Invited Paper, *Society of Cable Telecommunication Engineers, New England Chapter Meeting,* October 23-24, 2002.

DELIVERING ON THE 256 QAM PROMISE
- Aggregate Degradation Effects in QAM Links

Dr. Ron D. Katznelson, CTO,

Broadband Innovations, Inc., San Diego CA.

Abstract

The accumulation of degradation factors in the downstream channels is reviewed with focus on headend/hub transmission-related noise aggregation due to a plurality of downstream Quadrature Amplitude Modulation (QAM) transmitters and upconverters. Substantial increase in the number of QAM transmitters based on frequency agile upconverters is expected. Unlike fixed channel upconverters, these do not have narrow band filters at their output, consequently imparting appreciable levels of broadband noise on the network when several such units are combined. Based on these factors and other noise contributions, it is shown that additional impairments due to fluctuations associated with composite distortion terms on the HFC network dictate (perhaps non-intuitively) the adoption of noise margins higher than that provided by the relative insertion levels of 256-QAM signals.

A step-by-step calculation of aggregate noise contributions from multiple QAM transmission sources is presented and compared to effective noise level with certain measurement-based BER criteria. Based on these calculations, it is shown that under currently prevailing headend and HFC signal transport practices, mass deployment of certain classes of QAM transmitters and upconverters for Video-On-Demand (VOD), may not scale well and would render future 256 QAM operation unreliable. It is therefore demonstrated that it is an industry myth to suggest that VOD QAM transmitters need not necessarily comply with the RF specifications of DOCSIS. Rather, compliance with most DOCSIS downstream RF noise specifications is essential in order to assure the proliferation growth and reliable delivery of any 256 QAM service over multiple channels. It is further shown that appreciable lack of such compliance can also lead to excessive accumulation of broadband noise on analog channels at levels that exceed most MSOs' headend aggregate noise floor guidelines for the analog service.

The advantages of having a single figure of merit that permits characterization and comparison of QAM transmitters' noise and distortion performance are presented. Such figure of merit, called Aggregate Noise Factor (ANF) is introduced. It is a single number (in dBc) that can be objectively used to ascertain adequate performance of proposed QAM transmitters. ANF is an objective weighted noise factor expressing the power of all aggregated noise terms impinging on a given digital channel relative to its power level and thus it incorporates appropriately weighted aggregate contributions of Adjacent Channel spectral regrowth noise, Next Adjacent Channel spectral regrowth noise and Other Channels' broadband noise contributions – all emanating from the single transmitter being specified. The use of ANF along with other degradation factors for predicting the QAM link performance is demonstrated with examples.

1 Introduction

The advent of new digital services such as Cable IP Telephony, Video On Demand (VOD) and other Interactive TV applications places further demands on Hybrid-Fiber-Coax (HFC) system's digital spectrum and, in particular, the ability to scale upwards the VOD transmitter deployments. To date, most digital services are transmitted in 64 QAM. Although the installed base of digital subscriber set-tops and cable modems is predominantly 256 QAM capable, many cable operators have yet to migrate to 256 QAM transmissions successfully. Operating reliable 256 QAM downstream links is more challenging because 256 QAM has the following attributes:

(a) Symbol constellation that is four times denser than that of 64 QAM;
(b) Reduced burst error interleaver depth, a lower coding gain[1] and reduced spectral Roll-off factor from 0.18 to 0.12, increasing implementation loss compared to that of 64 QAM.
(c) Reduced immunity from CSO and CTB distortion products (as discussed below); and
(d) Higher susceptibility to phase noise [3] and 'microphonics'.

As a result of the cumulative effects of these factors, the noise margin left for further noise degradations in 256 QAM all but disappears. Cable operators have much less control over the signal performance in the subscriber terminal than that of their headends and hubs. A coveted 1 dB improvement in dynamic range at the subscriber location may well require as much as 10 dB improvements in the hubs and the headend. It is in this context that we present the performance goals of headend-based transmitters and upconverters, wherein the cost of such improvements are far less than those associated with wholesale last-mile subscriber signal improvements. We shall therefore begin by addressing headend-based noise floors in this section and in Section 2, followed by a presentation of other degradation factors in Section 3. In Section 4, we combine all noise and degradation factors to arrive at a total system $C/(N+I)$ at the subscriber tap in order to see the impact of the transmitter noise factors.

The proliferation of frequency-agile modulators and upconverters used in CATV headends and hubs presents new realities and challenges with respect to channel combining practices and the maintenance of satisfactory broadband noise levels at the output of such channel combining networks. Fixed frequency modulators and upconverters employ an output channel filter that filters out spurious signals and noise that are out-of-band, thereby enabling the combining of all such channels in the lineup without incurring excessive output noise floors. In contrast, frequency-agile transmitters do not have narrow band filters at their output and consequently they can produce appreciable levels of broadband noise [4]. To the extent that many such agile frequency CATV transmitters are used in combination, their composite noise can aggregate unfavorably. Other sources of noise that add to signals launched from headends and hubs can arrive from co-channel narrowcast interference associated with other nodes (discussed below) and even from fiber cross-talk effects when DWDM architectures are applied [5]. Further degradations might be encountered for QAM channels that are transmitted with substandard phase noise levels. All the factors raise system noise levels even before the downstream signals

---

[1] The North American standard for digital cable transmission provides for 256 QAM trellis code rate of 19/20, dedicating one bit out of 20 for forward error cerrection versus one out of 15 bits used in the trellis code for 64 QAM. Other unfavorable parameters are the interleaver depths limit of 66 μs for 256 QAM as opposed to 95 μs for 64 QAM and the spectral roll-off factor of 0.12 (vs. 0.18 in 64 QAM), further reducing demodulator "eye opening" margin. See description of these coding parameters in the SCTE standard [1], which became Annex B of an international ITU standard [2].

leave the hubs. Thus, the adjacent channel and broadband noise specifications constitute major criteria for accepting or rejecting a specific frequency-agile CATV transmitter for headend applications.

We begin by considering the output of digital transmitters carrying QAM signals, wherein the interference and degradation effects of the modulated distortion terms are practically indistinguishable from that of thermal noise with identical spectral density function. It is therefore the spectral density of the total noise and distortion that is of interest, which shall be hereinafter defined as "*Composite Noise*". In a companion paper co-authored by this author [6] the total aggregate broadband composite noise produced by output-combined CATV transmitters was defined and methods for measuring such aggregate composite noise were presented. Using the notation in that paper we note that for K transmitters tuned to distinct channels, the aggregate composite noise power $\mathbf{A}(M)$ integrated over a measured channel M is given by:

$$(1) \qquad \mathbf{A}(M) = \sum_{n=1}^{K} \mathbf{D}_n(M, n),$$

where $\mathbf{D}_n(M, n)$ expresses the integrated composite noise measured on channel M emanating from a transmitter tuned to a channel corresponding to index n. The index n can therefore viewed as the transmitter index. The aggregate composite noise $\mathbf{A}(M)$ measured on channel M generally depends on the *collection* of transmitters when combined and not merely on the performance of *a single* transmitter. However, it is shown in [6] that using such measure for a single transmitter representative of the collection of transmitters of the same model and making, a *self-aggregate* measure can be constructed to provide a single figure of merit attributable to such single transmitter. Thus, using a single unit, we drop the unit subscript index n in $\mathbf{D}_n$ of Equation (1) and obtain the broadband composite noise measure $\mathbf{A}(M)$ for each channel M.

