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Conditioning and Correction of Arbitrary Waveforms— Part 2: Other Impairments

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This article concludes the authors' discussion of factors that affect the accuracy of arbitrary waveforms and the techniques for obtaining the desired performance

Group Delay

For wideband digital communications systems, group delay is becoming an increasingly important phenomenon. Group delay is a measure of signal transmit time versus frequency as is illustrated in Figure 19. This transmit time varies for different frequency components that comprise a signal due to frequency selective components and devices, such as capacitors, filters, amplifiers, and on a system level, the entire signal path.

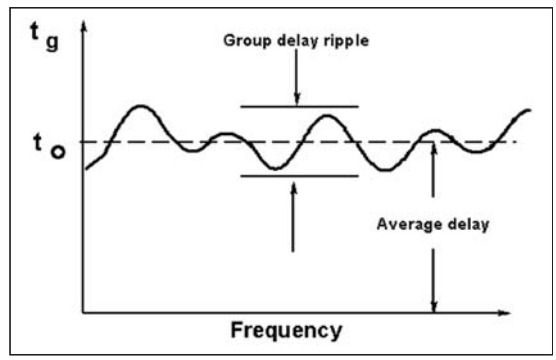

Figure 19 · Group delay ripple indicates a time-versus-frequency distortion.

Group delay is calculated by differentiating the phase response of the signal versus frequency, (i.e., mathematically it is the negative rate of change of phase with respect to frequency). As shown, the linear portion of the phase response can be converted to a constant value (representing the average signal-transit time) and deviations from linear phase are now viewed as deviations from constant group delay. Variable group delay across the signal bandwidth yields deviation from linear phase response and causes signal distortion, such as inter-symbol interference (ISI) and error vector magnitude (EVM).

Group delay is just another way to look at linear phase distortion. To correct for group delay, predistortion (or sometimes referred to as pre-emphasis) can be applied to the waveform to counteract the transfer function of the signal path. This can lead to considerable improvement in signal quality measurable through metrics such as ISI and EVM of digitally modulated signals or the linearity of radar FM chirp. To illustrate the effect of group delay corrections, consider the 400 MHz bandwidth orthogonal frequency division multiplexed (OFDM) signal shown in Figure 20. Over a 400 MHz bandwidth, frequency selective components can severely degrade EVM.

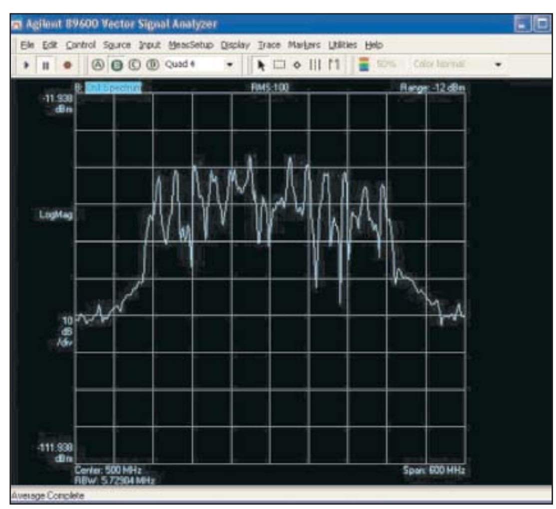

Figure 20 · 400 MHz bandwidth OFDM waveform spectrum.

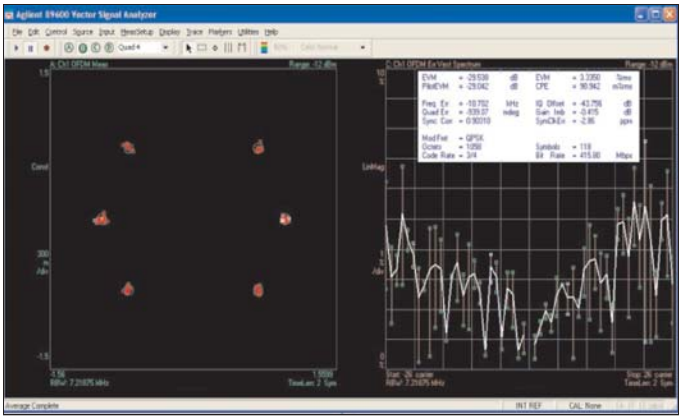

Figure 21 · Group delay errors before predistortion.

