ACCESS NETWORK TECHNOLOGIES

Testing for Nonlinear Distortion in Cable Networks

Prepared by:

Alberto Campos
Principal Architect, Advanced Technology Group
a.campos@cablelabs.com

Belal Hamzeh
Principal Architect, Access Network Technologies
b.hamzeh@cablelabs.com

Tom Williams
Principle Architect, Access Network Technologies
t.williams@cablelabs.com

October 2013

DISCLAIMER

This document is published by Cable Television Laboratories, Inc. ("CableLabs®") to provide information to the cable industry. CableLabs reserves the right to revise this document for any reason including, but not limited to, changes in laws, regulations, or standards promulgated by various agencies; technological advances; or changes in equipment design, manufacturing techniques or operating procedures described or referred to herein. This document is prepared by CableLabs on behalf of its cable operator members to facilitate the rendering, protection, and quality control of communications services provided to subscribers.

CableLabs makes no representation or warranty, express or implied, with respect to the completeness, accuracy or utility of the document or any information or opinion contained in this document. Any use or reliance on the information or opinion is at the risk of the user, and CableLabs shall not be liable for any damage or injury incurred by any person arising out of the completeness, accuracy or utility of any information or opinion contained in this document.

This document is not to be construed to suggest that any manufacturer modify or change any of its products or procedures, nor does this document represent a commitment by CableLabs or any member to purchase any product whether or not it meets the described characteristics. Nothing contained herein shall be construed to confer any license or right to any intellectual property, whether or not the use of any information herein necessarily utilizes such intellectual property.

This document is not to be construed as an endorsement of any product or company or as the adoption or promulgation of any guidelines, standards, or recommendations.

[1]

[1] Notice: Patent Pending

Table of Contents

List of Figures

ABSTRACT

Nonlinear distortion is a well-known problem in electronics. In Cable networks nonlinear distortion presents a limit on RF output levels, which effectively determines Cable signals' maximum reach, and a maximum number of RF channels that can be transported on a downstream plant. This nonlinear distortion constraint, along with random noise, greatly influences plant design. When the plant is transporting analog carriers, the traditional measures of distortion are composite triple beat (CTB) and composite second order (CSO). As plant has transitioned from carriage of analog to digital carriers, the resulting nonlinear distortion has shifted from beats centered at analog video carrier frequencies into a noise-like signal, called CIN (composite intermodulation plus noise), which is generally indistinguishable from random noise. This paper describes a technique for quantifying the level of nonlinear distortion in a vacant band using a full band downstream signal capture, followed by digital signal processing. Improved distortion and noise analysis leads to improved plant alignment, which can allow DOCSIS 3.1 cable modems to operate with a higher order modulation. A higher order modulation will allow higher data rates within the allowed downstream bandwidth. This analysis method will also allow plant problems to be detected and repaired.

1 INTRODUCTION

There has been much written about distortion measurements in the past. Generally one model that has been used is a Taylor series expansion over a range of operation. This is illustrated in Figure 1.

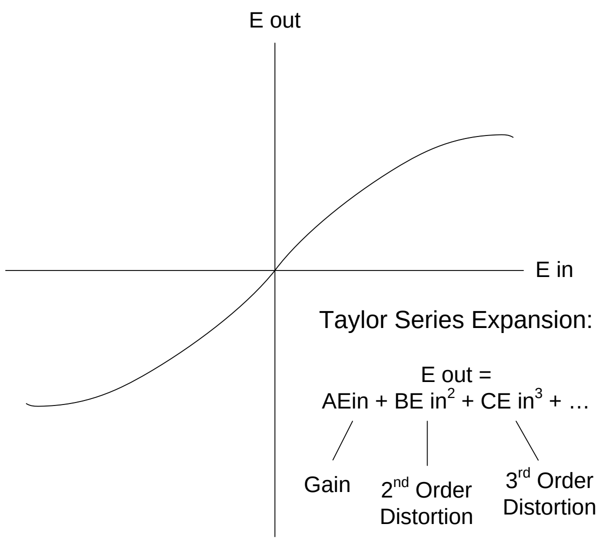

Figure 1 - Taylor Series Expansion Describes Output Voltage vs. Input Voltage

A Taylor series expansion is given by equation:

$$f(x) = Ax + Bx^2 + Cx^3 + \cdots \qquad (1)$$

Where x is a time-varying input signal, f() is a nonlinear operator, such as an overdriven amplifier (or a cascade of overdriven amplifiers). The A term is linear gain, B is a second-order distortion, and C is third order distortion. Even higher terms, such as D, E, and F may also be significant.

$$f(x) + f(y) = f(x + y) \quad (2)$$

Equation (2) describes a required condition for linearity. Equation (2) will only be valid when:

$$B = C = 0 \qquad (3)$$

One notable differentiator between linear distortion and nonlinear distortion is that linear distortion cannot create distortion energy at new frequencies, but nonlinear distortion can. Likewise, as the operational signal levels are increased, the relative output levels of carriers to distortions will be maintained for linear distortion, but will not be maintained for nonlinear distortions.

