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IN MICROWAVES

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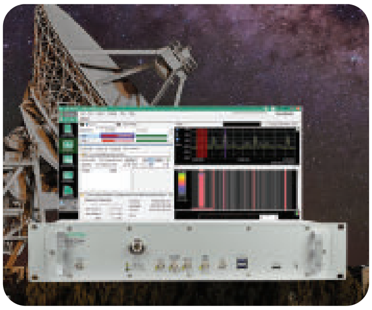

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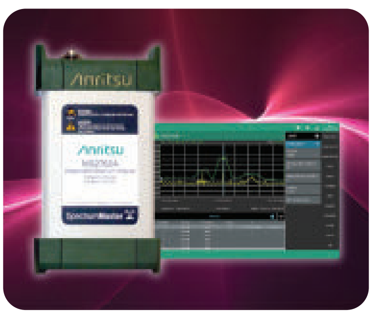

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Skyworks Solutions, Inc. is empowering the wireless networking revolution. Our highly innovative analog semiconductors are connecting people, places and things spanning a number of new and previously unimagined applications within the aero-space, automotive, broadband, cellular infrastructure, connected home, industrial, medical, military, smartphone, tablet and wearable markets.

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SKYWORKS®

FROM THE EDITOR

David Maliniak, Executive Editor

Thank Goodness for the **Innovators!**

Today's industry innovations aren't as earth-shaking as the transistor and the IC, but that doesn't mean they're not important.

INNOVATION—THE THEME of this special issue of *Microwaves & RF*—is the lifeblood of the industry. Imagine where we'd be if William Shockley, John Bardeen, and Walter Brattain of Bell Labs hadn't bothered to cobble together their point-contact transistor in 1947? The latter two, under the supervision of the former, were hoping to turn into reality something physicists had pondered since the 1920s. It's likely they didn't see their work as revolutionary as it happened. They were only hoping to make a better amplifier that drew less power than vacuum tubes.

Then, 11 years hence, Texas Instruments' Jack Kilby wanted to work out how to connect a few transistors while making them much smaller and more efficient. In 1959, TI filed a patent application for the "miniaturized electronic circuit," and the integrated circuit (IC) was born. Kilby got the patent for the concept, but Fairchild Semiconductor's Bob Noyce came up with the planar manufacturing process that made ICs take off. The rest, as we say, is history.

With all of the progress in the ensuing decades, it's become less commonplace for innovations in electronics to be quite as earth-shattering as the invention of the transistor and IC. That doesn't insinuate they're not important in the modern context. In this issue, we'll look at the impact wireless technologies are having across a range of industries, as well as some of the innovative technologies that will propel the RF and microwave industry forward in coming years.

For example, the extension of 5G networks into the mmWave portion of the spectrum will be a boon to the aerospace and defense markets. We'll be safer on the roads by virtue of improving advanced driver-assistance systems (ADAS) and vehicle-to-vehicle (V2V) communication links. And materials science continues to support the growth of wireless technologies through 3D printing of dielectrics, optimized dielectric constants in substrates, and more.

We hope you'll enjoy this special Innovators issue of *Microwaves & RF* as much as we did in putting it together.

David Maliniak

dmaliniak@endeavorb2b.com

Microwaves&RF

mwrf.com

EDITORIAL

Group Content Director: Michelle Kopier
mkopier@endeavorb2b.com

Senior Content Editor: Bill Wong
bwong@endeavorb2b.com

Executive Editor: David Maliniak
dmaliniak@endeavorb2b.com

Managing Editor: Roger Engelke
rengelke@endeavorb2b.com

Editor-at-Large: Alix Paultre
apaultre@endeavorb2b.com

Senior Staff Writer: James Morra
jmorra@endeavorb2b.com

Technical Editor: Jack Browne,
jack.browne@citadeleng.com

ART & PRODUCTION

Group Design Director: Anthony Vitolo

Art Director: Jocelyn Hartzog

Production Manager: Brenda Wiley

Ad Services Manager: Deanna O'Byrne

AUDIENCE MARKETING

User Marketing Manager: Debbie Brady
dmbrady@endeavorb2b.com

Article Reprints:
reprints@endeavorb2b.com

LIST RENTAL

Smartreach Client Services Manager:
Kelli Berry, kberry@endeavorb2b.com

DIGITAL & MARKETING

VP Digital & Data Innovation: Ryan Malec

SALES

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Jamie Allen, jallen@endeavorb2b.com

AZ, NM, TX: Gregory Montgomery
gmontgomery@endeavorb2b.com

CT, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT, EASTERN CANADA:
Elizabeth Eldridge
eeldridge@endeavorb2b.com