2 Aggregate Noise Factor

As shown in [6], even the self-aggregate composite noise measurements of $\mathbf{A}(M)$ could be an elaborate and taxing task. It is therefore desirable to arrive at a similar aggregate figure of merit by the use of noise *specification* items alone, that are typically provided for CATV transmitters.

Transmitters are often specified with a single broadband composite noise floor and an adjacent channel modulated distortion specifications. A reasonably good bound can be formed for their performance by assuming that the broadband noise is flat across the band of interest and that no significant level changes of modulated distortion are present when the transmitter is tuned to different channel. The estimated bound $\mathbf{A}_K$ for the aggregate composite noise from K channels is then given by using Equation (1) with fixed terms broken into broadband noise D_N and modulated distortion from the first adjacent channels (D_{N1}) and the second adjacent channels (D_{N2}), that is, $\mathbf{A}_K = K \cdot D_N + 2 \cdot (D_{D1} + D_{D2})$. Finally, using each of these terms in dB referenced to the desired signal power, we define a noise factor in dBc. It is given by the antilog of $\mathbf{A}_K$, which we call *Aggregate Noise Factor* (ANF), expressed in dBc:

$$(2) \qquad ANF_K = 10\log\left[2 \cdot \left(10^{AC1/10} + 10^{AC2/10}\right) + k \cdot 10^{BN/10}\right],$$

where $AC1$ and $AC2$ are respectively the transmitter's first adjacent and second adjacent channel distortion noise levels in dBc and wherein BN is the transmitter's broadband noise level in dBc, all measured in 6 MHz bandwidth, and wherein K is the number of channels aggregating noise. A depiction of the bands and channel boundaries from which these contributions arise is shown in Figure 1. The next-adjacent channel noise terms are typically third order intermodulation components and are often called "Spectral Regrowth" components, as their level grows 2 dBc per every dB of output power increase.

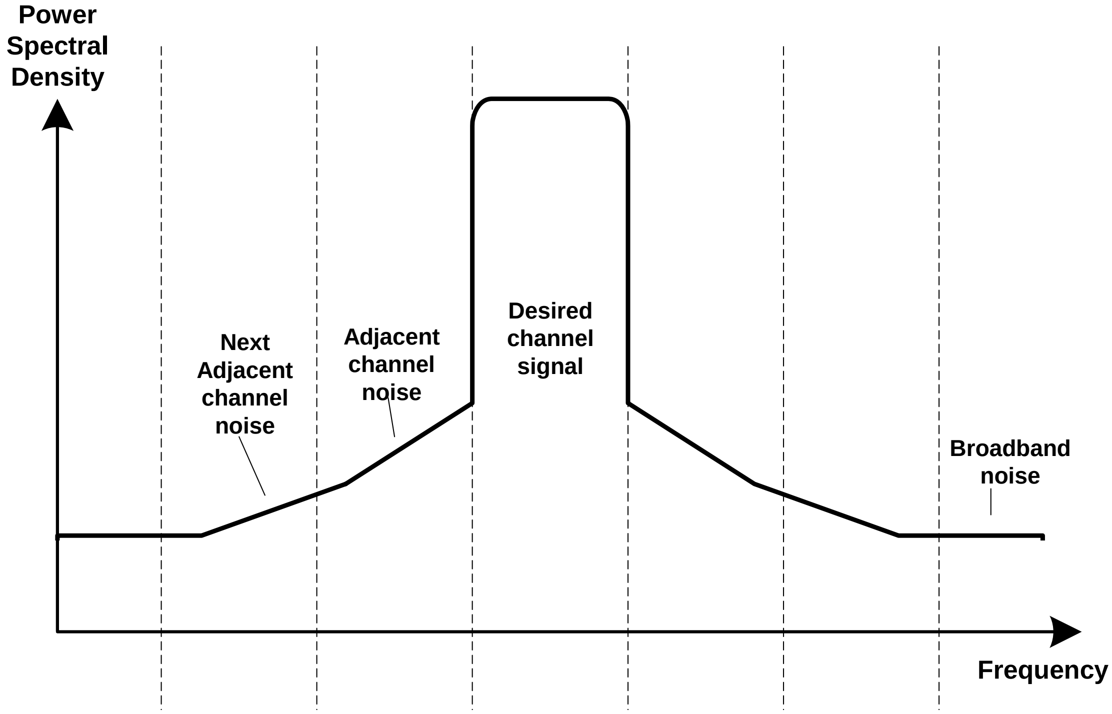

Figure 1. **Composite noise contribution terms in relation to channel boundaries and the desired channel.**

CASE		Broadband Noise in 6 MHz (dBc)	adjacent channel in 750 KHz (dBc)	adjacent channel in 5.25 MHz (dBc)	Second adjacent channel in 6 MHz (dBc)	Tx Aggregate Noise Factor in 6 MHz (dBc)
DOCSIS LIMIT	Relative level/Ch (dBc)	-73.0	-58	-62	-65	
	# degraders	136 channels	2 channels	2 channels	2 channels	
	Composite	-51.7	-55.0	-59.0	-62.0	-49.3
Typical Brand A measured	Relative level/Ch (dBc)	Note 1	-67	-64	-69	
	# degraders	136 channels	2 channels	2 channels	2 channels	
	Composite	-64.0	-64.0	-61.0	-66.0	-58.4

Table 1. **Aggregate Noise Factor (*ANF*$_{136}$) based on the DOCSIS mask (top) and a typical measurement on a headend grade upconverter (bottom). A value of 2 for the number of degraders in the adjacent channel categories corresponds to a channel above and a channel below the desired channel.** ***Note 1*****:** Broadband noise levels are not uniform but the aggregate noise from 136 channels is shown in the composite summary line.

Table 1 shows the result of an *ANF* calculation based on two examples assumed to have combined signals from 136 consecutive channels. The first, is an *ANF*$_{136}$ for a QAM transmitter that would pass Data-Over-Cable Service Interface Specifications (DOCSIS) requirements as provided in Table 6-15 of its Radio Frequency Interface Specification [7]. The second example is the ANF_{136} for a typical Brand *A* upconverter. The meaning of these *ANF* results at the output of the transmitter's combining network is that it provides the relative composite noise interference on one channel from all other transmitters tuned to other channels. To the extent that all other transmitters are of the same make and specifications, a single self-aggregate number like the *ANF* introduced above characterizes the quality of the headend. Therefore, it is a single number (in dBc) that can be used to objectively compare various types of transmitters and to ascertain adequate performance of proposed QAM transmitters. A schematic illustration of the contributions of various components of the *ANF* is shown in Figure 2.

