Detection of Passive Intermodulation in Drop Wiring by Burst Transmission Analysis

Diodes are common, but the network resists

A Technical Paper prepared for SCTE by

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1. Introduction

Home coaxial wiring and drop cable are expected to contain corrosion diodes created between dissimilar metals and metal oxides. Generally, corrosion diodes have not been a serious problem up to this point because continuous composite downstream radio frequency (RF) levels inside homes were not sufficient to force the corrosion diodes into hard conduction, which would create nonlinear distortion. DOCSIS® transmitted signals can be strong enough to force the corrosion diodes to conduct, but due to sub-split upstream frequencies, damage to downstream signals has been limited. It should be technically possible to automatically detect passive intermodulation (PIM) products at the headend due to their correlation with the main transmission and the spectral location of the nonlinear distortion. This paper discusses the mechanism for creating PIM in sub, mid and high split plant using orthogonal frequency division multiple access (OFDMA) transmissions. The paper also reports on PIM impairments created in our lab and analyzed using digital signal processing (DSP), discusses the potential impact of nonlinear noise on full duplex (FDX), and provides techniques to tackle this until now invisible plant impairment.

2. Background

2.1. Background on Nonlinear Distortion

Plant distortions can be separated into two categories: linear and nonlinear. Linear distortions consist of group delay, echoes, and channel ripple/tilt to name a few. Nonlinear distortions are created by mixing signals with themselves or other signals, and this mixing process creates energy at new frequencies. This distortion is also called intermodulation distortion (IMD). Cable plants have both types of distortions, and while linear distortion can generally be remedied with equalizers, nonlinear distortions are much harder to remove. Generally, it is best to avoid generating nonlinear distortions in the first place, if possible.

Mathematically, the input-output relationship of many devices can be described as a polynomial or Taylor series as shown below. More is explained in Appendix 8.3.

$$E_{out} = \mathrm{A} \cdot E_{in} + B \cdot E_{in}{}^{2} + C \cdot E_{in}{}^{3} \ldots \quad (1)$$

E_{out} is the composite output signal, E_{in} is a composite input signal, A is the gain, B is a coefficient for the second order distortion, and C is a third order coefficient. Additional higher-order coefficients typically exist and may not be ignored if input signal levels are large.

Figure 1 illustrates a transfer function modeled as a third order Taylor series. An input sine wave passes through a device with third order distortion, such as a push-pull amplifier. Most cable amplifiers are a push-pull design to cancel 2nd order distortions. In the figure, the resulting distorted output wave is illustrated as a red curve, while a desired undistorted amplifier waveform is black. The distance between the red curve and the black curve is the voltage of the distortion energy.

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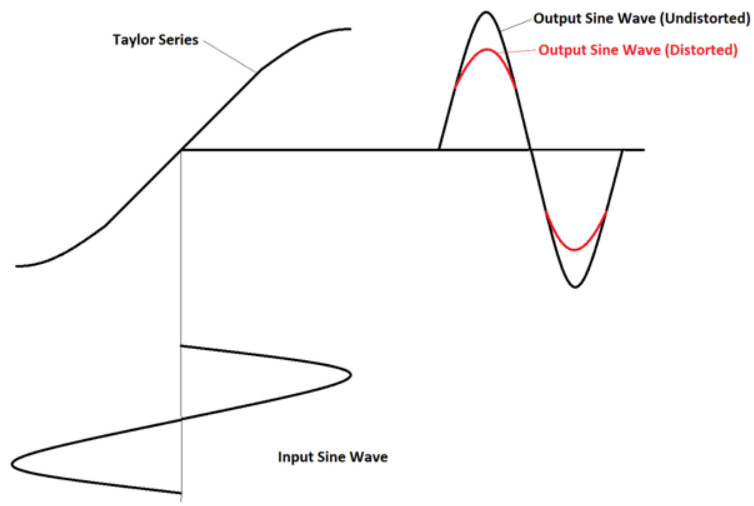

Figure 1 –Sine wave input applied to nonlinear circuit produces a distorted sine wave.

Figure 2 is a spectral plot of 2nd and 3rd order output products created by two sine waves, f1 and f2. Consider an input signal Ein comprised of just two sine waves, f1 and f2. They are mixed in a circuit with a transfer function with only 2nd and 3rd order distortions. Equation (1) may be expanded using trigonometric identities. Second order distortion products will be created at 2f1, 2f2, f1-f2, and f1+f2. Third order distortion products will be generated at 3f1, 3f2, 2f1-f2, 2f2-f1, 2f1+f2, and 2f2+f1.

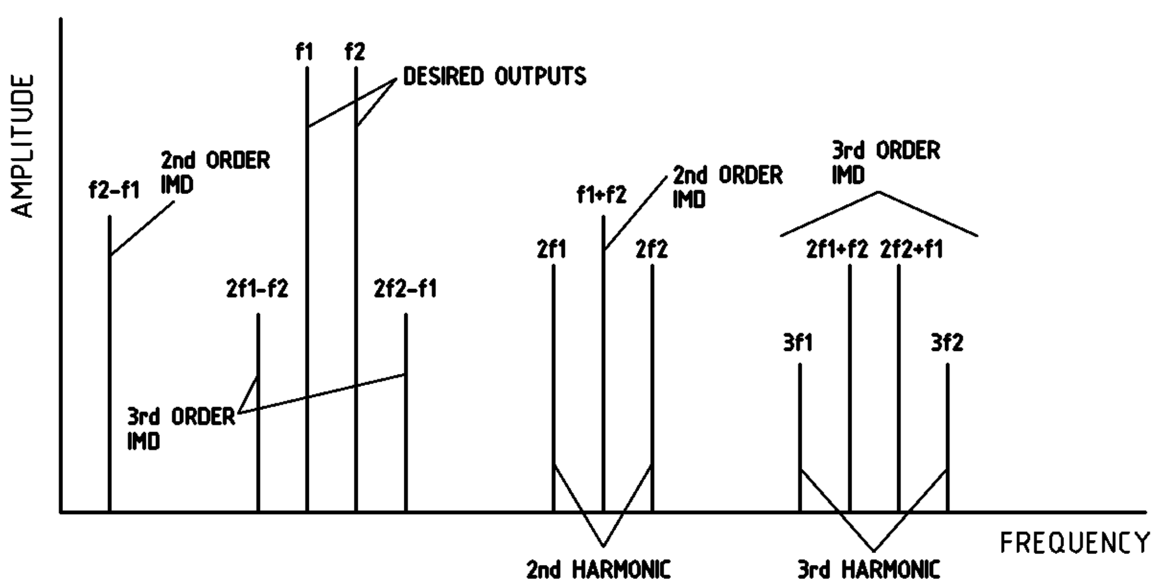

Figure 2 – 2nd and 3rd order spectral components created by sine waves at f1 and f2.

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Generally, higher order distortions than the 3rd order should be considered at high composite RF signal levels.

System designers use an intercept point diagram, as illustrated in Figure 3, to model nonlinear components. A plot is made of input signal level vs. output signal level, and the fundamental slope of that plot is the amplifier's gain. A second plot is made of 2nd order distortion level vs. input signal level, and that plot has a slope twice as steep as the fundamental due to the squared term in the Taylor series. Likewise, a third order distortion plot has a slope three times as steep as the fundamental due to the cube term in the Taylor series. If the 3rd order distortion line is extrapolated (red lines), it crosses the fundamental line at a point called IP3, or the 3rd order intercept point. This key number is used to predict expected distortion levels, and usually is specified on amplifier and mixer data sheets. Another point of interest on data sheets is the 1dB compression point, where the fundamental signal's output falls 1dB below its ideal level.

