Improve Plant Performance with Laser Clipping Suppression

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Introduction

Forward path digital loading has become common in HFC signal multiplexes over the past several years. The added bandwidth on HFC systems requires not just improved frequency response from the equipment in the distribution chain, but it also requires hardware with better dynamic range. As the forward path signal load increases with heavy digital loading, the total output power that must be achieved without degrading distortion is increased. Depending on plant layout, the total power could also be shared by backing down the analog load as a trade-off with the increasing digital load's effects. However, with slightly lower analog levels, CNR would degrade unless a lower noise floor exists. Thus, ideally, devices with improved dynamic range yield the most flexibility.

Towards this end, linear optics has improved significantly as the plant engineering focus has shifted to more sophisticated architectures spanning large geographical regions. Product families have been continually growing to support longer link lengths with higher power lasers and Erbium-doped fiber amplifiers (EDFA's). Lower noise lasers and ITU grid wavelengths also count as important achievements. Broader RF bandwidths and improved RF noise and distortion characteristics have also occurred in this time frame. This paper discusses a technique which crosses into the realm of both RF and optical to achieve its goals. This technique, laser clipping suppression, uses RF sensing to provide dynamic laser bias adjustments. This approach mitigates the laser's dominant impairment relative to digital signal carriage – laser clipping events – by shifting the laser's bias point at the onset of large RF envelope variations, which might otherwise introduce clipping.

Forward Path Operating Point and the Effect of Clipping on Analog and Digital Signals

Linear optics carries a composite signal multiplex for advanced HFC systems. The multiplex consists of traditional analog video channels, typically below 550 MHz. Above 550 MHz, digital signals are carried. Among these are digital video broadcasts, targeted services, cable modem traffic, and possibly telephony or other telecommunications services.

In all views of what HFC will be carrying in the future, heavier loading is a constant. Adding digital channels increases the total load on the transmitters, the significance of which depends on relative digital levels. It works out that the magic "10 dB" number, the rule-of-thumb threshold by which decibel addition of contributors means a negligible contribution, becomes violated for 300 MHz of digital loading at –6 dB relative to analog. The relative digital load at that point becomes about –8 dB of the total.

The need for high analog CNR results in the need for a particular per-channel optical modulation index (OMI). The above loading increase exacerbates this need, as the total power must be shared. The OMI level for high CNR is such as to generate clipping events that tend to drive the uncorrected BER performance of the QAM in the optical portion of the link. Thus, the RF drive to the laser is a careful trade-off between generating a high enough rms OMI per channel for the CNR needs of the analog video, and the clipping impairment associated with higher OMI. It also involves assuring that digital-on-analog composite intermodulation noise (CIN) does not degrade analog CNR, although this often becomes a bigger issue deeper in the RF plant where high output levels are required.

From the outset then, digital signaling in the forward path is confronted with clipping limitations of the linear optics, and relies on FEC to deliver the end-of-line performance. Of course, reliance on FEC for one impairment means less available FEC “budget” for other impairments in the forward path (microreflections, CTB, CSO, phase noise, frequency response variations). While FEC can be proven to mitigate clipping-induced errors, the movement to 256-QAM in the plant will place more constraints on the quality that the plant must deliver relative to CNR (6 dB worse than 64-QAM) and distortions [1]. The coding gain for 256-QAM is slightly weaker than the 64-QAM. Thus, it may be desirable to build the additional margin into the plant design to be prepared for the additional difficulty in transporting 256-QAM.

The average clipping repetition rate, ν, can be estimated [2], and is in units of 1/sec or Hertz. It is related exponentially to the rms OMI. The quantity νT, for QAM symbols of period T, is thus unitless, and represents the average number of clipping pulses per QAM symbol T. This term is valuable for a few of reasons. First, it points out the regularity with which a QAM symbol will be imposed upon by a clipping event – which does not automatically mean that an error will result. Second, the stress on the forward error correction (FEC) can be recognized, assuming it will be responsible for cleaning up some of these impulsive errors. Third, this parameter is part of the key to developing BER analysis for clipping in the forward path, and also plays a role in performing this same analysis for the case of clipping suppression.

Because of the short duration nature of clipping events, their effect on signal quality for analog and digital signals is different. The spectral nature of short duration impulses is, intuitively, wideband in nature. As clipping is gradually increased by increasing RF drive and optical modulation index (OMI), a noise floor is created that on a spectrum analyzer looks like additional white noise. The spectrum analyzer is an averaging device, or, correspondingly, a lowpass filtering device. The human eye also has filtering characteristics. Aside from the raw ability to overlook rapid changes, perception is influenced by what surrounds a picture element and the experienced brain’s expected observations. The impairment impact of clipping on analog signals can be correlated to the CNR degradation due to the carrier-to-nonlinear-distortion (C/NLD) associated with the laser clipping phenomenon.

For digital signals, this is no longer the case. The digital receiver, not the human eye, is the processing mechanism faced directly with the impulsive clipping effects. The receiver measures energy in each symbol (this is actually a simplified view of the processing in the demodulation stages). In any case, the digital receiver relies on symbol energy measurements over the small intervals of time corresponding to the symbol rate of the transmission. Because of this, impairments that the eye may not detect are imposed upon a transmission format (high rate digital symbols) that make them detectable, in this case ultimately manifesting itself via the familiar "tiling" associated with digital picture impairment.