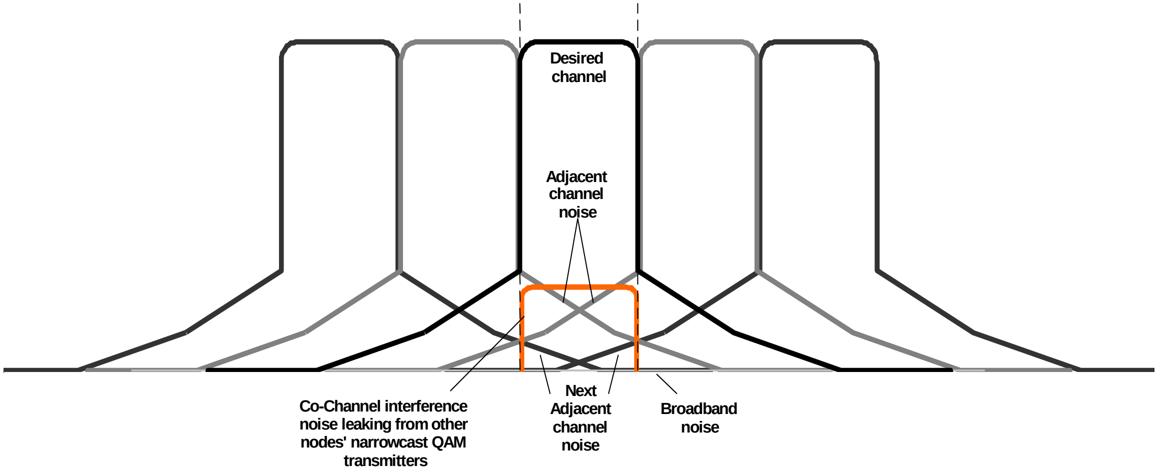

Figure 2. Headend composite noise components that aggregate on a given desired QAM channel. All components shown except the Co-Channel Interference noise are a result of QAM transmitter combining. The Co-Channel Interference term is due to Narrowcast-to-Narrowcast cross talk as discussed in Section 3.1.

Most importantly, *ANF* figures can be used in combination with other signal degradation factors in order to assess the full channel link all the way downstream to the subscriber terminal. Before we employ the ANF results obtained here, we address other significant degradation factors as discussed below.

3 Other Degradation Factors

QAM Broadcast digital services are better protected for the reasons shown below and because they are likely to remain mostly as 64 QAM services. It will be shown that a greater impairment potential exists for narrowcast 256 QAM services and, as such, we focus on analyzing impairments on these channels. We therefore combine the following additional impairment contributors with the *ANF*: (i) Co-Channel Interference crosstalk from other digital channels (ii) Composite distortion (CSO/CTB) terms from the analog channels and (iii) CATV plant noise contribution downstream from the headend and the hubs. These factors are addressed (not necessarily in the order of their relative magnitude) in the following sections.

3.1 Co-Channel Noise Interference

It is expected that much of the 256 QAM service deployment would be for narrowcast services targeted to individual nodes. Typical architectures for headend and hub combining/splitting networks for broadcast, local and narrowcast services are described in [8]. A relevant portion of the narrowcast combining is shown here in Figure 3. As shown, digital QAM signals on a given channel that is narrowcast to each zone constitute noise interference for the same channel on other zones with a relative level that is equal to the narrowcast-to-narrowcast isolation. However, in an *N*-way broadcast splitting network, there are *N*-1 such interfering sources, which all add up. A target narrowcast-to-narrowcast isolation suggested in [8] is a minimum of 55 dB with a preference for at least 65 dB. Most cable operators seem to adopt design guidelines of a 60 dB isolation specifications. Theoretically, under these conditions, aggregation of co-channel interference terms from 8 to 64 zones served by one broadcast splitter can result in substantial degredation to what would otherwise be expected from one –60 dBc interference term. Fortunately, isolation levels for splitters are not uniform across ports and typically better isolation than the specified minimum can be found in distant port pairs. Moreover, cascaded splitters provide an accumulation of isolation values, causing some ports to have isolation well over the level based on mere addition of isolation specifications of the splitter cascade.

