SWITCHING TO OVERDRIVE ON THE INFORMATION SUPER-HIGHWAY

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Abstract

The authors presented analysis and processing results of the vast data collected during characterization of the broadband optical links used for expanding broadband bandwidth to 1 GHz and for supporting full digital load.

Three different types of load for optical links were analyzed:

1. *A combination of the CW load with test QAM channels,*
2. *A combination of the NTSC modulated analog channel load with test QAM channels, and*
3. *Full digital load of QAM channels.*

The results indicate that the dominant types of distortion to digital 256-QAM signals are nonlinear products generated in optical links. These distortions affect the digital signals before laser clipping occurs. Alignment of the optical laser transmitters is critical to realize full capacity of the optical links up to 1 GHz. Similarly, the parameters of the QAM signal FEC, and especially the interleaver settings, are important to achieve this goal. The paper presents the conclusions and lists some pointers to apply in laser transmitter alignment.

INTRODUCTION

Drive for Bandwidth

The Cable TV industry is continuously striving to increase the maximum rate of data and video throughput capability of their networks. These efforts focus on absolute bandwidth expansion and/or on expansion of bandwidth per customer. In the first category are such efforts as:

1. Moving system capacity towards 1 GHz FDM limit with a combination of traditional analog video and digital QAM channels, and
2. Using spectrum above the existing nominal design limits of the broadband subsystem.

In the second category are efforts to:

1. Segment nodes into smaller serving areas,
2. Replace analog channels with digital channels (also known as analog bandwidth reclamation),
3. Increase QAM modulation levels for digital signals,
4. Increase coding capacity for digital video signals (introduction more efficient encoding and digital compression algorithms),
5. Reclaim digital bandwidth with switched digital architecture,
6. Increase stat-muxing efficiency of digital video signals.

Critical Link

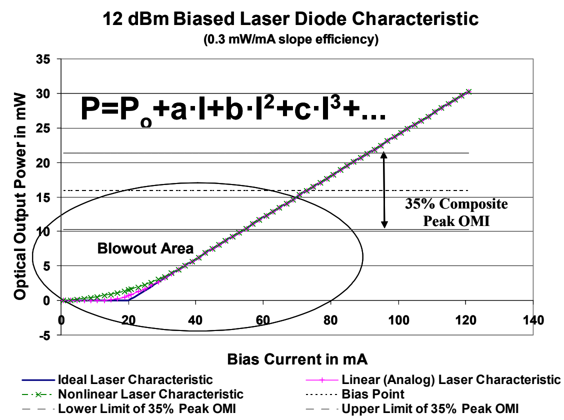
The optical links between headends/hubs and nodes are a critical part of these efforts. Their quality determines the absolute usable bandwidth and the levels of modulation for the QAM signals (bit/symbol capacity). Therefore, these links were tested and the test results were analyzed to determine their capability to deliver increased bandwidth to broadband customers.

Clipping or Nonlinear Distortions

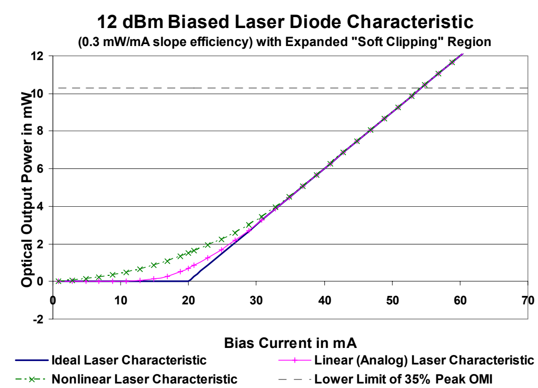
There have been several misunderstandings about what is causing impairments to digital signals of higher modulation orders (256 QAM and higher). Several publications [1, 2, 3] presented in-depth analysis on this issue in the past. Notwithstanding those findings, the popular believe persists that it is clipping that causes all the problems with QAM signals.

We tested this theory against the theory that clipping is not the main contributor to the problem of digital signal impairments and that different distortions affect the digital signals before clipping really contributes to BER.

Figure 1 represents the most likely explanation of the problem. The analog lasers are selected for their transfer function linearity and they are further linearized to achieve high level of performance required for analog links. However, for very practical reason, those linearization efforts are limited to an operational range of analog links. For 1310 DFB lasers, this practical limit is around 35% of peak OMI values. Beyond this range, linearization is not practical. Henceforth, the linearization efforts stop there. Even within these limits, the linearization techniques allow for higher digital modulation levels if they are applied with understanding of the problem. The test results allow for clear problem definitions and for focusing the linearization efforts on optimization of the optical links for all the signals (analog video and digital QAM) transmitted over analog optical links as opposed to the efforts of achieving the best results within the bandwidth occupied by analog signals. This assertion has been tested during the data gathering process and confirmed in several ways.



a) Laser Diode Characteristic



b) Blowout of the Threshold Area

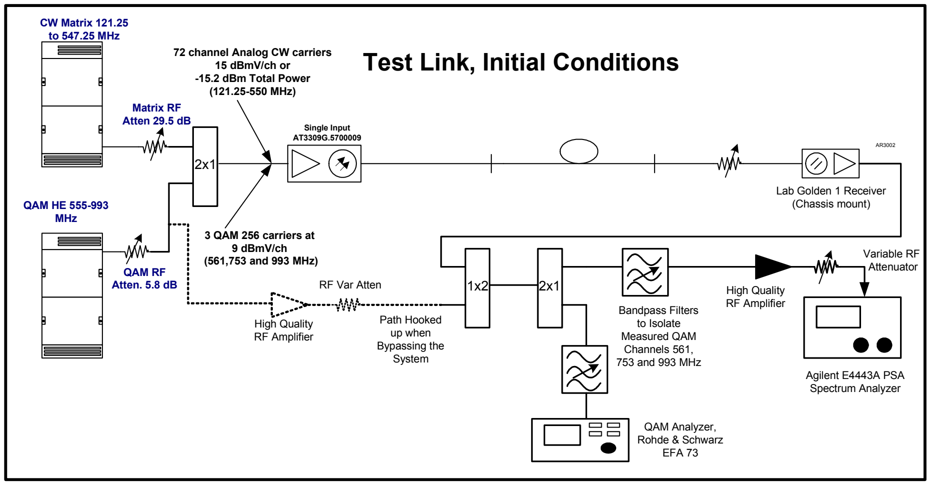
Figure 1. Laser Diode Characteristics – Linear Area for Analog Lasers

