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TEST EVOLVES TO SUPPORT WIRELESS SERVICES

TEST EVOLVES TO SUPPORT WIRELESS SERVICES

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Senior Editor
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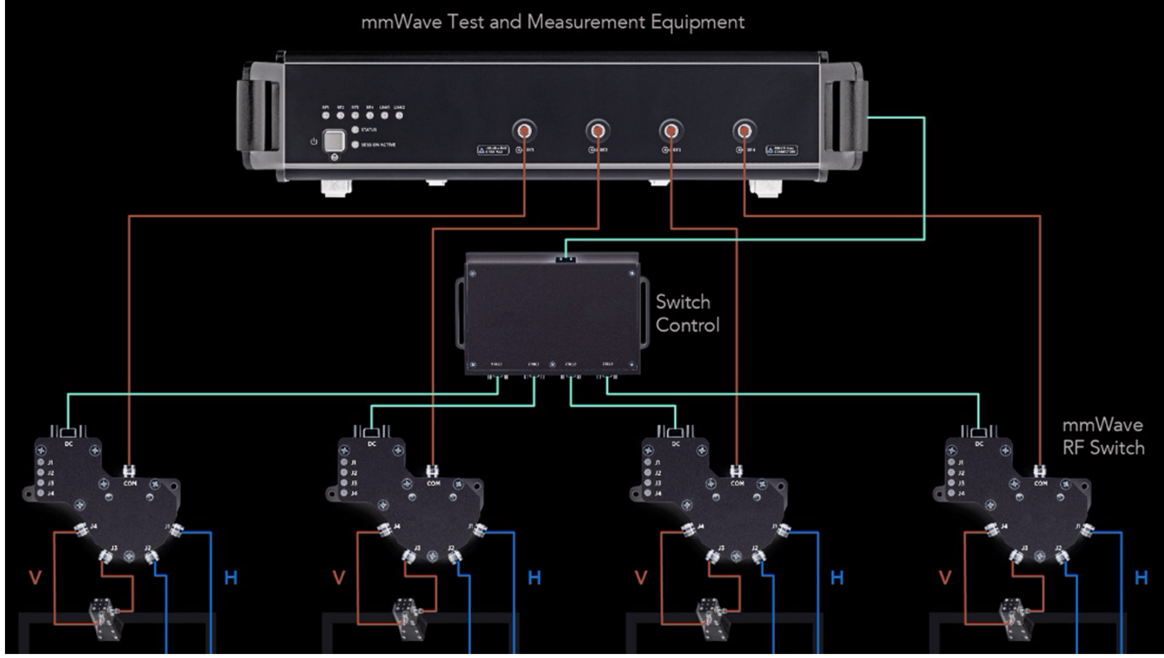
I've often heard it said that the engineers who devise test and measurement equipment need to be among the best in the business if the equipment and methodologies they devise are to keep up with test engineers' requirements. This is truer of wireless test than in any other segment of the electronic OEM industry. Wireless technologies such as 5G and UWB place exacting demands on test equipment in terms of evaluation, calibration, and validation. It's a full-time job just staying abreast of the developments in wireless test, and that's what we at Microwaves & RF hope this eBook will help you do.

In this eBook, you'll find articles on various aspects of wireless test:

- The test challenges and considerations associated with mmWave 5G
- How phase measurements and VNA calibration impact mmWave device verification
- An update on advances in 5G test, evaluation, and infrastructure
- Insider perspectives on the challenges facing the RF/microwave test industry
- How newly defined performance metrics for Wi-Fi router testing leads to test repeatability

It's our hope that the information you'll find in these articles will be helpful to you in present and future design projects.



CHAPTER 1:

Overcome Validation-Test Challenges to Reap 5G mmWave's Benefts

KHUSHBOO KALYANI, Marketing Engineer, LitePoint

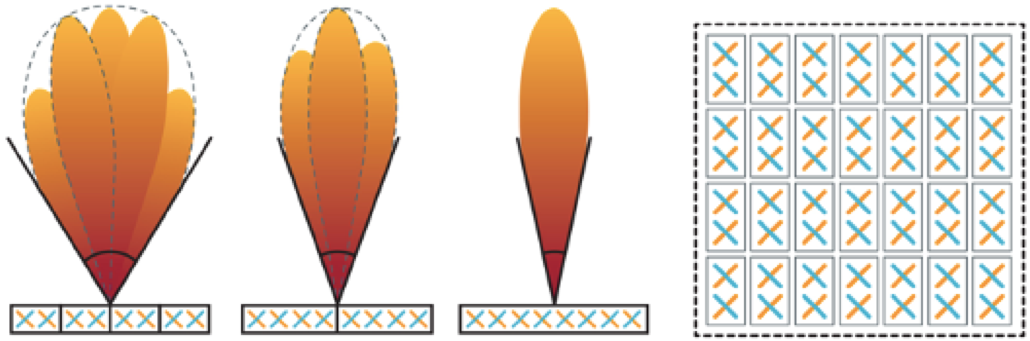
5G mmWave physical-layer changes have sparked significant RF hardware design and antenna changes. Let's explore some of the test challenges and considerations associated with operation at mmWave frequencies.

We're living in an era inundated with smart devices and their need for data and seamless connectivity. This influx will only intensify with the arrival and adoption of 5G.

Unlike previous generations of cellular technologies, which primarily focused on mobile communication, 5G is designed to offer more ubiquitous support for heterogeneous devices used in several industry verticals. 5G comes with a lofty promise of theoretical data rates as high as 10 Gb/s, latency lower than 1 ms, and massive connection density of nearly 1 million/connections/km^2.

5G is truly optimized to support not just data-hungry use cases like video streaming over smartphones, tablets, and customer-premises equipment (CPEs), but also latency-sensitive use cases such as remote healthcare and automotive connectivity as well as dense communication between indoor and outdoor IoT devices. But how does 5G deliver such enhanced capabilities?

5G brought about several transformations in the air interface to deliver high performance with improved efficiency, one of which is the addition of new spectrum. It's supported in both the sub-6-GHz frequency range 1 (FR1) spanning from 410 MHz to 7.125 GHz, and the mmWave frequency range 2 (FR2) spanning over mmWave frequencies from 24.25 to 52.6 GHz. Adding these higher frequencies not only enables more continuous spectrum, translating into higher bandwidths (100 MHz/400 MHz) and data rates, but allows for a flexible subcarrier spacing (15/30/60/120 kHz), facilitating a scalable deployment.



1. Shown is a graphical representation of beamforming using mmWave antenna modules.

5G Operation Over mmWave

With support for enhanced mobile broadband (eMBB) applications, 5G can operate over mmWave frequency bands. Though these frequencies offer wider channel bandwidths, dramatically improving throughput, they're exceptionally prone to path loss due to smaller wavelengths, causing reduction in power density and distance of propagation. As a result, the communication in the FR2 range requires devices to operate in a lower signal-to-noise ratio (SNR) environment, making it sensitive to RF impairments.

To compensate for this loss, 5G New Radio (NR) employs beamforming, which uses multiple phased-array antenna modules to maximize and steer radio energy in a specific direction **(Fig. 1**). This is achieved by independently feeding each of the elements in the array with a signal that's adjusted for phase and amplitude. As a result, there's a constructive addition only in the desired direction and null in other directions. This improves the SNR and increases the chances of signal reception at high frequencies.

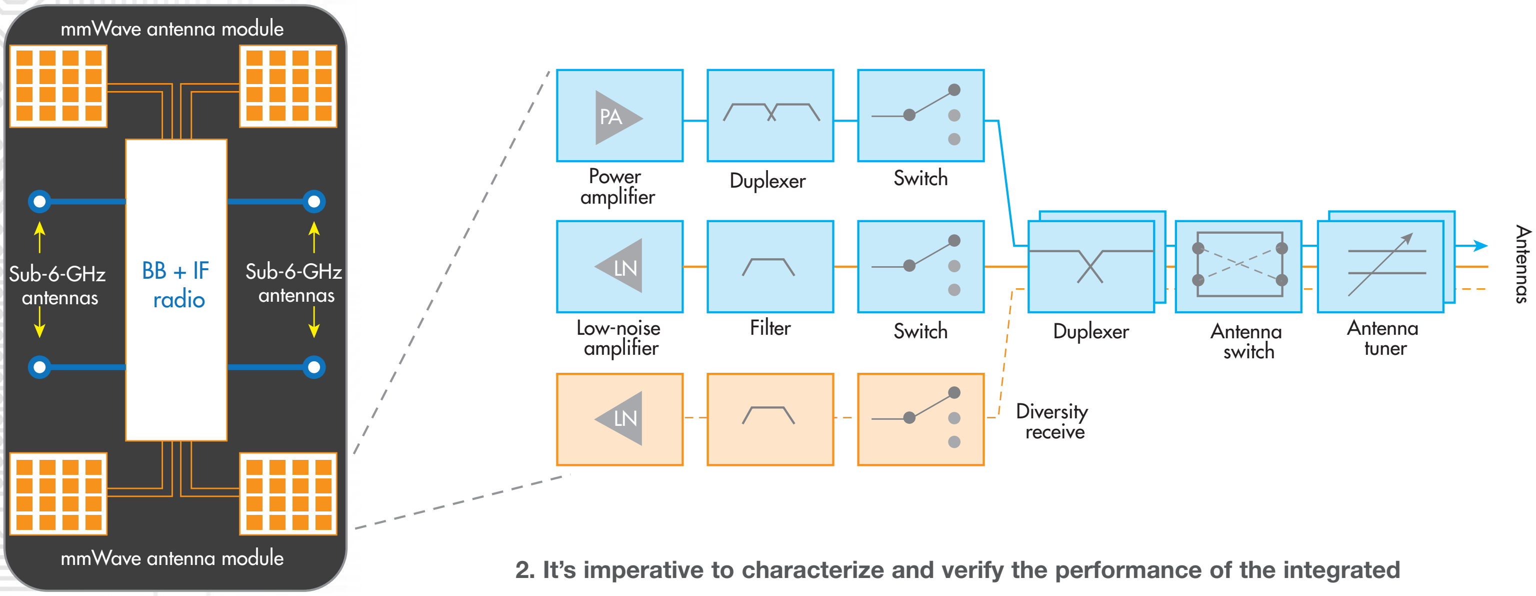
For a certain gain, the size of the antenna aperture is inversely proportional to the frequency. This necessitates that many of these elements be integrated in a physical antenna module to maintain a certain output power and capture capability.

Integrated RFFE

Though the beamforming technique may sound simple, it drives significant changes in the radio-frequency front end (RFFE) and antenna design.

A RFFE contains active electronic circuitry that's responsible for converting the information from the baseband to radio signals. The information for each band is processed by several elements in the RF chain (power amplifiers, low-noise amplifiers, filters, tuners, and so on) and fed at the appropriate power level to the right antenna. For devices designed to operate at lower frequencies, the RFFE circuitry and antennas are physically separate as the antenna dimensions are larger and the RF losses are low.

However, at mmWave frequencies, the RF circuitry densifies to feed both the horizontal and the vertical polarizations of several different antenna elements, making it extremely important to integrate the radiating antenna elements with the active radio circuitry, and shrinking the RFFE chain to minimize the signal attenuation. For this reason, it becomes extremely crucial to characterize and verify the performance of the integrated RFFE, also referred to as the mmWave antenna module (**Fig. 2**).



2. It's imperative to characterize and verify the performance of the integrated RFFE, also referred to as the mmWave antenna module.

5G mmWave Test Challenges

All of these physical-layer changes have also prompted significant RF hardware design and antenna changes, making it extremely important and, at the same time, challenging, to validate the end-user device performance. Let's explore some of the test challenges and considerations associated with operation at mmWave frequencies.

3D Beamforming Characterization and Verification

The integration of the RFFE and antenna arrays makes RF probing problematic, eliminating the option of conducted testing. At the frequencies used in LTE or 5G FR1, the performance of the transmitter and receiver is measured using the conducted test mode, and antenna performance is verified by a radiated test methodology. But at mmWave frequencies, all tests are performed over the air (OTA) in a shielded environment.

As described earlier, mmWave antenna arrays consist of multiple small elements, fed with a single data stream (polarization) or dual data streams (dual polarization) and thus

Table 1: RF Characteristics Referenced in Terms of Spherical Power Metrics

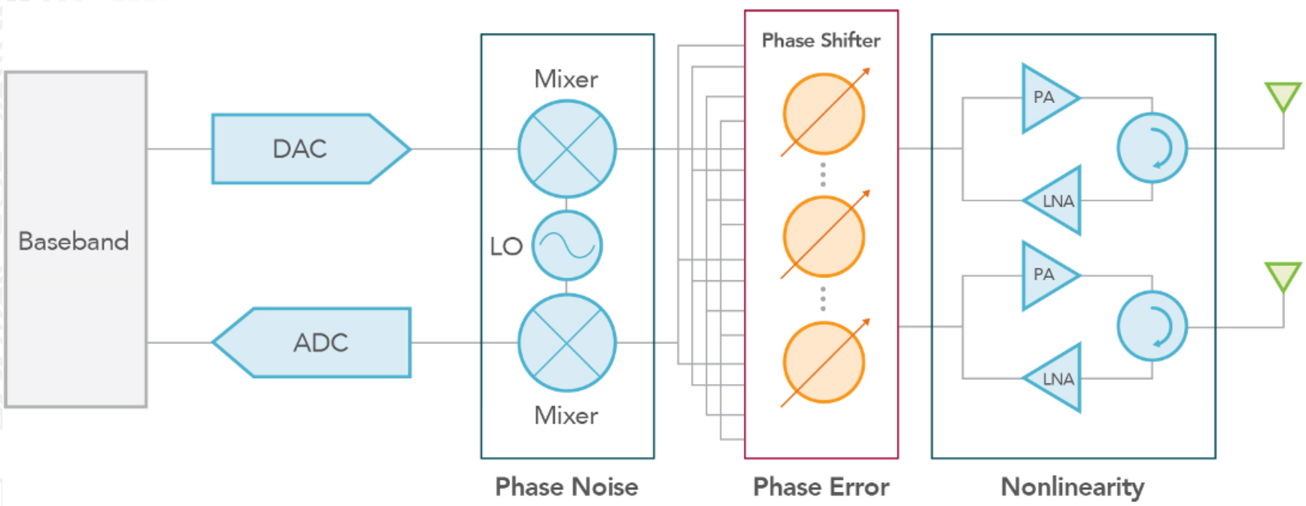
Characteristics	Test Item	mmWave (OTA)
Transmitter	UE transmitted power (max & min)	EIRP spherical coverage
	Transmit signal quality (EVM/Freq error/Carrier leakage/IBE)	Beam peak
	Output RF spectrum emission (occupied bandwidth/SEM/ACLR)	TRP
Receiver	Reference sensitivity	EIS
	Max input level	EIS
	Adjacent channel sensitivity	EIS

generating a three-dimensional (3D) spherical beam. As a result, we must characterize the beam's radiation pattern in a well-calibrated setup at multiple angles to verify the DUT's performance relative to the direction of propagation. The 3rd-Generation Partnership Project (3GPP) recognizes the spherical measurements—effective isotropic radiated power (EIRP), effective isotropic sensitivity (EIS), beam peak gain, and 3-dB beam width—as some of the key metrics to measure the performance of the transmitter and the receiver chain (**Table 1**).

To accomplish the above tests, the entire procedure necessitates the use of precise device positioning, alignment with the measurement antenna to avoid power loss and measurement inaccuracy, and a synchronized chamber positioner and DUT control. The overall methodology is time-consuming and can be very prone to setup errors.

Frequency Drift Resulting in RF Impairments

Figure 3 describes a typical mmWave transceiver circuit consisting of several components, including mixers, local oscillator (LO), phase shifters, power amplifiers, low-noise amplifiers, and integrated antennas.



3. A typical mmWave transceiver circuit consists of several components, including mixers, local oscillator, phase shifters, power amplifiers, low-noise amplifiers, and integrated antennas.

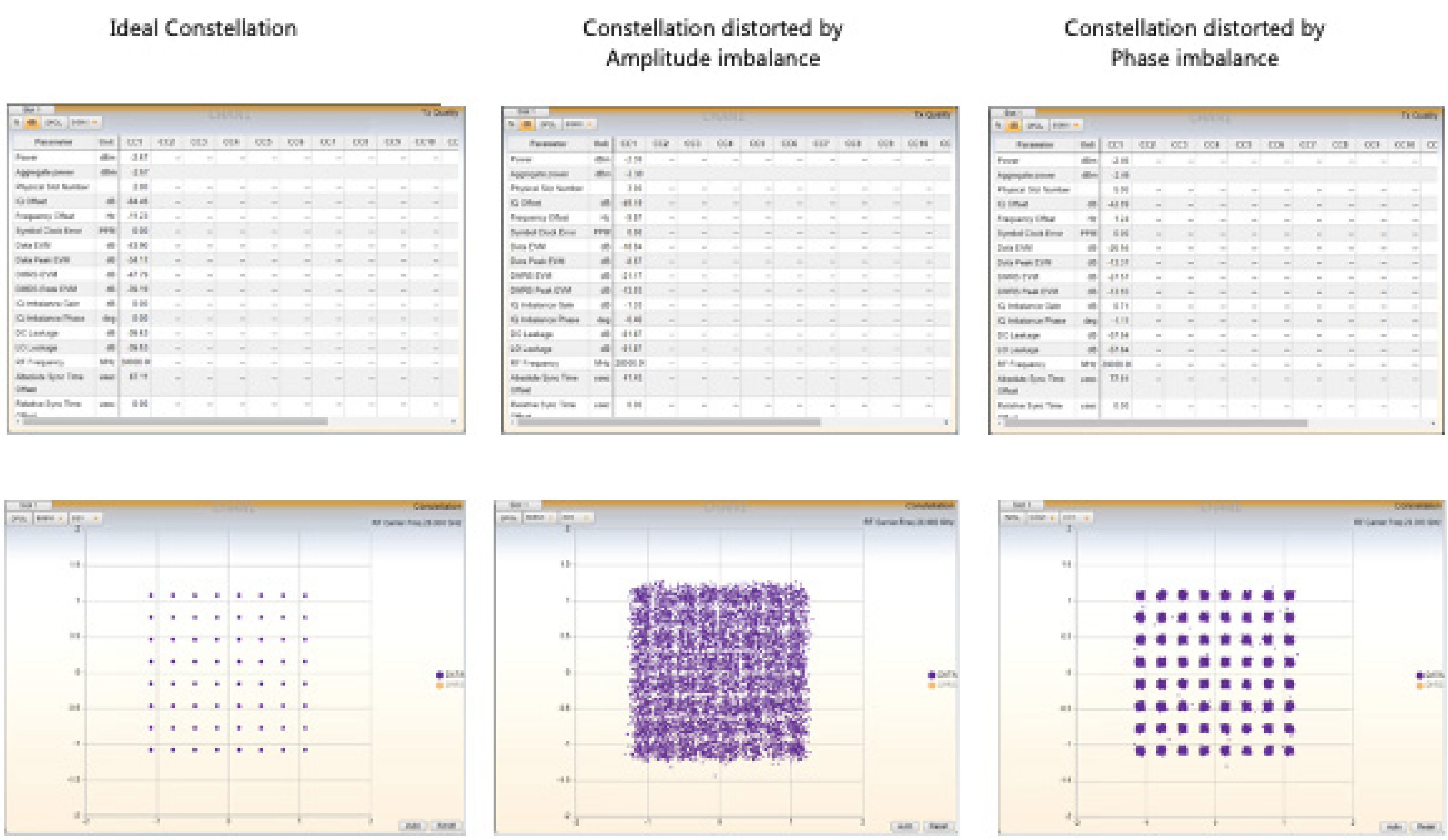
The characteristics of these components can largely affect the performance of the communication system. Any imperfections resulting from either a manufacturing defect or mutating frequency response can notably degrade signal quality, resulting in poor error-vector magnitude (EVM). These effects intensify even further at higher mmWave frequencies, denser modulation schemes, and larger antenna array sizes, making test and measurement highly sensitive to some RF impairments.

For example, phase noise resulting from the local oscillator could degrade the signal-to-noise ratio (SNR), thereby constraining the use of higher-order modulations and limiting the ability to detect and demodulate weaker signals. Other factors affecting modulation accuracy could be a dc offset due to LO leakage, phase imbalance caused by a phase shift between the I and Q output signal from local oscillator or amplitude imbalance resulting from gain shift between I and Q signals (**Fig. 4**), errors in digital-to-analog converters (DACs), or inconsistencies in the analog mixers. All of these defects could cause a shift in EVM, resulting in an attenuated signal and distorted waveform.

Implementing Comprehensive Test Coverage

To support a diverse array of devices across disparate industry verticals, 5G offers a wide range of physical-layer features to enable flexibility in implementation. **Table 2** exhibits support for wider bandwidths, flexible subcarrier spacings, multiple access schemes, and large carrier aggregation. All of it is supported over different mmWave frequency bands as specified in **Table 3**.