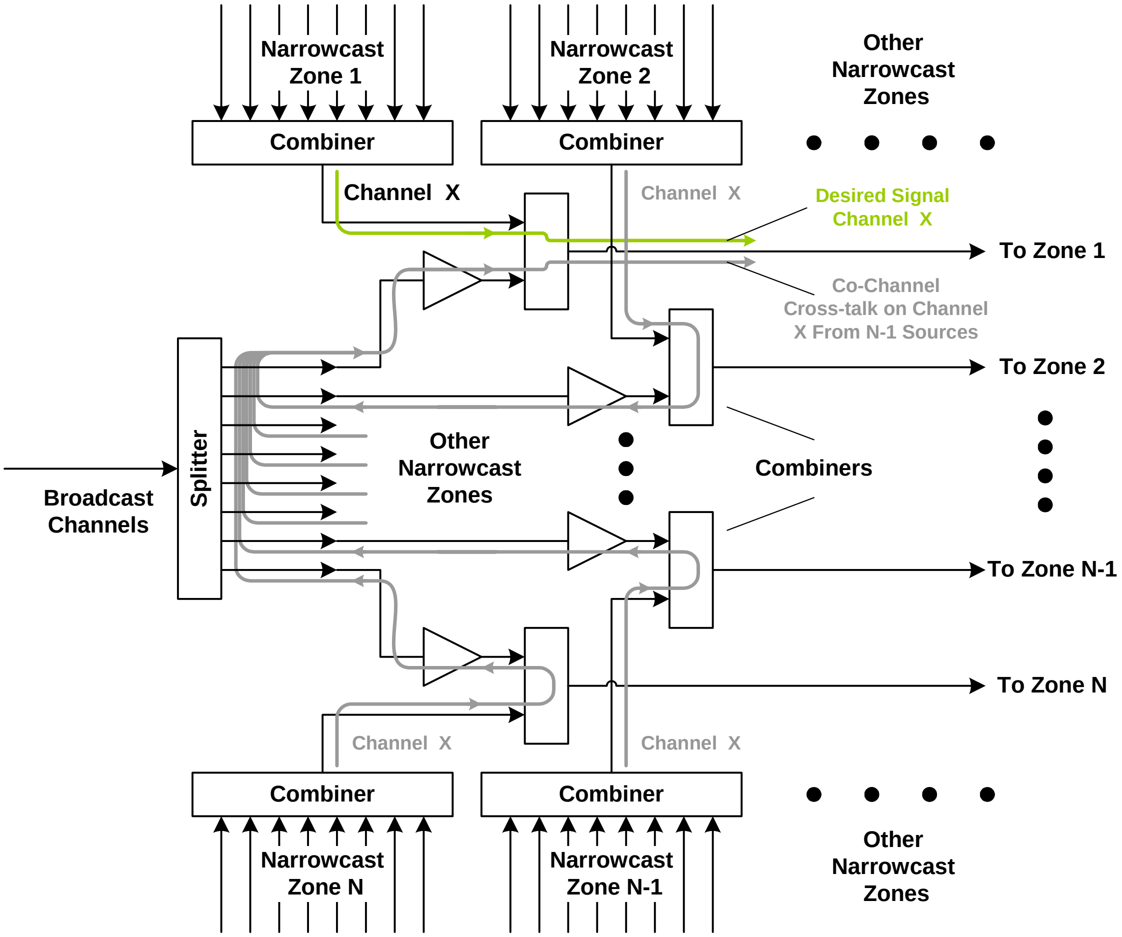

Figure 3. **In full VOD deployments, Co-Channel Interference on narrowcast channel X serving Zone 1 is a result of leackage through the Broadcast tier splitter from *N*-1 different narrowcast sources serving other zones. Interference levels in dBc can reach up to levels that correspond to the Narrowcast-to-Narrowcast isolation degraded by an additional 10·Log(*N*-1) dB.**

We therefore make the assumption that when considering all sources weighed appropriately due to unequal isolation and splitter cascade effects, the total leakage from all ports produces an equivalent of 15 equal full level sources that are isolated by 60 dB from the affected signal path.

This yields a co-channel interference of –54 dBc. Of course, one can add additional isolation amplifiers to improve narrowcast-to-narrowcast isolation, but that would be at the expense of additional cost, power consumption, reliability loss, and even increased composite distortion, which in itself, constitute a more potent source of degradation.

3.2 Composite Distortions

Composite Triple Beats (CTB) and Composite Second Order (CSO) distortion components produced by intermodulation of analog TV carriers can become the dominant degrading factor for digital cable QAM channels [9],[10],[11],[12],[13]. It is generally accepted that in strictly thermal noise environments, a Carrier to Noise Ratio (*C/N*) of 30-35 dB provides adequate operating margins for 256 QAM[2]. It is also generally known that cable systems normally operate with CTB or CSO levels that meet or exceed a Carrier-to-Interference (*C/I*) ratio of 53 dB, as required by industry specifications [14]. These levels correspond to a *C/I* of 47 dB for a QAM signal carried with levels that are 6 dB below the analog carriers. The question that may arise is *why should distortion components having average power levels that are 12-15 dB below the noise level have any appreciable degradation effects on the QAM channel performance?* The short answer is that the average envelope power of composite distortion terms (which is what one observes in a spectrum analyzer measurement) is deceptively low in comparison to its occasional peak envelope power fluctuations.

3.2.1 Amplitude Statistics of Composite Distortions

The statistical properties of CTB and CSO distortion terms associated with the analog channels are analyzed and simulated by this author in a companion paper [9]. Measurements of probability density functions of such distortion components were reported in [12]. Both simulation and measurement results show that these distortion components falling on individual channels have amplitude Probability Density Function (PDF) that is nearly Rayleigh distributed.

Figure 4 shows the probability density function of the amplitude of a simulated CTB term due to third order distortion in a CATV system employing the Standard Frequency plan with 75 analog video modulated carriers. For comparison, a theoretical Rayleigh density transformed to the dB scale (thus called Log-Rayleigh) is also shown. The Rayleigh density is relevant in this comparison because it describes the probability density of the envelope of a narrow-band Gaussian process, which is the limit case for a linear combination of a large number of arbitrarily distributed, statistically independent narrow-band random processes. One would expect that because the CTB and CSO terms encountered in CATV are comprised respectively from thousands and hundreds of beat components, the Rayleigh limit would be nearly approached. However, while there appears to be a good match at lower amplitude levels, relevant deviations at large relative amplitudes are seen for CTB in Figure 4. As further explained in [9], this slight deviation is due to the statistical dependence among these thousands of components. It is argued in [9] that, in this case, because there are only 2×75 = 150 *independent degrees of freedom* (random phase and amplitude of each of the 75 carriers) affecting the phase and amplitude values of the individual *thousands* of beat components, these must be statistically dependent. The degree and differences of the correlations for CSO and CTB terms and their respective effects on envelope statistics are further addressed in [9], as this topic is beyond the scope of this paper.

---

[2] The OpenCable interface standard calls for cable systems to provide a *C/N* of 35 dB for 256 QAM operation [14] while DOCSIS modem acceptance tests requires satisfactory operation at a *C/N* of 30 dB [17].

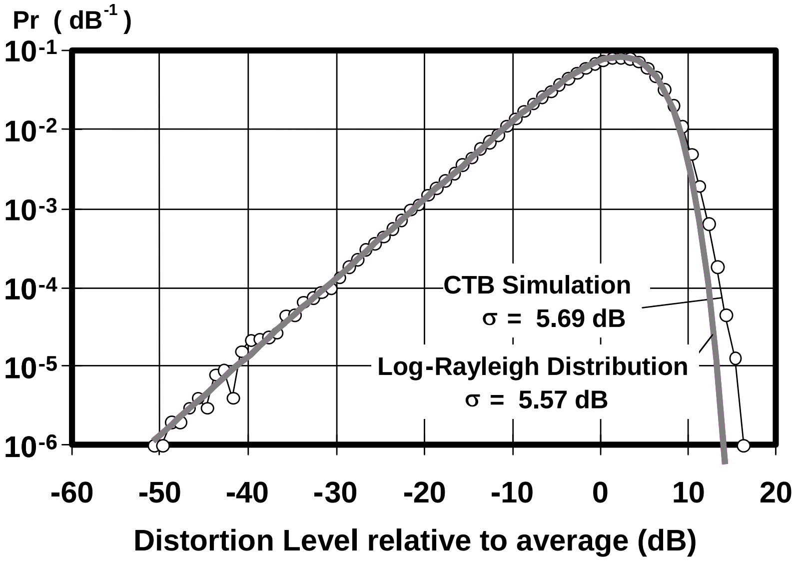

Figure 4. Probability density function of the amplitude of a simulated CTB term due to third order distortion in a CATV system using the Standard Frequency plan with 75 analog video modulated carriers. On the ordinate, the amplitude squared is expressed in dB relative to the average envelope value and the corresponding probability per dB is plotted in the co-ordinate. For comparison, a Rayleigh density transformed to the dB scale (thus called Log-Rayleigh) is also shown in solid line. Source: Ref. [9].

