APPLICATION NOTE

Wideband mmWave and MIMO Testing with Your UXR

Quick and accurate phase-coherent MIMO measurements

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MIMO Overview

Multiple-input/multiple-output (MIMO) is a signal transmission technique that promises higher data rates for a single user. It uses up to eight layers in frequency range 1 (FR1) and up to two layers in FR2 with data transmitted using multiple antennas. Multiple antennas transmit independent streams of data on the same frequency and at the same time without interfering with one another. That process exploits spatial differences in the channel to increase the overall throughput rate compared with a single-antenna single-input/single-output (SISO) implementation.

3GPP 5G New Radio (NR) offers the potential for increased data rates for enhanced mobile broadband applications compared with 3GPP 4G Long Term Evolution (LTE). Higher data rates are possible using higher-order modulation, wider modulation bandwidths at higher millimeter-wave (mmWave) frequencies, and MIMO.

Figure 1 shows a conceptual diagram of single-user 2x2 MIMO. Multiple spatial channels transmit and receive multiple and independent streams of data to increase the effective data rate for a single user. In this simple example, the receiver de-multiplexes the two data streams with knowledge of the channel [H]. Antenna coupling or channel/multibounce coupling can impact MIMO performance, depending on the channel condition.

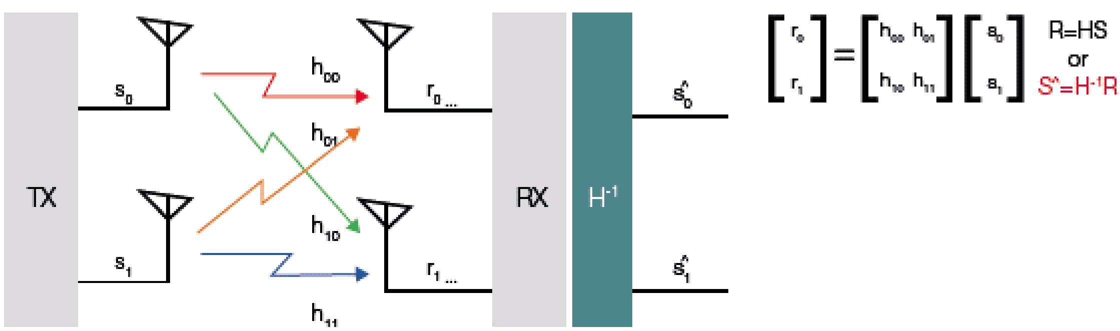

Figure 1. Single-user MIMO

Key Issue: Complexity of MIMO

MIMO is a complex technology for 4G and WLAN. However, MIMO may be significantly more complex for 5G NR in the FR2 band compared with LTE and WLAN, given the wide modulation bandwidths at mmWave frequencies. As engineers migrate from single-antenna SISO implementations to two-channel MIMO, complexity will increase significantly. That complexity introduces a multitude of design and testing challenges that impact peak data rates and make it difficult to troubleshoot and debug hardware performance issues. To ensure optimal performance in a multichannel MIMO implementation, engineers must perform comprehensive multichannel MIMO measurements, such as error vector magnitude (EVM), a key metric for transmitter performance. Radio-frequency (RF) and baseband impairments such as timing errors, local oscillator (LO) phase noise, power amplifier gain/phase distortion, and intermediate frequency (IF)/RF filter group delay can contribute to transmitter EVM degradation. Gaining insight into such error mechanisms is critical to uncovering potential MIMO performance problems.

For 5G NR and other emerging applications such as 802.11ay, the propagation loss at mmWave frequencies necessitates the use of phased-array technology and beam steering to achieve sufficient signal-to-noise ratio and link quality. This adds a layer of complexity in validating mmWave MIMO system performance under real-world scenarios.

UXR Solution

Keysight's UXR ultra-high-performance real-time oscilloscope enables direct digitization of mmWave wide-bandwidth signals for MIMO testing and debugging. The UXR provides up to four phase-coherent full-bandwidth channels with a maximum instantaneous bandwidth of up to 110 GHz at a sample rate of 256 GSa/s. The 10-bit ADC, coupled with the high sample rate, provides excellent signal fidelity and near-spectrum-analyzer-like dynamic range, perfect for in-channel demodulation measurements such as EVM for SISO and MIMO applications.

