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APPLICATION NOTE

Non-Linearity Testing Using Multitone Generation Techniques

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Introduction

This application note provides an overview of non-linearity measurements such as 1 dB compression point, 3 dB compression point, spectrum flatness, and third-order intercept. Particular detail is placed on different multitone generation techniques and some of the pros and cons of each. The highlight of multitone generation techniques is on synthetic two-tone, a test methodology used by NI to simplify test configurations for third-order intercept measurements, without compromising performance. An example is then given on using synthetic two-tone to test a low-noise amplifier.

Introduction to Non-Linearity

Amplifiers that are part of RF front ends, power amplifiers (PAs), and low noise amplifiers (LNAs) play a crucial role in modern communication systems, amplifying signals to levels suitable for transmitting or receiving. However, amplifiers exhibit non-linear behavior, which can distort signals and degrade system performance. Non-linearity arises due to various factors such as transistor characteristics, impedance mismatches, and saturation effects. The consequences of non-linearity include spectral regrowth, intermodulation distortion, and reduced dynamic range.

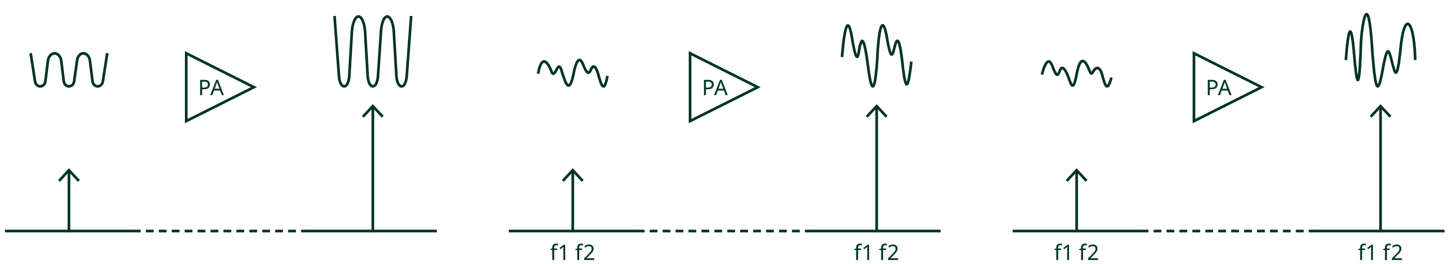

FIGURE 1
Linear and Non-Linear System

Characterizing PA linearity is essential to ensure signal integrity and system efficiency. Key parameters used for characterization include P1dB (1 dB compression point), P3dB (3 dB compression point), IP3 (third-order intercept), and spectrum flatness. Understanding and mitigating non-linear effects is vital for designing reliable communication systems.

P1dB and P3dB Test

The compression point of a PA refers to the input power level at which the output power begins to compress due to non-linear effects. The point where the gain starts to change since the power output is not increasing equally with the power input can be expressed as:

$$Gain=P_{out}-P_{in}$$

where P_{out} is the output power and P_{in} is the input power. This equation is expressed in dB. For an ideal PA, the gain remains constant for all P_{in} values. In the real world, the gain of PA reduces when P_{in} increases. That is called compression. Generally, P1dB and P3dB are used to characterize PA compression.

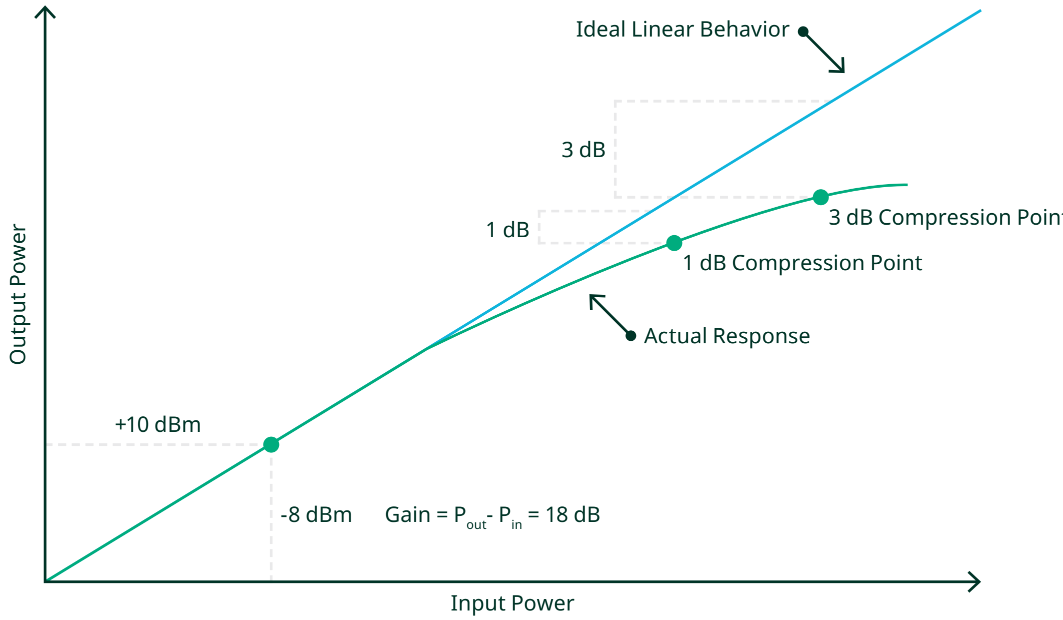

FIGURE 2
Gain Compression

To determine P1dB and P3dB, a signal generator applies a continuous wave (CW) signal to the input of the PA while gradually increasing the power level. The output power is measured, and the compression point is identified when the output power deviates by 1 dB for P1dB or 3 dB for P3dB from its linear behavior.

