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APPLICATION NOTE

Harmonic Measurements with Vector Signal Transceivers

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Introduction

Harmonic signals are generated by a non-linear device at an integer multiple of the signal's fundamental frequency. In the domain of RF test and validation, harmonic signals are unwanted because they can cause interference outside of operating frequencies. Therefore, accurate measurement of harmonic signals is key for device verification.

Traditionally, harmonic measurements are conducted by high-performance vector signal analyzers (VSAs) or dedicated harmonic measurement units (HMUs). Vector signal transceivers (VSTs) have not been considered for harmonics measurements due to their limited frequency range, analyzer noise performance, and in some cases, instantaneous bandwidth. The latest generation of VSTs overcome these limitations and provide additional benefits for harmonics testing.

VST Advantages for Harmonics Measurements

A vector signal transceiver (VST) combines an RF and baseband vector signal analyzer (VSA) and generator into a single device. The VST used for the measurements discussed in this application note is the PXIe-5842. This VST consists of the PXIe-5842 module and the high-performance dual local oscillator (LO) synthesizer PXIe-5655, known for its excellent phase noise performance. Built on the PXI platform, it offers significantly enhanced measurement capabilities, particularly useful when performing harmonics measurements.

Frequency Coverage and Bandwidth

The PXIe-5842 VST provides continuous frequency coverage from 30 MHz to 26.5 GHz. This wide frequency range allows for measurements of higher order harmonic frequencies and accommodates fundamental signals at lower frequencies compared to previous generation VSTs.

The PXIe-5842 VST has an instantaneous bandwidth of 2 GHz. For harmonics measurements of modulated signals, the required measurement bandwidth increases as a multiple of the fundamental signal bandwidth:

$$n^{th} \text{ harmonic BW} = n \times \text{fundamental BW}$$

The device under test (DUT) used as an example in this application note specifies second through fifth-order harmonic measurements for a fundamental signal with 100 MHz bandwidth. This requires more than 500 MHz of instantaneous measurement bandwidth from the analyzer for the fifth harmonic measurement. As new standards and communication technologies emerge, the need for higher bandwidth measurements at high-order harmonic frequencies will continue to rise.

Tight Module Synchronization

The PXIe-5842 is a component of NI’s PXI platform that enables the integration of multiple measurement modules within a single PXI chassis. These modules can communicate and synchronize seamlessly with one another. A shared frequency reference and trigger bus between a signal generator, signal analyzer, and other instruments facilitates easy synchronization of these devices. This synchronization is especially helpful for measuring the harmonics of modulated signals with burst waveforms. The signal generator can trigger the start of the burst to the analyzer, which will then only measure the harmonic signal when it is present.

Small Form Factor and Cost Effective

Using a VST for harmonics measurements will eliminate the need for a dedicated VSA or HMU, thus saving bench space and extra cost.

Learn more about the PXIe-5842 and other NI PXI VSTs.

VST Performance Compared to a Traditional VSA

When selecting an instrument to measure harmonics, key performance metrics include average noise density as well as analyzer-generated harmonics and spurs. In this section, we will compare the performance of these metrics between the PXIe-5842 VST and NI's traditional high-performance VSA PXIe-5668 with its optional preamplifier PXIe-5698.

Average Noise Density

Harmonic signals are typically very low power and require a signal analyzer with high sensitivity for accurate measurement. Average noise density specifies the amount of analyzer noise in dBm/Hz. Figure 1 shows a comparison of average noise density between the PXIe-5842 VST and the PXIe-5668 VSA. The PXIe-5668 VSA is paired with an optional PXIe-5698 preamplifier to further improve sensitivity.

