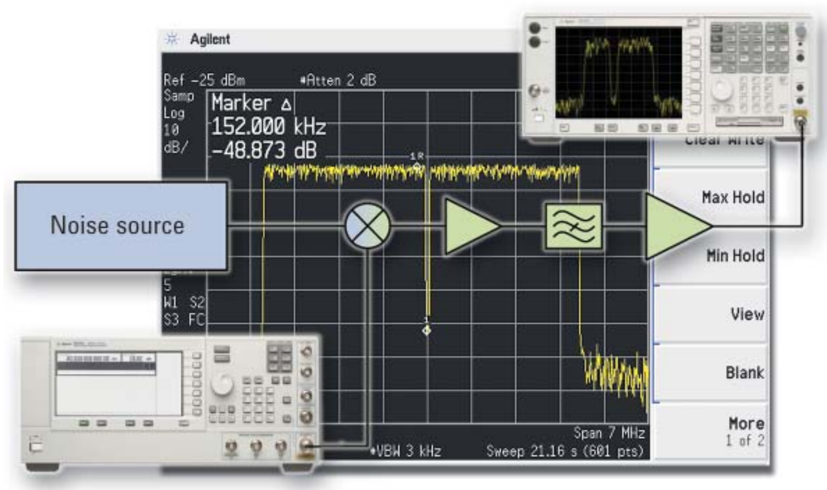
Improved Methods for Measuring Distortion in Broadband Devices

Application Note

Introduction

Recently developed advances in digital modulation and signal processing have enabled commercial and defense communication systems to transmit data at previously unattainable rates. Similar advances in the RF, microwave semi-conductor and transmission line technologies have allowed new communications systems like LTE and WiMAX™ to operate multi-channel communication on the order of tens of megahertz while modern radar and satellite communications systems can now operate over hundreds of megahertz of bandwidth so they can meet or exceed their mission needs.

This paper illustrates that it is more important than ever to characterize broadband commercial and defense systems for linearity. In determining the overall linearity of these systems, we will focus on the tests used to determine the level of a system's distortion products and how they relate to Intermodulation Distortion (IMD) and Intermodulation Distortion Noise (IMDN). Finally, we will compare these test methods and the instruments used.



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What is Distortion?

Before we discuss these tests it is important to understand what distortion is and its effect in broadband systems. The basic causes of distortion in a communication system are due to the non-linearity of the amplitude response versus the input level or the non-uniformity of the phase response versus the frequency of the input signal. There are several types of distortion. They are described below with respect to the mechanisms that cause them.

1. Harmonic distortion: This is typically generated by amplitude transfer characteristics of a circuit or device, preventing it from precisely tracking the input signal. It generates integer multiples of the input signal frequencies.

2. Intermodulation distortion: A spurious output resulting from the mixing of two more signals of different frequencies, whether created in the system or not. The spurious outputs occur at the sum and difference of integer multiples of the input frequencies. See Figure 1.

3. Crossover distortion: The result of characteristics at the device level which occurs when the device changes operating modes (operation class, push-pull).

4. Cross-modulation distortion: Occurs when modulation on an input signal is transferred to another input signal due to circuit linearity.

5. Phase distortion: Results from the deviation from a constant slope of the output signal phase versus frequency response of the circuit. This mechanism can cause echo responses at the output that precede and follow the original input signal.

These types of distortion, while created differently, manifest themselves by distorting the input signal. Each will contribute to harmonic and non-harmonic spurious outputs from the circuit or system. In broadband systems where multiple input signals are present, all of the mechanisms above contribute to IMD, which reduces the signal to noise of the circuit or system, degrading overall performance.

The noise-like nature of the data signals in broadband systems spread the effects of the IMD into broadband distortion. This effect creates noise-like components that degrade system performance over a broad range of frequencies. We call this intermodulation distortion noise (IMDN). Let's now discuss how to measure IMD.

Measuring IMD using Two Tone Intermodulation (IP3)

There are several techniques for evaluating IMD. Measurements of the magnitude of odd order harmonic products (3rd, 5th, 7th...) can be taken, however this technique is tedious in relating the IMD to the system linearity. A more simple and repeatable method is the two-tone third order intermodulation technique (IP3). The IP3 technique measures the third order distortion products produced by the non-linear elements of the system under test when two tones, closely spaced in frequency, are applied to the inputs of the system (See Figure 1). These distortion products are so close to the original input signals that they cannot be filtered out and therefore represent significant interference in communications systems.

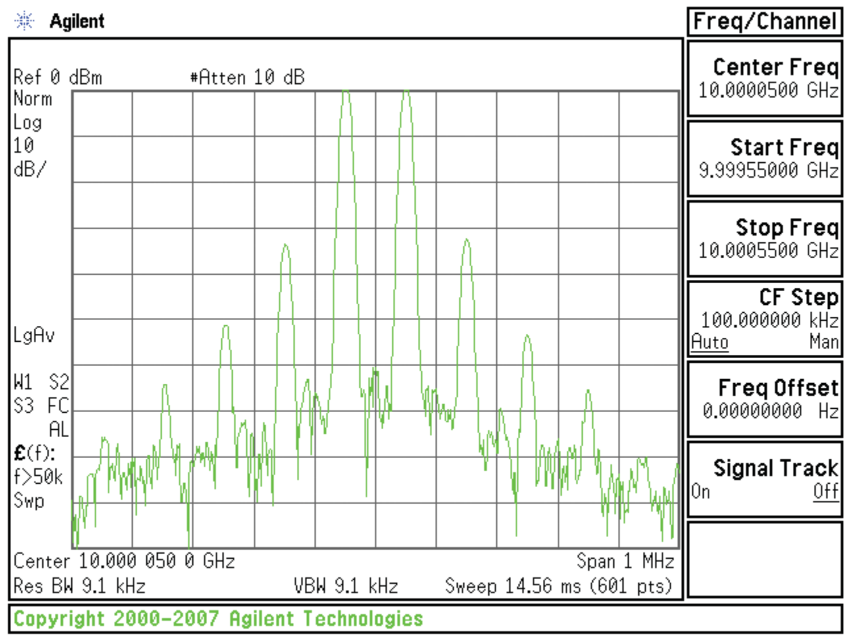


Figure 1. Multiple output distortion tones in a non-linear system

If F1 and F2 are the frequencies of the two test tones, then the third order distortion products occur on both sides of the input tones at 2F2-F1 and 2F1-F2. Assuming the amplitudes of the tones are of equal amplitude, then the difference between the levels of the input tones and third order products is defined by the following equation.