The NI RFmx Power Amplifier personality has built-in functionality for P1dB test as well as other non-linearity measurements. The RFmx Soft Front Panel (SFP) makes configuration, measurement, and data analysis of P1db fast and easy to understand.

Learn more about RFmx

Spectrum Flatness Test

Spectrum flatness in PAs can arise from various sources, including impedance mismatches, nonlinearities in amplification stages, and variations in component characteristics. These factors can lead to unequal amplification across frequency bands, resulting in spectral distortions.

Spectrum flatness is measured by applying multiple tones across the desired frequency band and analyzing the output spectrum. The deviation of the output power levels from the ideal flat response indicates flatness. Techniques such as Fourier Analysis or power spectral density estimation are commonly employed for measurement.

Linearity over a large bandwidth is usually evaluated using wideband measurements like adjacent channel leakage ratio (ACLR) and addressed using digital pre-distortion (DPD) techniques. Techniques for testing PAs under DPD conditions are outlined in the following application note:

Testing PAs under Digital Predistortion and Dynamic Power Supply Conditions

IP3 Test

The focus of this application note is some of the techniques used for third-order intercept (IP3) test, and in particular, measuring IP3 using the synthetic two-tone method. This section presents a brief explanation of IP3 and several of the techniques that can be used to measure IP3.

Intermodulation Distortion and IP3

Intermodulation distortion (IMD) occurs in power amplifiers (PAs) due to their inherent non-linear behavior. When a PA is driven by multiple input signals, the non-linear characteristics of the amplifier cause the generation of intermodulation products, which are unwanted signals at frequencies that are combinations of the original input frequencies.

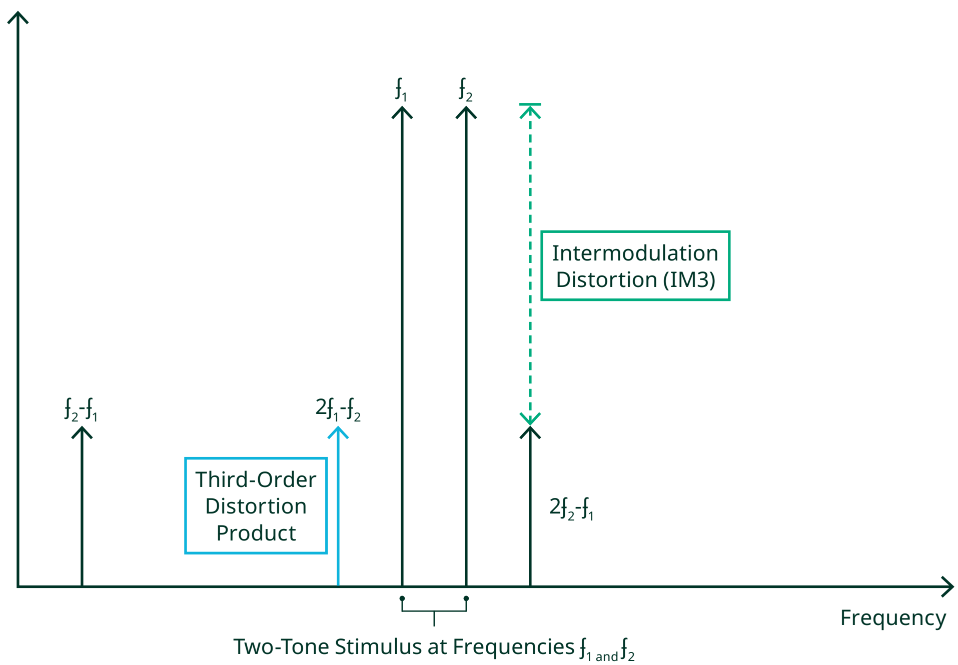

FIGURE 3
Intermodulation Distortion (IMD)

The input intermodulation third order (IIP3) represents the input power level at which the third-order intermodulation products generated by the PA reach the same power level as the desired output signal. The output intermodulation third order (OIP3) represents the output power at which this happens. The theoretical point where IIP3 intersects OIP3 is called third-order intercept point (IP3).