AK, NORTHERN CA, NV, OR, WA, WESTERN CANADA, AUSTRIA, BELGIUM, FRANCE, GERMANY, LUXEMBURG, NETHERLANDS, PORTUGAL, SCANDINAVIA, SPAIN, SWITZERLAND, UNITED KINGDOM:
Stuart Bowen,
sbowen@endeavorb2b.com

ITALY: Diego Casiraghi,
diego@casiraghi-adv.com

PAN-ASIA: Helen Lai
helen@twoway-com.com

PAN-ASIA: Charles Liu
liu@twoway-com.com

ENDEAVOR BUSINESS MEDIA

ENDEAVOR BUSINESS MEDIA, LLC

30 Burton Hills Blvd., Suite 185.,
Nashville, TN 37215 | 800-547-7377

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Wireless Technologies Boost Diverse Markets

By Jack Browne, *Technical Editor*

Adoption of wireless technology for electronic devices worldwide continues to ramp up across a range of industries—and that trajectory is expected to remain strong and steady for at least through the next decade.

WIRELESS TECHNOLOGY has supported billions of lives around the globe for several decades, typically in the form of cellular communications. But the reach of wireless is expanding far beyond cellular antenna towers, and the technology is growing rapidly in support of such major markets as aerospace and defense, automotive electronics, communications electronics, financial technology (fintech), healthcare/medical services, and industrial manufacturing and warehousing.

Adoption of wireless technology can be traced to how efficiently and effectively wireless-aided functions can be added to an application. It also depends on how well companies supplying hardware and software can realize those wireless functions in keeping with current trends within each market area.

As wireless integrators look to suppliers of wireless technologies for the most practical and timely solutions for their applications, those suppliers must develop innovative wireless products, and often methods to model and measure them, to fuel strong ongoing growth in the use of wireless equipment within many of these markets.

For many users, wireless technology begins each day with a cellular telephone on an advanced cellular network such as a 3G, 4G LTE, or 5G wireless system. But as the numbers of users on these networks rises to occupy more of their available frequency spectrum, the networks are running out of bandwidth.

Wireless 5G network operators have hoped that extension to higher frequencies in the millimeter-wave (mmWave) frequency range (24 GHz and higher) will add enough capacity for many new users. However, such dramatic increases in frequency coverage require installation and maintenance of higher-frequency 5G infrastructure equipment. The added bandwidth is being used by people and things, with growing numbers of Internet of Things (IoT) devices like sensors providing wireless access to data via the internet.

As wireless cellular networks expand their frequency ranges, they increase the need for higher-frequency test equipment. Growth of 5G networks and coverage requires essential test instruments such as oscilloscopes, signal generators, spectrum analyzers, and vector network analyzers (VNAs) with frequency ranges well into the mmWave frequency range.

GSMA, the global organization unifying the mobile communications ecosystem, recently projected (in a 52-page report) more than 6 billion mobile 5G subscribers worldwide by 2030. The report predicted many new 5G subscribers coming from India and Africa.

The benefit of 5G to the global economy is expected to be at least $950 billion in U.S. dollars (USD) by 2030. The business will come from smartphone users as well as many "things," such as wireless IoT devices, connected to the internet by fixed-wireless-access (FWA) services.

5G Networks Enhance Comms for Multiple Industries

In addition to wireless communications for the masses, 5G networks bring critical communications functions to automated industrial manufacturing assembly lines with fixed and mobile robots. Users in the general population can also gain internet access through public Wi-Fi systems.

Furthermore, 5G wireless networks are satisfying growing demands from individuals and businesses for virtual private networks (VPNs). These private wireless networks provide broadband connectivity for their owners and can be used for wireless connectivity throughout a company and its properties, such as warehouses, while still offering access to 5G networks. In some cases, automated factories and warehouses may employ communications by means of refined versions of 5G systems known as Private Industrial 5G networks, which meet the rigid requirements of manufacturing facilities.

Growth of 5G wireless communications systems will also be spurred by military users. Armed forces plan to adopt 5G spectrum, especially in the mmWave range, to apply 5G networks for real-time communications of command-and-control data for aerospace and defense applications. The generous spectrum capacity of 5G networks will boost the traditional DC-to-18-GHz frequency range of military systems, such as electronic countermeasures (ECM), electronic warfare (EW), and radar.

Extension of 5G networks into the mmWave frequency range will serve a growing number of applications within the aerospace and defense market, including for unmanned devices such as IoT sensors and unmanned aerial vehicles (UAVs) performing intelligence, surveillance, and reconnaissance (ISR) duties. Wireless 5G networks will share available bandwidth among commercial, industrial, medical, and military users as wireless applications expand in each market. 5G networks will provide military users with wireless access to high-speed data for critical missions, such as targeting and reconnaissance data.