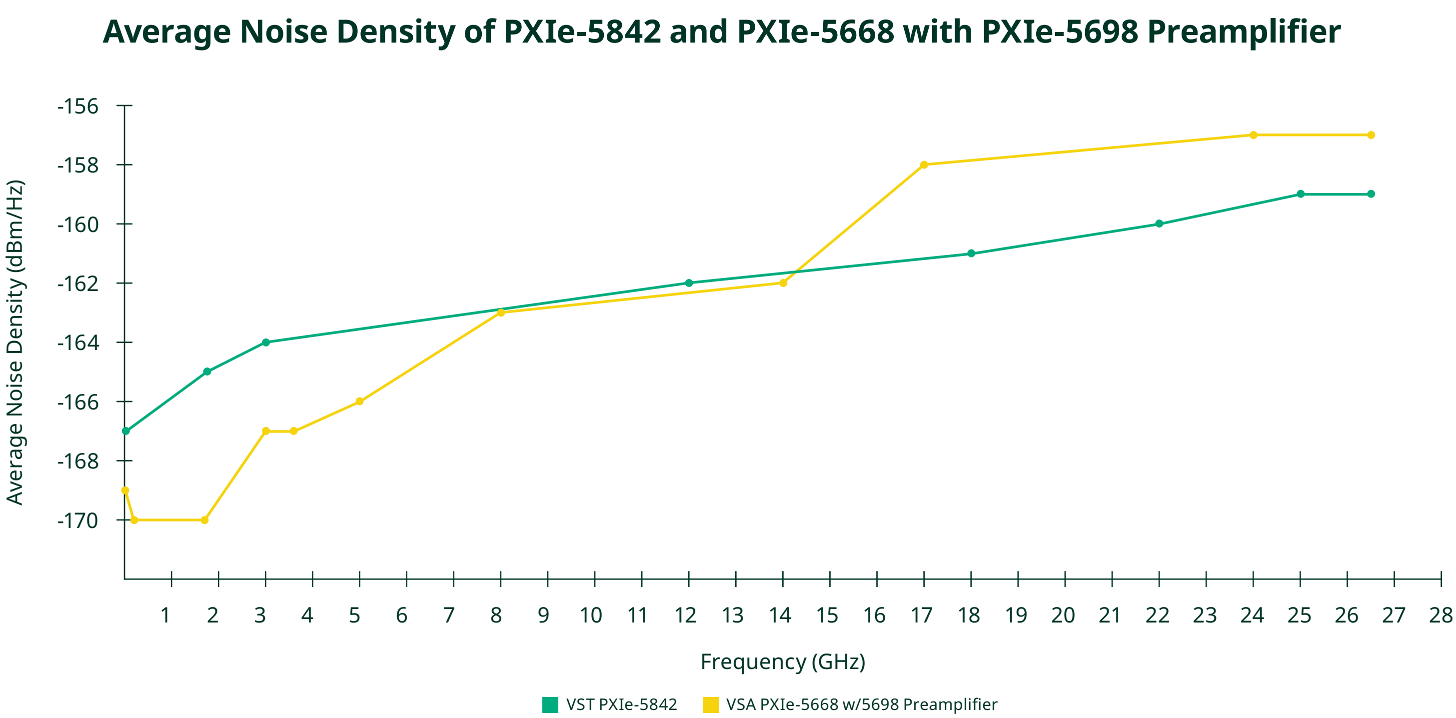

FIGURE 1
Average Noise Density of PXIe-5842 VST versus PXIe-5668 VSA

Signal analyzer specifications are often provided as displayed average noise level (DANL). To convert average noise density to DANL, subtract 2.51 dB. DANL is lower because it is computed using the average of the logarithm of measurement samples rather than the logarithm of the average of measurement samples as provided.

The results reveal that the PXIe-5842 VST and PXIe-5668 VSA have similar average noise density. The VSA has better average noise density at frequencies below 8 GHz, while the VST has better average noise density at frequencies above 14 GHz.

Analyzer Input Spurious Emissions and Harmonics

Because signal analyzers contain amplifiers and other non-linear components, they produce their own harmonic distortions and other spurious signals. These distortions need to be characterized to determine if they will impact the harmonic distortion measurement for a particular DUT.

The PXIe-5842 VST and PXIe-5668 VSA specify distortion differently and under differing test conditions in their datasheets. This makes it difficult to determine a direct comparison for harmonics measurement performance. To make a direct comparison, the VST and VSA were both given the same input test signal, and the analyzer distortions were measured concurrently.

In a typical harmonics measurement, the fundamental signal is removed by a filter or diplexer, allowing the analyzer to lower its reference level closer to the low-power harmonic signals and improve dynamic range. A common amount of diplexer rejection is 50 dB, so a continuous wave (CW) signal at -50 dBm was used to simulate the fundamental leakage at the analyzer input.

To avoid the non-linear effects from the generator, a diplexer was used to filter out the harmonics produced by the generator. The test setup depicted in Figure 2 shows how the VST generator is used as the signal generator, and the generator is swapped between the VST analyzer and the VSA.