As an example, the test setup below utilizes the 110 GHz UXR to perform a 2x2 5G NR MIMO EVM measurement in the 28 GHz FR2 band. *Note: Although the 5G NR example shown here focuses on 2x2 MIMO, four-channel high-performance oscilloscopes have performed 4x4 MIMO measurements. It is discussed in section 6.8.3, "Debugging MIMO Designs Using a Digital Oscilloscope" in Agilent Technologies' LTE and the Evolution to 4G Wireless book, second edition.*

Figure 2. 5G NR 28 GHz MIMO test setup

The test setup consists of a two-channel Keysight M9384B 44 GHz VXG microwave signal generator to generate 2x2 5G NR MIMO spatially multiplexed signals at 28 GHz. The two MIMO signals feed into two fixed rectangular probe antennas that are cross-polarized (one horizontal and one vertical). The device under test (DUT) is an 8x8 cross-polarized phased-array antenna courtesy of the University of California, San Diego (UCSD). The two 28 GHz output signals from the phased-array antenna feed into the two-channel UXR to directly digitize the 28 GHz test signals for demodulation with the Keysight 89600 VSA software.

The 89600 VSA software runs inside the UXR to perform the demodulation analysis. The VSA displays a large number of measurements, providing an in-depth look at the signal from different domains. That is particularly useful for verifying signal quality and troubleshooting complex issues down to the root cause. Additionally, you can enable markers in most measurement types and couple the markers in the other measurement domains. Hence, as a marker is positioned in a particular measurement, the corresponding markers in the other measurements automatically move to represent the same positions. The number of measurements, their placement on the screen, and their individual size are easily customizable, depending on the task at hand. In many of these measurements, you can filter the amount of displayed data according to what is of interest. For example, when viewing a complex constellation diagram with data from many channels, you can quickly simplify it by removing the data from the unnecessary channels.