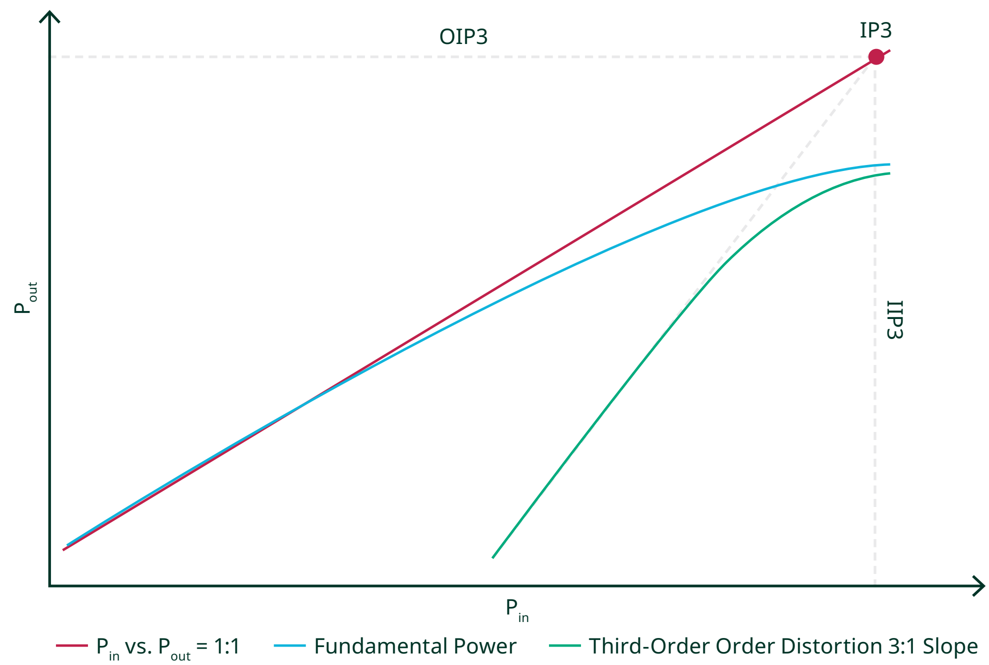

FIGURE 4

Third-Order Intercept

In Figure 4, IP3 can be expressed mathematically as:

$$IP3 = P_{in} + \Delta_{IMD}/2$$

$$\Delta_{IMD} = P_{tone} - P_{IMD}$$

where P_{in} is the input power level and P_{IMD} is the power of the third-order intermodulation product.

To get IP3, we need to measure P_{IMD} which is measured using two-tone testing, where two tones are applied to the input of the PA. The separation between the tones is adjusted to generate third-order intermodulation products. By analyzing the output spectrum, the intermodulation products are measured and then IP3 can be determined mathematically or graphically.

Devices under test (DUTs) usually list IP3 as a specification. To know the intermodulation power, we can compute the delta in dBc:

$$\Delta_{IMD} = 2(IP3 - P_{in})$$

In conclusion, multi-tone generation is a simple technique for characterizing PA non-linearity. By understanding and accurately measuring parameters such as P1dB, P3dB, spectrum flatness, and IP3, engineers can design and optimize PAs for various communication applications.

Single Signal Source

To measure IP3 and intermodulation (IMD), a single vector signal generator (VSG) can be used to create a two-tone signal at two frequencies. One of the challenges is that a VSG comprises digital-to-analog converter (DAC), upconverter, amplifiers, attenuators, filters, and switches—which contribute to the overall IMD3 performance of the instrument.

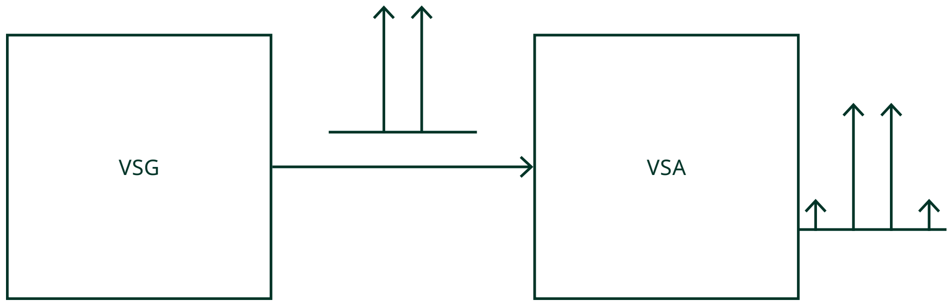

FIGURE 5
IMD3 Test with Single Signal Source

The usage is simple and straightforward. The waveform generator is used to generate two-tone signal while the RFmx SFP is used to capture the measurement data. These are shown in Figure 6 and Table 1.