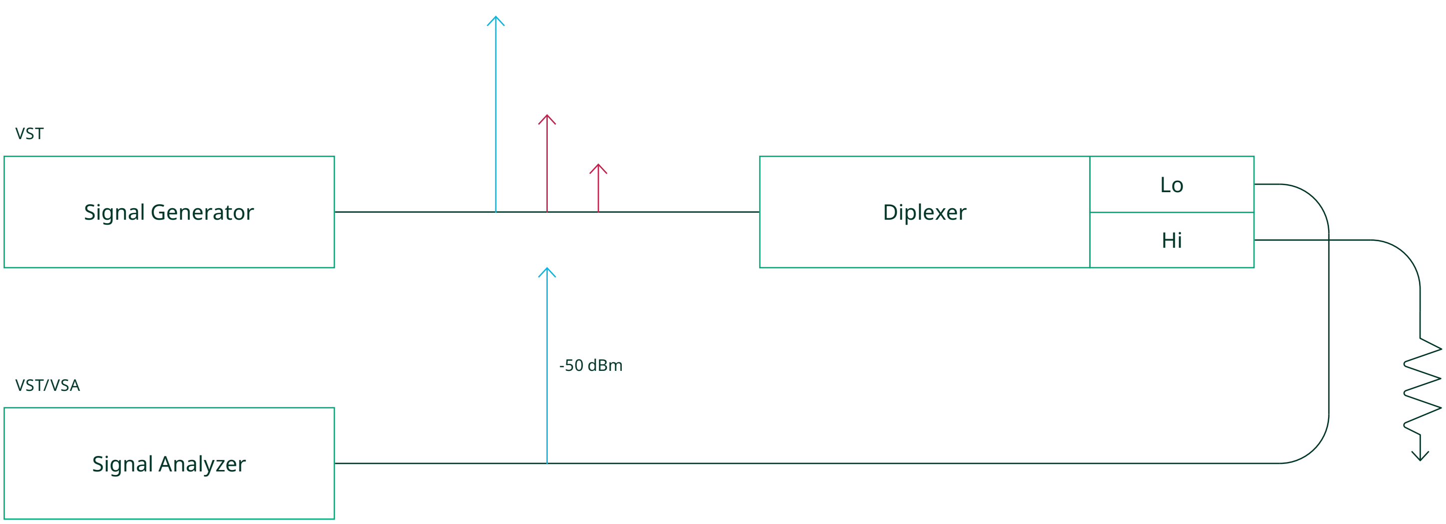

FIGURE 2

Test Setup for Analyzer Input Spurious Emissions and Harmonics Test

The measurement was captured for CW frequencies ranging from 800 MHz to 5.8 GHz. Figure 3 shows the result comparison for a CW frequency of 3.5 GHz. The diplexer has a crossover frequency of 6.5 GHz, so spurious signals below 6.5 GHz can be attributed to the generator. Overall, the spurious emissions are similar between the VST and VSA, with the VSA having one consistent spur near 10 GHz. The second harmonic can be seen at 7 GHz, and the VSA second harmonic is about 10 dB lower than the VST harmonic. The third harmonic and higher are below the noise floor for both the VST and VSA. This result comparison was consistent for the other CW frequencies tested.