Early Linear Optical Transmitter Development History

With the advent of linear fiber optics in the late 1980's, system architectures began to take on new and more reliable forms. The signals that were carried then were strictly analog channels, most often 42 or 60 channels of broadcast video. This lighter load relative to today's 110-channel analog or combined analog and digital systems reduced the design constraints on the laser transmitters. The baseline performance of the fiber optic portion of a network requires about a 50 dB CNR, and distortion levels better than about -65 dBc. These levels were achievable with state-of-the-art 42-channel laser transmitters in 1988, and have remained so with the increased channel count and improvements in transmitter design and linearization since that time.

The earliest fiber optic transmitters employed only second (even) order linearization circuits. Those linearization schemes often employed predistortion of the RF drive signal such that the laser's non-linearities were compensated by the distorted RF drive. In predistortion schemes in general, two features are characteristic: the non-linear element of the predistorter that generates the error signal used for correction, and the topology into which the non-linear element is configured. In this instance, the non-linear elements are pairs of amplifiers in a push-pull configuration, which are connected in a path parallel to the main signal path. A small portion of the main signal is split out of the main path, sent through the non-linear element, amplified, and phase adjusted before being added back into the main signal path. In a similar fashion, third (odd) order predistortion was added in an additional parallel path. This combination of multiple parallel paths and even and odd predistortion constituted the logical progression of the early optical transmitters.

Advances in predistortion technology have led to combined RF and optical subassemblies that previously were separately handled. The non-linear element is now diode pairs, and the topology has been simplified to one in which the elements are in the main signal path. This has allowed tuning of the predistorter in a more predictable and controllable manner, as the RF and optical subassemblies were combined onto a single board, enabling manufacturing cost and process savings.

The Anti-Clipping Concept

In the most recent advancement of the transmitter circuitry, anti-clipping technology has been added. Incoming RF signals can have large envelope variation, periodically becoming large enough to create distortion due to laser clipping. It is a somewhat similar phenomenon to amplifier clipping, but in that case the input-output transfer function is a soft distortion mechanism as the amplifier gradually loses dB-for-dB behavior. In the laser clipping case, the distortion mechanism is a hard clip, much like a perfect limiter, but occurs only in a single-sided manner for directly modulated lasers, when the instantaneous RF drive exceeds bias level. If the large amplitude RF drive can be avoided, or the laser biased to a high enough point, clipping does not occur. In the forward channel, the periodicity of the RF signal's peaking events are such that reasonable predictions can be made about its amplitude and repetition characteristics. Because of this, an "anti-clipping" circuit can be designed based on statistical knowledge of the events. The circuit samples the RF and predicts the duration of a high amplitude RF envelope occurrence. A drive circuit is used to partially control the DC bias point of the laser, and when a high amplitude event is recognized, the drive circuit temporarily biases the laser to a higher level to prevent the onset of clipping. The duration of the events and the mechanism of changing the laser bias point have not been detrimental to the overall operation or performance of the laser transmitter.

A simple way to understand the clipping mitigation approach is to think of it as a threshold detection mechanism followed by a laser bias adjustment, the period of which is determined by an RC time constant, or equivalent lowpass function. The input to a forward path laser is a composite multiplex of traditional analog video and digital services, typically riding above the analog spectrally. As mentioned above, the resulting signal has random qualities, creating a high peak-to-average ratio that looks much like noise. However, for the forward path, there is an inherent component of peaks of that occur, not coincidentally, with a 6 MHz repetition rate and predictable duration with which to set the time constant. The amplitude characteristics of this burst period depend upon the relative phases of the analog carriers. Because of the large number of (typically) independent carriers (not phase-locked), the randomness qualities vary slowly with the nature of crystal oscillator drift.

There has been a significant amount of study to determine the impact of laser clipping in composite analog/digital multiplexes on both the analog CNR and on the QAM BER. Analytical expressions have been derived and measurements take in support of these results to help system designers optimally align laser loads for both analog and digital performance. A recent contribution [3] provides simplified BER expressions under the practical assumption that, during a clipping event, the AWGN contribution is negligible compared to the clipping. The is particularly applicable to HFC systems, where clipping can still be considered a relatively rare event in terms of number of events on a per symbol basis, and where the CNR on any 6 MHz channel is relatively high.

Even for digital channels that are run backed off from the analog video by up to 10 dB, CNR's in the low 30's will exist as a minimum. For the optical link only, we assume that the only impairments of significance to deal with are AWGN (RIN, optical RX, interferometric intensity noise) and the clipping effect. The expression for BER under the above assumption can be represented as

BER(ν) = Prob(no clipping events in a symbol) • Prob(error/no clipping events) + Prob(clipping event in a symbol) • Prob(error/clipping event in a symbol),

or

BER(ν) = [1-νT] • Prob(error/AWGN) + [νT] • Prob(error/clipping event in a symbol) (1)

The first term in (1) is the traditional demodulator case – symbol detection in the face of the AWGN channel. The second term recognizes that a different error rate expression must be calculated when clipping events occur. This is because the impairment PDF has changed from Gaussian to something different.

This expression is a good starting point for predicting the effect of clipping mitigation, by relying on the prior work regarding the characteristics of the clipping impulses. It is described in [2] how clipping can be modeled as a Poisson process, with a parabolic pulse shape, the duration of which is Rayleigh distributed. The mean duration is related to the frequency content of the modeled spectrum and the rms OMI driving the laser.