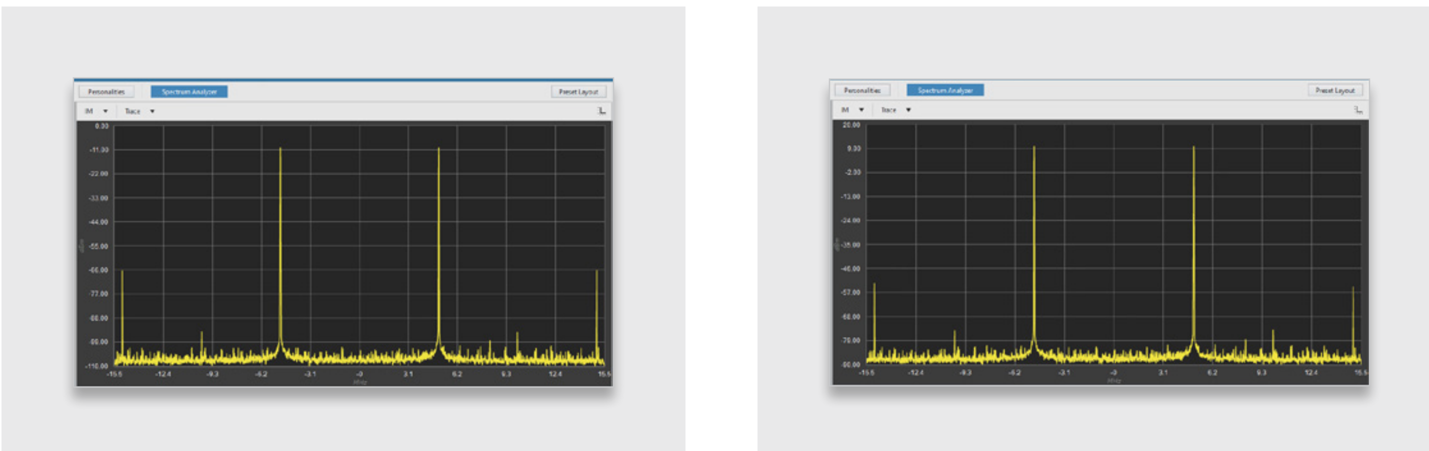

FIGURE 6
OIP3 Performance of Single Signal Source: -10 dBm (left) +10 dBm (right) per Tone, 10 MHz Spacing @ 5 GHz

		Regular Single Source
-10 dBm per tone	IMD3 (dBc)	-56
	OIP3 (dBm)	18
+10 dBm per tone	IMD3 (dBc)	-63
	OIP3 (dBm)	41.5

TABLE 1
IMD3 Performance for Single Signal Source

As noticed, the challenge of using a single VSG is that the intermodulation products generated by the device can be quite high, and in multiple cases higher than the intermodulation products created by the DUT. Thus, we cannot use this methodology. To measure lower intermodulation products, we will need to use two single-tone sources and externally combine them with passive components to avoid creating intermodulation products.

Dual Signal Sources

Compared with an IMD measurement solution with a single signal source, two sources are used to create tones at two frequencies and the signal is combined externally to create a two-tone stimulus to the device. This dual-signal sources solution will produce little to no intermodulation products and hence get better IP3 test results for the DUT.

However, using two signal sources is usually a more complex test solution. In addition, it is important to calibrate the losses introduced by the combiner and cables, as well as to achieve the desired power of individual tones at the input of the DUT.

