



Multi-Tone Signal Generation with AWGs

White Paper
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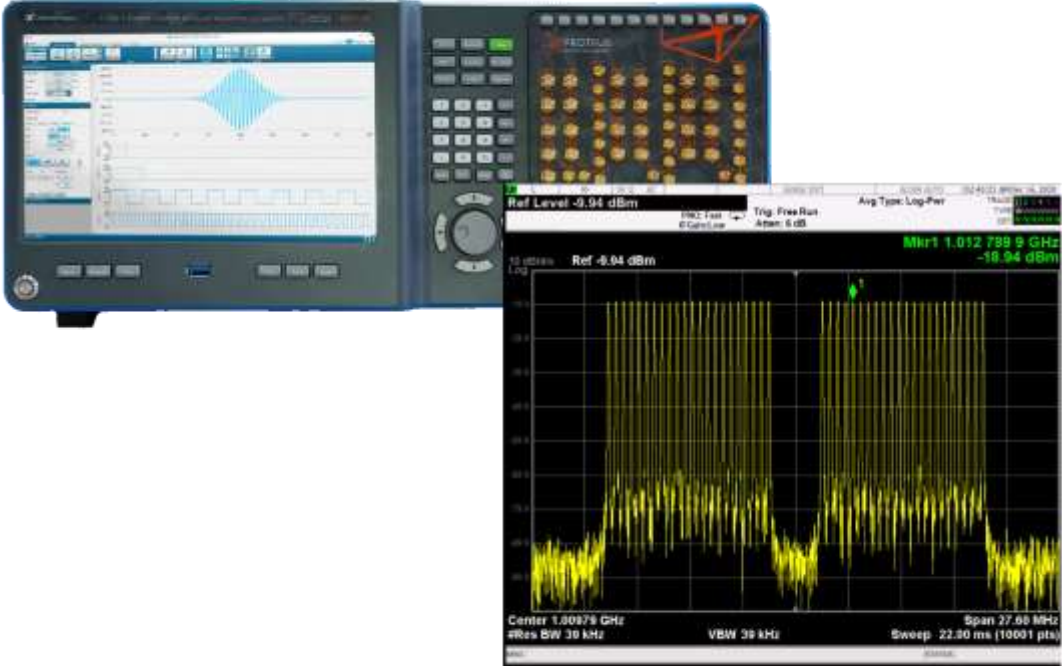


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1 Introduction

This white paper introduces how modern AWGs (Arbitrary Waveform Generators) can generate multi-tone signals that can compete in quality with those generated by multiple CW (Continuous Wave) generators while improving flexibility, number of tones and cost effectiveness.

High-performance AWGs can effectively generate high-quality multi-tone signals allowing users to precisely control all the generation parameters. The combination of raw performance in terms of bandwidth, sample rate and linearity combined with effective correction techniques for linear and non-linear distortions, results in a level of performance previously possible only through the integration of multiple CW generators.



Figure 1.1 Tabor Electronics 9 GS/s Twelve Channel RF Arbitrary Waveform Generator P94812B

2 Multi-tone Signals

Establishing the linear and non-linear behavior of any electric or electronic device or component requires a large variety of test stimuli and measurements. Pure sinewaves are the primary stimulus signal to test the linear and non-linear response of any supposedly linear system. A perfectly linear system will produce just another sinewave at the output of the same (i.e., a filter or an amplifier) or a different frequency (i.e., a mixer or a modulator). A non-linear system will produce other sinewaves at different frequencies in addition to the expected linear component.