However, this flexibility gives rise to an exponential number of possible comprehensive verification test cases that could be executed based on the number of carriers, slot combinations, massive-input massive-output (MIMO) configurations, modulation schemes, orthogonal frequency-division multiplexing (OFDM) types, and bandwidths. **Figure 5** shows almost 600,000 test cases for just a single mmWave frequency to cover all bandwidths, modulation schemes, and OFDM types.



4. Modulation accuracy can be adversely affected by a phase imbalance resulting from a phase shift between the I and Q output signal from the LO or amplitude imbalance caused by a gain shift between the I and Q signals.

Table 2: Physical-Layer Capabilities Supported by 5G NR mmWave over LTE

Parameter	4G LTE	5G FR2 (mmWave)
Frequency range	Up to 6 GHz	24.25 – 52.6 GHz
Duplex mode	FDD, TDD	TDD
Subcarrier spacing	15 kHz	60,120 kHz
Bandwidth	1.5, 3, 5, 10, 15, 20 MHz	50, 100, 200, 400 MHz
Access scheme	DL: OFDMA, UL: SC-FDMA	DL: CP-OFDM, UL: DFT-s-ODFM
Carrier aggregation	5 carriers (with maximum aggregated BW of up to 100 MHz)	16 carriers (with maximum aggregated BW of up to 1200 MHz)

Table 3: mmWave Frequency Bands as Defined by 3GPP Rel-16

Band	Frequencies (GHz)
n257	26.5 - 29.5
n258	24.25 - 27.50
n259	39.50 - 43.50
n260	37.0 - 40.0
n261	27.50 - 28.35

Furthermore, the process could still become much more complicated if the device were to support multicarrier operation in the form of carrier aggregation, necessitating a well-built automation framework to support validation across varied intra- and inter-band combinations. Not only does this magnify the effort of test case design, development, execution, and verification, but it also directly translates into increased time to market, significantly curtailing production throughput and overall cost economics.

Simplifying the Complex OTA Test Setup

The goal for any technology is to be the first to market while satisfying the competing motives of maintaining quality and high production yield—mmWave is no different. However, what does differ is the dramatic increase in test-setup complexity when scaled from R&D to production, especially when moving from single-DUT to multi-DUT testing.

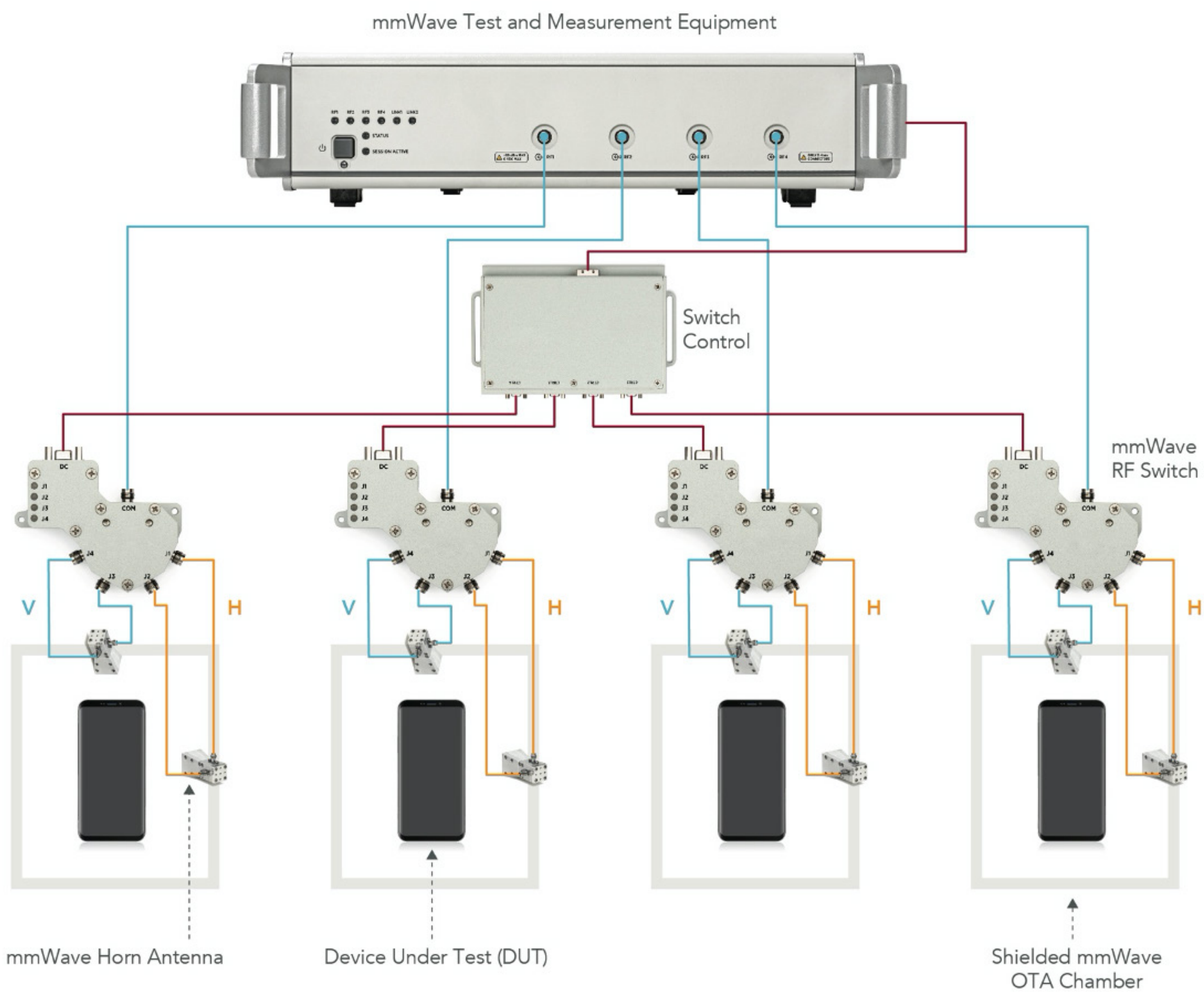
ODFM	SCS (KHz)	N_{RB}				Modulations	Number of CCs	Test case count with all possible RB sweep	Total test case count including all possible modulation schemes
		50 MHz	100 MHz	200 MHz	400 MHz				
DFTS	60	1145	3315	9288	-	5	1	13,748	68,740
	120	360	1145	3315	9288	5	1	14,108	70,540
CP	60	2211	8778	34980	-	5	1	45,969	229,845
	120	528	2211	8778	34980	5	1	46,497	232,485
							Total	27,856	601,610

5. Shown is a total test-case count sweeping across multiple resource block allocations. Note that the test-case count can vary significantly based on a combination of physical parameters under test.

An ideal R&D lab setup would look simple with a seemingly direct connection between the test equipment and the measurement antenna. However, in a production environment, the setup will mostly involve use of multiple additional components.

Figure 6 shows a four-DUT OTA test setup. Apart from the mmWave test equipment, DUT, and OTA chambers, the setup requires use of multiple RF switches, control box, measurement antennas, RF cables, and adapters. Each of these elements exhibits a certain performance loss or gain based on frequency of operation. For this reason, care must be taken to ensure:

- The components are compatible with each other, enabling seamless integration.
- The entire setup is well calibrated, with path loss determined and taken into consideration when making device measurements.
- Choice of a chamber with a far-field distance proportional to the antenna module under



6. This diagram depicts a representative multi-DUT OTA test setup.

test, thus limiting the OTA path loss.

- Avoiding the use of components that have limited operating life, minimizing operational cost.
- Software-automation tools enable simple customization and deliver fast test times.

Overcoming Test Challenges for Success

5G mmWave is still in its early stages of deployment, with evolving use models, implementation, and test methodologies. Nevertheless, with an increasing number of devices launching in the mobile and fixed-wireless-access ecosystem, ensuring quality by overcoming the test challenges outlined above will continue to be important to the success of these early products.

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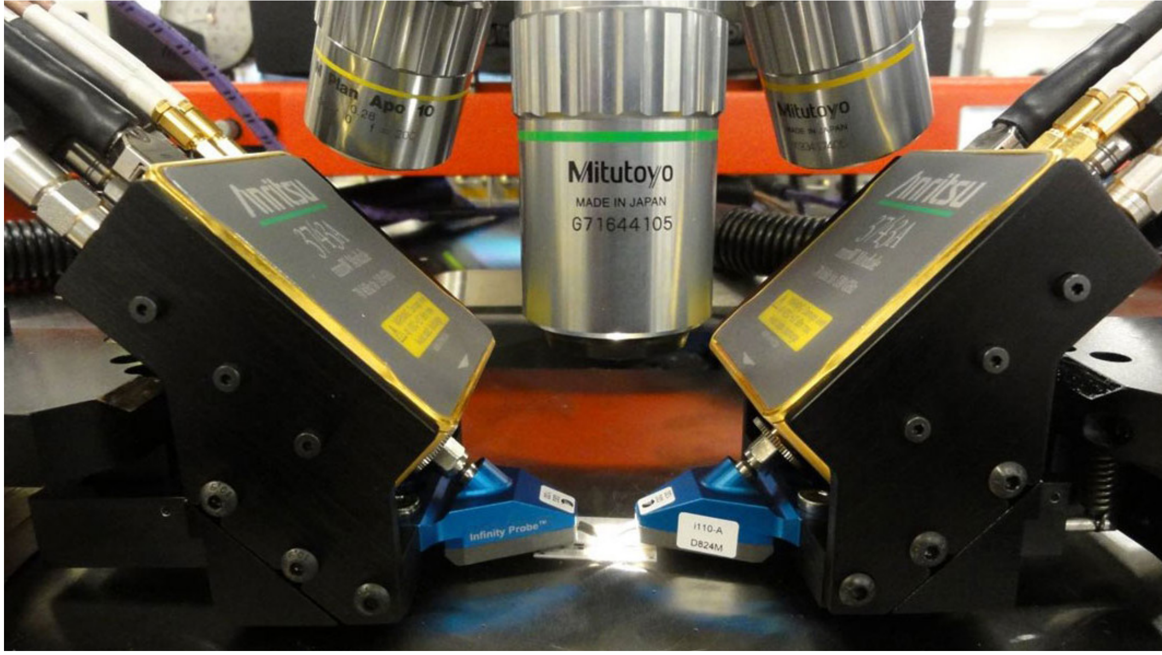


CHAPTER 2:

Phase Measurements, Calibration Critical in Verifying mmWave Designs

NAVNEET KATARIA, Product Marketing Engineer, Anritsu Co.

When mmWave frequencies and greater miniaturization coincide in a DUT, phase measurements and VNA calibration become important elements in device verification.

As commercial, military/aerospace, and other communications designs extend into the millimeter-wave (mmWave) spectrum, engineers must adapt their testing procedures and require more from instruments such as vector network analyzers (VNAs). Shorter wavelengths associated with mmWave frequencies place more weight on phase measurements, while also emphasizing the need for proper calibration.

Phase measurements have even gained in importance when verifying passive-component measurements. Phase differences can be very small, depending on the material, so a VNA must measure even the slightest variations. It does so by comparing the incident signal, leaving the analyzer with either the signal that's transmitted through the device under test (DUT) or the signal reflected from its input.

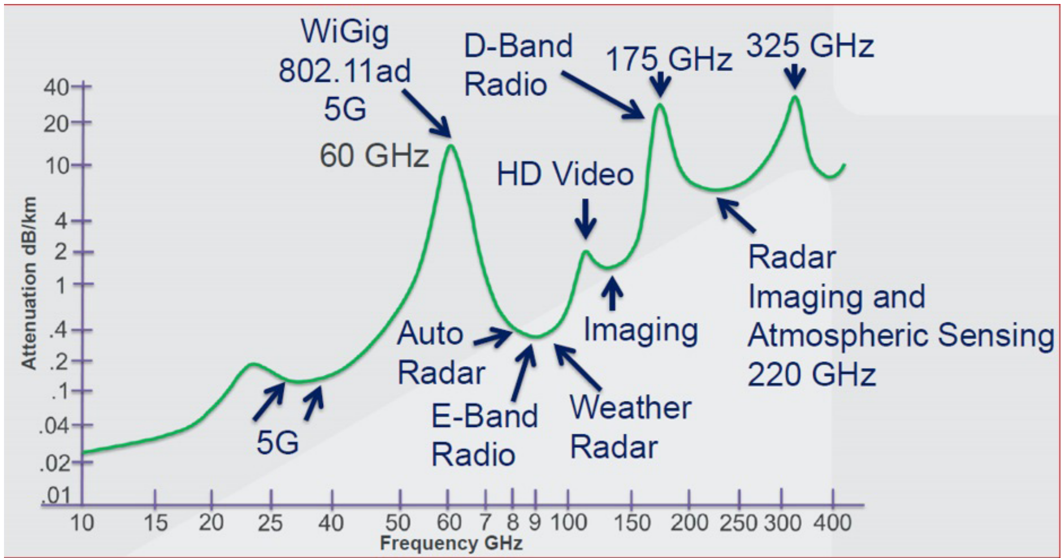
Influx of mmWave Designs

The mmWave band is defined as 30 to 300 GHz with a wavelength between 1 and 10 mm in the air. Its unique characteristics, such as penetration through fog, rain, and cloud, can enable a variety of applications. The wide bandwidth of the mmWave band also makes it very attractive for ultra-high-speed wireless and satellite communications. **Figure 1** shows common applications and related frequencies.

But increased frequency is only one part of the equation. Miniaturization of components/devices also adds to the importance of phase measurements in modern designs.

Waveguide Limitations

VNA calibration is crucial when it comes to accurately verifying designs utilizing these



1. This plot shows common applications and related frequencies in the mmWave bands.

technologies. It's particularly relevant, as mmWave measurements must be conducted over the air (OTA).

Accurate device characterization must sweep from near-dc to well beyond the harmonic frequencies to provide accurate models. Previously, engineers used different waveguides for high-frequency measurements. Waveguides are preferred for power-delivery applications, but there are some drawbacks for higher-frequency designs. One negative is the possibility of incorrectly mating apertures, which will adversely affect repeatability. RF leakage and slower/limited time-domain analysis are additional concerns.

Perhaps the biggest negative for high-frequency designs, though, is that waveguides are band-limited. Thus, engineers must "stitch" the measurements together when verifying their mmWave products. This is time-consuming and reduces accuracy and repeatability. A broadband VNA system can eliminate the need for waveguides by conducting sweeps of the entire range for more reliable modeling.

Calibration Technique

Testing at mmWave frequencies brings new and different measurement challenges. Minimizing measurement uncertainty is critical in the development of these new technologies. Calibration is one way to achieve this goal.

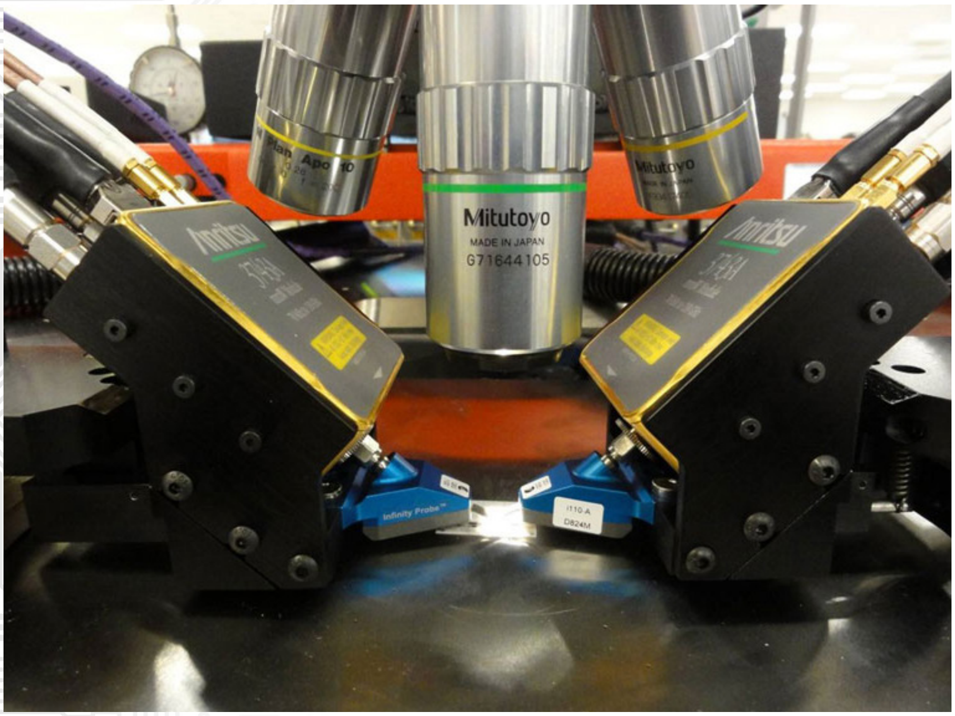
Calibration is essential due to a VNA's internal structure, as well as external factors that include cables, fixtures, and modules. They all have behavioral characteristics, such as frequency mismatches, that must be corrected to attain accurate measurements. Calibration needs to be done at the DUT end of the cables for the best possible results.

Engineers must perform tedious calibration routines to remove the amplitude and phase effects of those added cables and waveguide from mmWave S-parameter measurements. For these reasons, cables should be avoided at higher frequencies because they pose challenges to calibrating. Fortunately, mmWave modules that don't require cables have been developed—they improve repeatability and stability by eliminating the need to calibrate the cables (**Fig. 2**). And, of course, they remove the costs associated with expensive cables.

High-Frequency Calibration Options

The traditional calibration approach is to use a known standard, such as Short-Open-Load-Through (SOLT) or Short-Short-Short-Through (SSST). Standards compensate for internal losses and enable the device characteristics to be measured. The **table** shows the calibration algorithms, as well as their advantages and disadvantages.

Calibration techniques leave many uncertainties to be addressed. These include noise floor, trace noise, and residual calibration errors. However, the two most important at high frequencies, such as mmWave, are drift and repeatability.



2. As shown, mmWave modules can't be placed directly at the DUT.

The SOLT/SOLR (Short-Open-Load-Reciprocal) algorithms are often not recommended for higher frequencies due to the difficulty of fabricating a reasonable open standard beyond 65 GHz. An open waveguide flange radiates quite effectively, which results in instability and a relatively high return loss.

A coaxial open-circuit standard must use an enclosed approach. At the open end of the inner conductor, a frequency-dependent fringing capacitance is formed. Even if an open standard could physically be constructed with zero length, fringing capacitance will occur.

A coaxial short circuit can be constructed with almost ideal characteristics, enabling total reflection

COMMON VNA CALIBRATION ALGORITHMS

Calibration Algorithm	Description	Advantages	Disadvantages
SOLT (Short-Open-Load-Through)	Common coaxially	Simple, redundant standards; not band-limited	Requires very well-defined standards, poor on-wafer, lower accuracy at high frequencies
SSLT (Short-Short-Load-Through, also called Offset Short), shorts with different offset lengths	Common in waveguide	Same as SOLT	Same as SOLT an band-limited
SSST (Short-Short-Short-Through, also called Triple Offset Short), all shorts with different offset lengths	Common in waveguide or high frequency coax	Same as SOLT but better accuracy at high frequencies	Requires very well-defined stds., poor on-wafer, band-limited
Broadband Calibration SOLT/SOLR-SSST/SSSR	Combines SOLT/R and SSST/R in a single calibration (SOL below an entered frequency and SSS above it).	Saves time and connections when doing a broadband cal (no need to merge). Simple, redundant standards. Not as band-limited as constituents	Requires very well-defined standards. Generally poor on-wafer.