TESTING METHODOLOGY AND TEST PROGRAM

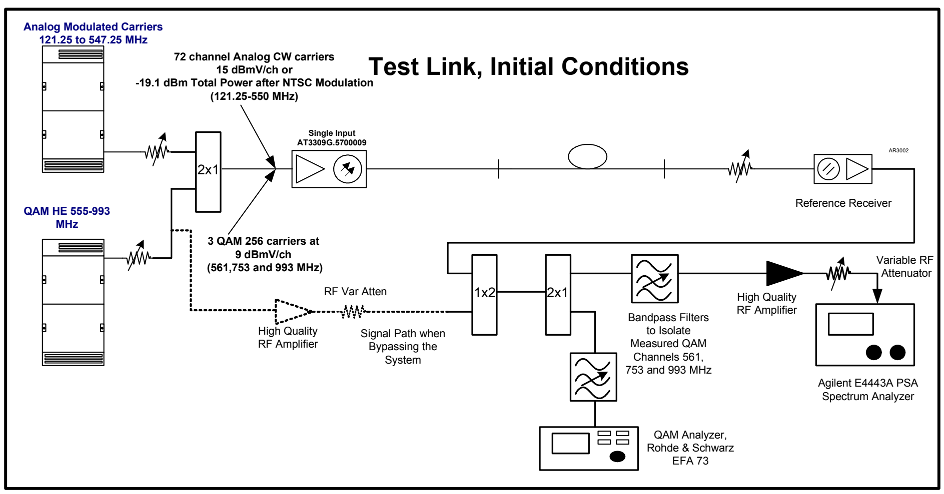
Test Setup

Three different types of load for optical links were analyzed:

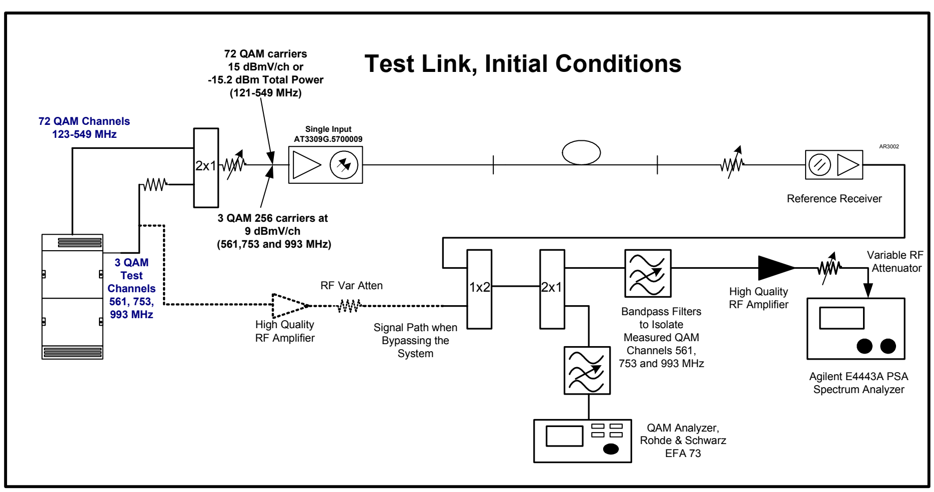
1. 72 CW carriers between 120 and 552 MHz,
2. 72 NTSC modulated analog channels between 120 and 552 MHz, and
3. 72 digital QAM channels between 120 and 552.



a) CW Load with QAM Test Channels



b) Analog Modulated Load with QAM Test Channels



c) QAM Load with QAM Test Channels

Figure 2. Test Set Up

The channels between 54 and 88 MHz were not included in the testing for the following reasons:

- To eliminate nonlinear distortions at non-standard frequencies;
- To account for a trend in NGNA frequency subsplit evolution towards 85/105 MHz;
- For ease of alignment of NTSC and QAM upconverters.

Three 256 QAM test signals at 561 MHz, 753 MHz and 993 MHz were used throughout the testing to measure digital transmission performance. The test QAM signals were compliant with ITU Recommendation J.83 Annex C or Annex B. The BER for these signals were tested in pre-FEC mode and in post-FEC mode. Annex C (implemented for example in Japan) signals were used to test pre-FEC BER. These signals allow for real pre-FEC BER testing while signals compliant with Annex B (implemented for example in the USA and Canada) have embedded Trellis coding in their constellation mapping and hence there is no access to errors before Trellis coding. However, signals compliant with Annex B allow for setting interleavers with different parameters (see Table 1). Therefore, these signals were used to test interleaver effectiveness in correcting bit errors. The test signals were:

- 6 dB lower in level relative to CW carrier level for CW load,
- 6 dB lower in level relative to peak levels of the analog channels with NTSC analog video load, and
- 6 dB lower in level relative to the QAM channel levels for the QAM load.