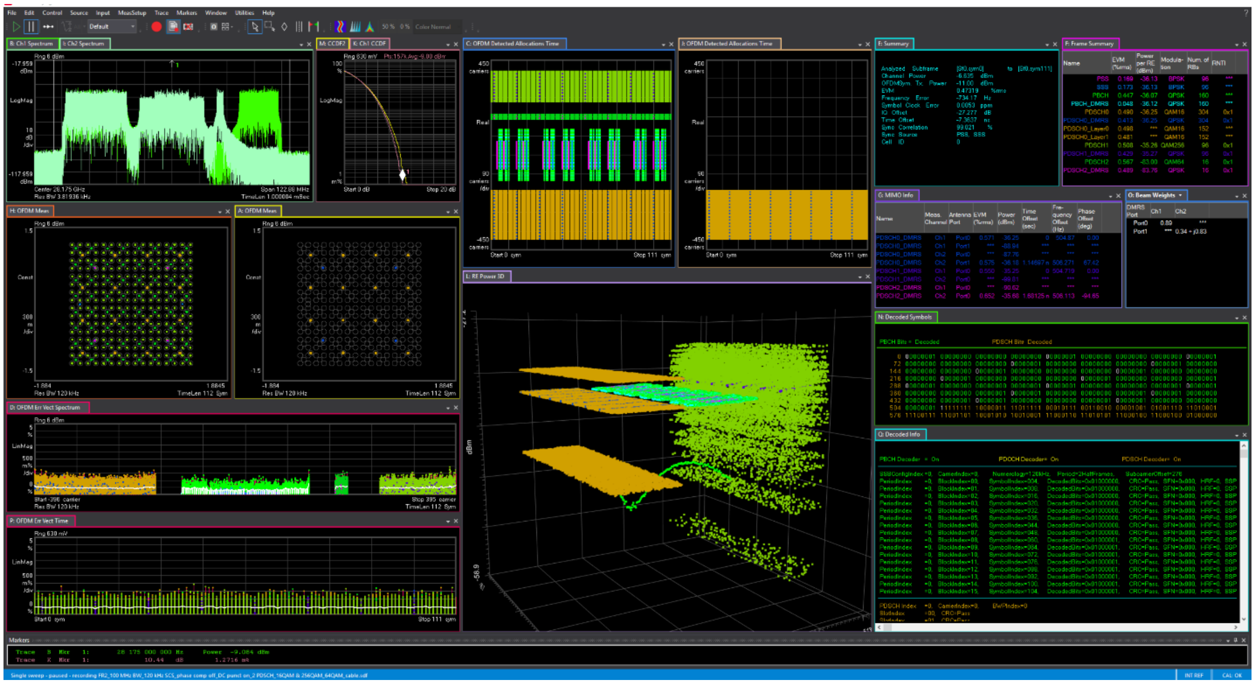

Figure 3. 5G NR 28 GHz MIMO demodulation results

Starting in the upper left of Figure 3, the spectrum from each channel is overlaid, with each port shown in a different color. Since this signal comprises both SISO and MIMO PDSCH channels, some spectrum resources are used concurrently while other parts of the spectrum are not. Additionally, the white vertical lines represent the bandwidth over which a pair of markers calculate the total power for one of the channels. That appears in the marker summary at the bottom of the screen.

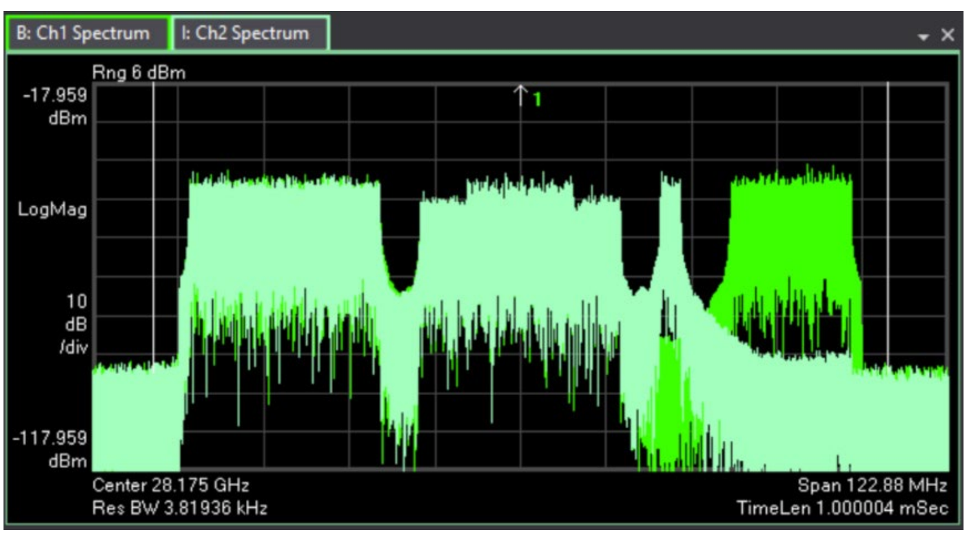

Figure 3a. 5G NR 28 GHz MIMO spectrum

The next trace to the right shows the complementary cumulative distribution function (CCDF) curve of both channels on top of each other and on top of the CCDF curve for additive white gaussian noise (AWGN) as a reference. These traces provide insights into the crest factor or peak-to-average ratio behavior of a signal. A marker appears on one of the channels to measure the peak value, which you can see in this window, as well as in the marker table at the bottom of the screen.

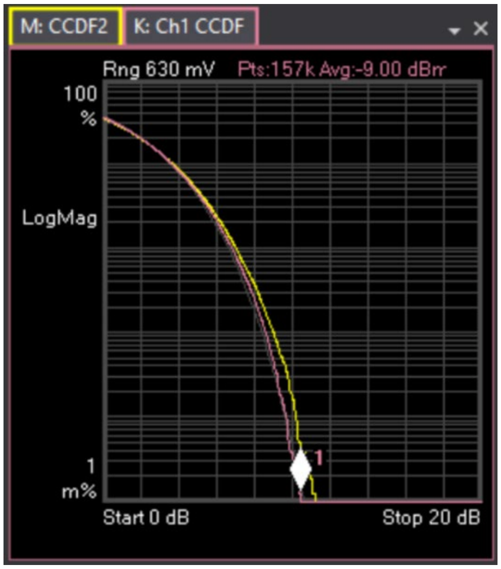

Figure 3b. 5G NR 28 GHz MIMO CCDF curves

The traces in the middle upper left represent the constellations of the two layers used in this signal. Layer 0 shows a range of modulation types — for example, 256 QAM, 64 QAM, 16 QAM, QPSK, and BPSK. They represent the different types of channels in the signal (that is, PDSCH, PBCH, DMRS) and the primary and secondary synchronization channels. The second layer contains a single PDSCH using 16 QAM (and QPSK for its DMRS). The upper-middle two traces show the corresponding detected allocations for Layer 0 and Layer 1, which show the organization of the channels in time and frequency. Frequency is on the y-axis, and time is on the x-axis.

