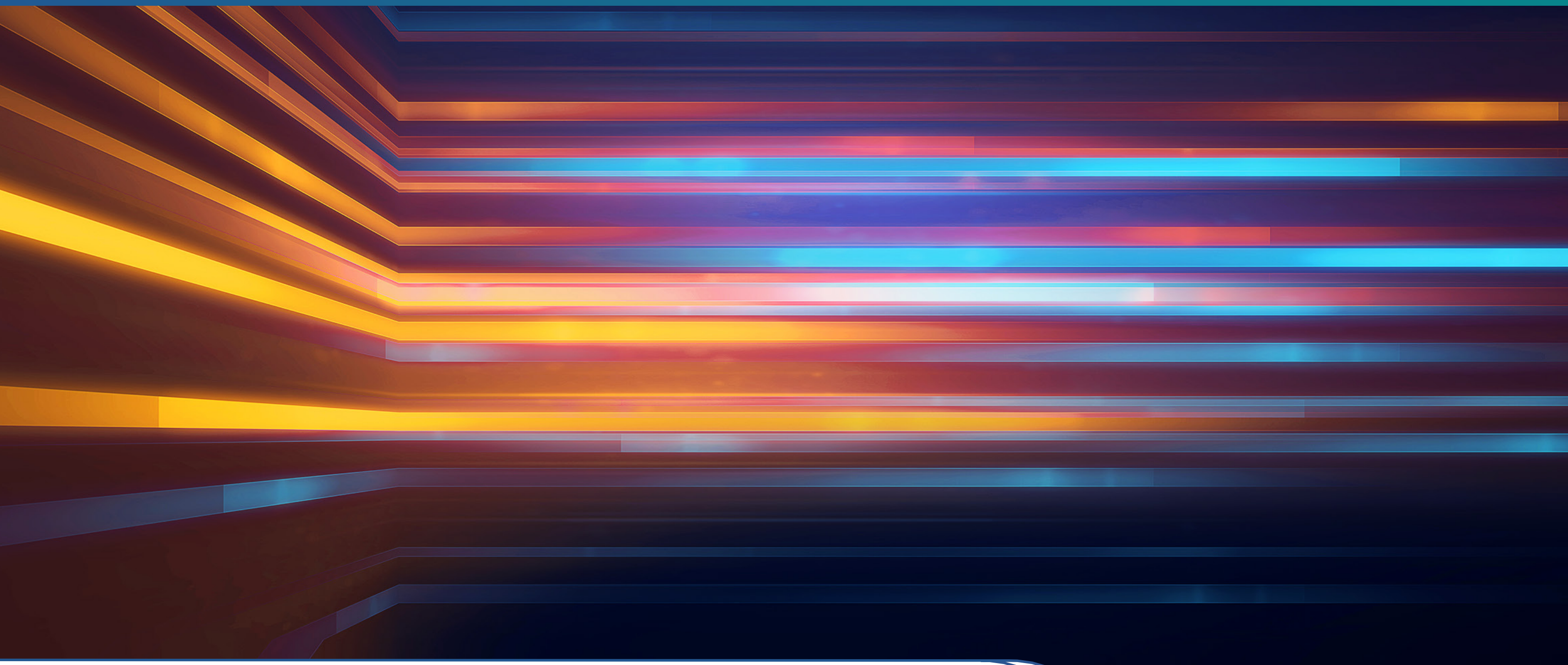


WHITE PAPER

A New Wideband R&D Millimeter-Wave Test Bed

to Tackle Emerging Millimeter-Wave Applications

Introduction

Large swaths of contiguous millimeter-wave spectrum have opened in the U.S, offering opportunities for using these bands for very high-data throughput applications. This requires careful consideration in testing millimeter-wave systems to gain insight into the actual performance.

Increasing data throughput is possible using several different methods. One method is to use higher symbol rates and more channel bandwidth. Higher-order modulation, such as 64 QAM, is possible if the radio's performance is sufficient. To measure the radio performance under these conditions, however, the millimeter-wave test bed system's residual EVM noise floor must be low enough so that the radio's true performance is measured. The millimeter-wave test bed's residual EVM performance should not be the dominant source of error; otherwise, it masks the radio's true performance.

This whitepaper will show a new R&D test bed which uses the latest developments in ultra-high-performance digital oscilloscope technology. This innovative technology will be applied to very-wide bandwidth emerging millimeter-wave applications.