Litmus Test for Clipping

To test the hypothesis that the laser clipping is not a dominant source of impairments to 256 QAM signals, a simple test was conducted: performance of the three test QAM channels was tested in two configurations, once while passing through the optical link with all other signals and second time after combining with the signals that were passed through the link after the optical receiver. If the clipping were the source of impairments, the BER in these two different configurations should be drastically different as the test QAM signals combined with the signals after the receiver (the second test) would not be subject to clipping.

To further test the clipping hypothesis, only the test QAM signal levels at the laser transmitter input were increased in 3 dB incremental steps and the BER performance was noted for all three levels. If clipping were the major contributor, the BER should not improve.

Cause of QAM Signal Impairments

An alternative hypothesis was tested based on the collected measurement results: that the QAM signal impairments were caused by the nonlinear distortions (second, third and higher orders).

Character of Impairment and Their Effect on QAM Signals

Three different types of load also allowed testing how the character of the nonlinear distortions affects QAM signals. The knowledge about the differences in the effect of distortions caused by different loads could allow for optimization of the links (laser transmitters) and the settings of the QAM signals.

Interleaver Efficiency against Different Impairments

Finally, the capability of adjusting interleaver settings for Annex B compliant QAM signals allowed testing the interleaver setting effectiveness in correcting errors caused by distortions of various characters.

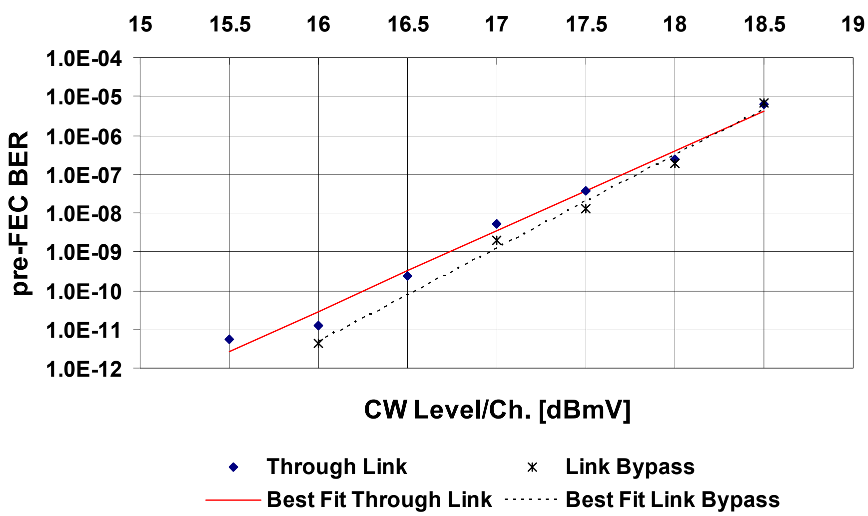
CLIPPING OR OTHER PROBLEMS

QAM Signal Quality: Passed through Optical Link and Bypassing Optical Link

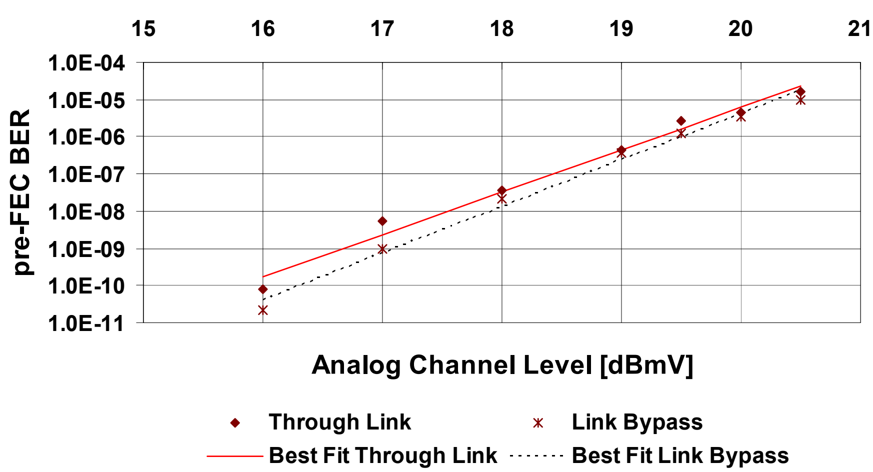
To determine whether clipping of the laser transmitter is a major source of QAM signal impairments, the performance of the test QAM signals was tested:

- when the test signals were transmitted on the same link as the load signals, and
- when the test signals were combined with the load signals after the optical receiver (only load signals were transmitted through the optical link).

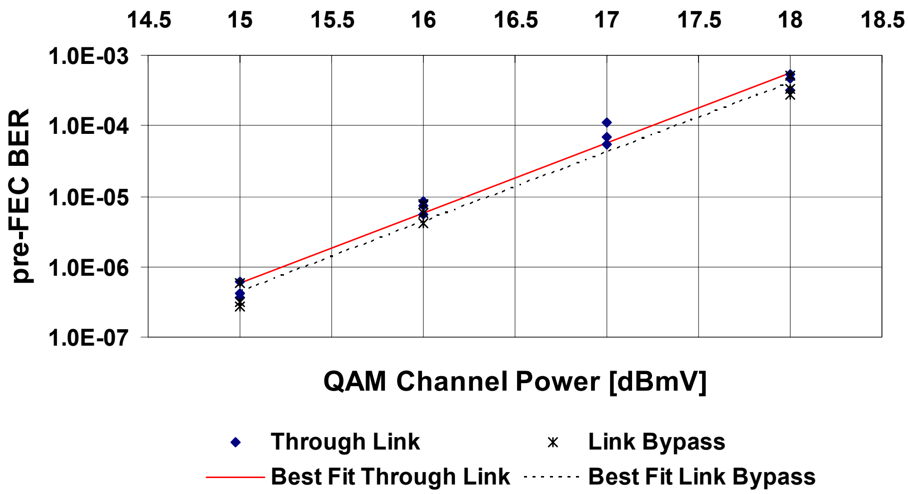
The results of this simple test for all three types of load are presented in Figure 3.