Noteworthy is the observation that as one inspects distortion terms on different channels, the absolute levels of the envelopes differ, but when normalized to their respective average envelope power, the PDFs of the CTB and CSO components on every channel essentially follow closely the results for the CTB term shown in Figure 4. Moreover, each of these distributions, like the Rayleigh distribution, has a variance that is proportional to its mean. When used on a 'dB relative to average' scale, this means that the standard deviation σ in dB is constant. For the Log-Rayleigh, case it can be shown that σ = 5.7 dB and we note that the results for CSO/CTB (as seen in Figure 4) terms do not differ appreciably from this value, although at the tail of the distribution CTB peak values are slightly higher than those of the CSO and Log-Rayleigh terms.

Turning back to the question raised at the outset, relating these statistics to the impact on digital channels is rather straightforward. As can be seen in Figure 4, both CTB and CSO components have significant likelihood of having peak envelope power fluctuations that exceed their average (measured) power levels by more than 12 – 18 dB. Unfortunately, when such fluctuations occur in a composite distortion term having an *average* level of –47 dBc, levels up to –29 dBc can be experienced. Thus, even in situations in which the prevailing noise floors are rather intuitively low, significant impairments can still be observed. To relate these results to 256 QAM Bit Error Rates (BER) and consequential video impairments we turn next to the temporal characteristics of these composite distortion components.

3.2.2 Time Domain Statistics of Composite Distortions

When large envelope excursions of composite distortion terms occur, bursts of bit errors can be generated on the 256 QAM link. Degradations due to bursts that are relatively short can be mitigated in part by the interleaving used on the digital link. Such interleaving is part of the Forward Error Correction (FEC) system used in QAM transmission. Clearly, burst errors with durations that exceed the interleaver depth capability would be more severe and remain uncorrected. Figure 5 shows experimental results that demonstrate this for 256 QAM. The figure shows that substantial reduction in coded error rate is achieved with interleavers that have depths longer than 50-100 microseconds. Improvements start to level off above 200 μs, indicating that there are much fewer burst events longer than 200 μs. This observation shows that the characteristic duration of CSO peak envelope fluctuations is on the order of 100 μs. These results appear consistent with other studies on CSO/CTB distortion effects. See for example the similar average durations (60 μs) reported by Germanov [10].

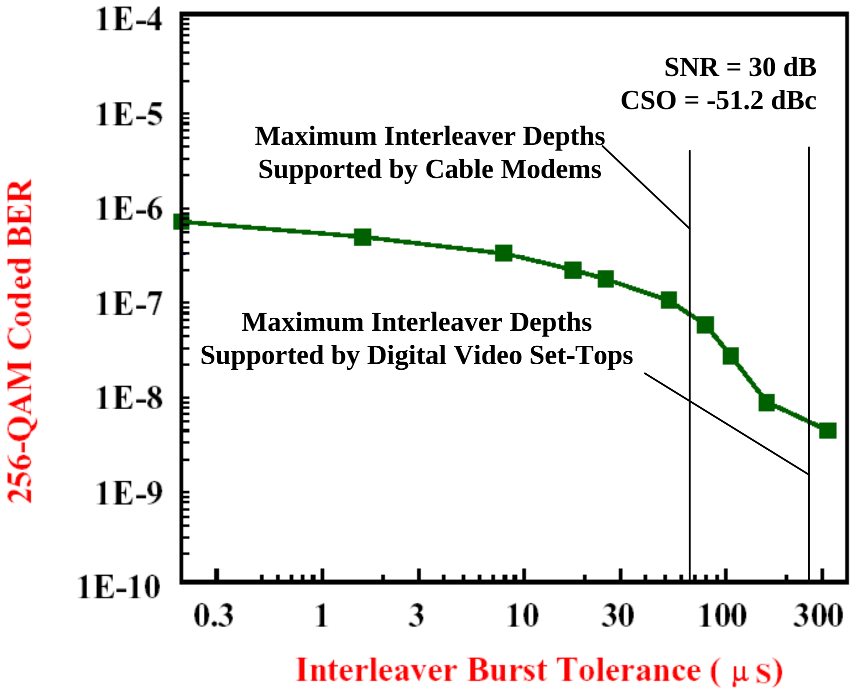

Figure 5. **Coded bit error rate of 256 QAM link perturbed by CSO distortion as a function of interleaver burst span. BER Source: Ref. [11].**

Whereas both [10] and [11] report the phenomenal fact of this characteristic duration times, neither suggests a mechanism, a reason or a cause for the observed 100 μS characteristic times. As explained by this author in [9], these characteristic times are simply related to the correlation times of the individual composite distortion components. These, in turn, are inversely related to the effective bandwidth occupied by such distortion components.

Figure 6 depicts a conceptual rendition of the power spectrum of a composite distortion term produced in a non-coherent frequency plan. Because most of the power of these distortion terms is distributed around frequencies that are a linear combination of the nominal frequencies of the contributing carriers (i.e. $f_1 \pm f_2 \pm f_3$ for CTB, or $f_1 \pm f_2$ for CSO), the spectral spreading for most of the energy will be on the order of several times the *frequency tolerance* of all transmitters. Some spectral energy due to video modulation in the first (dominant 15.7 kHz horizontal rate) sidebands will widen this somewhat to a power bandwidth on the order of 10 kHz. For such narrow-band processes, the correlation times are approximately inversely proportional to the power bandwidth Δf. For a 10 kHz wide CTB or CSO spectral “clump”, one obtains

$\tau = 1/\Delta f = 1/10^4 = 100\mu s$ as the characteristic time. Thus, for these narrow-band composite distortion components, the envelope value cannot change appreciably in less than 50-100 µs, thereby giving rise to durations of peaks on that order [9].

Ironically, modern transmitters (having higher frequency accuracy), or for that matter, for carrier frequencies produced in a coherent headend, wherein all distortion terms fall on the same frequency, the effective power bandwidth could be substantially smaller (as shown schematically in Figure 6). This will result in *longer* but *less frequent* burst errors associated with composite distortions. Unfortunately, as labeled in Figure 5, digital cable modems cannot be set to have sufficient interleaver memory (with longer delay) to adequately protect against the *most likely* burst durations, as DOCSIS modems are limited to a protection depth of 66 µs in the 256 QAM mode[3]. In contrast, that same memory limit provides a longer (95 µs) interleaver span in the 64 QAM mode, which further enhances the error tolerance of 64 QAM links as compared to 256 QAM. Most digital video set-tops operating in 256 QAM cannot fully protect against CSO/CTB error bursts, as their maximum interleaver depth is marginal at 264 µs.