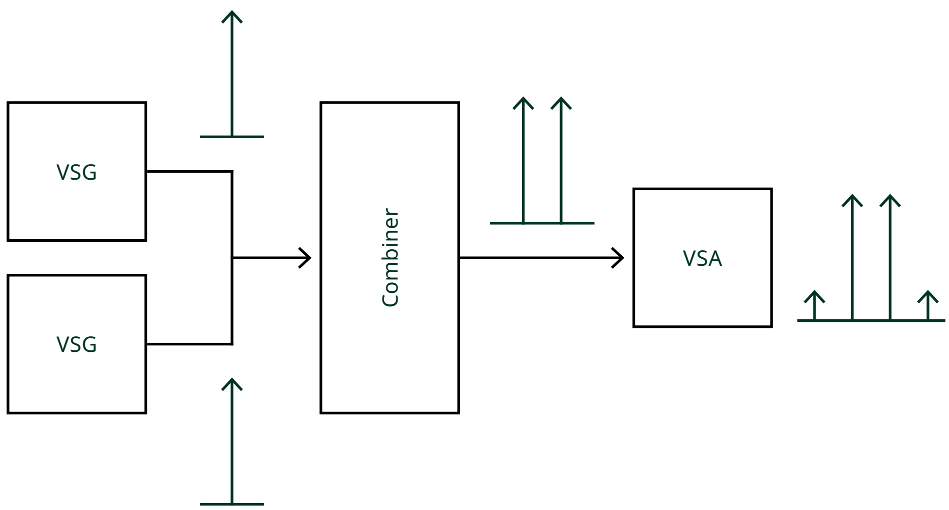

FIGURE 7
IMD3 Test with Dual Signal Sources

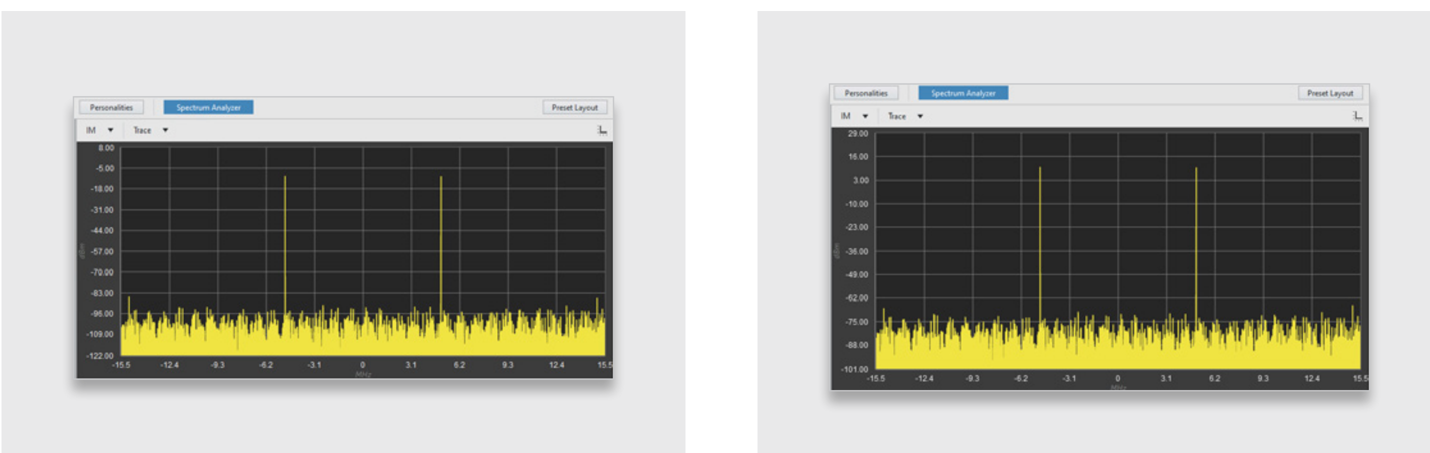

FIGURE 8
OIP3 Performance of Dual Signal Sources: -10 dBm (left) +10 dBm (right) per Tone, 10 MHz Spacing @ 5 GHz

The IMD products are below the noise floor. We can keep reducing the noise floor by reducing the resolution bandwidth (RBW) and we can keep doing this to get the best IMD measurement. However, smaller RBW translates to longer acquisition times. For practical purposes, we report the IMD values we measure with the following tone power settings.

		Dual Signal Sources
-10 dBm per tone	IMD3 (dBc)	<-82
	OIP3 (dBm)	>32
+10 dBm per tone	IMD3 (dBc)	<-76
	OIP3 (dBm)	>48

TABLE 2

IMD3 Performance for Single Signal Source

Figure 8 and Table 2 show the typical values of IMD3 performance for two PXIe-5842 Vector Signal Transceivers (VST).

It is possible to see IMD in Figure 8, especially if we lower the signal analyzer reference level. These IMD products come from the signal analyzer. It is important that the analyzer IMD products are lower than the DUT IMD products to ensure accurate results. The DUT IMD products are typically listed in the DUT specifications.

Synthetic Two-Tone

NI has a unique methodology that can be used with a single vector signal generator (VSG) to create a better-quality signal with smaller IMD products. This method is called synthetic two-tone.

In the signal chain of VSG, there are a series of amplifiers and step attenuators. These cascading components create non-linearity in the system that then contribute to the overall VSG output linearity or IMD. Synthetic two-tone measures the amplitude and phase of the VSG for a given condition with the VST internal loopback path. The cancellation tones are computed and deployed to minimize the IMD3 contributed by components between baseband and RF.