a) Test Signal BER vs. CW Signal Levels into the Transmitter



b) Test Signal BER vs. Analog Video Carrier Levels into the Transmitter



c) Test Signal BER vs. QAM Carrier Levels into the Transmitter

Figure 3. Performance of Test QAM Signals

The test results show that the performance of the test QAM signals are practically the same when they are passed through the transmitter and when they are combined after the optical receiver with the signals transmitted through the optical link and with all distortions generated by the load in the optical link. The logical conclusion from this test is that the distortions are the major contributor to the QAM signal impairments. At low levels of distortions (low input levels for CW and NTSC analog video carriers into the transmitter), some other impairments in the optical link may contribute to the slightly worse performance of the test QAM signals transmitted through the link but when distortions become dominant, the test QAM signal performance is the same in both test arrangements. This is opposite to the situation that would be caused by clipping (if clipping were dominant, the difference in performance of the test QAM signals in two different arrangements would increase with the increase of the transmitter load levels).

To re-confirm this hypothesis, an additional test was performed: at the high levels of load with CW carriers, the levels of the test QAM signals (compliant with Annex B) were increased in 3 dB steps (from 6 dB lower than CW carriers to the same power levels as the CW carriers) and the performance of the test QAM signals was recorded.

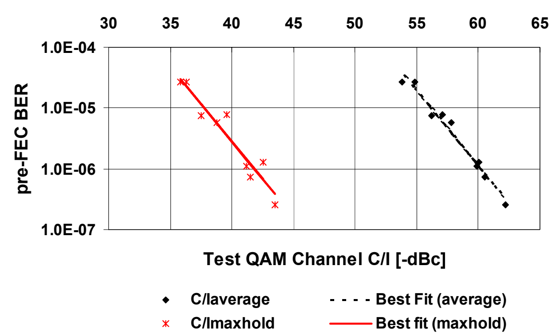


Figure 4. BER Improvements with Increase in Test QAM Signal Levels

The results were plotted versus C/I for QAM signals. Figure 4 shows BER performance as a function of C/I where "I" is a sum of power levels of all distortions within the channel. Two different sums were used to express I:

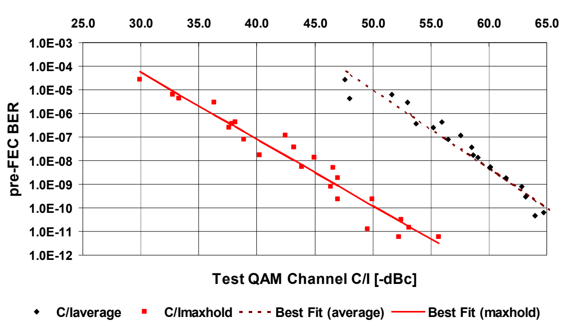
1. average RMS power of all distortions (measured as specified by NCTA Recommended Practices on Cable Television Systems, Third Edition),
2. 1-minute max-hold power with 1 kHz VBW setting of all distortions.

The second setting was used as a proxy of the peak value of the distortions throughout the entire testing process.

The performance of the test QAM channels improved linearly as their levels were increased (and the C/I was increased).

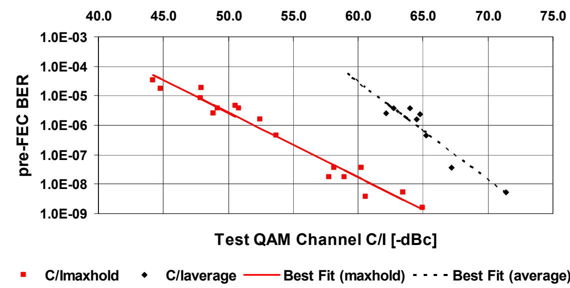
<u>Carrier-To-Interference: Main Contributor to BER Degradation</u>

The test results presented above clearly indicated that clipping was not a dominant source of QAM signal impairments at the transmitter driving levels tested. However, the BER performance of the QAM signals was strongly related to the levels of distortions. The next three figures present this strong log-log dependence with very high probability that this dependence is linear (on the log-log scale).



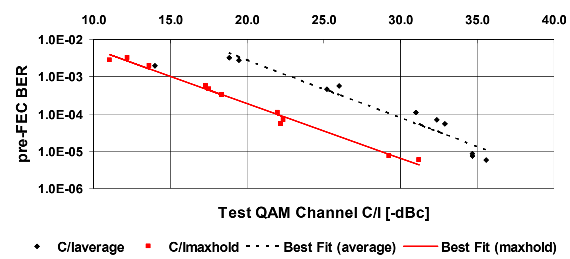
Regression Statistics for CW Load		
Parameter	Best Fit Average	Best Fit Maxhold
Multiple R	0.97164498	0.97175989
R Square	0.94409396	0.94431729
Adjusted R Square	0.94098807	0.94166573
Standard Error	0.43462985	0.49676825
Observations	20	23

Figure 5. BER versus C/I for CW Load (with Regression Analysis Statistics)



Regression Statistics for NTSC Modulated Load		
Parameter	Best Fit Average	Best Fit Maxhold
Multiple R	0.97822689	0.96476750
R Square	0.95692785	0.93077633
Adjusted R Square	0.95405637	0.92448327
Standard Error	0.31362594	0.29806038
Observations	17	13

Figure 6. BER versus C/I for NTSC Analog Video Load (with Regression Analysis Statistics)



Regression Statistics for QAM Load		
Parameter	Best Fit Average	Best Fit Maxhold
Multiple R	0.97243812	0.99324842
R Square	0.94563589	0.98654243
Adjusted R Square	0.93959544	0.98504714
Standard Error	0.25499442	0.11693500
Observations	11	11

Figure 7. BER versus C/I for QAM Load (with Regression Analysis Statistics)

As previously described, "I" represents sum of average power levels or max-hold levels of all distortions within the test channels for CW and NTSC analog video loads. For QAM load, "I" represents integrated power of noise and noise-like intermodulation products within 6 MHz test channel.