Electro Rent

KEYSIGHT
TECHNOLOGIES

A new approach for millimeter-wave analysis is now possible by using an ultra-high-performance 110 GHz real-time oscilloscope to directly digitize and analyze extensive bandwidth millimeter-wave signals. This new capability provides flexibility and scalability to address a multitude of millimeter-wave frequency bands, extreme frequency bandwidths, and multiple channels to address demanding emerging millimeter-wave test challenges.

Residual EVM performance will be shown for the test bed in the 60, 70, and 80 GHz frequency bands for different waveforms and various modulation bandwidths from 1 to ~7 GHz; and channel bandwidths up to ~8.6 GHz to highlight the R&D test bed's flexibility in addressing emerging millimeter-wave applications such as 802.11ay and 5G NR.

High-Band Millimeter-Wave Spectrum

The FCC and the United States are taking a leadership role in the future of 5G and beyond by opening up more spectrum as a result of this initiative. Spectrum is critical for the future of the Internet of Things (IoT), autonomous vehicles, virtual reality (VR), and telemedicine.

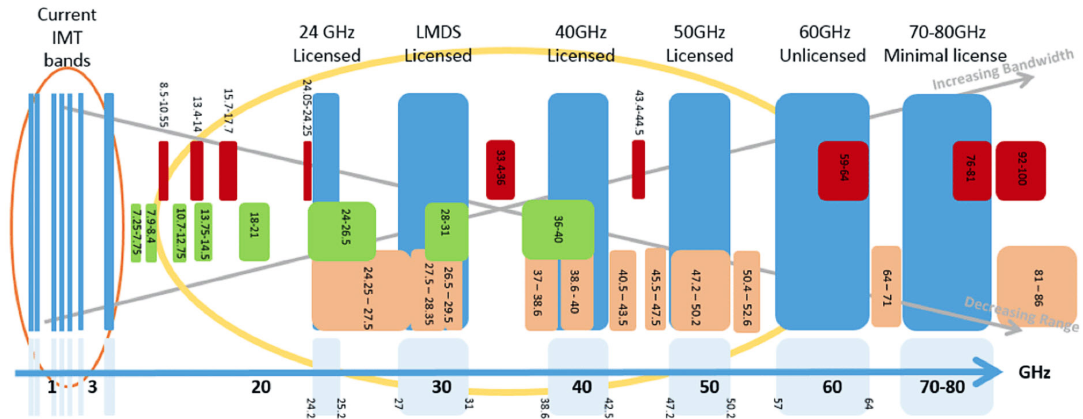
In recent years, technological advances have increased our ability to harness millimeter-wave (mmWave) technology for fixed and mobile wireless communications in high band spectrum, while the demand for connected products and services continues to grow.

The FCC has opened a new unlicensed band from 64-71 GHz which is adjacent to the existing 57-64 GHz unlicensed band. This creates 14 GHz of contiguous unlicensed spectrum in the United States, which could be used by emerging millimeter-wave applications such as 802.11ay, and other applications.

Figure 1 is a graphic of the available spectrum in the United States — the horizontal axis represents the frequency spectrum from approximately 1 to 90 GHz on a relative scale. The light orange bars in the middle and right of the figure displays approximately 11 gigahertz of new spectrum released by the FCC for both licensed and unlicensed use.

The vertical blue lines on the left show the fragmented spectrum that's available below 6 GHz.

The red and green blocks show frequency allocations for the aerospace and defense and satellite communications industries.



*Gigabit LTE and beyond: Mobilizing millimeter wave

Figure 1: Available spectrum in the United States

Emerging Millimeter-Wave Application 802.11ay

802.11ay is the next generation of 802.11ad, and it is backward compatible with 11ad. It has extended throughput, transmission range, and use cases. The requirement for the 802.11ay standard definition is to enable at least one mode of operation to support a maximum throughput of at least 20 Gbps while maintaining or improving the power efficiency. It's possible the technology could support speeds beyond 20 Gbps and reach distances of approximately 1,000 feet.

Figure 2 shows the channel configurations for 802.11ay [1]. The two-bonded channel configuration shown here is for 2 * 2.16 GHz of bandwidth, or 4.32 GHz. This is a mandatory configuration (channels 9-12). There are also other optional channel bonding configurations for 6.48 GHz and 8.64 GHz of bandwidth as well as some channel aggregation configurations.

Figure 2: 802.11ad/ay channels

Based on these requirements, Enhanced Directional Multi-Gigabit (EDMG) is defined for the 802.11 specifications for higher data throughput.

Spectrum for different regions has different frequency planning. Only the United States allocates all six channels. Figure 3 displays the other channel areas.