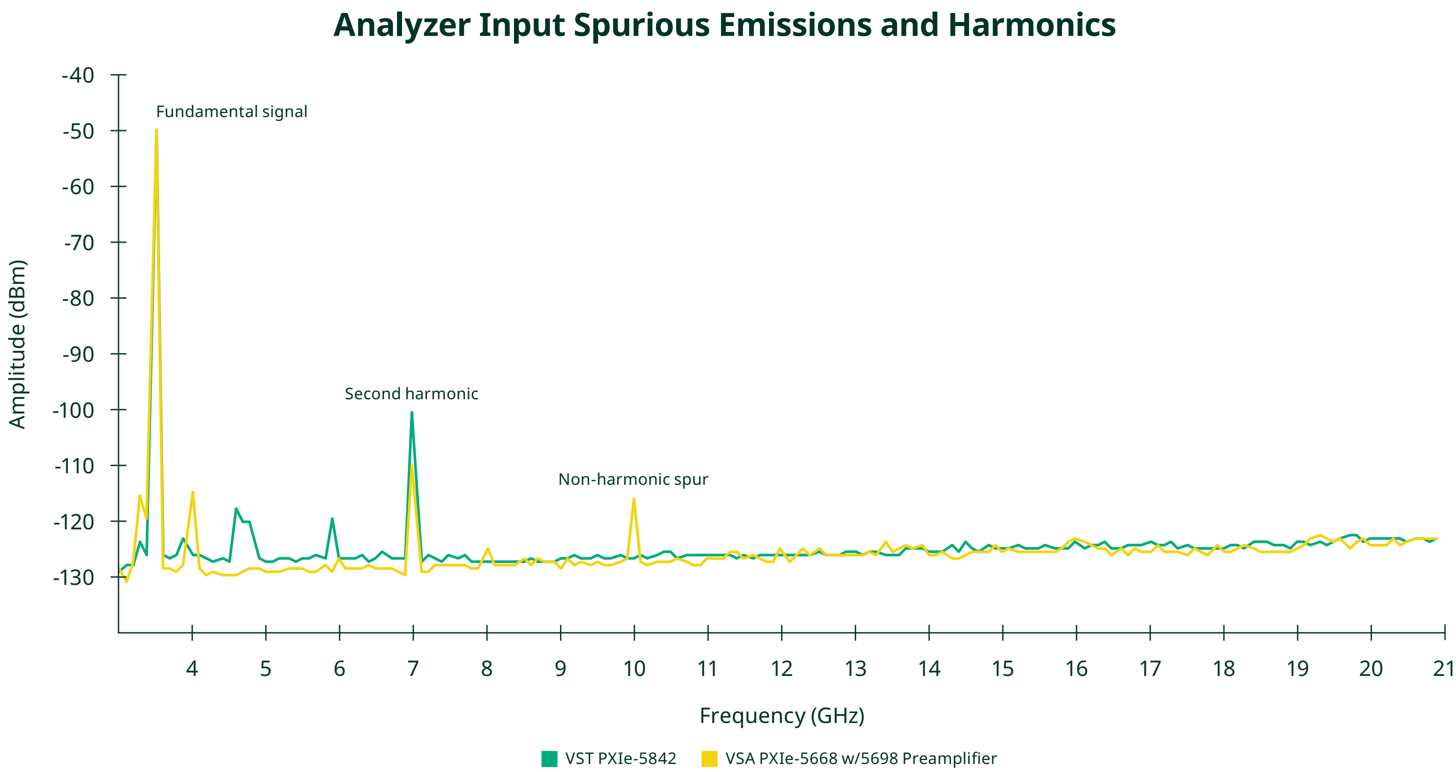

FIGURE 3

Analyzer input spurious emissions and harmonics results comparison for CW at 3.5 GHz. Test conditions: Resolution bandwidth (RBW) = 1 kHz, Span = 1 MHz, Reference level = -50 dBm.

The analyzer reference level setting will impact the amplitude of the second harmonic. The amplitude of the second harmonic can be reduced by increasing the analyzer reference level, with a trade-off of increased noise floor. Figure 4 shows the difference between the second harmonic amplitude and noise floor of the PXIe-5842 with the reference level increased from -50 dBm to -30 dBm. The second harmonic amplitude decreases by 8 dB, without an appreciable increase to the noise floor. The level of analyzer input harmonic distortion should be compared to the expected level of the DUT distortion to determine if the analyzer will impact the DUT measurement.