One operational test to determine the order (2nd, 3rd) of undesired energy in a vacant band is to elevate the input signal. If the distortion energy increases 3dB for a 1dB step increase on the input signal, the nonlinear distortion is probably third order. If the undesired energy increases 2dB for a 1dB step increase on the input signal, the nonlinear distortion is probably second order.

Appendix B describes the operation of nonlinear distortions on a rectangular block of noise, which can be used as an approximate model for one or more continuous digital carriers.

The nonlinear distortion energy is not random, and can be quantified with knowledge of the input signal that created it. It is particularly easy to quantify in vacant test bands, such as a roll-off region. If a vacant band is not available, one can be created by demodulating the RF signal occupying the band, and then subtracting it mathematically.

There are a few variants of how the detection of signal distortion signal can be done. One method is to capture the same signal twice: one copy of which is a clean undistorted signal at the headend, and the other copy is captured at a test point in the field. This method has the added complexity of requiring synchronized capture and the transfer of data to a central processing point, in addition to removing linear distortion differences between the nonlinearly distorted signal and the pristine headend signal. Another method would be to capture the signal at the input and the output test points of the amplifier, and then determine how much additional distortion was added by the amplifier. The linear distortion of the amplifier, including diplex filters response, tilt, and equalization still make this method non-trivial.

The rest of this paper will describe a test methodology that requires only a signal capture at a single location, where the single full band signal is captured in the field. The captured vacant band signal is stored as a “measured” signal, and processed with a “manufactured” signal. The level of match between the measured and manufactured signals determines how much nonlinear distortion was present in the captured signal’s vacant band.

2 TEST METHODOLOGY

2.1 NONLINEAR 1-SIGNAL DISTORTION TEST METHOD

The new nonlinear 1-signal distortion test method is implemented as follows:

1. Capture a full-band downstream signal with a digital oscilloscope having a sampling rate of at least 2.5 Giga-samples per second and a minimum of 12 bits of A-D resolution for 32,768 samples. That is, the downstream signal is digitized at a rate of at least $2.5 \cdot 10^9$ Hz. A low distortion preamplifier can be used to boost the full band downstream signal prior to capture. This can be necessary because digital oscilloscopes generally have a poor noise figure. Figure 2 illustrates a time domain signal captured by a digital oscilloscope operating at 2.5 Giga-samples per second and 12 bits of A-D resolution. The downstream signal processing requires a vacant band. This 54-860MHz signal was comprised of mostly digital signals, plus a few continuous wave (CW) carriers used as pilots and alignment aids. The signal contains a vacant band between 770 and 860MHz, which is not evident in the time domain trace.

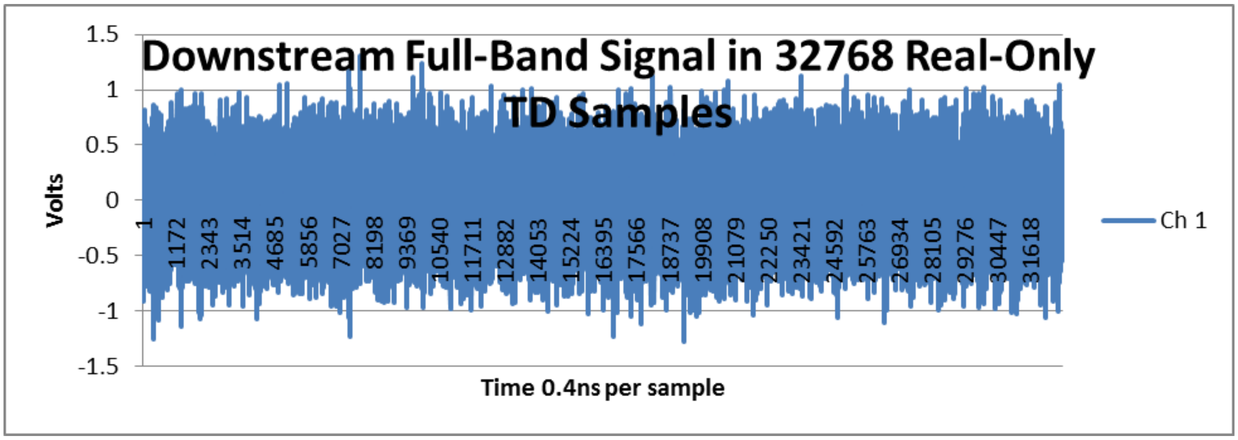

Figure 2 - A Captured Downstream Burst Lasting 16.384 US and Consisting of 32768 Samples

2. Convert the TD signal of Figure 2 into the frequency domain (FD) with a FFT (fast Fourier transform). This FD plot is illustrated in Figure 3. In the frequency domain, the vacant band energy values between 770 and 860MHz, with 1024 FD samples are cut and stored. These 1024 FD samples are called the “measured” vacant band distortion signal, and illustrated in Figure 4. Next, replace the vacant band energy in the FD signal between 770 and 860MHz with 1024 zeroes. This spectral plot is illustrated in Figure 5.