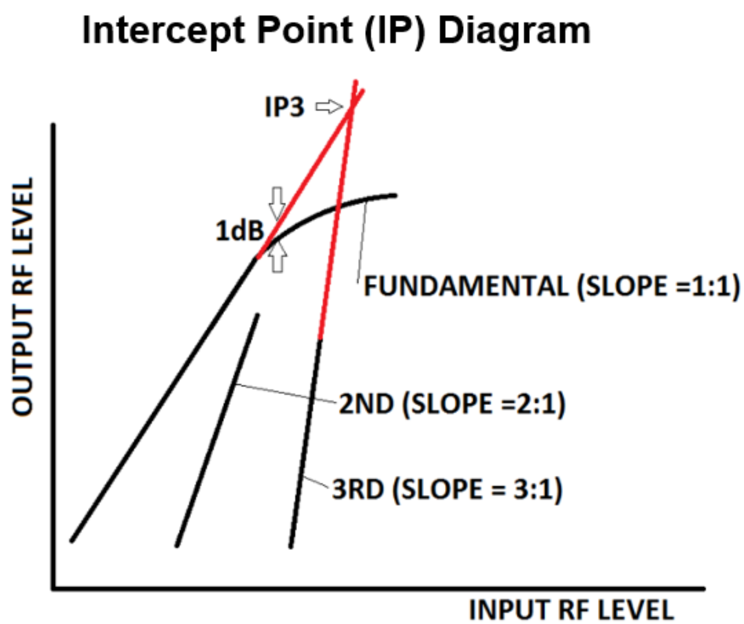

Figure 3 – Plots of fundamental, 2nd and 3rd order distortions vs fundamental RF levels.

In Figure 3, fundamental and 3rd order plot can be projected to find a third order intercept point. This method can be used to predict distortion levels in amplifiers or other nonlinear components. This projection graphing method applies also for corrosion diodes and shows how higher RF fundamental levels produce higher levels of nonlinear distortions.

For test purposes, cable engineers and technicians sometimes raise (or lower) plant levels by a decibel to identify if resulting nonlinear distortion energy goes up by 2 or 3 dB, identifying the distortion as 2nd or 3rd order. To properly perform this test, pilot signals must be held constant because amplifier automatic gain controls (AGCs) will attempt to change gain.

Typically, digital cable signals being transported have a flat spectral energy with an approximately rectangular spectral shape. An analysis method for nonlinear distortion is to use a double or triple frequency-domain convolution of the input signal with itself. This method is used because a convolution in the frequency domain is mathematically equivalent to a multiplication (e.g. squaring or cubing) in the

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time domain, and vice-versa. Figure 4 illustrates the creation of 2nd and 3rd order nonlinear distortion products. The convolution of a rectangular spectrum with itself produces a triangular shape on a linear vertical scale occupying twice the original rectangular spectrum, while a triple convolution of a rectangular spectrum with itself produces a “haystack” shaped spectrum occupying three times the original rectangular spectrum. Figure 4 illustrates a relatively narrowband input OFDMA signal 70 MHz to 100 MHz (red) which creates 2nd and 3rd order distortion products. Distortion products are not drawn to scale for the sake of clarity. The more convolutions a rectangular signal undergoes, the wider its resulting nonlinear distortion spectrum gets.

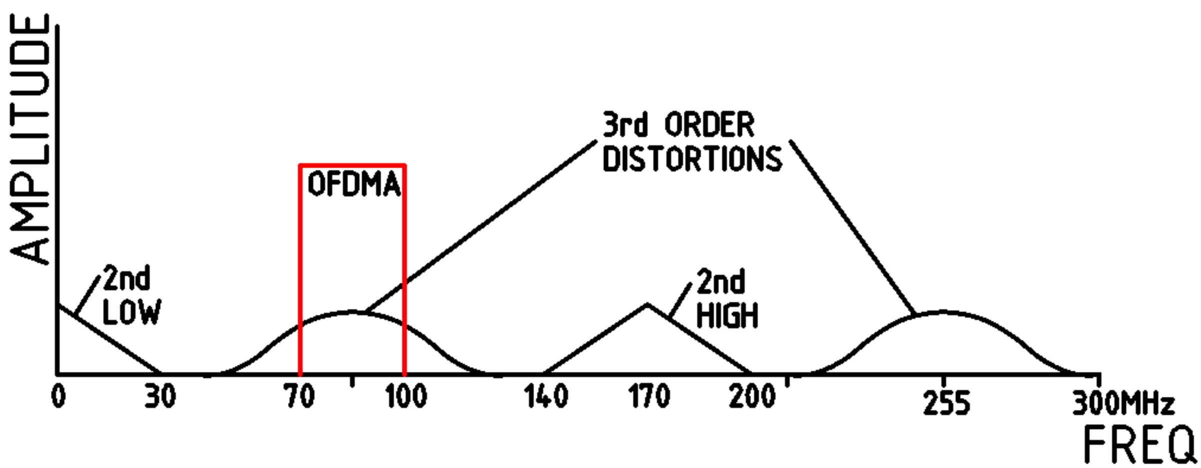

Figure 4 – Non linear distortion

The spectral plot in Fig. 4 shows how a rectangular-shaped block of spectrally-flat energy, such as an OFDMA or OFDM spectrum (in red) produces nonlinear distortion products (in black). The vertical scale is linear. The 2nd order products employ as double convolution, producing a triangular-shaped spectrum. 3rd order distortion products create haystack-shaped spectral energy. Occupied bandwidth increases linearly with each higher order distortion coefficient and the distortion takes on a relatively “flat” spectrum. This is particularly true for wide transmitted rectangular (bandwidth) blocks.

The spectral photo in Figure 5 explains why we generally have not been affected by nonlinear distortion products with a sub-split frequency plan inside home wiring up to this point. If, for example, an ATDMA upstream single carrier transmission at 30 MHz is 6.4 MHz wide, the second order difference term is 0 MHz to 6.4 MHz yet cable upstream amplifiers do not pass energy below 5 MHz. The second order sum products will be 12.8 MHz wide centered at 60 MHz, so 2nd order distortion can affect downstream signals located between 53.6 MHz and 66.4 MHz but received signal degradation occurs only for the duration of a burst upstream transmission.

