APP NOTE

# Cross-Correlation for Measuring Error Vector Magnitude

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## Continued Development in Wireless Connectivity

As wireless standards evolve to include wider bandwidths and higher-order modulation schemes to optimize spectrum efficiency and allow for increased data rates, modulation accuracy and reliability requirements accordingly become more stringent. One such standard, Wi-Fi 7 (IEEE 802.11be), includes channels of up to 320 MHz bandwidth with modulation schemes of up to 4096-QAM. With such tightly packed constellations in wide bandwidth channels, modulation accuracy is as important as ever to ensure high data throughput while maintaining reliable communications.

The error vector magnitude (EVM) limit for Wi-Fi 7 is −38 dB—a much harder measurement to capture than ever before, meaning that some methods for capturing EVM require reevaluation. While −38 dB is the standard limit, this is just the bare minimum for how a system under these standards must operate. Realistically, systems must perform better than what the standard specifies, and individual RF components must perform even better than that to account for inherent noise and distortion added at each stage of the signal chain. Also, when accounting for the test equipment floor to ensure accurate measurement capture and to add sufficient margins, test equipment must perform significantly better.

In short, higher throughput has meant higher order modulation, which has required more demanding EVM measurements in RF characterization.

## Significance of Accurate, Reliable EVM Measurements

EVM is the measurement of the difference between the ideal symbol and the measured symbol in a modulation scheme. When these two vectors are visualized on a constellation diagram, it is easy to see the noise and distortions that are inherently injected into a signal that can alter the measured value (Figure 1). The vector magnitude of the phase and amplitude shift (or IQ shift) is the EVM of a signal.

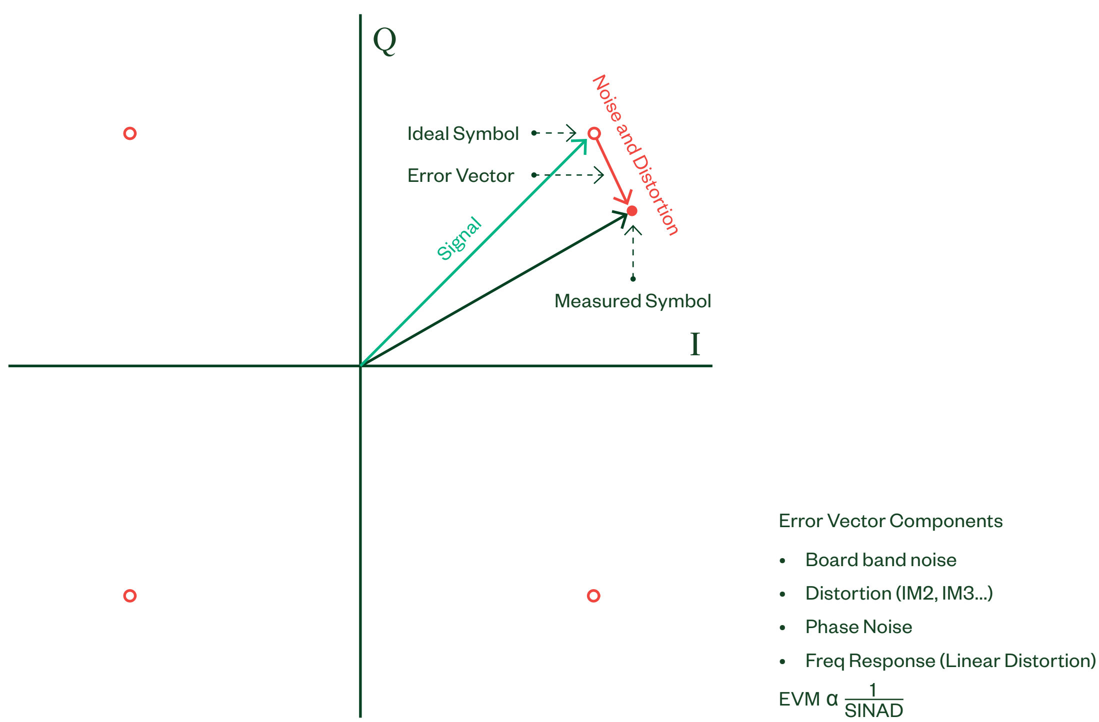



Figure 1. Error Vector Magnitude on a Constellation Diagram

What makes EVM such a useful signal characteristic is that, unlike phase noise, distortion, and frequency response, EVM is a comprehensive view of error, and as such, can be a single measure to quantify all of the different error components.