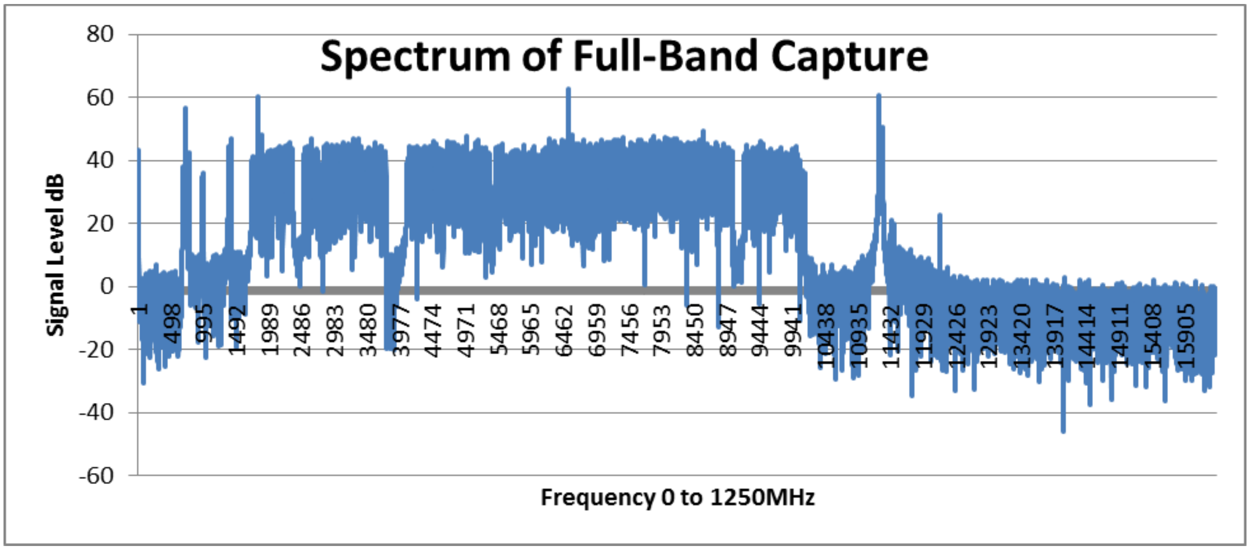

Figure 3 - A Full Band Downstream FD Signal Obtained by Performing an FFT on the Samples Illustrated in Figure 2

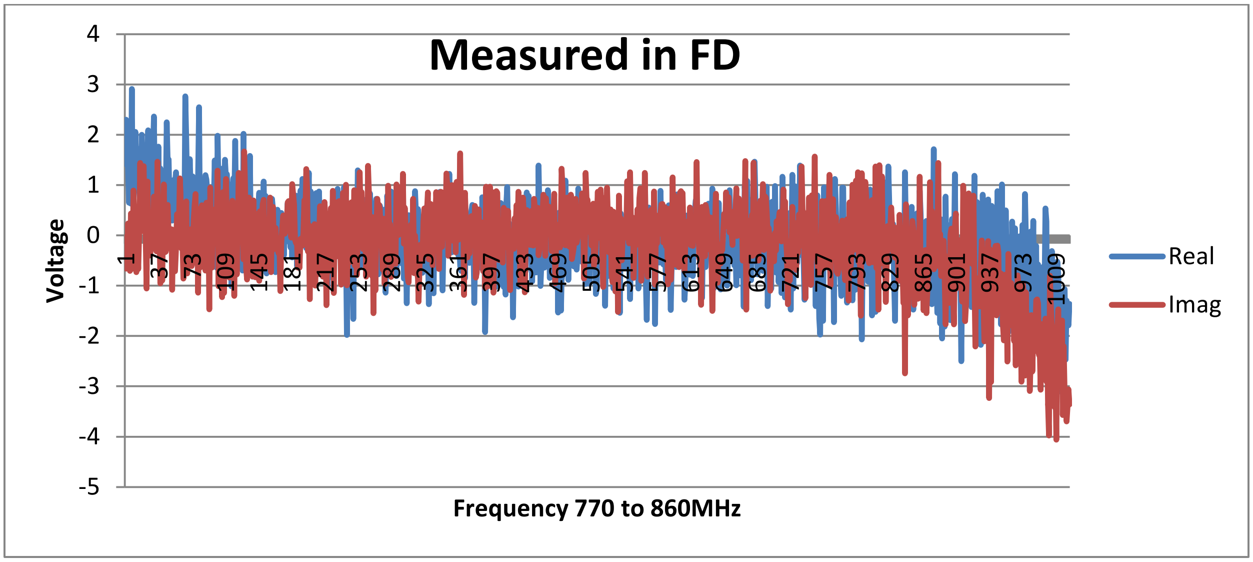

Figure 4 - 1024 Points of Measured Distortion from the Vacant Band

3. Next convert the 54-860 MHz signal of Figure 5 with the newly-vacated band back into the time domain with an IFFT and distort a resulting time sequence with a 2nd and 3rd order nonlinear distortion. This is accomplished by squaring and cubing each term in the time sequence. This creates a 2nd order "manufactured" signal and a 3rd order "manufactured" signal. This distorting manufacturing method gives a good approximate estimate because the nonlinear distortion components are small in cable networks (2). That is:

$$f(x) = Ax + Bx^2 + C^3 \sim Ax \quad (4)$$

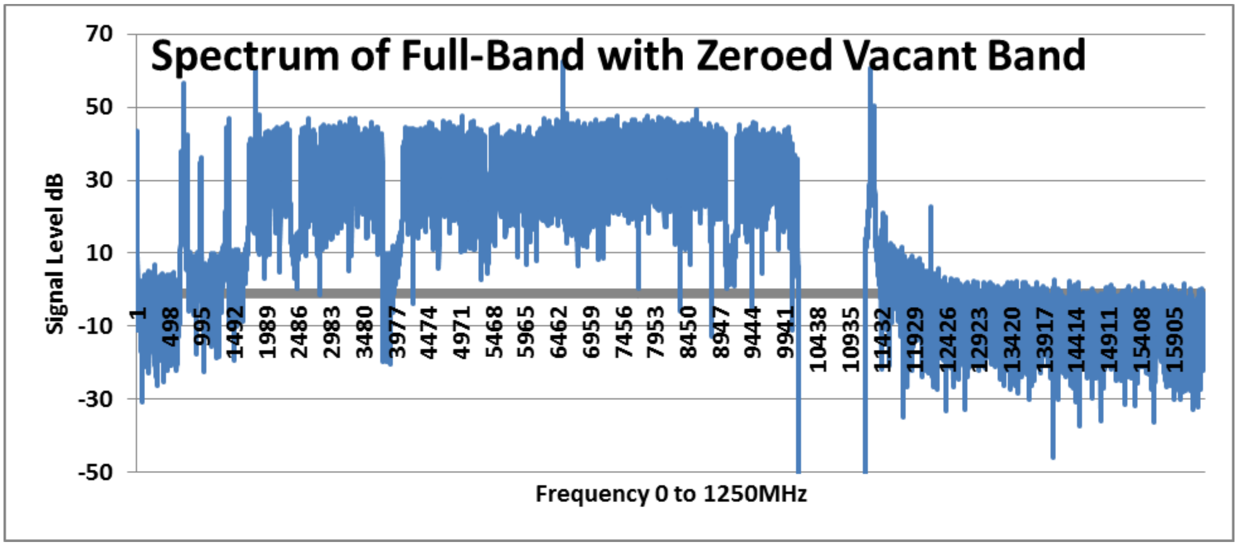

Figure 5 - A Full Band Downstream Signal with a Zeroed-out Vacant Band

4. Convert the "manufactured" signals back into the frequency domain and store only the 1024 distortion components in the vacant band. This is illustrated in Figure 6.

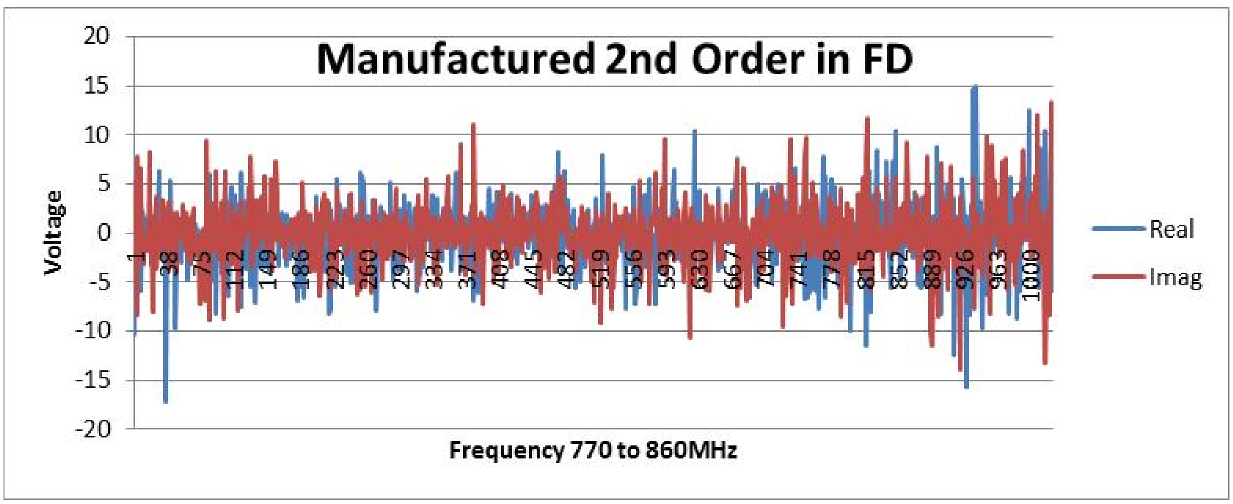

Figure 6 - 1024 Points of Manufactured 2nd Order Distortion from the Vacant Band

5. Process the 1024 point vacant band "measured" signal with the 1024 point vacant band "manufactured" signals. One processing method that has worked well is frequency domain division of the "manufactured" samples by the complex conjugate of the same frequency "measured" samples to produce 1024 FD quotients.