From this statistical information, the effect of the matched filter on the clipping event can be evaluated. In particular, the impulses are so short, on the order of nanoseconds, relative to the symbol periods (on the order of hundreds of nanoseconds) in real systems, that the parabolas look nearly like impulses to the input of a matched filter, which allows simplification of the filter output. Thus, the impulse response of the filter plays a key role in evaluating the effect of the short clipping pulse. Effectively what occurs is that the matched filter spreads the clipping energy out into the order of a symbol time, and the analysis simplifies to evaluating the impulse response of a matched filter, but with a noise term of a statistically varying output amplitude related to the clipping level. Since the matched filter integrates over a symbol period to determine an energy for symbol slicing (detection), the varying output amplitude is, in fact, a function of the Rayleigh statistics of the clipping impulse duration. The actual statistics of the output amplitude is a complicated expression [2] because the PDF of the impulse duration is modified by the matched filter operation. Refer to the probability density function (PDF) of this matched filter output amplitude due to a clipping impulse as $p_c(C)$.

How does this all relate to the analysis for the clipping mitigation case? Consider (1):

BER(ν) = [1-νT] Prob(error/AWGN) + [νT] • Prob(error/clipping event in a symbol)

What changes now to the predict performance of the equipment using this approach is that clipping mitigation that has been introduced. This effects the coefficient terms in this expression. In the analogy given above for the mitigation circuitry – an RC filter – when the onset of clipping is sensed, a bias change is introduced for a time period related to the duration of a burst of events. The period is governed by an RC time constant. That is, the nature of the forward path multiplex is that when there are clipping impulses, they typically come several or many over a period of time for which this time constant represents the average. The term νT would still represent the average rate of clipping occurring, the description here merely says that they occurrence is not necessarily evenly distributed over time.

Now, when clipping suppression kicks in, the further assumption is made that the error rate again reduces to the AWGN-only case. The new expression for BER can be written by noting that this occurs when the amplitude of the clipping event at the matched filter output exceeds some threshold. The threshold that must be exceeded is, of course, at the transmitter on the other end of the link. However, for a clipping impairment that dominates the AWGN contribution when both exist – an assumption from the beginning for this simplified analysis - it is equivalent to fixing a threshold at the matched filter output also. Call this threshold boundary at the matched filter b, then the BER expression becomes

$$\mathrm{BER}(\nu) = [1-\nu T + {}_b\!\int^{\infty} p_c(C)dC] \bullet \mathrm{Prob(error/AWGN)} + [\nu T - {}_0\!\int^{b} p_c(C)\, dC\,] \bullet \mathrm{Prob(error/clipping\ event\ in\ a\ symbol,\ modified)}. \quad (2)$$

The expression here shows how the mitigation of clipping events is taken into account to express the new likelihood's of the two BER's that make up the composite expression.

Physically, the interpretation of this expression is that, for the percentage of amplitudes that would exist above the threshold at which the laser bias is adjusted, it is assumed that clipping mitigation is employed and successful. Doing so reduces such a situation to the AWGN detection problem. Thus, the first term in the expression above corresponds to the case where no clipping events occur, naturally, combined with the case where a clipping event would have occurred, but was ameliorated by the mitigation effect of the technology. The second term corresponds to the case where clipping exists, but the amplitude of the impulsive event is not enough to trigger bias reduction. Thus, the detection problem is still one of detecting the signal in the face of a clipping event. The expression in the second term for probability of error of the remaining clipping impaired symbol, however, is not the same as that used in (1). The expression for the error probability given a clipping event is an integral expression. The region over which the integral is evaluated now is only over the range up to the threshold boundary, b. Thus, the probability of error given a clipping event in a symbol is slightly different in (1) and (2). An intuitive way to look art this is that in (2), this expression only applies for a subset of the cases of equation (1), the clipping events which do not exceed the threshold. Thus, the error probability given a clipping event in a symbol must be smaller.

This analysis can be used to predict performance as a function of the threshold of declaring a clipping region, channel CNR, and rms OMI.

Measured Results

A block diagram of the test setup is shown in Figure 1. Note that Figures 1 through 3 are all located at the end of the paper.

A Matrix generator was used to place 77 channels of analog video in the 52-550 MHz passband. This CW comb was RF combined with the simulated digital load, which consisted of a bandpass filtered wideband noise source, with the filter delivering a flat spectrum across 553-860 MHz. The combined signal was passed through a channel deletion filter at the location of the desired 256-QAM test channel, 555.25 MHz. The QAM test signal, an uncorrected 256-QAM RF carrier, is upconverted and combined at the proper relative power level to complete the signal load. This load is split three ways to drive three lasers. The three lasers represent three classes of performance from the Motorola product family. There is a standard performance product, the LM-9, a premium performance product, ALM-9, and finally the clipping suppression product, the ALM II-9. The –9 in each product represents the maximum optical link length the transmitter is designed for (essentially, this defines laser output power).

The transmitters are alternately run through an optical link of 20 km, where the signal is detected by a forward path optical receiver inside a node. The node in this case is a Motorola SG2000. Thus, it was assured that the performance were relative to the same link and optical receiver. The node's RF output feeds a bandpass filter for the QAM channel, through a subsequent downconversion to get to the test modem IF frequency. The demodulator interfaces with a BERT and a PC. This completes the test setup. All of the BER measurements are with no error correction.

The testing was broken down into a focus in three areas of study – digital bandwidth, relative digital levels, and increased analog levels. The test results are shown in Table 1, Table 2, and Table 3 corresponding to the three areas of focus.