IP3 = Po-Po3

Where Po is the level of one of the output tones and Po3 is the level of the third order product on either side of the two tones in dB.

The two tones injected into the system must be free from any third-order products. They are combined, or summed, at or before the system input. If they are not well isolated, they modulate each other and cause distortion. A signal combiner with good input-to-input isolation is recommended to minimize distortion of the input tones.

In a non-linear system a one (1) dB increase of the input signal will create a two (2) dB decrease in the IP3 measurement. Although these measurements are accurate and will indicate the level of the IMD, they do so only at one input signal amplitude. They only provide the IP3 measurement of closely spaced signals as shown in Figure 1. This is a narrow band measurement that when used to characterize a broadband channel would be prohibitively time consuming. Because of this, the two-tone method is only useful in characterizing the IP3 performance of narrow channels carrying one or a small number of narrow band carriers.

IP3 versus NPR

Noise in a communication system is essentially the sum of thermal noise and intermodulation distortion noise. As discussed, intermodulation noise is caused by receiver or transmitter nonlinearities. Intermodulation noise is critical because it is the only term whose contribution is proportional to increases in channel loading (increase in traffic).

One of the effects of IMDN is the degradation of the system signal-to-noise ratio (S/N), and therefore the degradation of the Bit-Error-Rate (BER) performance (assuming a digital system). In a broadband system, the two-tone measurement method does not provide enough of the required data to determine BER performance.

In contrast, using a broadband stimulus, the Noise Power Ratio (NPR) test creates large signal peaks that stress the communications channel more than IP3 can with two tones. Due to the nature of this stimulus the NPR method is the most accurate method of reproducing multi-carrier intermodulation effects and determining the system BER performance under real traffic conditions.

History of Noise Power Ratio

The concept of Noise Power Ratio (NPR) has been around since the early 1950's. It is still used today in analog Frequency Division Multiplexing (FDM) telephone systems. In these systems, 4-kHz wide voice channels are "stacked" in frequency bins for transmission over coaxial, microwave, or satellite equipment. A group of channels is composed of 12 voice channels and occupies a bandwidth of 48 kHz. These 48 kHz groups can then be combined to occupy a bandwidth of up to 8.2 MHz.

At the receiving end of the transmission link, the FDM data is de-multiplexed and converted back to 4-kHz individual voice channels. The FDM signal is therefore composed of many individual voice channels and passed through amplifiers, repeaters, channel banks, etc., which add noise and distortion to the signal. Early studies at Bell Telephone Labs (Reference 1) led to the conclusion that the composite signal in an FDM system having more than 100 channels can be approximated by Gaussian noise having a bandwidth equal to the bandwidth of the combined FDM signal.

The quality of an individual voice 4-kHz channel is tested by using the random data traffic on all the active channels except the specific channel under test. Noise and intermodulation distortion products fall into the unused channel causing less than ideal performance. The individual channel can then be measured for its NPR using a narrow-band notch (band stop) filter and a specially tuned receiver which measures the noise power inside the 4-kHz notch. NPR is simply a measure of the "quietness" of the unused channel in this multi-channel system.

A Modern Description of Noise Power Ratio

Today NPR is also used as a figure of merit for evaluating the performance of all types of solid state and Traveling Wave Tube (TWT) power amplifiers, transmitter and receiver circuits with regard to IMD. Evaluation of NPR requires a stimulus able to apply either an Additive White Gaussian Noise (AWGN) or a Narrowband Gaussian Noise (NBGN) signal to the device under test (DUT).

The stimulus can be generated either by analog or digital means, and the analysis can be carried out by digital or analog methods. While the two approaches are equivalent, analysis shows that the digital approach is superior in repeatability and execution time. Special care is taken to highlight and explain the differences between these two techniques.

Many factors influence the result of an NPR measurement. These include the characteristics of the stimulus used and the specifics of the measurement technique. The stimulus used for the evaluation of NPR is shown in Figures 2 and 6. It consists of a signal with AWGN or NBGN characteristics, from which a portion of the spectrum has been removed. This stimulus is applied to the DUT and the output is observed on a spectrum analyzer. Any non-linearity in the DUT leads to the generation of spectral components within the spectral notch, also shown in Figure 2. NPR is the ratio of the average power across the spectrum of the notch compared with the average power in an equal bandwidth of the pass-band of the stimulus.

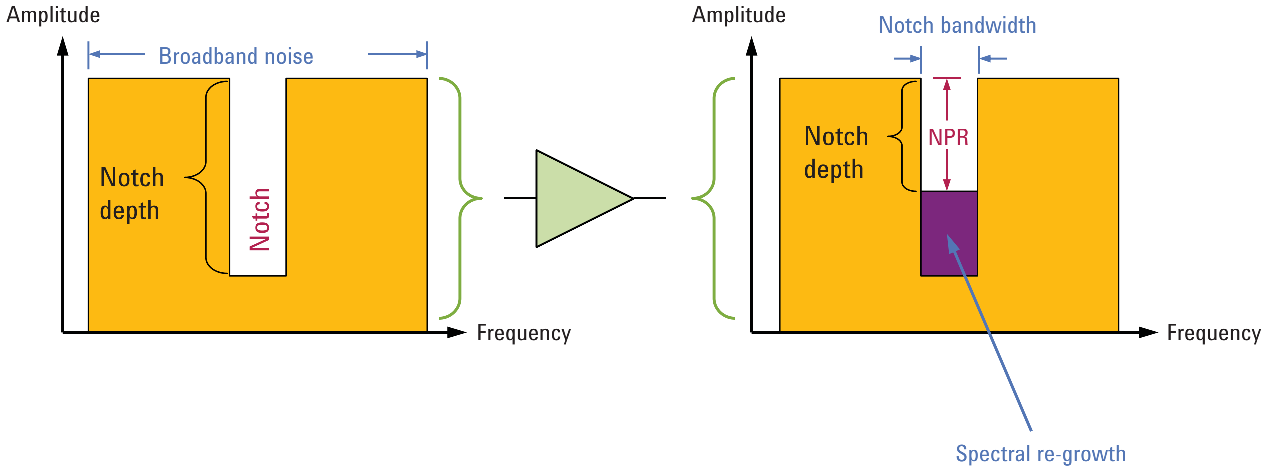


Figure 2. NPR stimulus before and after the device under test

Characteristics of NPR Stimulus

The following parameters define the NPR stimulus:

1. Average power: The total average power in the stimulus signal which can be measured with a conventional averaging power meter.