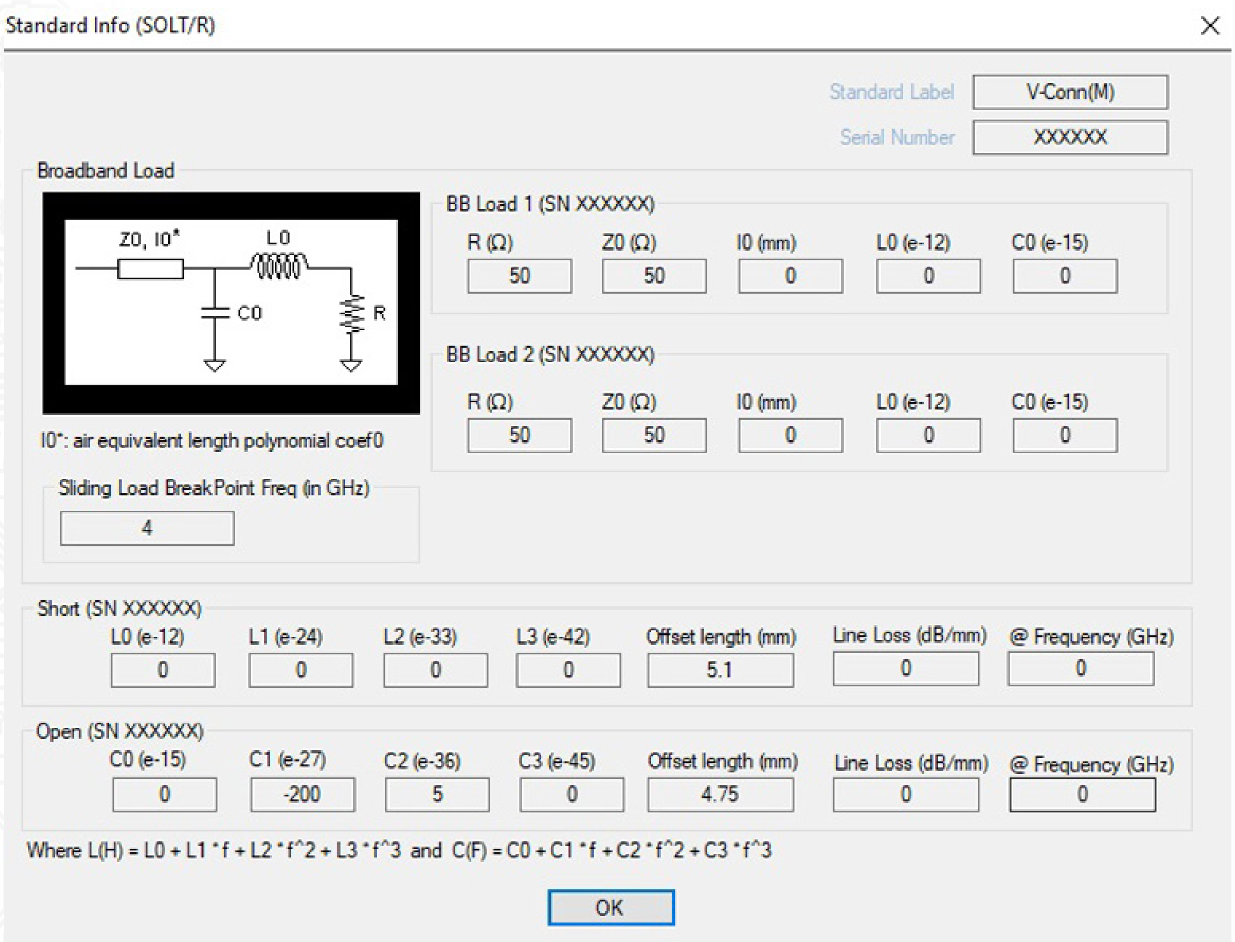
of the incident energy. Within the short circuit, there will be a small length offset. In coax, a zero-length short and a perfect shielded open exhibit 180-degree phase separation, while a matched load will provide 40- to 50-dB magnitude separation from the short and open. **Figure 3** shows the standard information provided by the SOLT/SOLR calibration algorithms.

For waveguides, the SSST/SSSR (Short-Short-Short-Reciprocal) approach is recommended at higher frequencies because a load standard isn't required. Accurate knowledge of the short offset lengths also is critical.

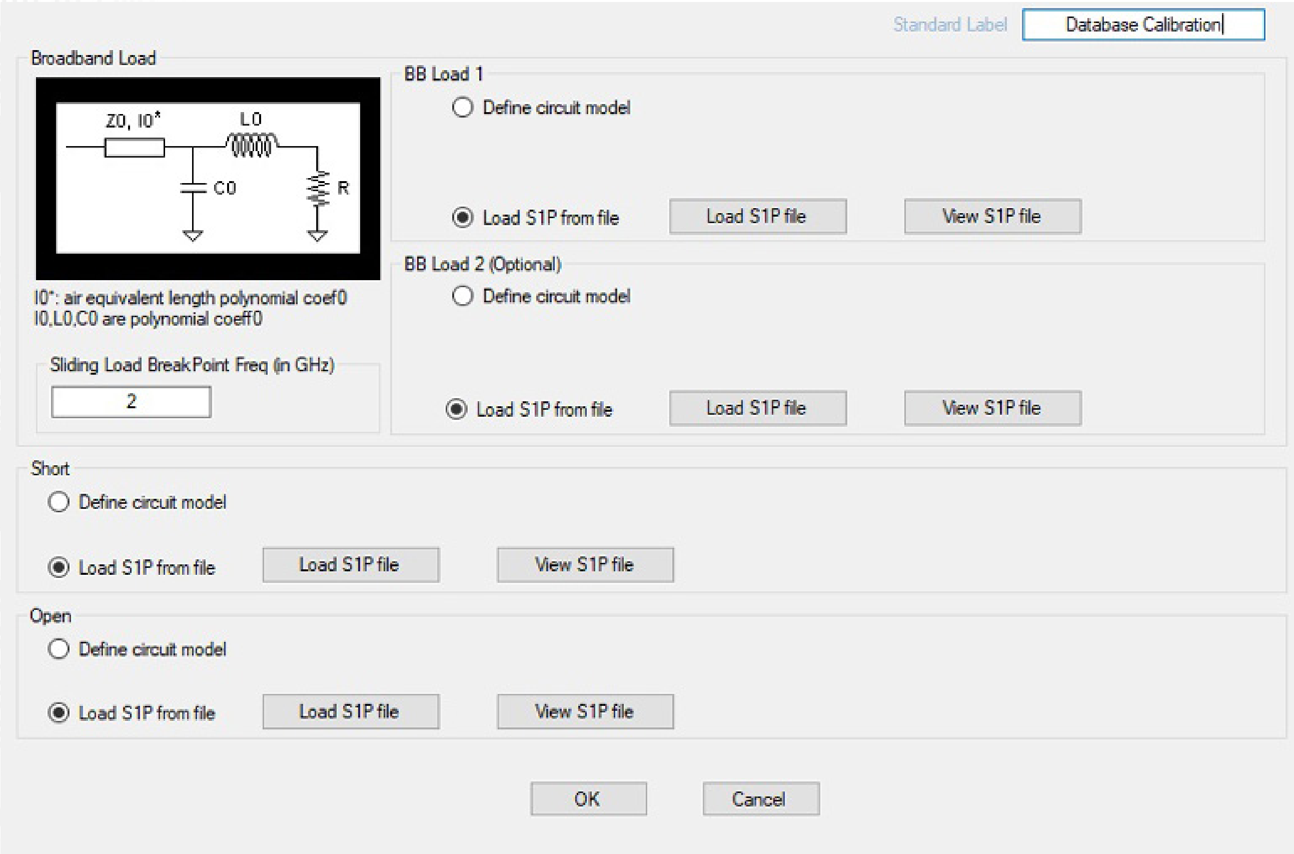
New calibration methods have been developed for mmWave designs. Until now, engineers only had access to the calibration coefficients (CCF) files. Inductance and capacitance values for the opens and shorts of the calibration kit, along with offset lengths for them, were contained in these files. It was all modeled data, so the residuals were high.

A new form of calibration kit, defined popularly as a database calibration kit, contains the exact S-parameter vs. frequency-response plots of each component of the calibration kit. It reduces residual errors in the calculations, as well as improves overall accuracy of the calibration algorithms.

S-parameter vs. frequency is provided to the user instead of just the calibration



3. This screen grab depicts the standard information provided by the traditional SOLT/SOLR calibration method.



4. This screen capture presents an example of database calibration kit inputs.

coefficients. This can be done via electromagnetic (EM) simulation or by transfer/real measurements performed at the manufacturer's facility. Lower ripple is another goal, as it helps improve measurements.

Figure 4 shows an example of the database calibration kit inputs. These calibration techniques are executed via high-performance coax, waveguide, or on-wafer.

Broadband Calibrations

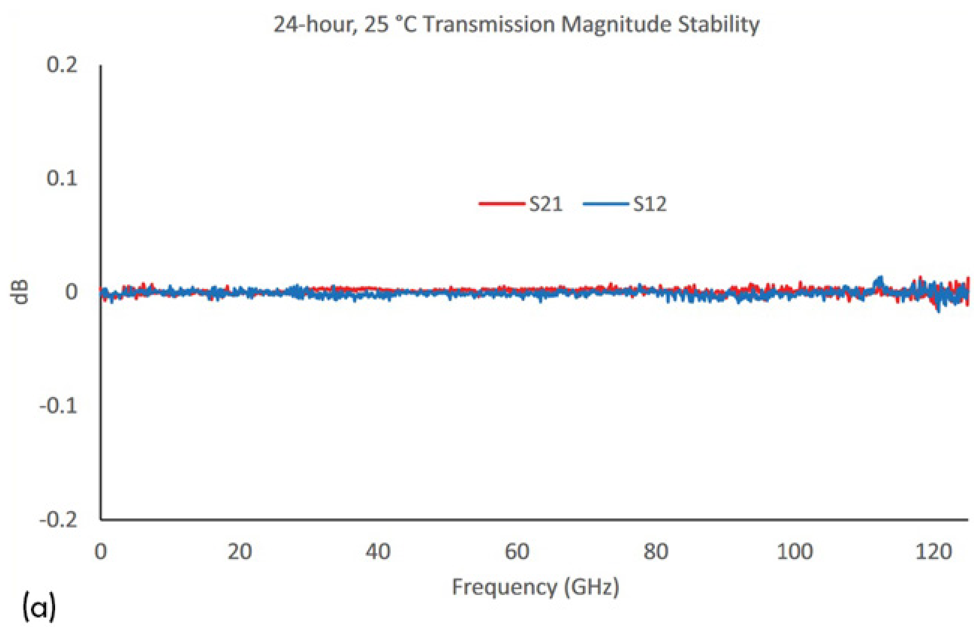
The list of calibration algorithms is huge. Some popular on-wafer/free-space broadband calibration algorithms, which are based on the characteristics of transmission lines and the delta between two or more of the same type, are discussed below. These algorithms rely on idealized transmission lines, as the various lines must have the same propagation characteristics, impedance, and connector interfaces. Here's a breakdown of each:

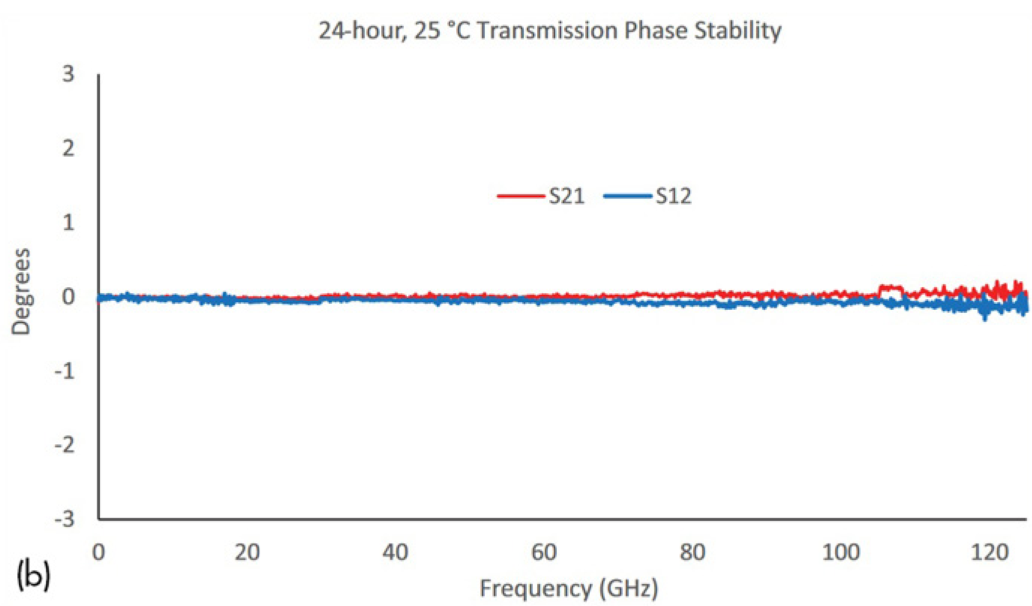
- *Line-Reflect-Line (LRL)*: Sometimes referred to as TRL, this algorithm's major advantage is that it provides the highest accuracy and has minimal standard definition. It requires very good transmission lines, though, and needs more care because it has less redundancy. It's also band-limited.
- *Multiline TRL (mTRL)*: This is a highly accurate method with minimal standard definition, too. One negative of mTRL is that it requires very good transmission lines. It also uses as many as 10 lines—all lines are used at each frequency in a least-square sense, with band limitations. It typically requires more lines than LRL for best performance.

Magnitude and Phase Stability

In broadband and mmWave measurements, stability often is of interest due to the possibility of long measurement sessions or longer calibrations. The preference is for a long-lasting calibration that reduces the chance of invalid measurements and overall time spent calibrating.

The modular broadband approach offers several advantages to help achieve these goals. For instance, it places the high-frequency couplers at the 1-mm (or 0.8-mm) connector to minimize raw-directivity degradation. Other benefits are a small integrated





5. The plots illustrate transmission magnitude (a) and phase (b) stability over a 24-hour period using the broadband approach.

package to avoid thermal gradients and a tightly integrated control system. The result is good stability in reflection and transmission over time (**Fig. 5**).

Measurement Challenges

Measurements may be made once the VNA is calibrated. For passive components, the S-parameter measurements necessary to determine phase are straightforward. One application—materials measurements—is affected by higher frequencies when measuring phase/group delay. Therefore, it's important to know which material category is being tested:

- *Insulators (dielectrics):* The energy gap between the valence and conduction band is extreme, so no free electrons are available.
- *Semiconductors:* The energy bandgap is smaller, so there may be some electron movement from the valence band to the conduction band.
- *Conductors:* The conduction and valence bands overlap, so electrons can move freely between the valence and conduction bands.

Some material measurement methods rely heavily on the change of phase imposed by the material under test. If the VNA isn't able to measure phase with a higher degree of resolution, the measurement accuracies will degrade significantly. Hence, the VNA becomes a very important tool when making material measurements.

Oftentimes, mmWave signals are at lower power levels than traditional RF or microwave applications. The power requirements for active devices operating at a higher frequency typically are extremely low, generally −25 dBm or below. Most current VNAs can't conduct sweeps down to a level of −50/−60 dBm very accurately to +10 dBm, so this measurement is difficult based on specification. There are exceptions, though, such as the Anritsu VectorStar VNA-based broadband mmWave system. It can go beyond −50 dBm with high accuracy thanks to the company's NLTL technology in the mmWave modules.

Because accurate measurements on active devices demand extremely low input power, a key factor is how a VNA applies power to the input of the device. A certain level of power handling must be assured or the DUT will be damaged. Certain VNAs, such as the Anritsu VectorStar, have automatic level control (ALC) to assure proper power handling. With ALC, engineers can conduct very accurate power measurements at lower levels and gradually increase power for greater design confidence. An external power meter also can be used to perform power calibrations.

It should be noted that complete calibration standards aren't always available at the end of the VNA fixtures. In these cases, advanced de-embedding and network extraction tools are necessary to achieve repeatable and stable measurements.

Conclusion

Phase has become an important measurement in verifying the new generation of designs that combine mmWave frequencies and small packaging. To ensure repeatable and stable measurements, proper calibration techniques must be instituted, thereby saving time and increasing design confidence.

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CHAPTER 3:

2021 Special Report: 5G Test

ALIX PAULTRE, Writer, Editor, Technologist

5G infrastructure is growing by leaps and bounds, with more and more capability being added to the system. However, the effectiveness of the solution is strongly based on how well the solution is evaluated, calibrated, and validated.

There are many aspects of 5G systems that need monitoring, evaluation, and management beyond the RF spectrum issues.

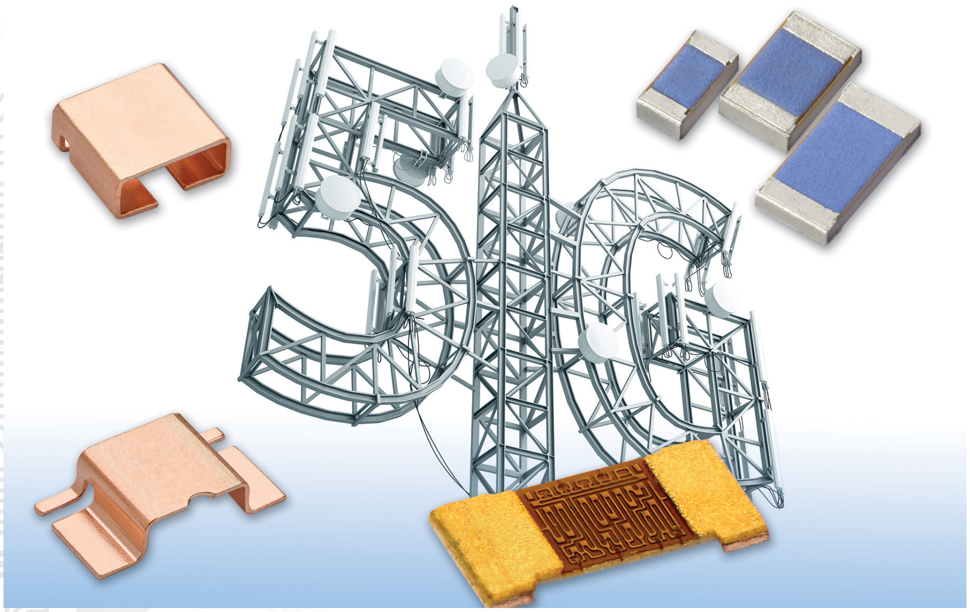
This important wireless space is on everyone's mind, as the infrastructures and devices to serve the 5G application space are being created and fielded. The 5G infrastructure is growing in leaps and bounds, with more and more capability being added to the system. However, the effectiveness of the solution is strongly based on how well the solution is evaluated, calibrated, and validated. Here is an update on some of the advances in the 5G test, evaluation, and infrastructure space.

Don't Forget the Passives

One of the aspects of the electronics marketplace is the tendency to focus on the "stars" of the circuit board, the microcontrollers, FPGAs, ASICs, and SoCs; there are a lot of passive components on the board as well. These passives are just as responsible for the success or failure of any design as much as the more glamorous parts on the board. VPG Foil Resistors, part of the Vishay Precision Group, currently offers three power brands: Vishay Foil Resistors, Powertron, and Alpha Electronics.

The demand for precision and accuracy in 5G systems extends to every component, and the performance of the company's Bulk Metal Foil resistor technology is well-suited for use in 5G test and evaluation equipment (**Fig. 1**). For example, the FRFS 0402 flip-chip resistor is a discrete, surface-mount device with a 40% smaller footprint compared to wraparound units, with a TCR of ±2.5 ppm/°C, and a load life stability of 0.01% after 2,000 hours. Like the rest of their Bulk Metal Foil resistor line, it is impervious to electrostatic discharge up to 25,000 V, is low noise, and is virtually noninductive and noncapacitive.

Alpha Electronics' RWs series of SMT chip resistors in 0603, 0805, and 1206 sizes offer a TCR of 2 ppm/°C and load life of 0.005% after 2,000 hours. Their CSMxY series, a cost-effective bare-metal current-sense resistor currently is available in 2726 and 4026 variations and boasts a TCR of 40 ppm/°C with a current rating of 100 A, well-suited for



1. The demand for precision and accuracy in 5G systems extends to every component.

testing the performance of the power system within any network array.

The challenge for VPG Foil Resistors components is that the parts are not made to be exposed to the data signal. While being unsuited to be incorporated into 5G signals themselves, their parts are well suited for the peripheral systems, providing stable performance no matter the temperature or life span of the product. 5G equipment consists not only of the antennas which relay the signal, but also measurement and calibration equipment, as well as the power management to create the signal, and the system management to control that power.

By ensuring the transition into the field is accurate and robust, the equipment manufacturers can be assured their systems remain calibrated, accurate, and will withstand the test of time. The initial cost of these new test systems requires any manufacturer to demonstrate their ability to be reliable such that their customer's ROI is maximized. VPG Foil Resistors components allow those subsystems to be calibrated less often, maintain their calibration throughout the various intended use environments (think Alaska in January and Phoenix in July), and to provide a lower cost of ownership to the ultimate end customer.

Covering the Spread

When we asked Joe Dussi, Director of Marketing Communications at Qorvo, about some of the challenges the company is seeing, he explained that one of the challenges facing the industry is maintaining adequate oversampling on waveforms to address wider and wider New Radio (NR) signals. It's important to field hardware implementations that capture the desired data, rejecting unwanted errors.

In addition, the customizability of 5G NR frame structure requires considerable nonstandard waveform generation. 5G NR supports two frequency ranges, using flexible subcarrier spacing derived from the one used in LTE. RF system designers require more power and bandwidth, while optimizing solution size and efficiency, especially when high reliability and performance are critical.

For example, the company's RF Fusion20 portfolio serves major 5G smartphone manufacturers, combining their gallium-arsenide (GaAs) power amplifiers, advanced bulk-acoustic-wave (BAW) multiplexing, and integrated RF shielding, offering enhanced performance and connectivity. Supporting all major baseband chipsets, Fusion20 modules integrate the receive path and low-noise amplifier, increasing receive performance and connectivity while saving valuable board space.

