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DIGITAL TRANSMISSION, PART 2

By RON HRANAC

Modulation error ratio (MER) is digital complex baseband signal-to-noise ratio (SNR) - in fact, in the data world, the terms "SNR" and "MER" are often used interchangeably, adding to the confusion about SNR, especially considering that, as mentioned in Part 1, in the telecommunications world, the terms "CNR" (carrier-to-noise ratio) and "SNR" are often used interchangeably.

Why use MER to characterize a data signal? It is a direct measure of modulation quality and has linkage to bit error rate (BER). MER is normally expressed in decibels, so it is a measurement that is familiar to cable engineers and technicians. It is a useful metric with which to gauge the end-to-end health of a network, although by itself, MER provides little insight about the type of impairments that exist.

Figure 1 illustrates a 16-QAM (quadrature amplitude modulation) constellation. A perfect, unimpaired 16-QAM digitally modulated signal would have all of its symbols land at exactly the same 16 points on the constellation over time. Real-world impairments cause most of the symbol landing points to be spread out somewhat from the ideal symbol landing points. Figure 1 shows the vector for a target symbol - the ideal symbol we want to transmit. Because of one or more impairments, the transmitted symbol vector (or received symbol vector) is a little different than ideal. Modulation error is the vector difference between the ideal target symbol vector and the transmitted symbol vector. That is (Eq. 1):

FIGURE 1: Modulation error is a measure of modulation quality. (Source: Hewlett-Packard)

If a constellation diagram is used to plot the landing points of a given symbol over time, the resulting display forms a small "cloud" of symbol landing points rather than a single point. MER is the ratio of average symbol power to average error power (refer to Figure 2) (Eq. 2):

MER(dB) = 10log(Average symbol power ÷ Average error power)

FIGURE 2: Modulation error ratio is the ratio of average symbol power to average error power. (Source: Hewlett-Packard)

In the case of MER, the higher the number, the better.

Mathematically, a more precise definition of MER (in decibels) follows (Eq. 3):

where I and Q are the real (in-phase) and imaginary (quadrature) parts of each sampled ideal target symbol vector and are the real (in-phase) and imaginary (quadrature) parts of each modulation error vector. This definition assumes that a long enough sample is taken so that all the constellation symbols are equally likely to occur.

In effect, MER is a measure of how "fuzzy" the symbol points of a constellation are. Table 1 summarizes the approximate ratio of the average energy ES per QAM symbol to the noise power spectral density N0 (ES/N0) range that will support valid MER measurements for various DOCSIS modulation constellations. The two values in the table for the lower threshold correspond approximately to ideal uncoded symbol error rate (SER) = 10-2 and 10-3, respectively. The upper threshold is a practical limit based on receiver implementation loss. Outside the range between the lower and upper thresholds, the MER measurement is likely to be unreliable. The threshold values depend on receiver implementation. Some commercial QAM analyzers may have values of the lower ES/N0 threshold 2 to 3 dB higher than those shown in the table.

Good engineering practice suggests keeping unequalized receive MER (RxMER) in an operational system at least 3 to 6 dB or more above the lower ES/N0 threshold. Many cable operators use the following RxMER values as minimum acceptable operational values: quadrature phase shift keying (QPSK) ~18 dB; 16-QAM ~24 dB; 64-QAM ~27 dB; and 256-QAM ~31 dB. This guideline will accommodate temperature-related signal level variations in the coaxial plant, amplifier and optoelectronics misalignment; test equipment calibration and absolute amplitude accuracy; and similar factors that can affect operating headroom. The lower ES/N0 threshold can be thought of as an "MER failure threshold" of sorts. That is, when unequalized RxMER approaches the lower ES/N0 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 article 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 ES/N0 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 divided by the square root of 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 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 (Reported by M. Cooper, et al, in the paper "Maximizing Throughput in the Return Path via DOCSIS 2.0" presented at SCTE Cable-Tec Expo 2006), 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 = Rs/2N, where Rs is the symbol rate. To achieve the DOCSIS specification value of BL = 50 kHz, for example, would require N = 54 symbols at Rs = 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 ES/N0 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 1.

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 ES/N0 is below the point that produces roughly a 1 percent symbol error rate - before trellis or forward error correction (FEC) decoding - as mentioned previously in the description of Table 1.

