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Smart Weapons Out-Thinking Humans? **p22**

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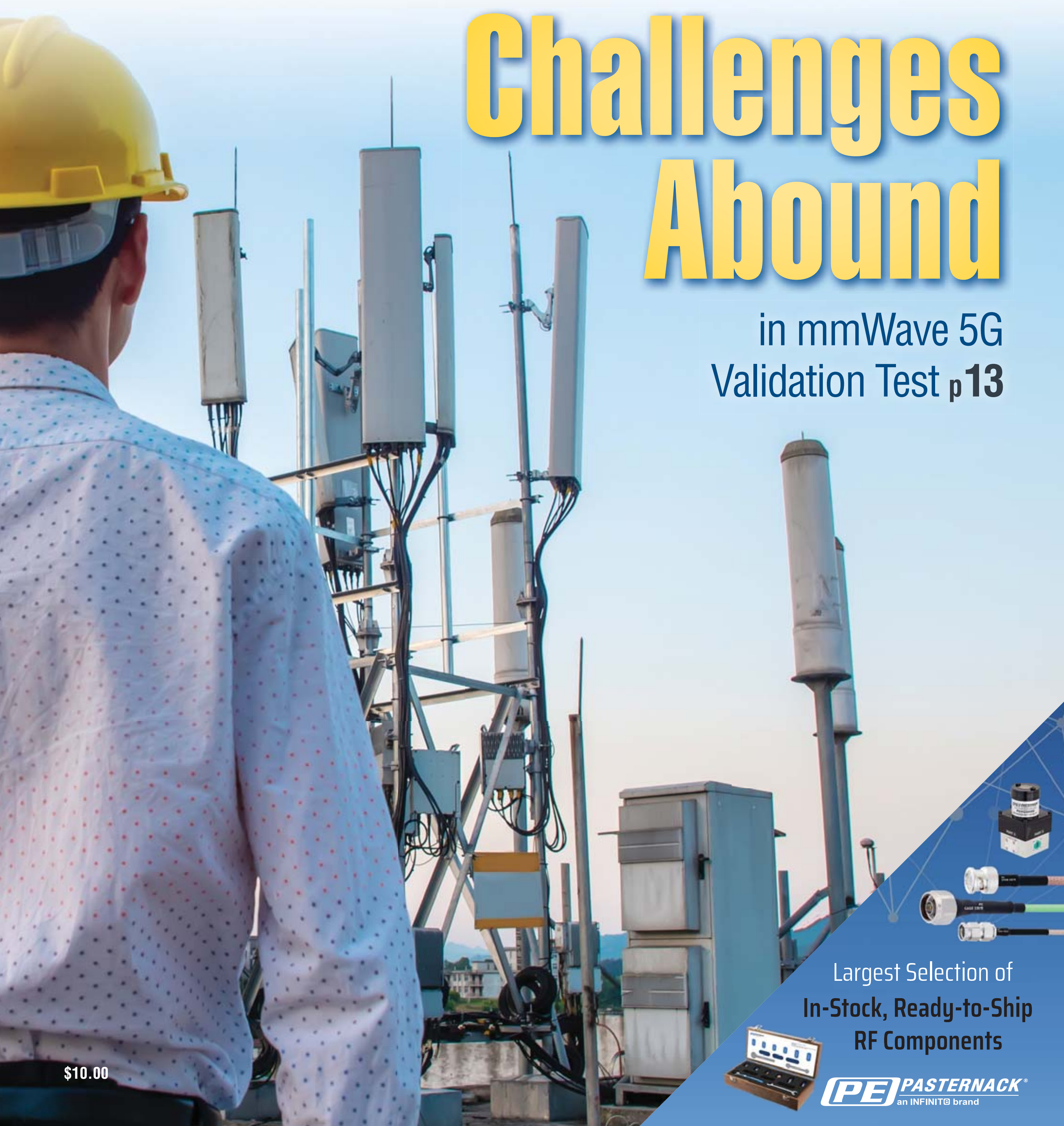
Challenges Abound

in mmWave 5G Validation Test **p13**



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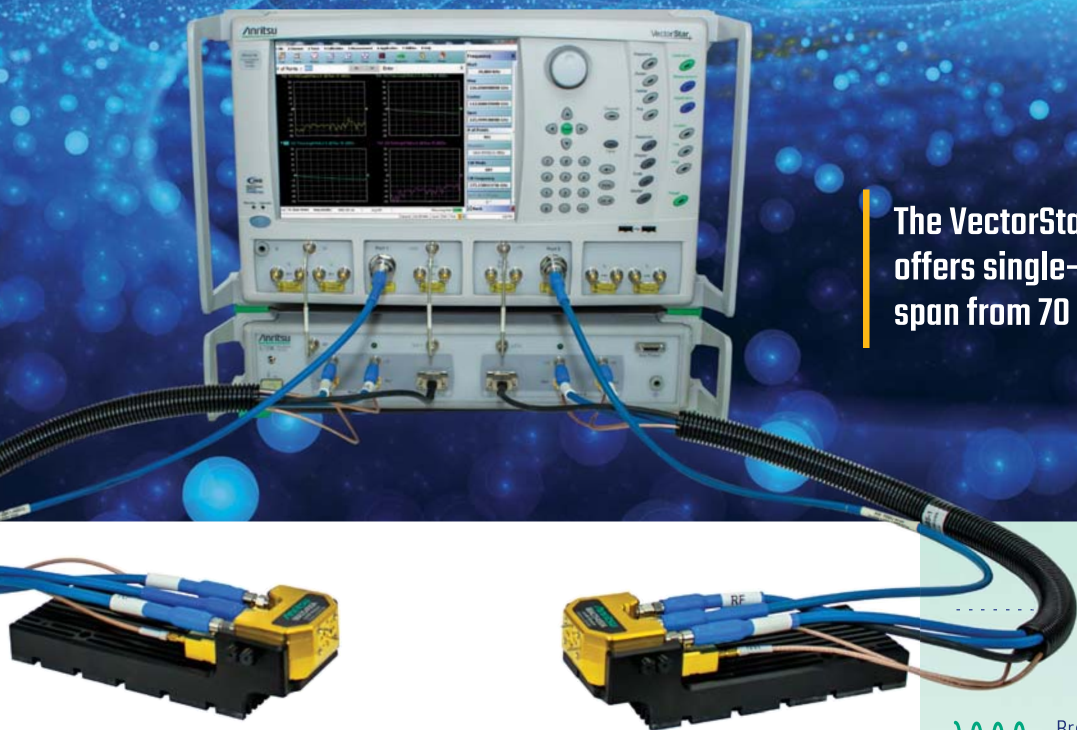

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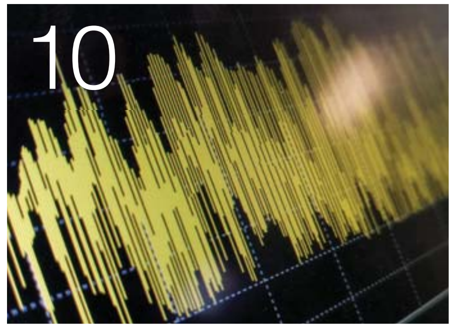

defense electronics

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Editorial

DAVID MALINIAK | Editor

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GLOBAL 5G SURVEY
Paints a Rosy Picture

A survey of telecom-carrier decision makers revealed that 99% of those polled predict 5G end users will benefit within five years; nearly half of carriers surveyed predict value for users within one year.

Industry watchers, myself included, tend to be a bit conservative regarding the arrival of 5G's full impact on the telecom industry and our day-to-day lives. But a new global survey of decision makers from telecom carriers commissioned by Molex begs to differ.

When it comes to the arrival of 5G as a significant transformation force, the feeling is, by and large, optimistic. More than half of those surveyed expect to deliver substantial end-user benefits within two to five years, while 47% reported that users already are seeing value or will within one year.

Conducted by Dimensional Research in February, the survey polled over 200 qualified participants in engineering, product, and R&D roles at network operators or mobile virtual network operators (MVNOs).