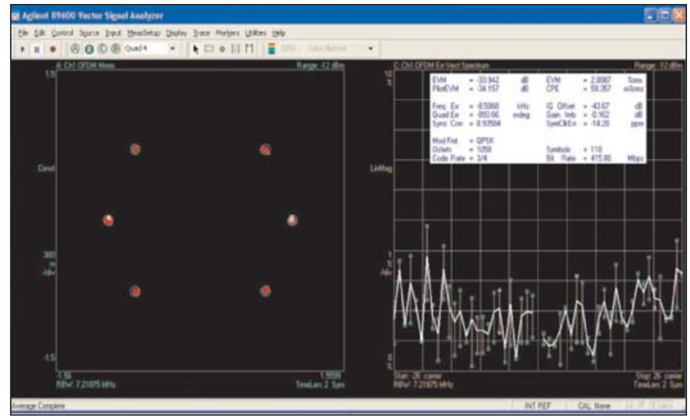

Figure 22 · Group delay after predistortion is applied.

Using EVM as a metric, that same 400 MHz OFDM signal measured in the I/Q plane yields an EVM of –30 dB (or 3.3%) prior to applying predistortion (see Figure 21). Although the constellation appears quite clean visually, the poor performance is clearly visible in the error vector spectrum measurement. The performance increasingly degrades as the frequency band edges are approached.

After corrections are applied (see Figure 22) the measured EVM is –34 dB (or 2.0%), which is an improvement of over 4 dB (or 1.3%). If you look closely and compare to the previous measurement, you can see that the constellation point spread has converged significantly. The error vector spectrum measurement clearly illustrates the improvement in EVM at the frequency band edges.

Peak-to-Average Power Ratio

The peak-to-average ratio (i.e., crest factor) of the transmitted signal can also affect the test stimulus signal quality. Average power is defined as the energy transfer rate averaged over many periods of the lowest frequency in the signal. The peak envelope power represents the maximum power excursion of the signal due to the multiple signal components that comprise the signal aligning in phase (see Figure 23). Peak power is often much higher than the average power for many popular digital modulation formats, such as CDMA and 802.11a/g WLAN as well as pulsed waveforms.

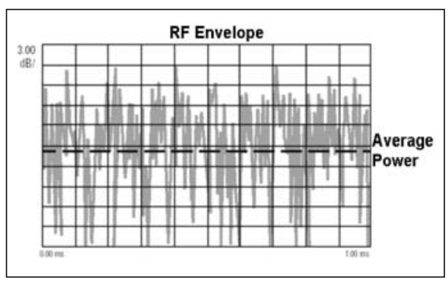

Figure 23 · Power envelope of an RF waveform.

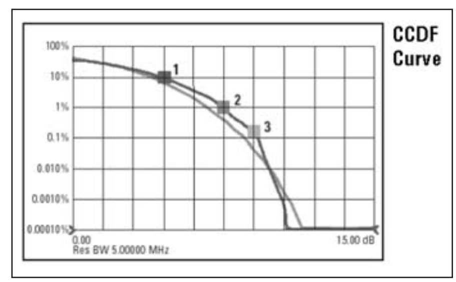

Figure 24 · Complementary cumulative distribution function of a RF waveform.

If the average power level of the signal generator is set too high, large power fluctuations could potentially overdrive the output stage resulting in an unleveled condition and the generation of unwanted distortion. This can be both in-band distortion that degrades signal quality and out-of-band distortion that degrades ACPR performance. Consequently, the crest factor of the test stimulus must be taken into account when determining the maximum available output power for a given signal.

A simple method to determine the crest factor of the test stimulus is to plot the complementary cumulative distribution function (CCDF) of the signal (see Figure 24). A CCDF curve is a plot of peak power levels relative to average (expressed in dB) versus probability. A CCDF curve provides insight into how much time the signal spends at or above the average power level. The probability aspect is important when trying to make tradeoffs between maximum available output power and the tolerable level of signal distortion.

