WHITE PAPER

6G: Going Beyond 100 Gbps to 1 Tbps

Exceeding 100 Gbps data throughput with a sub-THz testbed for 6G research

KEYSIGHT

6G research is in its very early stages. The vision for what the International Telecommunication Union calls Network 2030 continues to take shape. While the industry is years away from starting the standards development process, sub-terahertz (sub-THz) territory is a focus of active research.

Getting to 100 gigabits per second (Gbps) to 1 terabit per second (Tbps) data throughput is a key objective and an active area of research for 6G. This extreme data throughput could evolve into a Key Performance Indicator (KPI) for 6G. However, it poses significant challenges, both from an RF perspective and baseband perspective.

There are three fundamental approaches to increasing data throughput. One approach involves using higher-order modulation schemes such as 64 QAM to increase the number of bits transmitted for each symbol. Given a fixed and finite spectrum bandwidth, increasing the modulation order from QPSK (transmitting two bits for each symbol) to 64 QAM (transmitting six bits for each symbol) would increase the data throughput by a factor of three, if channel conditions and radio performance allow. A 1 GHz QPSK symbol rate would result in a 2 Gbps theoretical raw calculated data throughput without forward error correction (FEC) coding rate redundancy. However, increasing the modulation order to 64 QAM would result in a 6 Gbps data throughput, while using the same spectrum occupied bandwidth.

The second approach uses more spectrum bandwidth and increases data throughput by using a higher symbol rate. For example, the 1 GHz symbol rate, the occupied channel bandwidth is approximately 1.22 GHz, assuming a 0.22 root-raised cosine filter alpha (or excess bandwidth). Increasing the symbol rate by a factor of ten to 10 GHz would increase the QPSK data throughput to 20 Gbps, but would use a much wider swath of spectrum (approximately 12.2 GHz). Increasing the modulation order to 64 QAM could increase the data throughput to 60 Gbps, but supporting higher order modulation schemes at these extreme modulation bandwidths becomes much more challenging due to reduced Signal-to-Noise (SNR) ratio, greater linear amplitude and phase impairments, and other technical challenges [1].

A third approach transmits multiple and independent streams of data using multiple antenna techniques such as multiple-input/multiple-output (MIMO). MIMO exploits the channel and simultaneously transmits and receives multiple and independent data streams for higher data throughput. For the 1 GHz symbol rate with QPSK, by using MIMO encoding/decoding and transmitting two independent streams of data simultaneously, you may increase the data throughput. However, the actual increase in data throughput, would depend on the channel conditions and system overhead.

This whitepaper will discuss using the first two approaches at H-band (220-330 GHz) from an RF physical layer perspective, and show that it is possible to exceed 100 Gbps using 64 QAM modulation with an occupied bandwidth of 30 GHz.

IEEE 802.15.3d for Fixed Point-to-Point Applications

The standardization process has not yet begun for 6G. However IEEE 802.15.3d [2] is an example of an existing standard for fixed point-to-point applications using the sub-THz frequency range between 252 GHz and 325 GHz. In addition, IEEE 802.15.3d defines physical layer modes that enable data rates of up to 100 Gb/s using bandwidths up to 69.12 GHz.

Table 6-17j in the IEEE 802.15.3d specification shows eight different bandwidths supported for the sub-THz physical layer.

Description
Bandwidth 2.16 GHz
Bandwidth 4.32 GHz
Bandwidth 8.64 GHz
Bandwidth 12.96 GHz
Bandwidth 17.28 GHz
Bandwidth 25.92 GHz
Bandwidth 51.84 GHz
Bandwidth 69.12 GHz

Source: IEEE Std 802.15.3d -2017

Figure 1. IEEE 802.15.3d Supported Bandwidths

The bandwidths are multiples of the IEEE 802.11ad/ay channel bandwidths of 2.16 GHz and 4.32 GHz, respectively. Row 1 represents the 802.11ad channel bandwidth of 2.16 GHz. Row 2 represents the 802.11ay two-bonded channel (CB2) bandwidth of 4.32 GHz. Row 3 represents the 802.11ay four-bonded channel (CB4) of 8.64 GHz. Rows 4-8 represent integer multiples of the 802.11ay CB2 and CB4 channel bandwidths up to 69.12 GHz.

Sub-THz Testbed for H-Band, 220-330 GHz

Figure 2 shows the sub-THz testbed for H-Band, 220-330 GHz. The testbed uses a Keysight M8196A Arbitrary Waveform Generator (AWG) instead of the Keysight M8195A AWG that appeared previously for D-Band (110-170 GHz) and G-Band (140-220 GHz) [1].