Among other key findings, 92% expect to achieve 5G business goals within five years. 5G consumer devices will be the first generators of significant new revenue (43%), followed by industrial and IIoT (35%) and fixed wireless access (33%). Unsurprisingly, all respondents report issues with 5G deployment, with the top three challenges named as spectrum issues (41%), lack of consumer use cases (31%), and regulations (30%).

What are the key technology or industry changes that would propel network operators toward their business goals? Answers included reduced costs of 5G infrastructure and network equipment (41%); innovation in enabling technologies, including semiconductors and sensors (31%); availability of new types of connected devices (26%); and stable and consistent government regulations (22%).

Only 60% of survey participants expect a "killer app" or transformative use case to drive 5G adoption. Augmented reality, gaming, and smart-home applications topped the list of primary consumer devices while robotics, logistics, and factories were the leading 5G-enabled use cases for industrial and IIoT.

Among primary use cases for fixed wireless access, rural home access topped the list at 53%, followed by city and suburban home access (45%) and remote industrial infrastructure access (41%). In addition, autonomous driving, vehicle-to-everything (V2X) communications, and vehicle telematics will lead the way in automotive use cases. Remote patient monitoring, medical wearables, and remote surgery were identified as drivers for the medical market.

While only 25% of respondents believe that 5G is getting it done for consumers today, nearly all expect substantial benefits within five years. More than half say customers in Japan and Korea are seeing those benefits today, while China is viewed as a 5G giant in waiting. Meanwhile, 75% say it will take two to five years for U.S. consumers to reap 5G's rewards nationwide.

Small cell (48%), mmWave (46%), and private networks (46%) were identified as the top three technologies/topologies to play critical roles in enabling 5G advantages. While no consensus was reached on which technology would be first to impact users, mmWave emerged as the long-term leader, garnering 47% of the votes, followed by sub-6 (27%) and wide-area low power (26%). mw

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MPC-20R2G21R2G-CD-LNF


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PMI Model No.	Frequency Range (GHz)	Gain (dB)	Noise Temperature	Phase Balance	Size (Inches) Connectors
MPC-20R2G21R2G-CD-LNF https://www.pmi-rf.com/product-details/mpc-20r2g21r2g-cd-lnf	20.2 - 21.2	0 to +10	100 K	±3°	6.25" x Ø4.8" x 2.0" SMA (F)

PMI Model No.	Frequency Range (GHz)	Insertion Loss (dB)	Isolation (dB)	Phase Balance	Amplitude Balance (dB)	Size (Inches) Connectors
PMC-24-7D5-SFF https://www.pmi-rf.com/product-details/pmc-24-7d5-sff	2 - 4	7.5	18	±10°	±1.0	3.23" x 3.23" x 0.43" SMA (F)
PMC-2D22D4-6D8-SFF https://www.pmi-rf.com/product-details/pmc-2d22d4-6d8-sff	2.2 - 2.4	6.8	25	±4°	±0.4	3.56" x 3.56" x 0.43" SMA (F)
PMC-3G3D5G-6D8-SFF https://www.pmi-rf.com/product-details/pmc-3g3d5g-6d8-sff	3 - 3.5	6.8	23	±5°	±0.4	3.23" x 3.23" x 0.43" SMA (F)
PMC-33D7-6D8-SFF https://www.pmi-rf.com/product-details/pmc-33d7-6d8-sff	3 - 3.7	6.8	24	±7°	±0.5	3.23" x 3.23" x 0.43" SMA (F)
PMC-56-SFF https://www.pmi-rf.com/product-details/pmc-56-sff	5 - 6	7.0	20	±5°	±0.5	3.48" x 3.48" x 0.43" SMA (F)
PMC-9G10G-7D9-SFF https://www.pmi-rf.com/product-details/pmc-9g10g-7d9-sff	9 - 10	7.9	18	±6°	±0.6	3.48" x 3.48" x 0.43" SMA (F)
PD-CD-001-1 https://www.pmi-rf.com/product-details/pd-cd-001-1	9.3 - 9.9	8.0	30	±7°	±0.5	2.35" x 1.7" x 0.5" SMA (F)
PMC-9D5G10D1G-7D6-SFF https://www.pmi-rf.com/product-details/pmc-9d5g10d1g-7d6-sff	9.5 - 10.1	7.6	20	±5°	±0.5	3.48" x 3.48" x 0.43" SMA (F)
PMC-9D5G10D5G-7D6-SFF https://www.pmi-rf.com/product-details/pmc-9d5g10d5g-7d6-sff	9.5 - 10.5	7.6	20	±5°	±0.5	3.48" x 3.48" x 0.43" SMA (F)
PMC-12G13G-1D6-SFF https://www.pmi-rf.com/product-details/pmc-12g13g-1d6-sff	12 - 13	7.6	18	±5°	±0.5	3.48" x 3.48" x 0.43" SMA (F)


PMC-56-SFF
PMC-9G10G-7D9-SFF


PD-CD-001-1


PMC-9D5G10D1G-7D6-SFF


PMC-9D5G10D5G-7D6-SFF


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News

DEVELOPMENT ECOSYSTEM Drives G3-PLC Hybrid Connectivity into Smart Devices

Seeking to accelerate G3-PLC Hybrid connectivity in smart-grid and IoT devices, a pair of development kits centers on ST's ST8500 PLC modem chipset.

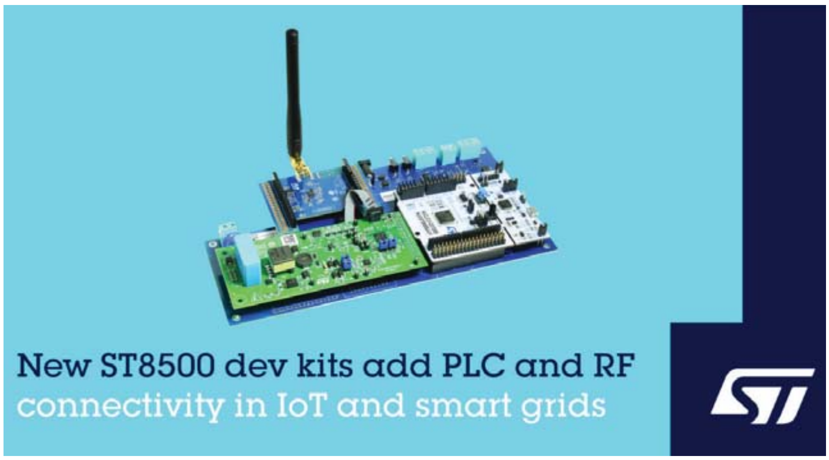
To accelerate G3-PLC Hybrid connectivity in smart-grid and IoT devices, STMicroelectronics has debuted a development ecosystem for its ST8500 programmable powerline-communication (PLC) modem chipset.

Comprising two evaluation boards targeting the 868-MHz and 915-MHz license-free RF bands, with documented firmware, the ecosystem helps users quickly build and test nodes that comply with G3-PLC Hybrid, the industry's first published standard for dual PLC and RF connectivity.

Equipment such as smart meters, environmental monitors, lighting controllers, and industrial sensors containing the ST8500 chipset, which supports G3-PLC Hybrid, can select the powerline or wireless channel autonomously and change dynamically to ensure the most reliable connection.

Launched in 2019, the chipset combines the ST8500 protocol controller system-on-chip (SoC), which runs ST's G3-PLC Hybrid firmware, with the STLD1 PLC line driver and S2-LP sub-GHz radio. Devices containing the chipset are backward-compatible and interoperable with any G3-PLC network.

ST's hybrid protocol stack is based on G3-PLC, IEEE 802.15.4, 6LowPAN, and IPv6 open standards. By embedding support for RF Mesh at the physical (PHY) and data-link layers, the ST8500 combines the strengths of powerline and wireless mesh networking for communication between smart nodes and data collectors. Unlike simple point-to-point links, hybrid mesh-networking interconnects nodes extensively to improve reliability, strengthen fault-tolerant connections, and extend communication distance.