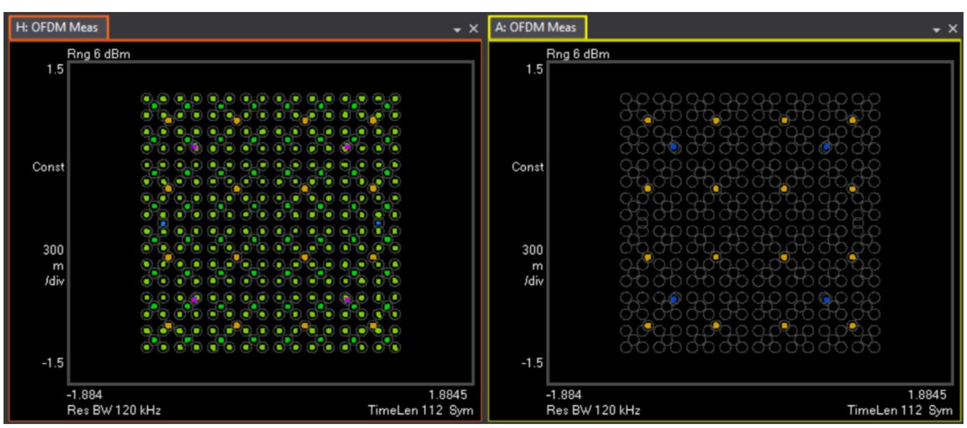

Figure 3c. 5G NR 28 GHz MIMO constellations, Layer 0 (left) and Layer 1 (right)

The upper-right display shows individual per-layer results for the different channels (each channel is in a color that corresponds to the other measurement results, where applicable). This table shows that the only MIMO signal is PDSCH0, as it has information for individual layers as well as composite information from both channels. It uses 16 QAM modulation. By looking at the other previously mentioned traces, you can see that this particular PDSCH uses the bottom-most subcarriers in each channel. The table in Figure 3d shows other valuable data, including EVM and the power-per-resource element.

G: MIMO Info

Name	Meas. Channel	Antenna Port	EVM (%rms)	Power (dBm)	Time Offset (sec)	Fre-quency Offset (Hz)	Phase Offset (deg)
PDSCH0_DMRS	Ch1	Port0	0.571	-36.25	0	504.87	0.00
PDSCH0_DMRS	Ch1	Port1	***	-88.94	***	***	***
PDSCH0_DMRS	Ch2	Port0	***	-87.76	***	***	***
PDSCH0_DMRS	Ch2	Port1	0.575	-36.18	1.14697 n	506.271	67.42
PDSCH1_DMRS	Ch1	Port0	0.550	-35.25	0	504.719	0.00
PDSCH1_DMRS	Ch2	Port0	***	-99.81	***	***	***
PDSCH2_DMRS	Ch1	Port0	***	-90.62	***	***	***
PDSCH2_DMRS	Ch2	Port0	0.652	-35.68	1.68125 n	506.113	-94.65

Figure 3d. 5G NR 28 GHz MIMO frame summary

The MIMO Info measurement trace immediately below gives per-port measurement data, including EVM and the time offset relative to each channel. The right-most middle trace shows the beam weights measurement trace, which represents a transformed version of the power and phase information in the MIMO Info measurement. The overall EVM as a function of time and frequency appears in the lower display. That information can help isolate errors that may occur intermittently, in a particular part of the spectrum, or both.

G: MIMO Info

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PDSCH0_DMRS	Ch1	Port1	***	-88.94	***	***	***
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PDSCH0_DMRS	Ch2	Port1	0.575	-36.18	1.14697 n	506.271	67.42
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PDSCH1_DMRS	Ch2	Port0	***	-99.81	***	***	***
PDSCH2_DMRS	Ch1	Port0	***	-90.62	***	***	***
PDSCH2_DMRS	Ch2	Port0	0.652	-35.68	1.68125 n	506.113	-94.65

Figure 3e. 5G NR 28 GHz MIMO information table

The large bottom center display shows a three-dimensional view of the power distributed across time and frequency. You can rotate the trace around any axis and zoom to view individual subcarriers if needed. In the current orientation, the orange channel appears to have three distinct layers because this PDSCH uses 16 QAM. Studying a quadrant of 16 QAM reveals that the constellation points have three different distances from the origin, hence the three visible layers. The embedded DRMS channel appears as blue subcarriers in the second orange layer. The middle green, pink, and blue colors appear as a single plane in the center part of the spectrum, because these channels utilize QPSK modulation. The right-most green channel shows a wide spread in power values but with distinct layers, since this PDSCH uses 256 QAM. You can see from this measurement that the green 256 QAM PDSCH transmits at the highest power level. The broadcast, primary synchronization, and secondary synchronization channels transmit with the lowest power.

