Coherent Addition of Intermodulation Distortion in Spectrum Analyzers

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Abstract — **Third-order intermodulation distortion testing using CW signals has long been known to be subject to errors due to the coherence of the spectral components generated in the device under test and the analysis device. The same effect occurs when the test signal is noise-like, such as a W-CDMA signal, even though such a signal appears to be noncoherent. This paper demonstrates the effect, so that the reader can be better prepared to optimize the accuracy of measurements of adjacent channel leakage in W-CDMA components.**

I. Introduction

Third order intermodulation distortion provides a challenge for RF engineers working with W-CDMA signals by introducing intermodulation products in the adjacent channel. Accurate measurements of this distortion are critical for designing components with minimal adjacent channel interference. The adjacent channel leakage ratio (ACLR) defined by the ratio of the adjacent channel power to the main channel power is a common indicator of noise and distortion performance. Spectrum analyzers are a powerful tool for measuring ACLR, however internal components in the analyzer also contribute third order distortion [1]. Without being able to distinguish between distortion from the analyzer and distortion from the device under test (DUT), analyzer distortion decreases the accuracy of the measurement. The level of inaccuracy depends on how the distortion products add, whether coherently or incoherently. For incoherent addition, the impact of the analyzer distortion is easily predicted because the powers simply add; however, for coherent addition two distortion components can add together resulting in a wide range of possible power levels depending on the phase relationship which is often unknown. This paper demonstrates the coherent addition of third order distortion, showing that ACLR accuracy specifications for all spectrum analyzer measurements should consider phase uncertainty.

II. Theory

Incoherent signals are incapable of destructive interference, for example two sine waves at different frequencies cannot cancel and the total power of the two waves is the sum of the individual powers.

$$P_T = P_1 + P_2 \tag{1}$$

If P_1 and P_2 are equal then P_T is twice P_1 or P_2. However, two sine waves with the same frequency but different phases are coherent and can add or subtract. The total power is proportional to the square of the sum of the voltages.

$$P_T \propto \left(\left|\vec{V}_1 + \vec{V}_2\right|\right)^2 \tag{2}$$

If V_1 and V_2 are equal in magnitude and phase then P_T is four times greater than the power in a single wave. If V_1 and V_2 are equal in magnitude but 180° apart then the total power is zero [2]. Complex signals can be coherent, incoherent or partially coherent. It is tempting to assume that third order distortion products are incoherent, because they are generated from pseudo-random signals. However, random signals from the same source with the same time waveform can be completely coherent. For example, a random digital signal can be split equally between two different paths. If one signal is inverted, then the signals can be recombined for cancellation [3]. Third order distortion in a DUT and the analyzer are both produced by the same signal and can be completely coherent.

The ACLR measurement accuracy of a spectrum analyzer depends on the change in the adjacent channel power (ACP) due to noise and distortion produced by the analyzer [4]. There are three main ACP components: thermal noise, phase noise, and intermodulation distortion. Each of these components vary differently with mixer power level in the spectrum analyzer [5]. Thus, there is a mixer level where the analyzer contributes the minimum ACP as shown in Figure 1. If all the components from the DUT and the analyzer added incoherently then this mixer level would also provide the best accuracy. However, the coherent addition of intermodulation distortion from the DUT and the analyzer can cause a much greater shift in power than the other incoherent components, and the magnitude of this shift is unknown due to the unknown phase relationships. Therefore, the mixer level that gives the best accuracy is not the same as the mixer level that provides the minimum ACLR of the analyzer. The difference between coherent addition and incoherent addition is illustrated in Figure 2.

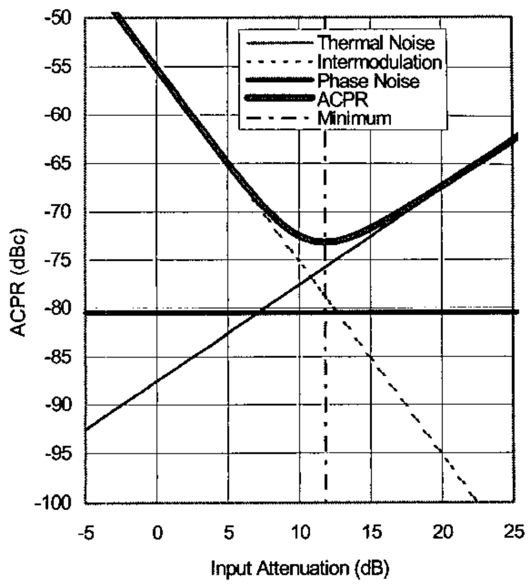


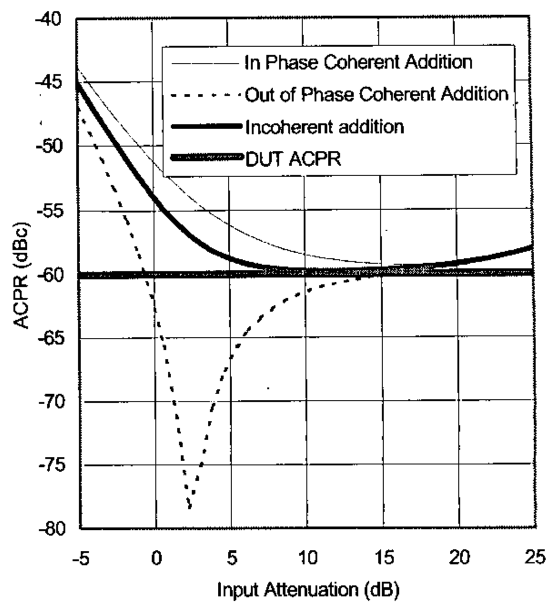
Fig. 1. The three ACP components (phase noise, thermal noise, and intermodulation distortion) add to give an optimal attenuation for minimum ACLR. This minimum does not coincide with the best accuracy due to coherent addition of the distortion products.