2. Occupied signal bandwidth: The width of the spectral content of the signal and all its components in the spectrum above a given amplitude threshold. The power can be measured as the sum of the individual spectral components in the spectrum or if the spectrum is rectangular, the power is the product of the power spectral density (Watts/Hz) and the occupied bandwidth (Hz). If the spectrum is not rectangular in shape, then one can invoke the concept of noise bandwidth. A non-rectangular spectrum introduces more uncertainties in the specification of the stimulus.

3. The bandwidth of the notch: The frequency width of the notch over which the noise power is measured. This is only true if the noise power measured in the stimulus notch is substantially lower than the noise power measured on the DUT. A separation of 13 dB gives an error of +0.25 dB in NPR, while a 15 dB separation results in an error of + 0.1 dB. If the separation is less than 10 dB corrections are needed. A non-rectangular notch shape leads to a more complex description of the stimulus and more uncertainty in the mea surement.

4. The spectral shape of the pass band: A non-rectangular shape leads to different intermodulation distortion than a rectangular shape. It is essential that the shape be uniform from one measurement to the next.

5. Statistics of the noise: The traditional NPR test uses an Additive White Gaussian Noise signal. Parameters that can be used to measure the power density of this noise-like signal are the mean, the root mean square (RMS) values of the power. The probability density (PDF) or complementary cumulative density functions of the signal (CCDF) can also be used to characterize this type of signal.

6. Peak value of the noise signal: This is described by the peak to average ratio, also known as the crest factor. This parameter is used because it is an indication of the 'stress factor' of the stimulus. It is expected that a higher crest factor will give rise to more inter-modulation distortion for the same average power and spectral shape in the stimulus.

7. Probability Density Function (PDF): This is another interpretation of the peak to average ratio of the noise stimulus. Plotted as a histogram versus the signal in the time domain. It provides statistical information on the noise signal.

8. Complementary Cumulative Density Function (CCDF): These curves illustrate what percentage of the time a signal spends at or above a given signal power. It is plotted on the y-axis as the percent of time a signal exists above a specified level on the x-axis. A full description of CCDF is presented in Appendix B.

White noise and synthetic noise

The terms white noise or AWGN refer to noise that does not repeat in time. It is characterized by a continuous spectral distribution rather than a discrete distribution as in the case of synthetic noise. The statistics of white noise depend on the type of source being used. In the case of the solid state avalanche diode the noise statistics depend on the material type and biasing of the diode. Average power is constant when measured in a sufficiently long period. Peaks in amplitude occur at random and are therefore not predictable in a precise manner.

The term synthetic noise in this paper refers to noise generated by digital means. It is characterized by a finite repetition period and it is very repeatable in amplitude versus time. In the frequency domain, the spectrum is finite with a band limited spectral line spacing equal to the inverse of the repetition period. The statistics are precise and repeat with each period.

Synthetic noise is very useful in measurements for a number of reasons:

1. The predictable period gives the shortest possible interval for averaging which leads to fast measurements with high confidence levels.
2. Triggers and timing signals can be used to start and end the averaging period. The statistics are well defined and repeatable, allowing accurate and repeatable characterization of a DUT in a predictable and relatively short time.
3. The PDF or CCDF of the input noise can be adjusted with advanced digital signal processing techniques to apply varying stress levels to the DUT. These terms are more fully discussed in Appendix B.
4. It is possible to distinguish inter-modulation distortion products from device noise or receiver noise. This allows evaluation of NPR possible under low SNR conditions. This situation often arises when the DUT has a large gain, as in satellite communications transponders.
5. Synthetic noise generator parameters are accurately reproduced from unit to unit.

For the reasons stated above conventional white noise excitation is not the best stimulus for NPR measurements. A stimulus that approximates the actual traffic as much as possible should be used. With synthetic noise one can create a precise 'brick-wall' spectrum that is accurate, stable and repeatable.

The Analog Technique

First let us take a look at the analog NPR technique. This is always characterized by an analog white noise or AWGN stimulus as well as a frequency selective analog measurement receiver, such as a traditional swept spectrum analyzer. See Figure 3.