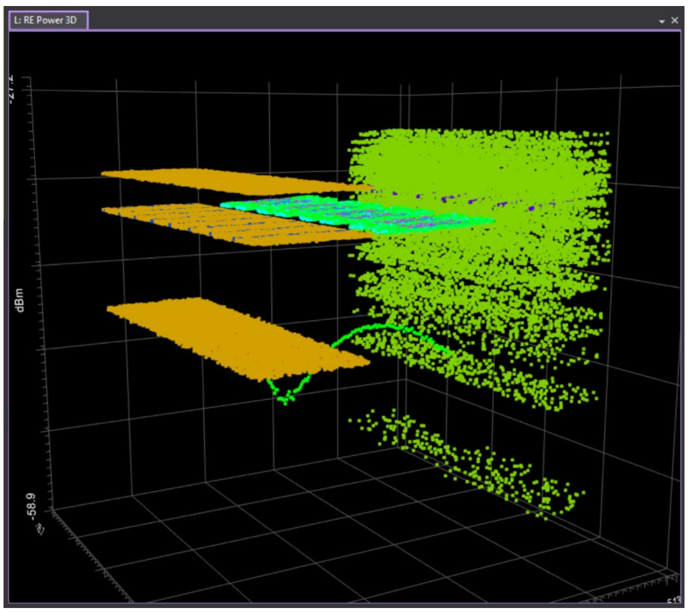

Figure 3f. 5G NR 28 GHz MIMO 3D view of power vs. time and frequency

The two bottom-right displays show the decoded symbol data and decoding of the PBCH, PDCCH, and PDSCH data.