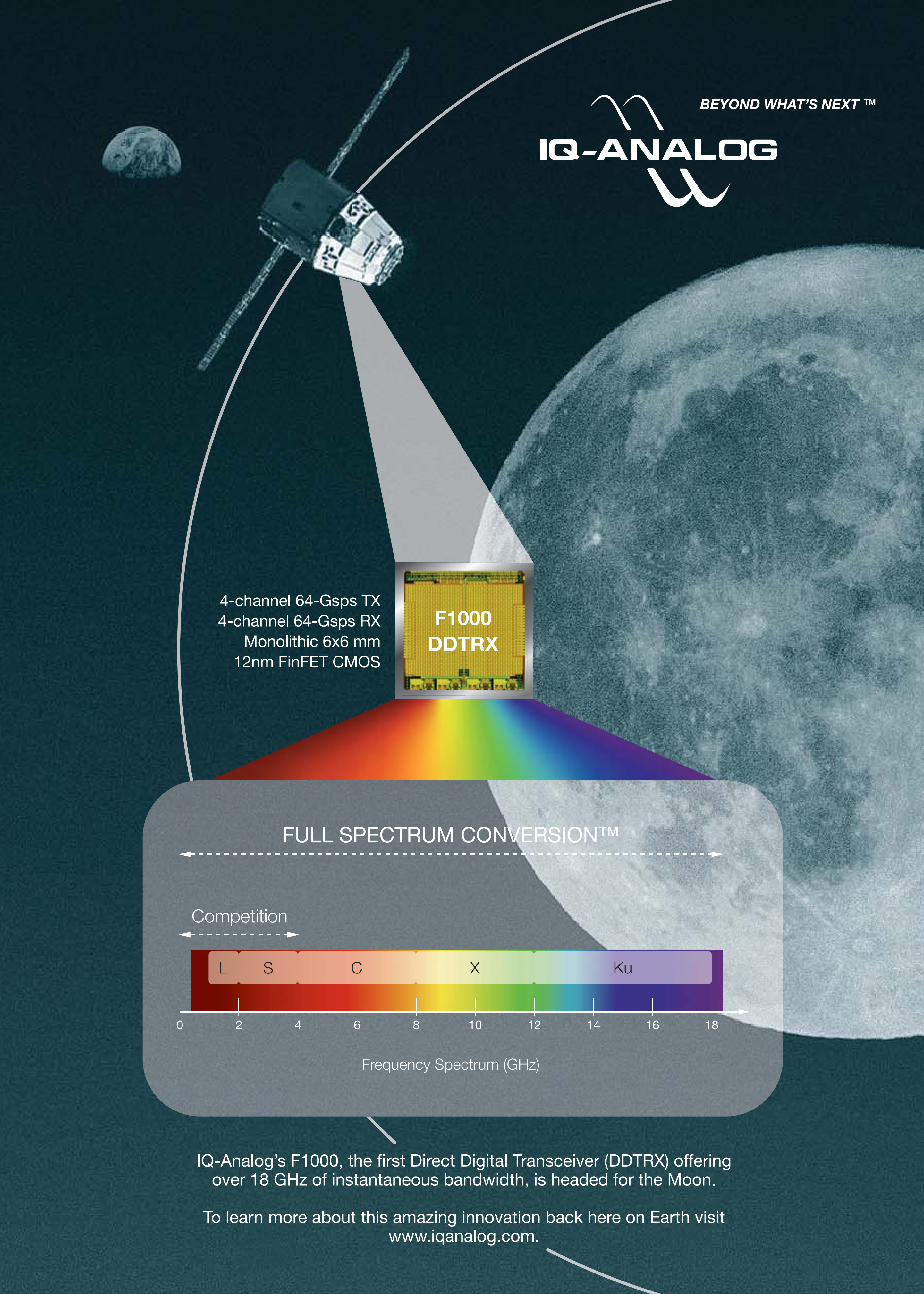


The two new hardware development kits handle PLC and RF connectivity as well as application processing. Each kit comes with the STSW-ST8500GH software framework and documentation.

The two new hardware development kits handle PLC and RF connectivity as well as application processing. The EVLKST8500GH868 kit is configured for 868-MHz RF operation as recommended in the EU, while the EVLKST-8500GH915 kit operates in the 915-MHz band used throughout the Americas and Asia. Each kit comes with the STSW-ST8500GH software framework and documentation.

Ready to combine with an STM32 Nucleo board for scalable application processing and compatible with ST's large portfolio of X-NUCLEO expansion boards for convenient function extension, the kits provide a platform for developing a wide range of smart-grid and IoT applications.

The EVLKST8500GH868 and EVLK-ST8500GH915 are available now from ST and distributors for $250. md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VECTOR SIGNAL GENERATOR Empowers Midrange 5G, Wi-Fi 6E, and Other Advanced RF Test

ROHDE & SCHWARZ claims its SMM100A is the only vector signal generator with mmWave testing capabilities in its class. The instrument meets the rigorous expectations for generating digital signals for the most advanced wireless communication devices entering production, as well as for developing future products and technologies. Manufacturers of state-of-the-art 5G devices wishing to test the whole frequency range possible, expect to do so with a single signal generator for both 5G NR FR1 and FR2 frequencies.

The R&S SMM100A vector signal generator displays excellent RF characteristics across the entire frequency range, from 100 kHz to 44 GHz. It covers all bands used by any wireless standards, including LTE and 5G NR, as well as the latest WLAN standards Wi-Fi 6 and Wi-Fi 6E (up to 7.125 GHz). Wireless personal area networks such as Bluetooth are covered, too. The instrument's maximum RF modulation bandwidth of 1 GHz meets requirements to generate the broadband signals used by devices making full use of the most demanding wireless standard specifications, including IEEE 802.15.4z Ultra-Wideband (HRP-UWB).

The R&S SMM100A offers a maximum output power of +18 dBm, which reduces the need for external amplifiers. Excellent modulation frequency response, error vector magnitude (EVM), and adjacent channel power ratio (ACPR) performance result in signal quality for reliable, repeatable test accuracy. The R&S SMM100A comes with six maximum frequency options from 6 to 44 GHz, and four modulation bandwidth options from 120 MHz to 1 GHz to meet all major device band requirements. Users can upgrade their instrument's capabilities according to their need anytime by simply entering a key code.

Both real-time signal generation with an internal baseband generator for one-box signal generation with on-the-spot configuration of signal parameters, and an arbitrary waveform generator (ARB) for waveforms defined with the R&S WinIQSIM2 simulation software, are available. The R&S SMM100A features a large ARB memory depth of up to 2 Gsamples and a high maximum sampling rate of 1.2 Gsamples/s. For production use, the Multi-Segment Mode speeds up test sequences even more, with fast switching between individual baseband signals.

With the built-in SCPI macro recorder, users can create error-free remote-control programs quickly and easily. Moreover, MATLAB or Python scripts can be executed, which can not only be reused on an R&S SMM100A, but on most Rohde & Schwarz vector signal generators currently available. ■

FOR FURTHER INFORMATION, visit *www.rohde-schwarz.com/product/smm100a.*


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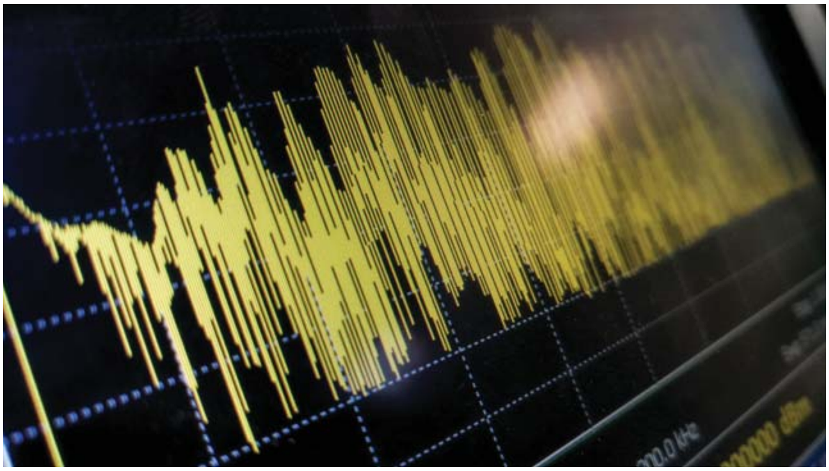
SEAN WALLACE | President, Spectra Labs

The Evolution of RF Signal-Observation Tools

Tools used to visualize RF signals have evolved over time from the spectrum analyzer to today's RF recorders. However, each era's tools have had limitations. This article shows how the modern approach builds on the best aspects of what's come before.