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 has the job of tracking out (removing) the low-frequency phase noise. In the DOCSIS Downstream RF Interface (DRFI) specification, phase noise below 50 kHz is separated out from the TxMER requirement because the phase noise is assumed to be largely removed by the receiver carrier loop. In general, a narrow (for example, 5 kHz) carrier loop will allow more phase noise to degrade the RxMER, but will pass less thermal noise through to the RxMER measurement. Conversely, a wide (for example, 50 kHz) carrier loop will allow less phase noise to degrade the RxMER, but will pass more thermal noise through to the RxMER measurement.

The net effect is that varying the receiver carrier loop bandwidth will affect the RxMER, so the correct measurement carrier loop bandwidth must be carefully specified. The effects of phase noise become more critical as the modulation order increases.

Ingress cancellation effects: Modern cable modem termination system (CMTS) burst receivers have ingress cancellers, which remove in-channel narrowband interference entering the cable plant from the environment. After ingress cancellation, the upstream RxMER will be much higher than the input carrier-to-noise-plus-interference ratio (CNIR) because the interference has been removed. The ingress canceller may add some white noise, depending on its implementation; the net result, however, is a dramatically improved RxMER.

Burst noise: Short, strong bursts of noise may have unpredictable effects on the RxMER measurement. When burst noise hits, the RxMER will register a decrease, depending on the amount of averaging in the RxMER measurement and the burst properties of the noise. Downstream or upstream laser clipping - and its accompanying clipping distortion - tends to affect all frequency channels simultaneously. This is known as cross-compression and usually degrades BER (the symptoms may be similar to burst noise) and, if severe enough, RxMER. In some instances, MER reported by instruments such as QAM analyzers will change little, if at all, in the presence of short, infrequent or weak burst noise because the instrument averages the measurement over many symbols.

Collisions: In a time division multiple access (TDMA) upstream, some time slots are "contention slots" in which multiple modems may randomly transmit. When two modems choose the same slot to transmit in, a collision occurs. At the receive slicer, the resulting signal looks like it has been hit by burst noise. RxMER measurements can be designed to exclude these noise contributions because contention slots are scheduled by the media access control (MAC) and, therefore, predictable.

Multiuser nature of upstream: In both TDMA and synchronous code division multiple access (S-CDMA) upstreams, the channel is shared by multiple users. In an ideal world with perfect ranging and equalization, all users would have equal RxMER. In reality, each upstream signal takes a unique route from modem to CMTS, so there will be slight differences in received power, transmit fidelity, etc., resulting in potentially different per-modem RxMER values. In DOCSIS, the upstream RxMER MIB measurement is defined as the average over a given number of valid bursts - that is, from many users, excluding contention slots.

Suboptimal modulation profiles: Modulation profiles define how upstream information is transmitted from the cable modem to the CMTS. These profiles set modem transmit parameters - burst guard time, preamble, modulation type, FEC protection and so forth - for request, initial maintenance, station maintenance, and short and long grant messages. Poorly configured modulation profiles can result in degraded upstream RxMER. For example, a preamble that is too short does not provide enough time for the tracking loops of the burst receiver to converge, resulting in lower RxMER. Interburst guard times that are not adequate result in interference from the end of one burst onto the beginning of the next, also degrading RxMER.

RxMER and DOCSIS upstream equalization

Let's briefly review DOCSIS upstream adaptive equalization. In DOCSIS 1.1 and later systems, each cable modem contains a pre-equalizer whose purpose is to predistort the transmit waveform so as to compensate for the upstream channel frequency response. In effect, the adaptive equalizer - the pre-equalizer of the modem - creates the equivalent of a digital filter with the opposite complex frequency response of the channel through which the upstream signal is transmitted. As defined in DOCSIS 2.0, the pre-equalizer is a 24-tap finite-impulse-response filter. When a cable modem is first powered on, it sends a specialized ranging burst (distinct from data traffic bursts) to the CMTS. The CMTS adapts its burst-receiver equalizer based on this "sounding" of the unique channel from the modem to the CMTS. The CMTS sends the equalizer coefficients back to the modem, which loads them into its pre-equalizer. Ideally, the pre-equalizer exactly corrects the response of the channel, and the data traffic bursts that the CMTS receives from that modem are free of linear distortion from then on. In a real system, the number and spacing of pre-equalizer taps limit the extent to which impairments can be compensated. The channel also varies with time. The modem sends periodic ranging bursts so that the CMTS can "tweak" the pre-equalizer coefficients of the modem in a tracking process. The pre-equalizer coefficients are updated by convolving them with the "residual" equalizer coefficients computed in the CMTS receiver on each ranging burst.