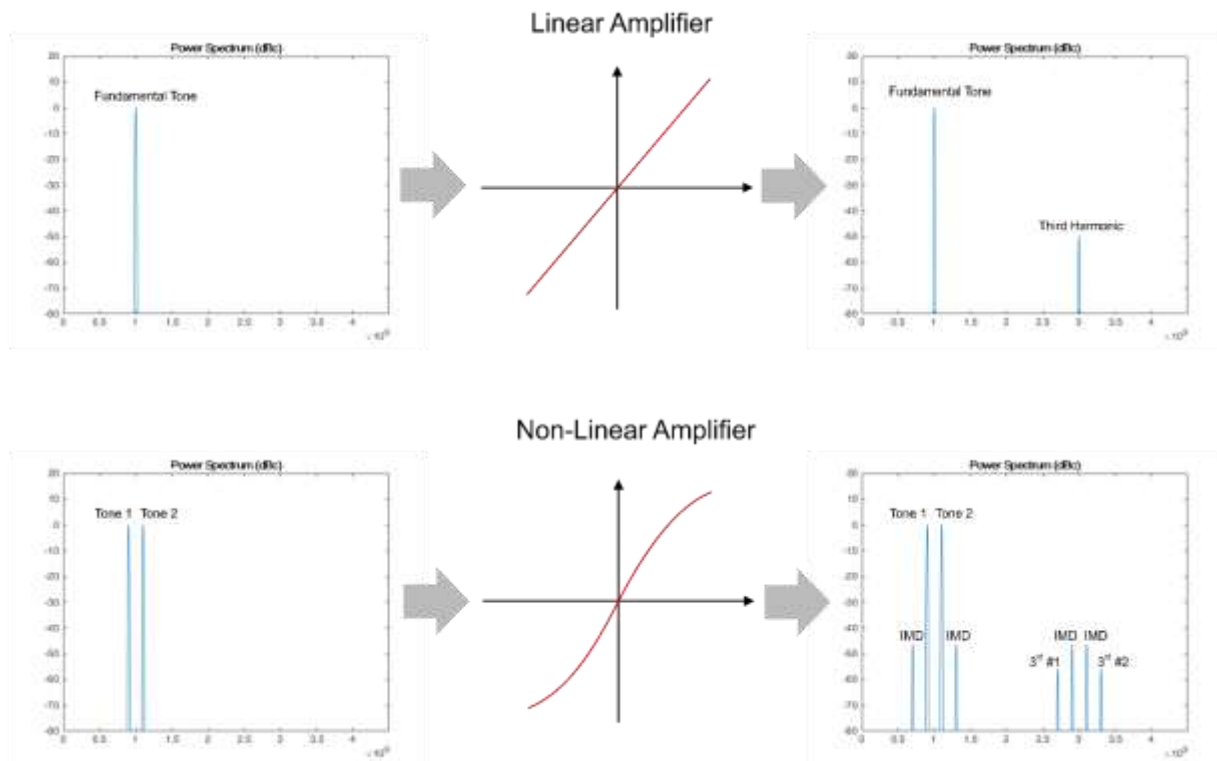


Figure 2.1 Linear systems do not create signal components, at the output at frequencies non present in the input (top). Non-linear systems create signals components at other frequencies (bottom). Those frequencies are not random and come from mixing (intermodulation) of the different components. Depending on the order of the distortion, frequency components can be found at harmonic frequencies or as addition of differences of the frequencies of the components. For one tone, the situation is simple as only harmonics will show up. However, when more than one tone is present, third-order modulation components will show up close to the location of the original tones. In the example above, two tones located at $2 \times f_1 - f_2$ and $2 \times f_2 - f_1$ are visible close to the original two tones.

As those components are located at different frequencies, they can be easily characterized using proper frequency-domain instrumentation such as Spectrum Analyzers. However, these unwanted products do not tell the whole story about how the system or device under test will perform in a real application.

RF signals typically use a limited band and all the components out of this band are removed through filtering. The most important effect of non-linearity on a sinewave is the creation of harmonics at multiples of the original frequency. These harmonics are typically out of the band of interest and even if the non-linear behavior is strong, their amplitude may be attenuated by the linear frequency response of the system. A different approach is using two tones located in the band of interest instead of one. Applying two tones to a non-linear system results in harmonics and IMD (Inter Modulation Distortion) products. Intermodulation products are particularly interesting as they are located at the $n \times f_1 \pm m \times f_2$ frequencies, where n and m are positive integer numbers (n or $m = 0$ are harmonics). The $n+m$ value is known as the “order” of the intermodulation. Again, many of these intermodulation products are located out of the band of interest. However, the third-order intermodulation products ($n+m = 3$) are especially important as some of their frequencies are located in a nearby frequency, potentially in the same or one of the adjacent channels intended for the final application. Measuring the level of the IMD products with respect to that of the test tones as a function of their absolute amplitude, is a good way to specify the non-linearity of the system under test, and to find out the optimal working point for it. One or two sinewaves are not close enough to the typical real-world signals implemented by the actual applications for those devices. A more realistic test signal could be a relatively large number of equally spaced, equal amplitude sinewaves using the full channel. This kind of signal is known as multi-tone.

