Enhancing Measurement Performance for the Testing of Wideband MIMO Signals

White Paper

How to generate and apply magnitude and phase corrections for multichannel baseband IQ measurements when using the Keysight M9703A AXIe digitizer

KEYSIGHT
TECHNOLOGIES

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Introduction

Testing the baseband modulation of 802.11ac MIMO signals introduces new challenges for systems engineers, such as the increased modulation bandwidth of up to 160 MHz, the support for up to eight MIMO spatial streams, and the increased requirement in EVM performance to support 256 QAM. Multichannel applications such as these require a wideband test solution capable of analyzing multiple IQ channels with highly accurate cross-channel performance. Extending 2-channel test solutions to support Multi-User MIMO (MU-MIMO) 802.11ac requirements for 160 MHz bandwidth testing can be complex, and the variation in frequency response, magnitude and phase, between channels can greatly impact measurement performance.

This white paper describes a simple method for the characterization and correction of channel frequency response in the Keysight Technologies, Inc. 89600 VSA software environment for baseband IQ (BBIQ) measurements over large bandwidths. This document describes the measurement methodology, the hardware configuration, and the application of user correction filters to improve demodulation performance results using 802.11ac signals. In this paper, 802.11ac BBIQ simulation and test are enabled through use of the following Keysight products:

– N5182B MXG RF vector signal generator for creation of 802.11ac waveforms with up to 160 MHz bandwidth.

– M9703A multichannel, high-speed digitizer for signal capture.

– 89600 VSA software for generation of user correction filters and signal analysis.

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Applications

The ever-increasing demand for higher data-throughput in consumer devices that support wireless LAN (WLAN) — including cell phones, tablets, and game consoles — is driving the need for the rapid deployment of new wireless technologies such as 802.11ac. The 802.11ac technology is backwards compatible with 802.11n and introduces several new feature enhancements such as wider bandwidths (up to 160 MHz), higher-order modulation (up to 256 QAM), MIMO and MU-MIMO with up to 8 data streams, and faster data rates up to 6.93 Gbps. While 802.11ac provides several key advances over prior Wi-Fi technology, it creates new challenges for test engineers.

The solution described in this document greatly enhances the measurement performance of digitizer platform, for the demodulation of BBIQ 802.11ac signals. This is achieved by compensating the frequency response across the individual I and Q digitizing channels.

Keysight provides a number of solutions for multichannel measurements of MIMO 802.11ac BBIQ signals for simulation, design, and test. Please refer to the following documents that provide details about additional MIMO applications:

– *Measurement Solutions for Multichannel Applications* (literature number 5991-2263EN)

– *Solutions for MIMO Receiver Test* (literature number 5990-4045EN)

– *MIMO Measurement Tips with Keysight P-Series Power Meters and U2000 Series USB Power Sensors* (literature number 5990-3546EN)

Magnitude and Phase Correction for Multichannel BBIQ Measurements

1. Measurement Methodology

In many multichannel wideband applications it is critical to have phase-coherent channels for accurate inter-channel time and phase measurement. Various methods can be used to measure cross channel skew. An application note entitled *Achieve High Speed, Multichannel Data Acquisition with Keysight M9703A AXIe Digitizer* (literature number 5991-1941EN) describes two possible measurement techniques:

- Sine-fit approximation, and
- Digital Downconversion (DDC)

Both of these techniques utilize the Keysight M9703A high-speed digitizer, to determine the measurement and analysis of cross channel skew in multichannel high-speed digitizers.

While each method has its advantages, the procedure described in this document to generate user correction filters is based upon the proven Sine-fit measurement method. This was chosen due to its ability to determine both the magnitude and phase across a large frequency range that can extend beyond Nyquist frequencies.

By stepping through and making measurements over a range of frequencies, such a method can be used to build a Bode plot of frequency response--the gain and phase characteristics of the channels can then be compensated. Within the Keysight 89600 VSA software environment, user correction filters can be applied to correct the magnitude and phase response over a defined frequency range.

Sine-fit Approximation Method

In this paper, a least-squares sine wave curve fitting approximation, as defined by the IEEE Standard 1057-1995 for digitizer specification, is used to determine the magnitude and phase parameters of an acquired sinusoid signal. This method fits a sinusoid model to a set of acquired data points, and uses a least-squares fit algorithm to minimize the difference between the samples and the model, as shown in Figure 1. In the IEEE standard, this process is used to compare the acquired data to an ideal performance, and thereby obtain various sampling digitizer parameters such as signal-to-noise ratio, Effective Number of Bits (ENOB), and gain errors among others. Through this approximation, we are able to construct the signal of frequency f and determine its sinusoid parameters as defined by:

$$A \sin \omega t + \varphi + C \tag{1}$$

where A is the amplitude, ω is the period ($1/f$), t is time, φ is phase, and C is the DC offset.