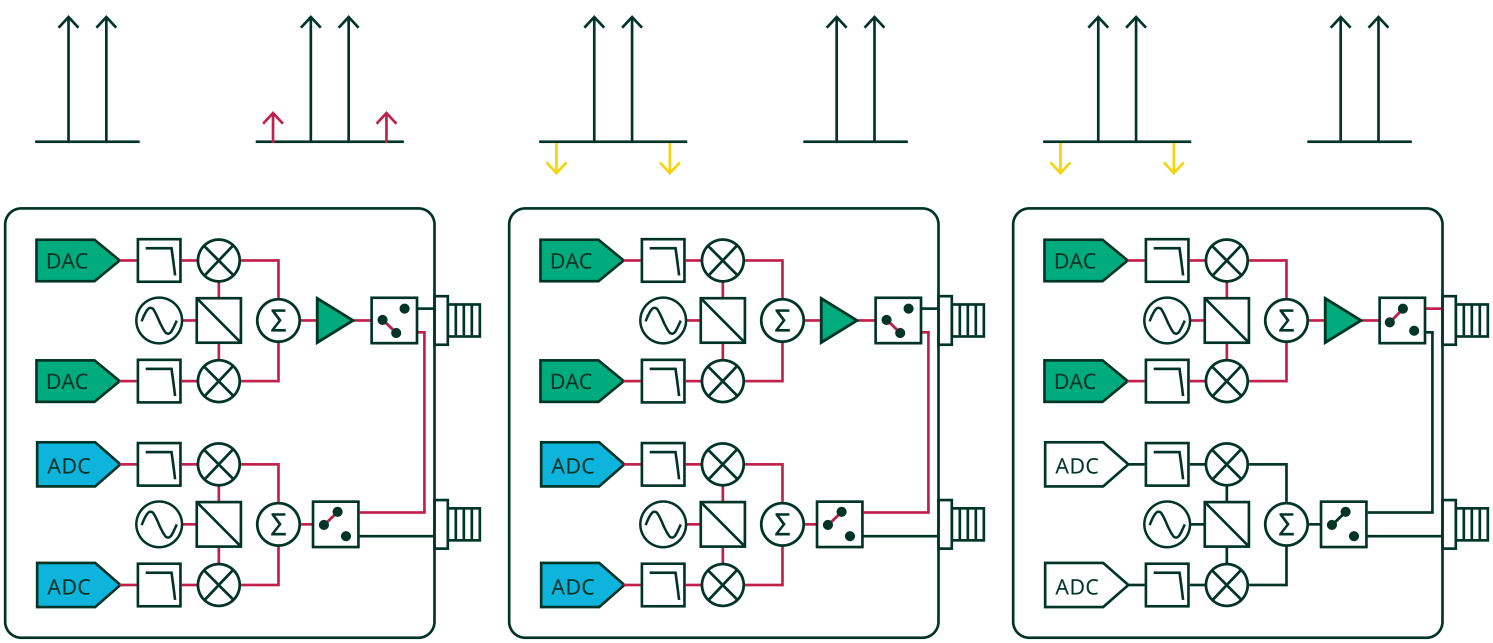

FIGURE 9

Synthetic Two-Tone

Figure 9 shows a general process for IMD cancellation. The first step is to measure the VSG IMD based on a specific combination of those factors, such as two-tone spacing, RF center frequency, and VSG configurations for gain and power, as well as device temperature. Then, the IMD cancellation tones are computed accordingly and applied to get a high-quality two-tone source under the same conditions.

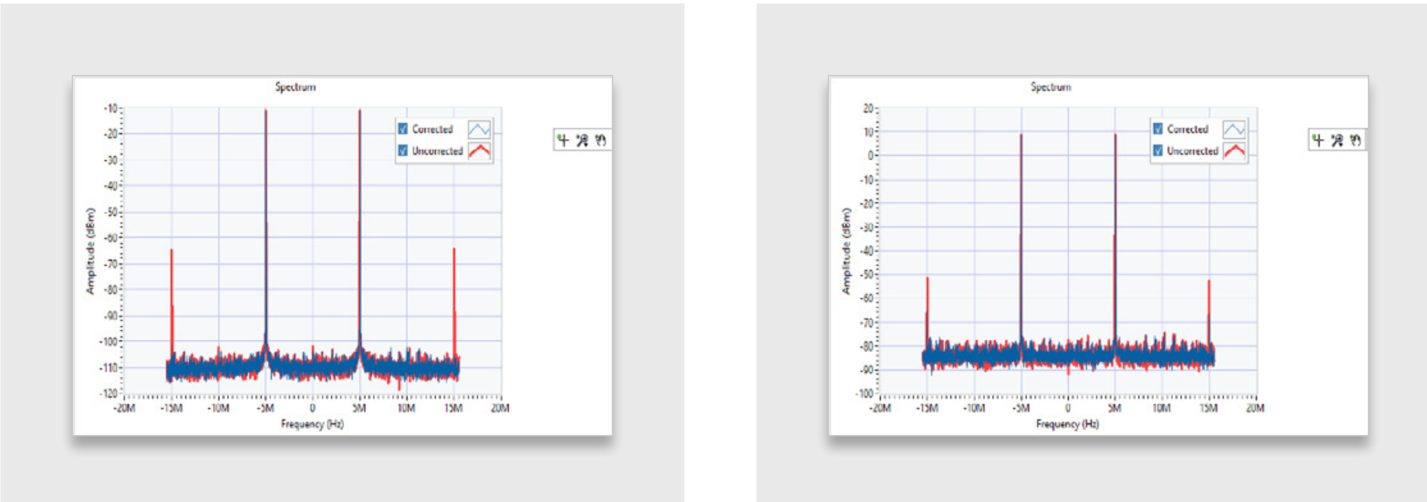

FIGURE 10

OIP3 Performance of Synthetic Signal Source: -10 dBm (left) +10 dBm (right) per Tone, 10 MHz Spacing @ 5 GHz

		Synthetic Signal Source
-10 dBm per tone	IMD3 (dBc)	-81
	OIP3 (dBm)	30.5
+10 dBm per tone	IMD3 (dBc)	-76
	OIP3 (dBm)	48

TABLE 3

IMD3 Performance for Synthetic Signal Source

Figure 10 and Table 3 show the IMD measurements in the PXIe-5842 loopback mode. The red curve represents the raw IMD measurement results from a regular single signal source, while the blue line is from a synthetic two-tone signal source. After IMD calibration and cancellation, the synthetic signal source can generate a lower IMD two-tone signal for IP3 measurement.

This method is useful in many situations—but is not an answer for all test cases. The benefit is that the setup is as simple as having one single source while the capability of measuring IMD products is improved. However, this method needs to be calibrated per setting and controlled to avoid recreating the original IMD products of the device.