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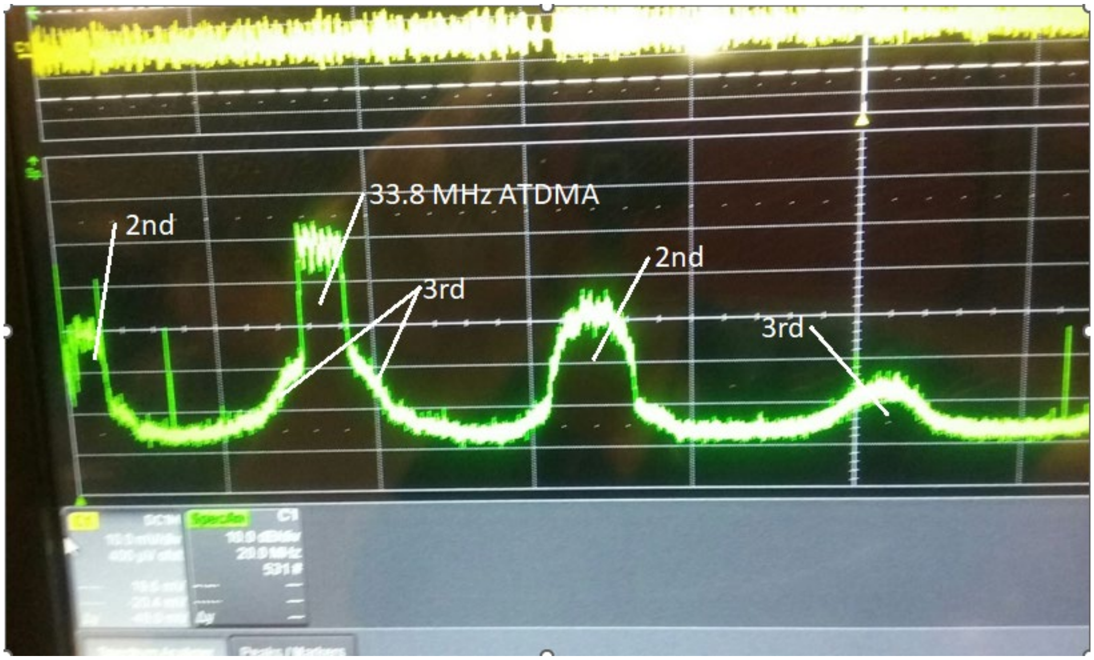

Figure 5 – Schottky Diode distortions

Figure 5 is a lab experiment of a single carrier 6.4 MHz signal at 33.8 MHz being distorted by a Schottky diode producing 2nd and 3rd order distortions (lower plot). LeCroy DSO digital oscilloscope has a horizontal frequency range of 0 MHz to 200 MHz, and 10 dB/div is vertical scale. Upper plot is voltage vs. time, captured at 500 Msamples/second.

2.2. Background on CPD and PIM

CPD has long been a known impairment source for downstream cable plant. The distortion is created by corrosion diodes in cable plant, usually located in hard line plant where signal levels are large due to nearby line amplification. High level downstream signals produce nonlinear distortion in all bands, but the distortion is visible in the upstream band. [9]

PIM is a well-known impairment in wireless systems also caused by corrosion, and it sometimes occurs on RF feedlines. Because bandpass filtering is possible, the biggest concerns are third order distortions located just above, just below, and on the carrier. Both CPD and PIM are caused by corrosion diodes, and result in nonlinear distortions in RF. Therefore, CPD can be considered a subvariant of PIM, which is a generic term.

A question arises why CPD only seems to affect upstream signals, while it appears to have relatively flat spectral content. See Figure 6, which shows typical upstream and downstream carrier levels (per 6MHz) at the output of a downstream amplifier, which is also the input of an upstream amplifier. Assuming CPD is spectrally relatively flat, with a -40dBc distortion relative to downstream carriers each at +50 dBmV, upstream signals experience a 18dB carrier-to-noise ratio. This ratio is below the threshold for a 64-QAM upstream receiver.

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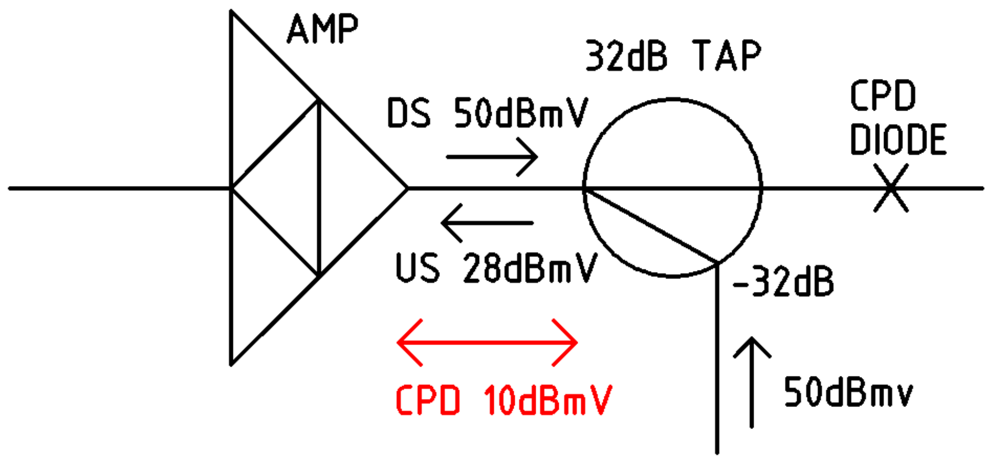

Figure 6 – CPD non linear distortions in downstream

Figure 6 is a diagram explaining why CPD nonlinear distortion is seldom observed on downstream channels. As an example, in a 6 MHz band, if a downstream signal is at 50dBmV and creates a spectrally-flat CPD distortion -40dBc relative to the downstream carrier level at the output of a downstream amplifier, distortion power level is -10dBmV. So, it is relatively harmless to a downstream carrier. But an upstream carrier, attenuated by a flat loss of a 32dB tap, suffers a modulation error ratio (MER) degradation of only 18dB (28dB-10dB). This is below threshold and is a continuous impairment to all upstream signals in the node due to noise funneling.

One advantage that coaxial cable signals have over long term evolution (LTE) signals is cable composite signal levels are much lower, such as approximately 1-2 watts for cable versus 20 watts for cellular transmissions. However, cable plant has many more connectors relative to a cellular feedline and antenna. Cable downstream also employs uptilt, placing more energy into the higher frequencies. This design will cause some distortion components to land at higher frequencies, which hopefully are out of band.

3. Lab Experiments

It has been observed in lab experiments that a wide OFDMA transmission can produce relatively flat distortion energy over a wide band. If a strong signal, such as a wide OFDMA transmission, mixes with itself in a corrosion diode, a difference product will start at DC (0 HZ) and extend to the bandwidth of the OFDMA carrier with a triangular-shaped spectrum (viewed on a linear display). This is a 2nd order difference mixing product. However, if the OFDMA transmission mixes with another strong signal, such as a MoCA® transmission or a citizen band (CB) transmission ingress signal, a difference product will not be centered at direct current (DC), but at a difference frequency, as expected. For example, an OFDMA transmission centered at 200MHz can mix with a MoCA signal centered at 1150 MHz and produce interference centered at 950 MHZ, which is in a downstream frequency band. The 2nd order interference will be a convolution of the MoCA signal's spectrum with an OFDMA signal's spectrum.

A first test was to pass an ATDMA single carrier 6.4 MHz signal through a corrosion diode simulator circuit, with a Schottky diode. The spectral plot was previously illustrated in Figure 5, showing the

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expected 2nd and 3rd order distortion products. This plot can be compared to Figure 4, which illustrates frequencies at which distortion products are expected.

The circuit used is illustrated in Figure 7 was used to produce upstream-only FDD distortion products. This circuit simulates corrosion in the outer conductor of a coaxial connection, such as a ground block. A shunt resistor's value was varied to increase the amount of distortion caused by the nonlinear 1N5711 Schottky diode with a given RF drive level. Two diplex filters were used to prevent downstream nonlinear distortion, which can potentially cause interference with the cable modem's (CM's) reception. The optional inductor was used to prevent DC bias on the diode and has very large inductive reactance at test frequencies.