| IEEE STANDARD | HIGHEST-ORDER MODULATION SCHEME | EVM LIMIT |
|---|---|---|
| 802.11a | 64-QAM | -27 dB |
| 802.11ac | 256-QAM | -32 dB |
| 802.11ax | 1024-QAM | -35 dB |
| 802.11be | 4096-QAM | -38 dB |

Table 1. EVM Limits for WLAN Standards

When measured correctly, EVM is a way to comprehensively quantify the accuracy of RF transmitters, measuring errors that can arise at different stages of the transmit chain. Because of this, EVM is used in a variety of applications in addition to wireless connectivity, including radio astronomy, acoustics, geophysics, and 5G; and is a reliable measure of accuracy in many different use-cases. Its use in such wide-ranging fields is an indication of how useful EVM measurements can be.

# Difficulties Measuring EVM

Although they are incredibly valuable, obtaining EVM measurements requires overcoming several unique challenges. As bandwidth increases, the signal-to-noise ratio (SNR) decreases. This means that modulation accuracy is likely to suffer as more noise is present in the system. This is compounded by the smaller allowable decision areas for tightly packed constellations such as 4096-QAM.

EVM is especially difficult to measure when signal power drops—and the noise ratio of the signal increases to a point that can make the test equipment report values that are better than what the system can deliver. This is because the noise pushes IQ symbols into a neighboring symbol's decision area and can make large EVM measurements appear smaller than their actual values.

In addition, measured EVM is reflective of both the device under test (DUT), transmit chain, and the analyzer used in the system, and is analogous to the signal-to-noise and distortion ratio (SINAD) of signal generators and receivers. This is difficult to overcome and can give mixed results because the true measurement of interest is the transmit EVM and not the added uncertainty that a signal analyzer introduces into the system.

# Traditional EVM Measurement Methods

Before cross-correlation, most EVM measurement techniques used a single-channel configuration with one signal analyzer, where the accuracy of the measurement was based on the quality of the signal analyzer. While there is plenty of RF instrumentation capabl of reaching the 802.11be standard limit (-38 dB) as we discussed, proper validation requires more accurate measurements than this.

Two methods of acquiring EVM measurements over a single channel include a digital-gain servo and reference-level servo. While these provide accurate ways to measure EVM, often, they do not meet EVM requirements for some of the most stringent standards and test cases that require measurements of -50 dB or better.

Additionally, single-channel methods reduce all random noise (from both the DUT and receiver). To truly capture modulation accuracy, it is useful to preserve DUT noise and only suppress the receiver noise to identify the transmit EVM. This can give a better indication of DUT characteristics and is a way to capture errors that arise at the various stages of the transmit chain.

# Multi-Instrument Technique: What Is Cross-Correlation?

Cross-correlation is a practice used in many different fields and industries. At its most basic, it is a signal-processing technique that compares the similarity of two known quantities. These can be functions, variables, or vectors, and while there may be different measures of similarity, cross-correlation gives an indication and quantification of the similarity between two known quantities.

Cross-correlation for EVM measurements involves the use of two separate vector signal transceivers (VST) in parallel to compare the same signal through two distinct receiver paths. The comparison of similarity (or dissimilarity) of these two paths is the basis for obtaining a more accurate EVM.