Magnitude and Phase Correction for Multichannel BBIQ Measurements

1. Measurement Methodology *(continued)*
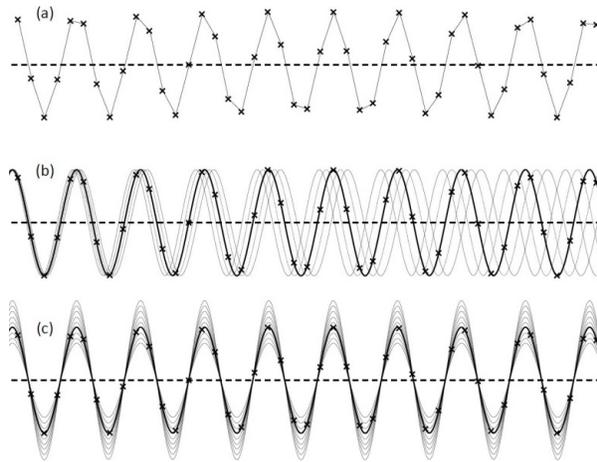
Sine-fit Approximation Method *(continued)*

Figure 1. Sine-fit estimation. From acquired data points (a) obtaining a best fit of frequency and phase (b) as well as offset and magnitude (c).

Using the Sine-fit approximation method described above, it is possible to calculate the magnitude (gain) and difference in phase for a pair of channels where both are supplied with the same signal. Since the absolute phase of the signal at the channel input is not known, it is not possible to calculate the absolute phase for each channel. However, if we select a reference channel and assume that this channel's frequency response is a fixed function of the input frequency, and that this function is stable over time, all of the channels can be aligned with respect to that response, and any measurements of phase difference can be determined across the corrected channels relative to the same reference.

Figure 2 shows a schematic of the measurement methodology. For each channel, the frequency response, in both magnitude A and phase φ as a function of frequency, is independent and fixed. Those functions are defined as $A_{ref}(f)$, $\varphi_{ref}(f)$ and $A_X(f)$, $\varphi_X(f)$ for the reference and test channel respectively.
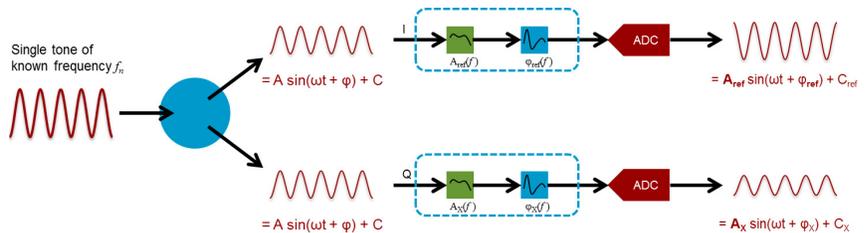

Figure 2. Schematic of two channel magnitude and phase calibration for a given frequency f_n.

Magnitude and Phase Correction for Multichannel BBIQ Measurements

Sine-fit Approximation Method (continued)

Using a source signal of known amplitude and frequency f_n at the input to each channel (1), the acquired waveforms in the channels will be modified by their frequency response to be:

$$A_{ref} \sin (\omega t + \varphi_{ref}) + C_{ref} \qquad (2)$$

$$A_X \sin (\omega t + \varphi_X) + C_X \qquad (3)$$

The response function for each channel at that frequency can then be calculated as:

$$A_{ref}(f_n) = A_{ref} - A \qquad (4)$$

$$A_X(f_n) = A_X - A \qquad (5)$$

$$\varphi_X(f_n) - \varphi_{ref}(f_n) = \Delta\varphi(f_n) = \varphi_X - \varphi_{ref} \qquad (6)$$

Where $\Delta\varphi(f_n)$ is the phase frequency response of the test channel *with respect to* the reference channel at that given frequency. By making multiple measurements at a number of predefined frequencies of f_n, it is possible to construct a map of the frequency response of the channels and corresponding Bode plot over a desired bandwidth.