In these tables, the term SNR has been switched to to represent the digital channels, while standard term CNR has been used to represent analog measurements. Note that the effective SNR improvement (the column labeled "BER SNR Delta") of the 256-QAM performance is based on converting from BER to SNR (or Eb/No in this case, the relationship is still one-for-one). Figure 2 shows a BER plot of 256-QAM in AWGN, relative to the BER curve for 64-QAM, 16-QAM, and QPSK. Note that the horizontal axis is based on Eb/No, and not SNR. To put in terms of SNR requires augmenting with the bits per symbol relationship. For 256-QAM, for example, the SNR is $10\bullet\log(8) = 9$ dB higher than Eb/No, since there are eight bits per 256-QAM symbol. This leads to the useful rule-of-thumb that a BER of 1e-8 requires (25+9) = 34 dB for uncorrected 256-QAM. This is useful because, in terms of SNR, the significant modulations are all about 6 dB apart. In other words, 64-QAM requires about 28 dB SNR for 1e-8 and 16-QAM requires about 22 dB SNR.

Varying Digital Bandwidth

In Table 1 below, the performance of the lasers against increasing the digital bandwidth is measured, for analog levels at nominal per-channel settings and a fixed relative to analog digital per-channel level of –6 dBc.

<u>Table 1 – Varying Digital Bandwidth</u>

Test Conditions w/9dB Link			256 QAM BER			BER SNR Delta
TEST #1						ALM II-9 vs. ALM-9/LM-9
			LM-9	ALM-9	ALM II-9	
550MHz Analog (nom per/ch) Single 256 QAM ch @-6dBc			6.30E-08	3.70E-08	1.00E-10	1.25 dB/1.50 dB
	547.25MHz	CNR	51.8	53.9	53.9	
550MHz Analog (nom per/ch) 200MHz digital @-6dBc w/555MHz			2.40E-07	1.40E-07	2.90E-09	1.00 dB/1.25 dB
	547.25MHz	CNR	50.9	53.0	53.6	
550MHz Analog (nom per/ch) 300MHz digital @-6dBc w/555MHz			8.70E-07	2.90E-07	4.90E-08	.50 dB/1.00 dB
	547.25MHz	CNR	51.4	53.4	54.0	

Evaluating Table 1, the following points are of note:

- The anti-clipping technique in the ALM II results in virtually error free performance when a single digital channel augments the analog multiplex; this verifies the anti-clipping mechanism as the standard models show error accumulation even for this favorable condition.
- There is about two orders of magnitude BER improvement for the ALM II for the first case and the 750 MHz system with 200 MHz of digital load.
- There is about an order of magnitude BER improvement for the heaviest loaded case of 300 MHz of digital; in this case the total digital power represents –8 dB of the total power, so it is no longer considered a negligible power load.
- There is 1-1.25 dB of effective SNR gain on the digital channels for 200 MHz of digital loading, and .5 dB-1 dB of gain on the 300 MHz of digital load.

The measurements verify the effect of the anti-clipping circuitry. The point of the CNR numbers taken on the last analog channel was to recognize that the analog performance was essentially unchanged around a high quality level of CNR performance. In addition to proving anti-clipping effects, this test shows the significant link gain available for the 200 MHz of loading. While the 300 MHz loading case shows less gain, this case also crosses the threshold at which the digital loading can be ignored as a percent of the total. In other words, the laser in this case is being driven above its nominal rms OMI because of the 100 MHz of additional digital loading. The following tests explore other options that may more efficiently use the performance gain.

Varying Relative Digital Levels

The emphasis in Table 2 below is on the level of the digital channels relative to the analog, for a fixed 300 MHz of digital bandwidth, and fixed analog levels at nominal per-channel settings.

Table 2 – Varying Relative Digital Levels

Test Conditions w/9dB Link			256 QAM BER			BER SNR Delta
TEST #2						ALM II-9 vs. ALM-9/LM-9
			LM-9	ALM-9	ALM II-9	
550MHz Analog (nom per/ch) 300MHz digital @-6dBc w/555MHz			8.70E-07	2.90E-07	4.90E-08	.50 dB/1.00 dB
	547.25MHz	CNR	51.4	53.4	54.0	
550MHz Analog (nom per/ch) 300MHz digital @-8dBc w/555MHz			1.50E-07	5.75E-08	2.10E-09	1.00 dB/1.25 dB
	547.25MHz	CNR	51.4	53.6	54.3	
550MHz Analog (nom per/ch) 300MHz digital @-10dBc w/555MHz			5.80E-07	3.46E-07	1.00E-10	2.00 dB/2.25 dB
	547.25MHz	CNR	51.6	53.7	54.4	
550MHz Analog (nom per/ch) 300MHz digital @-12dBc w/555MHz			2.40E-06	2.00E-06	4.00E-08	1.25 dB/1.25 dB
	547.25MHz	CNR	51.7	53.9	54.6	

Evaluating Table 2, the following points are of note:

- The performance of the ALM II actually improved as relative digital levels dropped, to a point. This is attributable to what was implied by the Table 1 measurements of 300 MHz of digital bandwidth – the significance of the power load. As the power load becomes once again negligible (-10 dBc relative levels), the laser experiences a typical level of clipping. The circuit is designed to handle typically found clipping statistics well, and the link becomes "less" clipping limited, instead of completely clipping limited, like the LM and ALM. This can be recognized by noting that BER does begin to degrade at the -12 dB relative level for the ALM II, because of lower QAM levels relative to the remaining impairments.