6. Convert the 1024 FD quotients into the time domain. This is illustrated in Figure 7 for 2nd order distortion and Figure 8 for 3rd order distortion. Energy in the first (DC) term indicates a match of the "measured" signal with the "manufactured" signal.

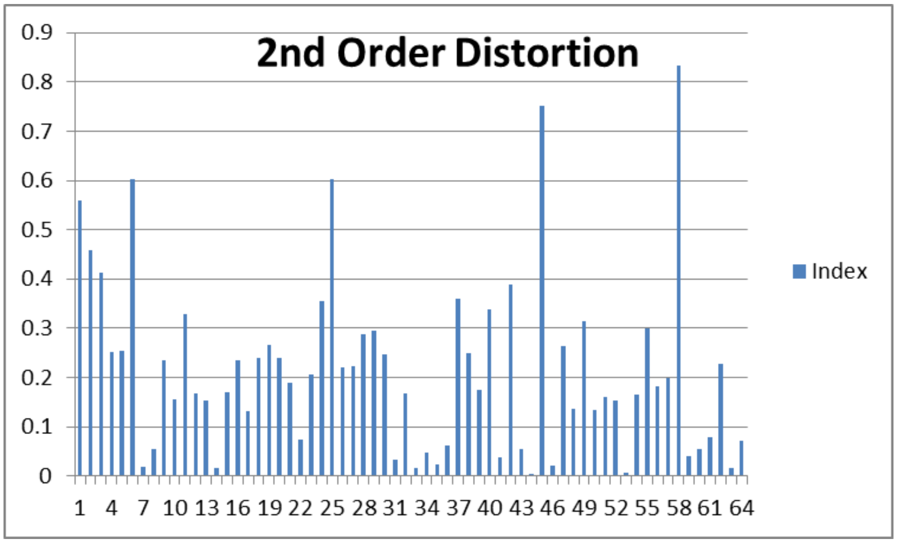

Figure 7 - TD Plot of Quotient Showing Large First Term, Relative to Other Terms, Indicating 2nd Order Distortion

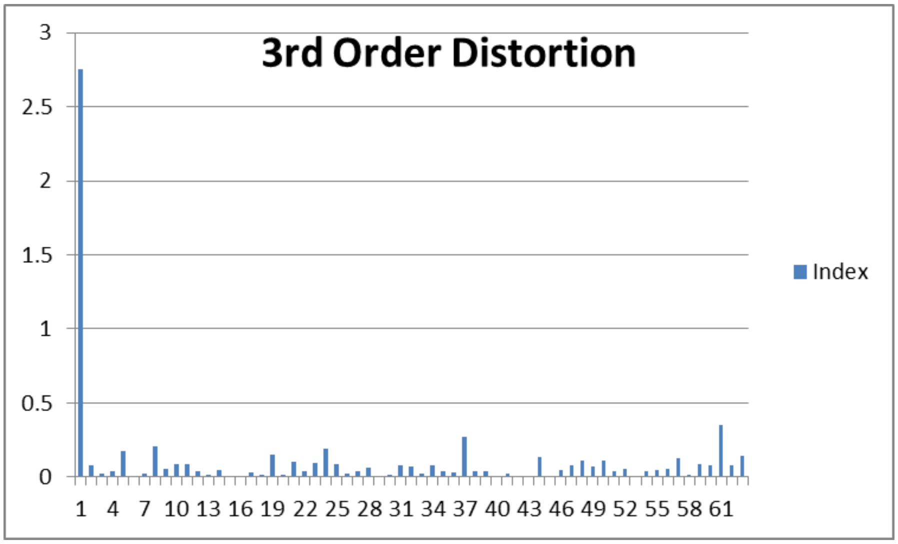

Figure 8 - TD Plot of Quotient Showing Large First Term, Relative to Other Terms, Indicating 3rd Order Distortion

7. If necessary, averaging may be used to better discern the DC term relative to the other terms. Note that the DC terms are correlated vectors that will add, but the other terms are uncorrelated.
8. Repeat steps for other orders of distortion you think might be present.

The plots of Figure 7 and Figure 8 are complex time series and only 64 of the 1024 points are illustrated. As a number of averages increases, the noisy components associated with using a noise-like downstream test signal are reduced. Another improvement to reduce noise in the plots is to use a larger percentage of vacant bandwidth relative to the occupied bandwidth. There is generally a delay (angle) to the distortion, and in most observed tests on distorted Cable amplifiers, the first term (t=0) contains most of the energy. As the amplifier's input drive level increases, both the level of nonlinear distortion and the angle of the DC terms change.

2.2 2ND ORDER DISTORTION DISCUSSION

2nd order distortion in cable networks should be substantially suppressed relative to 3rd order distortion because Cable systems use balanced push-pull amplifiers. These amplifiers cancel even order (2nd, 4th, 6th etc.) distortions. Expected potential sources of 2nd order distortions are imperfect analog downstream linear lasers, damaged, unbalanced push-pull amplifiers, and distortion diodes created by corrosion in the plant.