Fusion20 also features Qorvo's innovative MicroShield RF shielding, which minimizes the potential for undesirable interactions between RFFE components. Fusion20 helps support the most stringent 5G bandwidth requirements of up to 200 MHz, leveraging the QM77048 mid-/high-band, QM77043 low-band, and QM78207/208/209 ultra-high-band modules, in regional configurations to meet specific market requirements. Qorvo has optimized Fusion20 as a full 5G front-end solution complemented by Qorvo's Wi-Fi 6/6E modules.

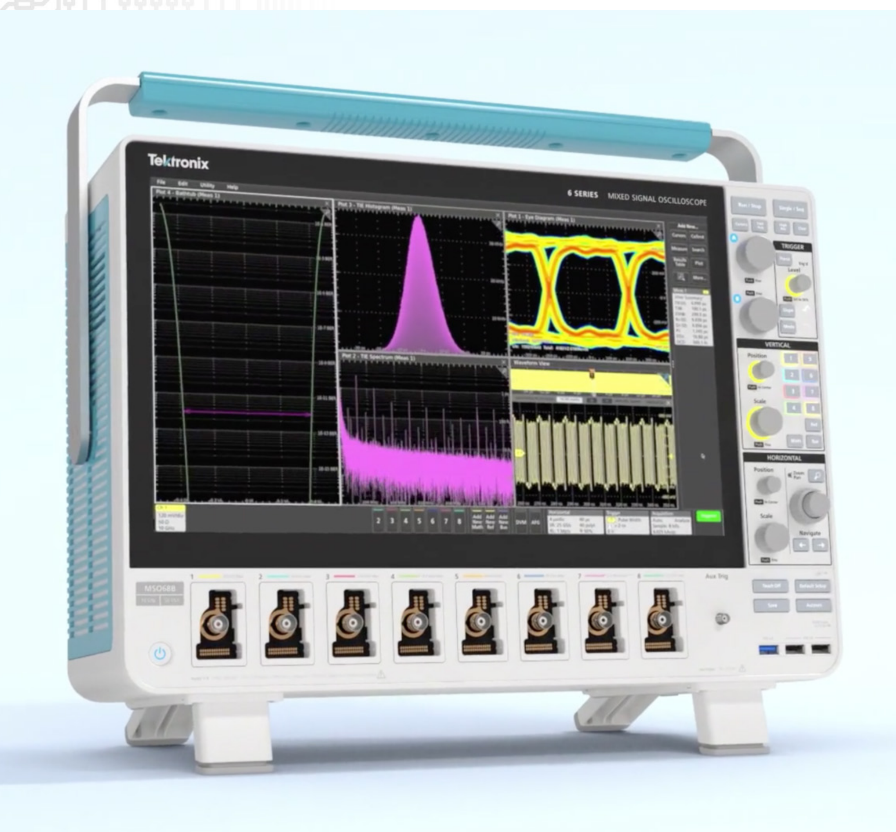
Beaming about Beamforming

Raajit Lall, Tektronix General Manager of Market Solutions and Software, brought up the two primary challenges they see that instrument vendors and customers face: the bandwidth requirements of 5G and the ability to test multidomain signals. For example, The MSO6B oscilloscope has a digital downconverter (DDC) built into the ASIC, which allows for simultaneous correlation of time domain and frequency domain tests (**Fig. 2**).

These tests are becoming critical because beamforming architectures require tight correlation between the digital signals and the phase array antennas in devices. The MSO6B also has up to 10GHz of time domain bandwidth and 2 GHz of DDC bandwidth, which allows test engineers to more future-proof their investments, and keep up with the increasing bandwidth requirements of 5G and 6G.

Tektronix has a wide portfolio of products addressing 5G testing, ranging from USB spectrum analyzers for narrowband measurements that apply to massive machine-type communications (mMTC) to AWGs and mixed-signal oscilloscopes that have the wide bandwidth needed for enhanced mobile broadband (eMBB). The MSO6B oscilloscope is an excellent instrument for wide bandwidth analysis of 5G signals and the AWG70000B arbitrary waveform generator delivers 5G signals with 10 GHz of receive and 20 GHz of transmit bandwidth each.

In addition, SignalVu-PC is an intuitive software that provides an intuitive UI for 3GPP-compliant measurements and a programmable interface for automation of measurements. The newly released Tektronix 8 series sampling oscilloscope provides up to 30 GHz of bandwidth for backhaul and data-center test applications including TDECQ, 400G, and PAM4. The 8 series sampling scope provides parallel measurements on up to four channels and provides a modular design all in a small form factor.



2. The MSO6B oscilloscope can perform simultaneous correlation of time domain and frequency domain tests.

MIMO and OTA

Two trends accelerated because of 5G and anticipated continuation into 6G technologies are MIMO testing and over-the-air (OTA) testing. MIMO especially proves to be an interesting challenge for test engineers, since not only do they have to test for multiple channels that are phase-aligned, but they also have to test large sets of channels at wide bandwidths. OTA provides a whole new set of challenges, since test engineers have to integrate chambers and positioners into their labs. Calibration of thermal chambers, with all the permutations of positions that the device needs to be tested, can be time consuming and error prone.

Tektronix instrumentation provides a variety of solutions for physical-layer testing of mMTC and eMBB. By using a single software package (SignalVu-PC) for high channel narrow band tests that can be done with USB spectrum analyzers; or wide bandwidth, high-performance spectrum analyzers and oscilloscopes test engineers can use a familiar interface for all of their physical-layer test requirements. Tektronix also has robust solutions for backhaul testing. Compliance and validation packages for 400G and PAM4 test wireless and wired communications.

New Radio and mmWave

On industry 5G challenges, Andreas Roessler, Technology Manager at Rohde & Schwarz USA, pointed out that 5G New Radio (NR) is the first standard to use the mmWave frequency region FR2 (i.e. beyond 24 GHz) for highest data transfer rates. The highly integrated front-ends and array antennas necessitate advanced OTA testing methods and new RF test metrics for assessing current and future mobile communication. Such test metrics include virtual cable calibration (VCC), which is mandatory for reproducible and reliable OTA throughput testing. For performance tests in which fading is emulated, the VCC method is crucial to assess defined antenna correlations with minimal crosstalk from the OTA link.

One of the biggest challenges for test and measurement manufacturers is implementing standardized evaluation and verification methods for UE under repeatable and realistic conditions, which are also reliable with mass production processes. For LTE and 5G NR FR1 tests, conductive testing methods are the norm for MIMO devices. During testing, the antennas of the device under test (DUT) are disconnected from the antenna ports, and the DUT is directly connected to the test system using a coaxial cable. However, for testing UEs in the FR2 bands, this approach is not practical: the large number of integrated antennas on the UE for spatial multiplexing and beamforming requires testing OTA, without cable connections.

The transmitted signal propagating in the OTA radio channel gets distorted by inherent interference due to cross-talk and by the receiver's noise. To have defined and reproducible conditions similar to conductive testing, the effects of the OTA channel must be eliminated. One approach to solve this issue is to calculate the unknown OTA transfer matrix by accounting for the complete OTA environment, including the transmitter and receiver antenna characteristics. This approach is complex and, in most cases, not possible as UE manufacturers are not required to give detailed information about their antenna characteristics (known as the "black box" assessment approach).

A suitable approach, developed by Rohde & Schwarz, equalizes the OTA channel matrix using only the Reference Signal Received Power per Branch (RSRP-B) feedback parameters, which can be retrieved from an NR UE according to the 3GPP standards. This OTA channel equalization enables having a quasi-conducted or "virtual cable" in an OTA test environment.

The approach lays the foundation for practical 5G UE performance testing, e.g. for maximum throughput. An equalized OTA channel is mandatory for all conformance tests under fading conditions, and it is recommended for all tests which rely on “ideal” radio conditions, such as protocol or application tests. Rohde & Schwarz introduced a high-speed virtual calibration tackling the challenge of noise- and resolution-limited RSRP-B feedback, which provides perfect prerequisites for the challenges of OTA testing.

Space Saving

In 5G NR FR2, all measurements are to be performed OTA. To reduce the required chamber space, CATR is a hot technology that Rohde & Schwarz has been addressing with compact and portable chambers such as the R&S ATS1800C. Now the next challenge comes along: RRM (radio resource management) testing in FR2. For this, the UE needs to be confronted with two independent base-station signals coming from different angular directions.

To accomplish this in a compact OTA setup, Rohde & Schwarz developed an extension of the R&S ATS1800C to create a multireflector setup that addresses this issue. With the R&S ATS1800M, a total of four reflectors can create six different pairs of incident angles at the DUT. This fulfills the requirements of the 3GPP RRM spec, but allows for even more flexible measurement setups where needed. Since each reflector can create an independent 30-cm quiet zone (QZ), these RRM tests can still be done using a black box approach, keeping the resulting measurement uncertainty low.

Besides RRM with one or two angles of arrival, the R&S ATS1800M can be used for RF conformance, protocol conformance and demodulation tests, making it a “one chamber for all requirements” solution that still only takes up about 5 sqm of lab space. The multireflector extension is designed in such a way that it can be added to an existing R&S ATS1800C as an upgrade at any time. The R&S ATS1800M will be available by summer 2021.

Voice-over-NR

Mobile voice services continue to play an important role, also in 5G. More and more network operators are starting to deploy 5G standalone (SA) networks. This opens the door for high-quality 5G Voice over New Radio (VoNR) voice and data calls for the traditional operators, but also for a variety of new verticals. Voice over NR represents the voice services provided by the 5G RAN, 5GC, and IMS. Voice over 5G works in a similar way as Voice over LTE, using IMS as service enabler.

The advantage is that IMS manages (like in VoLTE) the PDU session establishment with the relevant QoS flow for optimized voice quality. The prerequisites for VoNR are support for IMS voice over PS by the UE. In terms of testing voice services in 5G, first implementations and functional behavior is being tested. While the general test setup for VoNR is not that different from the one used for VoLTE, different test areas should be considered.

The testing aspects of voice over 5G include scenarios for VoLTE for non-standalone (NSA) mode as well as EPS fallback, providing a handover during connection setup from NR to LTE, or a RAT fallback if the LTE NG-eNB is connected to the 5GC. And last, but not least, VoNR functional tests and audio-quality tests have to be performed. From the perspective of speech codecs, a test system for voice over 5G has to support the legacy speech codes AMR-NB and AMR-WB in addition to the EVS codec.

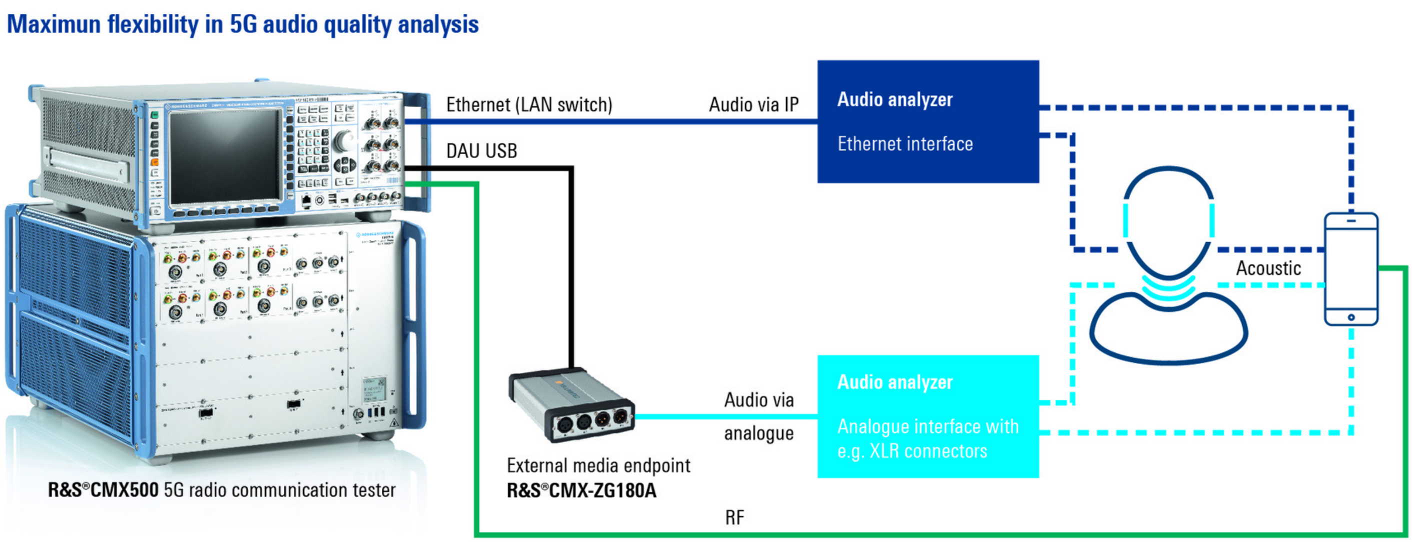
A test setup for voice and video applications in 5G is depicted in **Figure 3**, showing the mobile radio tester R&S CMX500 together with the R&S CMW500 supporting LTE and 5G NR for either standalone or non-standalone connectivity testing. The R&S CMX500 supports an internal IMS server, enabling virtual UE emulation and audio loop-back mode for fast and easy functional VoNR testing. The setup can be extended as shown by an audio analyzer connected either via "IP forward" or routing of the audio via "DAU USB" to an external media endpoint, the R&S CMX-ZG180A.

To permit audio tests according to IEC 62820-1 or ITU-T P.51 standards, the setup shown can either be used with an artificial head with artificial ear and mouth. For so-called electrical measurements, the DUT might be connected via the speaker output directly to the audio analyzer input, and the microphone output directly to the audio analyzer output. The R&S CMW500 platform, which has been very successful in the market for voice-quality analysis for 2G, 3G and 4G, is now being expanded for 5G VoNR applications with the R&S CMX500.

3GPP's Release 16 emphasizes—besides other things—the two market verticals, industrial Internet of Things (IIoT), and automotive. They challenge the industry with new sets of requirements such as increased reliability, security, and very low latency, typically summarized as ultra-reliable low-latency communication or URLLC. The second trend is that the hunt for higher data rates will continue. For upcoming Release 17, 3GPP discusses the support of 1024QAM in the downlink direction for the Frequency Range 1 (FR1).

For the extension of Frequency Range 2, often called FR2+, wider bandwidths are under discussion, for instance, up 2 GHz, 2.16 GHz, or even 3.2 GHz. Whatever the standardization body decides on will pose new challenges in designing devices and infrastructure components that support these additional capabilities. Fortunately, the R&S FSW signal and spectrum analyzer supports already today a signal analysis bandwidth of up to 8.3 GHz, which is unparalleled in the test and measurement world.

Rohde & Schwarz considers OpenRAN a technology evolution that incorporates new functions into the RAN, to disaggregate and modularize the architecture and to



3. The R&S CMX500 mobile radio tester and the R&S CMW500.

enable software-defined radio, real-time intelligent control, network management and orchestration, and networking techniques. In a very simplified way, T&M does not distinguish between traditional RAN and OpenRAN. Though most of the test requirements are similar, the company's portfolio includes test solutions for emulating the O-DU and test and verification of the O-RU.

Addressing Complexity

The kind people at NI told us that some of the key challenges they see are related to working with more complex, high-bandwidth signals, as their customers routinely develop devices that support at least 100-MHz-wide carriers, moving on to 200-MHz, 400-MHz, carrier-aggregated test scenarios with 8 x 100-MHz signals, and inter-band combinations. To increase the energy efficiency of their RF front ends, for example, they look for techniques such as digital predistortion (DPD) and envelope tracking (ET) to help them achieve their target performance.

But applying DPD linearization on large bandwidth signals is computationally intensive and requires even higher bandwidth instrumentation. Similarly, implementing ET on 100-MHz, 200-MHz, and wider signals is very challenging, if not impossible with current technology.

By taking advantage of the PXI platform, NI can give customers greater data-processing capabilities, and they collaborate with industry leaders like Maxlinear on cutting-edge digital predistortion.

NI is currently addressing three areas of research and development, among others: more capable instrumentation (hardware), more efficient measurement algorithms and software tools, and mission-ready system-level integration. In terms of instrumentation, NI continues to invest in wideband, high-linearity RF measurements for 5G Frequency Range 1 (FR1, sub 6 GHz) and Frequency Range 2 (FR2, or mmWave) through the vector signal transceiver (VST), an instrument that integrates both vector signal generation and analysis in one. The VST enables validation and test of the latest 5G cellular and early Wi-Fi 7 connectivity front ends, transceivers, and user equipment (**Fig. 4**).

Regarding measurement algorithms and software tools, NI continues to expand the waveform generation and analysis capabilities of its RF measurement experience (RFmx) API, keeping up with the latest advances in the 3GPP 5G standard. RFmx gives validation and test engineers flexibility to create and apply very large

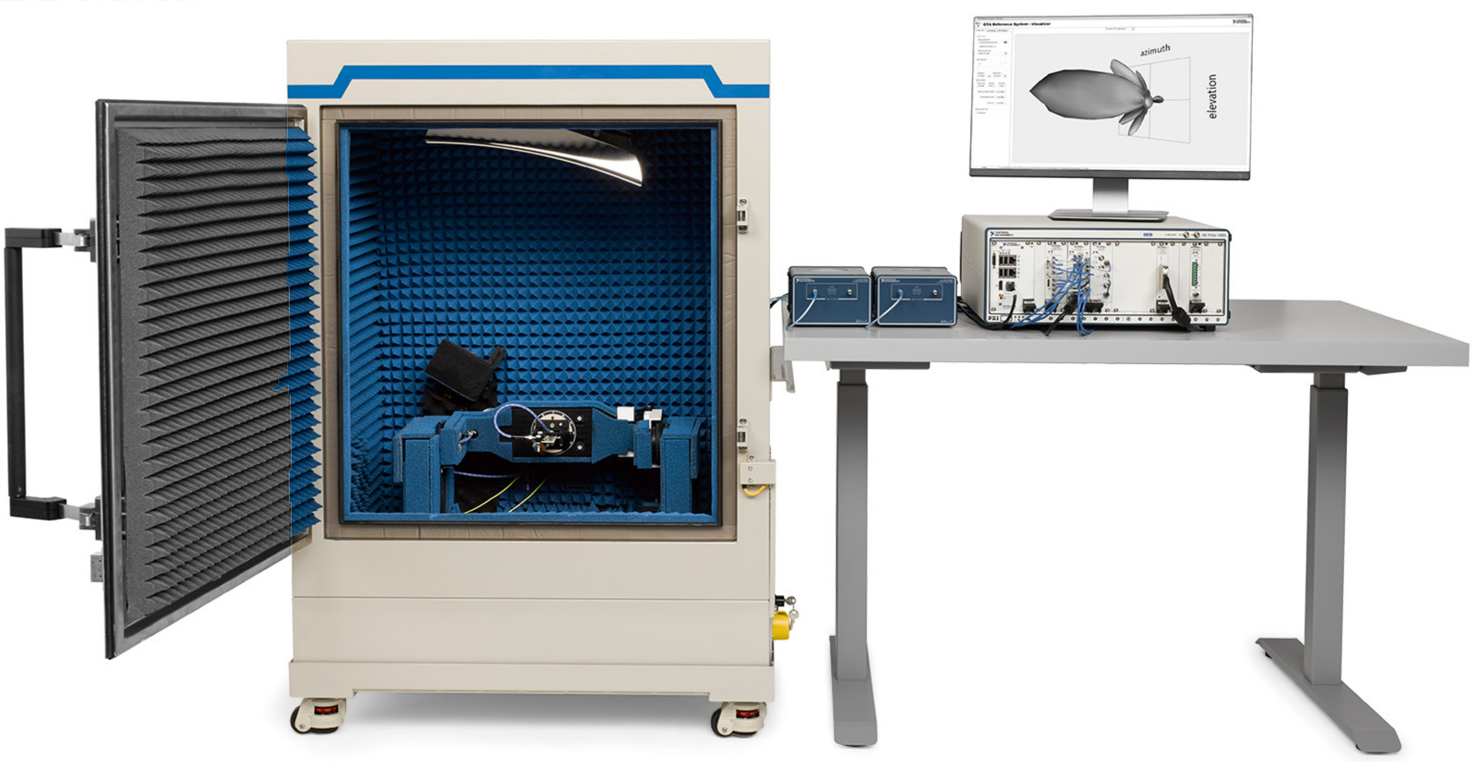
4. The VST enables validation and test of the latest 5G cellular and early Wi-Fi 7 connectivity front ends, transceivers, and user equipment.

combinations of 5G stimulus waveforms to their DUTs by varying multiple parameters, such as waveform bandwidth, subcarrier spacing, modulation scheme, and carrier-aggregation combinations. On the analysis side, RFmx implements multi-threaded, parallel-processing technology for accurate measurement results rapidly, compared to more traditional sequential-measurement approaches.

NI has a series of reference architectures and highly integrated automated test systems to validate and test 5G semiconductor and electronic devices. The RF Front-end Validation reference architecture gives validation engineers focused on wideband RF front ends a tightly synchronized PXI bench with multiple instruments, from dc, to digital, to RF, plus software for cockpit-like control of their benches, access to the latest DPD linearization algorithms, and a fast path to automated characterization.