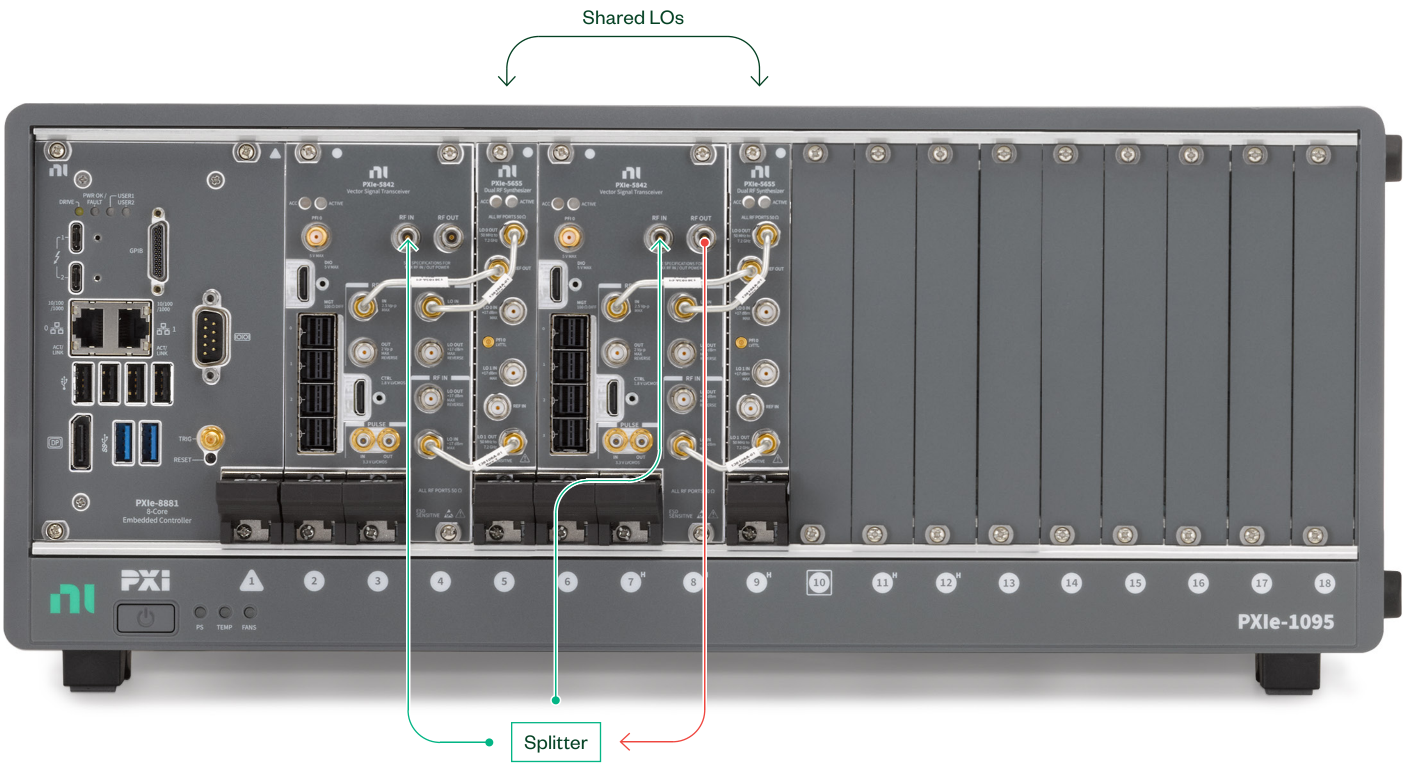
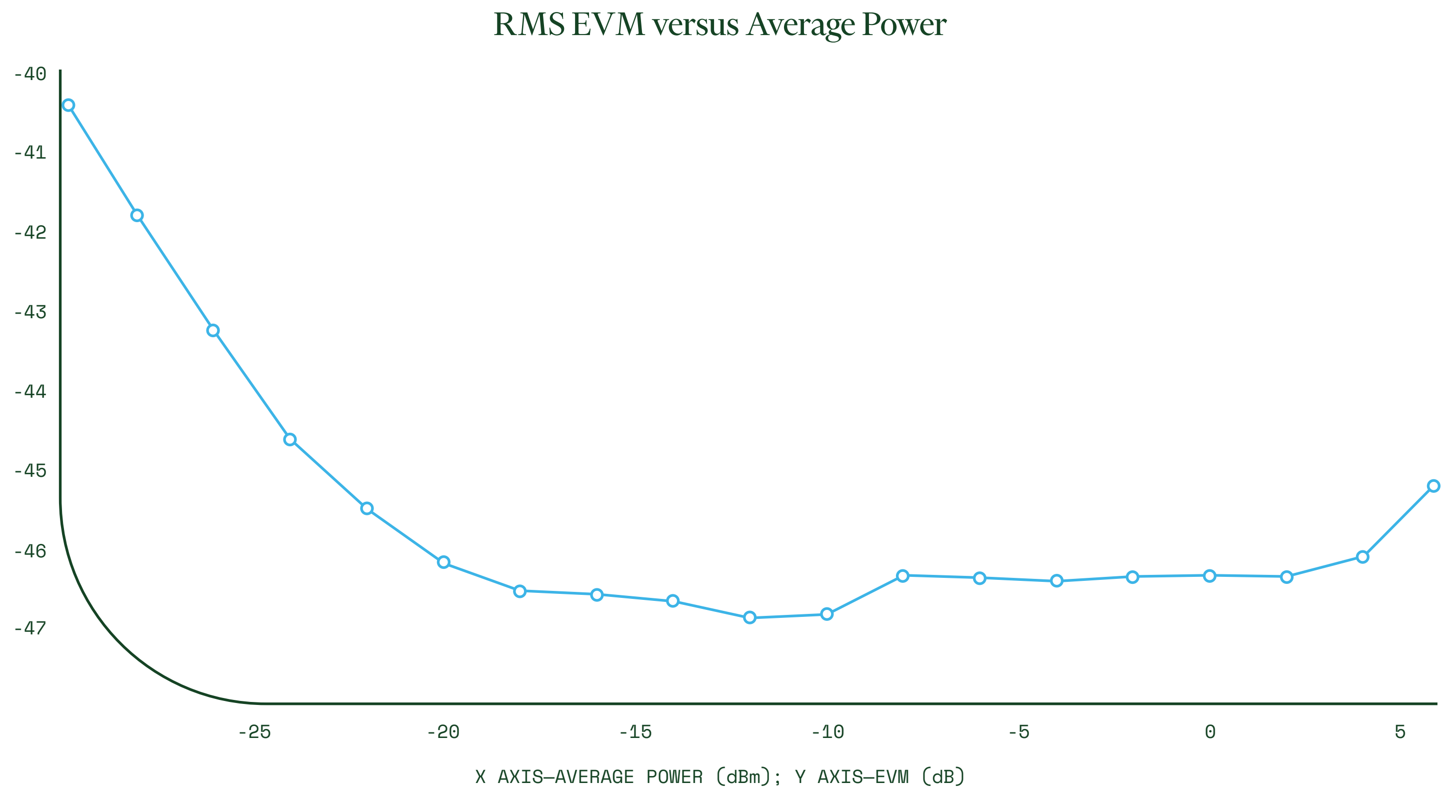