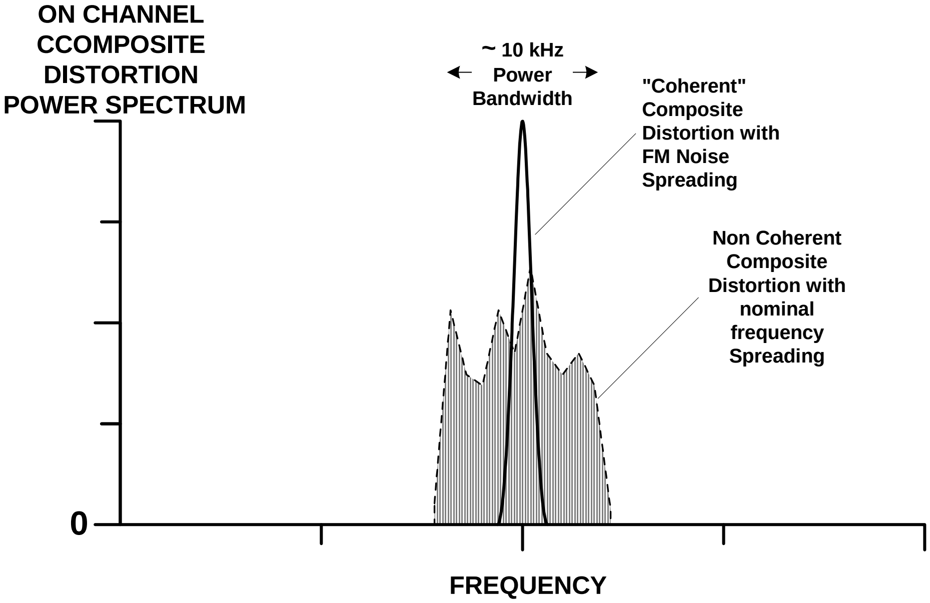

Figure 6. **Conceptual rendition of the power spectrum of a composite distortion term produced in a non-coherent frequency plan and that produced in a coherent plan, wherein all distortion terms fall on the same frequency. Because most of the power is distributed around frequencies $f_1 \pm f_2 \pm f_3$ (for CTB) or $f_1 \pm f_2$ (for CSO), the spectral spreading for most of the energy will be on the order of several times the frequency tolerance of all transmitters. Some energy due to video modulation in the first 15.7 kHz (horizontal rate) sidebands will widen this somewhat to a power bandwidth on the order of 10 kHz.**

It is in the context of this CTB/CSO burst vulnerable regime of 256 QAM that we examine the effect of additive noise in the channel. A *C/N* value of 30 dB, a value some would have judged as sufficient for 256 QAM, is shown in Figure 5 to be dramatically inadequate for 256 QAM operation under CSO distortion values that more than meet most MSO's operating standards. Figure 7 shows measurement results reported in [12] using real set-tops and real headend live

---

[3] The 66µs protection mode in 256 QAM can be set by selecting *I* =128,*J* =1 for the convolutional interleaver. Most set-tops can be set to a 264 µs protection by selecting *I* =128,*J* =4.

video sources to modulate each channel in the analog tier. Uncoded bit error rates were recorded as a function of total interference and noise power. Note that at target BER values of 10^{-8}, an additional 11-15 dB(!) of Noise+Interference margin is required for 256 QAM over that of 64 QAM. This increment is significantly larger than the 5.6 dB theoretical increment expected in pure random noise channels [15] and is related to the stacking of unfavorable parameters used in 256 QAM as enumerated in Section 1. Consequently, as further elaborated in [9] and in reference to the results shown in Figure 7, this author suggests that under CSO/CTB levels that are within current operational CATV specifications, a 40 dB $C/(N+I)$, corresponding to a 256 QAM BER of 10^{-6}, would *not* provide adequate margin for reliable 256 QAM operation and that rather, $C/(N+I)$ values in the range of 43 - 45 dB (approaching uncoded BER of 10^{-8}) would be required for a Quasi-Error-Free (QEF) operation[4] of 256 QAM.

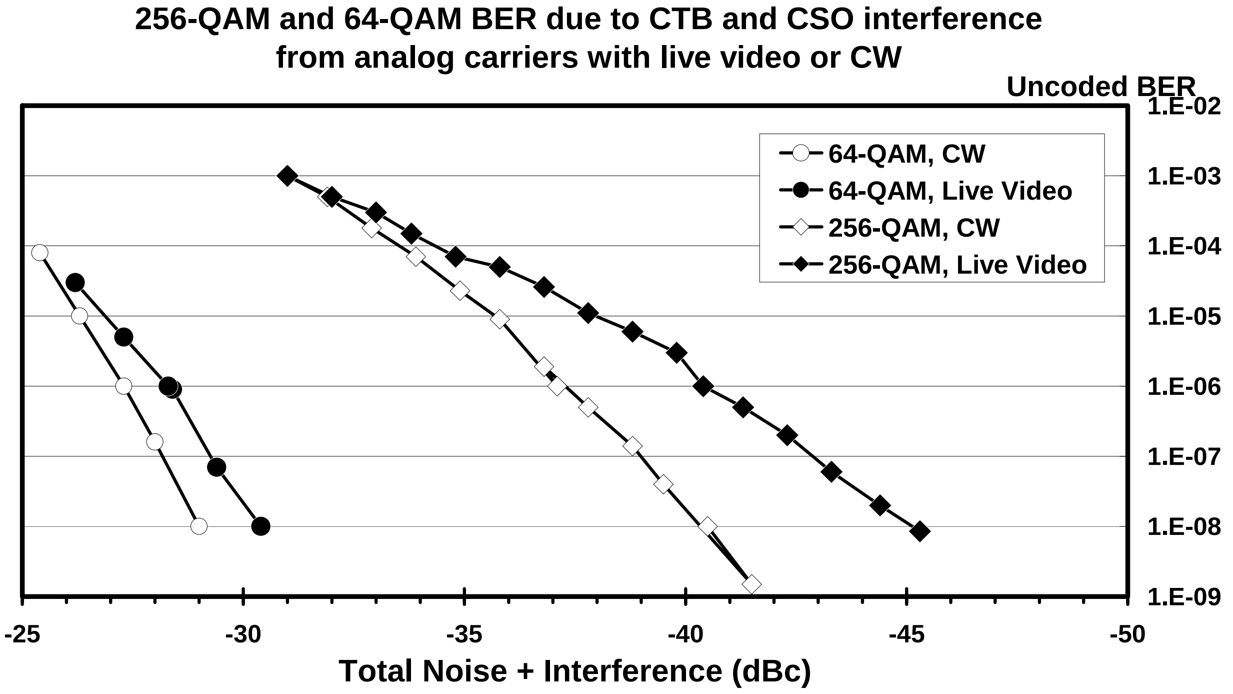

Figure 7. The measured effect of composite distortions on uncoded BER of 256 QAM link as compared with 64 QAM. CTB and CSO distortions were from analog carriers that were either modulated (Live Video) or unmodulated (CW). Note that at target BER values of 10^{-8}, an additional 11-15 dB of Noise+Interference margin is required for 256 QAM over that of 64 QAM. Source: Ref. [12].

