Don't Get Clipped on the Information Highway

D. Raskin, D. Stoneback, J. Chrostowski and R. Menna
Transmission Network Systems
General Instrument Communications Division
Hatboro, PA

Abstract

Signal degradation due to clipping is a threat to the performance of both the forward and the return path that has been given too little attention by our industry. In the forward path, the performance of fiberoptic transmission systems for broadband services is often limited by statistical clipping of the RF signal at the laser source. This means that systems meeting NCTA distortion and noise standards may nonetheless exhibit unacceptable video performance. Furthermore, the nature of these impairments is very different for directly-modulated, as opposed to externally-modulated optical sources. We report first on video tests of DFB lasers, indicating the nature and cause of clipping related impairments. Based on subjective picture quality tests, we have defined a straightforward quantitative test for determining acceptable clipping performance of a transmitter. The results of a similar test program for externally-modulated sources used in 1550 nm systems are described and compared with DFB's. Criteria for successful downstream data transmission jointly on lasers with analog signals are reported, as are preliminary investigations of 12VDC vs 24VDC RF amplifiers. Upstream digital transmission tests that investigate the effects of clipping both in return amplifiers and lasers are discussed, as well. Quantitative tests will be proposed as supplementary recommended practices for the industry.

INTRODUCTION

What causes clipping in CATV systems?

When an applied electrical signal amplitude goes beyond the level capability of a device, we say that the signal is "clipped" by that device. A simple, but extreme example would be an AC signal applied to a circuit through a diode. In that case the diode would clip 100% of one polarity of the AC current signal. In cable television systems, laser transmitters cause more subtle clipping of the RF signal when the amplitude of the composite signal exceeds either the bias current, in the case of a directly modulated semiconductor laser, or the modulation limits for an external modulator (ex-mod) in a 1550 nm or YAG solid state transmitter. This is shown graphically for a DFB laser and an ex-mod in Figures 1 and 2, respectively. Keep in mind that these diagrams are somewhat misleading because of their over-simplification of the highly complicated signal that is applied to a CATV analog laser. In a real CATV transmitter, clipping is supposed to occur only when all of the many individual signal amplitudes "line up." Fortunately with properly designed equipment in modern high-channel-count systems, statistical averaging works to make this a relatively rare event.

RF amplifiers can cause clipping, as well, when the input signal exceeds the bias of transistor elements. In nearly all cases this is not a problem in CATV, since the RF levels that cause noticeable clipping would already be significantly beyond the distortion limits of the amplifier. Recently, however, two changes in CATV operations and technology have raised questions about the importance of amplifier clipping: (1) the much greater signal loading of return systems has driven the RF levels at return node amplifiers close to clipping limits and (2) the desire to use GaAs amplifiers has encouraged the use of lower bias voltages (e.g., +12 VDC, rather than the traditional +24 volts). We have found situations in which clipping can be a problem in the return amplifiers. On the other hand, our initial investigation of 12V amplifiers does not indicate reasons for concern.

What are the effects of clipping?

From Figures 1 and 2 one can see that DFB lasers cause clipping only in the downward direction whereas the ex-mod clips bidirectionally. We can understand the effect of this difference by imagining the clipped output signal as the sum of an unaffected ("pure") signal and an error signal (Figures 3 and 4). For a sinewave input, the error signal in the DFB case is an even function, while that of the ex-mod is odd. This means that the clipping events will show up on a spectrum analyzer at the CSO beat frequencies for a DFB and at the CTB beats for an ex-mod.