Military demands for mobility and portability continue to encourage long-term design efforts for reduced size, weight, and power (SWaP) in electronic systems. Strategies to create components and PCBs with increased functionality and smaller size have carried over into other markets and supported component-dense monolithic microwave integrated circuits (MMICs) and power-dense semiconductor substrates such as gallium nitride (GaN).

In general, the use of 5G networks and adoption of newer technologies such as robots and UAVs are part of a general trend in the modernization of all branches of the U.S. armed forces. Both unmanned ground vehicles (UGVs) and UAVs employ wireless connectivity for communications and control.

Tactical UAVs are typically equipped with weapons, radar, communications systems, and GPS receivers to aid in target location, while ISR drones carry high-resolution cameras and their wireless communications links with bandwidths suitable for video exchanges. In all cases, remote-controlled battlefield drones require some form of wireless links or networking as the armed forces seek to adopt the most advanced electronic technologies available, including broadband wireless communications at mmWave frequencies.

Increasing use of UAVs for commercial business will also result in greater wireless use within those systems as numbers of commercial drones grow steadily within the next decade. According to research firm Grand View Research, the global commercial drone market was estimated at U.S.$19.89 billion in 2022 and is expected to grow at a compound annual growth rate (CAGR) of 13.9% from 2023 to 2030, contributing to the use of wireless technology in airborne applications.

Over the coming years, wireless radio waves can be expected to continue to fill frequency spectrum as electronic systems communicate through airwaves and space waves.

While military comms still largely depend on Earth-based infrastructure, a growing number of communications links will come from space as the U.S. Space Force increases the size of its constellation of low-Earth-orbit satellites (LEOs). Having recently absorbed the U.S. Space Development Agency (SDA), the Space Force is seeking to reinforce ground-based wireless functions such as communications and weather monitoring from orbiting satellites and will be adding to the numbers of LEOs.

At the same time, commercial wireless comms service providers will be growing their LEOs constellations in efforts to eliminate gaps in coverage in their 5G wireless networks, combining terrestrial and space-based infrastructure equipment.

Wireless Hits the Road

Increasing use of electronic components and systems in motor vehicles will continue to drive demand for practical semiconductor solutions for applications such as vehicle-to-vehicle (V2V) and advanced driver-assistance system (ADAS) equipment.

Whether for vehicles with traditional internal-combustion engines, electric vehicles (EVs), or hybrid electric vehicles (HEVs) with a combination of engine technologies, radar-based ADAS gear relies on safety-critical components. These devices must be cost-effective but also precise and reliable under a wide range of operating conditions. For many vehicle owners, ADAS is simplifying driving, adding such functions as emergency braking and lane monitoring, and will continue to advance toward more autonomous vehicles.

Safer ADAS vehicles and their mmWave radar systems rely heavily on accurate measurements. As a result, major instrument suppliers have been extending the frequency ranges of signal generators and analyzers, while some even developed specialized test system solutions for characterizing ADAS equipment.

As an example, Rohde & Schwarz recently introduced a radar test system (RTS) tailored to ADAS testing at mmWave frequencies. The R&S AREG800A automotive radar echo generator can perform single-sensor ADAS testing as well as 360° automotive radar testing from 76 to 81 GHz *(Fig. 1)*. Consisting of an automotive signal echo generator and the R&S QAT100 antenna array, the system will help trim the time-to-market for many ADAS equipment suppliers and support the growing wireless automotive market.

According to the research firm MarketsandMarkets, the 2022 U.S. market for ADAS electronic devices was $30.9 billion and is projected to grow to $65.1 billion by 2030 at a CAGR of 9.7%. About one-half of the worldwide automotive semiconductor market is served by five major suppliers: Infineon Technologies, NXP Semiconductors, Renesas Electronics, STMicroelectronics, and Texas Instruments.

Of course, as more vehicles on the road rely on ADAS safety systems and are linked by wireless interconnections, they become vulnerable to "hackers" capable of remotely controlling (and stealing) a vehicle by wireless transceivers. The growth of automotive wireless applications is elevating the need for automotive cybersecurity software and electronic security systems to ensure that a wirelessly equipped vehicle remains in its proper parking spot.

1. The R&S AREG800A automotive radar echo generator simulates operating conditions of ADAS mmWave radar pulses from 76 to 81 GHz. Rohde & Schwarz

Sometimes lost within the fast-growing automotive electronics market is the rapidly growing market for wireless-charging equipment, not just for EV batteries but for battery-powered medical and wearable electronic devices, cell phones, tablets, and other portable electronic devices. Grand View Research values the 2022 global wireless-charging market size at U.S.$12.92 billion and projects it to grow at a CAGR of 13.4% from 2023 to 2030. The growth rate is strong because of the use of wireless charging across so many different apps, including for aerospace and defense, automotive, healthcare, and industrial equipment charging.