Finally, it should be appreciated that many of the digital 256 QAM channels would likely be frequency-situated well above the 550 MHz boundary and, as such, would be subject to both CTB and CSO. In this case, two distortion contributions should be accounted for. For our purposes below, we assume two composite distortion components each at a level of –55 dBc.

---

[4] Quasi Error Free (QEF) reception should be distinguished from reception at the impairment Threshold Of Visibility (TOV). The Europeans set the QEF standard for DVB at levels achieving less than one uncorrected error event per hour [16]. In North America, J-83 Annex B defines QEF at less than one uncorrected error event per 15 minutes [1],[2]. The latter event error rate corresponds to a BER = 4.0E-11 at the input of the MPEG-2 demultiplexer. Because the FEC fails under bursty error conditions that overwhelm the interleaver, very little coding gain exists for these events and the *coded* BER is only slightly better than the *uncoded* BER. It is estimated that for these error events, a 10E-8 *uncoded* BER corresponds to the QEF threshold of 4E-11 *coded* BER.

This corresponds to -49 dBc with respect to the 256 QAM signal, resulting in an average composite distortion level of –46 dBc.

3.2.3 How Large Can CSO/CTB Envelope Fluctuations Become?

The answer to this question depends on the observation interval. For practical purposes, however, we attempt an intuitive approach to this problem, as it establishes better understanding of the reasons for a substantial rethinking of the required margins for reliable 256 QAM operation. It is shown in [9], that the envelope power level exceeds by more than 16 dB its mean value every 15 minutes on average.

3.3 CATV Plant Noise Contribution Downstream from Headend and Hubs

The noise floors discussed in Section 2 would be further degraded by noise introduced by distribution gear and line extenders. We make the simple assumption that, excluding the headend and hub based noise discussed above, the noise floor at the subscriber tap would be –49 dBc in 6 MHz, which corresponds to *C/N* of 43 dB for the 256 QAM signal at the subscriber tap.

3.4 Phase Noise of Downstream QAM Transmitters

As indicated above, 256 QAM is much more vulnerable to phase noise degradations. Due to cost considerations, the link budget for phase noise is essentially stacked in favor of permitting the most degradations in the subscriber tuner device while demanding much higher performance at the transmitter. Therefore, integrated phase noise specifications have been established in DOCSIS to limit any further degradation beyond that of the demodulator tuner. These phase noise specifications as specified in Table 6-15 of DOCSIS' Radio Frequency Interface Specification [7] are *spectrally integrated* specifications that do not provide permitted *spot* phase noise values. It is possible, however, to establish that under typical spectral characteristics of oscillator phase noise, a spot phase noise specification of **–95 dBc/Hz at 10 kHz offset** would be required in order to meet the DOCSIS integrated phase noise specifications. In what follows, we assume that the transmitters used are compliant with these phase noise requirements and thus no further degradations due to phase noise are included. If, however, non-compliant phase noise values are introduced, an additional degradation beyond that derived here must be taken into account, further reducing the likelihood of reliable operation with 256 QAM.

4 Putting it All Together

Having addressed all relevant degradation factors in Sections 2 and 3, we now combine them all together and power-sum them to obtain a sense of the impact of the *ANF* on the whole 256 QAM link. Unlike the ANF_{136} reference measure of Table 1 that assumed 136 digital channels in combination, we will assume here that a maximum of 50 digital channels are being used above the analog tier. Table 2 summarizes such noise power addition with ANF_{50} for two cases. Although the distortion and noise may not be strictly additive effects as might be implied by power addition analysis, they provide a reasonable measure for assessing accumulation of degradations. This is particularly true in light of the fact that data for such power combining is available as shown in Figure 7. The first case in Table 2 labeled "Inferior Model" corresponds to what this author believes to be a substandard QAM transmitter's specifications that was supplied by an unnamed vendor and recently deployed in a cable VOD system. The second row corresponds to a hypothetical QAM transmitter that would just pass the DOCSIS requirements. As in Table 1, individual composite components are power-added by ‘antiloging’ each entry to the left of the major colored column. As seen in this table, the worst DOCSIS compliant transmitter (just meeting the DOCSIS mask) has an ANF_{50} of –53.6 dBc, which is about 7 dB better than that of the Inferior Model transmitter. Evidently, this significantly impacts the end-of-line $C/(N+I)$ and the value of –39.9 dBc obtained for the Inferior Model transmitter would render 256 QAM operations unreliable under the conditions in the table (See the comment in the caption of Figure 7).

CASE		Broadband Noise in 6 MHz (dBc)	First adjacent channel in 6 MHz (dBc)	Second adjacent channel in 6 MHz (dBc)	Tx Aggregate Noise Factor in 6 MHz (dBc)	Other nodes' narrowcast co-channel interference	Composite Distortion (Referred to QAM)	Plant Contribution	Subscriber tap C/(N+I) (dBc)
Inferior Model	Relative level/Ch (dBc)	-68.2	-53	-56		-60	-49		
	# degraders	50 channels	2 channels	2 channels		4 Equivalents	2 CSO,CTB		
	Composite	-51.2	-50.0	-53.0	-46.5	-54.0	-46.0	-43.0	-39.9
DOCSIS Mask	Relative level/Ch (dBc)	-73.0	-62	-65		-60	-49		
	# degraders	50 channels	2 channels	2 channels		4 Equivalents	2 CSO,CTB		
	Composite	-56.0	-59.0	-62.0	-53.6	-54.0	-46.0	-43.0	-42.3

Table 2. Combining headend based *ANF* and other degradation factors to arrive at subscriber tap *C*/(*N*+*I*). Relative levels are based on 256 QAM channel set at –6 dB with respect to peak sync of the analog carriers.

In contrast, using a transmitter that performs slightly better than the DOCSIS mask would provide adequate margin since at this $C/(N+I)$ level, one is able to approach the uncoded BER of 10^{-8} required for a Quasi-Error-Free operation under the conditions set forth in Table 2.

Of course, less demanding conditions than those outlined in Table 2 can yield favorable results even for the Inferior Model transmitter. For example, Operator *X* may be using such transmitters today in a system that may employ only 10 digital broadcast channels at a benign level of –10 dB with respect to the analog carriers; and only 8 digital 256 QAM VOD narrowcast channels per node; and only two co-channel narrowcast zones per Broadcast split. Under these conditions, much less noise aggregation takes place and it may be possible to achieve satisfactory operation and thereby obtain a false sense of the margins that remain. The key message of this analysis, however, is that should Operator *X* add new services and attempt to expand into full VOD deployment using more of the same Inferior Model transmitters, the Inferior Model transmitter deficiencies would emerge as a barrier for the expansion.

