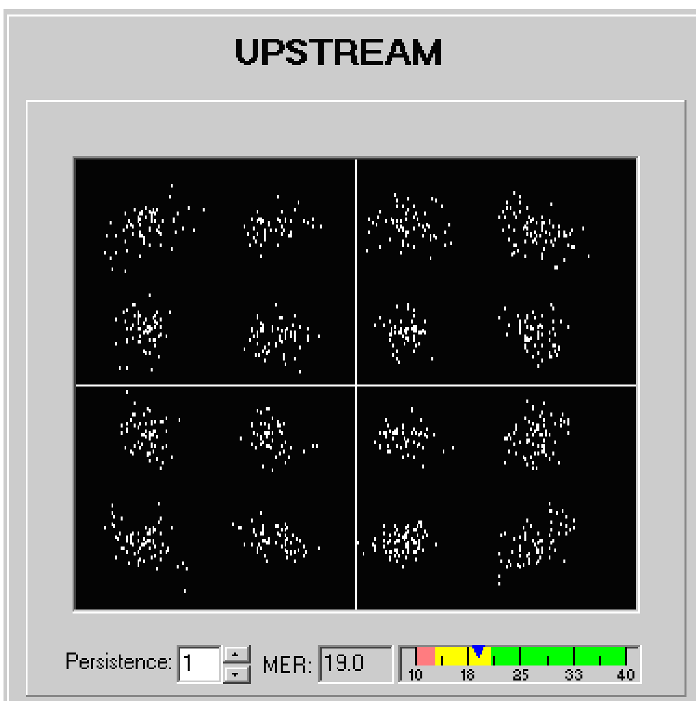

Figure 18: Impaired 16-QAM Digitally Modulated Signal; the Unequalized MER Is 19 dB (Courtesy Filtronic-Sigtek)

The spectrum analyzer screen shot in Figure 19 shows the upstream spectrum of a cable plant in the band from 0 to 100 MHz. The region from 5 MHz to 22 MHz contains relatively low-level ingress. Clean upstream spectrum is seen in the 22 MHz to 42 MHz range. The upstream DOCSIS carrier is located at 32 MHz under the rightmost red cursor. The diplexer roll-off is seen in the 42 MHz to 54 MHz range. This upstream is relatively clean: The CNR of the carrier is excellent at about 36 dB; there is no visible common path distortion, ingress, or strong impulse noise anywhere near the signal; and we see only a modest amount of ingress well below the signal frequency. Yet although QPSK worked fine in this upstream, unequalized 16-QAM was found to be unusable. The reason? Linear distortions. A severe impedance mismatch about 1100 feet from the node caused a micro-reflection, resulting in amplitude and group delay ripple. These distortions were not visible on the spectrum analyzer display, yet were significant enough to degrade the upstream RxMER and impair 16-QAM transmission. The CMTS reported low SNR —in reality, unequalized RxMER—of 21 dB, which agreed with third-party test equipment measurement of unequalized MER (refer to Figure 20 on page 39). To support 16-QAM transmission on this plant, the operator could enable the preequalization function that is available in DOCSIS 1.1 and higher modems, or increase the level of FEC coding.