An important parameter in an equalizer is the span, defined as the (Number of taps - 1) times the spacing of the taps. If the channel response contains a significant echo (micro-reflection) that is further out in delay than the span of the equalizer, the equalizer cannot compensate for it. Hence, the span is a design parameter that depends on the channel model. The spacing of the pre-equalizer taps is defined in DOCSIS 2.0 as "T-spaced," or symbol-spaced. At 5.12 Msym/sec, 24 taps gives a span of (24 - 1)/5.12 = 4.5 microseconds, which we may compare to the DRFI specification maximum assumed upstream micro-reflection or single echo parameter of >1.0 microsecond at -30 dBc.

Some CMTSs provide equalized RxMER measurements: The burst receiver adapts its equalizer on each data traffic burst as it is received, whether or not pre-equalization is in use. Other CMTSs provide unequalized RxMER measurements: The burst receiver does not adapt its equalizer on each data traffic burst as it is received. If pre-equalization is in use, there will be little difference between the RxMER measurements from these two types of CMTSs because the signal is already compensated when it arrives at the CMTS, and there is little equalization left to do in the burst receiver. However, if pre-equalization is not in use, as, for example, with older DOCSIS 1.0 modems, then the RxMER measurements from CMTSs that perform receive equalization will generally be higher than the RxMER measurements from CMTSs that do not perform receive equalization. One might notice in this instance that longer packets show a higher RxMER measurement than shorter packets because the receive equalizer has more time to converge to its steady-state coefficient values on a long packet. Using a longer preamble may also help the receive equalizer to adapt more completely on each burst.

DOCSIS MIB definition of upstream RxMER

In DOCSIS, the upstream RxMER MIB measurement is defined as an estimate, provided by the CMTS demodulator, of the ratio (Eq. 4):

The CMTS RxMER is averaged over a given number of bursts at the burst receiver, which may correspond to transmissions from multiple users. The MIB does not specify whether receive equalization is enabled; this is implementation-dependent.

EVM vs. MER

Another measurement metric that is closely related to MER is error vector magnitude (EVM). As shown previously in Figure 1, EVM is the magnitude of the vector drawn between the ideal (reference or target) symbol position of the constellation, or hard decision, and the measured symbol position, or soft decision. By convention, EVM is reported as a percentage of peak signal level, usually defined by the constellation corner states. Mathematically, EVM follows (Eq. 5):

EVM = (ERMS/Smax) x 100 percent

where ERMS is the RMS error magnitude and Smax is the maximum symbol magnitude. EVM is illustrated in Figure 3. From this, it is clear that the lower the EVM, the better. Contrast EVM with MER, where the higher the MER, the better.

FIGURE 3: Error vector magnitude is the ratio (in percent) of RMS error magnitude to maximum symbol magnitude. (Source: Hewlett-Packard)

EVM is normally expressed as a linear measurement in percent, and MER is normally expressed as a logarithmic measurement in dB. Why use EVM instead of MER to characterize a data signal? Many data engineers are familiar with EVM, and for some, linear measurements are easier to work with than logarithmic measurements. EVM links directly with the constellation display, and there is a linear relationship between EVM and a constellation symbol point "cloud size" or "fuzziness."

Maximum-to-average constellation power ratio and EVM/MER conversion

Because EVM and MER are referenced differently, in order to relate EVM to MER, we must first compute the ratio of the peak constellation symbol power to the average constellation power. The peak constellation power is the squared magnitude of the outermost (corner) QAM symbol. Its formula for a square QAM constellation on an integer grid follows (Eq. 6):

where M is the number of points in the constellation (M = 4, 16, 64, 256, etc.) and the points are spaced by 2 on each axis. For example, for 16-QAM, the I and Q coordinates take on values from the set {-3, -1, 1, 3} and the peak power is 2(4 - 1)2 = 32 + 32 = 18. (Use of the integer grid is for illustration purposes only and does not imply any particular power normalization.)