The plots for CW and NTSC load show that BER vs. $C/I_{average}$ line is steeper than the line for BER vs. $C/I_{maxhold}$. This can be explained by the fact that the max-hold values increase faster at higher load levels (see Figure 8). For QAM loading, the difference between average and max-hold level of distortions is approximately constant.

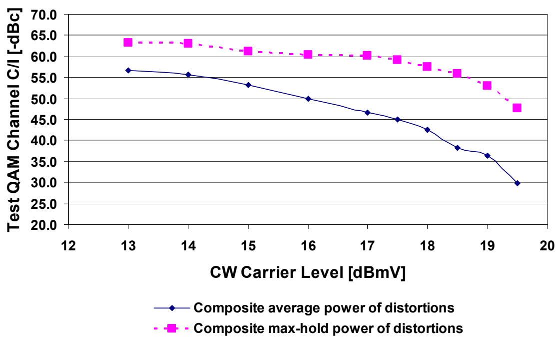
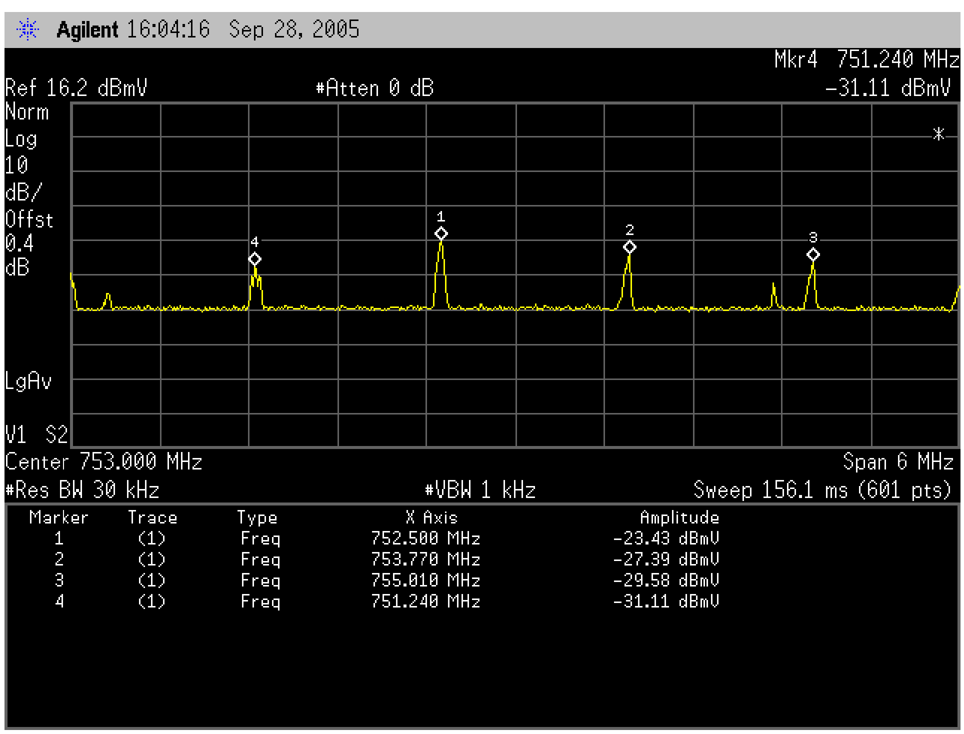


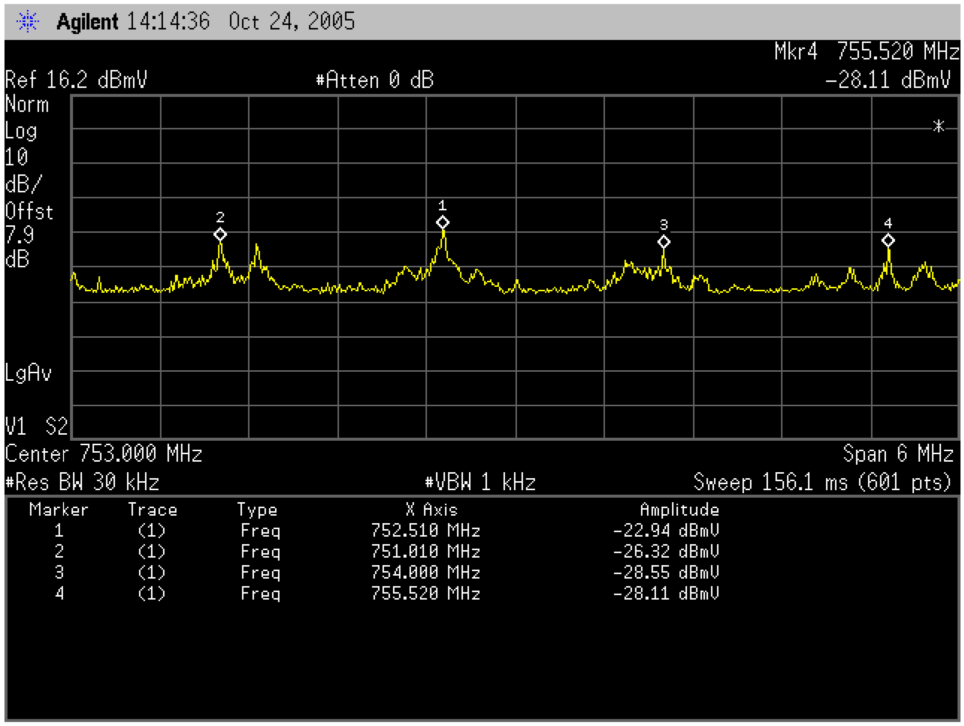
Figure 8. C/I versus Carrier Level for CW Load