Figure 1a: DFB Laser in Linear Operation

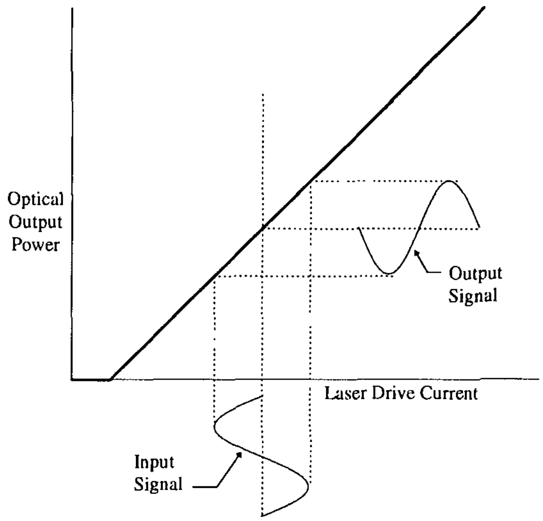


Figure 2a: Externally-Modulated Signal in Linear Operation

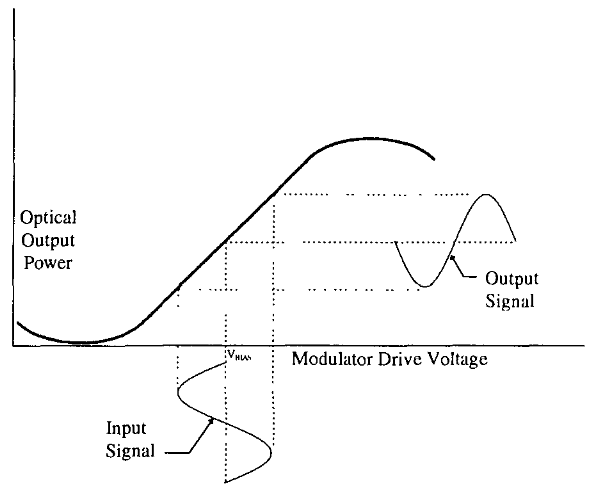


Figure 1b: DFB Laser in Clipping

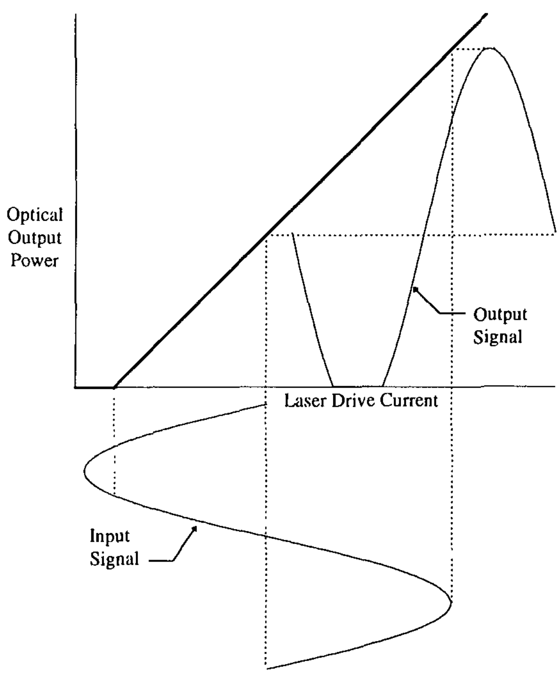


Figure 2b: Externally-Modulated Signal in Clipping

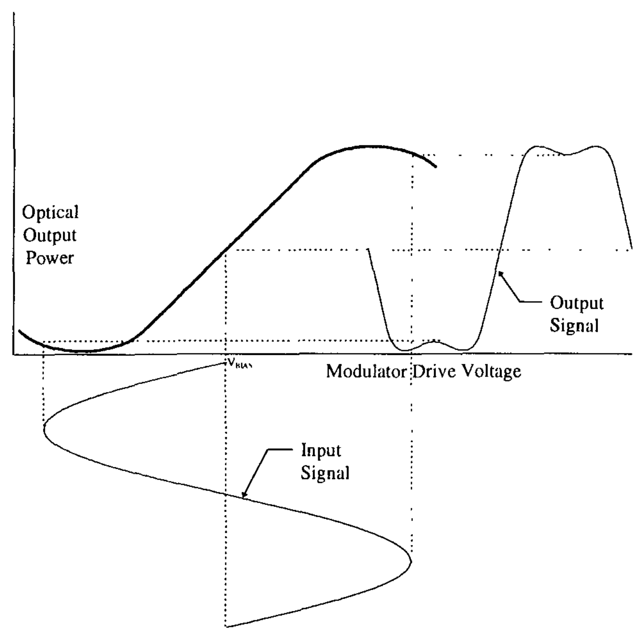


Figure 3: Decomposition of DFB Clipping

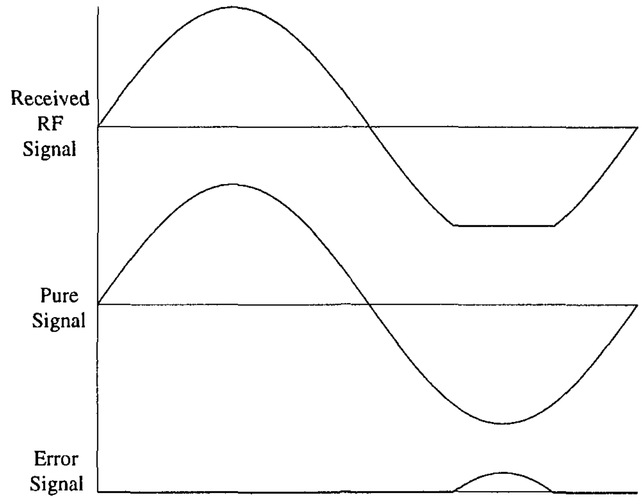
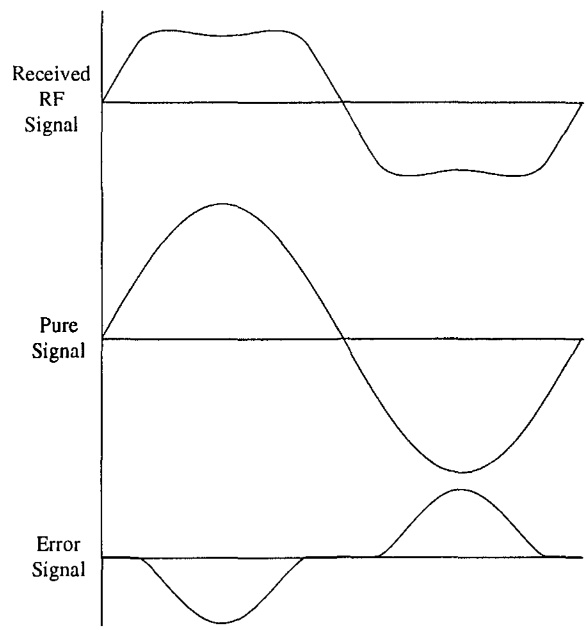


Figure 4: Decomposition of External-Modulator Clipping



A more critical difference between the clipping effects in these two types of transmitters results from the fact that in DFB's the laser is actually turned off (biased below threshold) when the RF signal gets too large in the negative direction. Unfortunately, the RF optical signal out of the laser does not appear to recover instantaneously. Typically this time delay is several microseconds, which is a significant fraction of the television horizontal scan time (62.5 μsec). Thus a laser clip looks like a white horizontal flash on a TV screen. This is easily seen in a display of a medium brightness flat field (≈ 50 IRE), which is how we made subjective evaluations of analog clipping. On the other hand, the light source in the ex-mod case is never turned off. When the modulator is over-driven, the optical power is still modulated in a continuous fashion. Although the signal during the clipping event may be rich in harmonics, the duration is very short. Thus analog clipping in an ex-mod shows up as random "busy-ness" on a flat field TV display. RF amplifier clipping would manifest itself in a similar way, since it is bi-directional and there is no latency in the active device.

Clearly these clipping events also have the capability of interrupting the flow of digital data, hence to cause errors. We have used uncorrected bit error rate (BER) measurements to determine the severity of clipping on these signals.

FORWARD PATH TESTING

DFB lasers

Over the past three years we have found that the subjective picture quality of signals transmitted over fiber by high quality DFB analog transmitters is limited by clipping in the lasers, rather than by the traditional second and third order distortions. As noted above this clipping shows up as annoying horizontal flashes in a picture. Because of the obvious need for a quantitative test to determine when a laser is operating properly, we examined a number of approaches. Ultimately a time domain measurement was found that correlated well with the flat field tests: a spectrum analyzer is set at zero span on a mid-frequency CSO beat frequency at resolution and video bandwidths of 30 kHz and is allowed to make a single sweep of 30 sec duration. The display will show a rough baseline with several distinct peaks due to clipping (Figure 5). We have found that the amplitude of the highest peak is not a good indicator of subjective picture quality. The height of the <u>tenth highest</u> peak, however, turns out to be a very good indicator of clipping quality: if the tenth highest peak measures greater than -45 dBc we observe noticeable clipping in the picture.