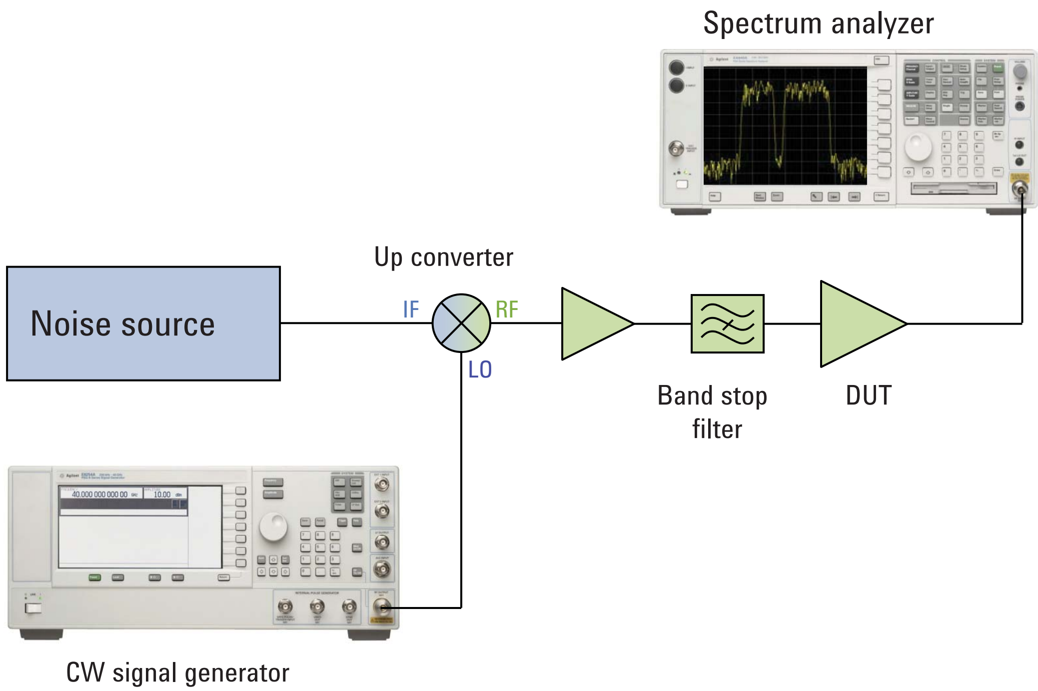


Figure 3. Traditional (analog) NPR test setup

The analog stimulus

The stimulus is generally created by taking the output of a noise tube or noise diode and conditioning it with amplification, frequency translation and band-pass and band-reject filtering. The spectrum of such a signal is continuous and its spectral shape is highly dependent on the actual filters used. Reproducibility from unit to unit is dependent on the filter tuning quality of the center frequency, width and shape factor as shown in Figure 4 and should be a source of concern particularly when testing on multiple test sets.

The RMS value of the signal is equivalent to the standard deviation in a Gaussian process and is actually the square root of the power as measured on a power meter or other true RMS indicating device. The measured value of the power fluctuates in time so the longer the averaging period, the more repeatable the measured values will be. It can be shown that the standard deviation of the measured power is 1/ (square root of the number of independent samples). Thus, if several sets of 100 samples are taken and the RMS value of each set is computed, the standard deviation of the RMS power for each set is 0.1, or approximately ±0.5 dB.

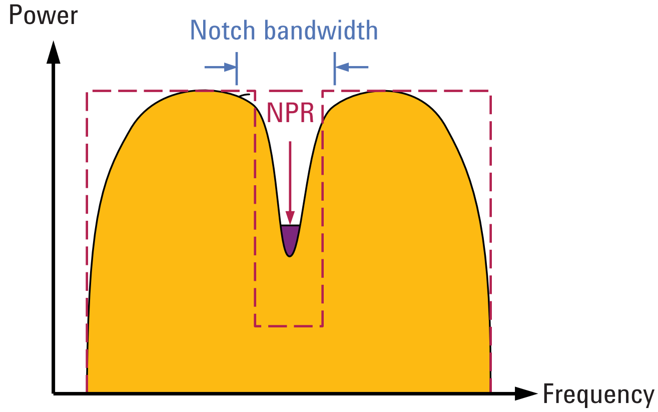


Figure 4. Spectral shape of analog NPR stimulus

The analog measurement receiver

A frequency selective instrument like a swept spectrum analyzer is typically used for the measurement. This provides an accurate measurement of the peak of the noise power of the stimulus to the bottom of the notch. The resolution bandwidth selected should be as wide as possible while still maintaining a capability to resolve the notch precisely.

Let's quickly examine some basics of the analog measurement process. If we are measuring the linearity of the 25 MHz bandwidth channel then a 25 MHz bandwidth noise signal and a 250 kHz to 2.5 MHz notch could be used. The resolution bandwidth should be no more than 10 kHz. When noise is passed through a 10 kHz wide filter and sampled, the spacing of the samples must exceed 1/ (10 kHz) or 100 us for the samples to be statistically independent. Therefore, in order to obtain RMS value estimates with a standard deviation less than 0.1, the averaging time must be at least 100 times 100 us = 10 ms per sample. A spectrum analyzer sweeping over a 1 MHz band with a 10 kHz resolution bandwidth would need to have a video filter that would slow the sweep down to at least 1 MHz/10 kHz x 10 ms = 1s. This condition ensures that the standard deviation of the fluctuations is less than 1 dB and that 96 % of the fluctuations are within 3 dB or ±1.5 dB. This is a measure of repeatability and is improved to ±0.5 dB by taking 10 averages of the 1s sweep. A further improvement to ±0.25 dB requires 40 averages or a measurement time of 40s. This will now be compared to the digital technique.

The Digital Technique

Measurement system configuration

In the digital technique, the measurement system is comprised of an Arbitrary Waveform Generator (AWG), an RF/microwave synthesizer with a broadband I/Q modulator and a spectrum analyzer that can be programmed as a receiver. The AWG is programmed to generate the baseband noise pedestal signal with the necessary characteristics. The synthesizer is used to up-convert the noise signal pedestal to the device under test's (DUT's) operating frequencies. The spectrum analyzer is used to calibrate the noise signal pedestal and notch for optimum performance and to obtain a reference NPR of the input signal. The finally it is used to measure the NPR at the output of the DUT (See Figure 5).

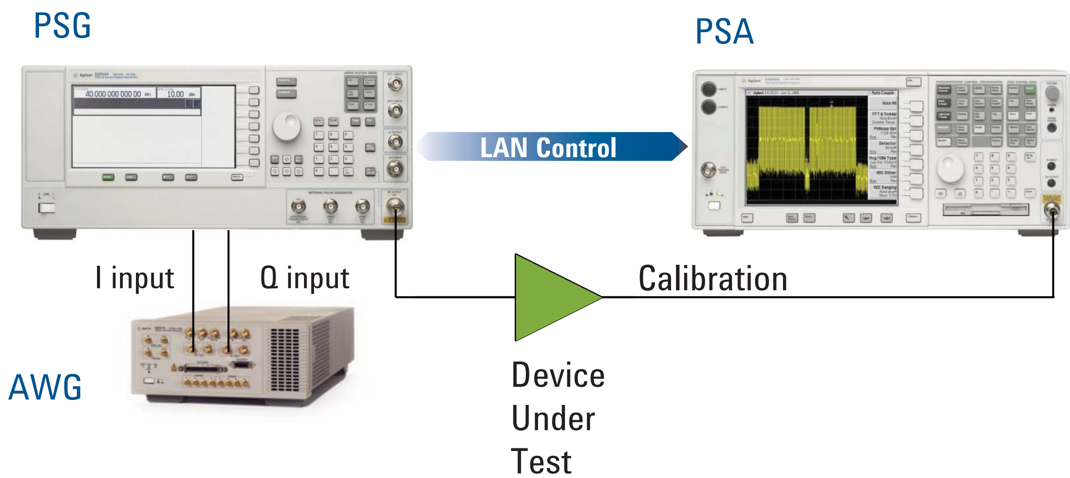


Figure 5. Digital NPR measurement system setup

The digital stimulus

The stimulus shown in Figure 6 is comprised of a series of equally spaced discrete tones with a random phase angle relationship between tones. The phase angles are determined using a pseudo-random bit sequence (PRBS) function initialized with a seed number set in the AWG software and with the angle resolution determined by the AWG bit resolution.