When the automatic level control (ALC) is on, average power is the amplitude value displayed on the front panel of most signal generators. However, when the ALC is off, the amplitude value displayed may be the peak power or average power. Regardless of how the power is reported on the signal generator's front display, it is still important to know the crest factor of the signal.

$$\text{Crest Factor} = P_{peak} - P_{average}$$

If only the peak power is known, then the crest factor is needed to compute the average power. If the average power is known, the crest factor is needed to compute the peak power. If this information is not known, then the signal generator may be over driven, leading to distortion stemming from the generator itself and causing misleading test results.

The example in Figure 25 illustrates the effect of overdriving the output stage of the signal generator. The crest factor of a 3-tone signal is around 5 dB. Consider a signal generator that can deliver +10 dBm level output power at 4 GHz carrier frequency. If the 3-tone signal is generated at +4 dBm output power, the peak power could be up to +9 dBm. At this level, the 3-tone test stimulus from the signal generator is virtually free of distortion products. However, if the output power of the signal generator is increased to +6 dBm output power, the peak power of the signal generator can be up to +11 dBm due to the crest factor. This is an unleveled condition due to overdriving the signal generator, and high levels of intermodulation distortion products are produced in addition to the 3-tone test stimulus.

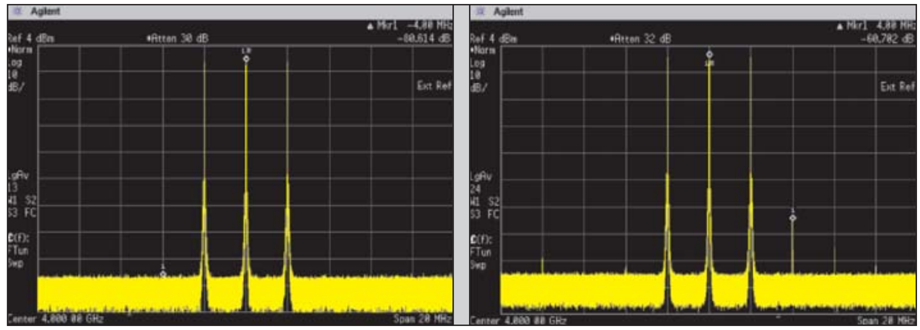

Figure 25 · Effect of power level on distortion.

Level Accuracy

Level accuracy varies across the frequency and output power range of the signal generator. Today's high performance signal generators typically deliver absolute level accuracy within 0.5 to 0.7 dB for most operating conditions.

The signal generator's level accuracy is maintained by monitoring the output power and adjusting the power as needed to correct for fluctuations. There are different ways to control the level accuracy of the signal generator, the most common being an automatic level control (ALC) circuit (see Figure 26). An ALC circuit uses a constant monitor and feedback technique to maintain a calibrated repeatable power level at the signal generator RF output. Essentially, the ALC varies the loop gain as needed to maintain the average output power set by the user, while trying to resist any level changes caused by the signal itself. The primary factors in the ALC that contribute to the level accuracy of the signal are the ALC detector bandwidth and the ALC loop bandwidth.

The ALC detector bandwidth is fixed and cannot be modified. When the ALC is enabled, the signal that is being transmitted should have a smaller bandwidth than the detector bandwidth. If not, level accuracy suffers because the ALC circuit cannot detect all the power being delivered. This is why power accuracy typically degrades for wideband and multicarrier signal generation. The ALC loop bandwidth determines the rate at which amplitude level corrections are applied. Another way to think of the ALC loop bandwidth is the amplitude modulation bandwidth over which the ALC circuit will attempt to correct. Typically, for vector modulated signal generation, it is desirable for the ALC to ignore high rate amplitude fluctuations in the signal since this is often the information being transmitted. A good example of this is quadrature amplitude modulation (QAM). ALC loop bandwidths for vector signal generators are typically limited to between 100 Hz and 100 kHz to correct for low rate amplitude fluctuations. Modern ALC circuits have a selectable loop bandwidth to optimize performance for a given signal (see Figure 27). If the loop bandwidth is too wide, degradation in error vector magnitude (EVM) will result as the ALC circuit attempts to correct for amplitude variations in the digitally modulated signal. However, if the signal bandwidth is relatively wide compared to the ALC loop bandwidth, the impact to EVM is minimal. Consequently, it is often desirable to use a narrow loop bandwidth to minimize EVM in vector modulated signals. The tradeoff for using a narrow loop bandwidth is degradation in switching speed. Depending on the test signal requirements, an ALC bandwidth should be chosen to optimize this tradeoff.