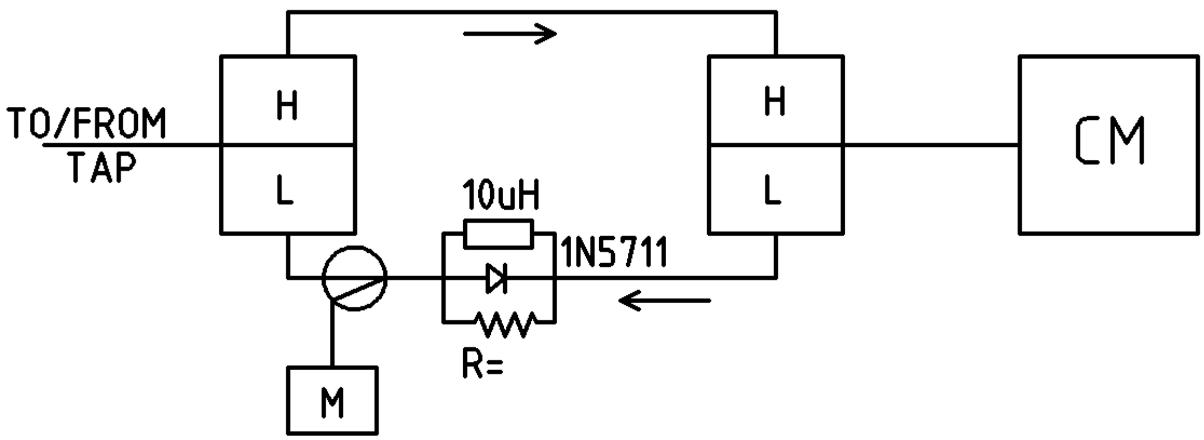

Figure 7 – Circuit simulation of corrosion in a drop.

Figure 7 is a circuit used in the lab to simulate corrosion in a drop. Two mid-split diplexers were used with a mid-split diplexer to limit the effects of distortion to only the upstream signal. The CM operates on a mid-split frequency plan. The shunt resistor (R=) is varied to increase or decrease MER caused by the nonlinear diode. The meter function (M), which may be located at the headend, samples upstream energy which is distorted.

Figure 8 is a pair of plots obtained from a LeCroy HDO 6104-MS digital oscilloscope. The top plot is voltage vs. time, and the lower plot is a fast Fourier transform (FFT) of the time samples. The sample rate was 500 M-samples per second. The corrosion diode is shunted with 0 ohms and thus had no effect. The OFDMA transmission was almost continuous due to heavy data loading, and the occupied bandwidth was 40 MHz to 80 MHz. Note that there is negligible nonlinear distortion.

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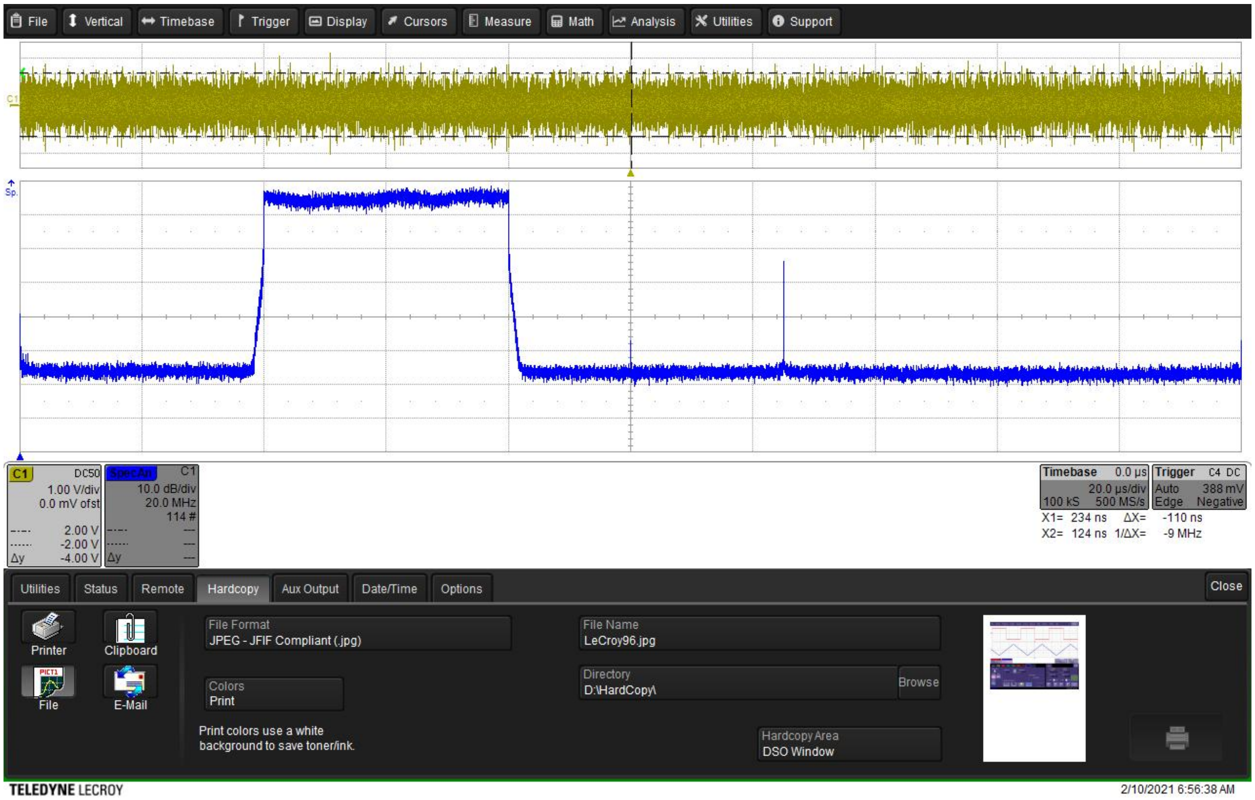

Figure 8 – OFDMA spectral plot

Figure 8 is a spectral plot of 40 MHz to 80 MHz OFDMA signal with R = 0 ohms (no corrosion diode effects). Top trace is voltage vs time, and bottom trace is dB magnitude vs. frequency. MER of 64-QAM OFDMA signal was an excellent 48.7 dB.

Figure 9 is a spectral plot with a shunt resistor value of 39 ohms, showing broadband distortion, notably sum and difference 2nd order.