As engineers develop multi-element antenna modules for FR2 mmWave connections, they face the tough challenge of validating and testing their beamsteering performance. Engineers must make their measurements OTA in a controlled RF environment inside anechoic chambers (**Fig. 5**). These chambers also must support rotation of the DUT in azimuth and elevation to determine the DUT's 3D spatial radiation pattern, the effective isotropic radiated power (EIRP), total radiated power (TRP), location of beam peaks and nulls, and other measurements.

These OTA measurements also help characterize the DUT's capabilities for beamforming and calibrate the beam direction based on specific DUT control words. To help engineers accelerate development in this area, NI introduced the 5G mmWave OTA validation reference architecture, which takes advantage of NI motion control to speed up 3D spatial measurements 5X to 10X, compared to more traditional methods.



5. Engineers must make their measurements over the air (OTA) in a controlled RF environment inside anechoic chambers.

At the semiconductor level, one of the biggest trends is in OTA validation and testing. First, devices keep pushing higher in frequency toward the upper range of FR2 around 48 to 52 GHz. Second, there's a growing need for very reliable and fast mmWave OTA production test solutions that support parametric testing of antenna modules. To meet the current trends in demand for mmWave capabilities in user equipment and customer premise equipment, these test systems must test thousands of units per hour.

mmWave capabilities will continue to propagate down from flagship devices to more mid-range user equipment. In user equipment, the mmWave configuration relies on multiple sub-arrays to make 3D beamforming possible and to avoid problems with a user's hands covering the mmWave beam. Typical configurations could include three or four antenna arrays on a smartphone, with each array consisting of four antenna elements. This will result in increased demand for faster and more cost-effective mmWave OTA test and evaluation solutions, capable of parametric measurements to indicate potential beamforming problems in the field.

Accuracy and Efficiency

When it came to the question of industry challenges, Dr. Houman Zarrinkoub, Principal Product Manager, Wireless Communications at MathWorks, said that the main challenges they see involve accuracy and efficiency. When it comes to accuracy, designers need to find accurate and reliable signal vectors and cover all of the test cases needed to qualify a system to be compliant with the 5G standard. MathWork's 5G Toolbox enables reliable access to these test vectors, rigorously verified by their engineers.

As far as efficiency goes, it takes a considerable amount of time to test the physical-layer (PHY) subsystems of 5G devices, with all their modes, frequencies, and parameters. Any environment and tool that can perform test vector generation, scripting, and executing (i.e., over-the-air transmission more efficient) can make test engineers substantially more efficient.

The company's Wireless Waveform Generator app is designed to make all of these three steps more efficient. By generating waveforms interactively, then generating MATLAB scripts that capture the waveform generation process as a test script and then connecting the waveforms directly to the RF instrument, the app goes a long way to address these challenges.

MathWork's 5G flagship product, 5G Toolbox, includes test models (NR-TM) and fixed-reference channel (FRC) signals defined directly as part of 5G standards documentation. This helps designers verify and validate their 5G designs accurately. Waveform generation is an important requirement for testing any design.

The recently introduced Wireless Waveform Generator app makes the testing process easier and more interactive. As an interactive and graphical tool for testing, the app generates, visualizes, and integrates 5G test signals within its test environment. As a result, any user, even those who are not MATLAB programmers, can easily generate 5G test vectors.

The app supports a wide range of wireless standard waveforms such as 5G, Wi-Fi, and Bluetooth. The app also supports off-the-shelf testing signals specified by standard documents including test models as well as the fixed reference channels. As of release 2021a, custom 5G waveform generation also is included in the app, which enables engineers to specify any arbitrary set of parameters and generate all types of 5G signals.

In addition, the Wireless Waveform Generator app directly connects to RF instruments (signal generators) from various vendors. It allows for transmission of generated 5G waveform OTA with a single click. This feature requires the use of our Instrument Control Toolbox, in conjunction with 5G Toolbox.

5G standards have introduced new frequencies in the mmWave range (above 24 GHz). Due to limited range of mmWave signals, transmissions at these frequencies are usually combined with use of large MIMO antenna arrays that boost the signal and hence increase the range. Trends related to use of mm Wave and how to test these types of signals, as well as combining testing with MIMO antenna arrays, are among the most important work in this area.

Picking Up the Pieces

The point Jon Semancik, Director of Marketing at Marvin Test Solutions, brought up was that production throughput is critical in mmWave semiconductor device test, and is one of the biggest challenges that most manufacturers are facing. The GENASYS Semi TS-900e-5G is presented as the fastest production test set currently available, with some benchmarks showing an order of magnitude faster execution times (**Fig. 6**). They accomplish this by implementing a parallel test architecture with up to 20 independent VNA ports per system, resulting in exceptional test efficiencies and test time reductions.

MTS's flagship offering, the TS-900e-5G 5G mmWave test system, is part of Marvin Test Solutions' GENASYS Semi suite of flexible, configurable, semiconductor test solutions, well-suited for both wafer probe and package test, with support for most popular production automation and handling tools. The system can support up to 20 independent VNA ports of 44-GHz signal delivery to the DUT, meeting the throughput requirements demanded by OSAT production.

Additionally, the modular architecture of the test system is well-suited to address the evolving needs of mmWave test, with expanded performance to 53 GHz scheduled for late Q2. The TS-900e-5G core system includes Keysight's high-throughput VNAs and ATEasy, Marvin's comprehensive suite of software tools that allows users to quickly develop and easily maintain test applications as well as ICEasy, which facilitates device test development and characterization.

6. The GENASYS Semi TS-900e-5G.

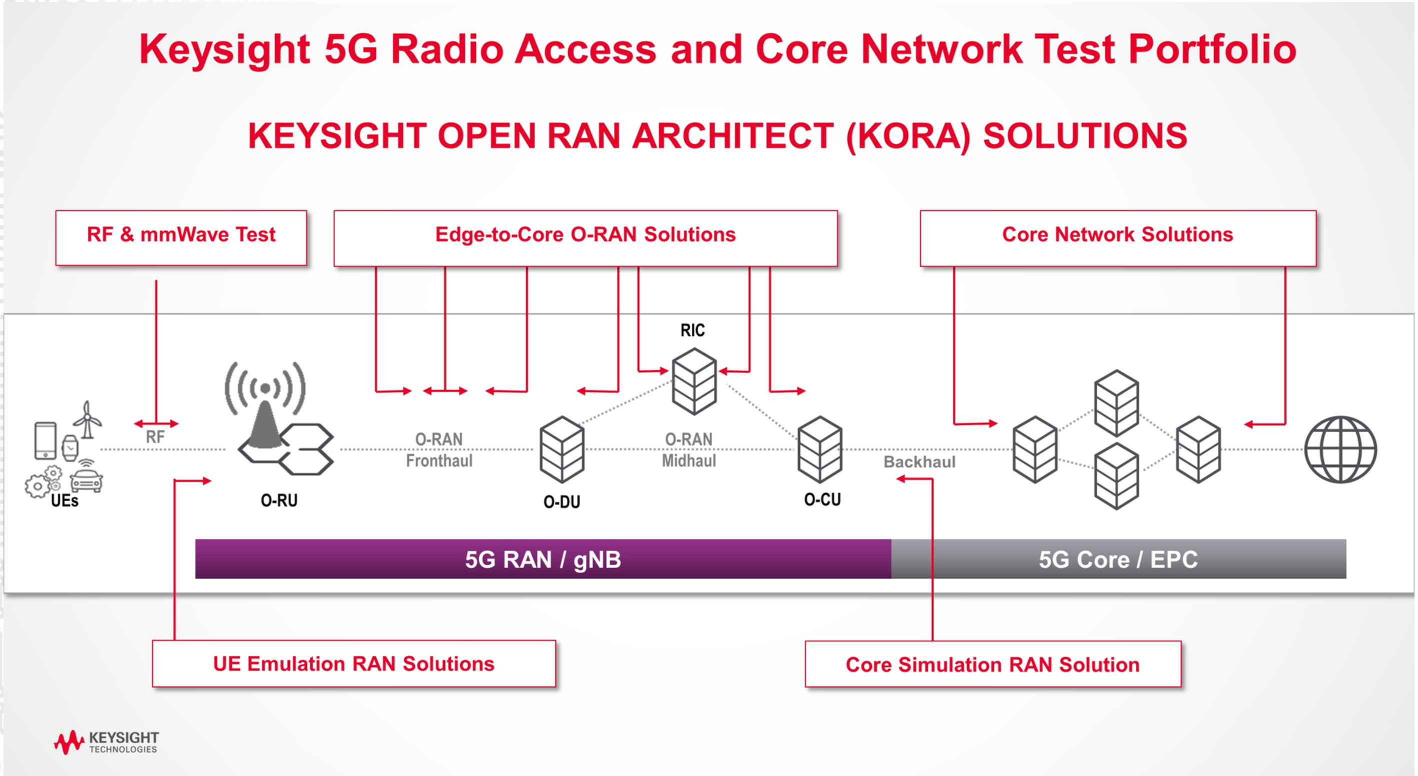
The TS-900e-5G core system also includes high-performance dynamic digital I/O with per-pin PMU to support SPI/I2C device communications and dc parametric testing.

The company also provides the ability to upgrade existing big iron test systems with the latest VNA and Digital I/O instrumentation utilizing the MTEK (Marvin Test Expansion Kit) Series. The industry continues to move toward higher-frequency devices. Just moving from 44 GHz to 53 GHz impacts many areas of the test set, starting with the VNA instrumentation but also including cables, interconnects, blind-mate interfaces, and of course system-level calibration. Industry demand for these devices will continue to grow with the proliferation and adoption of 5G, but the demand for mmWave devices extends beyond 5G to other application areas such as military, imaging, and security screening, to name a few.

Supporting the Ecosystem

Jessy Cavazos, 5G Industry Solutions Marketing at Keysight Technologies, talked about how they partner with leading chipset manufacturers like Qualcomm and Mediatek, network equipment manufacturers (NEMs) like Nokia and Ericsson, and leading operators like NTT Docomo and Verizon to stay ahead of the technology curve. They also partner with newcomers eager to innovate like the new entrants in the O-RAN space.

Keysight is also involved in various standard organizations such as 3GPP and the O-RAN Alliance, and is the editor of the O-RAN fronthaul conformance test specifications in Working Group 4 (WG4) of the O-RAN Alliance. They participate in several programs with universities around the world and work on technology way ahead of time. The



7. KORA, an end-to-end portfolio of solutions for Open Radio Access Network (O-RAN), enables ecosystem participants to emulate any part of a 5G O-RAN network.

company also is involved in things like the 6G Flagship program from the University of Oulu, Finland, for example.

Another example can be found in the Keysight Open RAN Architect (KORA), an end-to-end portfolio of solutions for Open Radio Access Network (O-RAN) (**Fig. 7**). It enables ecosystem participants to emulate any part of a 5G O-RAN network. Network vendors and mobile operators can verify the interoperability, performance, and security of multi-vendor 5G networks based on O-RAN standard interfaces. The transition to multi-vendor RAN networks introduces interoperability and performance complexity.

By performing comprehensive testing across a heterogeneous network, network vendors can extend the capabilities of their designs and operators can deliver solutions that support innovative service offerings. KORA provides integrated, software-driven solutions that accelerate the development, integration, and deployment of O-RAN compliant equipment. Each suite is tailored to the needs of participants in the supply chain—chipset makers, NEMs, mobile network operators (MNOs), and Open Test and Integration Centers (OTICs). KORA includes Open RAN Studio, UeSIM, RuSIM, CoreSIM, DuSIM, CuSIM, RIC Test, ATI Pentest, CyPerf, Breaking Point, Vision Edge, IxNetwork, CloudPeak, Nemo Outdoor, and channel emulation solutions.

One of the key additions to Keysight's 5G portfolio in 2021 comes from the acquisition of Sanjole. Sanjole wireless analyzers are industry-leading OTA communication sniffers serving as the source of truth to find anomalies, uncover issues, and quickly identify the root cause of issues in complex wireless systems. These software solutions enable modem, chipset, and RAN makers to perform interoperability testing with communications standards that are validated, debug issues fast, and accelerate their time to deployment. Deep-analysis tools provide visibility into events spanning multiple layers, making it possible to locate protocol exchange errors not found in end equipment logs and understand how the physical layer affects upper-layer performance.

The range of tools available include the S8708A Advanced Performance Test Toolset and S8709A Virtual Drive Test Toolset, which add real-world radio channel conditions for 5G device performance testing that also include the S8703A Functional KPI Toolset and the S8710A Device Benchmarking Toolset. The solutions consist of software, the UXM 5G network emulator, a PROPSIM channel emulator, and FR2 equipment (chamber, common interface unit, and remote radio heads).

Their P7000 software platform for base-station conformance testing provides preconfigured test cases that help NEMs validate their base-station performance against the latest 3GPP standards. Compliance declarations are one of the most time-consuming aspects of getting a product to market because of their complexity and constant evolution. With the P7000, R&D and integration and verification (I&V) engineers at NEMs and operators working on small-cell, macrocell, and O-RAN testing of disaggregated base-station components can interpret the standards and set up complex test cases faster.

The S8825A Satellite and Aerospace Channel Emulation Toolset is a channel emulation solution for 5G nonterrestrial network (NTN) satellite link testing. Included in the upcoming 3GPP Release 17 (Rel-17), 5G NTN is spurring development activity at cellular and satellite broadband companies to develop the necessary technology in time for the first solution to launch in 2023. Cellular companies need to integrate satellite interlinking and satellite access while satellite companies need to ensure the connection to cellular networks. Keysight's 5G channel emulator, PROPSIM, has been updated to support satellite use cases and help these entities overcome these challenges.

6G researchers require a flexible and scalable testbed to gain insight into their designs' performance while 6G evolves. Determining the level of error-vector-magnitude (EVM) system performance possible in sub-THz frequency bands and extreme modulation bandwidths is a key area of research. Keysight's testbed measures waveform quality through EVM measurements for the D (110–170 GHz) and G bands (140–220 GHz), with modulation bandwidths of up to 10 GHz occupied bandwidth. But channel characteristics are another unknown. Keysight's sub-THz testbed can perform 6G channel-sounding research with wide bandwidths at D-band. The testbed uses channel sounding signal generation and analysis software with the same hardware setup used for waveform quality EVM measurements.

Networks are becoming increasingly complex with 5G, densification, and more demanding applications. MNOs want to reduce CAPEX while controlling their OPEX and accelerate the delivery of innovative services to subscribers. Disaggregation of the gNB is also necessary to extend virtualization into the RAN. This transition causes significant disruption in the test and validation space. 5G NR continues to evolve. The second release of the standard, 3GPP Rel-16, is unlike any other second release for a cellular specification by expanding 5G's reach into new verticals, spurring a new wave of challenges in test and validation.

Powerful Packages

Brian Walker, Engineering Manager, RF Design at Copper Mountain Technologies, explained to us how their latest 5G Test & Evaluation solutions include vector network analyzers (VNAs) in the millimeter ranges needed to measure 5G components (**Fig. 8**). Their latest compact model, the S5243 operates from 10 MHz to 44 GHz. Its small form factor makes it an ideal addition to the 5G test bench or for embedding directly into a test station. Higher frequencies require expensive and delicate calibration hardware. Copper Mountain Technologies is working on methods to automate this process and provide accurate and durable solutions.

8. 5G test and evaluation solutions include vector network analyzers (VNAs) in the millimeter ranges needed to measure 5G components.

They also have solutions for measurement of widely separated antennas. Millimeter waves are highly attenuated in long lengths of coaxial cable. The mmWave CobaltFx Frequency Extender System is fed with a much lower microwave signal and produces the millimeter waves directly at the Device Under Test, thus greatly reducing signal loss and improving the dynamic range of measurement. Power amplifier test is another common requirement, and a vector network analyzer is a key piece of test gear for that. It can pulse-modulate our test signal such that a 10 W or higher-power amplifier may be evaluated with only a few hundred milliwatts of average power dissipation.

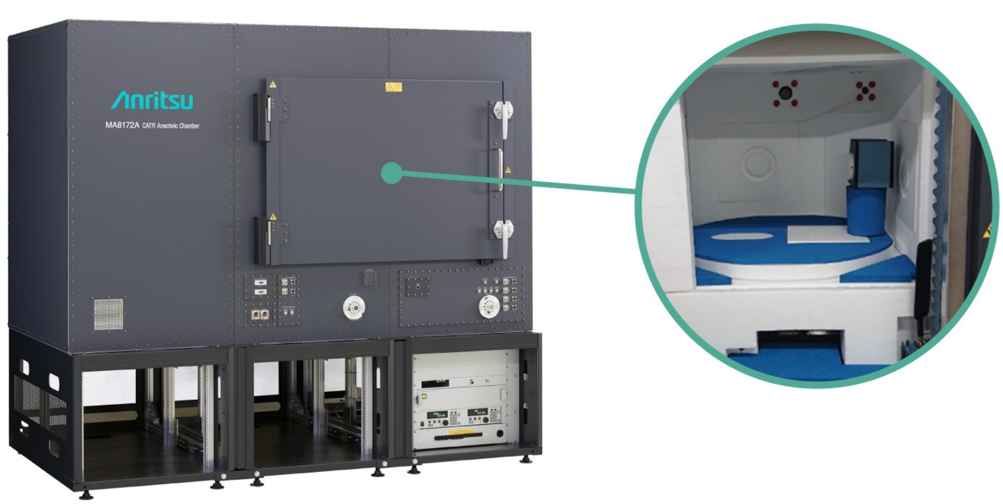
Serving the areas of upconverters, downconverters, components, power amplifiers, and antennas, among other applications, the frequency offset capability of the company's VNAs allow the user to evaluate the conversion gain or loss of a upconverter or downconverter. Triggered, pulse-modulated measurement allows for the measurement of high-power amplifiers at low average power. One-port VNAs can be installed directly on the antenna cable for fast and easy return-loss measurements with default factory calibration without the need for an additional test cable.

Compliance Testing 5G

Among their recently introduced test solutions, Anritsu's RF Regulatory Test System ME7803NR is a cost-efficient, easy-to-use single solution to conduct ARIB/ETSI/FCC-compliant Frequency Range 1 RF tests on 5G NR UE. Integrating the MT8000A with other hardware and dedicated software, it supports certified North American, European, and Asian bands, as well as emerging regional bands, including 5G NR bands and 5G non-standalone (NSA) mode LTE bands used as LTE anchors.

Their TRX Test Module MU887002A for the Universal Wireless Test Set MT8000A/MT8872A improves the efficiency of production-line inspection of 5G devices. With 24 RF connectors, the MU887002A supports 5G sub-6-GHz NR RF tests, as well as various simultaneous wireless communications tests, including WLAN, Bluetooth, and Global Navigation Satellite System (GNSS).

The CATR Anechoic Chamber MA8172A supports testing of 5G mobile devices utilizing Frequency Range 2 (FR2) mmWave bands in accordance with industry standards (**Fig. 9**). A new Temperature Testing Option MA8172A-010 facilitates previously difficult temperature tests for 5G mmWave UE, helping ensure compliance. The CATR Anechoic Chamber integrates with the Radio Communication Test Station MT8000A and New Radio RF Conformance Test System ME7873NR to facilitate confirmation of 5G mmWave UE RF characteristics in a controlled temperature environment.



9. The CATR Anechoic Chamber MA8172A supports testing of 5G mobile devices utilizing Frequency Range 2 (FR2) mmWave bands.

The Field Master Pro MS2090A real-time spectrum analyzer is designed for network operator field technicians and national regulators who need to validate the RF performance of 5G base stations as they are rolled out. It has frequency coverage up to 54 GHz to cover all 5G bands currently in use and 110-MHz instantaneous capture bandwidth to support full 5G carriers. 5G and LTE demodulation packages for installation and maintenance are available, and the MS2090A has real-time spectrum-analysis capability to capture narrow, intermittent, or signal-on-signal interference.

Virtualization and O-RAN create their own set of obstacles. Even though it leverages an open interface, engineers must test to ensure the interface is programmed correctly by the manufacturer. Testing also must be done to verify if an interface is compatible with hardware and software from different vendors. A test solution, such as the MT8000A, must have the protocol stack specifications properly implemented according to the specifications, as well as hardware that is robust and provides repeatable results. This is critical when making latency measurements, as a millisecond delta can be the difference in passing and failing.

Fewer countries are requiring full-fledged RF compliance testing during installation of 5G towers. The major need has been with interference hunting after the fact. As network performance issues are reported, test equipment is used to track and hunt down rogue sources of interference, including transmitters. New standards from industry organizations such as 3GPP are only a few pieces of the 5G design puzzle.

Ever-changing carrier acceptance and compliance testing are other factors that test solutions must address. The Field Master Pro is targeted at RF testing of physical-layer signal characteristics. This is typically useful in installation and maintenance of towers. Anritsu also offers power-level testing for coverage mapping and EMF measurements for safety testing.