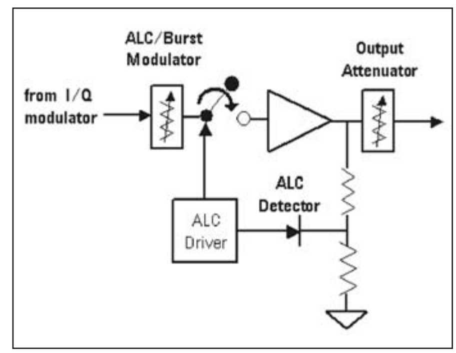

Figure 26 · Automatic level control circuit.

Burst Overshoot and Droop

For pulsed test signals commonly used in radar applications and framed or packet based TDMA communication formats, a different leveling approach needs to be taken. If the ALC is on, the ALC will try to level the on portion of the pulse as well as the off portion. This leads to overshoot and droop over the duration of the power burst. For these signal types, three different ALC options exist to ensure a stable output power over the pulse duration: ALC hold, ALC hold with RF blanking, and power search.

The best way to level a pulsed signal is to enable ALC hold. This is done by creating and routing a marker signal that follows the burst profile to the ALC hold control. When the marker enables ALC hold, the output power leveling does not respond to changes in the signal amplitude and the off-time is effectively ignored by the ALC circuit. If desired, the ALC hold can be enabled in conjunction with RF blanking (see Figure 28). The RF blanking feature will disable the RF output during the off-time and improve the on/off ratio of the signal. The example shows 1.6 dB overshoot and droop over the duration of a 3.125 ms Bluetooth packet transmission with the ALC on. Once RF blanking and ALC hold are enabled, the same packet transmission is flat within 0.1 to 0.2 dB.

Power search leveling holds the output power level to the average power level internally detected after measuring for a short period of time, typically milliseconds. This power level is only updated during frequency or power changes. ALC hold and RF blanking cannot be used with power search. Unlike ALC hold, power search does not level continuously during the on time of the burst and is therefore not as accurate. However, power search is capable of leveling very narrow pulse widths that ALC circuits cannot respond to and is often essential for radar applications.

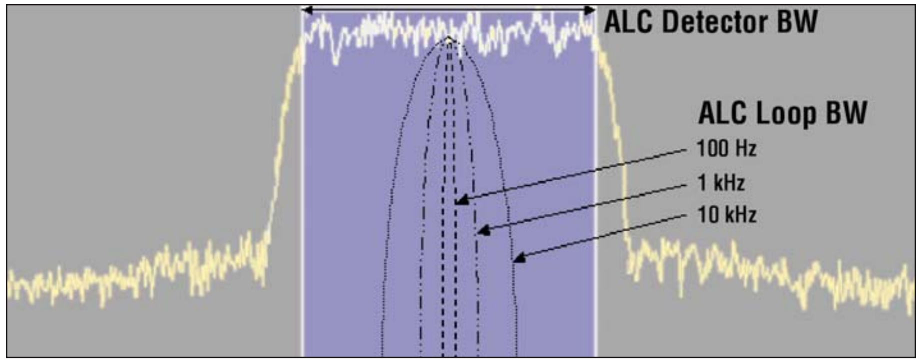

Figure 27 · ALC detector and loop bandwidth.