The separation of the spectral lines of the stimulus is determined by the signal source parameters for generating the noise spectrum and the requirements of the notch. Typical notch bandwidths should be between one and ten percent of the overall noise signal bandwidth. For example, it was stated earlier that a minimum of 100 channels of random data traffic would be needed for near Gaussian performance of a noise generator. If 1000 spectral lines are generated with a 1 kHz tone separation, the required bandwidth for a Gaussian noise-like signal would be 1 MHz. If the number of spectral lines is reduced by reducing the bandwidth or increasing the separation of the tones without increasing the bandwidth then this is not going to yield noise-like Gaussian performance. It will impair the integrity of the signal and impact the uniformity of the measured data in the notch.

The nature of the digital stimulus also increases the likelihood that non-linearities created in the channel by the stimulus will generate discrete IMD products in the notch when measured on the spectrum analyzer. This will be mitigated by the noise-like performance of the waveform if enough tones are used and their spacing is close enough. This is discussed in further detail in Appendix A. The benefit here is the flexibility to create a repeatable synthetic noise-like signal with more or less tones that accurately represents system data traffic and the related stress on the system electronics. The digital stimulus also provides an ideal spectral shape and deep programmable notch as needed. In addition, because this signal waveform (Figure 6) is very repeatable, when it is used to evaluate NPR on more than one setup, the measurement repeatability can be transferred to multiple setups.

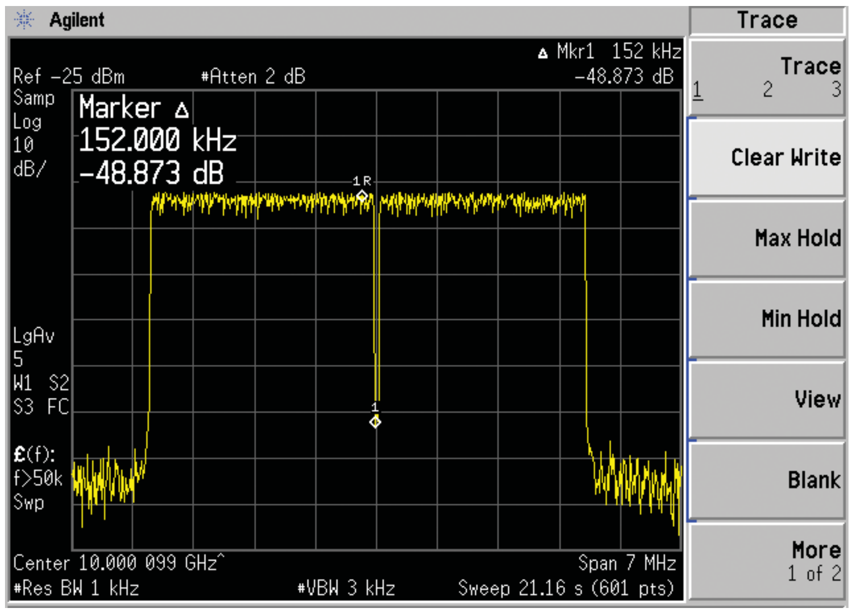


Figure 6. Digital stimulus spectrum measured in line mode

It is also important to note that the exact statistical characteristics or cumulative complementary distribution function (CCDF) curves of the stimulus signal can be programmed into the stimulus waveform. First, the CCDF of the waveform is unique to the specific PRBS phase pattern of the tones generated for NPR. The stimulus CCDF can be adjusted by changing the seed of the PRBS pattern for the waveform. The PRBS seed adjustment will significantly affect the statistical characteristics of the signals with fewer tones and in this case, care needs to be taken with this adjustment. However, if greater than the minimum number of tones is used, the change to the signal's statistics can create a near Gaussian CCDF.

This is a valuable capability in that the relative phase angles of the tone in the waveform can be further programmed to create different CCDF functions. By programming the relative phase of the tones in the NPR signal to certain profiles it is possible to model the linearity of the electronics in a system against specific stress profiles. This is discussed further in Appendix B.

Digital analysis

Now that we have generated our signal with the desired notch, this section addresses the actual measurement system, accuracy, repeatability and execution time. It is important to include execution time, because it has a direct effect on the cost of testing.

Microwave receivers used today are much more accurate than those of the past. The use of higher performance analog to digital hardware and higher speed digital electronics has enabled test instrument manufacturers of spectrum analyzers to replace analog components like RBW filters, log amplifiers, video filters and amplifiers with high speed digital hardware and digital signal processing (DSP) software algorithms. These technology upgrades have eliminated many sources of error and improved the repeatability of measurements in spectrum analyzers in particular. DSP has also improved the signal analysis capabilities of the spectrum analyzer using some of the technologies listed below:

1. Spectrum analyzer RBW and video filter setting can be set in fine increments (10%) to optimize the NPR measurement under many conditions which help to maintain very fast sweep times and optimize measurement throughput.
2. These RBW and video filters are digitally generated to allow the best type, settability, shape factor and acquisition speed for the best throughput.
3. Band power readings enable a quick measure of the average power over a given frequency range rather than relying on a particular point reading using a marker. Given the uneven noise-like measurement of the NPR stimulus pedestal this is very helpful
4. CCDF calculations of the input NPR waveform help determine the stress on the linearity of the channel under test. This is also helpful in determining how the channel distorted the output waveform when measuring the channel output. Refer to Appendix B for more information on CCDF.
5. Test system frequency response corrections can be made and mathematically applied to the input and output waveform measurements.

The following sections will address other areas where the digital spectrum analyzer plays a role in defining and improving NPR test.