Applications new to wireless technology are adding to demand for frequency spectrum and wireless connectivity. On the medical side, for example, wireless communications links are being incorporated into all healthcare monitors, such as heart-rate and blood-pressure monitors, to ease a physician's task of checking the status of patients within a hospital or a private practice.

Inclusion of a wireless connectivity scheme such as Bluetooth, Wi-Fi, or Zigbee within a healthcare monitor enables a doctor to monitor multiple patients while in motion throughout a facility, using a battery-powered laptop computer or tablet. Networking a patient's data within a healthcare facility also allows for greater freedom of movement for the patient and ready access to the patient's data for nurses and other medical professionals within a facility.

Proliferation of wireless technologies within the healthcare industry is supporting increasing home care and remote diagnostics of patients. That's often made possible by a combination of wireless connectivity standards such as in-building Wi-Fi linked to a wireless cellular system like 3G, 4G LTE, or 5G.

Trend Setters in Wireless Tech

Software-defined-radio (SDR) technology provides some degree of flexibility for applications facing harsh conditions, such as the radiation of space missions. Suppliers of modular SDR components, like Trident Systems, make it easier and quicker to develop space-qualified SDR communications systems.

In wide-area networks (WANs), where traffic is routed through the internet with the aid of cloud software, large amounts of data can be transferred between parties instantaneously. SDRs can facilitate that transfer. SDR systems include software-defined antennas (SDAs) typically implemented by densely integrated semiconductors, such as system-on-chip (SoC) devices, in which the equivalent functionality of a complete wireless system is housed within a surface-mount-technology (SMT) package.

As SDR and other radio architectures expand into different wireless markets and applications, opportunities emerge for innovative semiconductor technologies capable of supporting increased functionality in smaller-sized devices operating at lower power levels. One of the most impressive semiconductor technologies for present and future wireless systems is the approach employed by Analog Devices (ADI), in which what was once contained on several PCBs is now integrated within a single miniature package.

ADI's AD9084 Apollo mixed-signal front-end (MxFE) monolithic IC *(Fig. 2)* provides flexible, wideband multichannel transmit and receive functions by means of four digital-to-analog converters (DACs) and four analog-to-digital converters (ADCs). But these are not just any ADCs and DACs—the 12-bit ADCs and 16-bit DACs operate at a maximum sample rate of 20 Gsamples/s.

The IC features low-loss, high-speed interconnections and supporting components such as filters and multiplexers as well as more complex components like a clock multiplier and on-chip digital signal processor (DSP). It's housed within an 899-ball ball-grid-array (BGA) package measuring just 24 × 26 mm and capable of handling operating temperatures from −40 to +110°C. The device helps shrink the size of systems processing signals with wide instantaneous bandwidths, while consuming no more than 30 W. Versions are available for maximum transmit and receive RF bandwidths including Ku-band.

Material Matters

Advanced electronic materials are essential to support the growth of wireless technologies in all major markets, and novel ways of fashioning those materials will help enhance wireless performance.

2. The highly integrated model AD9084 Apollo SoC packs four ADCs and four DACs into a surface-mount package. Analog Devices

Three-dimensional (3D) printing, when starting with suitable substrate materials, can now produce circuit and device features with desirable characteristics at mmWave frequencies.

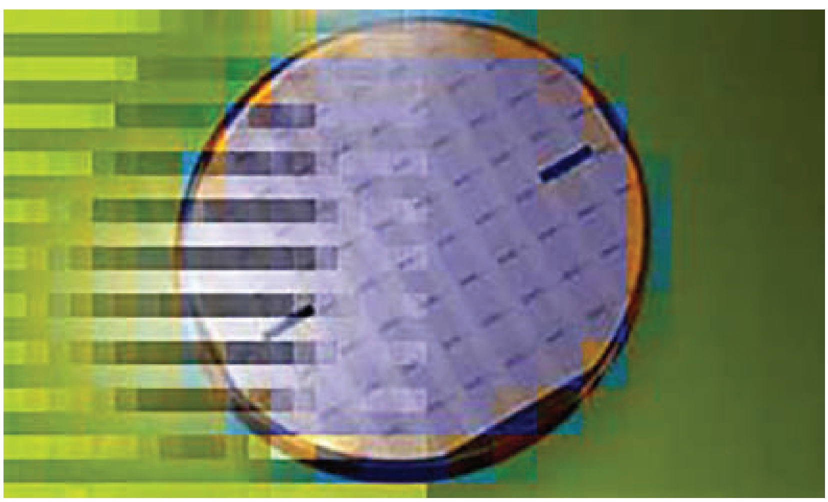
Printable dielectric materials such as Radix from Rogers Corp. speed the way to creating advanced 3D antenna systems for emerging wireless applications, even at mmWave frequencies. With a low dielectric constant (Dk) of 2.8 at 10 GHz in the z dimension (thickness) and loss or dissipation factor (Df) of typically 0.0046 in the z axis at 24 GHz, the dark blue resin can be quickly formed into a desired shape on a FLUX 3D printer from Fortify using the printer's digital-light-processing (DLP) engine.