The average constellation power (averaged equally over all symbols in the constellation) follows (Eq. 7):

For example, for 16-QAM, the average constellation power is (2/3) (16 - 1) = 10. Note that this result happens to equal the power of one of the constellation points; the point (3,1) also has power 32 + 12 = 10.

The maximum-to-average constellation power ratio (MTA) is, therefore, the unitless ratio (Eq. 8):

which approaches 3, or in decibels, 10log(3) = 4.77 dB, for very-high-order QAM. MTA (converted to dB) is tabulated in Table 2, which contains entries for the standard square constellations as well double-square constellations. A double-square constellation is a subset consisting of half the points of the next-higher square constellation, arranged like the black squares on a checkerboard, and contains the same peak and average values as the next-higher square constellation. DOCSIS uses 64-QAM and 256-QAM square constellations for downstream transmission and both square and double-square constellations from QPSK to 128-QAM for upstream transmission.

We can now convert from MER to EVM using the formula (Eq. 9):

EVM_% = 100 x 10-(MER_dB + MTA_dB)/20

where
EVM_% is error vector magnitude (percent).
MER_dB is modulation error ratio (dB).
MTA_dB is maximum-to-average constellation ratio (dB).

MTA vs. PAR of an RF signal

It is important not to confuse MTA with the peak-to-average ratio (PAR) of the actual transmitted signal. MTA accounts only for the distribution of the ideal QAM constellation symbols. Because of the subsequent spreading, filtering and modulation processes that operate on the symbols, the effective PAR of a single modulated RF carrier will typically lie in the range of 6 to 13 dB or more. (The effect of filtering was illustrated previously by the long tails in the distribution in part (c) of Figure 9 in Part 1, which ran in the June issue.) The actual PAR value depends on the modulation, excess bandwidth, and whether pre-equalization or S-

CDMA spreading is in use. HEYS Professional Services' Francis Edgington has measured practical PAR values in the 6.3 to 7.3 dB range for 64-QAM signals and 6.5 to 7.5 dB range for 256-QAM signals. The PAR of a combined signal containing multiple carriers (such as the aggregate upstream or downstream signal on the cable plant) can become very large. Fortunately, the peaks occur very seldom, and the aggregate signal can often be treated like a random Gaussian signal.

MER and EVM equipment and example measurements

Specialized test equipment such as a vector signal analyzer is generally needed to measure downstream or upstream EVM in a cable network, although some QAM analyzers support its measurement because the equipment must incorporate a digital QAM receiver in order to demodulate the signal to its complex baseband symbol constellation. Figure 4 shows a downstream 256-QAM digitally modulated signal whose EVM is 0.9 percent (circled). This value is representative of what might be seen in a headend or hub site or the downstream output of a node.

FIGURE 4: The EVM of this downstream 256-QAM digitally modulated signal is 0.9 percent. (Courtesy of Sunrise Telecom)

Figures 5 and 6 show two examples of a 16-QAM upstream digitally modulated signal. The constellation in Figure 5 illustrates a relatively unimpaired signal (the signal has a slight amount of phase noise, observable in the angular spread of the corner constellation points, but is otherwise what could be considered a "clean" signal) whose unequalized MER is 27.5 dB. Figure 6 shows an impaired signal, where the unequalized MER is only 19 dB. This level is close to the failure threshold for unequalized, uncoded 16-QAM for some demodulators. In fact, in Figure 6, we can see that some soft decisions are close to the decision boundaries. Note that there is really no way to tell for sure what is causing the low MER in Figure 6 by simply observing the display - it could be because of low CNR or perhaps because of one or more linear or nonlinear distortions.