10. 5G test and evaluation must address the latest RF performance requirements.

Keeping Up

Michael Derby and Steve Hayes from the Connected Technology group of Element Materials Technology explained some of the key challenges their customers are facing is that the R&D cycle time is ever-reducing. They also face challenges involving performing tests and certifying products to regulatory requirements, where new 5G/phone features mean that the regulations are not already in place. To overcome regulation issues, test lab capacity is a key consideration.

Another issue involves the new features that a given network operator wishes to deploy in their network. The phone, tablet, wearable, or other 5G-enabled equipment needs to be able to support these features, which requires both test labs and the test equipment vendors to constantly update the test plans, hardware, and software in test equipment to validate that the phone or other connected equipment conforms with the new requirements.

When it comes to 5G test & evaluation solutions from the company, they said their test labs are experienced and ready to assess 5G devices for radio transmitter and receiver communications, OTA performance, immunity to EMC phenomena, safety from hazards, and RF exposure to 5G signals (**Fig. 10**). One major testing trend Element is seeing is an increasing demand for higher capacity at testing labs.

The complexity of new network and phone features mean that the capital investment for labs is increasing. Manufacturers, driven by network operators, demand many new features, which increases the complexity of the testing, and yet the allocated time for testing and certification is reduced. Another trend is that it's not just phone manufacturers with an interest in 5G communication. Many people requesting testing for radio products will not be radio experts; they will be experts in their own product, into which they have put a radio.

Element has expertise in FCC, ISED, ETSI, and MIC testing and certification, CTIA OTA testing, RF Exposure assessment, Specific Absorption Rate (SAR)/ Power Density (PD), Electromagnetic Compatibility (EMC) Testing, Hearing Aid Compatibility (HAC), Radio Testing, Cybersecurity, safety testing, conformance testing, TCB/FCB and Notified Body, PTCRB/GCF, and CTIA.

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CHAPTER 4:

Special Report: RF/Microwave Test

RICK NELSON, Contributing Editor

Increasing complexity and the need for higher frequencies and bandwidths, multiple channels, low-power operation, and space constraints are placing considerable demands on RF/microwave test equipment. Solutions extend from simulation software to bench, modular, and portable instruments to complete systems, for applications from R&D to compliance test and field service.

Increasing complexity and the need for higher frequencies and bandwidths, multiple channels, low-power operation, and space constraints are placing considerable demands on RF/microwave test equipment.

"The RF/Microwave test field is witnessing a profound change related to the diffusion of technologies using RF signals (and, in the most advanced applications millimeter-wave signals) to communicate, transfer, and exchange information," according to an email message from Keysight Technologies. In the last few months, the company has introduced several hardware and software solutions.

"On the software side, Keysight's PathWave integrated software suite plays a critical role in 5G and mmWave design, verification, and test methodologies," the company said. "PathWave software streamlines the entire workflow from system-level modeling to RF/microwave circuit co-simulation and analysis. Companies like Nokia Bell Labs rely on PathWave and the entire Keysight ecosystem to gain the valuable engineering insights they need to push wireless technology to the next level. Keysight is also collaborating with Nokia on a new software approach that leverages artificial intelligence and advanced data analytics in the company's 5G base station manufacturing processes, significantly improving test efficiency."

On the hardware side, Keysight in 2019 introduced what it calls the first single-box multichannel solution for wideband mmWave measurements. "Based on the UXR-Series of oscilloscopes, it delivers fast, affordable, coherent analysis for wideband measurements up to 110 GHz. This solution accelerates the development of next-generation mmWave communications, satellite communications, and radar applications," Keysight said.

Characterization to Production

Rohde & Schwarz is addressing various aspects of RF/microwave test, including characterization, network rollout, automotive radar, and cross-channel measurements, according to Markus Lörner, market segment manager industry components, research and universities.

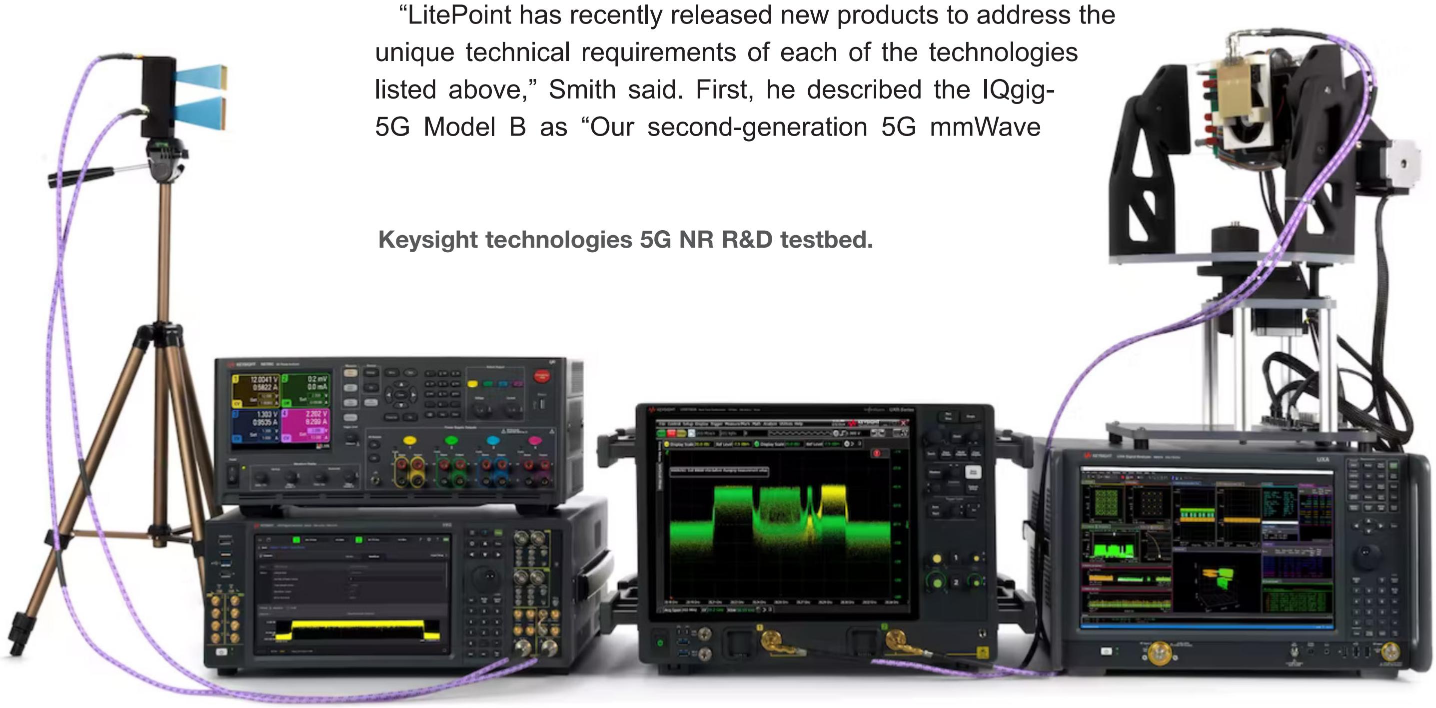
For network rollout, Lörner said, 5G operators can employ the R&S TSME30DC drive-test scanner. “Networks anchored in LTE, or making use of dynamic shared spectrum (DSS) to transmit 5G-related data using part of the LTE spectrum, or with separate networks utilizing FR1 and FR2 frequencies, can scan both frequency ranges simultaneously to save time and effort, by using the R&S TSME30DC with a suitable drive-test scanner,” he said, adding that frequencies from 450 MHz to 6 GHz and 24 to 30 GHz can be scanned simultaneously.

Lörner pointed out that automotive-radar applications are migrating from the 24-GHz band to 79-GHz. “The 4-GHz instantaneous bandwidth greatly improves the range resolution, accuracy, and reliability of object detection, and the higher frequency reduces the device size. The R&S ATS1500C over-the-air antenna test chamber has been designed to meet requirements for 79-GHz automotive radar test, for R&D, validation, and calibration, in combination with the R&S AREG.”

The R&S ATS1500C features a CATR reflector, providing a 30-cm diameter quiet zone—large enough to test the largest automotive radar sensor aperture used for the frequency band, Lörner said, while the R&S AREG100A automotive radar echo generator can include interference while generating up to four echoes simultaneously, all with the in-demand 4-GHz maximum instantaneous bandwidth.

According to Adam Smith, director of product marketing at LitePoint, the company’s product focus for 2020 is in three main areas: 5G, both sub-6-GHz FR1 and mmWave FR2; Wi-Fi 6E, utilizing the 6-GHz unlicensed band; and Ultra-Wideband (UWB), based on an emerging application space in accurate positioning and ranging.

“LitePoint has recently released new products to address the unique technical requirements of each of the technologies listed above,” Smith said. First, he described the IQgig-5G Model B as “Our second-generation 5G mmWave



Keysight technologies 5G NR R&D testbed.

Rohde & Schwarz ATS1500C over-the-air antenna test chamber.

product focused on scaling 5G mmWave FR2 end-products to high-volume manufacturing. Currently, the IQgig-5G is the only fully-integrated mmWave test system in the market, deployed on manufacturing lines testing up to four devices in parallel. Further, IQgig-5G offers best-in-class error vector magnitude (EVM) performance across all existing and forthcoming 3GPP bands, in a contiguous 23- to 45-GHz range."

Smith said the IQxel-MW 7G is specifically targeted at testing Wi-Fi 6E products. "The IQxel-MW 7G is a fully-integrated wireless connectivity test solution that addresses the high-performance needs of products launching later this year, operating in the new 6-GHz unlicensed band (6 to 7.125 GHz)," he said. "IQxel-MW 7G is a reference solution at silicon solution providers, backward-compatible with LitePoint's widely-deployed installed base of IQxel family testers, enabling companies integrating the latest Wi-Fi technology to get to market (and volume) quickly."

Smith also commented on the IQgig-UWB. "UWB technology introduces some very unique requirements that do not conform to traditional wireless connectivity standards like Wi-Fi or Bluetooth," he said. "Specifically, UWB operates in a frequency range up to 10.6 GHz at instantaneous signal bandwidths of approximately 500 MHz to more than 1 GHz. Additionally, instead of metrics like EVM that we have been accustomed to testing in OFDM-based technologies, UWB's performance metric is focused on accurate measurement of timing. IQgig-UWB uniquely includes a precise trigger mechanism to enable accurate time-of-flight (ToF) and jitter measurements for UWB products."

VNAs and Device Models

Wayne Wong, product marketing manager at Anritsu, cited a key challenge for RF/microwave test. "Accurate circuit simulation is important for rapid deployment of emerging RF/microwave communication systems because it provides accurate predictions of new designs," he said. "The result is greater chance for first-time design turns. First-time release becomes even more critical when the design cycle includes on-wafer development."

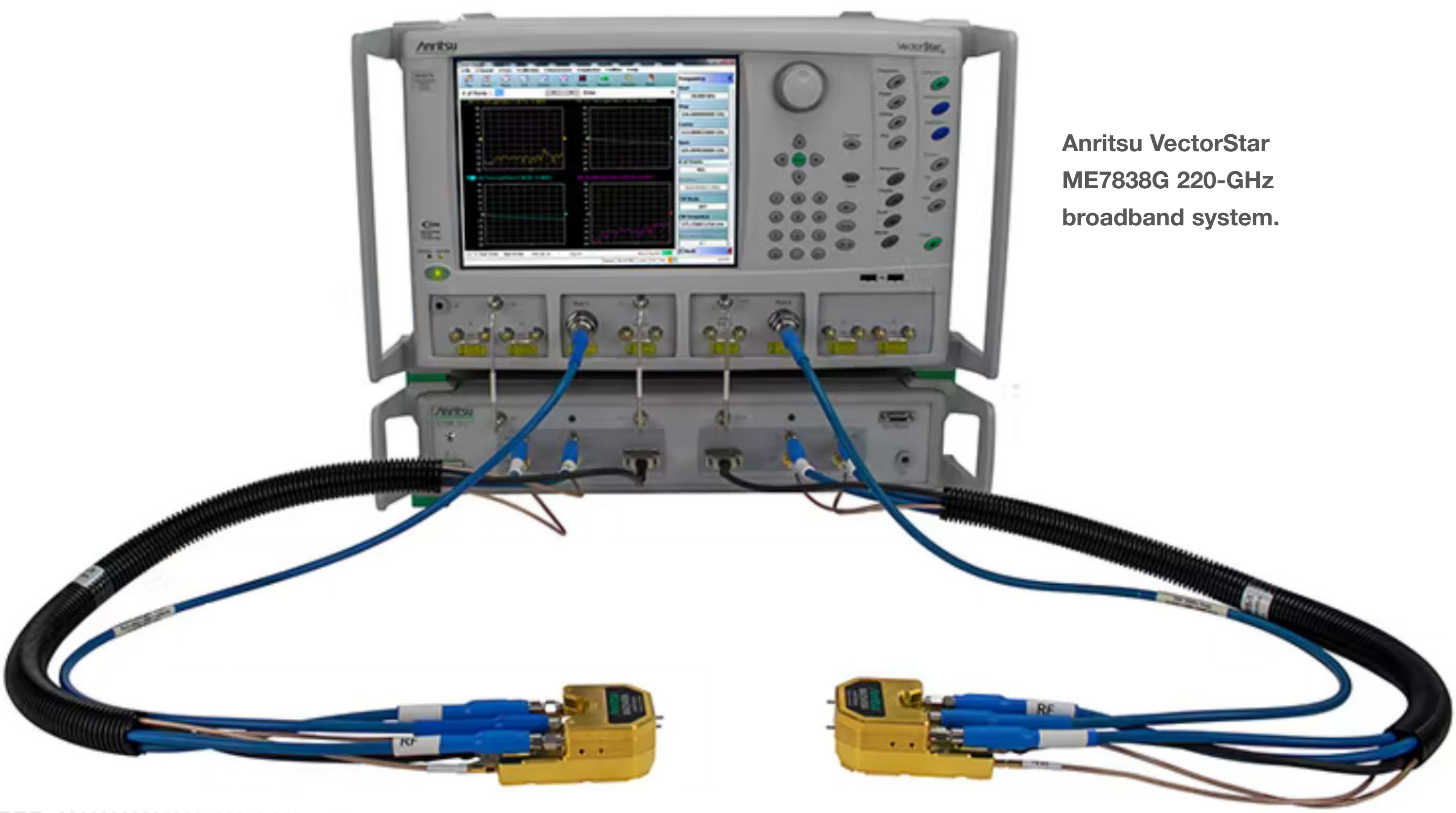
LitePoint IQgig-5G Model B second-generation 5G mmWave instrument.

Wong continued, "The key aspect for accurate circuit simulation is precise device models, which are developed using a VNA with as wide of bandwidth as possible. The universal migration of microwave components towards on-wafer media is driven by the need for compact subsystems, economies of scale, and highly-integrated systems for improved performance. The VectorStar ME7838G 220-GHz broadband system performs ultrawide single-sweep frequency characterization for optimal device characterization and accurate circuit simulation."

Wong said the VectorStar ME7838G system primarily supports on-wafer measurements where device characterization is required. "R&D device characterization for circuit simulation during the design phase of communication circuits is the first line of targeted applications, and can also be used in production environments where multiple circuits within wafers need to be verified."

He continued, "the ability to test a wide range of circuits from 5G cellular to D-band radios, means that when the ME7838G system is installed a probe station can be quickly and efficiently transformed for different application measurements. This can be done without having to dismantle the VNA and reconfigure for mmWave waveguide measurements."

Another key test challenge is to continually address higher frequency requirements in a cost- and space-efficient way, Wong said. "Removing the effects of cable and fixturing to achieve more accurate test results becomes more difficult, as frequencies climb and calibration standards become harder to implement on-wafer or in the form factor of the test fixture."



Anritsu VectorStar ME7838G 220-GHz broadband system.

Angus Robinson, Anritsu's product marketing manager, added, "For field testing, we see increased levels of spectrum interference and the need to identify nefarious signals. There is also more passive intermodulation (PIM) distortion in cellular networks. All of this means over-the-air (OTA) measurements of 5G mmWave radios are becoming more important."

In addition to the VectorStar ME7838G VNA, Anritsu offers the MS46131A 1-port VNA, the newest instrument in the ShockLine family. "It is available in three frequency ranges, including to a market-leading 1-port sweep range of 43.5 GHz," Wong said. "It is also modular, with the software on a single PC configuring one or two MS46131A VNAs on a session-by-session basis for excellent test setup flexibility."

The ShockLine MS46131A VNA targets production test of a range of RF and microwave components, Wong said, adding, "The performance supports limited design and verification requirements and the small form factor supports portability between test sites."

Wong also cited Anritsu's ONA (Optoelectronic Vector Network Analyzer), describing it as suitable for opto-electronic device characterization at frequency ranges up to 40/70 GHz for 850-nm/1,310-nm/1,550-nm wavelength devices. "The modular system is built on Anritsu's VectorStar VNA, and users can easily conduct electrical, electro-optical, or optical measurements. "The modular architecture of the ONA systems allows it to be used in all phases of a product life-cycle—from R&D to test verification and through production."

Robinson commented on portability. "The Field Master Pro MS2090A battery-powered handheld spectrum analyzer has been enhanced with IQ capture and streaming with 110-MHz bandwidth, enabling new applications for government agencies needing to monitor secure spectrum. It interfaces directly to the industry-standard Bird IQC5000B record and playback system." He added that the Field Master Pro MS2090A is used for R&D and spectrum monitoring and protection applications.

According to Brandon Malatest, COO at Per Vices, "Our Cyan platform is our latest release and pushes the limits of RF/microwave test equipment. The flexibility offers an extended operating frequency from near DC to 18 GHz, a customizable number of radio chains (up to 16), both transmit and receive functionality, with high bandwidths available (1 GHz per radio chain with possibility to extend to 3 GHz), and able to be optimized for high dynamic range or aggressive channel-masking applications as required."

Malatest said the company's products have been used in each stage of a product lifecycle. "Where the initial stages of R&D are typically serviced by our stock products, we do work with our customers to ensure we optimize the platforms to meet their specific production or field-test requirements." This optimization can include the incorporation of

Per Vices' Cyan platform.

additional IP; development of custom radio stages to accommodate noise, filtering, or channel-masking requirements; and mechanical and environmental changes, he said.

RF/Microwave Switching

Pickering Interfaces addresses switching. “We have focused on two areas in our product portfolio—first, our 40-88X solid-state switch family has been updated from a 6-GHz bandwidth to 8 GHz,” said Bob Stasonis, technical product specialist. “In addition, our microwave switching family now has bandwidth expanded to 67 GHz. With the expansion of 5G developments and rollouts, this is an important change. Our present PXI offerings feature 420 RF and microwave module choices. In addition, there are presently over 70 RF and Microwave LXI switching systems in our catalog.”

Pickering Interfaces’ 40-88X solid-state switch family.

Stasonis commented on applications. “Our RF and microwave offerings have been used primarily in MIL/aero applications, most of which we are not allowed to discuss, but we assume that a lot of our products are used for testing communications and radar systems,” he said. “In automotive, our impedance-controlled fault-insertion modules are part of HILS systems testing automotive networks. The addition of the 67-GHz switching products makes Pickering a provider for testing 5G devices. We have also recently been working in the healthcare industry to replace older, obsolete GPIB microwave switching.”

VTI Instruments, a product line in AMETEK’s Programmable Power business unit, also addresses switching. The company recently introduced its SMX-7xxx Series of 15 PXIe microwave switch modules, according to Chris Gibson, senior product manager. “These new modules extend functionality typically reserved for dedicated standalone systems into the PXIe form factor. The 26.5-GHz bandwidth operation as well as single- and dual-slot versions provide the ability to create multiple configurations, including SPDT, SP4T, SP6T, and transfer switches.”

He continued, “a pass-through adapter module extends functionality even further with programmable drive lines for controlling attenuators and other microwave devices.

Embedded web-browser control further simplifies setup and test debugging, which allows all relays to be controlled independently of application software and device drivers."

Amplifiers, Analyzers, and Generators

AR RF/Microwave Instrumentation continually releases updated amplifier models, according to Dale Hauck, applications engineer. "Of particular interest is AR's line of S-series amplifiers, spanning from 0.7 to 18 GHz," he said. "These amps, along with all of AR's amps, offer the widest bandwidth, highest output power, longest life, and best mismatch tolerance on the market."

Hauck added that AR's amplifiers serve in all stages of product life cycle, including R&D, production test, and field test. "AR amps are actively used for each of the stages, whether it's characterization testing, production chip testing, product compliance testing, or radar communications in the field, as well as many other applications," he said, adding that the company serves 5G, Wi-Fi 6, automotive radar, IoT, radar, and EMC compliance. He further noted that AR has formed strategic partnerships with companies including Keysight, Comtest, and Nexio to provide total solutions for customers.