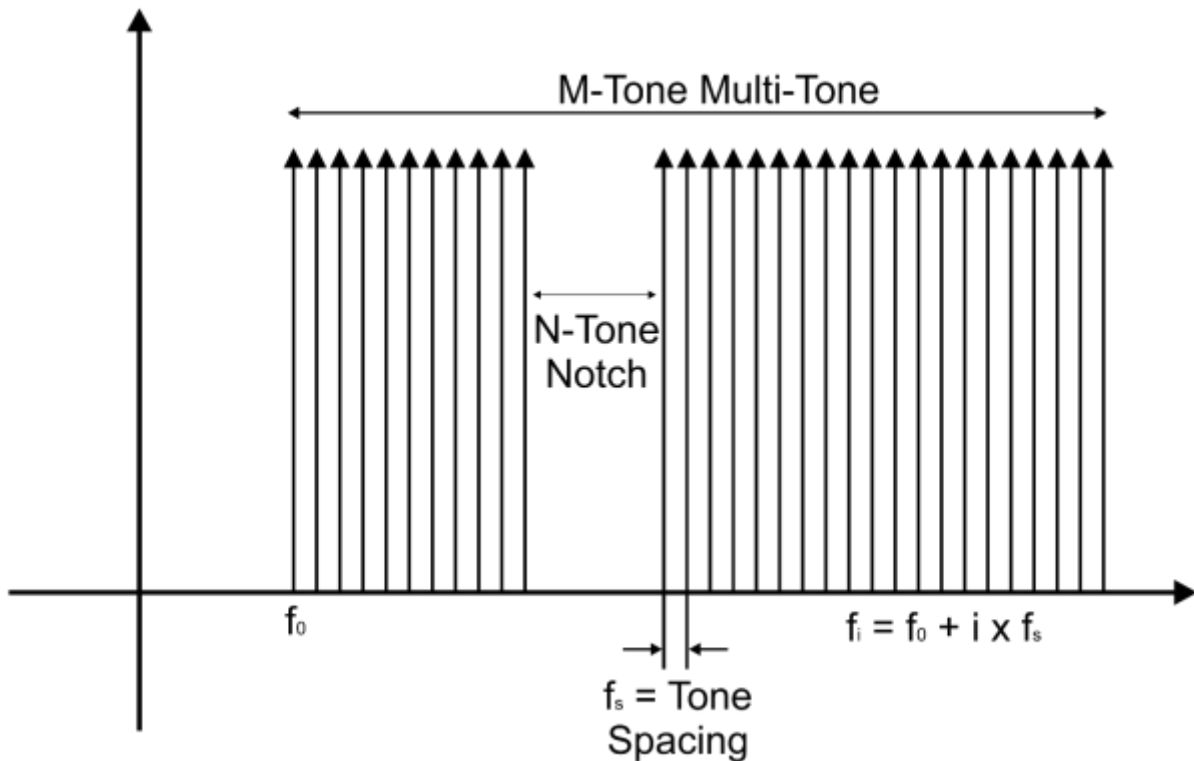


Figure 2.2 Multi-tone signals are simple to describe. They consist of a series of equal amplitude, equally spaced tones at frequencies located in a band of interest. They are ideal to characterize both the linear and non-linear behavior of a system. As tones are equally spaced, intermodulation components appear as tones equally spaced as well. As IMD products located within the band of interest are located exactly at the same frequencies regular tones are, a “notch” may be necessary to observe the IMD products within the band.

Such signals will produce intermodulation products within the channel and the adjacent ones. Intermodulation products within the channel will be located exactly at the frequencies of the tones, so it is very difficult to analyze the non-linearity of the system by performing measurements over the output signal. It will be possible to analyze the IMD products out the channel and to predict the actual ACPR (Adjacent Channel Power Ratio) performance in a working system. The only way to analyze the effects of the non-linear behavior within the channel using a multi-tone test signal is by removing one or more tones, and then measuring the amplitude of the IMD products located at the frequencies of the removed tones. The band of frequencies, where the removed tones were located, is known as the “notch”. The ratio between the average power of the IMD products in the notch and the average power of the regular tones (a component of NPR or Noise Power Ratio) can be used as a merit number directly connected to the non-linear behavior of the device under test.

Multi-tone signals, although simple to describe, may have a very complex and sometimes unpredictable behavior. A very important parameter, with a great influence over IMD, is the statistic distribution of

power over time (typically analyzed through the CCDF, or Complementary Cumulative Distribution Function graph) and the maximum peak power relative to the average power of the signal (known as Crest Factor or PAPR, Peak-to-Average Power Ratio) as shown in the figure below.