Audrius Merfeldas | *Dreamstime.com*

RF engineers have always been obsessed with pursuing new and better ways to observe and analyze RF signals. In the earliest days of RF engineering, pioneers like Nikola Tesla struggled to simply generate wireless signals, much less analyze them.

We can only imagine the daily struggle involved in attempting RF engineering without any instrumentation. It's quite a leap from the crude laboratory of Tesla to the sophisticated analyzer we take for granted today. But today's instrumentation is actually the result of many decades of incremental improvements. Here's a brief overview of the many steps in the evolution of tools for RF-signal observation.

The Swept-Tuned Spectrum Analyzer

Undoubtedly, the most important breakthrough in RF instrumentation occurred in the late 1950s and 1960s with the emergence of swept-tuned spectrum analyzers. At last, here was a means of viewing signals in the frequency domain. It knocked the oscilloscope off its pedestal as the most important instrument in the RF engineer's toolbox in much the same way as the Ford Model-T replaced the horse and buggy.

The repercussions of this class of instrumentation can hardly be understated as it played a key role in the exponential growth of the biggest test and measurement companies in the world. From this point, the race was on to incrementally improve the spectrum analyzer and overcome its limitations.

Limitations of the Swept-Tuned Spectrum Analyzer

The most fundamental limitation of the swept-tuned spectrum analyzer is its inability to cleanly characterize a time-variant signal. Because the instrument slowly sweeps a range of frequencies, the signal displayed on the screen is a composite of many acquisitions taken across the sweep time. The result: a screen display of a signal that never actually existed in the real world.

While this limitation may have been an acceptable compromise for relatively stable AM and FM signals, it was completely untenable for short, bursted signals like radar. In the ensuing years, various attempts were taken to overcome this limitation using more and more elaborate triggering schemes, correction factors, and zero-span modes. Ultimately, this struggle sowed the seeds for the next big breakthrough in spectrum analysis.

Emergence of the FFT Analyzer

Because signal analysis was a particularly pressing issue for defense applications, industry and government directed substantial resources toward developing a digital fast Fourier transform (FFT) spectrum analyzer. This new type of analyzer promised to capture the entirety of the wideband signal in one acquisition instead of creating a composite of many acquisitions.

Two technologies had to emerge to enable the FFT analyzer to become viable.

The first was high-speed analog-to-digital converters (ADCs). The second was digital processors that could quickly compute an FFT. The efforts were successful and by the late 1980s, very capable FFT analyzers were found on the benches of defense laboratories across the globe. By the mid-1990s, the emergence of digital cell phones accelerated the commercial adoption of FFT analyzers.

Limitations of the FFT Analyzer

The FFT analyzer was revolutionary for many applications, but it still had significant dynamic-range limitations. Even more importantly, it had substantial acquisition dead time as part of its measurement cycle. Ultimately, this resulted in limited fidelity in the time domain.

While the instrument was busy computing the FFT from the prior acquisition, it was blind to all other incoming signals. This became the catalyst for the next incremental improvement in spectrum-analysis instrumentation: the real-time spectrum analyzer (RTSA).

Real-Time Spectrum Analyzer

In the late 1990s, very fast DSP silicon emerged that was perfectly tuned to execute efficient FFT computations. This development made possible the creation of the RTSA.

At its core, the RTSA is an FFT analyzer with rapid FFT bolted onto the back end. The FFT computations occur so quickly that the RTSA provides the user with the illusion of continuous acquisition with no dead time. With this architecture, the probability of missing signals was dramatically reduced. This added capability is particularly important in spectrum monitoring and signal-intelligence (SIGINT) applications.

Limitations of the RTSA

Unfortunately, the real-time spectrum analyzer (RTSA) still presents the RF spectrum to the user as a series of separate acquisitions. The RTSA must break up the signal into multiple, discrete blocks to compute an FFT and present the information to the user.

However, even more importantly, the RTSA doesn't create a permanent record. Without a permanent record, signals are fleeting—they occur, they're displayed, and they disappear without a trace. The RTSA doesn't fundamentally change the operator's workflow in a way that would allow for multiple, transient signals to be frozen in time, replayed, and analyzed later.

Enter the RF Recorder

The RF recorder is the latest iteration in the century-long quest to improve spectrum analysis. It builds upon all previous generations of spectrum analyzers with the added capability of storing a permanent record of raw RF signal data.

Unlike the RTSA, most RF recorders don't need to break an incoming RF signal into discrete chunks for further FFT processing. Instead, these instruments natively capture time-series data. A truly continuous, gap-free stream of RF signal data is preserved as a permanent record.

Of course, most human operators will not gain much insight by viewing raw times-series IQ data on a screen. A well-designed RF recorder, such as Spectrum Labs' Spectrum Defender, will record time-series data but still allow the operator to view signals in a conventional spectrum-analyzer-style display. Under the hood, these RF recorders are retrieving time-series data from disk and computing a "just-in-time" FFT to create a user-friendly, frequency-domain display.

With a time-series RF recorder, there's no need to worry about the FFT length or resolution bandwidth used when the signal was originally observed or recorded in the field.

Importantly, this instrument architecture enables the user to change the FFT length (and related resolution bandwidth) to any desired value, at any point in the future, without fundamentally altering the underlying record of signal data. With a time-series RF recorder, there's no need to worry about the FFT length or resolution bandwidth used when the signal was originally observed or recorded in the field. This is a neat trick that the RTSA is hard-pressed to duplicate.

The permanent record provided by an RF recorder allows us to capture a true, continuous view of the electromagnetic environment with no acquisition dead time, and no advance knowledge of the optimum FFT length. Engineers can retrieve and interrogate any portion of the RF spectra on demand in the time domain, frequency domain, or joint time-frequency domain. The very latest RF recorders even allow engineers to capture spatial-domain information with multiple phase-coherent channels.

One hundred years ago, that wasn't something Nikola Tesla could have ever imagined. mw

KHUSHBOO KALYANI | Senior Product Marketing Engineer, LitePoint

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

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.

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.

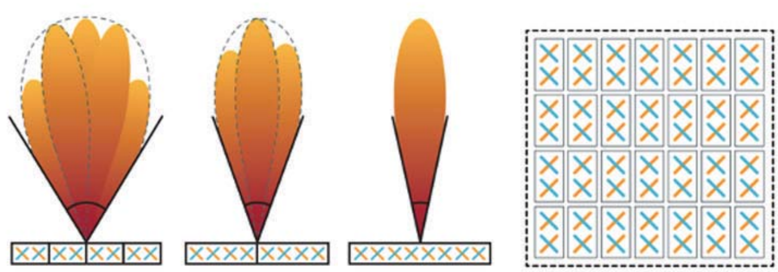
To compensate for this loss, 5G New Radio (NR) employs beamforming, which uses multiple phased-array antenna modules to maximize and steer radio energy in a specific direction *(Fig. 1)*. This is achieved by independently feeding each of the elements in the array with a signal that's adjusted for phase 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.