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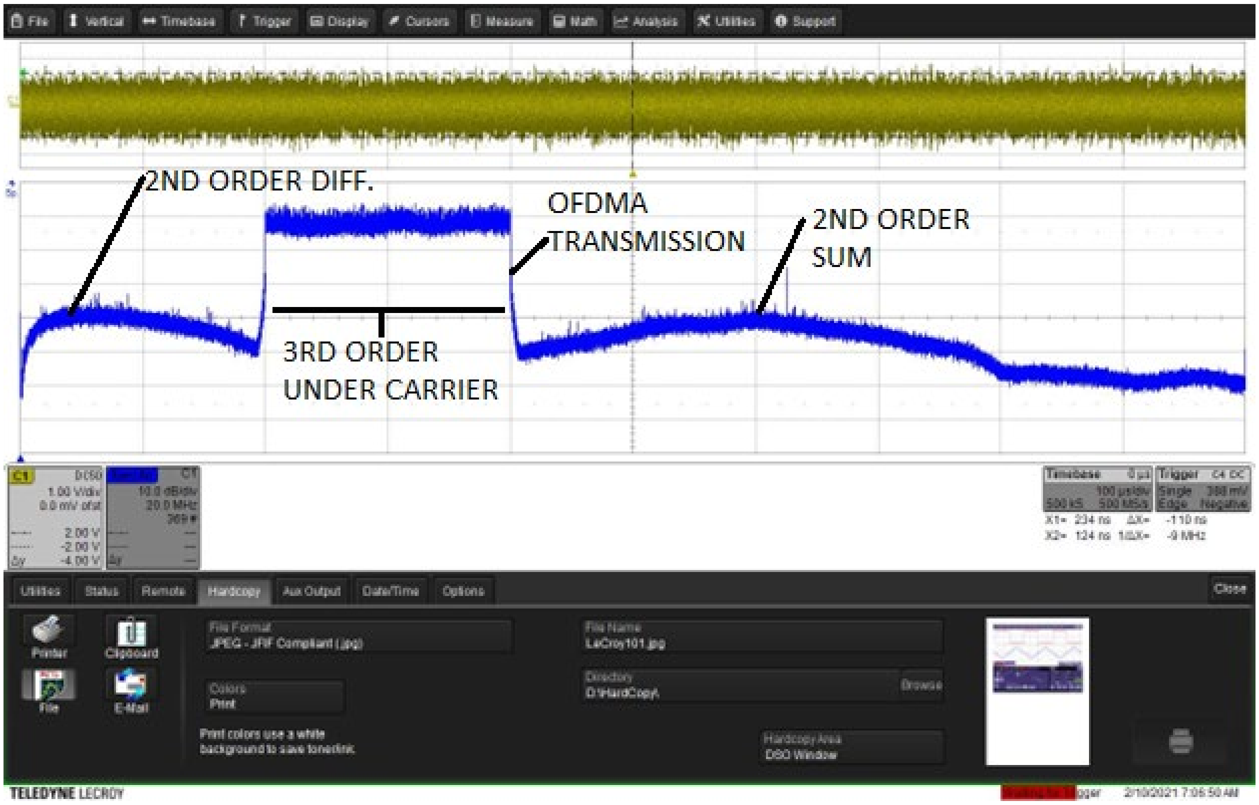

Figure 9 – OFDMA spectral plot (Shunting corrosion diode)

Figure 9 is a spectral plot of 40 MHz to 80 MHz OFDMA signal with R = 39 ohms (shunting corrosion diode). Transmit power was approximately 47 dBmV, and a MER of 64-QAM signal was 36.5dB. Observe wide spectrum of 2nd order distortion of difference products (on left) and sum products (on right). 2nd and 3rd order distortions overlap with a wideband transmission.

Figure 10 is a cross correlation plot of 2nd order measured lab distortion with 'manufactured' distortion. This method was published in 2013 [6]. It uses the received OFDMA carrier to manufacture a 2nd order distortion signal. That distortion energy is cross correlated with the filtered received energy at a frequency where 2nd order distortion is expected. This testing method is practical because upstream triggered upstream spectrum capture (UTSC) can capture a signal with nonlinear distortion. This cross-correlation method can be used for 3rd order distortion but works best where the cross-correlation capture is performed in a vacant band, such as with an active-quiet probe measurement.

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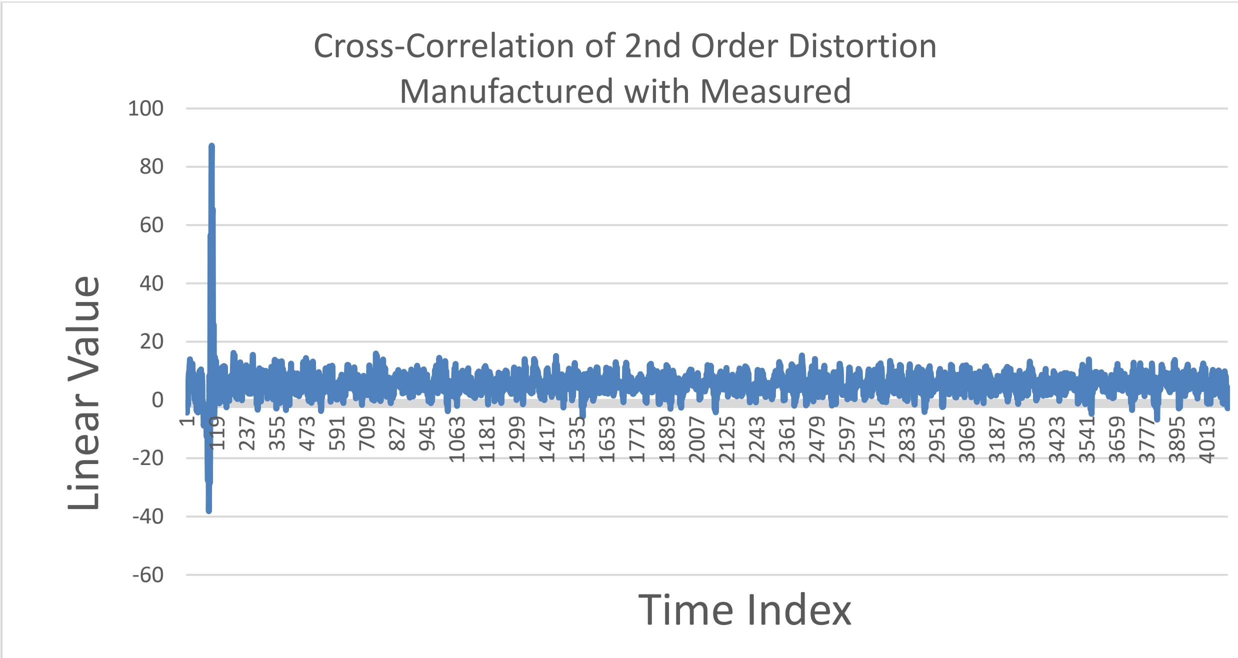

Figure 10 – Cross -correlation plot

Figure 10 is a cross-correlation plot of the filtered signal time domain signal (measured) illustrated in Figure 8 with a mathematically-created signal (manufactured) created by squaring the filtered time domain signal illustrated in Figure 8, top trace. See 2013 technical paper [6]. An impulse at zero time offset indicates significant energy is 2nd order distortion.

Figure 11 is a plot of modulation error ratio (MER) on a 40 MHz to 80 MHZ, 64QAM OFDMA transmission vs. shunt resistor value. Shunting the Schottky diode with a lower value resistor reduces distortion.