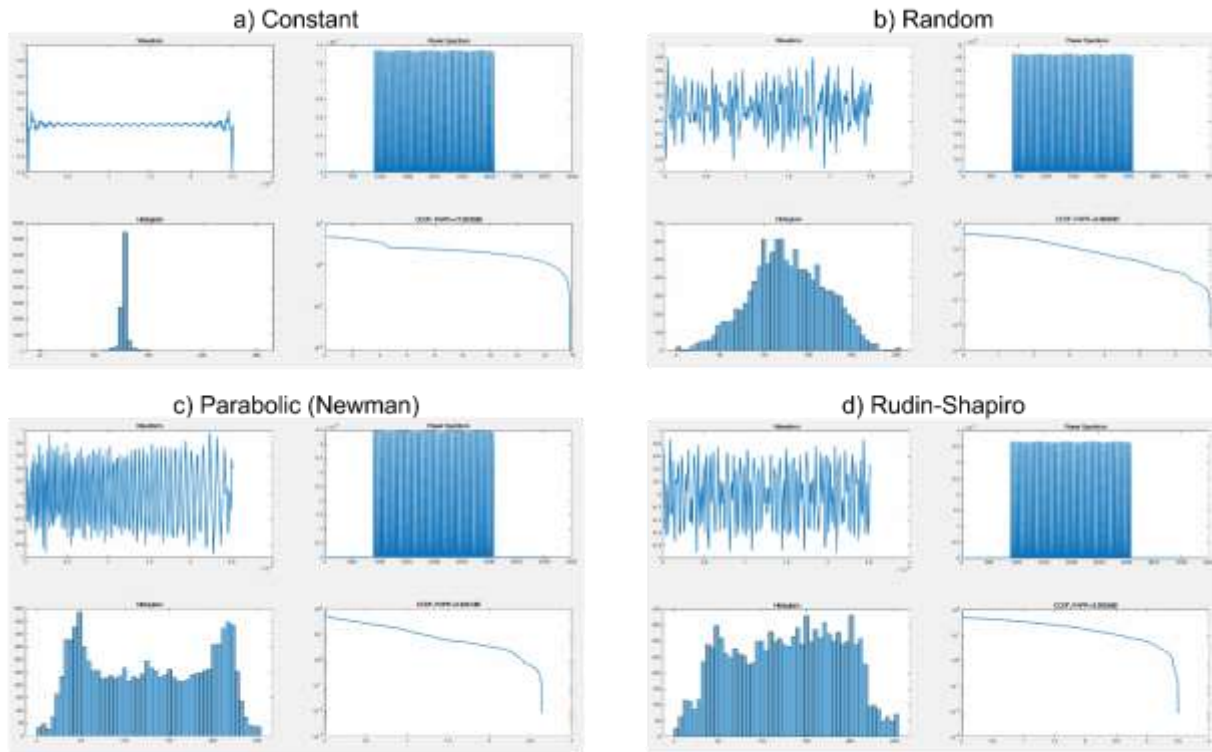


Figure 2.3 Although the definition of multi-tone signals is straight-forward in the frequency domain, their behavior in the time domain depends greatly on the number of tones and the phase distribution for them. Here, four common distributions are shown. In a) the same phase is assigned to all the tones, resulting in a very high Peak-to-Average Power Ration (PAPR). If phase is random b), the resulting signal looks closer to a limited bandwidth noise. The quadratic (or Newman) distribution is shown in c). This distribution results in a very low PAPR (2.6dB) and it does not depend on the number of tones unlike the constant or the random distributions. Additionally, its CCDF (Complementary Cumulative Distribution Function) and histogram is closer to those of a single tone. The statistics of the Rudin-Shapiro distribution are shown in d). PAPR is also low (2.995dB) and it does not depend on the number of tones. It only uses 0° and 180° for all the tones, but their good properties are only valid for a number of tones equal to a power of 2. Its histogram is quite constant over the full amplitude range.