- The traditional transmitter families show predictable BER degradation as signal level is dropped. These models are still impacted by clipping as the dominant impairment, and lowering the channel power makes the C/(clipping),the dominant impairment parameter, lower.

- For digital channels run –10 dBc, there is a 2-2.25 dB effective SNR gain in BER due to the anti-clipping design; the link runs virtually error free, versus E-7's for the traditional models.

- A major advantage of the lower digital levels - not recognizable in this link test – is the effect of the lower digital levels on the end-of-line plant distortion performance. As RF output levels increase to eliminate actives in fiber deep architectures, the imposition of digital CIN onto the analog CNR can become a major issue. This is particularly an issue at –6 dBc levels and above because of the additional power load mentioned above. The relative digital impact represents about an additional .6-.7 dB of total power, which is doubled for determining third order distortion impact – a noticeable result.

Increasing Analog Levels

In Table 3 below, the focus changes to the increase in analog levels for a fixed digital level, and fixed digital bandwidth. Please note that the digital levels relative to analog are absolutes. In other words, in Table 2 above, the first test was run with digital channel levels at –6 dB relative to analog levels. In the first test below, the analog levels have been increased by 1 dB. The digital level was not changed, therefore the digital level relative to the analog level now becomes –7 dB. In the last test of Table 3, it is noted that the analog levels are increased by 2 dB. The digital levels are noted as –12 dBc. This means that if the analog levels were at their nominal per-channel settings, then the digital levels would be –10 dBc. Thus, the digital level is set the same as it was in the third test in Table 2.

Table 3 – Increasing Analog Levels

Test Conditions w/9dB Link			256 QAM BER			BER SNR Delta
TEST #3						ALM II-9 vs. ALM-9/LM-9
			LM-9	ALM-9	ALM II-9	
550MHz Analog (nom per/ch + 1 dB)						
300MHz digital @-7dBc w/555MHz			7.10E-06	3.20E-06	5.70E-08	1.50 dB/1.75 dB
	547.25MHz	CNR	52.4	54.3	55.1	
550MHz Analog (nom per/ch + 2 dB)						
300MHz digital @-8dBc w/555MHz			1.60E-04	9.40E-05	3.80E-06	1.75 dB/2.00 dB
	547.25MHz	CNR	52.8	54.4	55.8	
550MHz Analog (nom per/ch + 2 dB)						
300MHz digital @-10dBc w/555MHz			2.10E-04	1.90E-04	1.53E-06	2.75 dB/2.75 dB
	547.25MHz	CNR	53.3	55.4	56.2	
550MHz Analog (nom per/ch + 2 dB)						
300MHz digital @-12dBc w/555MHz			5.30E-04	4.40E-04	4.30E-06	3.00 dB/3.00 dB
	547.25MHz	CNR	53.6	55.7	56.2	

Evaluating Table 3, the following points are of note:

- The additional 1 dB of analog level degraded the BER on the two traditional models, while for the case of the ALM II it remained virtually unchanged.
- For a 2 dB increase in analog levels, the traditional transmitters are creeping towards crashing with BER’s in the E-4 range. The ALM II is still comfortably in the E-6 range.
- The ALM II continues to show CNR increase with the additional 1 dB of analog level, while the traditional designs show the increase for a 1 dB increase in level, but not for a 2 dB

increase due to higher distortion and clipping contributions to CIN.

- Dropping digital levels accompanying the 2 dB analog increase causes further BER degradation from the additional relative CIN with low QAM on the traditional models, and the increase in clipping events caused by the analog levels. The ALM II again shows some slight improvement to a point, as it is not as clipping dominated. It again shows slight degradation as the composite of contributions to BER begins to appear only for the lowest digital levels.

- Effective SNR improvement due to the ALM II achieves values as high as 3 dB for the high analog/lowest QAM case shown. Even in this case, the ALM II shows BERs in the E-6 range, two orders of magnitude better than the traditional models.

- The same discussion of digital levels and CIN effects can be applied in this case. In fact, the increased analog levels have a greater impact on the total load than the increasing digital. It helps that the digital levels are not increasing in this case, although the dominant CIN effect for analog/digital is two analogs mixed with one digital.

- It is worthwhile to mention that FEC performance is generally considered capable of correcting BER's in the E-4 range, although it is not desirable to have all of it allocated to the optical link [1].

It is important to note that this paper discusses only the optical portion of the link. Thus, there is virtually no discussion of distortion impacts such as CTB, which is driven by performance of the RF plant. As it turns out, CTB can effect QAM BER under certain conditions [1]. In the sense of effecting the channel performance on the end-to-end system, the optical portion of the link has a major impact on CNR delivered and on the BER of the digital signals because of the clipping issue. Other BER impairments specific to the RF plant must also be well understood to understand the complete performance.

The results above point out that there are various ways to enhance plant performance with the anti-clipping approach. The various ways to spend the performance advantage are

- Lower uncorrected BER with typical analog and digital loading
- Wider digital bandwidth with the same analog loading
- Lower digital levels with the same analog loading
- Higher analog levels with a constant digital loading

Translated to SNR, BER improvements can be as high as 3 dB. The benefits to the total plant of lower digital levels also helps CTB performance under the heaviest digital loading at today's highest amplifier RF output levels. Because of the dB-for-dB digital contribution effect (two analog by one digital) of third order composite analog plus digital distortion, it can be roughly estimated that CIN drops a dB for every drop of digital level that can be implemented. Another scenario is systems squeezed for analog CNR margin for long links or multiple hops can afford an increase in level at no BER cost. Finally, upgrading the plant to add more digital can be done pain free because of the margin provided by the clipping mitigation to the loading effects.