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

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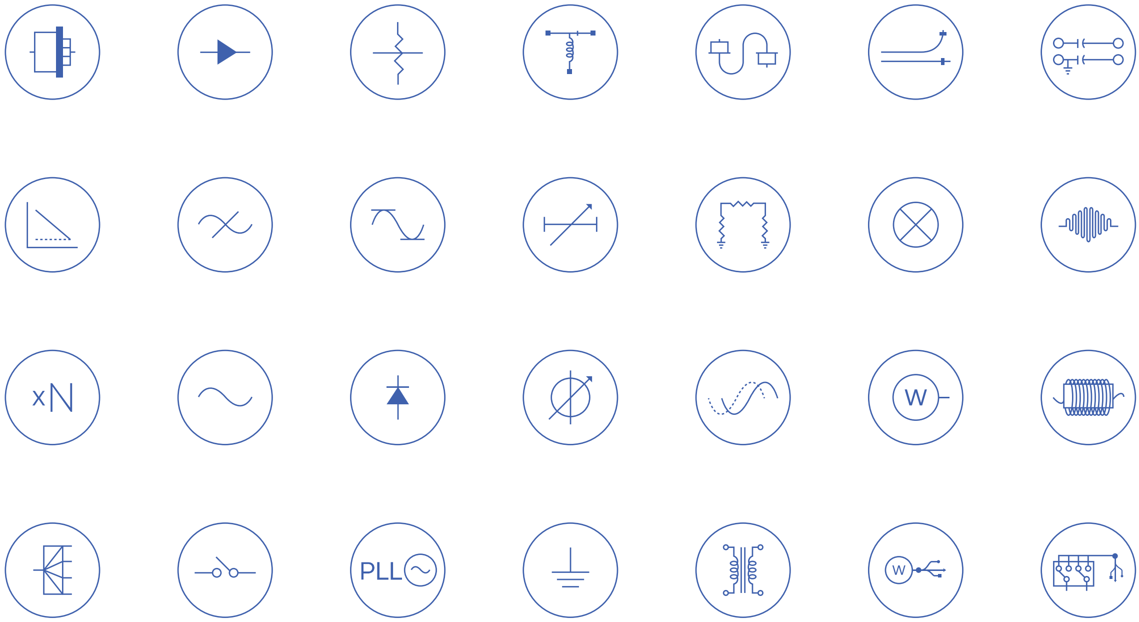

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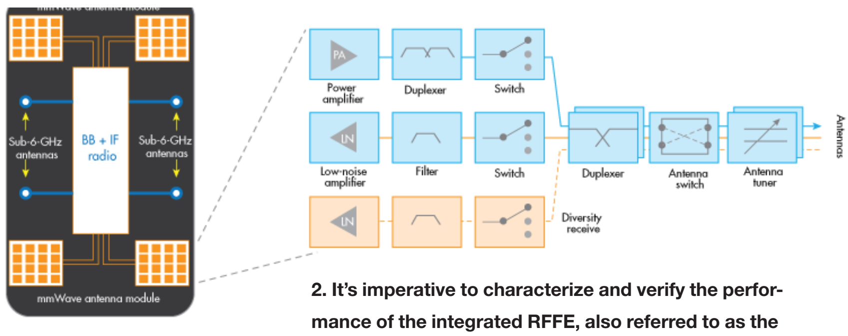


2. It's imperative to characterize and verify the performance of the integrated RFFE, also referred to as the mmWave antenna module.

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

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)*.

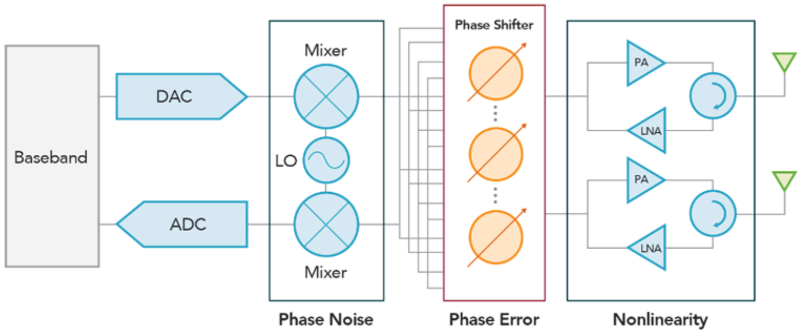
5G mmWave Test Challenges

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.

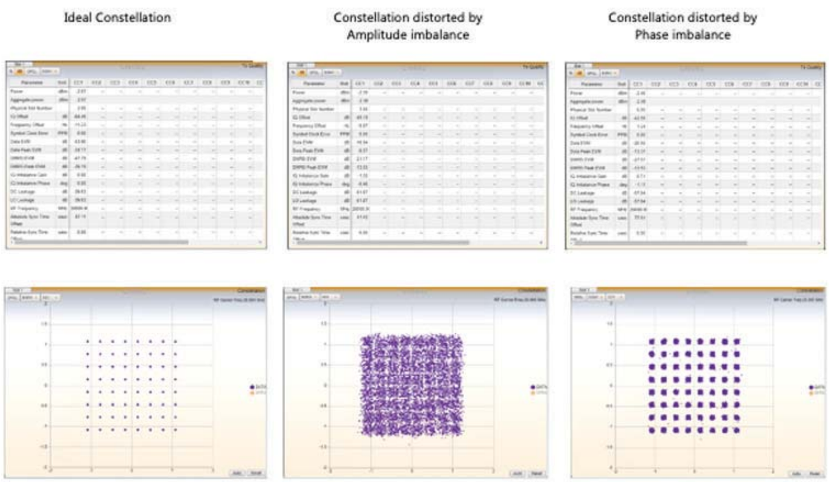
3D Beamforming Characterization and Verification

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 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)*.



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



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.

To accomplish the tests in *Table 1*, 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.

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

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.

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.

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.

An ideal R&D lab setup would look simple with a seemingly direct connection between the test equipment and the

(Continued on page 31)

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

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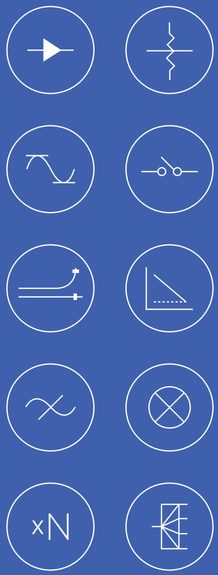

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Military and critical infrastructure operations depend on GPS signals, PNT data, time, and frequency to synchronize systems. ■

Software Design Tools Blend Shipboard Radar and Video

CAMBRIDGE PIXEL'S MARITIME DISPLAY FRAMEWORK (MDF) software design tools enable maritime integrators to speed development of automatic radar plotting aid (ARPA) radar display consoles.

The software provides a .NET framework, optionally with source code, that designers can use as the starting point for a custom shipboard application that displays primary radar, radar tracks, S-57/S-63 electronic navigational charts, secondary transponder information like AIS and ADS-B, and NMEA navigation data.

The MDF software can receive video from radar by Furuno, Hensoldt, JRC, Koden, Raymarine, Raytheon, Simrad, Sperry, and Terma, with control of the radar supported for certain models.

The MDF software supports bearing lines, range markers, trails, closest point of approach, and time to closest point of approach. It also supports camera video to integrate radar and camera display for security against piracy and smugglers.

The MDF software is compatible with Cambridge Pixel's radar processing products, such as SPx Server for target tracking and SPx Fusion. The Maritime Display Framework is written in the C# language and is designed for development of a Windows WPF-based client application. ■

SMART WEAPONS FORM THINKING BATTLEFIELDS

JACK BROWNE | Technical Contributor

1. The StormBreaker autonomously detects and destroys moving targets in foul weather, using AI to comb through data collected by multiple seekers including millimeter-wave radar, IR imaging, and laser-based systems. *(Courtesy of Raytheon Technologies, Raytheon Missiles & Defense)*

One of the fastest-growing segments of military electronics is the use of artificial intelligence and machine learning in guided weapons, which lets them do some of the thinking for themselves.

MODERN BATTLEFIELDS are immersed in electronic devices and data, whether on the ground, at sea, or in the air. The amounts of data from well-established systems and technologies such as radar, sonar, and LiDAR are becoming too much for any warrior to process, encouraging the development of semi-autonomous or "smart" weapons that can share in the decision-making.

Equipped with artificial-intelligence (AI) and machine-learning (ML) technologies, many of these weapons are guided by light, sound, or electromagnetic (EM) waves to reach a selected target with high accuracy. In addition, smart weapons can be programmed to filter unwanted signals in multiple-signal environments and find a specific target on a battlefield with many potential targets.