GaN is a semiconductor substrate material capable of high power density at high frequencies. It's been the basis for such devices as high-electron-mobility transistors (HEMTs) for high-power microwave and mmWave power amplifiers. These solid-state amplifiers are steadily replacing more traditional large-signal technologies such as traveling wave tubes (TWTs) and traveling-wave-tube amplifiers (TWTAs) in commercial, industrial, and military markets.

In addition to large-scale wafer and device capabilities from BAE Systems, Qorvo offers extensive GaN materials and devices for commercial and aerospace and defense applications *(Fig. 3)*.

For components that must handle higher power levels in limited space, low-temperature-cofired-ceramic (LTCC) materials support miniaturization without sacrificing reliability from heat at higher power levels. Using proprietary LTCC substrate materials, Mini-Circuits has developed high-frequency filters capable of handling 1 W or more power in miniature SMT packages.

For example, the model BFCQ-4302+ bandpass filter has a passband of 36.5 to 50.0 GHz, a lower stopband of 100 MHz to 27 GHz, and an upper stopband that extends to 70 GHz. With typical 2-dB passband insertion loss, it can channel



3. GaN substrates enable the formation of high-power-density semiconductor devices that contribute to the miniaturization of high-frequency electronic circuits. Qorvo signals of 1 W or more through a package that measures only 2.5 × 2.0 mm.

Put to the Test

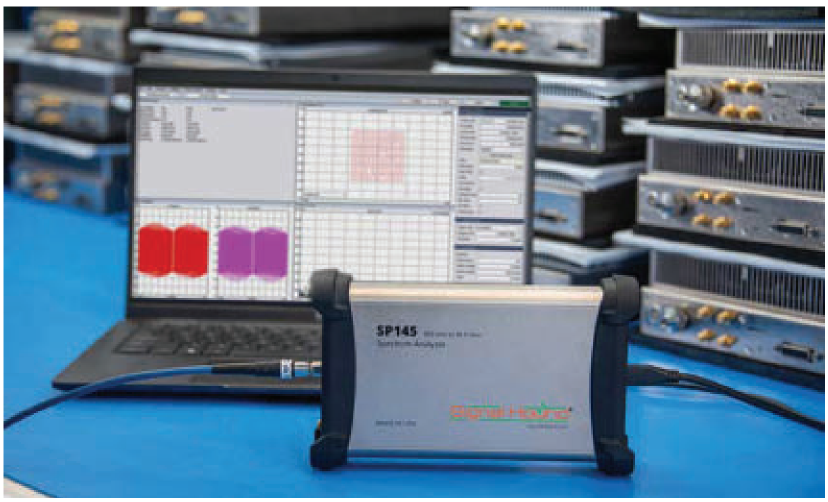
Rapid adoption of 5G and other wireless technologies must be backed by suitable measurement capabilities and test equipment. Many of the major test instrument suppliers have already developed test signal sources and analyzers capable of operation into the mmWave frequency to support evaluation and maintenance of applications such as 5G and ADAS equipment.

With the spread of wireless equipment, greater numbers of test instruments will no doubt be needed. Companies such as Copper Mountain Technologies and Signal Hound are developing practical solutions that don't sacrifice performance for cost.

The model S5243 two-port VNA from Copper Mountain Technologies is a compact module that connects to a computer via USB interface to form a VNA capable of measuring all four scattering (S) parameters from 10 MHz to 44 GHz *(Fig. 4)*. It can perform power sweeps along with linear and logarithmic frequency sweeps across a dynamic range of 135 dB and works with Windows or Linux test software. The VNA is representative of a trend in high-frequency test equipment away from larger, "rack-and-stack" equipment enclosures to smaller modules that support mobile and portable testing in facilities as well as on the road.

The SP145 real-time spectrum analyzer from Signal Hound packs all of the functionality of a full-size spectrum analyzer into a USB-C module measuring just 7.45 × 4.51 × 1.81 in. (189 × 115 × 46 mm) and weighing 1.1 lbs. (0.5 kg), but it's capable of scanning from 100 kHz to 14.5 GHz *(Fig. 5)*. With sweep speeds as fast as 200 GHz/s, displayed average noise level (DANL) of –160 dBm, and built-in GPS receiver, the little analyzer is well-suited for use as a remote-site spectrum monitor. It marks the latest addition to the company's lines of affordable and modular signal generators and analyzers.