Figure 2. Sub-THz Testbed for H-Band, 220-330 GHz

Testbed overview

A multichannel Keysight M8196A 92 GSa/s AWG generates wide bandwidth-modulated intermediate frequency (IF) signals and has an analog bandwidth of 32 GHz.

A Virginia Diodes Inc. (VDI) compact WR3.4 H-band upconverter (N9029ACST-U03) converts the IF frequency from the Keysight M8196A 92 GSa/s AWG to the desired sub-THz frequency. This upconverter uses a 12x multiplication factor for the local oscillator (LO) frequency. A Keysight E8257D PSG vector signal generator with option UNY provides a low-phase-noise LO for the VDI upconverter and downconverter. A VDI-Erickson PM5B power meter with WR3.4 waveguide taper performs the power measurements.

On the receive side, the VDI compact WR3.4 H-band downconverter (N9029ACST-D03) converts the sub-THz frequency to an IF frequency. A Keysight UXR multichannel high-performance oscilloscope with a sample rate of 256 GSa/s digitizes the IF signal.

The configuration in Figure 2 is for an over-the-air (OTA) transmission using diagonal transmit and receive horn antennas (N5262HORN-034). Measurements were also performed conducted, waveguide-to-waveguide using a WR3.4 waveguide bandpass filter, or a WR3.4 waveguide through section for wider modulation bandwidth test cases.

This testbed is scalable across D and G sub-THz frequency bands by using different VDI converters and a Keysight M8195A AWG. It is also flexible in terms of waveforms because it uses a variety of software platforms to generate and analyze candidate waveforms. The testbed supports software written for test applications, as well as Keysight PathWave SystemVue design software, VSA software, or IQtools (MATLAB-based). Because the testbed AWG and oscilloscope are multichannel, the number of channels is scalable for MIMO research.

Measurement examples

Conducted measurements were performed for the 4.32, 8.64, 12.96, and 17.28 GHz test cases shown in Figure 1 with a VDI WR3.4 bandpass filter and WR3.4 through section to connect the VDI compact upconverter and downconverter. For the sake of brevity, they do not appear in this white paper.

In addition, for the 25.92 GHz bandwidth test case, the symbol rate was set to six times the 802.11ay CB2 symbol rate (6 x 3.52 GHz = 21.12 GHz). The channel bandwidth is six times the 802.11ay CB2 channel bandwidth (6 x 4.32 GHz= 25.92 GHz). This bandwidth exceeds the WR3.4 bandpass filter's bandwidth, so it was removed for this test case.

The conducted waveguide-to-waveguide measurement results are shown in Figure 3 with baseband complex pre-corrections applied to the waveform before downloading it to the Keysight M8196A AWG.