Figure 5a: Clipping Test Passing

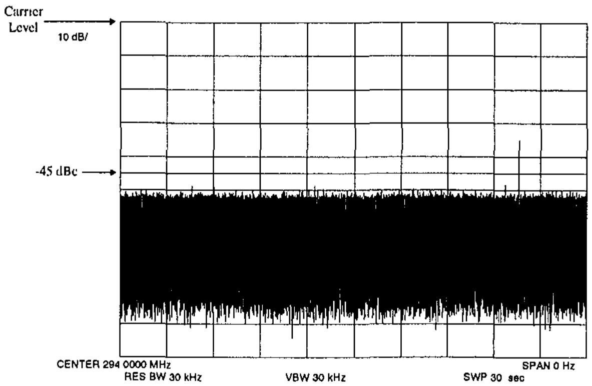


Figure 5b: Clipping Test Failing

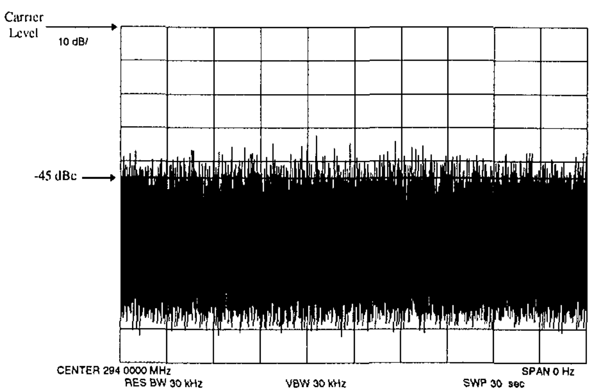


Table 1 gives the results of a number of different tests of forward lasers carrying 77 analog channels from 50 to 550 MHz and 200 MHz of simulated digital loading (including one channel of 64-QAM) from 550 to 750 MHz. These show the effects of different operating levels and of relative levels of digital to analog. The column "CSO Clip" gives the result of the time domain test described above. As stated above for DFB's: (a) there are no measured clips at the CTB points and (b) CSO clip numbers larger than -45 dBc are reliable indicators of observable video clipping. Interestingly, for the digital signals, if we define (somewhat arbitrarily) the acceptable level of uncorrected BER's as being $<10^{-9}$, then clipping appears to become unacceptable for the digital at essentially the same laser operating point as for the analog. (That statement applies only if the digital levels are set within 0 to 10 dB below the analog.) Since the 10^{-9} criterion is likely to be very conservative for error-corrected forward signals, it appears that digital signals in the forward path will generally not be limited by clipping.

TABLE 1: Directly Modulated DFB

Drive Level	Subjective Clipping Ch 36 (Mid Freq.)	Subjective Clipping Ch 77 (High Freq.)	BER	Mid Frequency CSO Clip	Mid Frequency CSO	Mid Frequency CTB	Mid Frequency C/N	High Frequency CSO Clip	High Frequency CSO	High Frequency CTB	High Frequency C/N
CW Loading; Noise & Digital 10 dB down:											
Nom	Very Visible	Very Visible	1.60E-06	-36	78	65.3	52.0	-34.5	62.5	64.9	53.2
-2	None	None	3.00E-10	-49.8	79	72.4	50.0	-46.2	65.5	71.1	51.1
CW Loading; Noise & Digital 5 dB down:											
Nom	Visible	Visible	1.30E-08	-39.6	78	66.5	51.3	-34.5	62.9	66.2	51.8
-1	Barely Visible	Barely Visible	>4E-10	-45.6				-42.7			
-2	None	None	>4E-10	-50.4	78.5	73.7	49.6	-51.5	66.1	72.1	50.2

Note: Drive Level is referenced to the "nominal" setting. Nominal refers to the level which is automatically chosen by the transmitter's AGC circuit to match the factory calibrated operation point.

TABLE 2: External Modulation

Drive Level	Subjective Clipping Ch 36 (Mid Freq.)	Subjective Clipping Ch 77 (High Freq.)	BER	Mid Frequency	Mid Frequency CSO	Mid Frequency CTB	Mid Frequency C/N	High Frequency CTB Clip	High Frequency CSO	High Frequency CTB	High Frequency C/N
Nom	None	None	1 E-09		-67.7	-64.8	49.9	-45.5	-66	-64.8	48.4
+1	None	Some CTB	3 E-09		-68.2	-62.7	50.2	-40.5	-66.4	-63.1	48.8
+2								-37		-62	

Notice that the laser input level that gives acceptable analog clipping performance is approximately 2 dB less than the level that gives a CTB of 65 and a CSO of 62. We have found that this is generally the case.