Accuracy

The uncertainty of the NPR measurement is the root sum of the squares of several factors including instrument linearity and uncertainty. The method of assessing the uncertainty of the NPR measurement consists of generating a signal with a specific NPR and measuring it on the system shown in Figure 5. The nature of the waveform and how it is measured by the spectrum analyzer is key to understanding the contributions to uncertainty in this measurement.

Due to the nature of the digital stimulus as a series of tones, a common source of NPR measurement error involves improper choice of the reference level for the notch depth. Notch depth should be measured relative to the average pedestal power level. When the top of the pedestal is rippled or titled, the proper reference level should be determined by averaging the changing levels across the top of the pedestal. For spot NPR measurements care should be taken to insure the pedestal level near the notch corresponds to this value. If it does not, either an appropriate correction factor should be added to the observed notch depth or, if the tools are available, the stimulus signal could be pre-distorted so it is flat across the necessary frequency range.

A better available tool was described in the Digital Analysis section. If the spectrum analyzer has band power reading capability, it should be used to remove the uncertainty of the noise pedestal level measurement above and notch level measurement discussed earlier. The power bandwidth should be centered in the notch and its bandwidth adjusted to include the entire notch. After the power reading is obtained the center frequency should be adjusted either up or down to measure the same bandwidth at the top of the noise pedestal. This will mitigate the uncertainty of spot measurements of both the high level and low level portions of the NPR signal.

The spectrum analyzer resolution bandwidth (RBW) settings are also critical to these measurements for two reasons. First, the measurement uncertainty of the reference reading and the average energy in the notch will be affected by the width and the shape of the RBW filter. Second, the RBW filter must be set narrow enough to have no impact on the shape of the noise signal. It should also be narrow enough to reduce the white noise level of the measurement to the level required by the measurement. The noise level is proportional to the RBW and be calculated by the relation.

Noise (dBm) = –174 dBm/Hz + spectrum analyzer noise figure + 20 log (RBW)

The uncertainty of the measurement receiver comes into account in both the input signal measurement and the measurement of the device under test. Fortunately, because NPR is a relative measurement, many of the uncertainties are ratioed out of the test. For example, during the input notch calibration, the measurement is a relative spectrum analyzer measurement which removes all of the frequency response related error. The main contributor is dynamic accuracy of the receiver. This parameter is very small (< ±0.1 dB) today with the use of digital I.F. processing.

Another systematic error is introduced when the measured NPR is close to the depth of the test set notch. This error is most significant when the bottom of the measured notch is within 10 dB of the test set notch depth or of the spectrum analyzer's noise floor (noise near noise). The error can be corrected with the use of the following correction.

$$NPR = 10 \log (10\text{-}(NPRm/10) - 10\text{-}(NPRt/10))$$

Where NPRm is the measured NPR and NPRt is the NPR of the test signal. As NPRm approaches NPRt measurement precision will be degraded even when the correction is used.

Repeatability as a function of time

Repeatability as a function of the measurement system is important to ensure the congruency of data obtained by different systems. This is especially true when multiple test sets are involved or manufacturing sites are separated geographically. In the repeatability examples of Table 1, three groups of measurements were made. Each consisted of 256 observations for which the maximum, minimum, mean and standard deviation values were recorded.

Table 1. Repeatability as a function of time

Group I	Group II	Group III
Avgs: 64, rms exp. Pwr BW 200 KHz Num points 401 RBW: 24 KHz	Avgs: 256, rms exp. Pwr BW 200 KHz Num points 401 RBW: 24 KHz	Avgs: 64, rms exp. Pwr BW 300 KHz Num points 1601 RBW: 5.9 KHz
Min: 38.71	39.11	39.53
Max: 39.99	39.72	39.98
Mean: 39.43	39.4	39.74
S dev: 0.23	0.1	0.073
Time: 2.5 s	12 s	3.5 s

The results illustrate that regardless of different settings of the spectrum analyzer, the NPR readings were stable with very low standard deviation. The main variable is the measurement time which is related to the number of averages taken rather than to analyzer settings like RBW or even the number of points measured. For instance, in column 3 of the table it shows that the standard deviation of the readings can be substantially improved by reducing the RBW without significant sweep time penalty. On the other hand, while increased averaging will stabilize the readings, throughput will be impacted.

Conclusion

We see that it is now more important than ever to characterize broadband commercial and defense systems for their linearity. It is also important to understand the mechanisms that create non-linearities in these systems and the characteristics of the waveforms that cause them. We showed that the traditional two-tone third order intermodulation technique takes too long to evaluate a broadband communication channel or system. We also found that the two-tone waveform does not represent the noise-like waveform of the data transmitted in the channel nor does it properly stress the channel for effective evaluation of linearity.

We demonstrated that NPR can be done two ways; analog and digital. The analog NPR technique, while readily available, has several drawbacks such as uneven noise waveform flatness, complicated stimulus implementation, shallow notch bandwidth, and no correction capability.

The digital NPR system with proper corrections and care to prevent inaccuracies is superior to both IP3 and analog stimulus and analysis measurements. It also shows that with good stimulus generation practices, the discrete stimulus is a great performance improvement over the continuous, analog stimulus for the evaluation of IMD distortion. Its waveform is so repeatable that it can be generated effectively for multiple test stands.

A complete discrete digital stimulus and analysis NPR system allows for ideal noise stimulus with several corrections for optimum noise generation, definable waveform probability distribution to provide optimum stress on channel (system) electronics. It has programmable notch placement for evaluating system performance margins quickly and easily. The digital NPR receiver provides more accuracy, faster averaging and better signal processing to improve measurement repeatability and throughput.

As digital modulation and signal processing technologies continue to advance, commercial and defense broadband systems are going to be able to transmit at higher data rates. Emerging communications systems like LTE and WiMAX will also continue to push the need for increased bandwidth and improved performance, making NPR testing imperative.

Appendix A

Uniformity of spectral line amplitude

When a stimulus with discrete spectral lines is used, the distortion spectral components in the notch will, generally, have non-uniform amplitudes. Figure 7 shows the distortion inside the notch span. Each distortion spectral component is the result of numerous IP3 products. Each product is an independent sample of a random process that is Gaussian or close to it. The actual level of the spectral component is the vector sum of the result of all the products. The intermodulation distortion products involved are 2/1, 3/2, 4/3...M/M-1, where M and N are integers.