Magnitude and Phase Correction for Multichannel BBIQ Measurements

2. Hardware Configuration

The following hardware is required to characterize the channel frequency response:

— a calibrated signal source

— a passive power divider with cables to connect it to the source

— a multichannel digitizer with controlling software

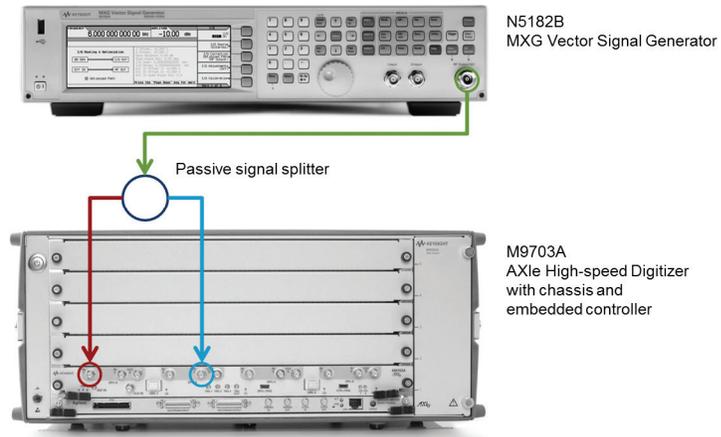Figure 3 shows a diagram of the test setup used in these measurements.

Figure 3. Diagram for characterization of channel 1 with respect to reference channel 4.

A Keysight N5181B-MXG vector signal generator was used to generate a single tone sinusoid of known, calibrated amplitude. The signal is fed through a passive power splitter covering DC to the required bandwidth and connected to two channels of the M9703A 12-bit, 8-channel, AXIe digitizer. A U2004A power sensor was used to calibrate the user flatness of the signal generator, such that the output amplitude specified programmatically, or on the instrument front panel, was correct at the two outputs of the passive splitter. In this example, channel 4 was selected as the reference phase channel; however, any other channel of the digitizer could also have been used. The lower frequency limit of 100 kHz of the signal source was used to derive the low frequency gain, but the skew for any DC signal must be zero degrees.

Magnitude and Phase Correction for Multichannel BBIQ Measurements

3. Signal Generation and Acquisition

The signal generation and acquisition parameters were controlled through a MATLAB script. Within this script a Sine-fit algorithm, as described in the IEEE standard for digitizing waveform recorders [ref IEEE standard 1057, Trial-Use Standard for Digitizing Waveform Recorders, 1989] was used to construct a best-fit sinusoid waveform to the acquired data points. Both the amplitude and relative phase could then be determined from the reconstructed waveforms.

As explained previously, it is not possible to determine absolute phase measurements of each digitizing channel; however, in test environments where measurements are predominantly between a reference signal and a test signal, determination of the differential phase correction is entirely adequate.

For each channel pair, the software would set the signal frequency of known amplitude, capture data on two channels of the digitizer, and perform a Sine-fit approximation on both data sets. From the two resultant models, the channel gain in dB was calculated for each channel and the differential phase response between the channels in degrees was recorded. The generated signal frequency was then changed, the measurement repeated, and so on, building a table of results to cover the required bandwidth. The size of the frequency steps was chosen according to the width of characterization and the required granularity in the filter—in these measurements for the M9703A, 5 MHz steps were used for 160 MHz analyses. Half way through this series of measurements, the software is paused, and the external connections to the digitizer inputs switched. This is done to eliminate any fixed delay in the two signal paths to the reference and test channels. At the end of the measurements, an array is built of the average values at each frequency step. Figure 4 shows the result for a pair of channels, with gain between 0 and −0.2 dB, and the phase difference between the channels diverging near-linearly from 0 to 1.2° over the 40 MHz frequency span.
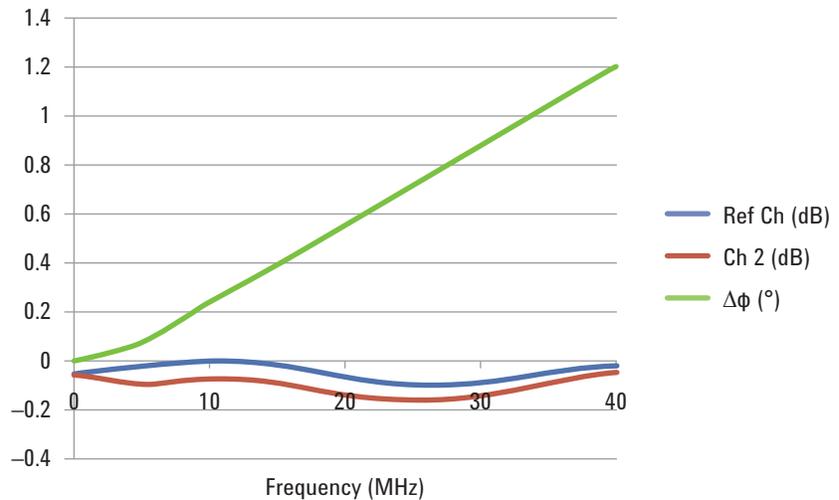

Figure 4. Frequency response for a pair of channels of M9703A, gain in dB, and phase difference in degrees.