Character of Impairments and Their Effect on QAM Signals

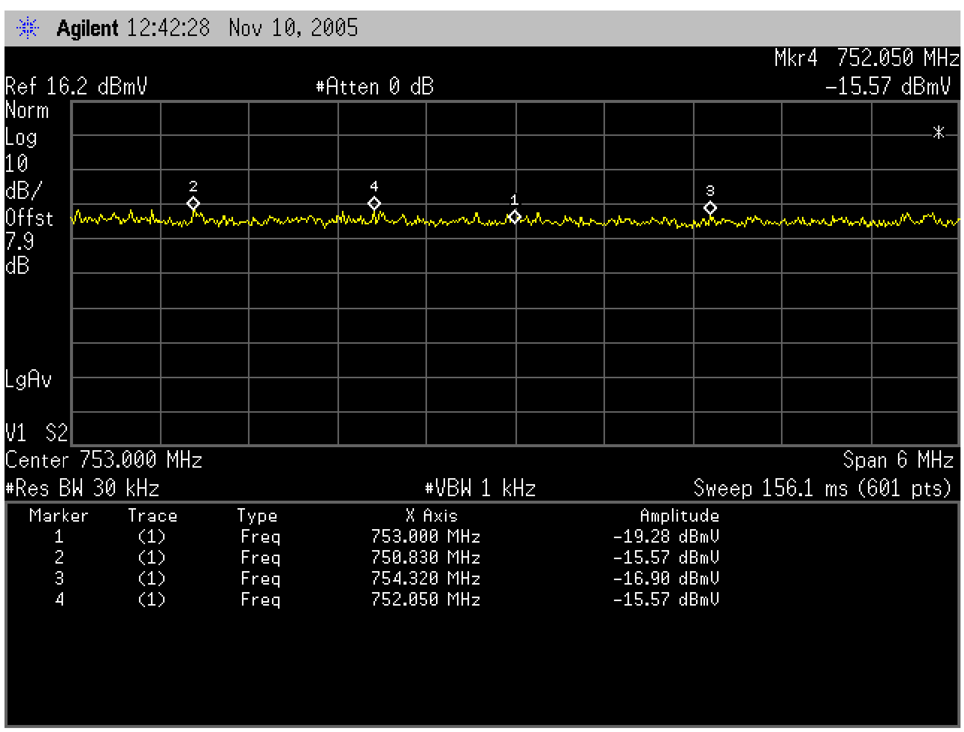
A comparison of plots in Figures 5 through 7 shows that BER values are different for the same C/I when "I" is caused by different loads. Obviously, the distortion characteristics are drastically different for distortion caused by CW load from those caused NTSC analog video carriers and those caused by QAM load. Figure 9 depicts screen shot examples of distortions for three different loads. Distortions generated by CW load are narrowband in nature (usually the power is concentrated within 30 kHz or narrower bandwidth), whereas distortions caused by NTSC analog video carriers are spread due to modulation sidebands and aeronautical frequency offsets and occupy up to several hundred kHz. Distortions caused by QAM load are wideband in nature and occupy entire bandwidth (noise-like character). The distortions caused by QAM signals are the result of the same nonlinearities of the optical link that causes nonlinear distortions if the loads are CW or NTSC analog carriers. The nonlinearity is clearly noticeable as their level rises with the input level rise into the transmitter and this rise accelerates at higher levels (higher order nonlinearities contribute to the distortion levels).



a) Distortions Caused by CW Load



b) Distortions Caused by NTSC Analog Video Load



c) Distortions Caused by QAM Load

Figure 9. Different Distortion Characters for Different Load

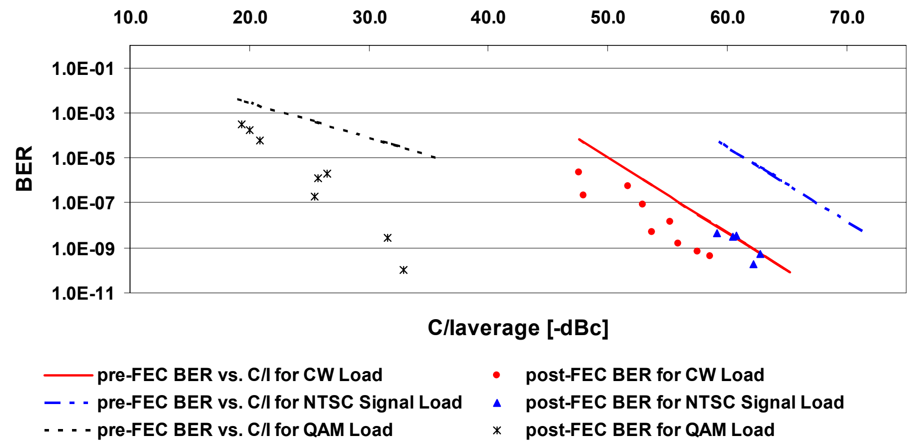


Figure 10. BER vs. C/I for Different Distortions

Figure 10 compares pre-FEC BER of QAM channels compliant with Annex C vs. C/I plots for all three types of load. It is apparent that the QAM signals are more sensitive to distortions generated by NTSC modulated video carriers than to distortions generated by CW carriers. This finding has been confirmed in the past [2]. The test results also show that QAM signals are least sensitive to the noise-like distortions caused by QAM load. This is also understood in light of commonly known and documented BER vs. SNR (or CNR) characteristics.