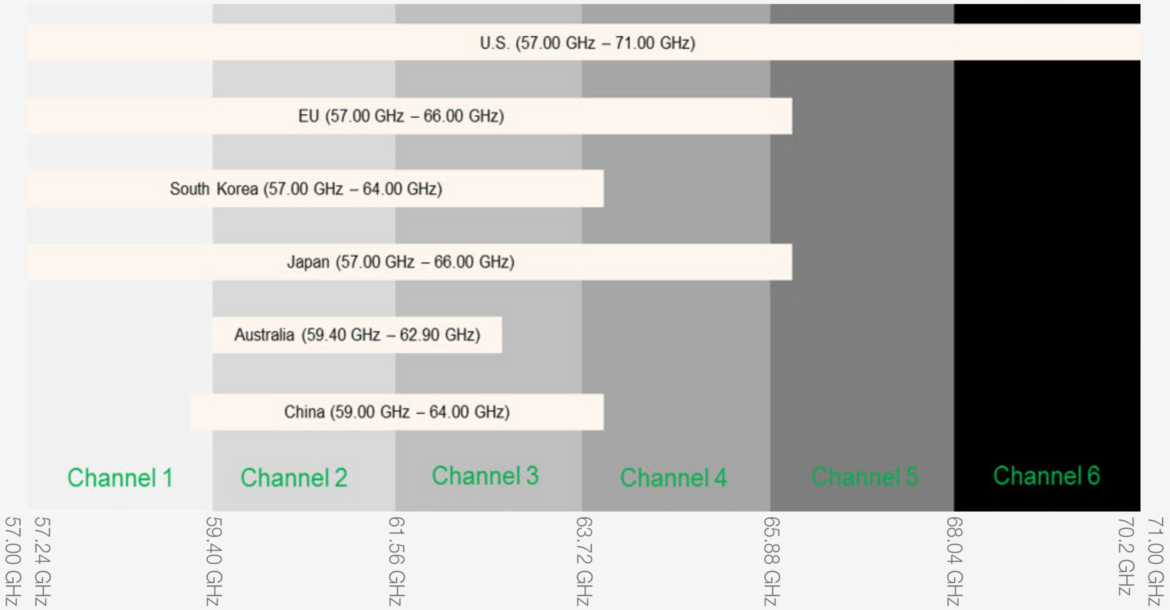


Figure 3: 802.11ad/ay regional frequency planning

Millimeter-wave transmission has some unique characteristics compared with sub-6GHz transmission. For example, the most significant difference is the substantial attenuation at higher frequencies, so directional transmission with the necessary gain is required. These millimeter-wave characteristics have advantages and disadvantages.

The MAC and PHY layers defined for 11ad/11ay include significant differences to those defined for sub-6 GHz spectrum and have adopted innovative techniques and procedures to overcome some unique challenges of millimeter-wave propagation.

A New Wideband R&D Millimeter-Wave Test Bed

A new wideband R&D millimeter-wave test bed is available to address the bandwidth and performance demands of emerging millimeter-wave applications such as 802.11ay, while providing flexibility for new applications such as 5G NR.

This R&D test bed utilizes a new UXR ultra-performance real-time 110 GHz oscilloscope to directly digitize and analyze wide-bandwidth high-frequency millimeter-wave signals up to 110 GHz. The Keysight UXR provides flexibility and scalability in addressing a multitude of frequency bands, extreme frequency bandwidths, and multiple channels to address demanding emerging millimeter-wave test challenges.

802.11ay will first be investigated, as an example of an emerging millimeter-wave application that can be addressed with this testbed.

Measurement Performed after WWC Cal

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

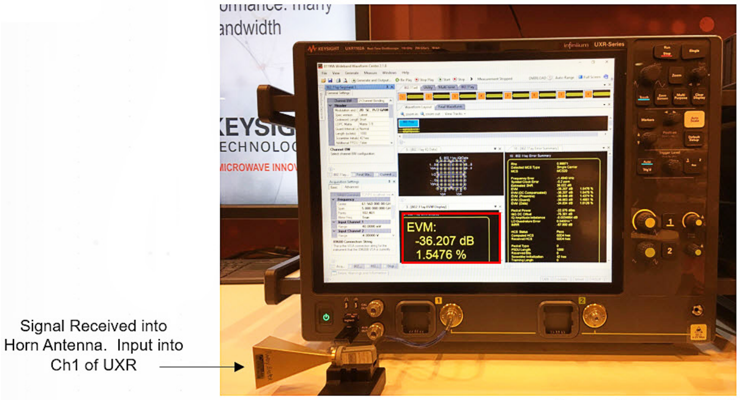
A multi-channel, eight-bit Keysight M8195A 65 GSa/s AWG is used to generate wideband modulated IF signals. Although the M8195A has an analog bandwidth of 25 GHz, an IF frequency anywhere from 4-5 GHz is typically used to provide a high enough IF frequency so that the undesired image product can be filtered after upconversion to the millimeter-wave frequency band. This also keeps the IF frequency low enough to achieve optimal EVM performance due to the oversampling processing gain with the M8195A’s sampling rate.