2.3 3RD ORDER DISTORTION DISCUSSION

3rd order distortion is the dominant nonlinear distortion in cable systems. Generally high powered amplifiers are used to provide needed dynamic range. Cable systems are operated with up-tilt to provide more uniform distortion over the downstream band. The potential sources mentioned above for second order distortion can also contribute to third order distortion.

2.4 TEST RESULTS FROM FIELD LOCATIONS

Figure 9 is a composite plot from different 7 locations for 2nd order distortion test results, and Figure 10 contains 3rd order distortion results. Fifteen separate tests were run to determine if the measurements were repeatable, and 10 averages used. Locations 6 and 7 had downstream high pass filters to pass only data traffic.

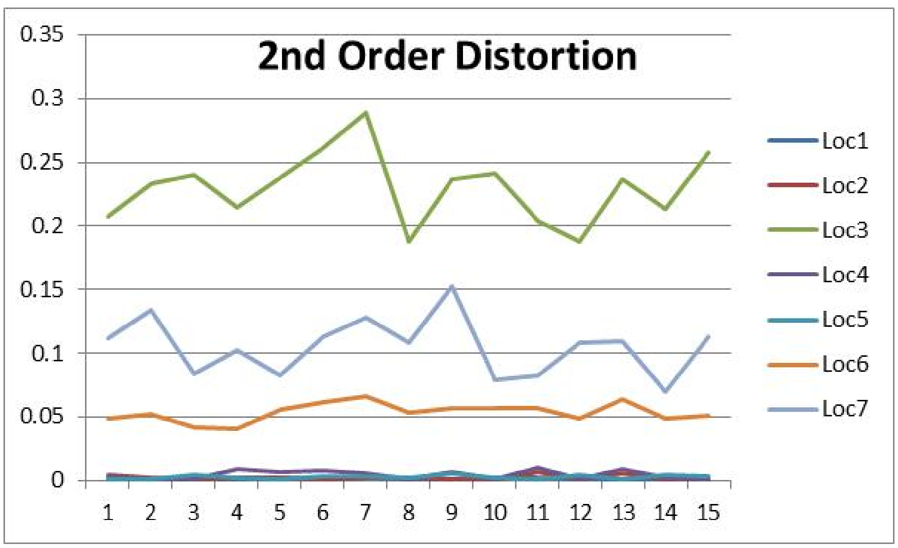

Figure 9 - Second Order Results for 7 Locations (15 Tests Each Location, 10 Averages)

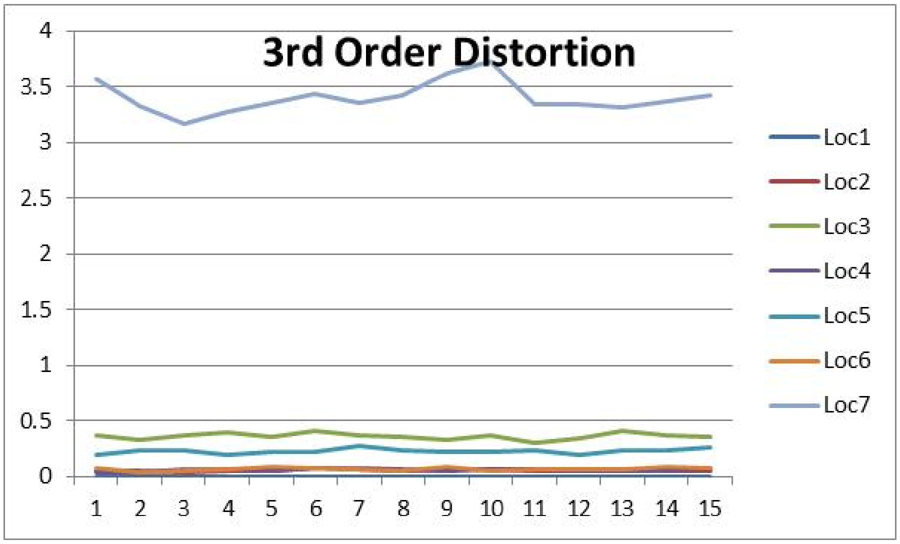

Figure 10 - Third Order Results for 7 Locations (15 Tests Each Location, 10 Averages)

As the nonlinear distortion is created in amplifiers, the amps are generally being operated with an up-tilt as mentioned above. In an attempt to improve the match of the manufactured and measured signals, the input signal used for manufacturing distortion was mathematically tilted by +/- 10dB**.** Figure 10 shows the third order match of the "manufactured" signal improves with input signal up-tilt.