FIGURE 5: Unimpaired 16-QAM digitally modulated signal; the unequalized MER is 27.5 dB. (Courtesy of Filtronic-Sigtek)

FIGURE 6: Impaired 16-QAM digitally modulated signal; the unequalized MER is 19 dB (Courtesy of Filtronic-Sigtek)

The spectrum analyzer screen shot in Figure 7 shows the upstream spectrum of a cable plant in the band from 0 to 100 MHz. The region from 5 to 22 MHz contains relatively low-level ingress. Clean upstream spectrum is seen in the 22 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 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 (CPD), ingress, or strong impulse noise anywhere near the signal, and 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 1,100 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. (See Figure 8.) To support 16-QAM transmission on this plant, the operator could enable the pre-equalization function that is available in DOCSIS 1.1 and higher modems or increase the level of FEC coding.

FIGURE 7: 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 of Sunrise Telecom)

FIGURE 8: Upstream unequalized MER for the digitally modulated signal in Figure 7 is only 21 dB, and the EVM is a relatively high 6.4 percent. (Courtesy of Sunrise Telecom)

Figures 7 and 8 emphasize the SNR (RxMER) vs. CNR confusion that often occurs in cable systems. The cable operator's network operations center (NOC) might find that the CMTS reported upstream SNR (RxMER) is low (~21 dB in this instance), while a spectrum analyzer shows good CNR (~36 dB) and no apparent problems. The fact that unequalized 16-QAM would not work on this particular upstream - and QPSK was fine - indicates something is amiss.

TDMA and S-CDMA effects on upstream RxMER measurement

Beginning with DOCSIS 2.0, both TDMA and S-CDMA modes are included in the upstream. S-CDMA indicates that multiple cable modems can transmit at the same time, while being separated by orthogonal spreading codes. Because various numbers of codes can be transmitted or quiet in a given S-CDMA frame, care must also be taken to properly normalize the signal measurement to avoid errors in S-CDMA MER measurement. TDMA implies that upstream transmissions have a burst nature: Multiple cable modems share the same upstream frequency channel through the dynamic assignment of time slots.

Because a TDMA signal is bursting on and off, care must be taken to measure the signal power only when the signal is on. If an RF spectrum analyzer is used to measure CNR, the duty factor must be accounted for. The TDMA duty factor can be estimated and normalized out of the CNR measurement. For example, if the channel is active 90 percent of the time, the factor 10log(0.9) = -0.46 dB results; a correction of 0.46 dB must be added to the CNR measurement. Another approach is to measure both signal and noise with the spectrum analyzer in maximum-hold mode, resulting in the analyzer trace filling in the areas where the signal was off. However, this method is susceptible to errors in that the highest TDMA user's power is being measured, not the average signal power; and any high-noise excursions are measured, not the average noise.

CMTS burst receivers can measure RxMER on each upstream burst that is received, thereby avoiding the problem of the quiet times when no signal is present. Because the receiver synchronizes to each upstream burst, it ignores the dead times between bursts.

As mentioned previously, the DOCSIS MIB defines the CNIR measurement as the ratio of expected burst signal power to average noise plus interference during the times when no signal is present. This measurement is tailored to the TDMA nature of the upstream.

S-CDMA introduces a new SNR concept: ES/N0 or RxMER per code. First, let's review the basics of S-CDMA. Figure 9 shows the fundamental concept of S-CDMA data transmission: Each symbol of data is multiplied by a spreading code at the cable modem transmitter and summed with other spread symbols originating both from the same cable modem and from other cable modems on the plant. The composite signal travels across the upstream RF channel, where noise is unavoidably added. At the CMTS burst receiver, the signal is applied to 128 despreaders, which reverse the process by multiplying by the respective spreading codes and summing over all 128 chips in the code. This process reproduces the original data symbols at the receiver output, perturbed, of course, by the noise.

FIGURE 9: Upstream S-CDMA data transmission consists of spreading at the transmitter and despreading each code at the receiver.

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" ES/N0. The ES/N0 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 10. 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 10: 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 ES/N0 in each code is the same as the overall ES/N0 of the channel. Figure 11 shows a received S-CDMA constellation after the despreaders, with 25 dB ES/N0 or RxMER.