4. The S5243 module connects to a personal computer via USB interface to form a two-port, 44-GHz VNA. Copper Mountain Technologies



5. The model SP145 14.5-GHz real-time spectrum analyzer fits into a USB-C module measuring just 7.45 × 4.51 × 1.81 in. (189 × 115 × 46 mm). Signal Hound

Conclusion

Over the coming years, wireless radio waves can be expected to continue to fill frequency spectrum as electronic systems communicate through airwaves and space waves. The market areas detailed here should all experience strong expansion, with some markets, such as wireless medical equipment, undergoing significant growth over the next decade.

The increased reliance on wireless electronic interconnections for smaller, more lightweight electronic products will encourage the continuing development of highly integrated, miniature designs. This also challenges test-and-measurement suppliers to perform more advanced measurements at higher speeds in support of accelerated times to market and increasing product-line volumes. ■

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ACCEL-RF INSTRUMENTS CORPORATION

WEB | www.accelrf.com
EMAIL | info@accelrf.com
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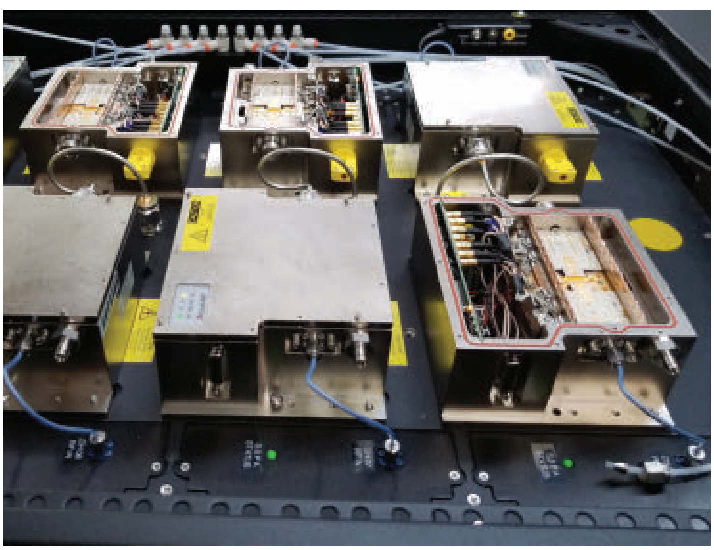
For 20 years, **Accel-RF Instruments Corporation** has been the world leader in supplying equipment for performing high temperature, long-duration reliability testing on compound semiconductors. Accel-RF specializes in the development, design, and production of accelerated life-test/burn-in test systems for GaN and other RF compound semiconductor devices. These systems are turn-key integrated instruments that provide a cost effective, high value proposition for device manufacturers, fab-less device suppliers, testing-service providers, original equipment manufacturers, system integrators, and research and development laboratories. These test platforms are capable of identifying device wear-out and performance degradation to end-of-life (EOL) expectations, usually measured in millions of hours. Accel-RF's test equipment has enabled the successful technology development, product launch, and industry adoption of GaN transistors and MCMs into the space, military, and commercial wireless 4G/5G markets.



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Accel-RF
Instruments Corporation
4380 Viewridge Ave., Ste D
San Diego, CA 92123
858-278-2074
info@accelrf.com
www.accelrf.com

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Despite Supply-Chain Disruptions, the Microwave Industry Powers Ahead

Though challenges persist in the defense, automotive, and IoT sectors, the microwave and RF industry continues to proliferate and is forecast to maintain that pace into the foreseeable future.

***By Joel Levine,** President, RFMW*

THE SUPPLY-CHAIN ISSUES that affected many industries in recent years have also had a significant impact on the RF and microwave industry. The shortage of semiconductors and other components led to production delays, increased prices, and reduced innovation. Despite the challenges, the industry will continue to grow in the coming years, driven by greater use of RF and microwave technologies in applications ranging from 5G and IoT to satellite communications and defense systems.

Nonetheless, the industry hasn't been immune to disruption. As a distributor of RF and microwave components and subsystems, RFMW has a wide-angle perspective of the broader RF/MW market and its myriad of customers because it serves not just itself, but the dozens of companies whose products it sells. From this vantage point, RFMW has seen and continues to see the consequences of what's occurred since 2020.