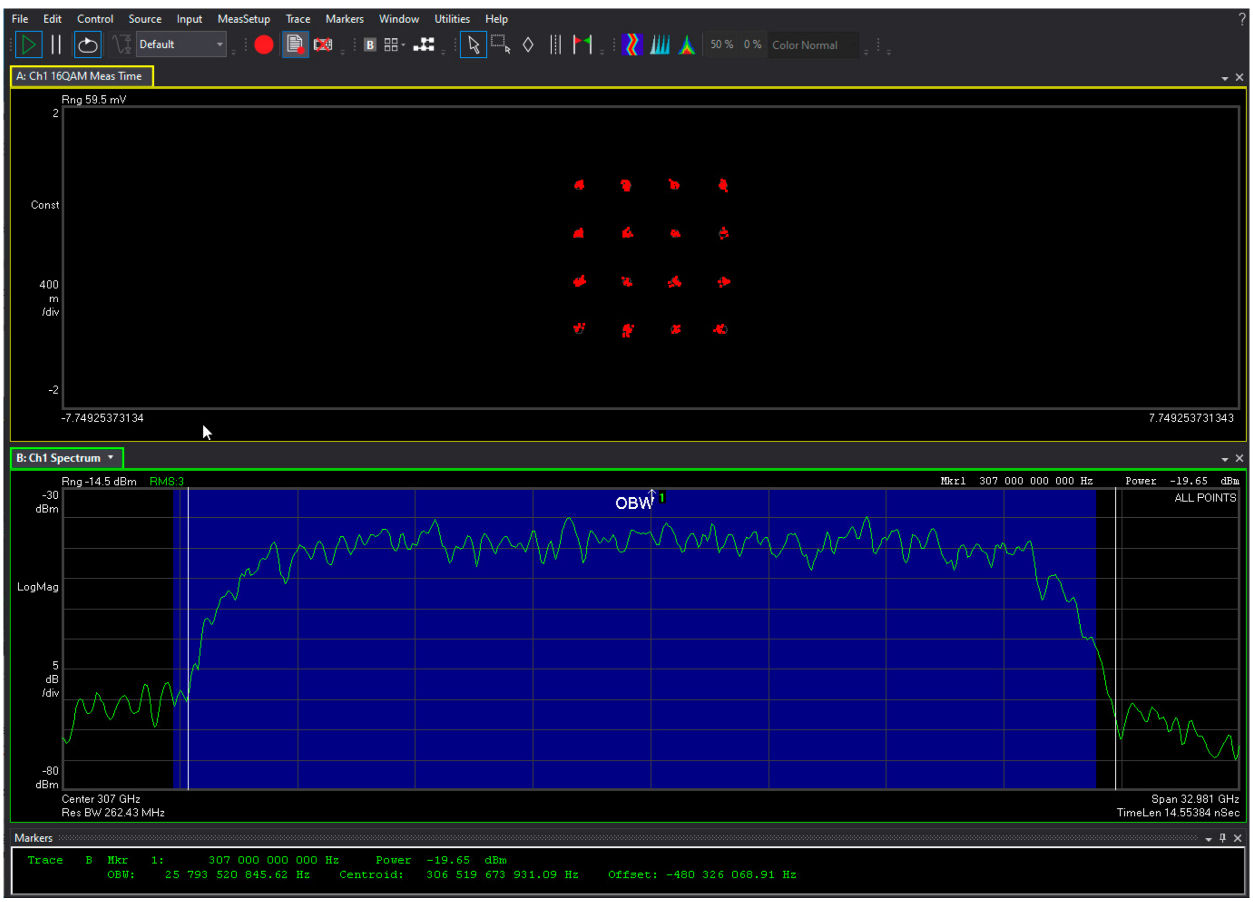

Figure 3. Conducted Measurement Results at 307 GHz for the 25.92 GHz Bandwidth Test Case

The measured occupied bandwidth is 25.7 GHz, which corresponds to the 21.12 GHz symbol rate multiplied by the root raised-cosine (RRC) filter alpha (21.12 GHz x 1.22= 25.76 GHz).

The symbol rate was 21.12 GHz, so the theoretical raw calculated data rate without forward error correction (FEC) coding rate redundancy comes to 21.12 G symbols/sec * 4 bits/symbol (16 QAM) = 84.48 Gb/s for a single stream of data.

To push the data throughput rate beyond 100 Gb/s, the 802.15.3d 21.12 GHz symbol rate was increased to 25 GHz. The modulation order was also increased from 16 QAM to 64 QAM to transmit 6 bits/symbol instead of 4 bits/symbol.

Measurements were performed both conducted (waveguide-to-waveguide), as well as over-the-air (OTA) in a chamber; only the OTA test case is appears here. The OTA test case used diagonal horn antennas (N5262HORN-034) that appear in Figure 4.

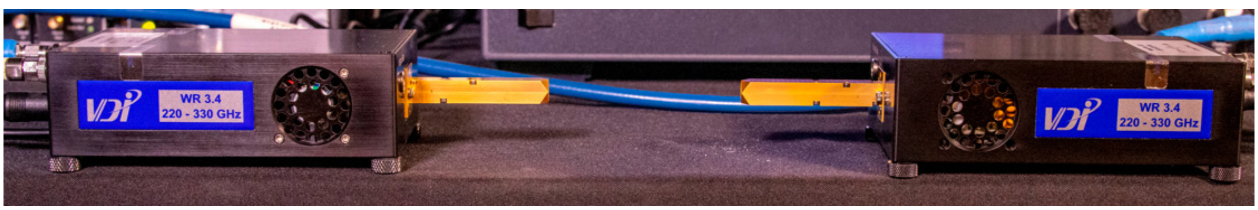

Figure 4. Over-the-air (OTA) Test Case Using Diagonal Horn Antennas

Image courtesy of Virginia Diodes Inc. (VDI)

The OTA measurement results appear in Figure 5 with baseband complex pre-corrections applied and an approximate 6-inch edge-to-edge spacing between the VDI compact upconverter and downconverter.