4.1 Impact on the Analog Tier

In relation to the analog channels situated below the digital tier, Operator *X* may find that 8 combined Inferior Model transmitters (set 6 dB lower than the analog carriers) produce a broadband noise floor that just makes the 65 dB aggregate *C/N* requirement [8] for the analog tier. Should he attempt to combine up to 50 of these transmitters, an aggregate noise floor producing a 57.2 dB *C/N* on the analog tier would result based on the Broadband Noise column of Table 2, frustrating his 65 dB *C/N* goal. At that point, Operator *X* may have the option of inserting sharp high-pass filters on each narrowcast port to protect the analog tier (thereby re-engineering his network and disrupting service) or he might opt to have used transmitters based on devices better than, or similar to, that shown in the second row of Table 1, thereby more than meeting all requirements.

4.2 DOCSIS RF Downstream Requirements Are Not Just for CMTS

Except for the RF power level that must be available at the output of a downstream transmitter, essentially all RF specifications found in the downstream section of the DOCSIS RF Interface Specifications [7] would be required for reliable operation of 256 QAM links. With respect to the broadband and adjacent channel noise specifications, this can be seen from the analysis in Table 2. With respect to Phase Noise specifications, it is clear that any relaxation of those specifications is likely to ‘eat-up’ noise and interference margin that the worst DOCSIS compliant transmitter lacks.

These conclusions would not have been necessarily drawn in the world of 64 QAM, where relatively much higher margins exist. However, based on the cited measurements and calculations for 256 QAM, it is shown that under currently prevailing headend and HFC signal transport practices, mass deployment of certain classes of QAM transmitters and upconverters used (or proposed to be used) today for VOD, may not scale well and would render future expanded 256 QAM operation unreliable. Indeed, contrary to an industry myth holding that VOD QAM transmitters need not necessarily comply with the RF specifications of DOCSIS, *compliance with most DOCSIS downstream RF noise specifications is essential in order to assure the proliferation and reliable delivery of any 256 QAM service over multiple channels*.

5 Summary and Conclusions

A systematic approach to specifying and evaluating noise specifications of QAM transmitters is provided in this paper. A review of additional impairment mechanisms including composite distortions revealed the reasons for a substantial rethinking of the required margins for reliable 256 QAM operations. It is argued that composite distortion terms having envelope peaks that can reach up to 16 dB above their average level, leave very little room for further noise degradations at *any* level of the signal distribution. It is shown that some currently deployed transmitters coupled with currently prevailing link budget design practices do not provide sufficient margin for reliable Quasi-Error-Free 256 QAM operations, particularly in systems that are rich with digital channels and narrowcast combining of digital channels such as cable modem and VOD applications. An application of a new transmitter figure of merit derived from specifications called Aggregate Noise Factor is introduced and its use demonstrated. Cable operators are encouraged to use such measures and establish the DOCSIS downstream noise standards not just for cable modem digital transmission but also for all other downstream digital transmissions and adopt such criteria for downstream transmitter qualification to ensure the ability to expand the 256 QAM service.

6 References

1. American National Standard, *Digital Video Transmission Standard for Cable Television*, ANSI/SCTE 07 2000 (Formerly SCTE DVS 031). (Downloadable at http://www.scte.org/standards/documents/pdf/new/ANSISCTE072000DVS031.pdf).

2. ITU-T Recommendation J.83 Annex B. "*Digital Multi-Programme Systems for Television Sound and Data Services for Cable Distribution*". (April 1997).

3. Robert L. Howald, "The Exact BER Performance of 256-QAM With RF Carrier Phase Noise", *NCTA Technical Papers*, (2001).

4. William Woodard, "Agile Modulator Characteristics and Their Effects on CATV Systems". *NCTA Technical Papers*, pp. 141-145, (1988).

5. Sudhesh Mysore and Oleh Sniezko, "Effects of Crosstalk on Bi-Directional And Hybrid QAM/Digital DWDM Systems", *NCTA Technical Papers*, (2001).

6. Steven I. Rubin, Andre Basovich, Brani Petrovic and Ron D. Katznelson, "Specifying and Measuring Aggregate Broadband Noise of CATV Modulators and Upconverters" in this *Cable-Tec Expo® Proceedings*, SCTE, (2002). (Available at http://www.broadbandinnovations.com/pubs/frm-pubs.html)

7. *DOCSIS Radio Frequency Interface Specification*, SP-RFIv2.0-I01-11231. CableLabs, December 31, (2001). (Avialable at http://www.cablemodem.com/specifications.html).

8. Oleh Sniezko, "Multi-Layer Headend Combining Network Design for Broadcast, Local and Targeted Services". *NCTA Technical Papers*, pp. 300-315, (1997).

9. Ron D. Katznelson, "Statistical Properties of Composite Distortions in HFC Systems and their Effects on Digital Channels". *NCTA Technical Papers*, New Orleans, May 7, 2002. (Revised copy available at http://www.broadbandinnovations.com/pubs/frm-pubs.html).

10. Vitaly Germanov, "The Impact of CSO/CTB Distortion on BER Characteristics by Hybrid Multichannel Analog/QAM Transmission Systems". *IEEE Transactions on Broadcasting*, Vol. **45**. No. 3, pp. 348-352, (September 1999).

11. Shlomo Ovadia, "The Effect of Interleaver Depth and QAM Channel Frequency Offset on the Performance of Multichannel AM-VSB/256-QAM Video Lightwave Transmission Systems". *NCTA Technical Papers*, (1998).

12. Dean Stoneback, Robert Howald, Timothy Brophy and Oleh Sniezko, "Distortion Beat Characterization and the Impact on QAM BER Performance". *NCTA Technical Papers*, (1999) (Available at http://www.gi.com/whitepaper/CTBNCTA99Final.pdf).

13. Robert Howald, "QAM Bulks Up Once Again: Modulation to the Power of Ten". In this *Cable-Tec Expo® Proceedings*, SCTE, (2002).

14. *Digital Cable Network Interface Standard*. SCTE 40 2001 (Formerly DVS 313), (2001). (Available at http://www.scte.org/standards/documents/pdf/new/SCTE402001DVS313.pdf)

15. Dojun Rhee and Robert H. Morelos-Zaragoza. “Error Performance Analysis of a Concatenated Coding Scheme with 64/256-QAM Trellis Coded Modulation for the North American Cable Modem Standard, *Proceedings of the 1998 IEEE International Symposium on Information Theory* (*ISIT '98*), p. 61, MIT, Cambridge, August 17, (1998).

16. European Telecommunications Standards Institute, “Digital Video Broadcasting (DVB) Framing Structure, Channel Coding and Modulation for Digital Terrestrial Television” *EN 300 744* (January 2001).

17. *DOCSIS Acceptance Test Plan*, TP-RFI-ATPv1.1-I02-010919. CableLabs, September 19, (2001). (Available at http://www.cablemodem.com/specifications.html).