Electronic warfare (EW) has long relied on the development of novel technologies such as LiDAR and radar, typically to gain an edge over an adversary or provide advanced warning of an adversary's actions. Smart military-guidance systems once referred to steering by Global Positioning System (GPS) satellite signals. However, operations that take place in areas in which GPS signals aren't available, or are being jammed by an adversary, require alternative guidance based on available AI and ML technologies.

Smart weapons and guidance systems use AI and ML empowered by embedded computers to "share" some of the decision-making concerning a response with their human controllers. Weapons in which human guidance is still required are known as semi-autonomous devices. Ultimately, organizations such as the Defense Advanced Research Projects Agency (DARPA) and the U.S. Army Combat Capabilities Development Command Armaments Center (CCDC) are developing different types of smart weapons with an eye toward fully autonomous versions that can make a decision on a strike or respond on their own.

DARPA recently announced that six teams will receive funding as part of the Next-Generation Nonsurgical Neurotechnology (N3) program to develop technology for two-way communication between human brains and machines without requiring surgery. The program assumes that humans, overwhelmed by the amount of data received on the battlefield, would have AI-powered machines as partners and require almost instantaneous response times.

Humans now suffer delays in decision-making with machines due to the way the nervous system interacts with machine microprocessors. The program would explore the use of viral vectors or viruses that carry proteins into the brain for detection of light from neurons. By detecting the activity of neurons, it may also be possible to determine a human's thoughts and thought processes for faster interaction with AI-driven systems.

A government-appointed panel has reviewed the benefits and risks of smart weapons on the battlefield. The independent National Security Commission on Artificial Intelligence (NSCAI), created in 2018, recently completed a 130-page draft report that's scheduled for submission to the U.S. Congress this month. It recommends the use of AI and ML technologies for military use, noting that AI-enabled weapons are expected to make fewer mistakes than human combatants and can play a vital, positive role in national security.

Future battlefield strategies are being planned with AI as a vital component in analysis of battlefield situations on land, at sea, and in the air.

The panel was led by Eric Schmidt, the former chief executive of Google. It was opposed by a coalition of non-governmental organizations and 30 countries that has pushed for a treaty banning smart weapons on the grounds that human control is necessary for the ethical management of the battlefield.

Future battlefield strategies are being planned with AI as a vital component in analysis of battlefield situations on land, at sea, and in the air. AI will be used as part of embedded EW systems to provide augmented-reality (AR) information to operators.

The AR data will be collected by many different battlefield sensors, such as those aging radar and LiDAR systems. It will be presented on different forms of displays to human soldiers and/or smart electronic weapons systems that will be programmed to respond to the inputs via actions that include identifying threats as well as friendly troops, classifying threats, and prioritizing targets.

The Path to Autonomy

Systems currently called smart weapons are limited in their autonomous capabilities, although the use of AI and ML technologies is expected to increase significantly within the next decade. The concept of computing machines for the battlefield isn't new. In fact, it's been in development since the aftermath of World War II with the creation of tables of firing statistics that were analyzed and used to increase the targeting accuracy of ballistic missiles.

Military system designers are planning for three levels of AI: artificial narrow intelligence (ANI) with limited decision-making capabilities for specific tasks; artificial general intelligence (AGI) with decision-making capabilities that can match human intelligence for any task; and artificial superintelligence (ASI) with decision-making capabilities that exceed human intelligence for any task.

Although the vision of many system planners is for fully autonomous weapons operating without supervision, many applications will require advanced human-machine training and interaction. The use of multiple robotic systems is one such case.

For example, it might apply to remote direction of a "flock" of miniature unmanned aerial systems (UAS) for surveillance purposes, or when miniature drones armed for attack must be guided to a target and detonated. This need for a reliable, remote man-machine interface under battlefield conditions emphasizes the importance of military-grade communications networks capable of handling large amounts of data under hostile operating conditions, including cyberattacks.

Increasing Effectiveness

A starting point for many smart weapons is the application of AI and ML to EW systems for improved performance, such as increased targeting range and accuracy. Northrop Grumman Corp. was recently contracted by DARPA's Tactical Technology Office (TTO) for an advanced technology weapon capable of much greater range and accuracy than current systems when deployed against airborne threats.

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General Atomics and Lockheed Martin also received contracts as part of the first phase of the program. Appropriately named LongShot, the program will leverage the contractors' expertise in AI and digital signal processing (DSP) to develop new lethal-engagement concepts for unmanned aerial systems (UAS) powered by multiple propulsion systems, capable of being deployed by bombers as well as much smaller fighter aircraft. The LongShot system is being designed for external transport on fighters and internal transport on bombers.

According to Jaime Engdahl, the program director for kinetic weapons and emerging capabilities at Northrop Grumman, the development of smart weapons is a necessary response to the growing number of robotic and autonomous threats. He said, "Our collaboration with DARPA is the critical first step in the development of innovative operational concepts and solutions that will enhance our warfighter's combat capability against a rapidly growing threat."

Concerning LongShot, Engdahl added, "The LongShot program enables us to combine our digital engineering skillset with our extensive knowledge in advanced technology weapons, autonomous systems, and strike platforms to increase weapons range and effectiveness."

The pairing of Lockheed Martin's Long-Range Anti-Ship Missile (LRASM) and BAE Systems' missile seeker technology also combines AI techniques with sensor fusion to steer the missile over distances as far as 200 nautical miles. The system has been in production for several years. It was initially part of a joint project by DARPA, the U.S. Navy (USN), and U.S. Air Force (USAF) to create an anti-ship missile that could launch from a USN F/A-18E/F Super Hornet fighter/bomber or USAF B-1B Lancer bomber. As GPS-jamming capabilities have increased among adversaries, demand for the LRASM has grown—a weapon that can cover long distances without relying on GPS, using the LRASM's on-board radar and semi-autonomous guidance systems.

Thinking Through Weather

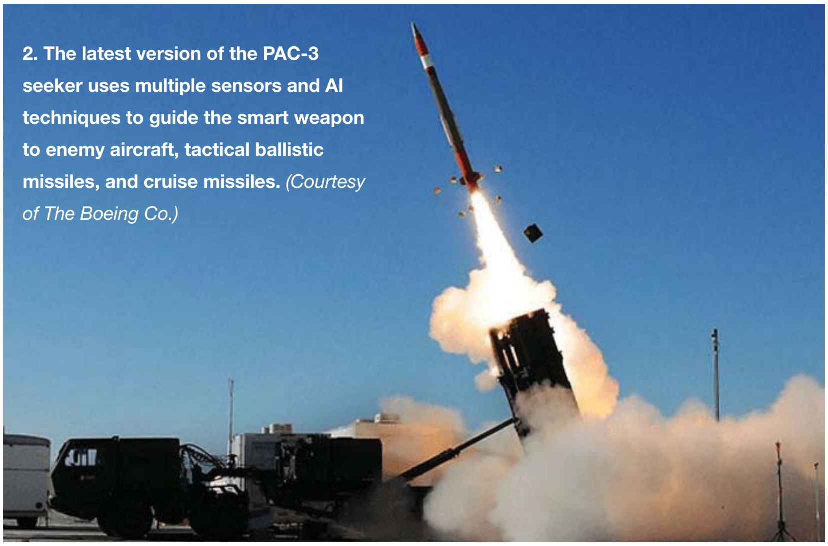
Current intelligent weapons systems often use AI and ML to enhance operation under adverse conditions, such as the aptly named StormBreaker from Raytheon Technologies and its Raytheon Missiles & Defense division. The smart weapon *(Fig. 1, page 22)* is designed to destroy moving targets despite the worst weather conditions. It autonomously detects and classifies moving targets in darkness, bad weather, through smoke, and even in the dust stirred up by helicopters over a battlefield.

StormBreaker's built-in intelligence is aided by a multimode seeker with a host of powerful sensors, including a millimeter-wave radar system, an infrared (IR) imaging system to differentiate targets from friendly forces in foul weather, and a semiactive laser system that can track ground-based or airborne targets. Because the data from the seeker's multiple sensors are shared, the system can accurately identify and track fixed or moving targets even under the most challenging environmental conditions.