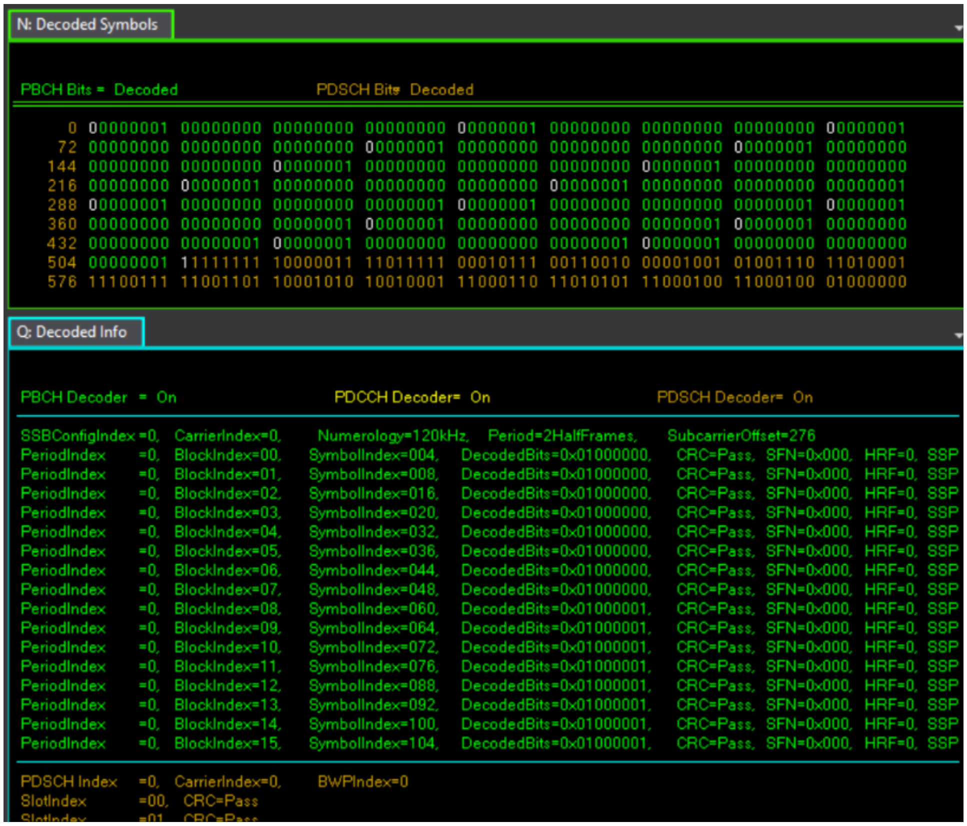

Figure 3g. 5G NR 28 GHz MIMO decoded symbol data and PBCH, PDCCH, and PDSCH data

Consideration: Extreme Bandwidths

Emerging high-band mmWave applications demand extreme bandwidths. One example is 802.11ay, which specifies a two-channel bonded configuration for 2 * 2.16 GHz, or 4.32 GHz of channel bandwidth. 802.11ay specifies other optional channel bonding configurations for 6.48 GHz and 8.64 GHz of channel bandwidth, as well as some channel aggregation configurations.

In addition, standards bodies are considering an optional MIMO feature for 802.11ay.

This R&D mmWave testbed uses a new UXR ultra-performance, real-time, 110 GHz oscilloscope to directly digitize and analyze wide-bandwidth, high-frequency mmWave signals. The UXR provides flexibility and scalability in addressing a multitude of frequency bands, extreme frequency bandwidths, and multiple channels to address demanding emerging mmWave test challenges. Figure 4 shows the testbed generating and analyzing an 802.11ay two-channel bonded signal with 4.32 GHz of channel bandwidth.

Figure 4. Millimeter-wave R&D testbed with the 110 GHz ultra-high-performance UXR oscilloscope

A multichannel, 8-bit Keysight M8195A 65 GSa/s AWG generates wideband modulated IF signals. Although the M8195A has an analog bandwidth of 25 GHz, an IF from 4–5 GHz is typically enough to filter the undesired image product after upconversion to the mmWave frequency band. This also keeps the IF low enough to achieve optimal EVM performance because of the oversampling processing gain with the M8195A's sampling rate.

A compact VDI V-band upconverter converts the 4 GHz IF from the M8195A to the 60 GHz frequency band. This VDI upconverter uses an effective X2 multiplication factor for the LO frequency, providing improved signal-to-noise ratio and lower conversion loss for the upconverted signal, compared with traditional systems that use an X6 multiplication factor. Also, the X2 multiplication factor enables the use of a high-quality LO source that ensures low phase noise at higher frequencies. A PSG signal generator with option UNY provides a low-phase-noise LO for the VDI upconverter. VDI E-band (60–90 GHz) and W-band (75–110 GHz) upconverters can address applications for other frequency bands.

A VDI amplifier, VDI bandpass filter, and horn antenna transmit the 802.11ay signal over the air. On the receive side are two horn antennas. On the left, the first receive horn antenna receives the signal and feeds it into the new 110 GHz UXR oscilloscope to digitize and demodulate the 61.56 GHz 802.11ay signal directly. The maximum sampling rate is 256 Gsa/s per channel (up to four channels) with 10 bits of vertical resolution.

On the right, a second receive horn antenna receives the signal and feeds into the 110 GHz N9041B UXA signal analyzer to measure the out-of-band spectrum.

The direct measurement of the 802.11ay MCS20 64 QAM signal at 61.56 GHz shows an EVM result of 1.54%, or –36.21 dB after transmitting and receiving the signal over the air with the horn antennas. EVM is measured after performing a wideband waveform center (WWC) calibration. WWC is preliminary software used for waveform generation and analysis.

A test setup similar to the one shown in Figure 4 measured a single-carrier waveform with the symbol rate set to 7.04 GHz with a 0.25 RRC alpha using the UXR and Keysight's 89600 VSA software to emulate the widest 802.11ay channel bonding configuration.

Figure 5 shows a VSA measurement result for the widest bandwidth case, 7.04 GHz symbol rate, and 8.64 GHz channel bandwidth.