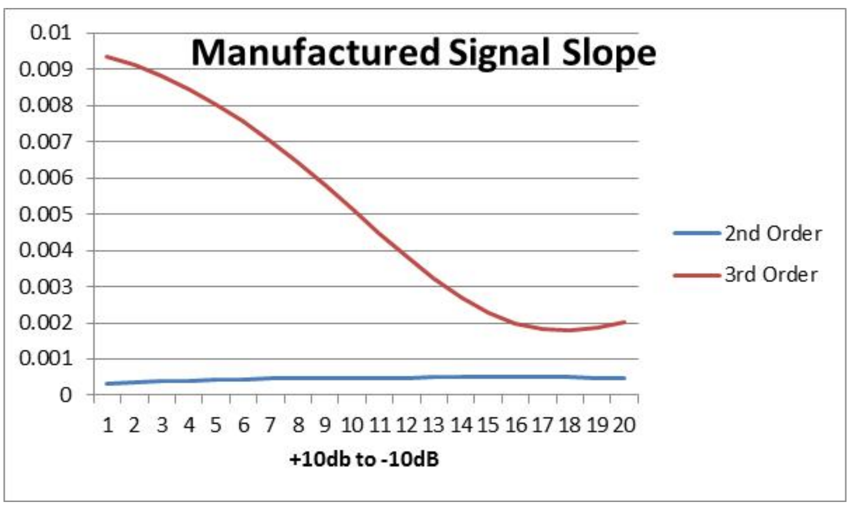

Figure 11 - Curves Showing Improved Matching of Manufactured with Measured Signal, with Tilting of Full Band Signal Used for Manufactured Signals

NOTE: Curve indicates that 3rd order distortion was likely created in amplifier operating with up-tilt.

One observation that can be drawn from the data is that the third order distortion should possibly be somewhat higher than was observed in most of the locations. This could potentially yield improved random noise performance. However, if an error in amplifier alignment levels occurs, it is probably better to run amplifier levels lower rather than higher. This is due to 3rd order distortion rising 3dB for every additional dB of input level, while signal to random noise level will only rise by 1dB for each dB of reduced input level. Another observation was that some locations had second order distortion.

Another observation is that this technique relates percentage of nonlinear distortions to random energy in a vacant band. MER (modulation error rate) could be degraded by either nonlinear distortion or uncorrelated energy, such as random noise. If the MER of the signals are good, the plant probably does not necessarily need to be adjusted.

Other applications for this technology are programming digital pre-distortion circuits that improve the linearity of high power amplifiers, and narrowband amplifier measurements.

3 CONCLUSION

In conclusion, it is now possible measure the undesired energy accompanying Cable signals to determine if they are nonlinear distortion, or some other uncorrelated energy such as random noise or ingress.

APPENDIX A MATLAB CODE FOR NONLINEAR DISTORTION ANALYSIS

```
clear all
close all
clc
lengthFFT=32768;
Ts=.4e-9;   Fs=1/Ts;
N=lengthFFT;
windowFunction=window(@hann,N)
Average_TD_AnalysisSignal_CTB=zeros(1024,1);
Average_TD_AnalysisSignal_CSO=zeros(1024,1);
fid = fopen('trace.txt', 'r');
for count=1:15
      data = fscanf(fid, '%f', [1 lengthFFT]);
      data=data';
      TD_data=windowFunction.*data;
      FD_data=fft(data);
      savedSamples=FD_data(10160:11183);
      FD_data_zeroed=FD_data;
      FD_data_zeroed(10160:11183)=0;
      TD_data_zeroed=ifft(FD_data_zeroed);
      TD_distSignal_CTB=TD_data_zeroed.^3;
      FD_distSignal_CTB=fft(TD_distSignal_CTB);
      CreatedDistortion_CTB=FD_distSignal_CTB(10160:11183);
      FD_AnalysisSignal_CTB=savedSamples.*conj(CreatedDistortion_CTB);
      FD_AnalysisSignal_CTB(1)=0;
      TD_AnalysisSignal_CTB=ifft(FD_AnalysisSignal_CTB);
      TD_distSignal_CSO=TD_data_zeroed.^2;
      FD_distSignal_CSO=fft(TD_distSignal_CSO);
      CreatedDistortion_CSO=FD_distSignal_CSO(10160:11183);
      FD_AnalysisSignal_CSO=savedSamples.*conj(CreatedDistortion_CSO);
      FD_AnalysisSignal_CSO(1)=0;
      TD_AnalysisSignal_CSO=ifft(FD_AnalysisSignal_CSO);
            Average_TD_AnalysisSignal_CTB=Average_TD_AnalysisSignal_CTB+TD_An
      alysisSignal_CTB;
```

```
      Average_TD_AnalysisSignal_CSO=Average_TD_AnalysisSignal_CSO
+TD_AnalysisSignal_CSO;
end
fclose(fid);
Average_TD_AnalysisSignal_CTB=Average_TD_AnalysisSignal_CTB/15;
Average_TD_AnalysisSignal_CSO=Average_TD_AnalysisSignal_CSO/15;
figure(1);
subplot(3,1,1),plot(0:Ts:((length(TD_data)-1)*Ts),TD_data);
subplot(3,1,2),plot(0:Fs/N:.5*Fs-
Fs/N,10*log10((abs(FD_data(1:16384)))));
subplot(3,1,3),plot(0:Fs/N:.5*Fs-
Fs/N,10*log10((abs(FD_data_zeroed(1:16384)))));
figure(2)
stem(abs(Average_TD_AnalysisSignal_CTB))
title('Composite Triple Beat')
figure(3)
stem(abs(Average_TD_AnalysisSignal_CSO))
title('Composite Second Order')
```