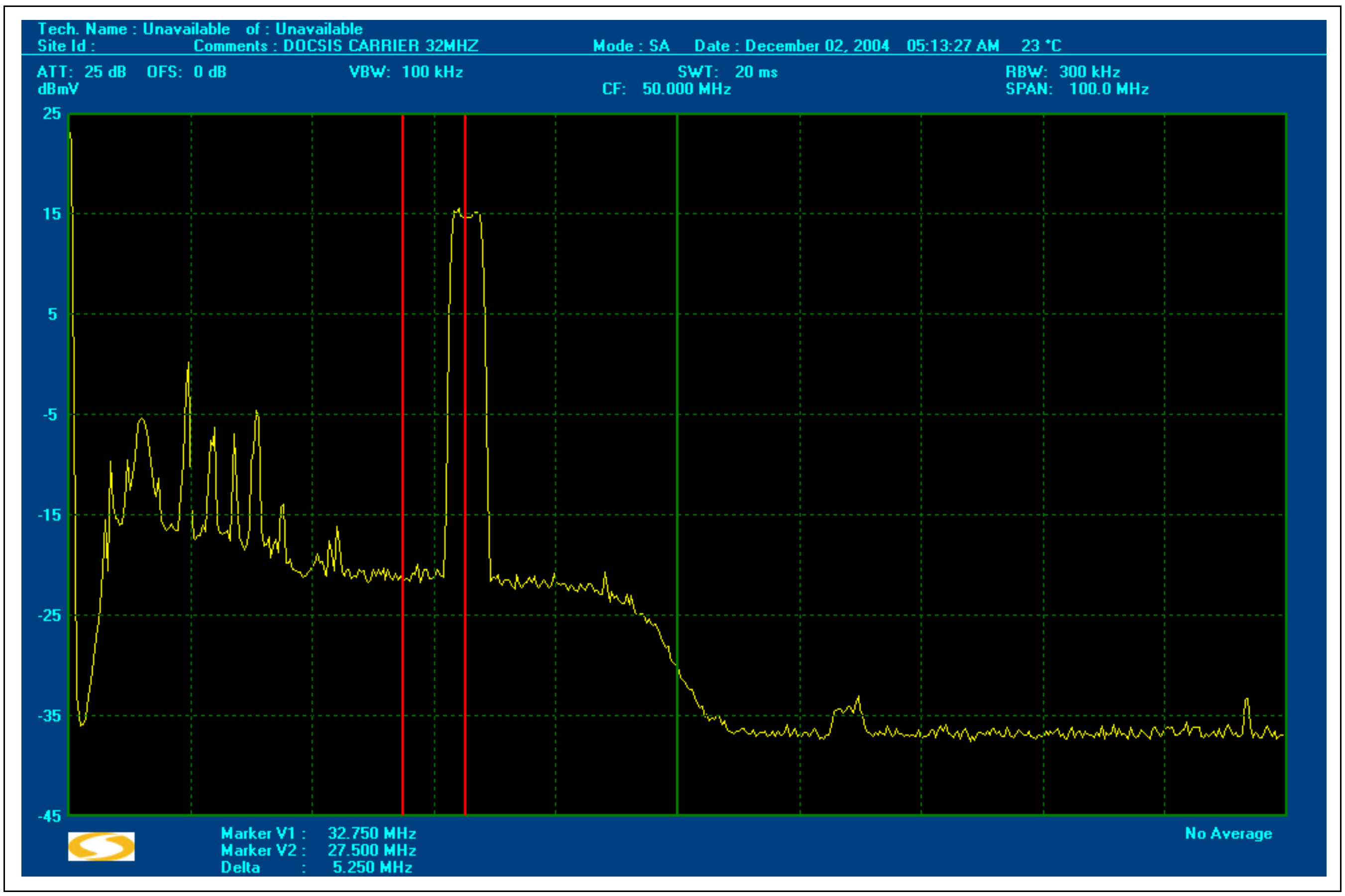

Figure 19: A Spectrum Analyzer Display Shows What Appears to Be a Relatively Clean Upstream, But Unequalized 16-QAM Would Not Work. The CNR Is About 36 dB. (Courtesy Sunrise Telecom)

Each S-CDMA symbol is stretched 128 times longer by the spreading process. For example, consider a 3.2 MHz-wide channel (modulation rate 2.56 MHz). An S-CDMA symbol is made up of 128 chips, with each chip duration 1/2.56 MHz = 0.39 microsecond (the same duration a TDMA symbol would have in the same width channel). The S-CDMA symbol duration is 0.39 microsecond x 128 = 50 microseconds. This duration was designed to be longer than most bursts of noise that occur in the upstream, explaining why S-CDMA is resilient to impulse or burst noise.

Orthogonality of S-CDMA Codes

The S-CDMA codes possess the property of *orthogonality*, meaning that each despreader output ideally depends only on its assigned code, and not on what is happening on the other codes. In effect, each code acts like an independent communications channel, with its own noise component and "per-code" E_S/N_0. The E_S/N_0 in one code does not depend (to a first approximation, assuming perfect orthogonality) on whether the other codes are even being transmitted. This situation is depicted in Figure 22. In a real system, perfect orthogonality is never achieved because of imperfect equalization; phase, frequency, and timing errors; and other implementation effects, which result in intercode interference (ICI).

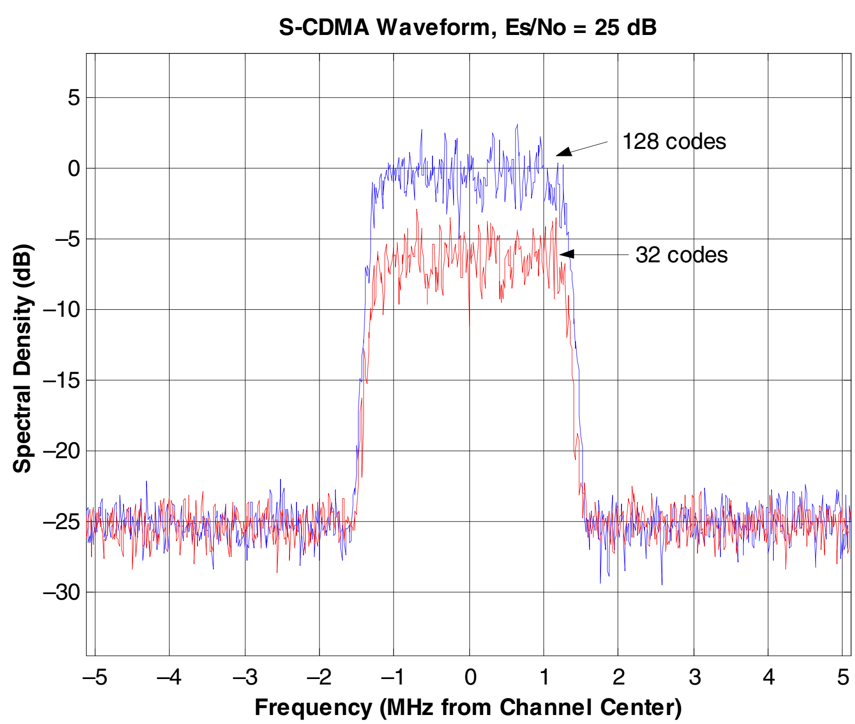

Figure 22: Conceptually, S-CDMA Can Be Thought of as Having an Independent Upstream Channel for Each Code, Each with Its Own Noise Component.

Assuming ideal ranging, all codes are received at the CMTS at the same level, with the total received signal power divided equally among the 128 codes. The white-noise floor from the channel is also divided into 128 equal parts by the despreaders, which function as a bank of 128 filters. Because both the signal and noise are reduced by the same factor of 1/128, the E_S/N_0 in each code is the same as the overall E_S/N_0 of the channel. Figure 23 shows a received S-CDMA constellation after the despreaders, with 25 dB E_S/N_0 or RxMER.

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