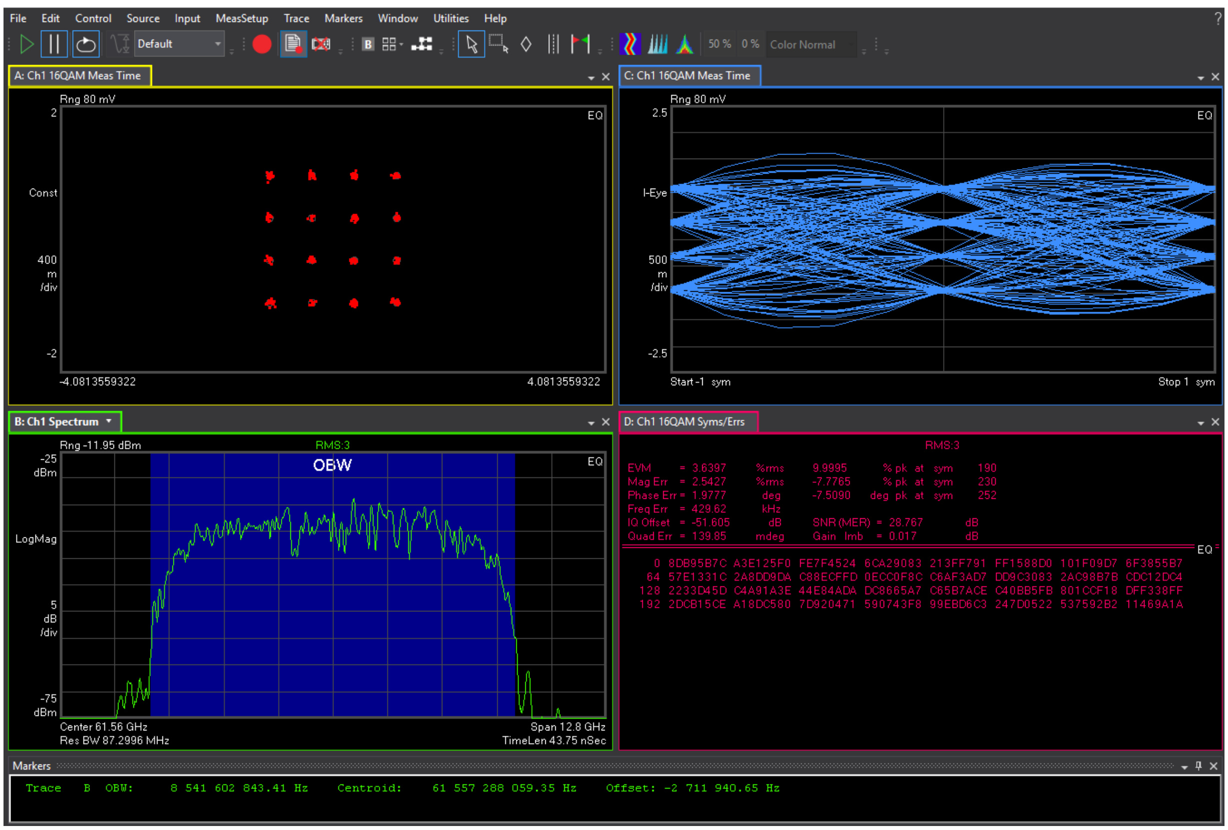

Figure 5. UXR measurement for 16 QAM symbol rate set to the 802.11ay four-channel bonded case, 7.04 GHz symbol rate, 8.64 GHz channel bandwidth

The EVM is 3.6% with adaptive equalization. The EVM normalization reference is set to Reference RMS. For more information, please see http://literature.cdn.keysight.com/litweb/pdf/5992-3721EN.pdf.

Consideration: Phase Noise

The UXR has the low noise, wide bandwidth, multiple channels, and flat frequency response to measure 5G NR MIMO mmWave signals. But that is not enough. A clean, coherent clock is essential for optimal signal capture. Broadband noise goes up with bandwidth by 10 * log (BW increase). But phase noise goes up with center frequency (CF) by 20 * log (CF increase). Moving a 5G carrier from 3 GHz to 39 GHz will increase phase noise by more than 22 dB if there is no improvement in the frequency reference. Low phase noise is essential for a good mmWave measurement. For good MIMO measurements, this low-phase-noise clock must be distributed to multiple channels without degradation. The length (10 mS) and wide bandwidth (800 MHz) of 5G NR mmWave signals demand a measurement with both excellent close-in phase noise and high-offset phase noise.

The UXR starts with a clean 8 GHz clock (–130 dBc/Hz @ 100 kHz offset) and distributes this to all four channels. This is the clock for the ADCs. The clock is then multiplied up to 128 GHz for the samplers to collect data at 256 GSa/s. This fixed multiplication chain allows the use of proprietary Keysight amplifiers and filters to nearly eliminate phase noise beyond the 20 * log (CF increase) mentioned above. Fixed multiplication maintains tight coherency between channels. The jitter added by making multiple channel measurements over single channel measurements is specified as < 10 fs rms.