It hasn't been easy. First came the pandemic in early 2020 that caused factories in China and other countries to shut down or reduce production, after which the U.S. imposed tariffs on Chinese goods, including electronics components. Then, around September 2020, the demand for all types of components surged, driven by people working from home or school. And to make matters worse, severe winter storms in Texas damaged factories, and a drought followed in Taiwan.

The result of all this has been a frantic back and forth between supply and demand, with prices increasing, then decreasing, then increasing again, and so forth. It's also caused companies to place orders for large numbers of devices to ensure supply, only to decide later that they don't need them for some reason.

1. The Next Generation Jammer (NGJ) airborne electronic attack system for the EA-18G Growler electronic warfare aircraft, which uses a GaN-based active electronically scanned array (AESA), relies extensively on advanced microwave devices. Raytheon

This further contributes to issues that disrupt the supply chain and needlessly prolong the problem.

All of this has occurred as the wireless industry tries to deploy 5G infrastructure, the satellite broadband industry continues to launch more satellites, and vehicles become wirelessly connected. The defense industry is faced with trying to supply Ukraine with electronic warfare, electronic countermeasures, radar, and air defense and communications systems while attempting to replenish resources at home.

Such systems rely on RF and microwave components from passives to discrete semiconductors and MMICs, integrated microwave assemblies, and multifunctional solutions driven by software-defined radios that combine analog and digital devices in a single package.

Delays in Defense System Production

The defense industry has been hit rather hard by the shortage of RF and microwave components because they're foundational components of so many platforms *(Fig. 1)*. The shortage has led to production delays, increased costs, and even shortages of some critical military equipment. In several cases, the U.S. Department of Defense was forced to delay or cancel projects.

For example, the Navy's Littoral Combat Ship program has been delayed by several years due to the shortage of RF and microwave components, and the Air Force F-35 Joint Strike Fighter program felt the impact as well, with some aircraft supplied without critical components. The Army's Abrams tank program has been affected by the shortage, too, with some tanks being delivered without the latest communication systems.

Military electronics suppliers, from printed-circuit-board makers to prime contractors and system integrators, are pivoting from traditional procurement practices to accommodate the reality of today's markets. In short, they must get creative and find new ways to source components and materials and manufacture and evaluate their products.

Another sector severely hit by RF and microwave device shortages is the automotive industry. These are the critical components for radar systems used in adaptive cruise control, automatic emergency braking, and situational awareness. They're also implemented in tire-pressure monitoring and keyless entry systems.

Connected vehicles rely on RF and microwave devices for communication, navigation, and infotainment systems. The shortage of these devices has made it difficult for automakers to produce vehicles with the required level of connectivity, leading to production delays and increased costs. The shortage of radar chips has forced automakers to either delay production of these vehicles or remove the radar systems altogether.

The satellite communications industry has also felt the effects of the chip shortage, with delays in manufacturing and launch schedules. SpaceX said that the chip shortage delayed the production of new user terminals for its Starlink satellite broadband service *(Fig. 2)*.

OneWeb, a satellite broadband company competing with Starlink, said that the chip shortage delayed the launch of its constellation of satellites. The company has also been forced to make some design changes to its satellites to use fewer chips. And Inmarsat stated that the chip shortage made it difficult to procure the necessary components for its ground equipment.

2. Space X currently has more than 5,700 Starlink satellites in orbit, launched at up to 64 at a time from a payload bay like this one. Wikipedia www.coppermountaintech.com

COPPER MOUNTAIN®
TECHNOLOGIES

About CMT

In 2011, Copper Mountain Technologies launched the industry's first metrology-grade USB VNA. This gave users access to affordable and portable analyzers **without sacrificing performance.** Since then, the company has provided engineers not just with flexible VNA solutions, but also included comprehensive support from expert RF engineers with each VNA purchase.

CMT's product line includes over **30 instruments and VNA solutions** in configurations up to 16-ports, measuring in frequency ranges up to 330 GHz, with options for direct receiver access, frequency extension, and software compatibility for Windows and Linux OS.

CMT provides superior customer value through an unparalleled combination of price, performance, and partnership. We believe that it is critical for engineers to have access to equipment that allows them to do their best work. We provide complete VNA solutions that deliver all the functionality you need with **no hidden fees and a standard 3-year warranty**. Every user has access to rapid technical support from VNA experts, **empowering users** to get the most out of their equipment.