Using the above method to determine the frequency response of the digitizer channels, a user correction filter could then be built, to correct the magnitude and phase response when using the channel pairs in the Keysight 89600 VSA software environment.

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Magnitude and Phase Correction for Multichannel BBIQ Measurements

4. Generation of User Correction Filters in 89600 VSA Software

Once the frequency response of the acquisition channels is known, compensation for the behavior can be made using various techniques, such as the implementation of finite impulse response (FIR) filters. The user correction interface of Keysight 89600 VSA software is intended to compensate for external devices connected to a calibrated instrument. However, this same functionality can be used to correct for the frequency response between different channels of a waveform digitizer. Frequency response parameters can be corrected using either a radio frequency (RF) or intermediate frequency (IF) filter. Both are intended to compensate for external filters, amplifiers, tuners, etc; however, RF filters compensate only for magnitude over a bandwidth defined with absolute frequency values. An IF filter will compensate for both magnitude and phase around a center IF frequency. The frequency of the correction data is placed relative to this IF.

The user correction interface is shown in Figure 5. The filters are implemented as text files, with a header that describes the frequency range and frequency steps, followed by a simple list of correction values.

Figure 5. User correction interface in the Keysight 89600 VSA software environment.

Magnitude and Phase Correction for Multichannel BBIQ Measurements

4. Generation of User
   Correction Filters in
   89600 VSA Software
   (continued)

For BBIQ measurements, an IF user correction filter centered at 0 Hz is required. In the example above, measurements of each channel from 0 to 40 MHz were taken, with 5 MHz steps. This data can be used to construct an 80 MHz baseband IF correction, substituting the conjugate-symmetric of the measured frequency response for the negative frequencies. For more details in the user correction file format, consult the Keysight 89600 VSA documentation. Figure 6 shows a visualization of the parameters for an 80 MHz IF user correction filter based on the data shown previously in Figure 4.
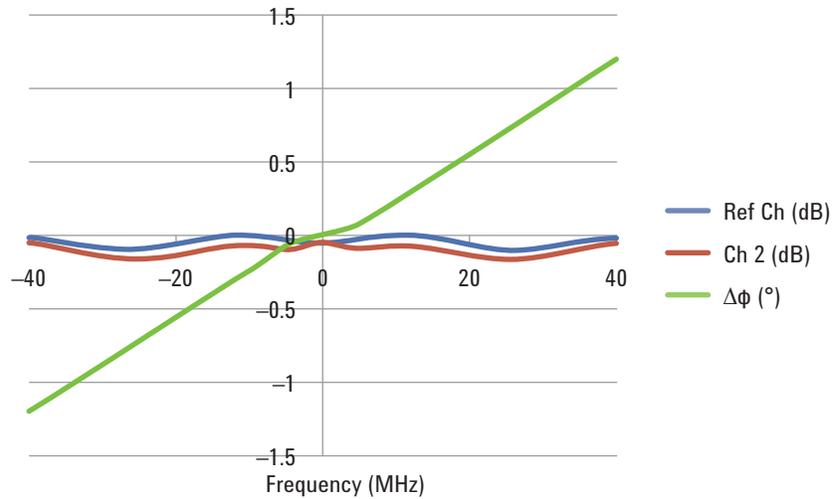

Figure 6. User correction data for an 80 MHz BBIQ filter based on the data shown in Figure 4.

Using the data obtained from the characterization of each channel relative to the reference channel, it is possible to build a set of BBIQ filters for all 8 channels of the M9703A digitizer. Since the phase correction of all of the channels is measured with respect to the reference channel, any pair of channels can be used as one of the IQ pairs for BBIQ measurements. Although the reference channel can also be used to capture data, it is not necessary to use it as one of the measurement channels. However, all 8 channels of the M9703A digitizer, including the reference channel, can be used to perform phase coherent measurements, and for measurement of a quad BBIQ for MIMO 802.11ac testing.