Figure 2. Cross-Correlation Connection Diagram with Two PXIe-5842 VSTs

NI's **patented** EVM cross-correlation technique takes accurate EVM measurements by removing the uncorrelated noise contributed to the system by the signal analyzers while preserving the transmit EVM.

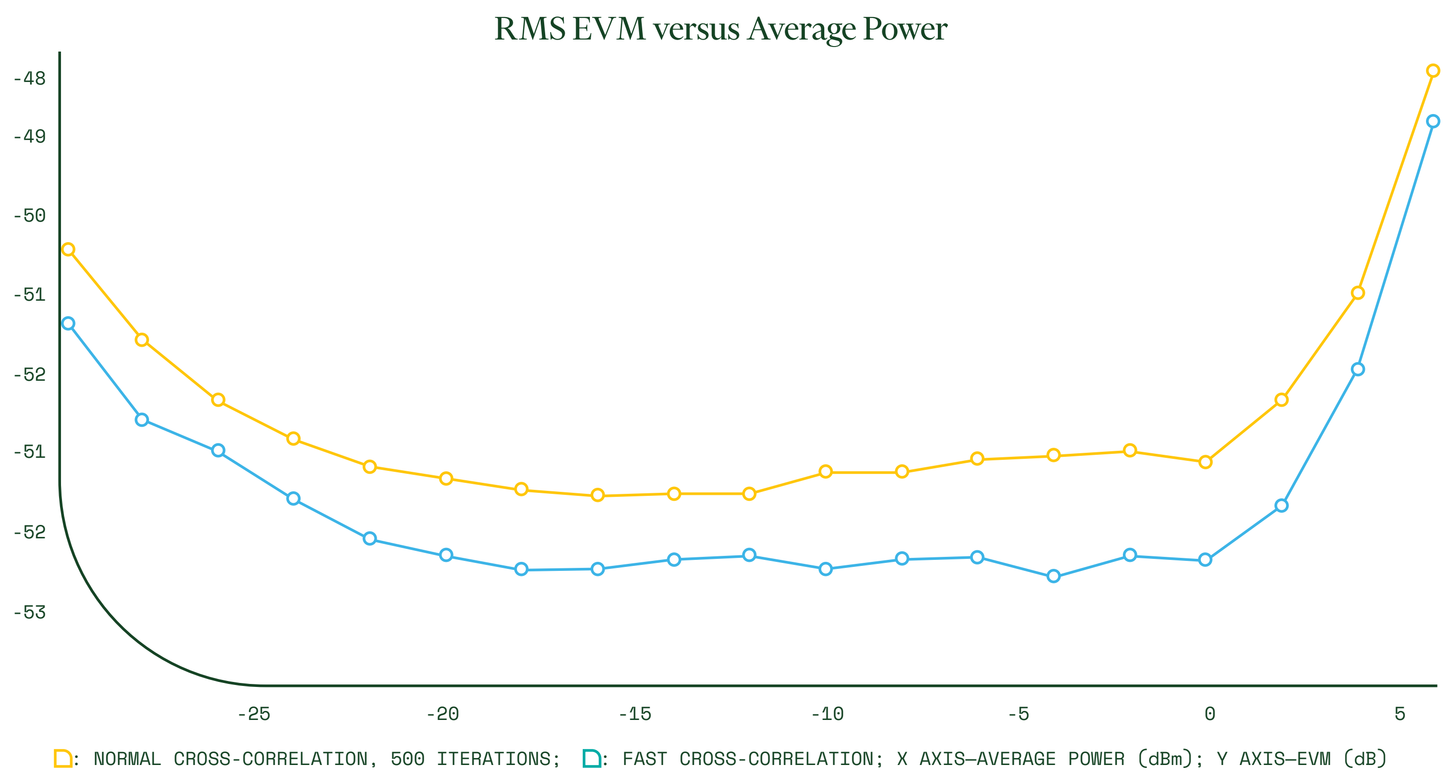
This is possible because the deterministic error in each signal analyzer is repetitive and cannot be removed when using one instrument. By using two signal analyzers, uncorrelated noise is now distinct to each analyzer and is removed from the system with each iteration as the noise from each signal analyzer is identified.