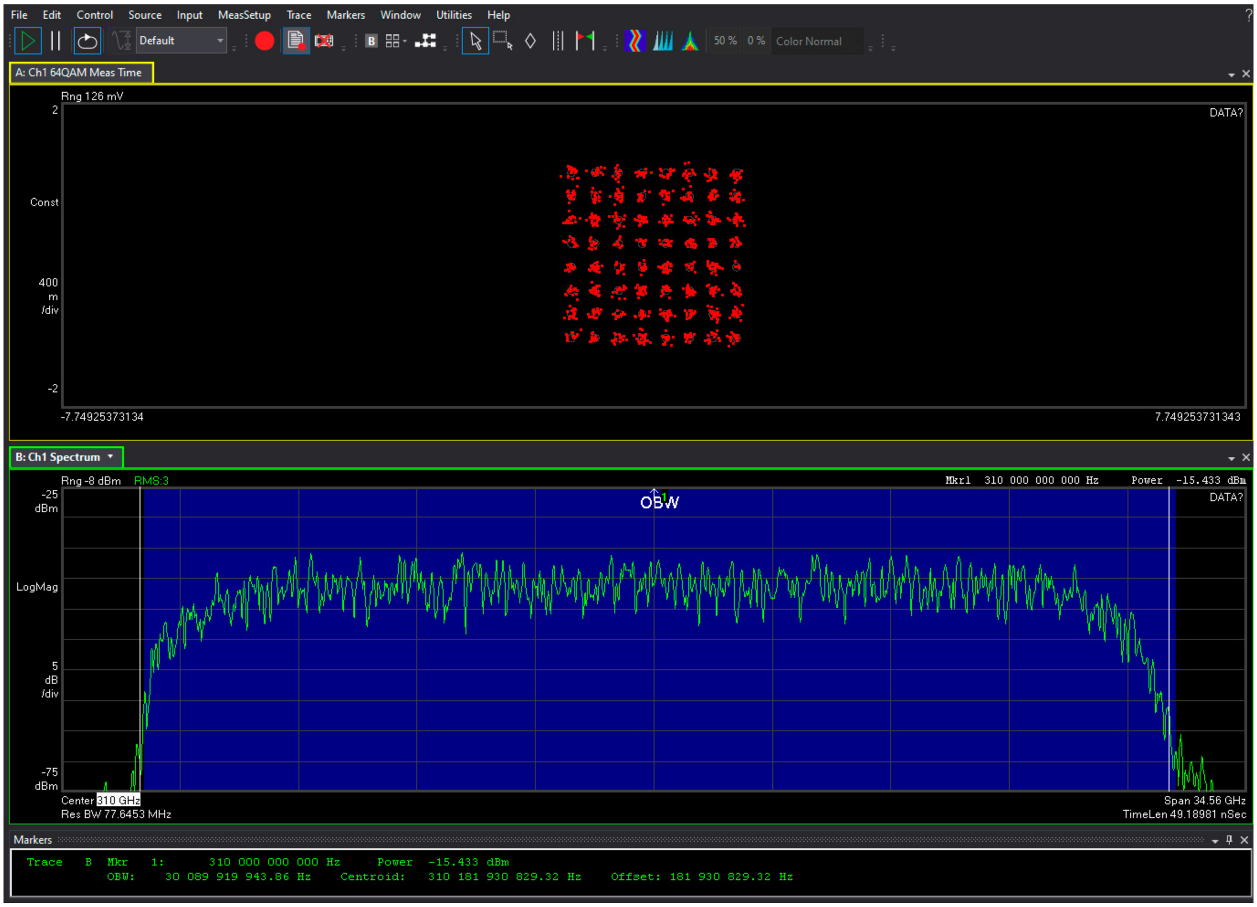

Figure 5. Over-the-air (OTA) Measurement Results at 310 GHz for the 30 GHz Bandwidth Test Case

The measured occupied bandwidth is 30 GHz, which corresponds to the 25 GHz symbol rate multiplied by the root raised-cosine (RRC) filter alpha (25 GHz x 1.22= 30.5 GHz).

The symbol rate was 25 GHz, so the theoretical raw calculated data rate without forward error correction (FEC) coding rate redundancy comes to 25 G symbols/sec * 6 bits/symbol (64 QAM) = 150 Gb/s for a single stream of data. Lowering the modulation order to 16 QAM would yield 100 Gb/s.

Summary

This white paper presents an R&D sub-terahertz testbed for 6G research which supports 30 GHz of bandwidth at H-band 220-330 GHz for 100-150 Gbps applications. This extreme data throughput could evolve into a Key Performance Indicator (KPI) for 6G.

IEEE 802.15.3d is an example of an existing fixed point-to-point standard in the sub-THz frequency range between 252 GHz and 325 GHz. In this white paper, we use the standard test cases up to 25.92 GHz bandwidth then increase the symbol rate to 25 GHz to exceed 100 Gbps using 64 QAM modulation with an occupied bandwidth of 30 GHz.

Acknowledgments

Keysight Technologies acknowledges Virginia Diodes Inc. (VDI) for providing the VDI H-band WR3.4 220-330 GHz hardware that appear in this white paper.

Resources

1. A New Sub-Terahertz Test Bed for 6G Research – White Paper
2. IEEE Std 802.15.3d -2017, IEEE Standard for High Data Rate Wireless Multi-Media Networks, Amendment 2: 100 Gb/s Wireless Switched Point-to-Point Physical Layer