Magnitude and Phase Correction for Multichannel BBIQ Measurements

5. Demonstration Example to Test Results of Correction

The demodulation of several wideband signals was performed in order to test the efficiency of the compensation using correction filters that were built using this process. Channels 1 and 2; 3 and 4; 5 and 6; and 7 and 8, were each tested as IQ pairs with a modulated signal generated by a Keysight N5181B-MXG vector signal generator with external IQ output option.

Tables 1 and 2 illustrate the EVM results of the IQ pairs without correction and with the application of an IF user correction filter for both the 80 MHz and 160 MHz 802.11ac WLAN standard.

Without user correction (Table 1), and with the same signal at the channel inputs, each IQ channel pair provided respectable performance but with a large difference between the minimum and maximum EVM measurements. Without the application of the IF user correction filter, the average EVM of IQ channel pairs is –44.9 dB and –41.0 dB, for 80 MHz and 160 MHz modulation respectively. The difference in performance is also quite large. The best performing channel pair (7 and 8) and the worst performing (5 and 6) is 4.5 dB for 80 MHz modulation, and 3.3 dB for 160 MHz 802.11ac.

The characterization routine for the individual channels indicated that over the 160 MHz bandwidth, the gain in channels 5 and 6 were matched to within ±0.2 dB, whereas all other channel pairs were matched to ±0.1 dB. This difference in gain matching was a principal source of error when using these channels as IQ pairs without any user correction; however, as shown in Table 2, with the application of the IF user correction filters, the individual frequency responses are all corrected to the same level. The EVM is reduced to an average level of –47.4 dB and –45.1 dB, for 80 MHz and 160 MHz modulation bandwidths respectively, and the worst performing channel pair (5 and 6), shows an improvement of over 5 dB, to align all four channels to within ±0.3 dB for the 80 MHz signal and to within ±0.2 dB for the 160 MHz signal.

Table 1. EVM results of the IQ pairs before application of an IF user correction filter

| | EVM (dB) | | | |
| | Channels 1 and 2 | Channels 3 and 4 | Channels 5 and 6 | Channels 7 and 8 |
	Without correction filter	Without correction filter	Without correction filter	Without correction filter
802.11ac 80 MHz	–45.45	–45.44	–42.04	–46.52
802.11ac 160 MHz	–42.04	–41.98	–38.73	–41.06

Table 2. EVM results of the IQ pairs after application of an IF user correction filter

| | EVM (dB) | | | |
| | Channels 1 and 2 | Channels 3 and 4 | Channels 5 and 6 | Channels 7 and 8 |
	With correction filter	With correction filter	With correction filter	With correction filter
802.11ac 80 MHz	–47.39	–47.71	–47.12	–47.50
802.11ac 160 MHz	–45.15	–45.14	–45.01	–45.19

Summary

The Keysight M9703A provides a unique solution for multichannel measurements of 802.11ac BBIQ simulation and test. The measurement performance of Keysight's M9703A AXIe digitizer can be optimized through the characterization and correction of the frequency response of each input channel. For proven measurement improvement, corrections can be implemented with the correction filter in the Keysight 89600 VSA software.

This white paper described use of the Sine-fit approximation method to calculate the magnitude and phase variation for each channel of the M9703A multichannel digitizer relative to a reference channel to build a set of BBIQ IF filters to flatten the magnitude and phase response across channels. Other techniques, including the use of wideband chirps, or multi-tone signals could also be used, for the same ends.

The resulting EVM performance in benchmark tests demonstrated a significant improvement over uncorrected measurements for wideband multichannel signals. Such correction can be implemented due to the long-term stability of the frequency response of the digitizer channels used.

The characterization and correction methods shown in this paper used the 802.11ac wideband modulation to demonstrate the capabilities of the process and hardware platform. The same techniques can also be used for many wideband multi-antenna applications requiring phase-critical measurements.

About the Author

Richard Soden has been an Application engineer and Product Manager for Keysight's high-speed digitizer products since 2004. Prior to his work in defining new data-conversion technologies, Richard was using such technologies in various posts as an Applications Engineer, Project Manager and Development Engineer in the material characterization, and non-destructive testing industries.

Richard holds a Bachelors in Engineering in Optoelectronics and Laser Systems from the University of Hull, UK, and a Ph.D in Optical based Nondestructive Testing techniques from the University of Manchester Institute of Science and Technology, UK.

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