As a further test, the fiber link was connected to the peak-to-RMS ratio measurement system described in Appendix 1. This system allows a measurement of the peak-to-RMS ratio of the device being tested. The maximum ratio observable is about 15 dB. At nominal levels, the laser's ratio was about 14 dB. When the drive level was increased by 1 and 2 dB, the ratio decreased to 13 and 12 dB, respectively. The histogram clearly showed that only one side of the waveform was clipping. This is expected with a directly modulated DFB. The ratio of the other side of the waveform remained at 14 dB.

Externally-modulated transmitters

Limited tests of a 1550 nm ex-mod transmitter (Table 2) confirm our expectation that clipping is less of a concern in these units. Note that the clips occur at the triple-beat frequency, as expected. Essentially all three drive conditions give tenth-clip-event heights greater than -45 dBc, but the pictures did not appear to have objectionable clipping. As the modulation depth is increased, CTB becomes noticeable in the picture before any clipping impairment is observed. Thus some other test or criterion would have to be established to quantitatively judge clipping performance in ex-mod transmitters, if this were deemed worthwhile.

RF amplifiers

We have confirmed the expectation that clipping degradation is highly unlikely for conventional push-pull and power-doubled hybrid amplifiers in a wide range of normal operating points. The test setup is described in Appendix 1. The multiple carrier generator was inserted into a 750 MHz power doubled amplifier. The output voltages can be predicted as follows:

For an output level of +44 dBmV per channel for 110 channels into 75 ohms, the RMS value will be:

$$RMS_{110} = 10^{\left(\frac{44}{20}\right)} * \sqrt{110} / 1000 = 1.66 \ volts$$

and assuming a peak-to-RMS ratio of 14.8 dB, the peak value will be:

$$PEAK_{110} = 10^{\left(\frac{14.8}{20}\right)} * 1.66 = 9.1 \ volts.$$

The peak-to-RMS ratio remained constant at 14 to 15 dB until levels were increased to more than +52 dBmV per channel at the amplifier's output. The CTB was an unacceptable -55 dBc at +51 dBmV output. At +55 dBmV the peak-to-RMS ratio decreased to about 12.5 dB. The calculated peak voltage at this level exceeds the 24 volt supply, so it is no surprise that the peaks are clipping. The conclusion is that the amplifier does not clip until the CTB is intolerably bad.

As a further confirmation, a 12 volt amplifier was tested at +44 dBmV output per channel for 110 channels. The peak-to-RMS ratio was 14.9 dB, which is taken to signify that there was no clipping of the output.

RETURN PATH TESTING

QPSK digital

The effect of clipping on an HFC communications network is not limited to the forward path. Both the amplifiers and lasers in the return path can adversely affect the performance of digital signals if they are being operated too far into clipping. To investigate this phenomena, various components were loaded with a signal consisting of a real QPSK signal and filtered noise, all at a constant-power-per-Hz loading, to yield a total bandwidth of 35 MHz. In order to measure the amount of Composite Intermodulation Noise (CIN), there was a 50 dB notch in the middle of the noise. The depth of this notch directly correlates to the CNR of the link for any system that is loaded on a constant-power-per-Hz basis[1]. The CNR was compared to the average Bit Error Rate (BER) for various drive conditions. A typical result is shown in Table 3. Note that throughout this paper BER's are measured with no error correction.

Table 3: QPSK at Various OMI

dB Relative to 35 %	RMS OMI (%)	Peak OMI (%)	CNR (dB)	BER
---	35	124	44	$< 1*10^{-9}$
3	49	174	36	$< 1*10^{-9}$
6	70	248	27	$< 1*10^{-9}$
9	99	351	19	$< 1*10^{-9}$
10	111	394	---	$2*10^{-2}$

The RMS-to-peak ratios for various types of modulation and for noise are given in Appendix 2. The Peak OMI in Table 3 is calculated with an assumed average ratio of 11 dB. Note that the laser is always very far into clipping. However, the

BER does not get bad until the CNR degrades. Essentially, the limiting factor here is distortion, not clipping. The table demonstrates that a measurement of CNR should be sufficient for predicting BER, with no special consideration needed for clipping.