FIGURE 11: S-CDMA 16-QAM constellation with 25 dB RxMER

Divergence of CNR and MER in S-CDMA

Because the codes are effectively independent, as shown previously in Figure 10, turning some codes off reduces the total signal power in the channel, but does not affect the ES/N0 on the other codes, meaning the CNR seen on a spectrum analyzer will appear to fluctuate as some codes are transmitted and others are not, but the ES/N0 per code will remain constant. This effect is seen in Figure 12. In the upper trace, all 128 active codes are transmitted. The CNR, ES/N0 per code and RxMER per code are all approximately equal to 25 dB. In the lower trace, all but 32 of the codes have been turned off, while keeping the received power per code unchanged. The CNR is reduced by 6 dB, but the ES/N0 per code and received RxMER remain approximately unchanged at 25 dB. Thus, in S-CDMA, the CNR measured on a spectrum analyzer can vary dynamically and is a valid indication of the ES/N0 or RxMER per code only when all active codes are being transmitted in a given frame.

FIGURE 12: S-CDMA upstream spectrum with ES/N0 per code = 25 dB. Upper Trace: All 128 active codes are transmitted; CNR = 25 dB. Lower Trace: Only 32 of the 128 active codes are transmitted; CNR reduces to 19 dB, but ES/N0 per code is still 25 dB because of 6 dB spreading gain.

Spreading gain in S-CDMA

A "spreading gain" or "processing gain" results when fewer than all the active codes are transmitted; in the lower trace of Figure 12, the spreading gain is 10 log(128/32) = 6 dB. Of course, the throughput is also reduced by a factor of 4 for this frame. This situation might occur temporarily in a lightly loaded S-CDMA upstream channel, in which the CNR might be seen varying up and down dynamically by a few dB, analogous to the carrier pulsing on and off in a lightly loaded TDMA upstream. The RxMER, however, remains steady at 25 dB in both the S-CDMA and TDMA cases. In fact, the RxMER may even show a slight improvement when fewer codes are transmitted because spreading gain tends to reduce residual intersymbol interference (ISI) effects.

We can also view this concept by building from the bottom up. Consider an S-CDMA transmission of a single code, consisting of 128 chips. (Illustrative example only; in DOCSIS, the minimum number of spreading codes permitted is two.) When we despread it, we have a spreading gain of 10log(128) = 21 dB. Using the same parameters as in Figure 12, the single-code signal has a CNR of only 4 dB, but an ES/N0 of 25 dB because of its processing gain. If we add multiple orthogonal codes, the total power goes up proportionally with the number of codes, as does the CNR, but the ES/N0 stays at 25 dB because each code is independent of the others.

Maximum scheduled codes and MER in S-CDMA

S-CDMA spreading gain can be applied in more than one way. In the example of Figure 12, when the number of transmitted codes was reduced from 128 to 32, the power per code was held constant, thereby keeping the ES/N0 per code and RxMER constant while reducing the total transmitted power, and, hence, the CNR, by 6 dB. Conversely, we could use the 6 dB spreading gain differently: We could reduce the number of transmitted codes from 128 to 32, while keeping the transmitted power and CNR constant. This setup would cause the ES/N0 per code and RxMER to increase by 6 dB. In fact, we could apply the 6 dB spreading gain to transmit power in any amount not restricted to the previous two cases; for example, reducing the transmitted power and CNR by 3 dB, while increasing the ES/N0 per code and RxMER by 3 dB.

DOCSIS provides a mechanism, called Maximum Scheduled Codes (MSC), to give this spreading-gain boost to a cable modem that is otherwise unable to produce the required RxMER at the CMTS receiver, perhaps because of increased cable and splitter attenuation in a multidwelling complex where the modem is located. A cable modem using MSC will have reduced throughput because it is using fewer codes, but will have increased transmitted power per code.

If the spreading gains given to the modems using MSC equal their increased upstream path attenuation and all other parameters are equal, the CMTS burst receiver will see equal received power per code and RxMER for MSC and non-MSC modems. The overall upstream throughput is also unaffected by the application of MSC because the codes not being used by an MSC cable modem can be scheduled by the MAC for use by other cable modems on the plant.