A comparison summary of all the methods in VST loopback mode is shown in Table 4.

		Regular Single Source	Synthetic Signal Source	Dual Signal Sources
-10 dBm per tone	IMD3 (dBc)	-56	-81	<-82
	OIP3 (dBm)	18	30.5	>32
+10 dBm per tone	IMD3 (dBc)	-63	-76	<-76
	OIP3 (dBm)	41.5	48	>48

TABLE 4
IMD3 Performance Comparison

IP3 Test with a DUT

In this section, we will demonstrate the IP3 performance differences among single signal source, dual signal sources, and synthetic two-tone method based on a low-noise amplifier (LNA) whose IMD is unknown.

The system diagram is shown in Figure 11. The source measure unit (SMU) is used to power up the LNA while the NI PXIe-6571 digital pattern instrument is used to enable the LNA. The LNA is connected to VSG as the input and VSA with 30 dB attenuator as the output.

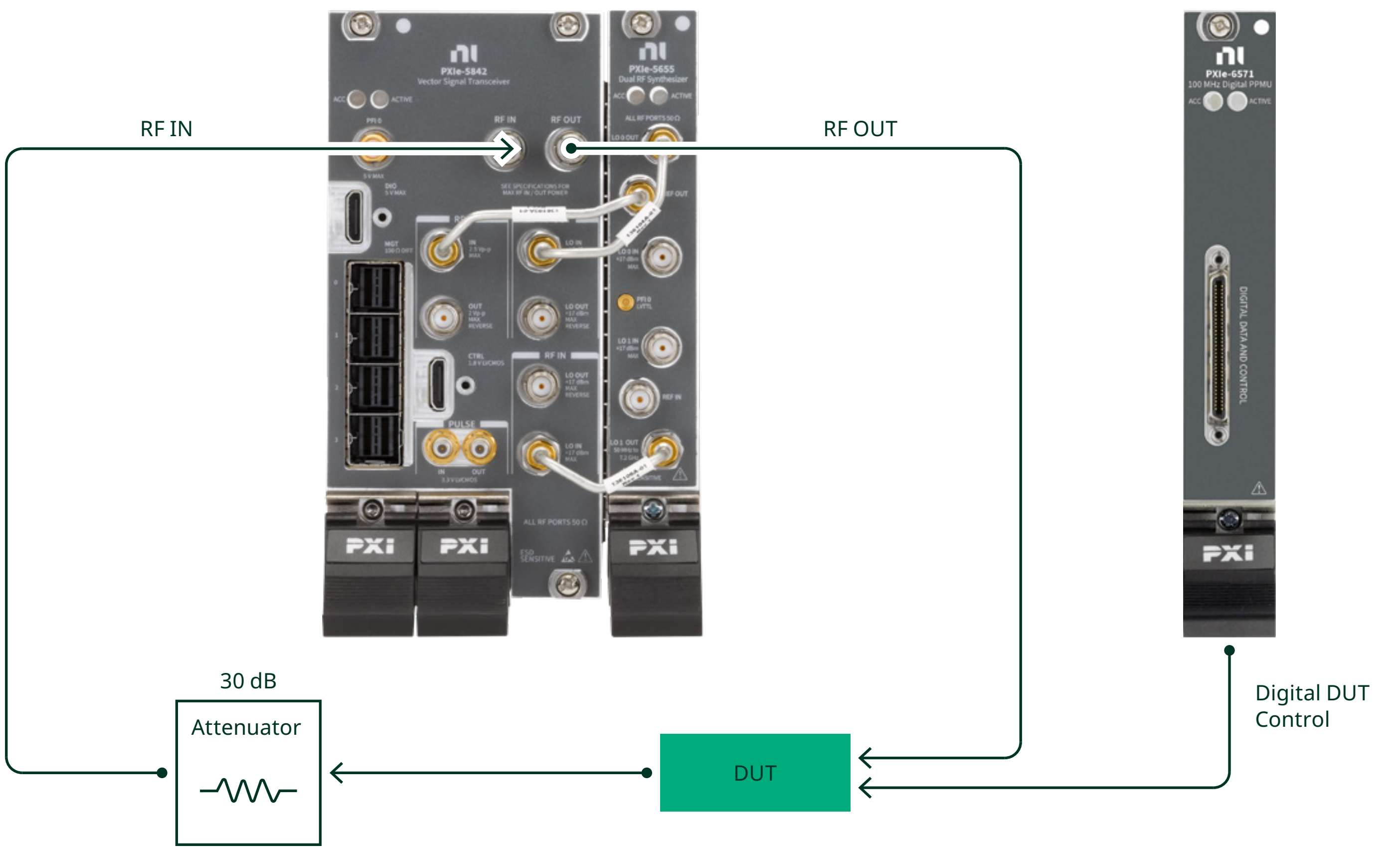

FIGURE 11
IP3 Test Setup

The NI RFmx Waveform Creator is used to generate a two-tone signal as the LNA input at the specified frequency and power and RFmx Soft Front Panels are used to analyze the output signal and measure the IP3.