APPENDIX B NONLINEAR DISTORTION CREATION BY FREQUENCY DOMAIN CONVOLUTION

Figure 12 is a block of noise in the frequency domain, approximately modeling a single QAM carrier, or a block of contiguous carriers. Figure 13 shows a triangular spectral shape resulting from a second order distortion, and Figure 14 shows a resulting haystack-shaped spectrum from a third order distortion. Figure 15 shows the rectangular block of noise overlaid with the haystack spectrum it created. Observe that nonlinear distortion can be underneath the carrier as well as in adjacent sidebands. The energy in the upper and lower sidebands is sometimes referred to as "spectral regrowth".

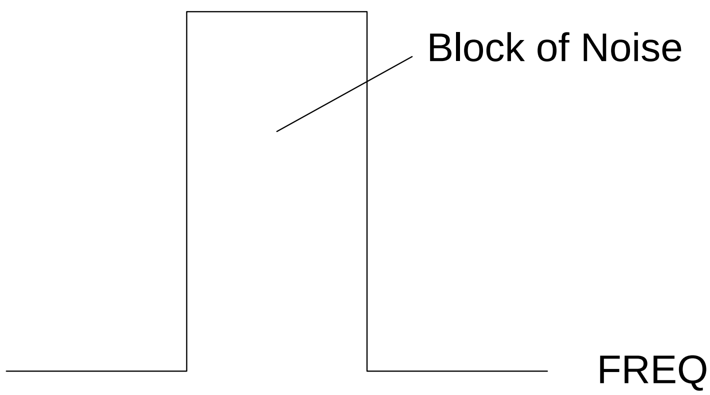

Figure 12 - A Rectangular Block of Random Noise Modeling a Digital Signal, or a Block of Contiguous Digital Signals

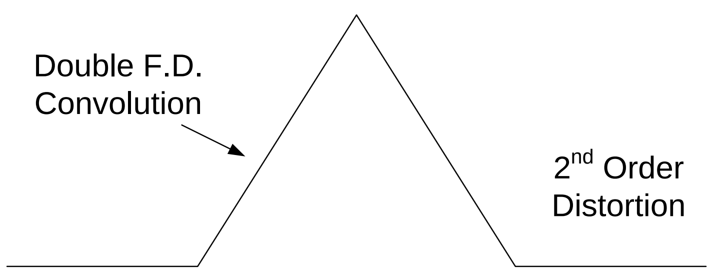

Figure 13 - 2nd Order Distortion Created by a Frequency Domain Double Convolution of the Signal of Figure 2

If the signal of Figure 12 was centered at 100MHz and 10MHz wide, the second harmonic signal of Figure 13 would be at centered at 200MHz and be 20MHz wide.

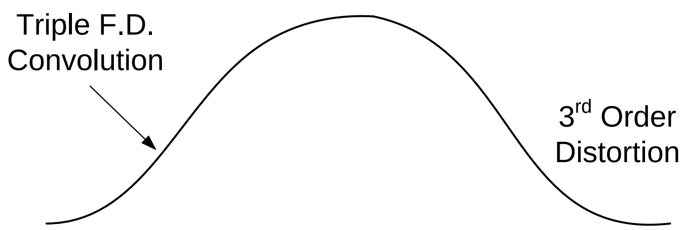

Figure 14 - 3rd Order Distortion Created by a Frequency Domain Triple Convolution of the Signal of Figure 12

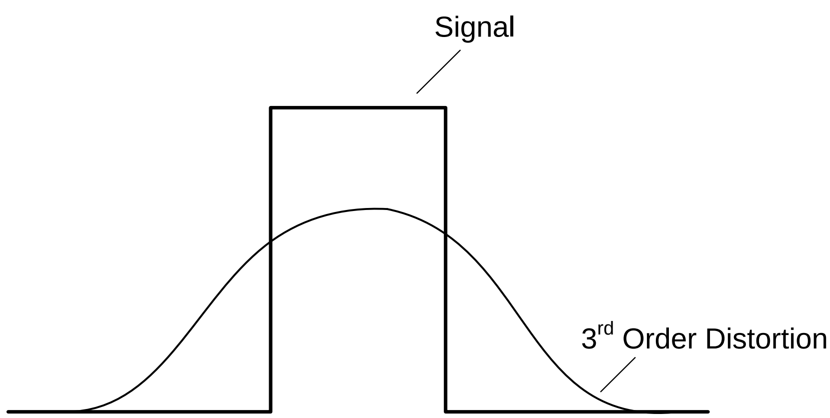

Figure 15 - An Overlay of the Signal of Figure 12 with the Signal of Figure 13

This 3rd order spectrum will be centered over the 100MHz carrier and be 30MHz wide. This spectrum will also appear at the 3rd harmonic frequency of 300MHz.