III. MEASUREMENT

Coherent addition of third order distortion components was demonstrated for a W-CDMA signal. An artificially produced distortion wave was produced by mathematically cubing the time waveform of a W-CDMA signal. This distortion wave was then added to the W-CDMA signal and fed into the spectrum analyzer. The phase of the artificial wave was switched between 0 and 180° to demonstrate coherent addition and subtraction with the distortion components produced by the analyzer.

First, the baseband I and Q waveforms for W-CDMA signals were downloaded from the Agilent E4437B ESG-DP Series Signal Generator and imported into MATLAB [6]. The signal source modulates the I and Q waveform to result in a composite signal given by

$$V = I\sin(\omega t) + Q\cos(\omega t) \quad (3)$$



Fig, 2. This graph shows the combination of adjacent channel noise from a DUT (–60 dBc) with noise from a spectrum analyzer where the intermodulation products add in three different ways: in phase coherent, out of phase coherent, and incoherent. Given typical values for an Agilent Performance Spectrum Analyzer (E4440A), the total ACLR varies dramatically between the three curves.

Therefore, this waveform was cubed in MATLAB to simulate the distortion produced in the analyzer. V^3 can be written in terms of sin(ωt), cos(ωt), sin(3ωt), and cos(3ωt). The tripled frequencies are thrown away because they are out of band, so the remaining expression gives

$$V^3 = \frac{3}{4}(I^3 + IQ^2)\sin(\omega t) + \frac{3}{4}(Q^3 + I^2Q)\cos(\omega t) \quad (4)$$

Converting this back to baseband gives a new I and Q waveform for the distorted wave

$$I_d = \frac{3}{4}(I^3 + IQ^2) \quad (5)$$

$$Q_d = \frac{3}{4}(Q^3 + QI^2) \quad (6)$$

where I and Q represent the I and Q waveform of the W-CDMA signal. I_d and Q_d were multiplied by a constant to provide an ACLR of –48 dBc with the appropriate phase. Then, the distorted wave was added to the main W-CDMA signal resulting in

$$I_n = k_1 I_d + I \quad (7)$$

$$Q_n = k_1 Q_d + Q \quad (8)$$

A second W-CDMA signal was produced with a 180° phase shift in the distortion components by subtracting I_d and Q_d from the W-CDMA signal to give,

$$I_{n180} = -k_2 I_d + I \quad (9)$$

$$Q_{n180} = -k_2 Q_d + Q \quad (10)$$

where k_2 and k_1 are normalizing constants chosen to give the desired ACPR. The new I and Q waveforms, I_n and Q_n, were uploaded into the Signal generator, modulating a carrier at 2 GHz, and fed into the RF input of the spectrum analyzer. The source amplitude was adjusted until the distortion components of the analyzer were equal in power to the artificially introduced distortion. The I and Q waveforms were then switched to I_{n180} and Q_{n180}. The measured ACP dropped 15 dB down to the noise floor of the source as seen in Figure 3. The input attenuation of the analyzer was increased by 20 dB and the experiment was repeated to verify that the change was purely from coherent interaction with the analyzer distortion products. Now, switching from one waveform to the other resulted in no significant change in power. At that mixer level the noise and distortion from the analyzer are insignificant, so any change in power has to be inherent to the two waveforms. Because there was no change at a low mixer level, the 15 dB change at a high mixer level must be from coherent addition.

IV. Conclusion

The assumption of coherent or incoherent addition of the distortion components has a large effect when calculating the accuracy of a spectrum analyzer for measuring ACLR. This paper demonstrates the coherent addition of intermodulation distortion. Therefore, the measurement uncertainty resulting from unknown phase relationships must be included in the overall inaccuracy.

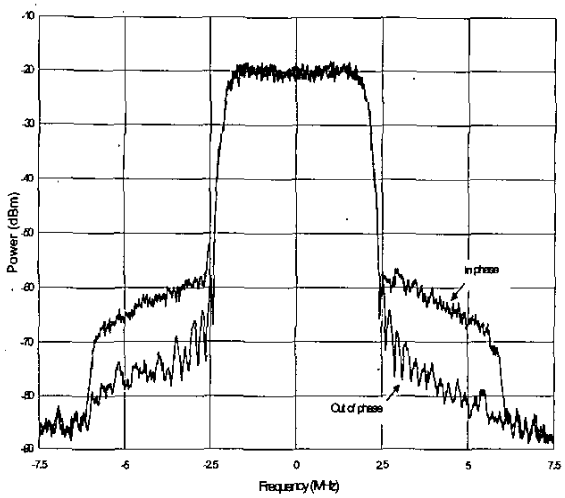


Fig. 3. This graph shows the change in ACP resulting from a 180° phase shift of the artificial distortion.

References

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