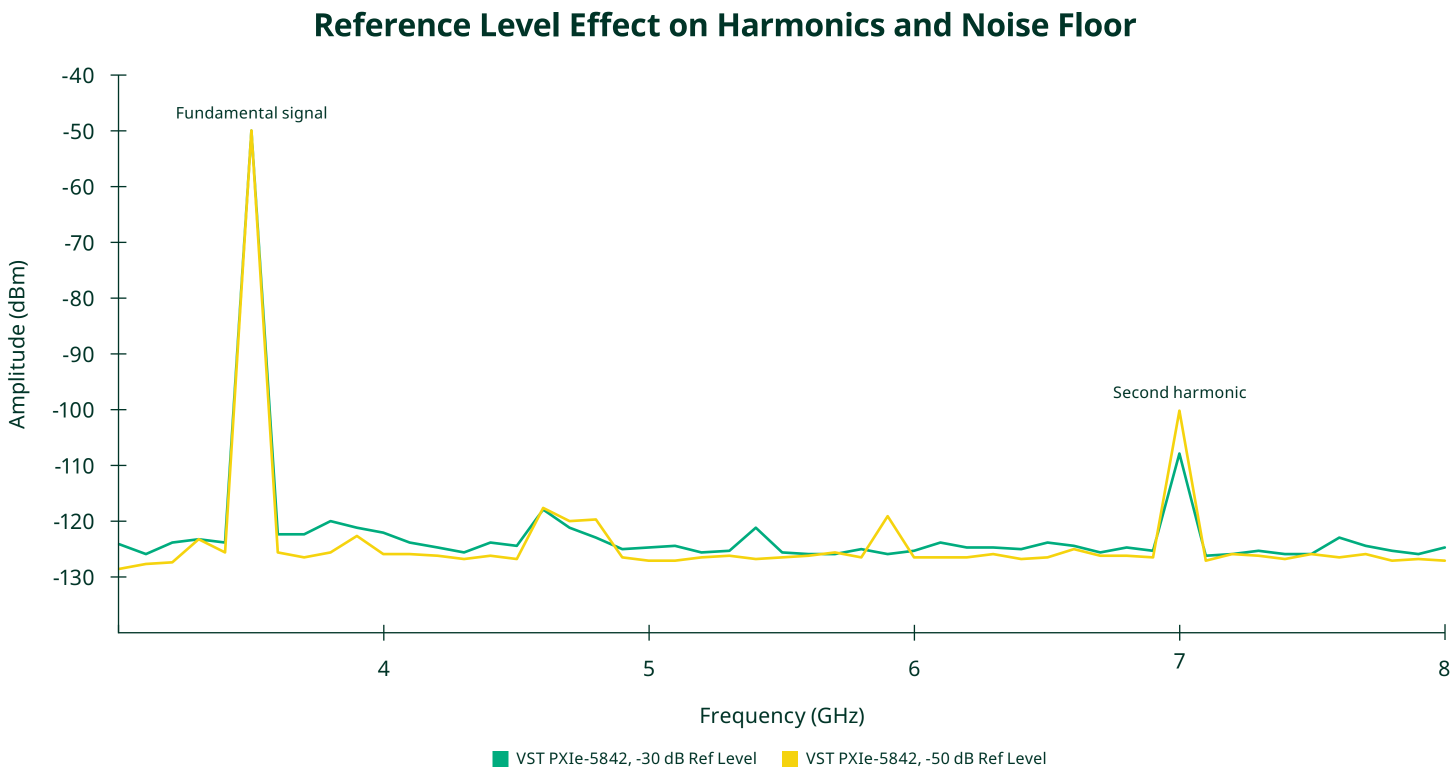

FIGURE 4

VST Second Harmonic and Noise Floor Levels with Reference Level Settings of -50 and -30 dBm

Measuring DUT Harmonics with a VST

This section of the application note outlines a harmonics measurement on an amplifier DUT using the PXIe-5842 VST. The DUT used in this measurement is a 5G New Radio (NR) power amplifier (PA) that operates near 3.7 GHz. The DUT datasheet specifies its harmonics performance using a 5G modulated test waveform with 100 MHz bandwidth at +27 dBm DUT output power. The DUT harmonic performance is specified through the fifth harmonic.

Test Equipment Setup

VSTs contain non-linear devices and thus create their own harmonics. Ideally, only the DUT harmonics are measured. To obtain optimal results, external filtering is used to remove the harmonics generated by the VST. In this case, diplexers are used as either low-pass or high-pass filters. Traditional filters have steeper roll-off than diplexers, but diplexers typically have higher rejection outside of the passband, which is beneficial for the harmonics measurement. Most importantly, a diplexer presents a broadband matched load to the signal generator, reducing reflections back to the generator, unlike typical filters with poor return loss in their stop-bands.