A compact V-band upconverter is used to upconvert the 4 GHz IF from the M8195A up to the 60 GHz frequency band. This VDI upconverter uses an effective X2 multiplication factor for the local oscillator (LO) frequency, providing improved signal-to-noise ratio (SNR) and lower conversion loss for the upconverted signal, relative to traditional systems that use a 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 is used to provide a low phase noise LO for the VDI upconverter. VDI E-band (60-90 GHz) and W-band (75-110 GHz) upconverters could also be used to address applications for other frequency bands.

A VDI amplifier, VDI bandpass filter, and a horn antenna are used to transmit the 802.11ay signal over the air. On the receive side, there are two horn antennas. On the left, the signal is received with the first receive horn antenna and fed into the new 110 GHz UXR oscilloscope to digitize and demodulate the 61.56 GHz 802.11ay signal directly. This UXR ultra-performance real-time 110 GHz oscilloscope offers breakthrough capability in being able to directly digitize and analyze wide-bandwidth high-frequency millimeter-wave signals up to 110 GHz. The maximum sampling rate is 256 Gsa/s per channel (up to 4 channels) with 10 bits of vertical resolution.

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

Below is the measurement performed with the UXR and receive horn antenna after upconverting to 61.56 GHz and transmitting the signal over-the-air. The UXR is directly digitizing the received 802.11ay millimeter-wave signal at 61.56 GHz with a sampling rate of 256 Gsa/s. We can see that the direct measurement of the 802.11ay MCS20 64QAM 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. Wideband Waveform Center, or WWC, is preliminary software used for waveform generation and analysis.

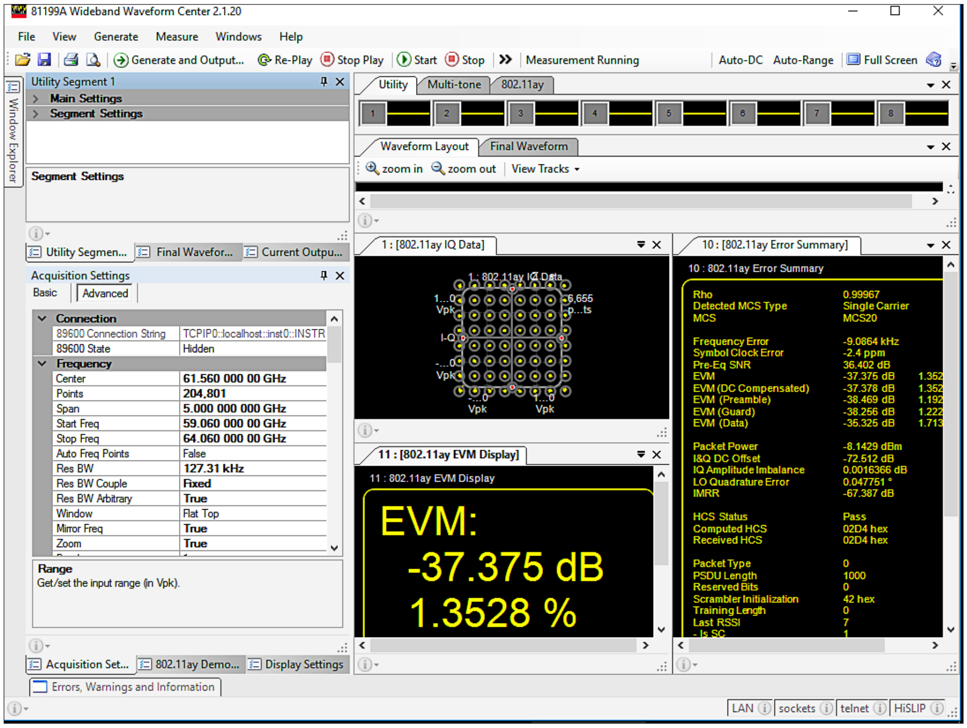


Signal Received into Horn Antenna. Input into Ch1 of UXR

Measurement Performed after WWC Cal

Figure 5: Close-up of UXR 802.11ay OTA EVM measurement at 61.56 GHz; no down conversion

Transmitting over the air can introduce channel impairments, so to evaluate the actual performance without channel impairments the measurement is performed without the horn antennas. The WR15 waveguide output of the VDI filter is directly connected to the WR15 to 1mm adapter and fed into the UXR with a 1mm cable. The measured EVM is -37.3 dB, or 1.35%, after performing a WWC calibration.