Return Path Application

Linear optics are also used in the return path. It is thus natural to consider this technology for return path applications. While this is under investigation, there are two reasons that this technique is of less value in the return path. First, unlike to forward path, the return path is a bursty, generally time domain (and frequency domain) accessed channel. It is thus very rare, under normal operating and alignment conditions, for the reverse path band to be loaded heavily enough for clipping to have consistently expected occurrences the way the forward path does. For example, consider Figure 3, which represents the output Carrier-to-Noise-plus-distortion [C/(N+NLD)] versus total input level. The plot is an example of a Noise Power Ratio (NPR) curve, and is valuable in determining how best to align laser drive as a compromise of performance and robustness in the return path. Assume that the setup point of the laser is backed off from the optimum point of C/(N+NLD) by 3 dB. The set point is based on a fully loaded band of return signals, typically allocated on a power-per-Hz basis, although this condition is very unlikely in practice. Backing off of the peak performance is common to guard against signal level variations, equipment variations, and other unexpected events. The goal is to have enough room from the peak such that the slippery slope of the NLD part of the curve is avoided.

For the return path, the NPR back-off is often set greater than the forward, to account for outdoor plant and level variations, as well as protect against noise and interference transients (or constants) that can overload the reverse path. Assume that it is set only 3 dB off of the peak NPR. Further assume that the maximum simultaneous usage of the return path is 25%, such that the maximum loading ever present to the laser is yet 6 dB lighter. This is a total of 9 dB back off from the NPR peak. This region of the NPR curve is clearly noise dominated, as opposed to noise and NLD, and the probability of clipping even for a Gaussian-like noise signal is extremely small. The number can be quantified easily by analyzing the Gaussian probability distribution function (PDF) and integrating the curve to provide the likelihood of exceeding the 9 dB peak to average in one direction only. However, suffice to say without the math, that to attempt to mitigate the events of very low probability will have very little impact on typical performance.

Secondly, even if the return were fully loaded, the statistical nature of the clipping events would differ significantly. It has been described how, in the forward path, the approach taken is a rather simple one - recognizing the onset of a clipping event, and using the a-priori information we know about these events. Their duration and statistics of their duration, as well as their shape, has been analyzed in detail [2]. It has also been discovered, not surprisingly, that there is a strong 6 MHz periodicity of peaking to the composite forward path load. Obviously, this relies on analog carriers, and if the load were to be switched over to all digital channels, there would be some complexities. By knowing the nature of the periodicity of the forward path time domain waveform, the timeframe with which the laser bias must be adjusted can be "predicted" on average, and mitigated against. The known characteristics of the forward path's waveform and its 6 MHz-related characteristics do not apply in the return path. There are no fixed channel assignments (or few, none of significance to loading), no fixed service bandwidths, and no clear-cut relationships to leverage for bias changes enabling efficient clipping suppression as there is in the forward path.

Digital reverse paths make the return clipping suppression idea seem of less value. In principle, however, it is still very applicable, as an A/D converter has NPR characteristics similar to a laser because of its tendency to clip. For the A/D, however, clipping is two-sided in nature, and this reveals itself as the steeper slope on the distortion side of the curve. In fact, digital technology offers the opportunity to manipulate the bits to deal with sensed clipping events from an A/D's overload flag, as opposed to in the analog transmitter, providing more flexibility in processing techniques to consider. However, the reasons above apply still in terms of use of the concept in the context of return paths.

AM-VSB/M-QAM Hybrid Lightwave Systems," IEEE Transactions on Communications, October 1996.

Conclusion

Linear optics has made the development of the HFC plant possible. Continuing advances have allowed HFC to evolve into a variety of architectural scenarios. The deployment of digital signaling on HFC created a need to have a deeper understanding of the laser clipping issue, as the clipping phenomenon manifests itself as BER impairment on the digital channels. This paper describes the first significant product attempt to specifically address laser performance from the standpoint of clipping mitigation. It has been shown that by addressing the clipping issue in the design of the transmitter directly, using some known stochastic properties of the clipping events, significant performance gain is achievable. How this performance gain is used is up to the designer. However, the advantage can be translated into simple a lower digital BER. Or, it can be spent as wider digital bandwidth with the same analog CNR and BER, higher analog levels and analog CNR with the same BER, or lower digital levels of the same BER and thereby higher CNR due to lower CIN.

References

[1] Howald, R. et al., "Distortion Beat Characterization and the Impact on QAM BER Performance," 1999 NCTA Technical Papers.

[2] Pan, Qi and R. Green, "Amplitude Density of Infrequent Clipping Impulse Noise and Bit-Error Rate Impairment in

[3] Pan, Qi and R. Green, "Simplified Analysis of QAM BER Impairment in Hybrid AM/QAM Lightwave Systems," IEEE Transactions on Communications, April 1999.

Acknowledgement

The author would like to recognize the efforts of Mike Short, Tech Specialist in Systems Engineering in Motorola BCS' Transmission Networks business unit.