Wireless network, broadcast and mobile telephony signals implement complex modulations with their own typical CCDF and PAPR characteristics. Ideally, multi-tone signals used to characterize any device or system should show a similar CCDF and PAPR profile. Both items are basically influenced by the total number of tones and the phase distribution for the tones. The power envelope for multi-tone signals repeats every $1/\Delta f$ if the relative phase among carriers remains constant. This is typically the case when all the carriers are locked to a common reference. It is sufficient to analyze one of these periods to get

the full picture about the CCDF. Different phase distributions may result in very different CCDF and PAPR profiles for the same number of tones. Some distributions may greatly depend on the number of tones while others may be insensitive to that parameter. These are the most popular and used phase distributions:

- Constant: The initial phase for all the carriers is the same. Therefore, all the carriers reach the maximum amplitude in phase at some moment in time. This means that they show the worst possible scenario for the PAPR parameter. PAPR is directly proportional to the number of carriers.
- Random: When phase is randomly assigned in the full $-180/+180$ degrees range to each one of the tones, the CCDF is close to that of Gaussian noise. PAPR grows gently with the number of tones. However, two different random distributions with the same number of tones can result in a very different PAPR. The statistical behavior of these multi-tone signals may be closer to that of the real-world signals to be processed by the DUT (Device Under Test).
- Parabolic (or Newman): This distribution uses a quadratic expression (thus the parabolic name) to calculate the phase for each individual tone as a function of its position in the sequence. This distribution results in a near optimal PAPR value (2.6 dB while a single tone shows a 0 dB PAPR). The time domain signal is close to a linear sweep with some amplitude variations. A regular, flat, periodic linear frequency sweep (PAPR = 0 dB) will result in a set of equally spaced tones. However, their amplitude will show some ripples, especially in both ends. Additionally, it will have additional tones beyond the initial and final frequencies of the sweep. This is not the case for the parabolic distribution. PAPR is not a function of the number of tones in this distribution. However, its statistical behavior can be far away from that of the actual signals to be handled by the DUT. The parabolic distribution, given its high average power (which result is a high dynamic range), can be especially useful to characterize the linear behavior of any device or component.
- Rudin-Shapiro: This distribution assigns either of two phases (0° , 180°) to each tone following a simple recursive algorithm and it is designed to produce low PAPR signals when the number of tones is a power of two (2^N). Despite its simplicity, it results in a relatively low PAPR (3dB), and it does not depend on the number of carriers when it is a power of two.

While a low PAPR guarantees a good dynamic range for the measurements (as average power is higher for the same peak power), the Parabolic and Rudin-Shapiro distributions spend more time at higher amplitudes than most real-world signals (many of them using OFDM (Orthogonal Frequency-Division Multiplexing) modulation schemes), so the influence of non-linear behavior will be higher if the same peak amplitude is generated, while it will be lower if the same average power is kept. Another important issue is the behavior of the different distributions when a notch is applied to the signal. Random distributions tend to reduce PAPR when a notch is added, while the Parabolic distribution increase PAPR quite gently. Rudin-Shapiro distributions are very sensitive to the introduction of notches or using a number of tones not being a power of two. The conclusion is that for linear response test, the best phase distribution is the parabolic one, as it provides the best dynamic range and SNR (Signal-to-Noise Ratio). For non-linear behavior characterization though, the random distribution may be much more realistic for systems handling complex OFDM-based modulation schemes or multiple, independent signals (such a multi-channel amplifier), while the parabolic or Rudin-Shapiro distributions may be more

adequate for systems using low PAPR modulation schemes (most single-tone modulation schemes such as QAM, N-PSK, FSK, etc.).

Multi-tone signals may be used in a large variety of tests.