Acquisition Settings

Basic | Advanced

Connection	
89600 Connection String	TCPIP0::localhost::inst0::INSTR
89600 State	Hidden
Frequency	
Center	61.560 000 00 GHz
Points	204,801
Span	5.000 000 000 GHz
Start Freq	59.060 000 00 GHz
Stop Freq	64.060 000 00 GHz
Auto Freq Points	False
Res BW	127.31 kHz
Res BW Couple	Fixed
Res BW Arbitrary	True
Window	Flat Top
Mirror Freq	True
Zoom	True

Range
Get/set the input range (in Vpk).

```
EVM:
  -37.375 dB
  1.3528 %
```

```
10 : 802.11ay Error Summary

Rho                          0.99967
Detected MCS Type            Single Carrier
MCS                          MCS20

Frequency Error              -9.0864 kHz
Symbol Clock Error           -2.4 ppm
Pre-Eq SNR                   36.402 dB
EVM                          -37.375 dB      1.352
EVM (DC Compensated)         -37.378 dB      1.352
EVM  (Preamble)              -38.469 dB      1.192
EVM (Guard)                  -38.256 dB      1.222
EVM  (Data)                  -35.325 dB      1.713

Packet Power                 -8.1429 dBm
I&Q DC Offset                -72.512 dB
IQ Amplitude Imbalance       0.0016366 dB
LO Quadrature Error          0.047751 °
IMRR                         -67.387 dB

HCS  Status                  Pass
Computed HCS                 02D4 hex
Received HCS                 02D4 hex

Packet Type                  0
PSDU Length                  1000
Reserved Bits                0
Scrambler Initialization     42 hex
Training Length              0
Last RSSI                    7
- Is SC                      1
```

Figure 6: UXR 802.11ay EVM measurement at 61.56 GHz, WR15 waveguide directly connected to the UXR's 1mm input

What is Driving the Residual EVM Performance- Is it the Source (M8195A upconverted to mmWave) or the Receiver (UXR)?

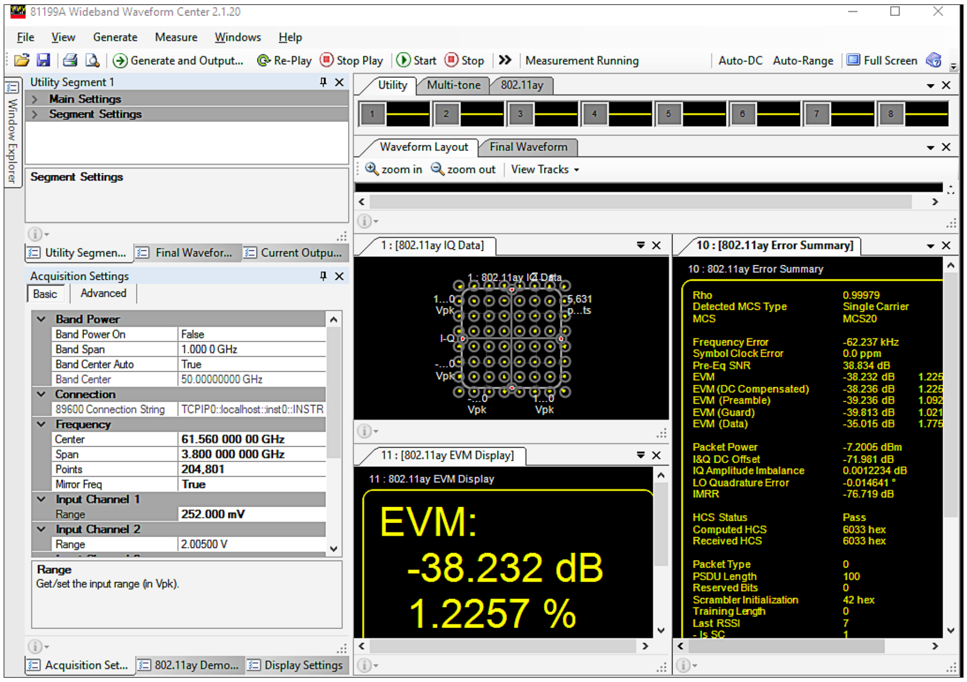
When performing measurements with connected source and receiver, it is difficult to determine if the source performance (M8195A upconverted to millimeter-wave) is limiting the measurement result or if the receiver performance (UXR) is limiting the measurement result. Without a golden signal source or golden receiver, the impairments of both the source and the receiver will contribute to the overall measured results — it is not easy to separate their individualcontributions to the overall EVM.