In general, all products of the form M/N are possible. Numerous spectral lines are involved in creating the resulting IP3 products. The number of spectral lines is analogous to the number of independent samples considered in the analog method. If we compare the standard deviation of the RMS value of three different stimulus signals with less than the minimum 1000 tones needed to comply with the requirement above, we find that the repeatability of the NPR measurement is directly related. For instance, the standard deviation of measured RMS values 0.41, 0.58 and 0.81 dB results in a repeatability of about ±0.6, 0.87 and 1.2 dB respectively which is three times the standard deviation. It is clear from Figure 7 that there is variation in the level of the individual lines in the notch. This is the fluctuation that can be expected when stimulus signals that do not provide the minimum Gaussian requirement are used. However, the RMS value of a number of adjacent lines has less variation. If more lines are included in the RMS calculation, the variation becomes less.

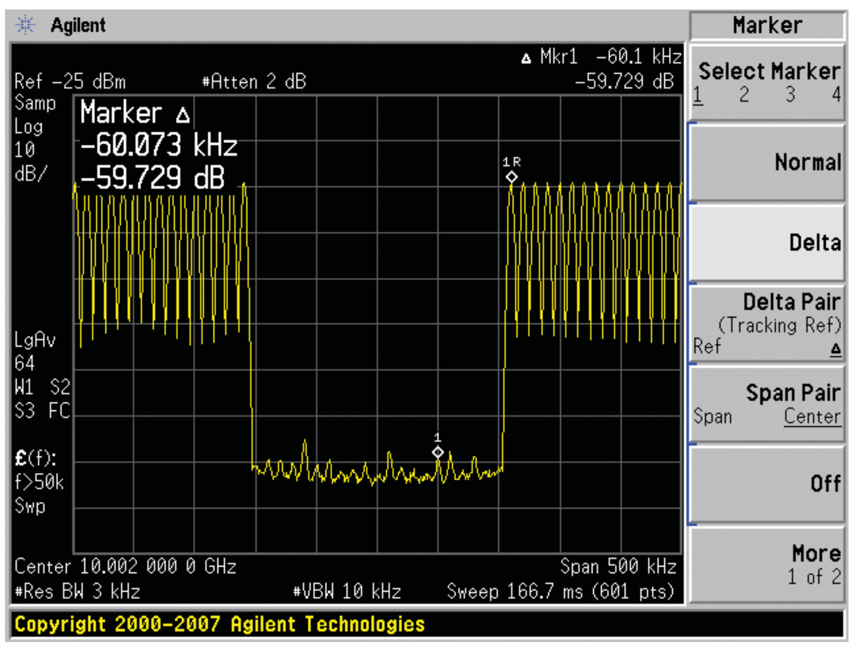


Figure 7. Spectral uniformity with discrete tones

Practice has shown that NPR measurements using the digital stimulus and analysis are valid in terms of producing consistent and reliable results. Table 2 shows the results of NPR measurements made on the same device under test at the same power level, but with different line spacing on the stimulus.

Table 2. NPR as a function of Stimulus Spectral Density

Line Spacing	100 Hz	1000 Hz	10000 Hz	20000 Hz	40000 Hz
NPR (dB)	59.55	59.62	59.9	59.7	59.75

Table 2 shows that the value of NPR is not affected by the spectral density of the stimulus as long as the total number of lines does not decrease. The NPR measurement is then made with the 100 Hz line spacing on the stimulus, but using different random seed values for the generation of the stimulus. The seed values used were 99991, 99997, 00128 and 11111 respectively. These seed values represent the starting point of the PRBS pattern for the computation of the noise algorithm. The results of these NPR measurements are shown in Table 3. Again changes to the seed values show virtually no change in the value of the NPR results.

Table 3. NPR measured for different random functions at 100 Hz Line Spacing

Seed	99991	99997	128	11111
NPR (dB)	59.55	59.4	59.6	59.6

Appendix B

Crest factor and CCDF

Digital modulation and digital signal processing techniques have created revolutionary change in the generation of RF and microwave waveforms. This has yielded complex digitally modulated signals that contain higher peak-to-average power ratios (crest factors) than previously possible.

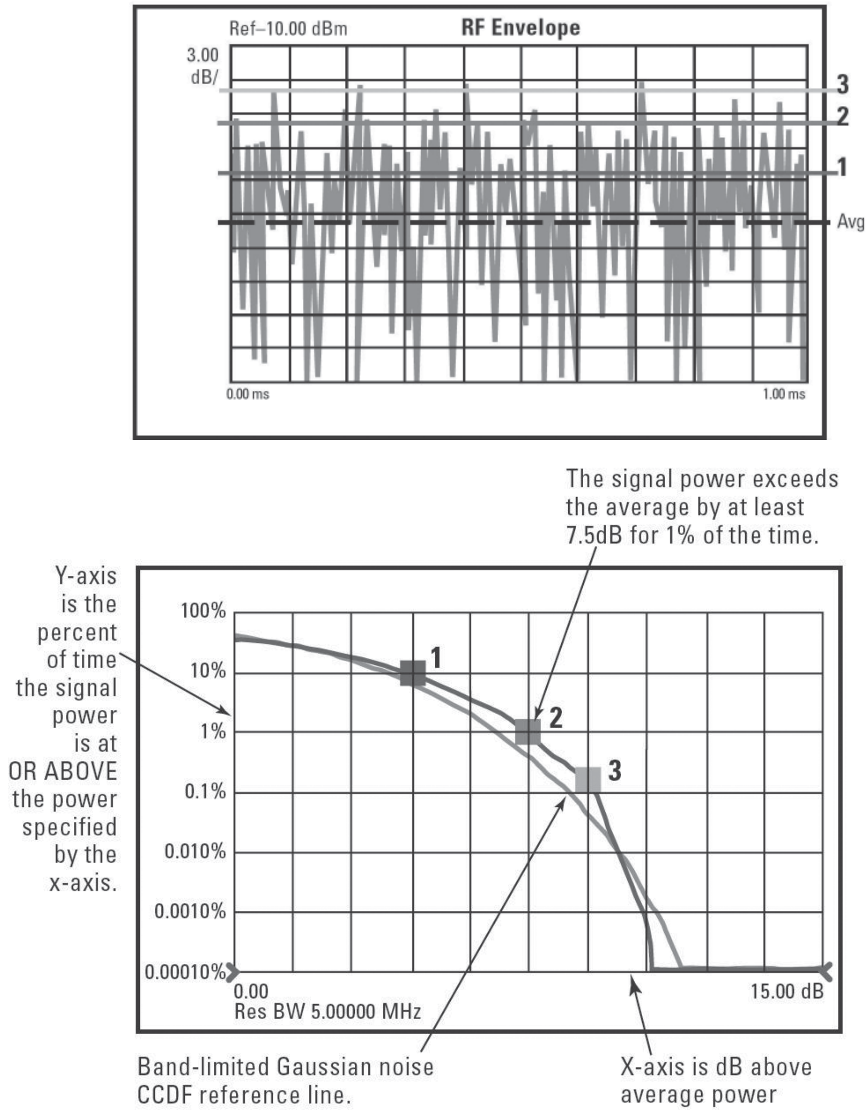
Analog FM systems operate at a fixed power level which have low peak to average ratios. Double-sideband large-carrier (DSB-LC) AM systems cannot modulate over 100% (a peak value 6 dB above the un-modulated carrier) without distortion. Third generation digitally modulated systems on the other hand either combine multiple channels or multiplex extremely high bandwidth serial data. This results in a peak-to-average ratio that is dependent upon not only the number of channels being combined, but also which specific channels are used and how wide they are. This signal characteristic can lead to higher distortion unless the peak power levels are accounted for in the design of system components.