Tabor Electronics has recently introduced two RF/microwave test products, according to Mark Elo, US manager. The first is Proteus, "...a 9-GHz bandwidth arbitrary waveform transceiver that not only generates directly to RF and microwave frequencies, but also has a receiver architecture with FPGA processing built in. This allows you to generate real-time signals based on feedback from the receiver, which are then processed onboard in the FPGA."

The second is Lucid, which, Elo said, redefines analog signal generation. "This 12-GHz modular instrument has specifications comparable to leading bench/rack instrumentation," he said, adding that it is available in four form factors: a basic brick module, a multichannel unit for R&D and production (available in benchtop or rack-mount models), and a portable version for field support.

Elo commented on applications. "Proteus focuses on wide-bandwidth applications in the communications, automotive, electronic warfare, and physics verticals, and can generate up to 4.5 GHz of instantaneous bandwidth. This is frequently used in signal-simulation applications for emulating next-generation wireless systems, such as Wi-Fi 6 and 5G, and radar signals for automotive and electronic warfare applications. We also simplify the quantum-physics experiment setup by providing the ability to generate signals direct to microwave, eliminating the need for complex measurement setups."

He added that Lucid has broader applications. "It has been used in EMI applications, chamber test (especially with the increase in frequency ranges driven by Wi-Fi 6 and even UWB systems), product RF calibration systems, military field test, multichannel applications such as those required in up-and-down conversion chains, and other applications where multiple channels of coherent carriers are required."

Several companies have recently introduced signal and spectrum analyzers. For example, B&K Precision's 2680 Series spectrum analyzers, offer frequency ranges from 9 kHz to 2.1 GHz, or to 3.2 GHz. "Each model includes advanced measurements such as channel power, adjacent channel power, occupied bandwidth, total power, and third-order-intercept, along with a 2D and 3D spectrum monitor," said Jamie Pederson, product marketing manager. "The standard preamplifier, tracking generator, and 1-Hz minimum RBW round out the list of features," he added.

Siglent SSA3000X-R real-time spectrum analyzer.

Siglent's RF development team has been busy this year, according to Jason Chonko, applications marketing manager, Siglent North America. "We announced 7.5-GHz additions to our swept-superheterodyne and VNA product lines, as well as our first real-time spectrum analyzer series, the SSA3000X-R. They all feature solid RF performance, easy-to-use UI, and toolkits that really tailor the instruments for EMI, broadcast, and RF development work."

In addition, Keysight launched the N9021B MXA X-Series Signal Analyzer to meet the evolving needs of advanced wireless communications design-validation-and-test and manufacturing engineers. According to Lörner at Rohde & Schwarz, the R&S SMBV100B vector signal generator and the R&S FSVA3000 spectrum analyzer provide heavy-lifting RF test solutions for the production line. A subsequent article will provide details on signal- and spectrum-analysis tools.

USB Vector Network Analyzers

Copper Mountain Technologies focuses on USB vector network analyzers. "We introduced lower-cost M models of our Compact Series vector network analyzers, which provide the same great metrological performance at a very competitive price, as an economical option for engineers who don't need advanced features in the software," said Brian Walker, senior RF design engineer. "We also introduced SC models for our Compact Series vector network analyzer series with 16-ms measurement speed, more dynamic range, and higher output power."

Walker said the company's VNAs are used throughout the lifecycle of many RF products. "VNAs are used in the design, manufacturing, and ongoing preventative maintenance in the field for RF and microwave products, and is a critical measurement tool for all RF applications. Our customers participate in a wide variety of applications, such as 5G, IoT, automotive, defense, and more. Our VNAs are easy to integrate into a test system, helping them to work seamlessly in many types of industries and applications."

Pico Technology also offers USB VNAs and has been emphasizing education. "The explosive growth of RF, microwave and ether-borne applications, particularly in the 1 to 6 GHz spectrum, is drawing more engineers, students, technicians, scientists, educators, and even medical professionals, into a field that they have not previously had to master," said Mark Ashcroft, RF business development manager. “Training in RF, microwave, and propagation disciplines, whether in design, test and measurement, or field support of RF systems, has needed to spread rapidly to an ever-wider audience.”

He explained, “skills in network, antenna matching, testing, and metrology are of course central to that. Fortunately, the low-cost USB vector network analyzer has brought affordable professional-grade measurements to educators and students alike. This enables unprecedented access to instrumentation and calibration standards to practice techniques and gather real-world measurements in the classroom or on every desk.”

Ashcroft continued, “Adding value and flexibility to the highly successful PicoVNA 106 6-GHz Vector Network Analyzer, Pico Technology has recently announced its Network Metrology Training Kit and two important interfaces to major CAD software products. Partnered with the PicoVNA, or indeed any other VNA, Pico’s Network Metrology Training Kit provides, in a single carry or storage case, a variety of passive and active test networks and low-cost calibration standards and test leads. A teacher and student need only these to begin the practice of calibration, measurement, and feedline elimination techniques and to explore and compare errors that can arise. The kit is provided with a comprehensive user/training guide, useful instrument settings files, and typical calibration standard and de-embed data.”

Pico Technology Network Metrology Training Kit.

Ashcroft said a trainer can optionally add professional-grade calibration standards, test leads, and verification standards. “Expanding the initiative to cooperation with others, Pico has also become a Cadence AWR Connected Partner by integrating the PicoVNA directly to the AWR Design Environment. A freely downloadable software wizard provides remote control of the PicoVNA and single-touch data transfer from live on-screen measurement directly into your Microwave Office project—perhaps into a comparative plot or as measured data for use in simulation.”

From Chassis to Thermal Platforms

Pixus Technologies, a provider of embedded computing and enclosure solutions, offers products such as a 6U OpenVPX chassis platform with a mix of VITA 66.4 optical connectors and VITA 67.3 RF connectors. “The VITA 67 standard brings RF capability to OpenVPX open-standard architecture systems,” said Justin Moll, vice president of sales and marketing. “The products can serve in both prototype test and deployed systems, addressing applications including radar and C5ISR.”

TotalTemp Technologies Model SD288 cryogenically cooled thermal platform.

“We are working with board vendors for backplane/chassis solutions that are interoperable with their OpenVPX/RF modules,” said Moll. “We’ve also worked with government labs and institutions to provide VITA 67 and OpenVPX chassis platforms for their development. Our open-frame test enclosure provides easy prototyping for SOSA/HOST and other OpenVPX applications utilizing RF. With a wide range of VITA 67/OpenVPX backplanes, Pixus can leverage existing designs for a customized solution for most applications.”

TotalTemp addresses thermal RF test, and the company has recently introduced larger sizes of thermal test platforms. For example, their Model SD288 addresses fast and efficient testing of larger or multiple RF modules, according to John Booher, chief technology officer.

The platforms serve in both R&D and production test, supporting customers’ challenges in obtaining effective heat transfer for their RF modules. He cited an easy-to-use temperature controller with advanced automation and temperature control as a key feature of the platform.

Ground-Vehicle Radar

dSPACE addresses the ground vehicle market. "For over 30 years, dSPACE has been delivering tools to the ground vehicle engineering community for developing and validating in-vehicle software," said Vivek Moudgal, their vice president, of business development, dSPACE Inc., and Andreas Himmler, senior product manager, autonomous driving systems, dSPACE GmbH. "For the community working in the ADAS and AD domains, dSPACE has developed both hardware- and software-based tools to allow the community to speed up their design and verification work and deliver robust and reliable functionality to the consumers."

They added that the company has been integrating best-in-class products into its offerings for automotive radar applications. "In early 2019, dSPACE partnered with ITS and miro·sys and acquired IP, which will continue to be refined to provide the engineering community with the tools they have come to expect from dSPACE." DARTS (dSPACE Automotive Radar Test System) is the company's offering to the automotive radar development and testing community.

"In early 2019, dSPACE released a series of compact DARTS systems (DARTS 9030-M, DARTS 9020-S and DARTS 9030-MS) with very high capability and performance," Moudgal and Himmler said. "These devices are designed to serve multiple segments of the value chain, from radar chip designers to ECU developers, as well as OEMs for function validation. More recently (at the end of 2019), dSPACE released a new offering—the DARTS 9018-D, designed for end-of-line use by Tier 1 suppliers, OEMs, and the aftermarket."

They explained, "Depending on the model, the available bandwidth is 1.2 GHz or 4 GHz, and with a simple change of the radio front-end (one connection for each RX and TX), the base unit can be switched to work supporting K-band radars to E-band radars or vice-versa. The K-band range supports 23 to 26 GHz, and the E-band range supports 75 to 82 GHz as a standard."

They continued, "Based on application needs, DARTS devices are capable of simulating targets at distances of less than 1 m, all the way to 1,000 m, with 6- or 10-cm resolution over the entire distance simulation range. With the capability to simulate Doppler frequencies of ±700 km/h, these devices are capable of being used for all known ground-vehicle applications where relative speed measurement is needed."

They added that DARTS devices can be used in R&D, production testing, and field testing as well as in aftermarket—body shops, Periodic Technical Inspection (PTI), etc.—applications. "Their compact size and ability to be powered by DC power sources makes them extremely portable and easy to package," they said. "Another specialized use case for DARTS is for closed-loop function validation using a hardware-in-the-loop setup." They concluded.

Device Perspective

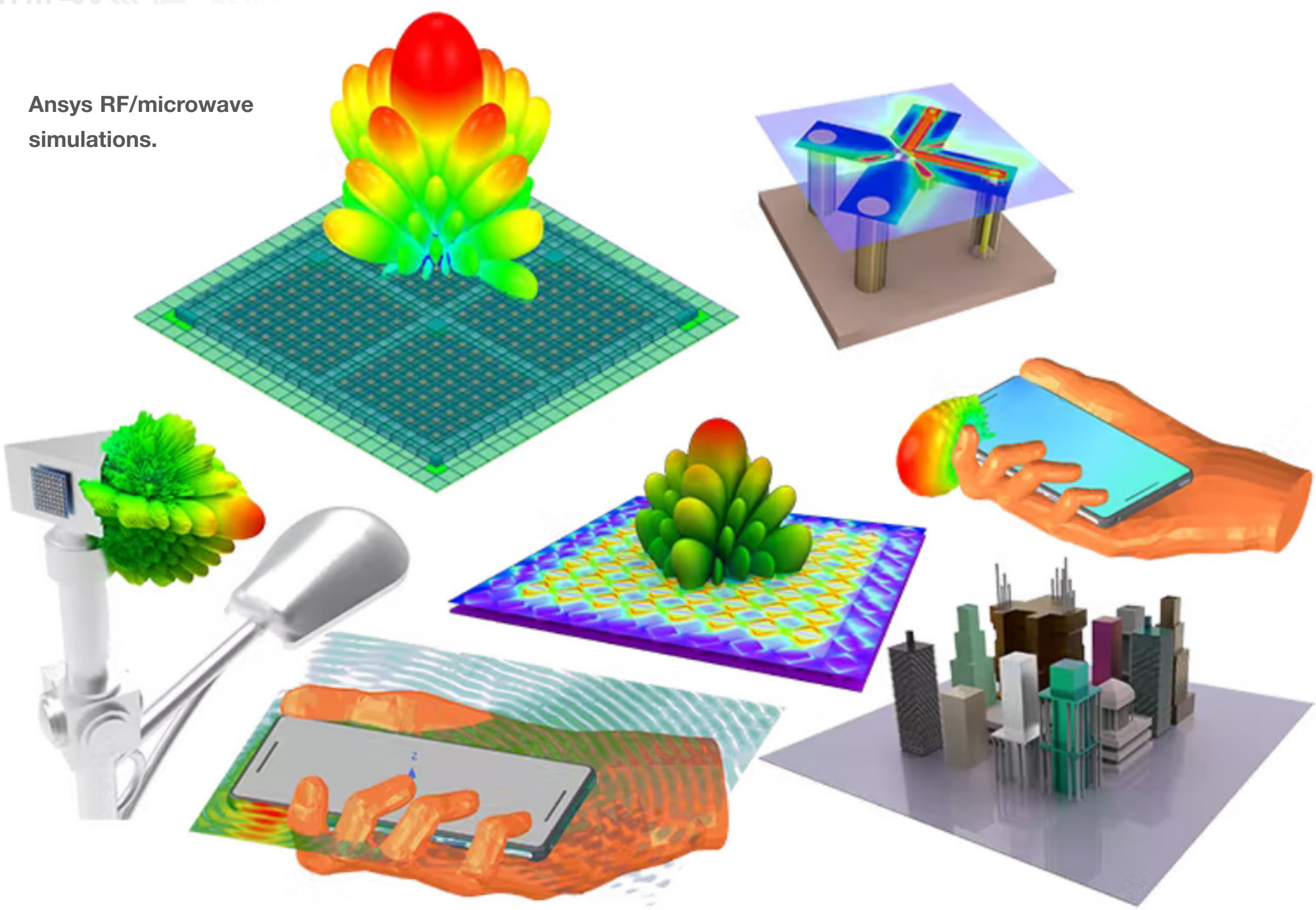
Randy Oltman, RF and high-speed instrumentation segment director at Analog Devices, cited two main challenges to the RF test and measurement industry, both related to 5G. "First, millimeter-wave 5G continues to push towards 50 GHz with successful auctions in the 39-GHz and 47-GHz bands," he said. "3GPP defines frequencies above 50 GHz, but band allocations and licensing worldwide for 50 to 55 GHz is less clear. However, test and measurement makers designing new equipment want to be considerate of future needs and look to push frequency coverage as high as possible."

Oltman continued, "Second, OTA methods are not finalized for testing mmWave 5G devices with embedded antennas. Finding an appropriate method that allows rapid testing of mmWave devices in production will be essential to the a mass rollout of mmWave devices."

Oltman said Analog Devices' advanced RF modeling and packaging expertise enables development of novel and higher performance parts. "RF-considerate multi-die packaging dramatically reduces parasitics leading to superior broadband performance, highly important for instrumentation," he said. "Further, these multi-die devices integrate common functions which are usually discrete, greatly reducing PCB area and simplifying the design through fewer parts."

Oltman cited several recently introduced devices, including the ADPA7006. "This new part joins the recently launched ADPA7002 and ADPA7005," he said. "These 18- to 44-GHz mmWave amplifiers, with power levels up to 1 W, are available both in SMT and die form. These devices offer a unique novel combination of power and bandwidth, with up to +42-dBm OIP3 and 31-dBm P1dB."

Other recently introduced parts include the ADF4372 16-GHz single-chip synthesizer, ADMV8420/ADMV8416/ADMV8432 tunable band pass filters, ADRF5043 SOI switch, LT3072 dual LDO, and LTM8078 Silent Switcher. With regard to the LTM8078, he said,



Ansys RF/microwave simulations.

"These are one of the lowest-noise switching regulators in the industry. Previously, a designer never would consider powering a VCO or amplifier with a switching regulator. The LTM8078 is the latest in the line of silent switchers that are game changers for applications where greatly improved power efficiency and/or large regulated voltage drops are required."

Simulation and Modeling

Ansys offers modeling and simulation solutions to design RF/microwave and wireless communications devices for a broad range of industries, according to Manohar Raju, their senior product specialist at Ansys. "These solutions are used to compress the number of tests and design cycles," he added.

The company recently introduced key solutions in RF/microwave and wireless communications. "We are the first to offer a novel solution to model antenna arrays used in diverse applications," Raju said. "Significant increase in speed and accuracy as well as decreased memory requirements are the key benefits of this solution in Ansys HFSS."

He continued, "A new product in our portfolio, the Ansys RaptorH employs HFSS to extract S-parameters and parasitics for RFICs with unprecedented speedquickly and accuracytely." He explained that S-parameter data is fed to circuit simulators to predict the signal integrity of these components. "Similarly, SI issues for large and dense PCBs and packages are analyzed by hybrid solutions of HFSS and SIwave to take advantage of their best attributes and yield S-parameter data of superior accuracy,." he added.

Further, Raju said, "Designers of RF components and systems must ensure that their devices do not cause unintended emissions, radiations, or overstep regulatory standards. In-built EMI/EMC 3D components of Ansys HFSS and uniform simulation workflows help achieve compliance faster and economically for electromagnetic impulse (EMP), conducted emissions CISPR25 and CISPR2, and other standards."

Remcom offers tools including XFdtd electromagnetic simulation software, WaveFarer automotive radar simulation software, and Wireless InSite 3D wireless prediction software, according to Stefanie Lucas, director of marketing. The products support R&D and simulated testing, across a variety of verticals, including 5G, Wi-Fi, automotive radar, IoT, indoor consumer electronics (smart speakers, laptops), mobile device design, and wireless network planning, she said.

XFdtd includes full-wave, static, bio-thermal, optimization, and circuit solvers, and can simulate electrostatic discharge (ESD) testing, enabling engineers to identify potential locations of dielectric breakdown and components at risk of damage. The automotive version of WaveFarer supports drive scenario modeling at frequencies beyond 79 GHz. A, and Wireless InSite supports the analysis and design of wireless systems for communication, networking, sensors, and other applications in urban, indoor, or rural environments.

MathWorks offers a range of tools for wireless and radar system design. "These tools are built on our platform products, MATLAB and Simulink," said Rick Gentile, product manager, RF and signal-processing systems. "The tools cover RF, antenna, and phased-array design and analysis. They also cover the signal-processing and data-processing system components."

Gentile said modeling building blocks, algorithms, and system simulators are available for standards-based wireless systems including 5G NR systems. "We also support broad workflows for multifunction radar design," he added. "System developers use our tools to ensure architectures and designs will work at the earliest point in the project life cycle. The unique aspect is that MATLAB and Simulink as platforms span such a broad range of disciplines and a broad range of workflows (requirements analysis through deployment on hardware). This enables a development environment that eases system-level integration across diverse teams at the very earliest stages of a project." Building on that foundation, MathWorks' most recent solutions are available in the company's R2020a release, which became available for download in March.

Gentile cited a challenge that faces test vendors and customers across the RF/microwave arena. "We see the rise in system complexity as the main challenge," he said. "This complexity is driven by many external factors such as the need for higher bandwidth, lower power systems. The RF spectrum is crowded and the chance for interference is greater than ever. Systems that previously were focused on a few key functions now need to perform a more diverse set of tasks. Today's systems also get deployed in ways that were never possible in the past."

Gentile noted further that system development teams may be smaller today than in the past and are likely to be spread out across the world. "All of the challenges described above add risk," he said. "Our goal is to make it easy for system developers and integrators to model and simulate their systems before they build them. Finding issues early in a project greatly reduces the cost in fixing these issues. We want to help reduce risk. We also want to help system developers leverage all of their modeling work by making it easy to deploy code directly from models. System reliability is critical, so we work to make it easy to verify designs directly from the modeling results as well."

Markets and Challenges

EE asked contributors to this report to elaborate key features of their offerings and to comment on the markets they serve and challenges facing the industry. Read on to see what they had to say.

What are Other Key Features of Your Solutions You Would Like to Emphasize?

Moudgal and Himmler, dSPACE: "Characteristics that describe DARTS devices include ultra-compact, lightweight, low-power-consuming, RUT-modulation-scheme-agnostic, and quick-changeover between K-band and E-band applications. Industry-leading performance makes DARTS a very versatile instrument for a wide range of applications, from radar chip design and calibration to end-of-line testing at Tier 1s and OEMs, to function validation in the lab, and to aftermarket applications."

Stasonis, Pickering Interfaces: "Our customers really appreciate the LED switch-path status indicators on our PXI and LXI products. It allows them to visually see if their code is closing the correct switch. Our customers who are configuring a large number of microwave switches and multiplexers into a complex configuration have found that our Switch Path Manager (SPM) signal-routing software makes programming their switching system extremely easy. Once the test engineer has defined the cabling interconnections, all that is necessary is to program a particular test point that is to be connected to a particular instrument, and SPM automatically makes the necessary connections."

Gibson, VTI Instruments: "VTI custom RF interface units (RFIUs) are switch systems designed to meet customer specifications that require integrating the RF source and measurement instrumentation with the device(s) under test. RFIUs allow signals to be routed, attenuated, combined, split, filtered, and amplified. AMETEK provides RFIU customers with a combination of the following services: RF engineering for component selection and system design; control engineering for signal routing management; mechanical engineering for enclosure design, component layout, and temperature control; software engineering for development of both an LXI-based virtual front panel and IVI drivers, and complete documentation and test data for accurate reproduction of the system as needed."

Wong, Anritsu: "The ShockLine and VectorStar families of VNAs take advantage of Anritsu's patented Non-Linear Transmission Line (NLTL) technology to achieve higher frequency capabilities in more compact and cost-efficient packages. Many ShockLine models and VectorStar modules are compact enough to direct connect to the DUT or on-wafer probe, thus minimizing cable and fixture losses and maximizing measurement stability.

"ShockLine VNAs also offer Anritsu technology developed for the high-end VectorStar VNA family to de-embed fixtures and probes using partial calibration standards with the Universal Fixture Remove (UFX) option. The NLTL harmonic samplers provide the highest third-order intercept (TOI) performance that enables high-performance measurements of active devices in the VectorStar VNA line.