As a result, we minimize error terms while preserving the DUT noise—which is the measurement of value. We see significant improvement in EVM measurement accuracy without reporting values that indicate better-than-actual results that occur upon removing DUT noise.




Conditions: 802.11be, MCS 13, 320 MHz bandwidth @ 6.5 GHz, PAPR 11.72 dB, noise reconstitution enabled, ModAcc Auto Level: Enabled; RF OUT digital gain servo (increase RF OUT digital gain until DSP overflow reported) Splitter: Mini Circuits ZC2PD-5R263-S+.applied

Figure 3. Single-Channel PXIe-5831 Loopback EVM, Measured vs Average Power




Conditions: 802.11be, MCS 13, 320 MHz bandwidth @ 6.5 GHz, PAPR 11.72 dB, Splitter: Mini Circuits ZC2PD-5R263-S+.

Figure 4. Cross-Correlation and Fast Cross-Correlation with PXIe-5831 Loopback EVM, Measured vs. Average Power

### CROSS-CORRELATION FOR MEASURING ERROR VECTOR MAGNITUDE

Cross-correlation can offer improvements of up to 3 dB over single-channel performance with one VST. Figures 4 and 5 above show single-channel EVM, cross-correlation EVM, and fast-convergence cross-correlation EVM results using the **PXIe-5831** VST.

Also supported with cross-correlation is NI's third-generation VST, the **PXIe-5842**. Incorporating the PXIe-5842 into this setup gives industry-leading EVM performance at both the instrument level and when leveraging cross-correlation. We see improvement over many different bandwidths, standards, and other conditions for EVM measurements: Cross-correlation adds accuracy to already exceptional EVM performance.

| SPECIFICATION | PXIE-5842 PERFORMANCE |
|---|---|
| Frequency Range | 50 MHz to 23 GHz |
| Bandwidth | Up to 2 GHz |
| Tx/Rx Amp. Accuracy | ±0.4 dB typ. |
| Tx/Rx Flatness | ±0.45 dB typ. (2 GHz BW) |
| EVM (5G NR) | -54 dB (100 MHz, loopback, measured) |
| EVM (802.11be) | -49 dB (320 MHz, loopback, measured) |
| Maximum Output Power | <+20 dBm typ. (CW @ 5 GHz) |
| Tuning Time | <230 µs |
| PXI Express Slots | 4 |

Table 2. **PXIe-5842 Specifications**

It is important to note that, although converging to a representative EVM requires many iterations, waveform repetition is not needed across each iteration to arrive at an overall RMS EVM or per symbol/per subcarrier EVM. Every frame can be independent and unique, and you can use a scrambler, if needed. You also can use the same waveform for each iteration, as is typical with PA validation.

NI's patent-pending **Fast Convergence Cross-Correlation** brings additional benefits in capturing EVM measurements. Standard cross-correlation techniques require several iterations to converge to the true EVM of a DUT. This can lead to long test times and, as a result, slower time to market and development cycles.

In standard cross-correlation, the entire error vector is used in calculation and then averaged across all iterations. When using all error components, this leads to a lengthy calculation, which takes several iterations to remove from the algorithm. To avoid this, NI implements a unique fast-convergence calculation in which the magnitude of the error vectors is the focus of measurement. For an in-depth explanation, refer to **eq. 12, pg. 6, in the patent publication**.