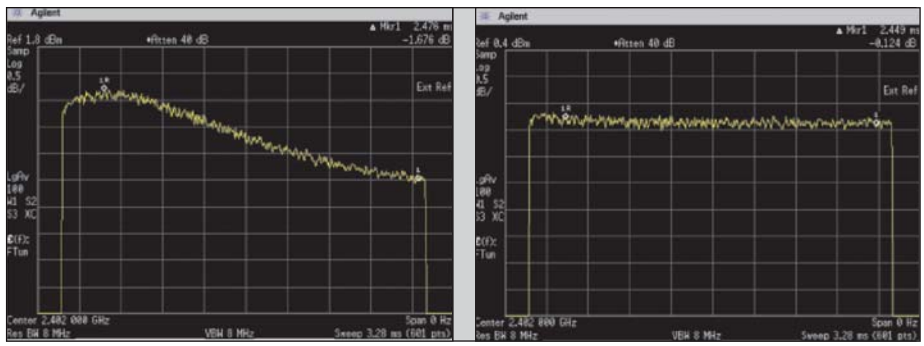

Figure 28 · Effect of RF blanking on ALC operation.

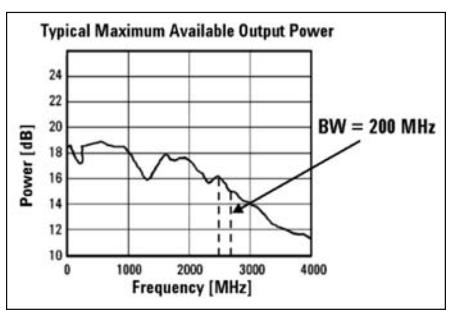

Figure 29 · Pass band ripple and roll-off of a signal generator.

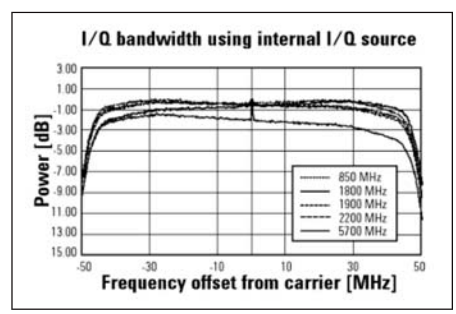

Figure 30 · Agilent ESG baseband bandwidth.

RF Amplitude Flatness

As signal bandwidth increases, output power flatness increasingly impacts level accuracy. Fluctuations in the signal generator's power flatness are clearly illustrated in Figure 29, a graph of typical maximum available output power. The ALC controls the power only within a certain bandwidth on this power curve. So, while the average power is still accurate for most wideband signals, the power accuracy at the band edges can degrade due to amplitude tilt or ripple in the signal generator response.

Ideally the RF amplitude would be flat across the entire bandwidth of the signal independent of the carrier frequency. Unfortunately, RF amplitude flatness does vary depending on the center frequency. As shown in the graph of Figure 30, even though many signal generators have level accuracy of 0.5 dB, this does not mean that the bandwidth is flat across the entire frequency range.

Like phase error, amplitude flatness error can be improved through predistortion. This requires characterization of the amplitude response of the signal path and applying pre-emphasis to the waveform to compensate for amplitude fluctuations. Because the amplitude response of the signal generator is carrier frequency dependent, new predistortion coefficients will need to be determined and applied for different carrier frequencies. Flat amplitude response is important for many applications, including wideband and multicarrier signal generation and multitone distortion test.

To illustrate this, consider the RF amplitude flatness before and after predistortion measurements for a 32-tone test signal as shown in Figure 31. The signal occupies 80 MHz of RF bandwidth. To emphasize the RF flatness, a scale of 0.5 dB per division is used. Before predistortion, the worst-case amplitude variation between tones was 2.4 dB. After predistortion, all tones are within 0.1 dB relative amplitude. This level of accuracy is essential to minimize measurement uncertainty of non-linear distortion measurements. Rather than manually tuning the amplitude of each tone like when summing analog signal generators, the amplitudes are adjusted by apply predistortion coefficients to a new I/Q waveform. The predistortion coefficients are derived from measurement data of the original signal.