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Test with 40-80MHz OFDMA carrier, 64QAM
500 Msamples/sec on LeCroy DSO

R= ohms	MER	TX power
0	52.3	48.7
2.7	50.1	48.3
7.5	48.6	47.7
15	43.4	47.7
39	36.5	46.95
68	32.9	46.95
100	30.7	46.6
470	22.5	46.4

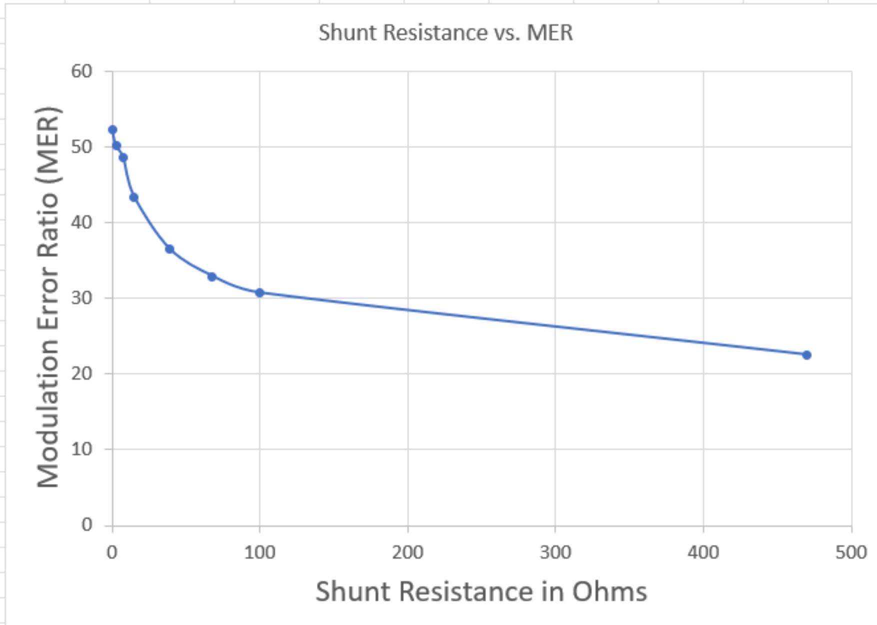

Figure 11 – MER of OFDMA signal

Figure 11 is a plot of MER of an OFDMA signal vs. shunt diode resistance, illustrated in Figure 6. When the shunt diode approaches zero, the corrosion diode is still present, but has no effect. A low value shunt resistance across a shunt diode is achieved by a high clamping force, achieved, for example, by a tight seizure screw or properly torqued housing bolts.

3.1. FDX

The process of PIM creation in FDX is going to be similar to FDD, but the lack of a diplex filter in the 108 MHz to 684 MHz FDX band means that distortion products can affect both upstream and downstream signals simultaneously.

Another concern is the adaptive equalizer in the fiber node won't be able to equalize non-linear distortion: it is designed to equalize linear distortion.

3.2. PNM

UTSC is essential in detecting anomalous US noise and distortion. Currently not all vendors implement this feature. Data should be in complex format for DSP. Furthermore, a UTSC capture needs to occur while a specific CM is transmitting at high power.

4. Field tests

CMs and cable modem termination systems (CMTSs) today are in some cases able to capture frequencies outside of their receiving ranges. Some CMs can capture low frequencies, and others can work in sub split mode on a mid-split or high split plant, etc. CMTSs can in some cases provide spectrum capture data (free run mode of upstream triggered spectrum capture or other means) for the downstream as well as upstream bands.

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5. Detection Methods for Corrosion Diodes

Nonlinear distortion detection is a difficult problem because, in normal operation, upstream CM transmissions are brief RF bursts which are difficult for test equipment to capture (trigger on), and a source of which is generally difficult to identify.

A first detection method is to observe the MER for a particular CM's transmissions and compare them to the MER in transmissions from other CMs in the same node in approximately a same time period. Because of additive noise funneling, it is expected that all CMs in a fiber node should be experiencing a common noise background. However, a common noise background can vary with time. On the other hand, nonlinear distortion instantaneously follows the RF level of a transmission. A worse MER (relative to other subscribers in the node) could indicate nonlinear energy contamination in a signal path that a CM is using, but variable common background noise must be considered. An upstream MER test can be made on several CMs with nearly simultaneous upload speed tests at high RF power levels. This approach should yield a good indicator of homes with nonlinear distortion.

A second method is to look for distortion energy above the transmitter's frequency as a sum product or as harmonics. A challenge with this method occurs when the harmonics land in the downstream spectrum, which propagates away from the headend. Detection of nonlinear distortion in a CM on downstream caused by a CM's upstream transmissions may be considered a self-inflicted wound. However, using full band capture (FBC), if a CM can be forced into a speed test at a predictable transmit frequency, distortion energy may be observed either in a vacant band, or in the spectral null between two adjacent RF carriers. 2^{nd} and 3^{rd} harmonics can be observed with this method. A delta FBC plot can be made between CM transmitting and CM not transmitting.

A third method is to look for distortion energy below the transmitter's frequency, as a difference product. This method looks promising, but a UTSC needs to be done while a CM is at transmitting at high composite power levels. Testing needs to be initiated with a process such as a speed test, concurrent with a UTSC trace capture. It is expected that UTSC traces will contain 4096 in-phase and quadrature time samples.

A fourth method is to look for out-of-band energy that "follows" an RF transmission in time. Nonlinear distortion is created simultaneously with a transmission, so detection can be done in the time domain.

A fifth method is to plot a histogram of time domain voltage samples and look for non-symmetry, indicating signal clamping by a corrosion diode conducting. This method requires relatively severe clipping (distortion).

A sixth method is to analyze the MER error vectors in the OFDMA signal and correlate them with 3^{rd} order distortion created from the error-free symbols. This requires the symbols in the OFDMA signal to not cross decision boundaries. [7]

Another method involving bonded upstream ATDMA signals is to get multiple upstream channels to transmit simultaneously from a single CM at high power. A block of three or four 6.4 MHz wide carriers can be approximately treated as one wide OFDMA-like block of random energy.

Distance ranging can be done to facilitate locating a corrosion diode in house. For example, the Optus (Australia) method using DSP can be employed using a test waveform such as a chirp signal. A display can show a technician TDR results for both linear and nonlinear distortions on the same screen. If timing matches, a linear discontinuity is the source of nonlinear distortion. This will speed troubleshooting.

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The cable industry desperately needs functional, consistent, correct, upstream triggered spectrum capture capabilities. We don't yet generally have the ability to trigger an upstream spectrum capture for say a particular CM, which would be very helpful for finding PIM. Lacking that, we need alternate methods to identify and localize nonlinear impairments caused by upstream signals. Campos, Hamzeh, and Williams created a solution in 2013 [1]. Ultimately, capturing spectrum from a single CM transmitting would allow us to look for that PIM signature. If we are able to use UTSC to capture that signal, we could identify the distortion by the harmonics. If two narrow frequencies are transmitted, then a mixing product would reveal PIM if it appears. Note that two CMs transmitting at the same time, on two frequencies, could potentially create a mixing product in the plant, though that is less likely due to transmission loss leading to lower energy levels at potential points of corrosion diodes. Still, it may be possible, and may be found.

6. Conclusion

The question plant engineers have been asking is where are the corrosion diodes in my plant? A better question to ask is “where are the high value shunt resistors?” as very many junctions in the cable plant are candidates for a corrosion diode. A loose seizure screw is an example of how a shunt resistor may be created.

Calling a distortion-producing diode a PIM diode or a CPD diode is a relatively arbitrary distinction, as a single diode can be both a CPD diode producing upstream distortion, or a PIM diode producing downstream distortion. CPD is viewed as a subvariant or type of PIM.

For wide bandwidth transmissions, nonlinear distortion, particularly 3rd order, can be detected in adjacent frequency bands using UTSC, aided by a command to a CM to transmit a powerful signal, such as a speed test. An UTSC signal, captured as in-phase and quadrature component signals, can be processed to detect the presence of nonlinear distortions.

Clamping screws need to be correctly tightened to keep corrosion diodes shunted with low value resistors.