Note that this is distinct from predictive methods of determining the value at which EVM will converge after a certain number of iterations. This is a true measurement of representative EVM that is obtained with far fewer iterations of cross-correlation.

The cumulative effect of all these factors results in better and faster EVM measurements, optimizing time to market while ensuring robust and thorough characterization.

## NI Differentiation

NI offers other unique pieces of hardware and software to EVM measurements that can further improve how these measurements are taken and accuracy of the results.

Natively integrating and synchronizing the necessary **PXI VSTs** in a single PXI chassis means that all instruments operate through the same backplane and interface. PXI controllers and chassis are designed with effective timing and synchronization in mind, so this integration brings an intuitive connection and easy-to-use interface between both VSTs. Combine this with NI's third-generation VST, the **PXIe-5842**, and the result is best-in-class EVM performance at both the instrument level and through cross-correlation in an integrated platform.

**Learn more about the PXIe-5842.**

On the software side, NI's RFIC Test Software integrates many common RF measurement panels and drastically reduces your time to first measurement by eliminating the need for writing code. By giving a high-level starting point for using RF instrumentation, RFIC Test Software helps you quickly begin taking measurements and easily transition to automated validation.

**Learn more about RFFE validation.**

# RF Characterization Benefits

As RF semiconductor devices become increasingly complex and shorter time to market continues to be crucial to increasing market share, the benefits of faster RF front-end validation become strikingly clear.

While we've shown that cross-correlation can improve EVM measurement accuracy and effectively isolate transmit EVM, cross-correlation and fast convergence algorithms bring additional value to EVM measurements.

Cross-correlation advantages are even more pronounced at low power. Because the SNR of a system is much lower at low power, the uncorrelated noise that is removed is a much larger component of the signal being analyzed and the EVM improvement is more significant.