Figure 10 also presents post-FEC BER measured vs. C/I for Annex C signals. The test results clearly indicate different FEC effectiveness in correcting errors caused by distortions generated in optical links by different loads. This finding is investigated below.

Interleaver Effectiveness

Figure 11 presents FEC effectiveness in correcting errors for Annex C QAM signals (see Table 1). For distortions caused by QAM load, the interleaver setting in Annex C (I=12, J=7) allows FEC to correct pre-FEC errors occurring at a rate of 1.0E-5 and improve BER to levels below 1.0E-12. It is significantly less effective in correcting errors caused by distortions generated by NTSC load. Pre-FEC errors occurring at a rate of 1.0E-5 are corrected to BER levels below 1.0E-9. The effectiveness in correcting errors caused by CW load is very low for this interleaver setting (from 1.0E-5 pre-FEC BER to just below 1.0E-6 post-FEC BER)

Why such a big difference. Let us first analyze the distortion characteristics.

1. The distortions caused by CW carriers are the narrowest in bandwidth. The correlation times for a process are inversely proportionate to the process bandwidth. For 30 kHz CTB, the correlation time is 33 µs. This means that once the interference reached the peak values, they do not change appreciably over the time equal to the correlation time.
2. The distortions caused by modulated carriers (some of them with 12.5 kHz offset) are of much wider bandwidth. Hence, they have lower correlation times and the peak burst, if happens, is shorter in duration.
3. The intermodulation noise generated by QAM load is practically uncorrelated and hence it is not bursty in nature.

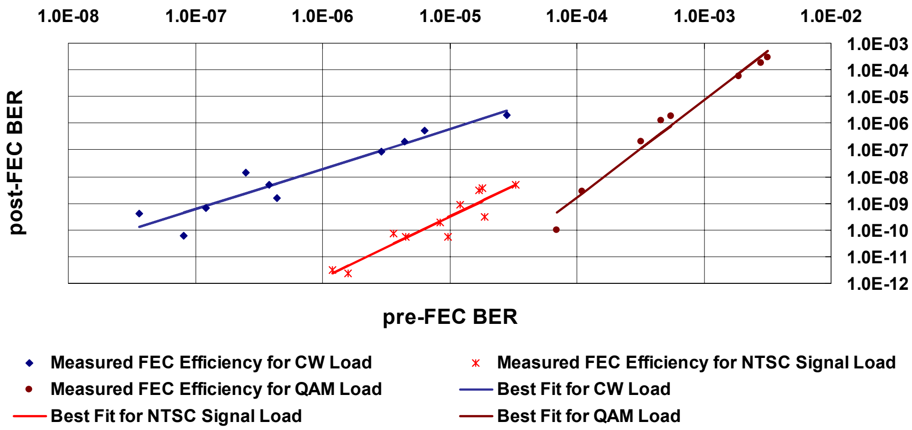
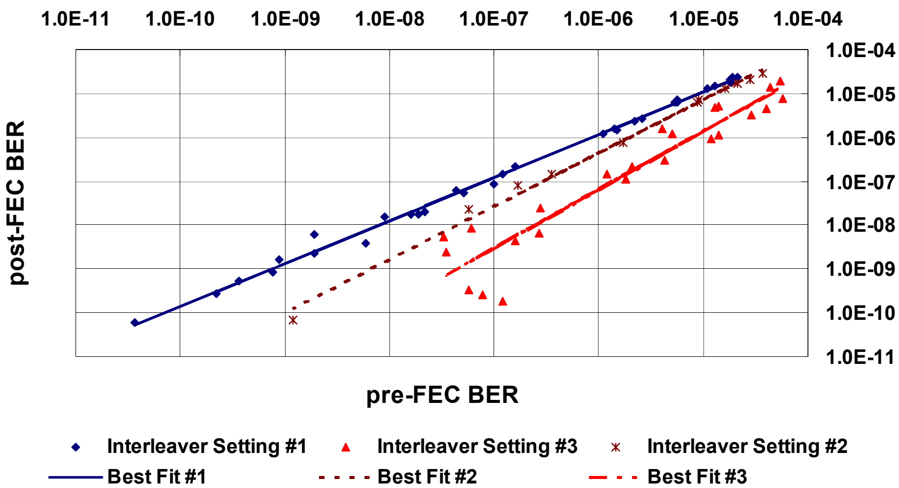
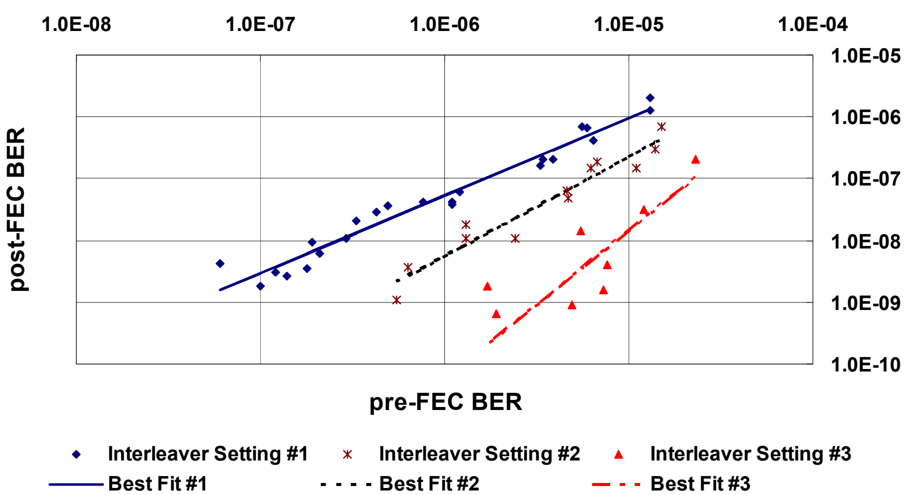


Figure 11. FEC Effectiveness



a) FEC Effectiveness for CW Load Distortions



b) FEC Effectiveness for NTSC Load Distortions

Figure 12. Effectiveness of FEC for Different Interleaver Settings

For more detail explanation of this analysis, please refer to [3].