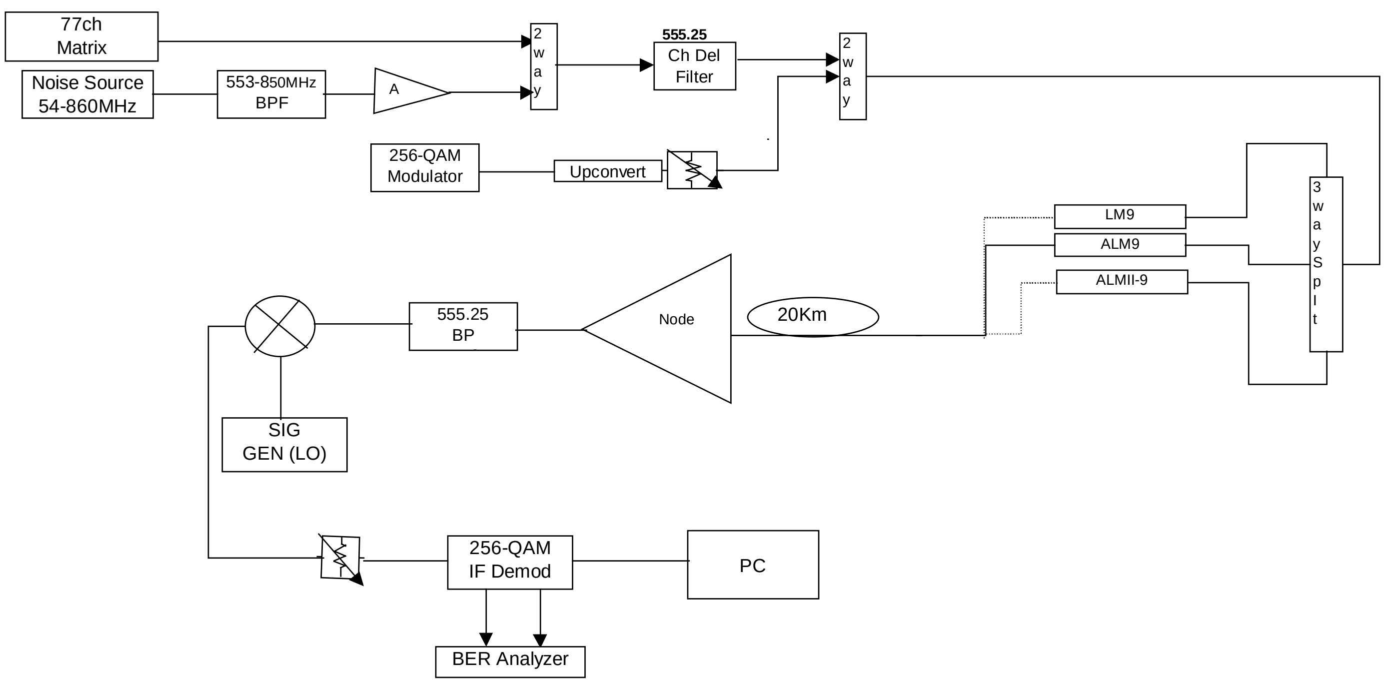

Figure 1 – Test Setup Block Diagram

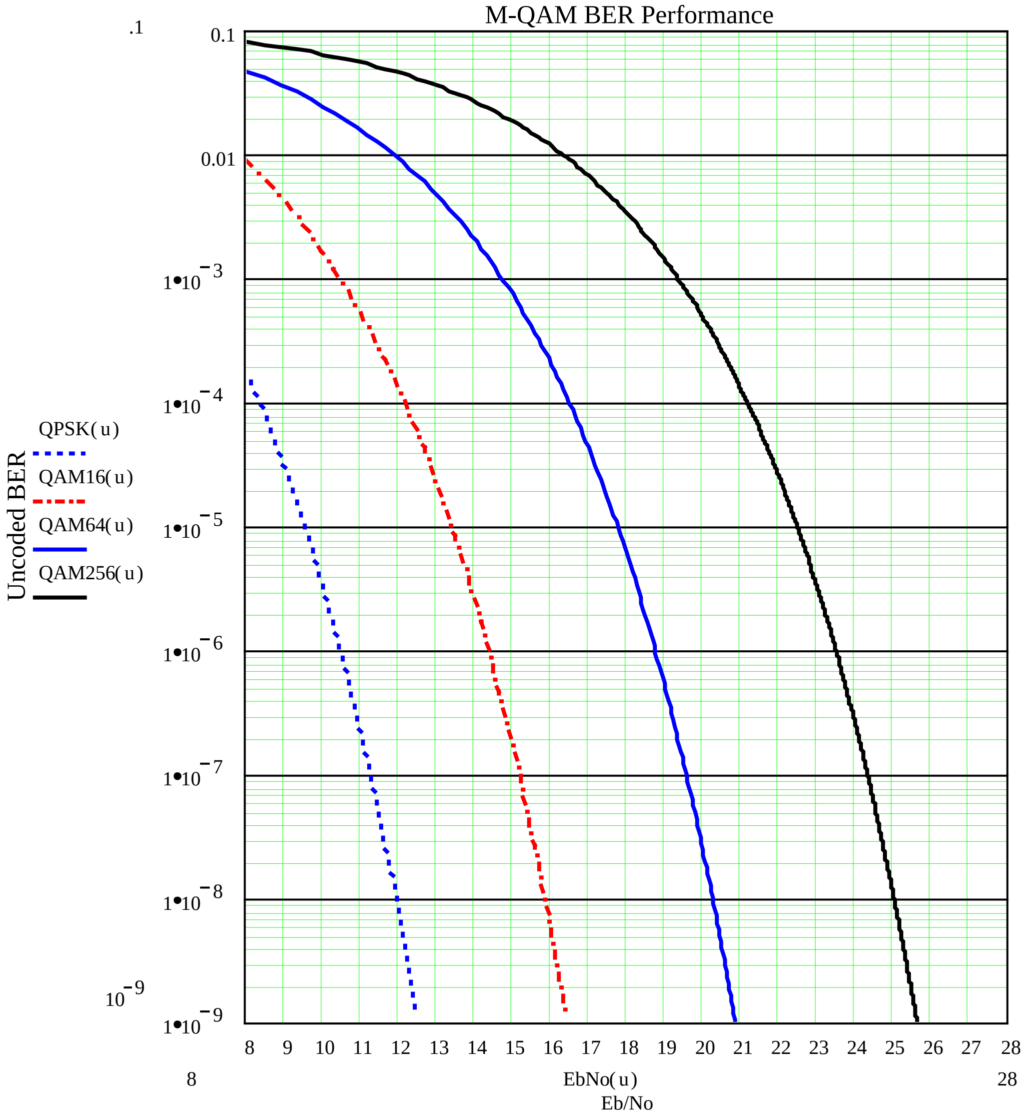