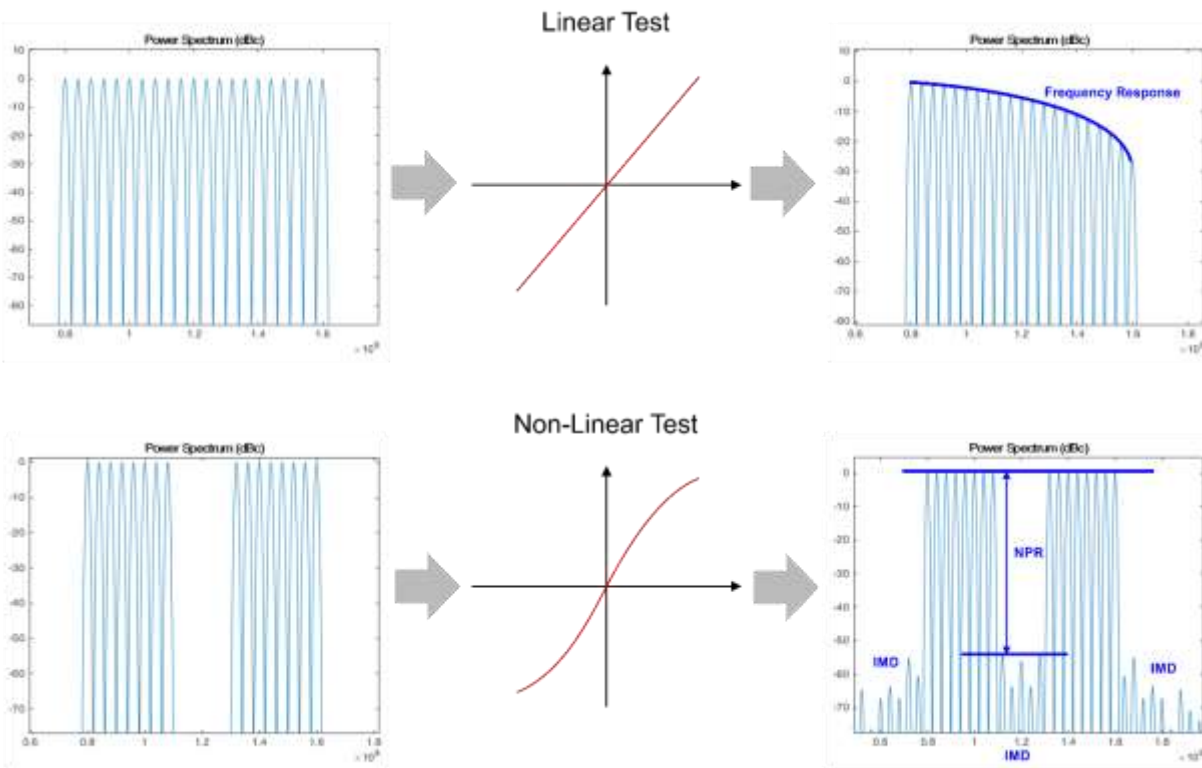


Figure 2.4 Multi-tone signals can be used to test both the linear (top) and non-linear (bottom) behavior of a system. Amplitude and phase linear frequency response can be obtained by comparing the tones at the input and the output. Non-linear behavior can be established by measuring the IMD products out of the band or within an in-band notch. NPR (Noise Power Ratio) testing uses this methodology to assess the overall non-linearity of a system such as an ADC converter.

This is just a short list:

- Linear frequency response: The analysis of the amplitude and phase (if the phase of the tones at the input is known) of the tones at the output of a quasi-linear system will describe the frequency response of the system being characterized.
- IMD and ACPR: Non-linear behavior can be extracted from the IMD products showing up in the adjacent channels (upper and lower bands of equal BW close to the one occupied by the multi-tone test signal) if the IMD products of the test signal itself are much lower than the ones being generated by the DUT's non-linearities.
- NPR (Noise Power Ratio) test: This test is performed by analyzing the IMD products within the channel within an empty band called "notch". Within the notch, no tones are generated so any signal located in the location of the unused tones will result from inter-modulation distortion

and noise within the channel. The NPR value, or the ratio between the power of the signal in the notch and the power of the original tones before removal, is a factor of merit relative to the IMD within the channel.

- I/Q Modulator imbalance characterization: Convenient complex (I/Q) multi-tone signals may be applied to I/Q modulators, so the unwanted images caused by amplitude imbalance and quadrature error can be established over the whole modulation bandwidth at once.
- ADC testing: The NPR measurement methodology can be applied to Analog-to-Digital Converters to establish both the linear and non-linear responses. NPR measurements can be converted to effective bits (ENOB) for narrow and wideband signals in a more realistic way than single-tone tests. However, the useful dynamic range of the multi-tone signal itself must be much better (at least 4 times, or one effective bit) than that of the ADC under test.

Resources & Contact

For more information on microwave signal generation challenges and solutions, review the following resources:

- ◆ White Paper: [Multi-Nyquist Zones Operation-Solution Note](#)
- ◆ Solution Brief: [Envelope Tracking – Solution Note](#)
- ◆ Datasheet Proteus - Arbitrary Waveform Generator / Transceiver: [Module Desktop Benchtop](#)
- ◆ Datasheet Proteus - RF Arbitrary Waveform Generator / Transceiver: [Module Desktop Benchtop](#)
- ◆ Online Webinar: [Experiment design considerations for real-time, closed-loop pulse streaming](#)

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