However, by replacing the existing source with another source known to have a lower residual EVM noise floor (if one exists) can provide insight into whether the measurement results are source limited or receiver limited.

For example, if the existing signal source were replaced with another signal source known to have a lower residual EVM noise floor and the measured EVM result does not change, then the measurement system may be receiver limited. If this were the case, the UXR's residual EVM noise floor would be limiting the EVM measurement results. However, if the existing signal source were replaced with another signal source known to have a lower residual EVM noise floor and the measured EVM decreases, then the measurement system may be source limited. In this case the existing signal source residual EVM noise floor is limiting the EVM measurement results, not the UXR.

As an experiment, the existing 802.11ay signal source (M8195A IF upconverted to 61.56 GHz with VDI upconverter) was replaced with an undisclosed Keysight configuration to generate a signal at 61.56 GHz. This undisclosed configuration cannot be used for general purpose 802.11ay testing and is known to have a lower residual EVM noise floor for some specific and limited configurations.

Figure 7 is the UXR 802.11ay measurement at 61.56 GHz performed using the undisclosed configuration without the horn antennas. The EVM is -38.2 dB (1.22%) versus -37.3 (1.35%), indicating that the measurement results are source limited not UXR receiver limited. This measurement result shows that the UXR's residual EVM noise floor is low enough to measure DUT EVMs of -38.2 dB (1.22%) directly at 61.56 GHz.



Acquisition Settings

Basic | Advanced

Band Power	
Band Power On	False
Band Span	1.000 0 GHz
Band Center Auto	True
Band Center	50.00000000 GHz
Connection	
89600 Connection String	TCPIP0::localhost::inst0::INSTR
Frequency	
Center	**61.560 000 00 GHz**
Span	**3.800 000 000 GHz**
Points	**204,801**
Mirror Freq	**True**
Input Channel 1	
Range	**252.000 mV**
Input Channel 2	
Range	2.00500 V

Range
Get/set the input range (in Vpk).

EVM:
-38.232 dB
1.2257 %

Rho	0.99979	
Detected MCS Type	Single Carrier	
MCS	MCS20	
Frequency Error	-62.237 kHz	
Symbol Clock Error	0.0 ppm	
Pre-Eq SNR	38.834 dB	
EVM	-38.232 dB	1.225
EVM (DC Compensated)	-38.236 dB	1.225
EVM (Preamble)	-39.236 dB	1.092
EVM (Guard)	-39.813 dB	1.021
EVM (Data)	-35.015 dB	1.775
Packet Power	-7.2005 dBm	
I&Q DC Offset	-71.981 dB	
IQ Amplitude Imbalance	0.0012234 dB	
LO Quadrature Error	-0.014641 °	
IMRR	-76.719 dB	
HCS Status	Pass	
Computed HCS	6033 hex	
Received HCS	6033 hex	
Packet Type	0	
PSDU Length	100	
Reserved Bits	0	
Scrambler Initialization	42 hex	
Training Length	0	
Last RSSI	7	
- Is SC	1	

Figure 7: UXR 802.11ay EVM measurement at 61.56 GHz displaying lower residual EVM noise floor

The measurements shown in the next few sections are performed with the UXR but will also include the signal source contributions of the M8195A IF upconverted to millimeter-wave in the EVM measurements presented.

Measuring Signal Bandwidths Greater Than 4 GHz

802.11ay also specifies other optional channel bonding configurations for 6.48 GHz and 8.64 GHz of channel bandwidth, as well as some channel aggregation configurations. This section will show the EVM performance which is achievable for these wider bandwidth configurations.

A test setup like the one shown above in Figure 7 without horn antennas was used to measure single-carrier waveforms with symbol rates (SR) set to 3.52, 5.28, and 7.04 GHz with a 0.25 RRC alpha using the UXR and Keysight's 89600 VSA software to emulate these wider channel bonding configurations. The channel bandwidths correspond to 4.32, 6.48, and 8.64 GHz with the 0.25 RRC filter alpha (Channel BW= SR*1.25). The measurements were performed at 61.56 GHz using a WR15 waveguide to 1 mm adapter to connect the VDI hardware directly to the UXR's 1 mm input connector.

The M8195A AWG IF frequency is now set to 5 GHz, instead of 4 GHz to avoid upconverter image issues for the wider-bandwidth 7.04 GHz symbol rate case. Figure 8 shows the measurement results at 61.56 GHz.