The StormBreaker system is extremely compact, allowing fighter jets to carry multiple systems. An F-15 fighter jet can carry seven groups of four StormBreaker smart weapons or a total of 28 munitions systems. The system provides high precision so that explosions are kept within a small footprint.

StormBreaker also is intelligent, with a high-speed data link that allows a fighter pilot to interact with the smart weapons system and change targets even as the weapon is gliding to the ground toward its initial target. The system has been approved for use on the F-15E fighter, and the U.S. Air Force and Navy have begun integration of StormBreaker systems into F-35 Joint Strike Fighter (JSF) and F/A-18E/F Super Hornet fighter aircraft.

As part of smart-weapons systems, AI and ML technologies can be used for guidance, intelligence collection, surveillance, and in some cases, as part of electronic countermeasures (ECM) responses to an adversary's AI-guided robotic systems. For example, Boeing has been working with



2. The latest version of the PAC-3 seeker uses multiple sensors and AI techniques to guide the smart weapon to enemy aircraft, tactical ballistic missiles, and cruise missiles. *(Courtesy of The Boeing Co.)*

Lockheed Martin on the development of a next-generation seeker for the U.S. Army's Patriot Advanced Capability-3 (PAC-3) missile system while continuing production of current generations of the PAC-3 seeker. The seeker is a key component in the guidance system of the PAC-3 missile system *(Fig. 2)*, used as a defense against enemy aircraft, tactical ballistic missiles, and cruise missiles.

Defending against autonomous threats is considered an essential part of future battlefield planning. On that front, Boeing recently upgraded its directed-energy weapon, the Compact Laser Weapon System (CLWS) for a U.S. Department of Defense (DoD) customer. The upgrades include increased beam power and reliability for situations involving growing numbers of larger unmanned aerial vehicles (UAVs) on the battlefield.

Kurt Sorenson, Boeing program manager for CLWS, explains, "The upgraded units will provide warfighters with enhanced protection against larger and more numerous hostile unmanned aircraft systems. They will also enable them to defeat threats more quickly and efficiently." The CLWS has proven successful against UAVs in numerous exercises requiring target acquisition and tracking of multiple moving miniature aircraft.

Intelligent Countermeasures

One aspect of learning to fight alongside smart weapons is effective integra-

3. The Smart D2 is an autonomous ECM subsystem that combines AI with secure data collection and AI-guided analysis. It can be integrated into existing and future ECM systems. *(Courtesy of BAE Systems)*

4. ARL is advancing its knowledge of ground-based robotics systems at its Aberdeen Proving Ground, pushing the limits of AI processing to adapt to difficult terrain. *(Courtesy of the U.S. Army Research Laboratory)*

tion within a working battlespace and not discarding current systems for the sake of "more intelligent" ones. The Smart D2 system from BAE Systems is an automated threat-management system designed for integration into current and future ECM systems. It provides AI, secure communications, and automation in the form of core components such as a programmer, sequencer, and dispenser. The programmer features a regularly updated database of threats and can identify optimum payloads, quantities, and dispensing intervals of weapons used for each ECM response.

The Smart D2 system incorporates NATO's standard Smart Stores Communication Interface (SSCI) for communication between dispenser system and smart ECM systems, and provides two-way communication of mission-critical information for human pilots to make their own decisions about appropriate ECM responses *(Fig. 3)*. A Smart D2 System can be integrated into an aircraft's ALE-47 Airborne Countermeasures Dispenser System. Instead of replacing an ALE-47 system, its main elements are swapped out for Smart D2 elements.

On the ground, the U.S. Army Research Laboratory recently expanded its Robotics Research Collaborative Campus (R2C2) north of Baltimore, Md. to evaluate unmanned ground vehicles (UGVs) and terrestrial smart weapons. The Aberdeen Proving Ground uses about 200 acres for testing of ground-based systems *(Fig. 4)* and simulation of battlefield conditions for the use of AI-driven robotics systems.

The in-field testing follows computer-based simulations of UGVs, providing test data based on a realistic operating environment. Both hardware and software, such as the ARL Autonomy Stack of algorithms, can be checked in the outdoor laboratory to evaluate such effects as frequency and erratic terrain changes and large obstructions. The test results help develop ML solutions for future performance improvements in the UGVs.

Thinking machines and smart weapons may be some years away from sharing a battlefield with human combatants. Nonetheless, major defense organizations such as DARPA and the DoD are committed to the development of weapons leveraging AI and ML technologies capable of sharing with decision-making processes in data-dense environments.

The growing use of small UAVs or drones, for example, can create extremely hazardous operating environments where human warriors with conventional weapons lack the necessary firepower to defend against swarms or hordes of robotic adversaries. A generation of human warriors raised on video games may find that reality is starting to resemble those games. mw

Arbitrary Waveform Generator Leads Way With 256-GS/s

Keysight Technologies recently announced the release of its new M8199A, a 256-GS/s arbitrary waveform generator (AWG) with 65 GHz of analog bandwidth, which the company states delivers twice the sampling rate, 50% more analog bandwidth, and increased ENOB compared to other AWGs on the market. The M8199A features four channels with 128 GS/s and two channels of 256 GS/s with interleaving, and sports a 65-GHz nominal bandwidth of up to 80 GHz with roll-off calibration. The increased performance is driven by a new digital-to-analog converter application-specific integrated circuit (DAC-ASIC), translating the memory data into an analog signal. Keysight states that it has also created a new package that avoids soldering sensitive radio frequency (RF signals) by placing an RF connector at the DAC-ASIC to avoid signal degradation.

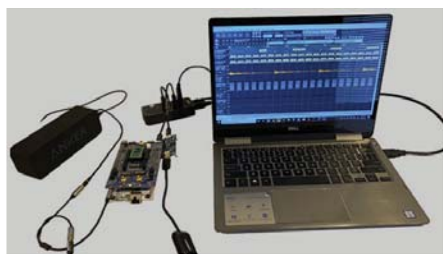
KEYSIGHT TECHNOLOGIES, https://www.keysight.com/en/pd-3076690-pn-M8199A/

High-Power Amplifier Targets 5G Apps

Spacek Labs' solid-state, high-power amplifier, Model SP392-35-33, maintains excellent performance characteristics from 36 to 41 GHz. With a saturated output power greater than 33 dBm, it is a candidate for applications such as 5G. The unit has a nominal gain of 38 dB with VSWR less than 2:1 using 2.92-mm coaxial connectors (waveguide I/O available). The amplifier requires a bias voltage of +8 V dc with 2.4 A quiescent current and ~4 A at 1-dB gain compression. It is supplied with a heat sink and dc fans which are removable for integration. Overall size without the heat sink is 1.70 x 1.54 x 0.31 in. (43.18 x 39.12 x 7.87 mm).

SPACEK LABS, www.spaceklabs.com

Ecosystem Provides for Analog Voice Activity Detection



Aspinity's Voice-First Evaluation Kit (EVK2) is a complete ecosystem providing an ultra-low-power edge processing platform for analog voice activity detection and preroll. The system allows developers to integrate analog machine learning and analog data compression into battery-operated voice-enabled devices, including hearables/wearables, smart speakers, and smart TV remotes. The EKV2 features the company's RAMP (Reconfigurable Analog Modular Processor), which uses near-zero power to analyze raw analog microphone data at the start of a signal chain to determine if a voice is present before triggering a wake-word engine. It also minimizes the power-on time of an ADC converter and WWE (Wake-Word Engine), increasing battery life by up to 10X.

ASPINITY, https://www.aspinity.com/Download-EVK2-Product-Brief

Power-Saving Infrared LED Serves VR/MR/AR Applications

ROHM's CSL1501RW ultra-compact side-emitting (side view) infrared LED is well-suited for head-mounted displays, industrial headsets, and VR/MR/AR (xR, virtual reality) gaming systems. The CSL1501RW delivers a peak wavelength of 860 nm in an industry-small (1.0 x 0.55 mm, t = 0.5 mm) side-view design that emits light parallel to the mounting surface, providing exceptional design flexibility. In addition, ROHM leverages its strengths in element manufacturing to improve luminous efficiency and reduce power consumption by more than 20%. The device serves as a light source for eye tracking in VR/MR/AR applications that require greater performance.