A common problem with the return path is the existence of large interferers (ingress). To determine how much interference can be tolerated, a CW interferer was injected into the laser along with the QPSK and noise payload discussed previously. The result is that, once again, the CNR is a good representation of the achievable BER. As the CW level was increased, the CNR would go down (due to an increase in CIN), and eventually, so would the BER. However, if the interferer was injected at a much higher frequency (such as 100 MHz) where the spectrum of the beats with this carrier did not fall on top of the QPSK signal, the CNR did not degrade and neither did the BER. This was true even with the CW at an OMI of 350%. This clearly indicates that clipping is not directly a threat.

n-QAM digital

The QPSK tests described above were repeated for 16-QAM and 64-QAM in an effort to determine the effect of clipping on amplitude-dependent signals. The data in Table 4 shows only slight differences between the drive-level dependence of the QPSK and 16-QAM data streams, which may be attributable to measurement error. The 64-QAM is somewhat more sensitive, due to its higher carrier to noise requirement. However, for a given BER, the higher order QAM modulation formats require a higher CNR as the laser is driven into clipping. This is most likely due to the amplitude component in n-QAM which does not exist in QPSK.

Table 4: Required CNR to obtain 10^{-6} BER

	QPSK	16-QAM	64-QAM
Direct	23	24	28
Laser Overdrive	19	23-28	35-39
Amplifier Overdrive	21	25	40

The data given in Table 4 has a several dB margin of error because the actual modulation signal was at 44 MHz, whereas the CNR was measured at 22 MHz. Nevertheless, some trends are evident. The term "overdrive" refers to a signal which is higher in amplitude than the recommended operating level of the device. The drive levels were increased until the BER degraded to 10^{-6}. Both QPSK and 16-QAM are relatively unaffected by either the laser or the amplifier overdrive. The 64-QAM, however, requires an increased CNR for equivalent performance when passed through a device that is being overdriven. This can be explained by the peak-to-RMS data given in Appendix 2. At a BER of 10^{-6}, the laser is 3 dB above nominal and the hybrid is at +67 dBmV total power out. Table A2 demonstrates than at these levels, the peak-to-RMS ratio is being compressed. This compression is likely to cause errors in the amplitude component of the 64-QAM signal. Similarly, 64-QAM is not as immune as QPSK to large out-of-band CW interference (such as the 100 MHz CW carrier at 350% OMI mentioned in the previous paragraph).

Amplifiers

The ability of return path amplifiers to handle large amounts of high level data was tested. The tests conducted were very similar to those described above for return path lasers. Table 4 indicates that 64-QAM signals are sensitive to overdrive conditions. As previously mentioned, this can be explained by referring to Table A2. Note that as the amplifier's output level is increased above 65 dBmV total power, the peak-to-RMS ratio decreases. Regardless of whether this is due to compression or clipping, the result is that some of the amplitude information gets compressed.

In order to determine how high the output levels should be in return path amplifiers, the output level was compared to CNR and BER. Table 5 shows performance for a 25 dB gain hybrid return path amplifier when subjected to overload.

Table 5: BER and CNR vs Output Level for Return Path Hybrid

Total Output Power (dBmV)	CNR	QPSK BER	16-QAM BER	64-QAM BER
45	>50	$< 10^{-9}$	$< 10^{-9}$	$< 10^{-9}$
65	48	$< 10^{-9}$	$< 10^{-9}$	$< 10^{-9}$
68	39	$< 10^{-9}$	$< 10^{-9}$	$2*10^{-6}$
73	24	$< 10^{-9}$	$1*10^{-6}$	
75	21	$1*10^{-2}$		

A fully loaded return path will have a total energy of approximately 60 dBmV at the output of an amplifier. Table 5 demonstrates that at levels of approximately +65 dBmV, the amplifier is getting close to affecting BER's of higher order modulations. Since CIN is dominated by third order distortion which cascades on a 20*log factor, one must be careful not to use amplifiers with inadequate distortion performance

CONCLUSIONS

We have determined that the upper drive level limit for forward analog DFB transmitters is determined by clipping, rather than by the conventional distortions. We have defined a simple quantitative test that correlates well with subjective evaluations and we are proposing that it be considered for general use by the industry. Within practical limits, it is likely that digital signals carried along with analog will not be limited by clipping (that is, not before the analog signals themselves will be impaired by clipping). We have found that clipping does not appear to be a performance-limiting problem in externally-modulated transmitters or in forward RF amplifiers.