	3.52 GHz SR (Channel BW=4.32 GHz)	5.28 GHz SR (Channel BW=6.48 GHz)	7.04 GHz SR (Channel BW=8.64 GHz)
UXR 61.56 GHz	1.67%	2.36%	3.91%

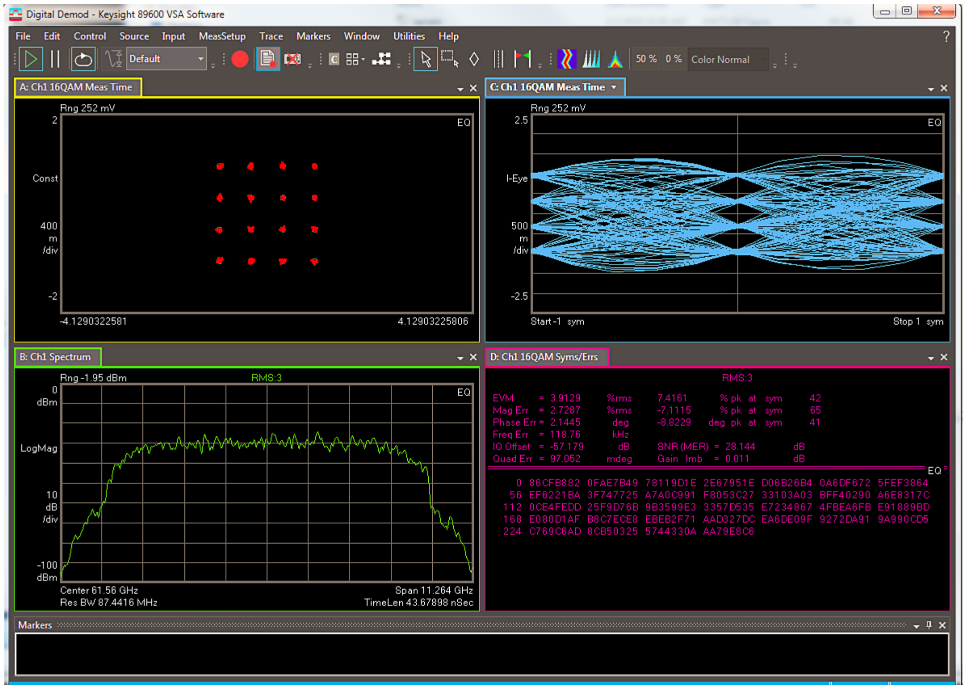
Figure 8: UXR measurements for 16 QAM Symbol Rates (SR) is set to the 802.11ay wider bandwidth channel bonding configurations; CB3, and CB4 — where SR = 1.76 x NcB GHz

All measurement results used reference RMS as the EVM normalization reference with adaptive equalization enabled.

The resulting EVM at 61.56 GHz with a 3.52 GHz symbol rate is higher than the previous 802.11ay EVM because of using a 5 GHz IF from the M8195A instead of the 4 GHz IF used previously for the 802.11ay two-channel bonded case. There is less oversampling processing gain at a 5 GHz IF versus a 4 GHz IF, so the M8195A IF EVM is higher. However, the 5GHz IF was used for all three cases to compare the impact of increasing the symbol rate.

EVM increases as the symbol rate is increased for the three-channel bonding configuration (CB3) and four-channel bonding configuration (CB4). This is expected because of increased integrated noise within the increased signal bandwidth; decreasing SNR. There can also be increased linear amplitude and phase error across the increased signal bandwidth, but adaptive equalization is enabled to help address this.

The VSA measurement result for the widest bandwidth case, 7.04 GHz symbol rate or 8.64 GHz channel bandwidth is shown in Figure 9.



```
                                RMS:3
EVM        =  3.9129    %rms    7.4161       % pk  at  sym     42
Mag Err    =  2.7287    %rms    -7.1115      % pk  at  sym     65
Phase Err  =  2.1445     deg    -8.8229    deg pk  at  sym     41
Freq Err   =  118.76     kHz
IQ Offset  =  -57.179     dB    SNR (MER)  =  28.144        dB
Quad Err   =  97.052    mdeg    Gain  Imb  =  0.011         dB
                                                                 EQ
   0  86CFB882  0FAE7B49  78119D1E  2E67951E  D06B26B4  0A6DF672  5FEF3864
  56  EF6221BA  3F747725  A7A0C991  F8053C27  33103A03  BFF40290  A6E8317C
 112  0CE4FEDD  25F9D76B  9B3599E3  3357D535  E7234867  4FBEA6FB  E91889BD
 168  E080D1AF  B8C7ECE8  EBEB2F71  AAD327DC  EA6DE09F  9272DA91  9A990CD5
 224  C769C6AD  8CB50325  5744330A  AA79E8C6
```

Figure 9: 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 BW. Reference RMS EVM normalization reference with Adaptive Equalization.