Figure 2 – Theoretical BER of 4/16/64/256-QAM vs. SNR per Bit

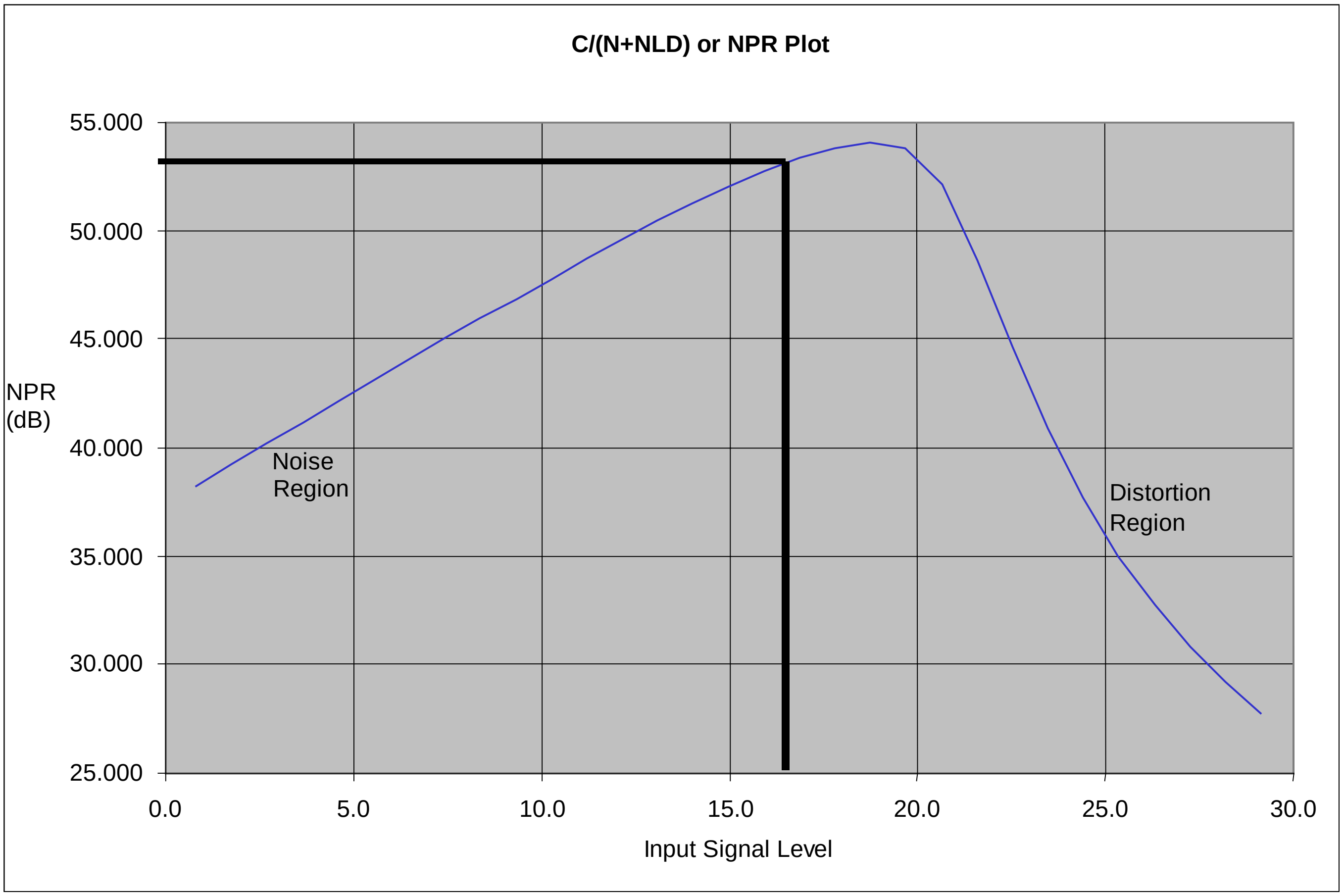

Figure 3 – NPR for Return Operating Point with Headroom