The conclusion of this analysis is that the depth of the interleaver is quite important in correcting errors caused by nonlinear distortions. To investigate effectiveness of the interleaver in correcting errors, Annex B QAM signals were used as they allow for flexibility in interleaver parameter setting. The following interleaver settings were tested:

1. I-16 and J=8,
2. I-32 and J=4, and
3. I-128 and J=1.

The test results indicated strong dependency of the FEC effectiveness in correcting errors caused by bursty interferences (distortions generated by CW and NTSC loads) on the depth of the interleaver. They also indicate that the FEC with the same interleaver setting is more effective in correcting errors caused by distortions generated by NTSC load (shorter burst duration). This finding bears significantly on the settings of the interleaver parameters for different services (see the latency contributions for different interleaver settings in Table 1). This is a well known finding (see also [4]) but applied here to the errors caused by nonlinear distortion of bursty character.

I (Number of Taps)	J (Increment)	Burst Protection (μs) 64 QAM/ 256 QAM	Latency (ms) 64 QAM/ 256 QAM	Comments
128	4	379/264	16/11	Annex B, for digital video only
128	3	285/198	12/8.4	
128	2	190/132	8/5.6	
128	1	95/66	4/2.8	Annex B
64	2	47/33	2/1.4	
32	4	24/16	0.98/0.68	
16	8	12/8.2	0.48/0.33	
8	16	5.9/4.1	0.22/0.15	
12	7	23/18	0.196/0.147	Annex C
12	7	18/14	0.156/0.116	Annex A

Table 1. Interleaver Parameters

Test results showed that an increase in the interleaver depth improved effectiveness of the FEC in correcting errors caused by nonlinear distortions. The importance of this effectiveness is obvious if we analyzed data from Table 2. To achieve QEF (Quasi Error Free) reception as defined for Annex B in North America, we need to achieve better than 2.6E-11 post-FEC BER.

Symbol Rate/Bit Rate	Average Error-Free Period	Required BER	Comments
5.3605370 Msps/42.885 Mbps (256 QAM Annex B)	2.5 sec	9.33E-8	Commonly Accepted
	1 min	3.89E-10	
	5 minutes	7.77E-11	
	15 minutes	2.59E-11	QEF for Annex B (Quasi Error Free)
	1 hour	6.48E-12	QEF time for Annex A (requires lower BER due to higher symbol rate)

Table 2. BER Requirements for Error-Free Reception

SUMMARY AND CONCLUSIONS

Load

The findings of the extensive testing effort are obvious: QAM signals, and especially 256 QAM signals, are very sensitive to distortions caused by analog load (see also [2]). Fortunately, only at levels exceeding the nominal input levels by 5 dB for NTSC analog video load, the pre-FEC BER approaches 1.0E-5 level for well aligned laser transmitters (see Figure 3). Even for CW load, the nominal input levels would need to be exceeded by 2 dB to approach this level of pre-FEC BER.

The encouraging test results for purely QAM load show that the QAM signals can be 6-7 dB higher than the levels they are set today on hybrid analog/digital optical links to approach 1.0E-5 pre-FEC BER levels and that the FEC is quite effective in correcting errors caused by distortions generated by QAM loads (see Figure 11). It seems that the optical links can be safely aligned 3-4 dB above their normal levels (6 dB below analog carriers) over the entire operational bandwidth for pure-digital load links at very good performance levels. This translates to lower transmitter cost (2 dB lower power for the same RX output) for pure-digital systems.

Alignment

One critically important conclusion for laser transmitter alignment is to concentrate on optimizing levels of nonlinear distortion throughout entire operational bandwidth as opposed on achieving the best performance within the analog load bandwidth.

Interleaver Setting

The crucial finding of the testing was that the specification requesting 1.0E-5 or better performance at all frequencies for 256 QAM Annex C signals is sufficient to achieve QEF transmission. An analysis of Figure 3 and Figure 12 allows for this conclusion. Figure 3 shows that for the level of CW load for which pre-FEC BER reaches 1.0E-5, the pre-FEC BER for NTSC load only slightly exceeds 1.0E-7. Figure 12 shows that for 256 QAM Annex B signals with interleaver setting of I-128 and J=1 and pre-FEC BER caused by NTSC load equal to 1.0E-7, the post-FEC BER is lower than 1.0E-11. This outcome is a result of several factors:

1. Significantly lower distortion levels for NTSC analog video load (10 to 12 dB lower);
2. Drastically improved effectiveness of the FEC in correcting BER caused by distortions generated by NTSC analog video carriers.

Although these improvements are partially offset by higher sensitivity of QAM signals to distortions generated by NTSC load (see Figure 10), the net result is still positive.

However, it is also important to note that the interleaver setting resulting in lower interleaver depth (for example, at I=32 and J=4), this conclusion does not hold true and the post-FEC BER would be higher than 1.0E-10, which may be not acceptable for video reception (see Table 2). Therefore, it is critical to select the interleaver settings that are optimal for the service provided with higher interleaver depth for error-sensitive services that can tolerate high latency and lower interleaver depth for services sensitive to latency. There are some services that may not allow for this optimization. Among these are IP video streaming and video games. For these services, signal placement at frequencies with lower level of interferences may be the only choice (if the operator does not wish to select better quality laser transmitters or higher power laser transmitters modulated at lower OMI).

ACKNOWLEDGEMENTS

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