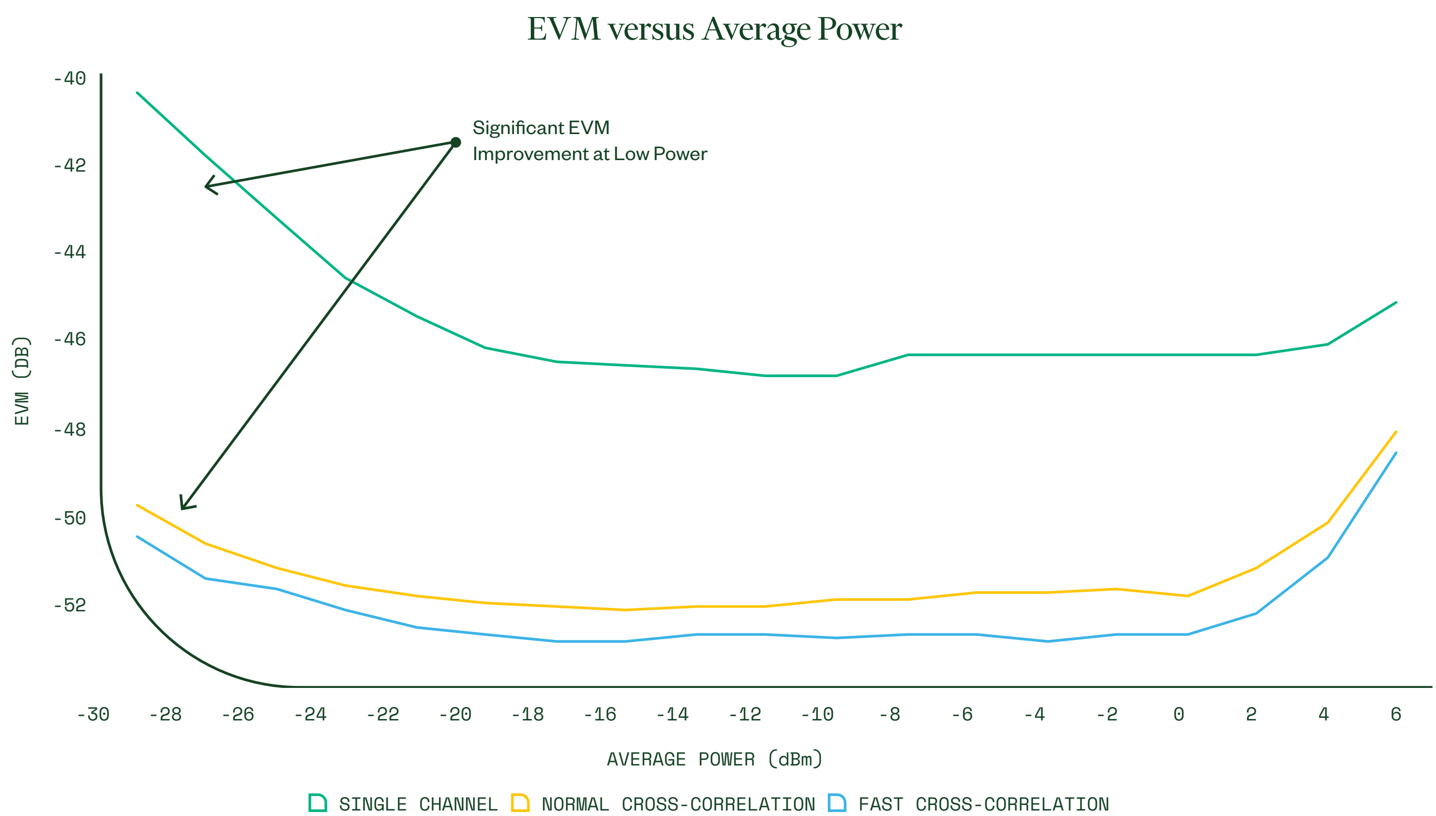
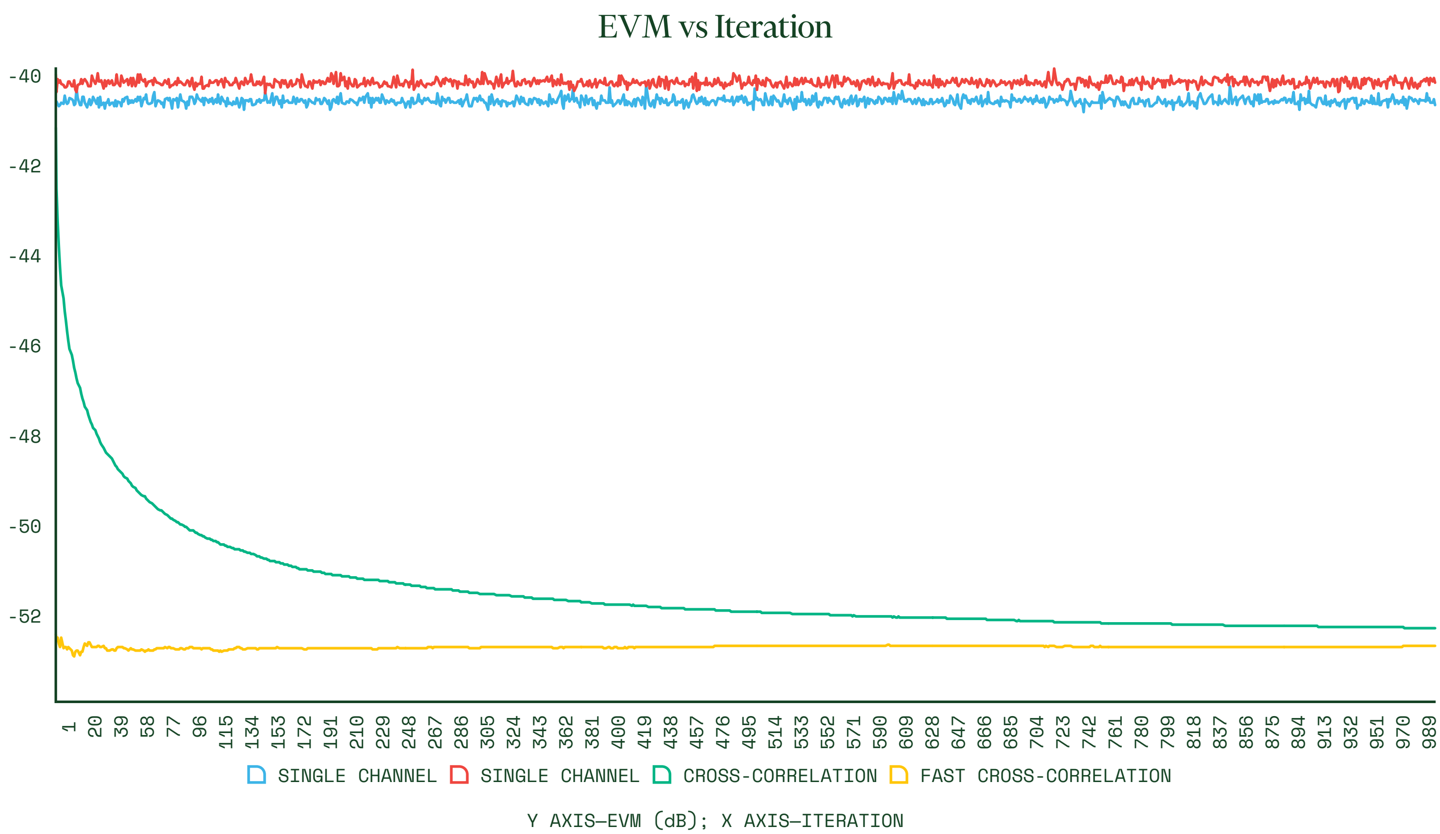