Figure 5 shows the test setup of the harmonics measurement. The diplexer after the signal generator is used to filter the harmonics of the generator and pass the fundamental signal. Another diplexer after the DUT is used to filter the fundamental signal and pass only its harmonics to the analyzer. This configuration allows the signal analyzer to operate at a much lower reference level for measuring the low-power harmonic signals. It also reduces the amount of distortion created by the analyzer. The diplexer crossover frequency needs to be between the fundamental frequency and the second harmonic of the DUT. The DUT operates at 3.7 GHz, so the second harmonic will occur at 7.4 GHz. Hence, diplexers with a crossover frequency of 6.5 GHz were used in this measurement.

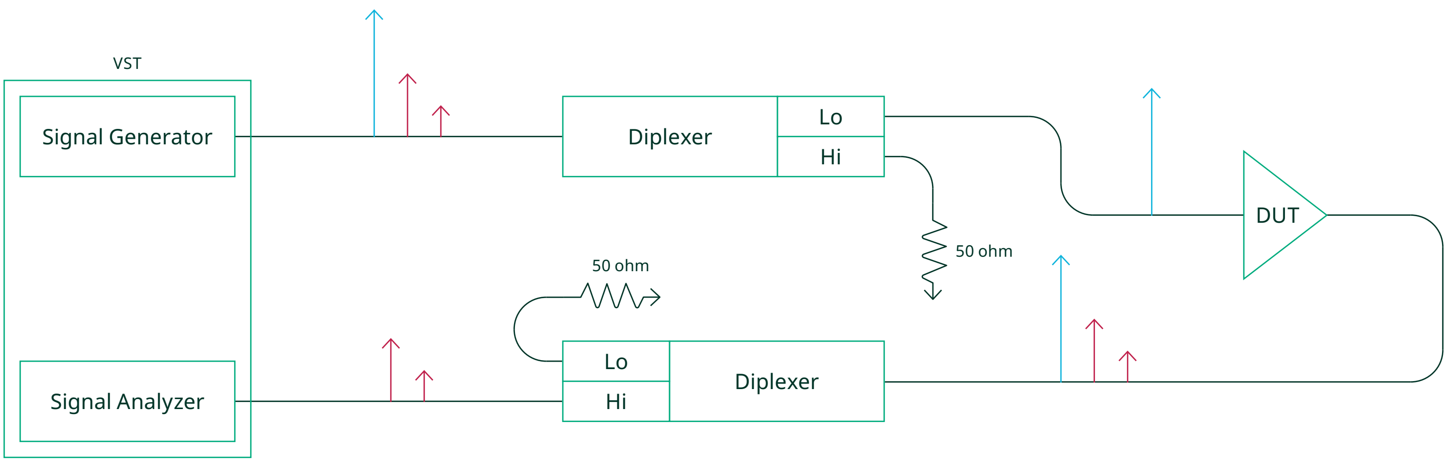

FIGURE 5
Test Setup of DUT Harmonics Measurement

Measurement Setup

The following steps were implemented to perform the harmonic measurement. The seemingly daunting list was made trivial with the use of RFmx, NI's set of interoperable software applications, and InstrumentStudio™, NI's front panel software that works with the PXIe-5842 VST and many other instruments.

1. De-embed the test cables, connectors, and diplexers by sweeping them with a vector network analyzer. Apply the appropriate de-embedding files (usually .S2P) to the measurement.

2. Configure the analyzer for a time-domain, zero-span transmit power (TxP) measurement at each harmonic frequency. Time-domain measurements are significantly faster than channel power (ChP) measurements because there is no need to convert the signal to the frequency domain. Because the signal is modulated, the following equations are used:

$$n^{th} \text{ harmonic frequency} = n \times \text{fundamental frequency}$$

$$n^{th} \text{ harmonic RBW} = n \times \text{fundamental RBW}$$

$$n^{th} \text{ harmonic measurement interval} = \frac{\text{fundamental measurement interval}}{n}$$

a. The fundamental center frequency is 3.75 GHz, and the measurement will include each harmonic up to the fifth (3.75 GHz x 5 = 18.75 GHz).

b. The fundamental signal has a bandwidth of 100 MHz, so each subsequent harmonic will increase in bandwidth by 100 MHz, up to 500 MHz (100 MHz x 5).

c. The test waveform has repeated bursts 6 ms in duration. The VST sends a trigger from the signal generator to the analyzer to measure at the start of each burst. The measurement interval is set to 6 ms to ensure the burst is measured without idle time, that is, when the signal is off.