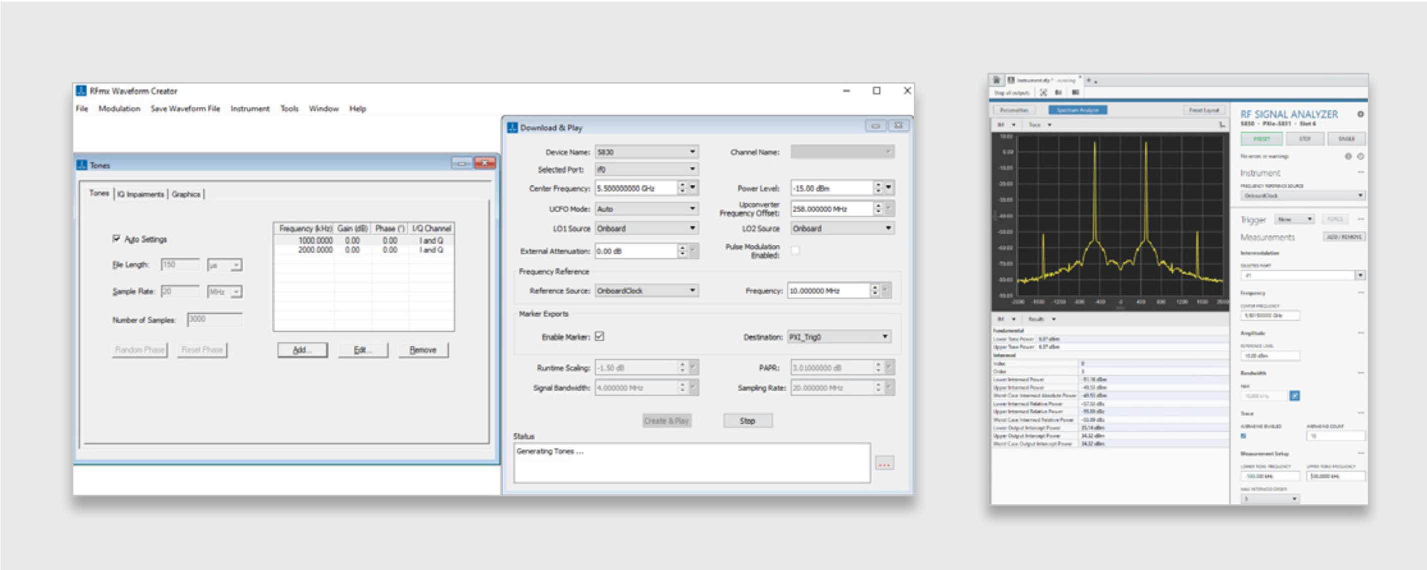

FIGURE 12
RFmx Waveform Creator (left) and RFmx Soft Front Panel (right)

The IMD measurement results are listed in Table 5. It shows that the DUT IMD products are lower than what our single signal source is; therefore, the regular single source method is not correctly measuring the DUT IMD products. However, the synthetic two-tone method can be used to get correct IMD results—which also correlates with the dual-source method, the standard in IMD.

		Regular Single Source	Synthetic Signal Source	Dual Signal Sources
-10 dBm per tone	IMD3 (dBc)	-56	-72	-70
	OIP3 (dBm)	18	26	25

TABLE 5
IMD Measurements on the LNA

Conclusion

Non-linearity measurements such as P1dB (1 dB compression point), P3dB (3 dB compression point), and IP3 (third-order intercept) require some unique considerations during test. IP3 (or TOI) is a standard figure of merit for evaluating non-linearities on power amplifiers. In this application note, three methods were introduced for IP3 testing: the single-signal source, dual-signal source, and synthetic two-tone signal source. We showed that regular single-signal source is used to measure the DUT whose IP3 is lower than that of the instrument itself. For the DUTs with high linearity or high IP3, the synthetic two-tone signal source is suggested to be used. In all cases, dual-signal sources can be always used for IP3 testing; however, as mentioned, this is not always practical in real-world scenarios. Finally, we show how we can carefully calibrate our tones and use synthetic two-tone to create a cleaner single-source IMD testing. The summary for those IP3 measurement approaches is shown in Table 6.

	Pros	Cons
Regular single signal source	Applicable for DUTs with IP3 lower than the instrument IP3	Not applicable for DUTs with high IP3
Dual signal sources	Applicable in all cases (as long as signal analyzer IP3 is better than DUT IP3)	Higher test setup complexity and higher cost
Synthetic signal source	Cost efficient for DUTs with high IP3	Needs calibration for each test case (similar to system calibration)

TABLE 6

Pros and Cons of IP3 Test Methods

To accelerate your productivity and innovation while lowering the cost of test, NI equips you with high performance RF instruments, such as PXI VSTs, production ready ATE solutions such as semiconductor test system (STS), and powerful software tools/IPs in the laboratory validation and production test.

Learn more about the **VST** and **STS**.

Contact NI support or sales if you need more information on the synthetic two-tone for IP3 testing.

References

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NI PXIe-5842 Specification

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Austin, TX 78759-3504