Measuring Signals at Other Millimeter-Wave Frequency Bands with the UXR

In addition to the 57-64 GHz and 64-71 GHz frequency bands, there are two additional frequency bands in the United States which may be of interest for emerging millimeter-wave applications: 71-76 GHz and 81-86 GHz. Figure 10 shows the EVM performance achievable for these additional frequency bands with varying bandwidth configurations.

Row 1. Results after upconverting a 4 GHz IF from the M8195A to 61.56 GHz
Row 2. Upconverting to 73.5 GHz; the center of the 71-76 GHz frequency band
Row 3. Upconverting to 83.5 GHz; the center of the 81-86 GHz frequency band

For the 73.5 GHz and 83.5 GHz cases, an E-band WR12 VDI compact upconverter was used, in addition to a VDI E-band amplifier and VDI 71-76 GHz or 81-86 GHz waveguide bandpass filters. The measurements performed at 73.5 and 83.5 GHz used a WR12 waveguide to 1 mm adapter to connect the VDI hardware directly to the UXR's 1 mm input connector.

	1 GHz SR (OBW=1.22 GHz)	2 GHz SR (OBW=2.44 GHz)	3 GHz SR (OBW=3.66 GHz)	4 GHz SR (OBW=4.88 GHz)
UXR 61.56 GHz	1.18%	1.28%	1.48%	1.71%
UXR 73.5 GHz	1.36%	1.57%	1.79%	2.08%
UXR 83.5 GHz	1.45%	1.86%	2.15%	2.45%

Figure 10: UXR EVM measurements for varying 16 QAM symbol rates in the 60, 70, and 80 GHz frequency bands

All measurement results used reference RMS as the EVM normalization reference with adaptive equalization enabled.

EVM for a given symbol rate (e.g. 1 GHz) increases as the upconverter millimeter-wave frequency increases from 61.56 GHz to 83.5 GHz. Also, EVM for a given millimeter-wave frequency increases as the symbol rate increases from 1 GHz to 4 GHz due to reduced SNR from the wider signal bandwidths.

Flexibility to Navigate for Emerging Millimeter-Wave Applications

A key challenge and risk for R&D engineers working on emerging millimeter-wave applications are that activities may need to begin before the standards are finalized. Furthermore, R&D activities may even begin while the standards are actively evolving.

Take 5G NR as an example — At the time of this writing, 5G NR frequency bands have not yet been finalized in the upper millimeter-wave bands above 50 GHz. Any of the frequency bands discussed are potential candidates; 57-64, 64-71, 71-76, and 81-86 GHz. A risk is that hardware development could begin assuming a given frequency band, but later may require a different frequency band dependent on finalization of the standards.

The flexibility to address multiple frequency bands is critical to navigating through this initial phase while the standards are evolving. The UXR’s flexible millimeter-wave frequency extension option enables a cost-effective lower-bandwidth UXR to utilize a 5 GHz or 10 GHz analysis bandwidth. This is achievable across multiple channels anywhere within the UXR’s 110 GHz frequency range with the performance shown in Figures 9 and 11. This provides the flexibility and performance needed to address emerging millimeter-wave applications.

Summary

This whitepaper presented a new R&D test bed which utilizes the latest developments in ultra-high-performance digital oscilloscope technology applied to very-wide bandwidth emerging millimeter-wave applications. This R&D test bed is flexible and scalable to address a multitude of frequency bands, frequency bandwidths, and waveform types. This flexibility allows you to tackle the new challenges presented by emerging millimeter-wave applications such as 802.11ay and 5G NR.

The R&D test bed uses the UXR ultra-performance real-time 110 GHz oscilloscope, which enables very-wide bandwidth millimeter-wave signals to be directly digitized and analyzed up to 110 GHz. This new capability gives you flexibility and scalability to address a multitude of millimeter-wave frequency bands, extreme frequency bandwidths, and multiple channels to address the demanding emerging millimeter-wave test challenges.

The UXR’s flexible millimeter-wave frequency extension option helps you mitigate risk by providing flexibility to use a 5 GHz or 10 GHz analysis bandwidth across multiple channels anywhere within the UXR’s 110 GHz frequency range.

References

[1] IEEE P802.11ay Draft 1.4, July 2018

[2] WFA, WiFi Certified WiGig Messaging Architecture v1.0

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