Figure 5. PXIe-5831 EVM, Measured vs. Average Power, With and Without Cross-Correlation, in the Same Conditions as Figures 3 and 4

When it comes to implementing fast cross-correlation EVM, speed is the key advantage. Fast cross-correlation EVM measurements can converge to a representative EVM up to 50 times faster than conventional cross-correlation. While this is still slower than some single-channel configurations, the added accuracy that cross-correlation brings, combined with the added speed of fast convergence algorithms, means that there is the added benefit of both accurate measurements and fast test times.




Conditions: 802.11be, MCS 13, 320 MHz BW, PXIe-5831 @ 6.5 GHz,
-20 dBm average power, PAPR 11.72 dB, Splitter: Mini Circuits ZC2PD-5R263-S+

Figure 6. Fast-Convergence CC EVM Results

# Cross-Correlation Considerations

For all the benefits of cross-correlation, there are some factors to consider. For example, system setup, including cabling and splitter choice, requires special care to ensure measurement accuracy.

With cross-correlation, thermal noise collapse across power dividers is a phenomenon that typically limits this type of measurement. To learn more, read **Cross-spectral Collapse from Anti-correlated Thermal Noise in Power Splitters**. Thermal noise that is not equal across both cross-correlation channels due to splitter type can over- or under-transfer source thermal noise in cross-correlation. The workaround is to use a Wilkinson splitter, which always collapses the thermal noise almost perfectly. This means that the contribution of the thermal noise in the EVM measurement will be nearly zero. Then, the thermal noise is manually readded to the measurement, depending on the power level of a given measurement.

Despite this challenge, thermal noise collapse and eventual noise reconstitution can end up being an advantage in cross-correlation for EVM if there is attenuation between the source where EVM is measured and the power splitter. Thermal noise reconstitution can give more accurate results than otherwise possible. This feature is enabled with both Wi-Fi and 5G NR waveforms in NI's cross-correlation software.

Cross-correlation and fast cross-correlation EVM measurements improve measurement speed and accuracy; however, if these are measured against the wrong constellation point, the results can appear better than actual. To account for this, we can introduce a reference trace to properly align an EVM measurement with a reference waveform. NI cross-correlation has IP in place to determine the ideal waveform to compute EVM against. This can help limit the initial underestimation of EVM by taking the measurement with respect to this waveform as a reference, as opposed to simply using the nearest constellation point.

Lastly, the nature of cross-correlation requires two VSTs. However, this complex and highly accurate test setup is unlikely to be replicated many times in a lab—rather, it may best function as a "golden bench," being at the cutting edge of measurement capability. Additionally, the way in which we can use NI RF hardware and software in conjunction offers repurposing options for many other RF test applications—as well as test combinations with other **DC**, **analog**, and **digital** instruments. Properly leveraging this capability translates to higher reuse in a lab environment and can reduce the overall footprint and quantity of hardware needed for RF characterization.

**Learn more about scalable and versatile instrumentation on the PXI platform.**

# Summary

The current generation of PXI VSTs plus NI's cross-correlation techniques offer a significant and differentiated EVM performance advantage. Measurement accuracy improvement proves that cross-correlation is more than sufficient to meet the latest cellular and connectivity standards and is set to help future-proof test systems as these standards further evolve—vital to keeping pace with innovation. You can minimize validation timelines while keeping intact EVM measurement quality and accuracy for meaningful insights in RFIC characterization.

NI's cross-correlation, fast cross-correlation, and industry-leading EVM performance extend well beyond this brief explanation. For more information, please contact a technical expert to learn how NI can help you achieve faster and better modulation accuracy measurements for Wi-Fi 7 and 5G—and stay ahead of these evolving standards.

**Learn more about NI's semiconductor test solutions.**