Chip MER in S-CDMA

Referring back to Figure 9, the input to the RF channel at each modulation interval consists of the sum of up to 128 S-CDMA chips. Each chip is the equivalent of a TDMA symbol in duration; for example, Tchip = 1/5.12 MHz. Normally, a chip is not specified individually, but only in the context of a full sequence of 128 chips, which represents one QAM symbol before spreading or after despreading. That is, although individual chips may have low MER in the presence of AWGN, the signal is restored to high MER by the despreading process. However, DOCSIS also levies a TxMER requirement on each individual chip, called MERchip. Its purpose is to guarantee that fidelity is maintained at low transmit signal levels, for example, when only two of the 128 spreading codes are being transmitted. This requirement is intended to place a limit on the noise-funneling effect that occurs when many modems transmit simultaneously and their transmitted spurious noises sum at the CMTS receiver. The DOCSIS physical layer specification provides details of this requirement.

Conclusion

This article investigated the common ways that SNR is defined and measured in digital transmission over cable systems. It shows that RF and baseband measurements of CNR and SNR have to be treated differently and that digitally modulated signals require their own precise definition and measurement of SNR.

CMTSs can report what has for many years been called upstream SNR, a parameter that is often confused with CNR. In reality, the upstream SNR of a CMTS is equalized MER, or in some cases, unequalized MER - specifically, as defined in the DOCSIS MIB, RxMER. Cable modems and most digital set-top boxes also can report an SNR value. This value is not CNR, but is equalized downstream RxMER. Likewise, QAM analyzers and similar test equipment used by the cable industry can report MER values for downstream - and, in some cases, upstream - digitally modulated signals. These values, too, are not CNR, but are RxMER. Most QAM analyzers report equalized MER measurements, although some also can provide unequalized MER measurements (or the equivalent of unequalized measurements). RxMER provides a "baseline" indication of signal quality, but must be interpreted carefully to gain the full value of this important measurement.

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Sidebar: Summary of CNR, SNR and MER

SNR is a general signal-to-noise ratio measurement and can refer to measurements performed at RF or baseband. The cable industry has long used SNR to refer to a baseband measurement, for example, baseband video or audio. CNR is the RF carrier-to-noise ratio seen on a spectrum analyzer. ES/N0 is the most common measurement of the quality of a digitally modulated signal. RxMER (often called receive SNR estimate) is the modulation error ratio of the demodulated digital constellation, a "baseline" measurement that includes transmitter imperfections, plant distortions, thermal noise and receiver imperfections. CINR is the carrier-to-interference-plus-noise ratio, which includes narrowband ingress in addition to white noise.

SNR, CNR, ES/N0, RxMER, and CINR are equal in an ideal system with no impairments other than AWGN, and with full traffic loading. When impairments occur in a real system, the differences among these measurements provide clues about what the problem is.

Downstream RxMER is measured by the cable modem after the adaptive equalizer, which cleans up most linear distortions. Upstream RxMER is reported by the CMTS burst receiver, usually also after equalization, although some implementations may report an unequalized value. Most QAM analyzers provide equalized MER measurements.

If upstream RxMER is low but the spectrum analyzer shows high CNR, there is most likely a plant or equipment problem to be addressed. Likely candidates are micro-reflections from impedance mismatches or high group delay variation from the roll-off of diplex filters. If DOCSIS pre-equalization does not cure the problem, then nonlinear impairments such as phase noise, spurious, burst, or impulse noise, etc., may be involved.

TDMA CNR measurements are complicated by the fact that a signal is not continuously present, but the noise is. The maximum hold function on the spectrum analyzer may help. However, maximum hold will display the signal power of the highest-power cable modem burst and highest noise, if the noise is fluctuating in time, typically resulting in errors in the average CNR measurement of 1 to 2 dB or more.

S-CDMA presents challenges for accurate ES/N0 measurement because the power of an S-CDMA burst depends on the number of codes used in the burst. If a small amount of data is transmitted, only a small number of codes will be required, and the signal power will be low, and low CNR, which may erroneously be perceived as implying low ES/N0, will result. An accurate measurement of CNR and ES/N0 from a spectrum analyzer can best be obtained when all possible codes are transmitted in a burst. Maximum hold on a spectrum analyzer can provide a reasonably accurate measurement as long as at least one burst is transmitted with all codes used during the measurement period.

CNR measurements accurate to within tenths of a dB are difficult and require knowledge of proper measurement bandwidths, conversion formulas, and compensation for instrument imperfections. If measurements are required only to within 1 to 2 dB or so, straightforward delta marker measurements will suffice, as long as proper bandwidth compensations are made.

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