"The Anritsu ONA solution takes advantage of the NIST traceability (with an in-house calibration lab that characterizes all the customers' OE modules) for the OE modules for traceable measurements. The flexibility and upgradability in terms of frequency for the VNA, the OE module, and the EO convertor is a considerable advantage to our customers."

Raju, Ansys: "Ansys is the first to offer a novel solution to accurately model antenna arrays for applications such as 5G mmWave base stations and microcells, automobile radars, satellite communications, aerospace, naval, etc. Leveraging HFSS 3D Component, the technique is built upon the HFSS Domain Decomposition method (DDM) for large-scale analysis, and is a breakthrough technology for solving large and complex arrays. It eases the burden of matrix factorization and decreases memory requirements resulting in significantly faster array simulations."

Malatest, Per Vices: "Our products aim to meet the needs of many customers out of the box; however, some customers do have strict requirements that are not met by the stock products. For these customers, we work very closely to leverage the flexibility of our platforms along with our existing IP to help develop a solution to meet their needs. For our existing customers, this has resulted in a more cost-effective solution, faster time to market, and higher performance platform than any alternative."

Smith, LitePoint: "Usually, when we look at the increasing technical requirements of new wireless technologies, it is usually tied to something related to a more advanced modulation technique and a race to higher data rates. However, with the emergence of UWB technology, we find a completely different set of requirements. Instead of jamming gigabits-per-second through the air, UWB technology (specifically the 802.15.4z IEEE standard amendment) uses very short pulses to transmit information that enables a companion device to accurately determine its relative distance and direction.

"The 'money spec' in UWB is time, or more specifically, time-of-flight (ToF). ToF is not only useful for accurately determining location, it is more importantly able to provide an additional layer of security to an application by enabling improved location authentication.

Other wireless technologies (such as Bluetooth) can be intercepted and rebroadcasted to 'fake' the appearance of location (aka, a relay hack). This allows a thief to steal your wireless car key, or even credit-card information, if they can get physical proximity to your transmitted signal. The time-based nature of UWB does not allow for this kind of vulnerability. It is relatively simple to defeat signal-strength (RSSI) authentication methods. It is very difficult to defeat methods that rely on the authentication of a time stamp.

"Accurately calibrating and measuring the performance of UWB devices requires the test equipment being able to very precisely measure and respond to a device in time. For example, in 1 ns a radio signal travels approximately 30 cm. In order to know a location with roughly 10-cm accuracy, the timing precision of the measurement equipment needs to be less than 100 ps. LitePoint's IQgig-UWB test system has a timing architecture that enables this level of timing and response repeatability."

Keysight: "Modern devices are highly integrated. As a result, wireless and high-speed-digital engineers often test devices with more than four ports. In wireless RF, front-end modules (FEM) for multiband operation and MIMO antennas require multiport characterization for all their components. Testing high-speed digital technologies like HDMI and USB 3.1 is even more tedious. Not only do digital cables have multiple internal cables and connectors, but each must undergo testing twice— once in the time domain, and once in the frequency domain. The need for multiport test accelerated the development of switch-based solutions for traditional vector network analyzers (VNAs). When switch-based solutions were not adequate to keep up with multiport test, the VNA itself was re-imagined and optimized for multiport test."

What Vertical Applications Areas Do Your Products Serve?

Wong, Anritsu: "The VectorStar ME7838G and ONA solutions address the needs of designers developing solutions for 5G, automotive radar, microwave backhaul communication links, opto-electronic markets, and other applications with high-speed data throughput. The MS46131A ShockLine VNA targets 28-GHz and 39-GHz 5G antenna testing, along with other microwave 1-port applications."

Robinson, Anritsu: "Field applications, including interference hunting, spectrum protection, and 5G NR installation and maintenance, are where the Field Master Pro MS2090A is used."

Malatest, Per Vices: "Our products are being primarily used for applications in the following markets: radar systems, medical-imaging systems, radio links and mobile base stations, and GPS navigational systems. The specific functionality depends on the markets and the customers; however, the use of our products as test and measurement equipment has been present in each of the above."

Gibson, VTI Instruments: "VTI RF/microwave switch systems serve all the wireless telecommunication and wireless industrial applications. VTI switch systems are not limited to testing a specific wireless protocol."

Raju, Ansys: "For automotive, our tools accurately simulate RFICs and the standalone and installed performance of radar. Engineers virtually recreate dynamic ADAS scenarios involving V2V and V2X communications in Ansys HFSS SBR+. Finally, with Accelerated Doppler Processing capabilities following simulations in Ansys HFSS SBR+, vehicle radar sensors are accurately evaluated. ADP uses high-fidelity simulations to model synthetic radar signatures from automotive radar sensors with unmatched speed and efficiency.

It's difficult and costly to test and measure active safety scenario corner cases, such as an autonomous-car driving scene involving a pedestrian crossing the road. Using Ansys simulation tools is economical and faster to study regular, corner, and edge cases. Moreover, simulation also be used to consider cases involving potential loss of life and property damage."

Gentile, MathWorks: "Our customers work across a broad spectrum of applications across all industries. Wireless technology is ubiquitous and enables connectivity across the board. This standards-based wireless connectivity including 5G, Bluetooth, and WLAN. We also enable radar system development for commercial (for example, consumer, automotive radar) and aerospace/defense applications."

Moudgal and Himmler, dSPACE: "The current line-up of DARTS is specifically designed to support the K-band (24 GHz) and E-band (77 GHz) automotive radar programs. In the future, if other frequency bands are needed, the DARTS devices are easily upgradable by switching out the radio front-ends to match the frequency band of interest."

What Do You See as Key RF/Microwave Test Challenges?

Chonko, Siglent: "I think that a key area of development is knowledge, and the gap between new engineers and folks that have been in the industry for a long time. Over the past 10 years, the interest in RF has ballooned, but I'm not sure that the number of engineers with practical experience has matched the need. Many experienced engineers are retiring, and this may leave a significant gap in what we can do today vs. where we go tomorrow."

Raju, Ansys: "Designing RF/microwave devices and communications systems to be successful requires ensuring precise signal integrity, accuracy, and fidelity of RF devices, systems, packages, and antennas. With miniaturization, more ICs, SoCs, packages, and wireless systems are being integrated into a single high-speed digital device. This could create interference due to unwanted out-of-band emissions by co-located RF systems (RF cosite) as well as broadband noise and harmonics by digital signals (RF desense).

Stasonis, Pickering Interfaces: "From a switching standpoint, as frequency increases, the interaction with the user interface of switching components we incorporate on our switch modules becomes increasingly critical. For example, extreme care is necessary when cabling is installed on Microwave connectors, as the signal interfaces are quite small & manufactured to precise tolerances. In any case, higher power and bandwidth are always in demand."

Malatest, Per Vices: "The biggest challenge faced by vendors of RF/microwave systems is designing a system with the flexibility to support many customers while still remaining cost-effective. Our products leverage our existing IP and economies of scale to help ensure that the cost remains very competitive and the underlying designs ensure flexibility."

Ashcroft, Pico Technology: "IoT, 5G, WiFi, V2X—has there ever been a bigger market explosion than the use of the antenna, and within very challenging locations? Optenni Lab CAD software simplifies the immense complexity of antenna and array optimization. The package performs real-time interpretation of network measurements to present optimized lumped or line-matching circuits for the measured antenna(s). Already an AWR Connected partner, Optenni has also integrated the PicoVNA into this market-leading CAD software suite."

Lörner, Rohde & Schwarz: "It is not an exaggeration to say that antenna technology for consumer wireless devices is exploding. Firstly, in terms of the number of antennas built into even handheld devices, MIMO really does mean "multiple" these days. Secondly… the techniques used with active beam-forming add performance well beyond the passive multipath propagation initially introduced with multiple antennas.

"While just a few years ago almost all wireless devices included a special interface to connect a cable for test purposes, this is no longer the case. As well as 5G user equipment, there are whole markets for very small inexpensive wireless devices (personal network technologies such as Bluetooth, LoRa, or Zigbee) and of course the enormous variety of Internet of Things devices, that do not include a test interface from a mixture of cost and space reasons. Then there are more complex devices with multiple miniature antennas where it would be physically impossible to connect a cable."

"Last but not least, with increasing frequency, the mechanical difficulties of making a reliable physical connection also increase out of proportion. Over-the-air test, with all RF communication with the device under test via the antennas it uses for normal operation has introduced whole new complexities to test and measurement, requiring new fields of expertise on our part."

Elo, Tabor: "Bandwidths and frequency ranges are getting higher. Twenty years ago, most systems were less than 3 GHz, and a 1-MHz bandwidth was state-of-the-art. Then ten years later, most systems were sub-6-GHz with bandwidths ranging from 20 MHz to 160 MHz. Now, we have extended beyond 6 GHz for technologies such as Wi-Fi 6, and standards such as 5G and LTE fiercely contend for spectrum sub-6-GHz and even share unlicensed or military/government spectrum. Finally, mmWave bands opened up by 5G access points and automotive radars have increased the Bandwidth demands from MHz to GHz."

Moudgal and Himmler, dSPACE: "Automotive radars are, and will continue to be, a very valuable sensor in most—if not all—automotive applications. Radars play a very important role in both safety applications (ACC, AEB, etc.), as well as convenience applications (automatic deck-lid actuation). This technology can operate in a wider environmental range, compared to cameras and lidars, and more and more radar sensors are being used in ADAS and AD applications."

"The challenge customers are facing today is with testing production radar ECUs. These ECUs have to be properly calibrated before they can be deployed on vehicles, as well as during end-of-line testing as vehicles come off the production line. These needs are still being investigated and evaluated. A bigger challenge to be faced is with garages and body shops that are expected to realign and recalibrate radar ECUs that are impaired in accidents. To carry out these activities properly will require an investment in specialized equipment and training."

Keysight: "Next-generation wireless systems such as 5G cellular communications, fronthaul and backhaul networks, military and automotive radar, and IEEE 802.11ad and 802.11ay WiGig are targeting a range of new capabilities including higher bandwidth, more connected devices, low latency, and better coverage. To address the wide bandwidth requirements, researchers are exploring higher frequencies in the centimeter and mmWave bands where more spectrum is readily available."

"Compared to the traditional bandwidths used at sub-6-GHz for cellular communications, the use of hundreds or even several gigahertz of spectrum at these higher frequencies create several challenges. The higher the frequency, the more difficult the design, and the more visible design imperfections become. Imperfections that would be inconsequential at a 5-GHz carrier frequency with 20 MHz of modulation bandwidth could make a 100-GHz carrier with 3.5-GHz wide [modulation bandwidth] incomprehensible. If we look at the components, the request for portable yet multifunction devices or network appliances is strong.

"The semiconductor industry, defying Moore's law, is pushing component miniaturization further. Commercial 5-nm-node production is ongoing. Compared to 7-nm scale, this technology will enable chip developers to reduce power consumption by 20% or improve performance by 10%, allowing more applications than today's technology. mmWave technology comes in handy allowing [engineers] to design very small antennas and circuits able to work very efficiently."

"Of course, there is a price to pay: the design and the characterization of those components present unique challenges. Higher frequencies amplify error sources, including cable losses, connector repeatability, and phase shifts that are mostly negligible at radio frequencies. Above 60 GHz, an entire radio structure including a phased-array antenna can be integrated in a single chip leaving space for other elements and functionality. Multifunction components, however, imply complicated measurement setups to take in account the contribution of the various elements integrated in the circuit under test making repeatable measurements very challenging."

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CHAPTER 5:

Repeatable Wi-Fi Testing is Key for Device Performance Validation

LINCOLN LAVOIE, Senior Engineer, Broadband Technologies, UNH-IOL

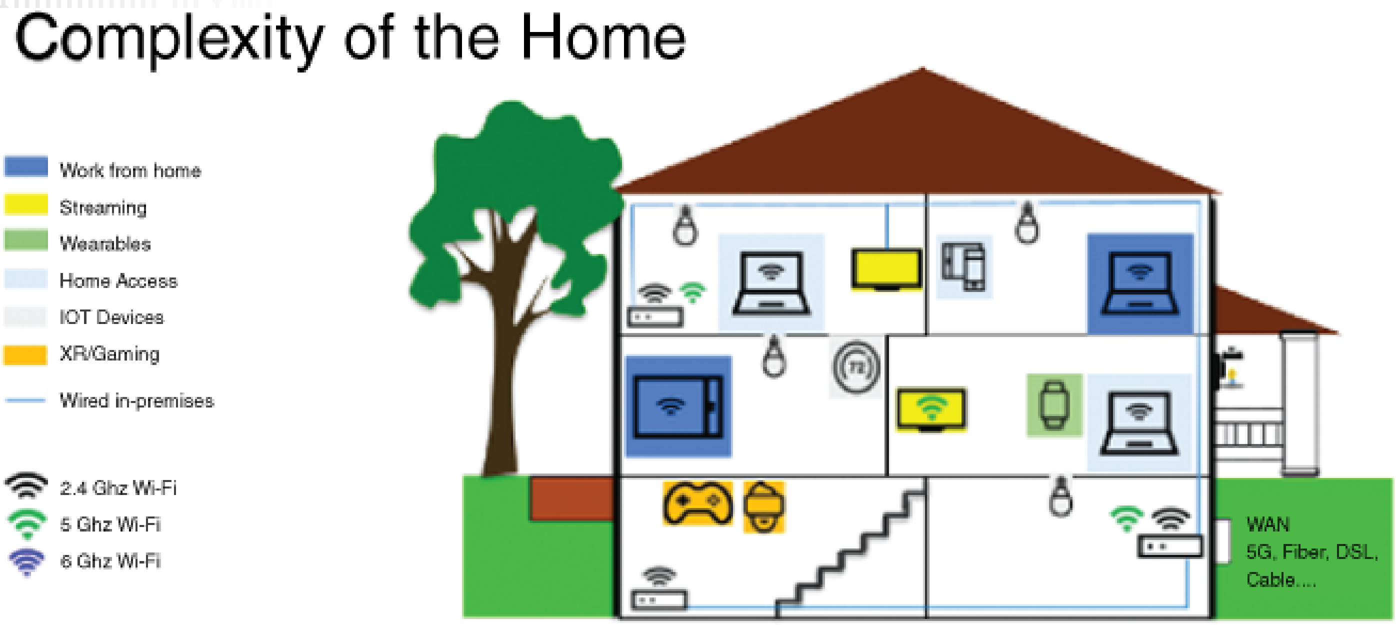
This article provides a technical look at newly defined performance metrics for Wi-Fi router testing in different scenarios and explores the challenge of building repeatable Wi-Fi testing that enables validation of devices used in broadband deployments.

Developing and implementing testing for Wi-Fi shares many of the same challenges you would expect in testing any wireless or RF technology. With the new TR-398 Issue 2 test plan, a strong focus has been on creating a repeatable set of test procedures, setup, and configurations. It's been necessary to ensure the testing can produce repeatable pass or fail results from absolute performance requirements.

This focus sets the TR-398 testing apart from much of the other widely available Wi-Fi testing that's focused on interoperability or functionality of specific features or components of the IEEE Wi-Fi specifications. Combining these two categories of testing—functionality and interoperability—with TR-398 performance testing creates a reliable process that manufacturers and service providers can use to deliver truly carrier-grade Wi-Fi to their subscribers.

Service providers have faced a seemingly endless task of keeping up with growing application bandwidth along with the simultaneous expansion of device count. In Wi-Fi, where the physical layer is a shared and scarce resource, these two parameters are directly at odds with each other. The problem compounds as subscribers view end-application performance as a measure of the overall internet performance observed on mobile or small devices with limited space available for antennas.

To help provide the service providers with the most applicable data on the expected performance of their Wi-Fi devices in the field, the focus and design of TR-398 test cases has been on performance as would be observed by an end user. For example, testing defines performance requirements for cases using two spatial streams instead of four spatial streams, or 20-MHz bandwidth configurations for 2.4 GHz instead of 40 MHz.



1. Wi-Fi performance testing plans should emulate real-world complex deployment scenarios. (Source: Verizon)

Testing Real-World Scenarios

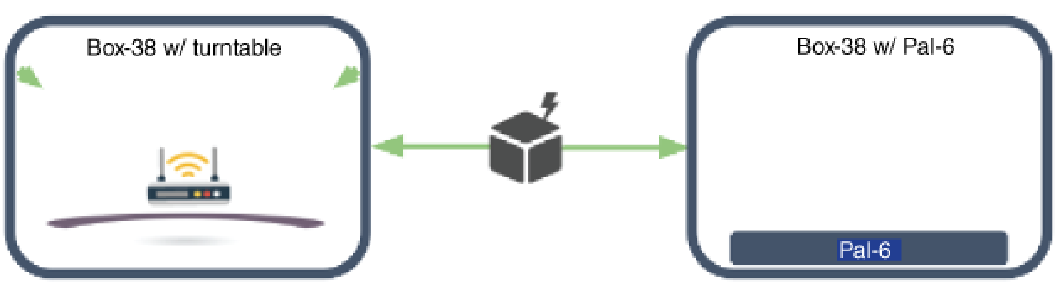
As such, the overall test coverage of TR-398 Issue 2 has focused on performance testing of real deployment scenarios for how Wi-Fi is used by broadband subscribers (**Fig. 1**). More specifically, the testing could be broken down into a few key areas: coverage, capacity, and robustness.

Coverage testing

Coverage testing measures the items, including spatial consistency, to ensure the device under test (a.k.a. the access point or AP) provides the required performance regardless of the angle or orientation toward the station. With spatial consistency as the first dimension of coverage testing, an equally important test is the range vs. throughput testing. This testing verifies the AP achieves a minimum expected level of throughput performance as the station moves closer or further away from the AP.

In the lab, the range or distance between the devices is implemented using programming attenuators. **Figure 2** shows a simplified view of the test setup that's used to implement many of the test cases. The AP is placed into a Faraday cage, with near-field antennas coupling the RF signals into the device. This is by design and ensures the device's antenna design and layout is taken into account when measuring the device's performance.

The near-field antennas connect to the programmable attenuators, which then connect to the station emulator (an Octoscope Pal-6). The emulator enables the lab to simulate



2. A basic test setup for TR-398 Issue 2 Wi-Fi performance testing.

a connection load on the AP of many stations simultaneously and with precise control. Finally, the AP device under test also sits on a turntable in the Faraday cage, allowing for automated control of its orientation relative to the near-field antennas. This setup creates a high degree of control and repeatability, especially when the testing is controlled through automation.

Capacity testing

Capacity testing focuses on the maximums supported by the AP device, including verifying the AP can support a minimum number of stations simultaneously. As the number of IoT devices continue to expand, it's not unusual to see Wi-Fi networks saturated with 30 or more devices. On another dimension, a test checks for the maximum throughput supported by the device, while other tests measure the performance of the AP device for bidirectional throughput (i.e., transmitting and receiving simultaneously).

The testing is carried out on multiple Wi-Fi technologies, including IEEE 802.11n, IEEE 802.11ac, and IEEE 802.11ax, sometimes referred to as Wi-Fi 5 and Wi-Fi 6. IEEE 802.11n testing is run on 2.4 GHz only, since this is the predominant deployment mode. IEEE 802.11ac testing is obviously run on 5 GHz, while the IEEE 802.11ax is run on both 2.4 and 5 GHz. The pass/fail metrics for the 6-GHz variant of IEEE 802.11ax, a.k.a. Wi-Fi 6E, will be released as part of the forthcoming Issue 3 version of the test plan under development now. Since AP devices will see connections from multiple generations of devices, on both the 2.4- and 5-GHz bands, another test case verifies the performance of the AP transmitting or receiving on both bands at the same time.

Robustness testing

All of this functionality, performance, capability, and coverage would mean little if the AP isn't able to remain running at these performance levels for long periods of time. This is the final category of testing: verifying the stability or robustness of the AP.

There are two key tests in this category. First is the coexistence test case, which measures the AP's performance in an environment with other Wi-Fi networks in operation. This scenario would exist for subscribers in multi-dwelling buildings or cases where multiple APs are in use (and in some cases misconfigured to overlap in the Wi-Fi channel usage).

The second test case in this category is the longest test case in the TR-398 test plan—the long-term stability test case. It could be referred to as a "soak" test case, where the AP is run over a long duration, at a fixed performance level, while carefully observing its performance and watching for degradation, errors, or packet loss. In addition, during the stability test run, other stations beyond those measuring the performance are set up to join and leave the Wi-Fi network at regular intervals.

In summary, that's a lot of testing! A TR-398 Issue 2 test run, for both Wi-Fi 5 and Wi-Fi 6, takes several days to complete. The end results of that effort ensures and verifies the performance that can be expected of the AP devices in real deployments, giving service providers a critical tool in preparing new devices or new software/firmware versions for rollout into the field. Service providers can expect better performing Wi-Fi networks, less support calls, happier subscribers, and ultimately less subscriber churn.

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