In the return path, signal levels into Fabry-Perot lasers are limited mainly by CIN and not by clipping. The upper limit for DFB lasers is no higher than that of FP's. The limits for 16-QAM digital signals do not appear to be any tighter than those for QPSK. 64-QAM signals, however, appear to be somewhat clipping sensitive.

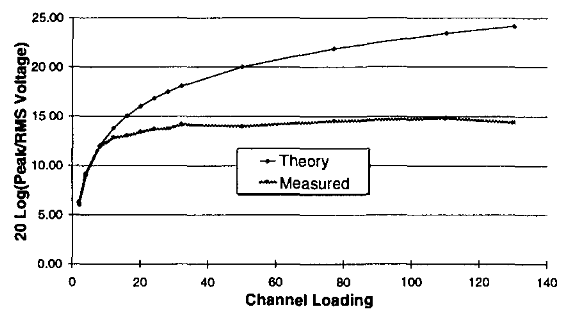
APPENDICES

Appendix 1: RMS vs peak

A test method was devised which would allow a measurement of the peak-to-RMS ratio of muticarrier signals. Our evaluations consisted of a multiple carrier generator which produced up to 130 independent CW carriers and a high speed (35 GHz) sampling oscilloscope. First, a baseline was established by measuring the output of the carrier generator directly. The output of the generator was connected to the scope and the level was adjusted to maximize the dynamic range of the scope. The scope was set to free run at a rate of 500 kHz and the timebase was 100 ps/div. Several million samples were allowed to accumulate in the infinite persistence mode (about 20 minutes). Since the scope was free running at a very high acquisition rate, the distribution of dots which accumulated on the display represented the distribution of voltages present in the composite signal. A histogram was then obtained from the scope and relevant points were recorded. This was done for many different channel loadings from 2 to 130 channels. In each case, the value of the highest and lowest points were recorded as well as the values for the mean, and one, two, and three standard deviations. The ratio of the peak value to the RMS value was calculated in each case. The results are compared to the theoretical values in Figure 6.

Figure 6

dB Ratio of Peak/RMS Voltages vs Channel Loading



Note that the theory predicts a continuous increase in peak-to-RMS ratio as the number of channels grows. However, the test results indicate that the ratio levels out between 14 and 15 dB. We believe that the reason the peak-to-RMS ratio does not continue to increase as predicted has to do with noise in the system. In particular, the phase noise and frequency stability of the CW generator are likely fluctuating enough to prevent any more precise coherent adding of the carrier phases.

Appendix 2: Peak-to-RMS ratios for various signals

The following table summarizes the peak-to-RMS ratio for some common signals. The measurement method was described in the previous appendix.

Table A2: Measured Peak-to-RMS Ratios

Type of Signal	Peak-to-RMS Ratio (dB)
CW signal	3.2
Unfiltered Noise (5-1000 MHz)	7.8
Filtered Noise (5-40 MHz)	13.5
Modem Brand "A"	
QPSK @ 10 MB/sec	9.2
16-QAM @ 20 MB/sec	11.3
64-QAM @ 30 MB/sec	10.2
Modem Brand "B"	
QPSK @ 256 kB/sec	6.7
QPSK @ 2 MB/sec	6.6
Laser with Filtered Noise Loading	
35% RMS OMI	13.8
62% RMS OMI	9.2
78% RMS OMI	7.8
Hybrid with Filtered Noise Loading	
+45 dBmV total RMS Power	13.5
+65 dBmV total RMS Power	12.4
+70 dBmV total RMS Power	9.6
Hybrid with CW Loading	
+45 dBmV RMS Power	3.2
+65 dBmV RMS Power	3.2
+70 dBmV RMS Power	3.2
+75 dBmV RMS Power	3.0

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[1] D. Stoneback and W. Beck "Designing the Return System for Full Digital Services". SCTE Conference on Emerging Technologies, San Francisco, CA, January 1996.