A 39 GHz carrier run into two channels of a UXR, measured with 1 GHz instantaneous BW, will show < 1/2 deg rms of jitter between them.

Not only does this performance make the UXR a good choice for mmWave EVM measurements, but it also enables the scope to make excellent phase noise measurements. It can use multiple channels and cross-correlation to remove the noise contribution of the channels, making very low-noise, very wide (many gigahertz) offset phase noise measurements. Below, cross-correlations measure phase noise at 10 kHz to 10 GHz offsets from a 60 GHz carrier (from PSG with UNX option).

Figure 6. UXR phase noise measurements

Consideration: Speed

With standard hardware, an oscilloscope is not the tool of choice for making EVM measurements of 5G NR signals because of the slow processing speed associated with the high sample rates these measurements require. To gain high signal fidelity and a low noise floor measurement result, a signal needs to be acquired using a high sampling rate. Oversampling will result in a more accurate and lower EVM result. However, using a high sampling rate increases the EVM demodulation processing time because of the larger data set that must be processed. The UXR oscilloscope hardware supports a technique called digital downconversion (DDC) that enables high-frequency content of an RF signal to be appropriately down-sampled before storing it to the oscilloscope memory.

The oscilloscope hardware accomplishes this down-sampling by first applying a bandpass filter to a user-specified frequency span of interest. The bandpass filter prevents out-of-band noise from aliasing into the passband region during the down-sampling process. A series of half-band decimators are applied to perform frequency shifting and decimation of the data via the bandpass sampling technique. The number of half-band decimators used, and thus the amount of decimation applied, depends on the size of the user-specified frequency span of interest. The UXR oscilloscope hardware supports a series of discrete frequency spans, ranging from 40 MHz to 2.16 GHz. Smaller frequency spans enable more decimation to be applied, resulting in lower output sample rates and less data being stored to memory than would be required when capturing the full sample rate data record. This smaller data size requires less data transfer and post-processing time. It enables the VSA software to calculate measurements such as EVM several orders of magnitude faster than it could on a full sample rate data record.

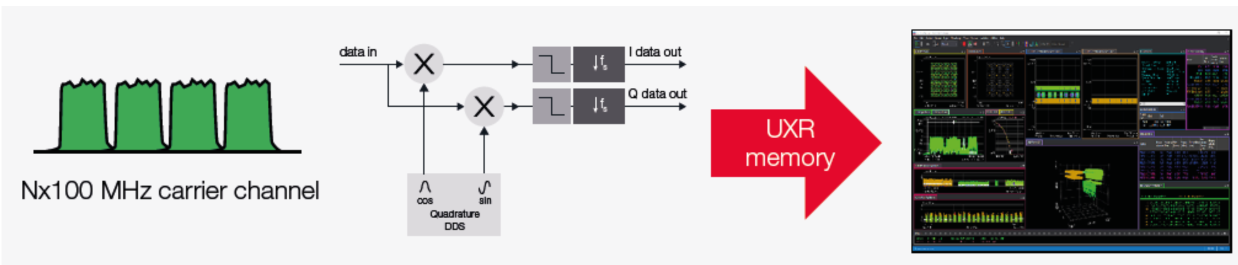

Figure 7. The DDC feature on the UXR oscilloscope captures and decimates signals into memory for VSA processing

Conclusion: UXR Enables Quick and accurate phase-coherent MIMO measurements

The UXR ultra-high-performance real-time oscilloscope enables direct digitization of wide-bandwidth mmWave signals for MIMO testing and debugging. This paper uses 2x2 5G NR MIMO EVM measurement results for the UXR in the 28 GHz FR2 band to demonstrate this. The DUT was an 8x8 cross-polarized phased array antenna. The UXR's DDC technique enabled VSA 5G NR MIMO EVM measurements to be performed with improved speed over traditional approaches.

The UXR provides up to four phase-coherent full-bandwidth channels with a maximum instantaneous bandwidth of up to 110 GHz at a sample rate of 256 GSa/s. This enables the UXR to address and tackle emerging high-band mmWave applications with extreme bandwidths. The UXR analyzing an 802.11ay-like 16 QAM signal with a 7.04 GHz symbol rate and 8.64 GHz channel bandwidth demonstrates this.

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