ROHM, https://www.rohm.com/products/optical-sensors/infrared-light-emitting-diodes/surface-mount-type-sideview/csl1501rw-product

Directional Coupler Monitors 40 to 65 GHz

Mini-Circuits' model ZCDC10-E40653+ wideband directional coupler maintains high directivity with excellent coupling flatness from 40 to 65 GHz. Directivity is typically 19 dB from 40 to 50 GHz and typically 17.9 dB from 50 to 65 GHz with 10-dB coupling within ±0.4 dB across the full frequency range. Mainline insertion loss (including coupling loss) is typically 1.4 dB from 40 to 50 GHz and 1.7 dB from 50 to 65 GHz. Input and output return loss is typically 21.1 dB from 40 to 50 GHz and 22.6 dB from 50 to 65 GHz. The RoHS-compliant directional coupler can pass as much as 300-mA dc current from input to output and can handle as much as 12-W RF input power across the full frequency range. The 50-Ω directional coupler is well-suited for testing and monitoring millimeter-wave signal power levels. It measures 1.25 × 0.63 × 0.50 in. (31.75 × 16.00 × 12.70 mm) in a rugged metal case and is supplied with 1.85-mm female connectors. The coupler has an operating temperature range of -55 to +100°C.

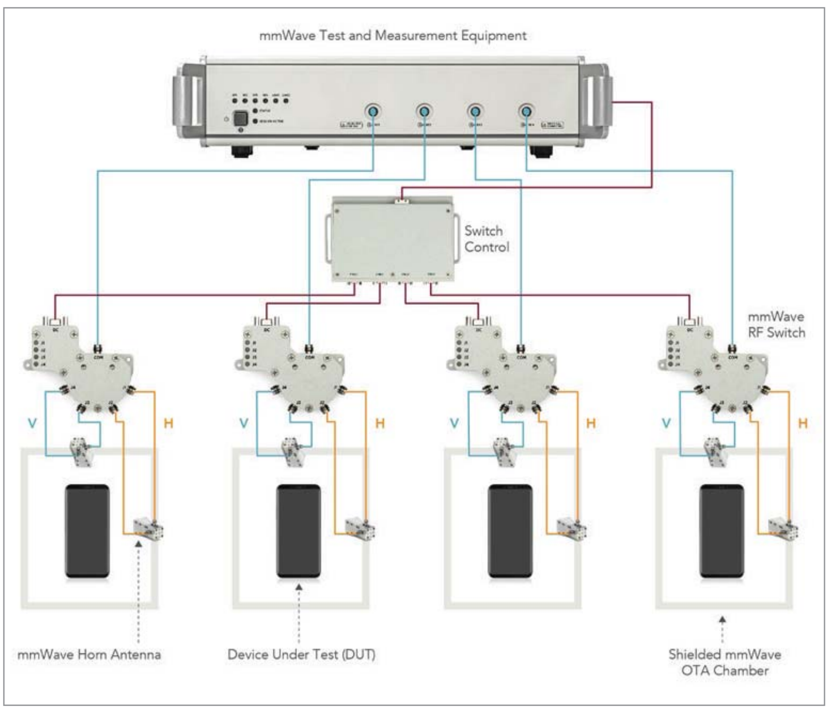
MINI-CIRCUITS, https://www.minicircuits.com/WebStore/dashboard.html?model=ZCDC10-E40653%2B

Validation Test for 5G mmWave

(Continued from page 18)

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:



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

- 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 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 in this article will continue to be important to the success of these early products. **mw**

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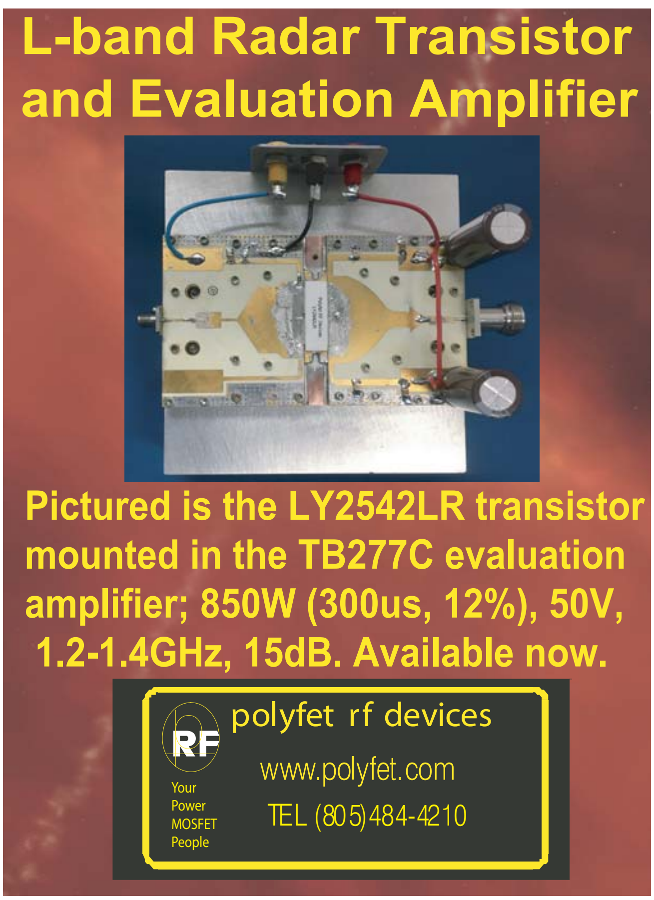
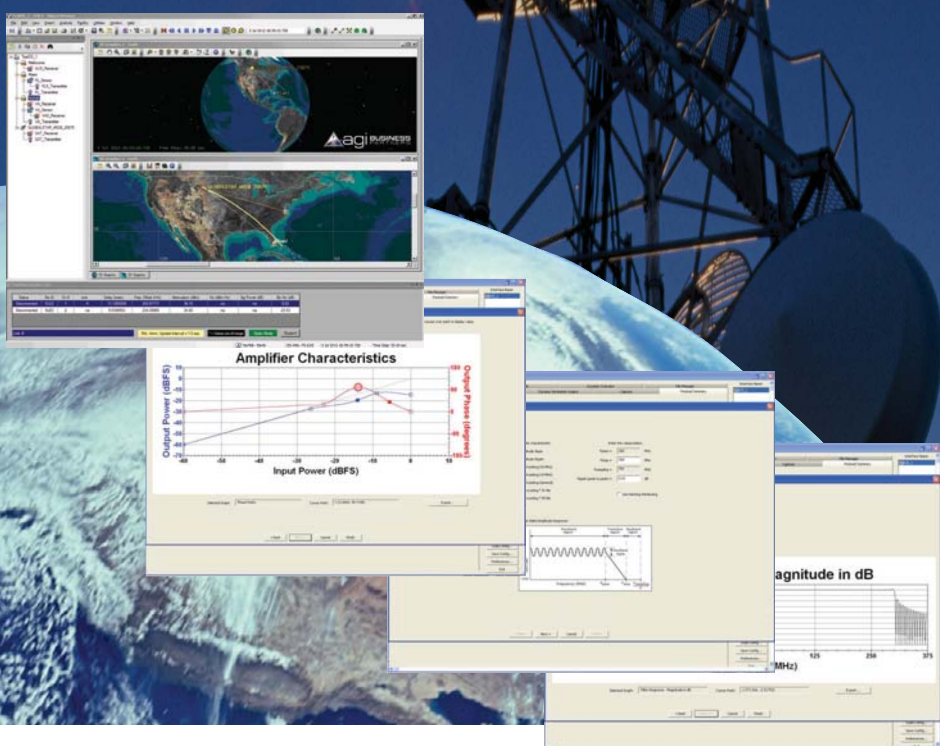


dBm
Advanced Channel Emulator



Amplifier Characteristics
Output Power (dBFS)
Input Power (dBFS)
Output Phase (degrees)
agnitude in dB