3. Lower the analyzer reference level until it is near the peak power of the fundamental signal without overloading the analyzer's ADC. This will enable the ADC to utilize most of its dynamic range. To verify if the signal analyzer is contributing to the distortions, vary the RF input attenuator setting. If the measured distortion amplitude does not change on varying RF attenuation, the distortion is entirely because of the DUT. However, if the distortion amplitude changes, then the signal analyzer is also contributing to the distortion. If this is the case, try raising the reference level until the analyzer is no longer contributing to the distortion.

The settings used for the harmonic measurement are summarized in Table 1.

Number of Harmonics	5				
Measurement Method	Time Domain				
RBW Filter Type	Flat				
Reference Level (dBm)	-10				
	Fundamental	Second Harmonic	Third Harmonic	Fourth Harmonic	Fifth Harmonic
Frequency (GHz)	3.75	7.5	11.25	15	18.75
RBW (MHz)	100	200	300	400	500
Measurement Interval (ms)	6	3	2	1.5	1.2

Table 1. Measurement Settings for Harmonic Measurement

Learn more about RFmx.

Learn more about InstrumentStudio.

Measurement Results

The harmonic measurement results are shown in Figure 6. The total harmonic distortion and average relative power values are derived from the fundamental signal. However, these values should be ignored due to the fundamental signal being filtered by the diplexer.

The key values are the harmonic frequencies, the RBWs of each harmonic, the measurement intervals (as seen on the trace), and the average absolute power of each harmonic.

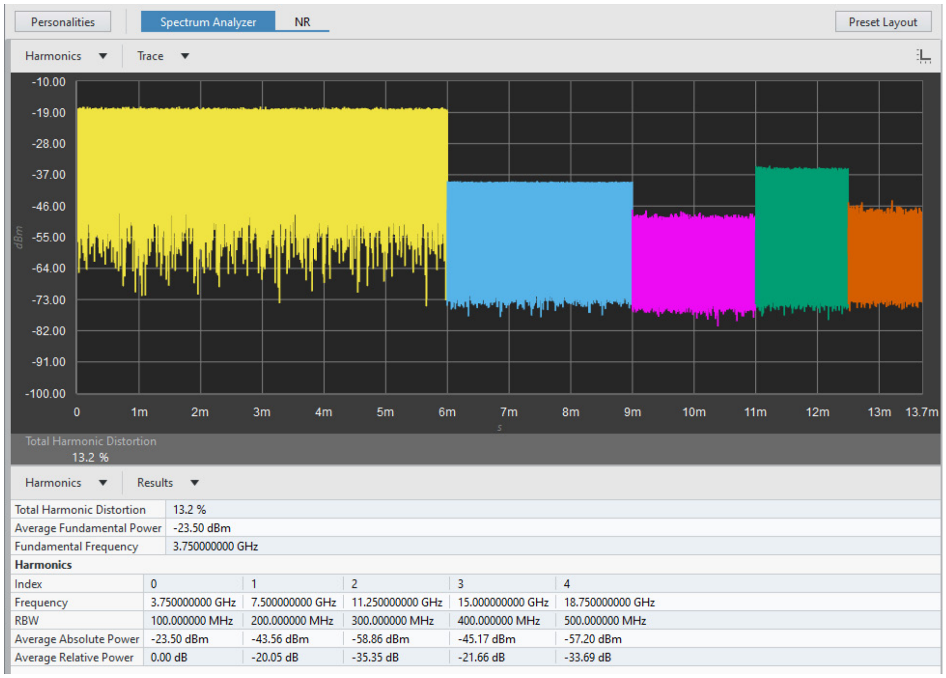

FIGURE 6

Harmonic Measurement Results

The DUT specifies the limits of the second through fifth harmonics in absolute power (dBm). Table 2 shows the specified limits against the measured values, all of which pass with margin.

Harmonics	DUT Specified (Typical)	Measured	
Second Harmonic	-40	-43.56	dBm
Third Harmonic	-50	-58.86	
Fourth Harmonic	-35	-45.17	
Fifth Harmonic	-50	-57.2	

Table 2. Harmonic Measurement Specified versus Measured Values

Conclusion

The latest generation of VSTs has overcome previous limitations and can compete with traditional high-performance VSAs and HMUs for harmonic measurements. Using a VST for harmonic measurements can reduce the cost and bench space required for other dedicated instruments.

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