Acknowledgements

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Abbreviations

AGC	Automatic Gain Control
ATDMA	Advanced Time Division Multiple Access
CB	Citizens Band
CMTS	Cable Modem Termination System
DC	Directional Coupler
DSP	Digital Signal Processing
FBC	Full Band Capture
FDD	Frequency Division Duplex
FDX	Full Duplex
FFT	Fast Fourier Transform

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IMD	Intermodulation Distortion
LTE	Long Term Evolution
MER	Modulation Error Ratio
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PIM	Passive Intermodulation
RF	Radio Frequency
TDR	Time Domain Reflectometer
UTSC	Upstream Triggered Spectrum Capture

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7. Appendix

7.1. Appendix A Diode Equation for a I-V Curve

The I-V curve (diode characteristic curve) can be found by the following nonlinear equation. The equation is also known as ideal equation of a diode or diode law:

$$i = I_s(e^{\frac{qv}{kT}} - 1)$$

Where

i = Current flowing through the diode

Is = Reverse or dark saturation current (Typical value for silicon is 10^{-12} amperes)

e = Base of the natural logarithm (2.71828)

q = Charge on electron (1.602×10^{-19}) in coulombs, which the absolute value of an electron charge.

v = applied voltage across the diode

k = Boltzmann's constant (1.380×10^{-23} joules/kelvin)

T = Absolute temperature in degrees Kelvin (room temperature is about 300 kelvin)

7.2. Throbbing CPD Caused by Loose Seizure Screws.

In Williams and Rupe, "Common Path Distortion in Cable Networks," [8], CPD is studied.

Instead of using two fixed CW carriers to implement the SCTE-109 CPD lab test procedure, if one (or both) of the two carriers is made tunable, the frequency of a returning CPD CW difference beat will also vary. The two downstream CW carriers are combined at the headend (or node insertion point) to make a headend 2-CW test signal. CPD in plant is revealed by the presence of the difference signal in the return band.

The difference signal is a 2^{nd} order impairment and was observed in 7 out of approximately 70 nodes. 3 of the nodes had a static difference product (CW), but 4 were dynamic.

In [8], dynamic upstream CPD on a sub-split plant was observed to go up and down in power level at a 120 Hz rate. This was observed in four nodes in the hub site containing approximately 70 nodes, so dynamic throbbing was about a 5.7% problem, and static CPD was also about a 4.3% problem. Two CW signals, one at 800 MHZ and one at 840.5 MHz, were applied at analog video carrier level into the downstream, and a modulated difference product at 40.5 MHz was observed. Figure 12 is a plot of RF level in dB vs. time, and repetition rate was 120 Hz. The spectrum analyzer's span was set for 0 Hz.

Fortunately, currently available CPD location gear detects both throbbing and static CPD.

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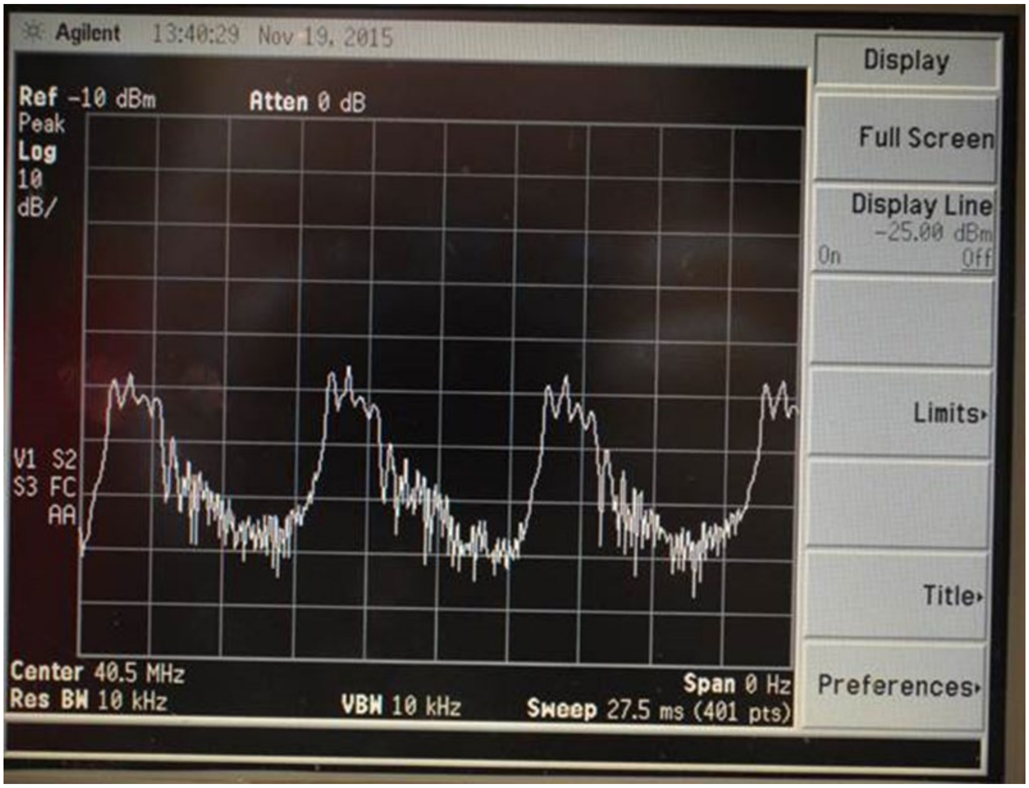

Figure 12 – 120 Hz CPD level vs. time.

In the field the level of a 40.5 MHz CW distortion (difference) signal at was observed to vary at a 120 Hz rate. The 40.5 MHz CPD signal is a distortion product created by mixing 800 MHz and 840.5 MHz CWs.

Figure 13 is a diagram of a seizure mechanism, which is one possible way that 120 Hz modulated CPD can be created. At point "A," a resistive connection is made from a loose seizure screw, and several amperes of AC current are flowing to power amplifiers. This condition causes an AC voltage difference between the seizure screw and coax center conductor that is proportional to AC current. Nearby, at points "B," corrosion diodes are present. The corrosion diodes can only actively mix downstream signals while the AC voltage difference is small. Increasing clamping force makes the distortion disappear.

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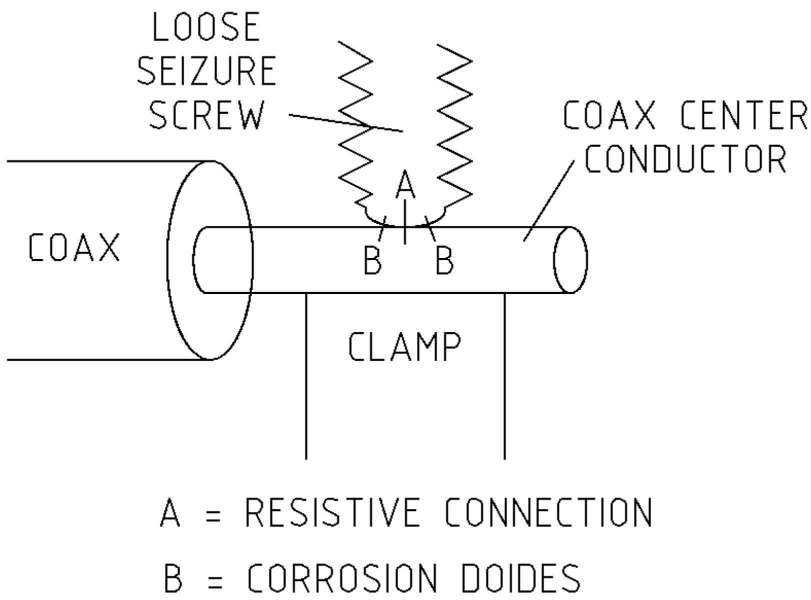

Figure 13 – Shunt resistance-nonlinear distortion

A diagram showing how a loose seizure screw creates a high value shunt resistance, which enables nonlinear distortion to occur.