A second example shown in Figure 32 illustrates RF amplitude flatness before and after predistortion for an ultra-wideband (UWB) signal. The signal occupies 500 MHz RF bandwidth. Again, to emphasize the RF flatness, a scale of 3 dB per division is used. As shown, with proper conditioning the flatness can be improved even over very wide bandwidths using advanced predistortion techniques.

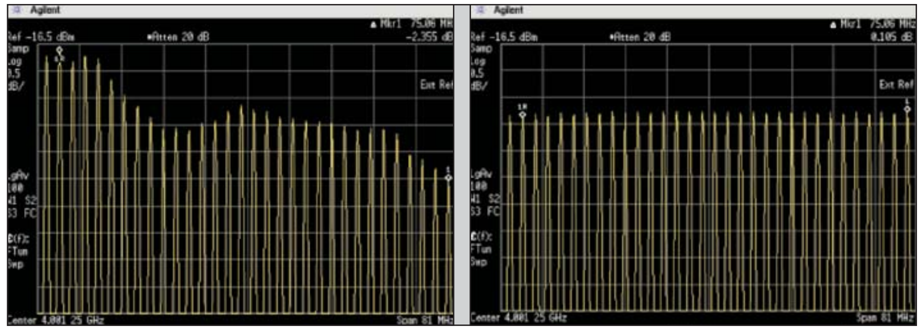

Figure 31 · Effect of predistortion on amplitude flatness.

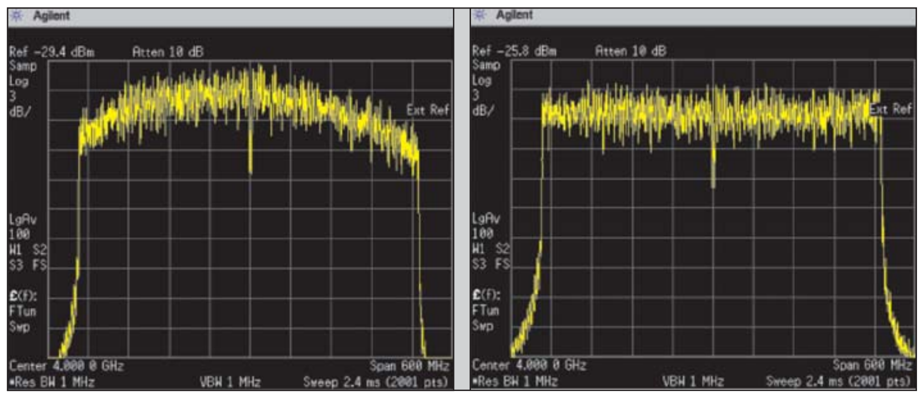

Figure 32 · Effect of predistortion on the flatness of a UWB signal.

Instrument Dependent Corrections

One of the drawbacks of predistortion is that corrections tend to be instrument specific. This is due to the strong dependency on the channels frequency, phase and amplitude characteristics. These characteristics vary enough from signal generator to signal generator that sharing predistorted waveforms between instruments is rendered impossible. In fact, after predistortion is applied to a waveform for a specific signal generator, if that waveform is then transferred to another instrument, the signal quality of the second signal generator will typically degrade to a level below what it would have been without applying corrections to the waveform at all.

To achieve the highest signal quality, there is always a tradeoff. If predistortion techniques are used, they must be applied independently for each signal generator in use. The inability to share waveform files between instruments may be less convenient and more time consuming, but the necessity for accurate test results likely outweigh the additional burden.

Conclusion

Many sources of error typically encountered when employing a vector modulated test stimulus have been identified in this paper. Methods to address them have been also discussed. However, it is important not to lose sight of the bigger picture. The goal is to create an objective test environment that yields accurate measurement results. To do so, the test equipment influences on the DUT measurement uncertainty must be minimized. A key step in this process is optimizing the signal quality of the test stimulus.

Author Information

Mike Griffin is currently a product manager for Agilent Technologies' Electronic Product and Solutions Group. He is the lead marketing engineer for Agilent's signal creation software product line.

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