Traditionally, a common measure of stress for a stimulating signal has been the crest factor. The crest factor of a wave is defined as the ratio of the peak voltage to the RMS voltage. The power envelope parameters can be measured by means of a peak power meter and a power-sensing probe. It is easy to extend the concept of crest factor from the voltage envelope to the probability density envelope (PDF), since instantaneous power is the square of the instantaneous voltage.

The ratio in dB is identical in both cases. The significance of a peak in the envelope of the signal, whether voltage or power, is directly related to the amount of stress it places on the device under test (DUT). A high peak that occurs very seldom does not cause as much distortion as lower peaks that occur more frequently. Crest factor is of no value for these waveforms because it does not take into account the percentage of time amplitude peaks are present. This is necessary to accurately reflect the stress on the channel.

A much more powerful measurement of peak- to –average energy in a waveform is the Power Complementary Cumulative Distribution Function (CCDF). CCDF curves provide critical information about the signals encountered in broadband systems. These curves also provide more meaningful peak-to-average power data needed to describe the stress on a communication system. It can also more accurately describe the "stress" on system components that create distortion.

Figures 8A and 8B illustrate this relationship graphically. These graphs show how the time domain of the waveform maps to the CCDF curve. The x axis shows the signal power in dB above the rms value. The y axis shows the percentage of time that the signal spends at or above that level. For more information on the factors that affect power CCDF curves, and how CCDF curves are used to help design systems and components, see Agilent application note, *Characterizing Digitally Modulated Signals with CCDF Curves* (Literature number: 5968-6875E).



Figures 8A and 8B. High peak-to-average waveform in the time domain envelope with corresponding CCDF plot

For an NPR measurement, the statistics of a multi-tone signal can be described in a CCDF plot and compared to the CCDF plot of Gaussian Noise. The CCDF curve of a single Continuous Wave (CW) signal would be a point at 0 dB and 100%. On the other hand, two CW signals at different frequencies create a time-domain waveform with fluctuating amplitude, similar to an AM signal. The CCDF curve of a two-CW signal differs significantly from that of the single CW signal. Figure 9 shows sets of CCDF curves for 4-CW, 64-CW, and 1000-CW signals. As can be seen, increasing the number of tones more closely resembles Gaussian noise when the tones all have random phase relationships. This effect also applies to multiple digitally modulated signals at different frequencies sent through a single amplifier. Many of today's schemes to achieve broad band or multi-carrier signals must consider such effects.

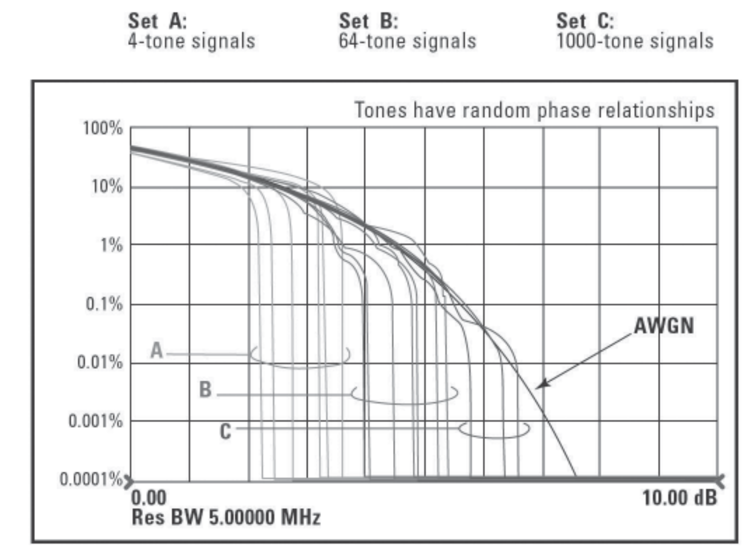


Figure 9. CCDF Curves of Randomized Multi-tone Signals

References

1) *Noise Power Ratio (NPR) – A 65-Year Old Telephone System Specification Finds New Life in Modern Wireless Applications* by Walt Kester and Rob Reeder REV. 0, 10-03-2005

2) *Noise Power Ratio Measurement Tutorial,* by Allen Katz and Robert Gray Linearizer Technology Inc.

3) *Noise Power Ratio: Theory And Applications,* Stan Soonachan, Senior Staff Systems Engineer; Lockheed Martin Missiles & Space, Sunnyvale, CA; 20th AIAA International Communication Satellite Systems Conference and Exhibit 12-15 May 2002, Montreal, Quebec, Canada

4) *Characterizing Digitally Modulated Signals with CCDF Curves,* Agilent Application Note, Literature number 5968-6875E

5) *Agilent Signal Studio for Noise Power Ratio,* Technical Overview, Literature number 5988-9161EN

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