7.3. Mathematics of nonlinear signals

To evaluate non-linear behavior up to a third order we represent the composite input E_{in} as:

$$E_{in} = \sin(\omega_1 t) + \sin(\omega_2 t) = \frac{e^{i\omega_1 t} - e^{-i\omega_1 t}}{2} + \frac{e^{i\omega_2 t} - e^{-i\omega_2 t}}{2}$$

where $\omega_1 = 2\pi f_1$ and $\omega_2 = 2\pi f_2$.

The composite output E_{out} is defined in equation 1 as:

$$E_{out} = A \cdot E_{in} + B \cdot {E_{in}}^2 + C \cdot {E_{in}}^3$$

Expanding the composite input signal

$$A \cdot E_{in} = A(\sin(\omega_1 t) + \sin(\omega_2 t)) = \frac{A}{2}\left(e^{i\omega_1 t} - e^{-i\omega_1 t} + e^{i\omega_2 t} - e^{-i\omega_2 t}\right)$$

Expanding the square of the composite input signal

$$B \cdot {E_{in}}^2 = B(\sin(\omega_1 t) + \sin(\omega_2 t))^2 = B((\sin(\omega_1 t))^2 + 2\sin(\omega_1 t)\sin(\omega_2 t) + (\sin(\omega_2 t))^2)$$

$$4{E_{in}}^2 = \left(e^{i\omega_1 t} - e^{-i\omega_1 t}\right)^2 + 2\left(e^{i\omega_1 t} - e^{-i\omega_1 t}\right)\left(e^{i\omega_2 t} - e^{-i\omega_2 t}\right) + \left(e^{i\omega_2 t} - e^{-i\omega_2 t}\right)^2$$

$$4{E_{in}}^2 = \left(e^{i2\omega_1 t} - 2 + e^{-i2\omega_1 t}\right) + 2\left(e^{i\omega_2 t}e^{i\omega_1 t} - e^{i\omega_2 t}e^{-i\omega_1 t} - e^{-i\omega_2 t}e^{i\omega_1 t} + e^{-i\omega_2 t}e^{-i\omega_1 t}\right) + \left(e^{i2\omega_1 t} - 2 + e^{-i2\omega_1 t}\right)$$

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$$4{E_{in}}^2 = \left(e^{i2\omega_1 t} - 2 + e^{-i2\omega_1 t}\right) + 2\left(e^{i(\omega_1+\omega_2)t} - e^{-i(\omega_1-\omega_2)t} - e^{i(\omega_1-\omega_2)t} + e^{-i(\omega_1+\omega_2)t}\right) + \left(e^{i2\omega_1 t} - 2 + e^{-i2\omega_1 t}\right)$$

Expanding the cube of the composite input signal

$$C \cdot {E_{in}}^3 = C(\sin(\omega_1 t) + \sin(\omega_2 t))^3$$

$${E_{in}}^3 = (\sin(\omega_1 t))^3 + 3(\sin(\omega_1 t))^2(\sin(\omega_2 t)) + 3(\sin(\omega_1 t))(\sin(\omega_2 t))^2 + (\sin(\omega_2 t))^3$$

$$8 \cdot {E_{in}}^3 = \left(e^{i\omega_1 t} - e^{-i\omega_1 t}\right)^3 + 3\left(e^{i\omega_1 t} - e^{-i\omega_1 t}\right)^2\left(e^{i\omega_2 t} - e^{-i\omega_2 t}\right) + 3\left(e^{i\omega_1 t} - e^{-i\omega_1 t}\right)\left(e^{i\omega_2 t} - e^{-i\omega_2 t}\right)^2 + \left(e^{i\omega_2 t} - e^{-i\omega_2 t}\right)^3$$

$$8 \cdot {E_{in}}^3 = e^{i3\omega_1 t} - 3e^{i\omega_1 t} + 3e^{-i\omega_1 t} - e^{-i3\omega_1 t} + 3\left(e^{i2\omega_1 t} - 2 + e^{-i2\omega_1 t}\right)\left(e^{i\omega_2 t} - e^{-i\omega_2 t}\right) + 3\left(e^{i\omega_1 t} - e^{-i\omega_1 t}\right)\left(e^{i2\omega_2 t} - 2 + e^{-i2\omega_2 t}\right) + e^{i3\omega_2 t} - 3e^{i\omega_2 t} + 3e^{-i\omega_2 t} - e^{-i3\omega_2 t}$$

$$\begin{aligned} 8 \cdot {E_{in}}^3 = {} & e^{i3\omega_1 t} - 3e^{i\omega_1 t} + 3e^{-i\omega_1 t} - e^{-i3\omega_1 t} \\ & + 3\left(e^{i\omega_2 t}e^{i2\omega_1 t} - 2e^{i\omega_2 t} + e^{i\omega_2 t}e^{-i2\omega_1 t} - e^{-i\omega_2 t}e^{i2\omega_1 t} + 2e^{-i\omega_2 t} - e^{-i\omega_2 t}e^{-i2\omega_1 t}\right) \\ & + 3\left(e^{i\omega_1 t}e^{i2\omega_2 t} - 2e^{i\omega_1 t} + e^{i\omega_1 t}e^{-i2\omega_2 t} - e^{-i\omega_1 t}e^{i2\omega_2 t} + 2e^{-i\omega_1 t} - e^{-i\omega_1 t}e^{-i2\omega_2 t}\right) \\ & + e^{i3\omega_2 t} - 3e^{i\omega_2 t} + 3e^{-i\omega_2 t} - e^{-i3\omega_2 t} \end{aligned}$$

$$\begin{aligned} 8 \cdot {E_{in}}^3 = {} & e^{i3\omega_1 t} - 3e^{i\omega_1 t} + 3e^{-i\omega_1 t} - e^{-i3\omega_1 t} \\ & + \left(3e^{i(2\omega_1+\omega_2)t} - 6e^{i\omega_2 t} + 3e^{-i(2\omega_1-\omega_2)t} - 3e^{i(2\omega_1-\omega_2)t} + 6e^{-i\omega_2 t} - 3e^{-i(2\omega_1+\omega_2)t}\right) \\ & + \left(3e^{i(2\omega_2+\omega_1)t} - 6e^{i\omega_1 t} + 3e^{-i(2\omega_2-\omega_1)t} - 3e^{i(2\omega_2-\omega_1)t} + 6e^{-i\omega_1 t} - 3e^{-i(2\omega_2+\omega_1)t}\right) \\ & + e^{i3\omega_2 t} - 3e^{i\omega_2 t} + 3e^{-i\omega_2 t} - e^{-i3\omega_2 t} \end{aligned}$$

Therefore, by expressing ω as 2πf and analyzing the first second and third order distortion, we have that the frequency components in E_{out} are:
f_1, f_2, $2f_1$, $2f_2$, $3f_1$, $3f_2$, f_1+f_2, f_1-f_2, f_2-f_1, $2f_1-f_2$, $2f_2-f_1$, $2f_1+f_2$, $2f_2+f_1$

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