Price

The development of metrology-grade USB VNAs resulted in giving more users access to high-quality VNA measurements at an affordable cost. The **FREE** VNA software features an intuitive user interface and can be installed on multiple PCs without a license. Advanced software features, such as time domain reflectometry and gating, frequency offset, TRL Calibration, etc., come at no additional cost, enabling **maximum functionality for ALL users.**

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CMT's metrology-grade analyzers provide traceable performance and measurement accuracy. From antenna design to SAW & BAW filters and cable assemblies production, to telecom systems field service, CMT analyzers are used by thousands of engineers worldwide. The VNAs are designed for easy customization to deliver **high-performing insertable measurement modules** for unique applications. The versatility of CMT VNAs has enabled successful integration into NASA space station fuel systems, a breast cancer detection system, ultrasound technology, crop moisture and ripeness sensors, and various R&D projects. The list of complex environments benefiting from CMT VNAs continues to grow.

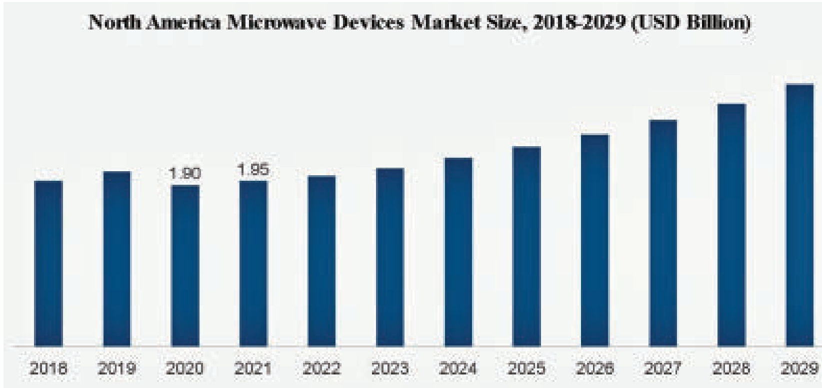
Partnership

All customers are supported by expert applications engineers who work as an **extension of your team** to ensure the best implementation of your measurement application. Timely customer support is included as part of our **total VNA solution**. Our team supplies automation scripts and programming manuals, assists with system integration, and performs remote demonstrations, as well as helping with the overall design, development, and implementation of your measurements. In addition to our Indianapolis headquarters, we offer global support with international sales offices, as well as an R&D and service center at CMT Europe in Cyprus which provides a more convenient repair and calibration location to our customers worldwide.

"I'd say the technical support has been the separator, CMT's support team was very patient and helpful as they walked me through all my questions. They also provided custom Python scripts that resolved my issue and made automation trivial."

– Andrew Betts, Butterfly Network

Metrology-Grade USB Vector Network Analyzers
Measurements from 9 kHz to 330 GHz



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IoT Takes a Hit

One of the most significant impacts of the shortage revolves around the production of smart-home devices that rely on RF and microwave devices for connectivity. Limited supply of these devices has led to delays in product launches of IoT devices that inherently rely on connectivity.

For example, wearable devices use RF and microwave devices for wireless communication, GPS tracking, and heart-rate monitoring. The shortage of these devices has made it difficult for manufacturers to produce wearable devices, leading to delays and increased costs.

It's also impacted the medical instruments market, where these components are essential for devices ranging from MRI machines and X-ray machines to pacemakers, defibrillators, and other monitoring systems.

As Taiwanese contract manufacturer TSMC accounts for about two-thirds of global semiconductor fabrication, looming uncertainties could create a major problem for a large portion of the electronics industry. And even though TSMC has been slowly creating a foundry in Arizona, it's still looking for employees with the experience to run it.

However, for the RF and microwave industry, other foundries play a more important role than TSMC. For example, WIN Semiconductors, the world's first pure-play, 6-in., gallium-arsenide (GaAs) foundry continues to expand its capabilities to meet the demand for GaAs MMIC and RFICs. In addition, Qorvo fabricates a broad range of RF and microwaves, from gallium-nitride (GaN) SoCs to power-management ICs, switches, RF front ends, filters, and many others.

Costly Materials

Another challenge facing the RF and microwave industry is the increased cost of raw materials such as copper and gold, which has risen significantly in recent years and led to higher prices for some RF and microwave products. Other materials, such as rare-earth metals, have also bumped up in price. Although the industry doesn't require enormous amounts of metals, such as is the case with cobalt in the automotive industry, copper is fundamental to everything it makes.

It also uses gallium in reasonably large quantities, which has also increased in price, and China's decision to almost cut the U.S. entirely off from importing gallium and germanium hasn't helped. According to various reports, exports to the U.S. slumped to zero in August.

Even traveling-wave tubes use rare-earth metals like samarium and cobalt in their permanent magnets and others such as iron, copper, and zirconium. Some have become more expensive and sometimes difficult to procure due to the rapid development of electric vehicles. Fortunately, they use these metals in lesser amounts, and the industry's total global consumption is a tiny fraction of what the EV market demands, so supply-chain disruption has remained moderate.

RF and microwave companies are also redesigning their products to make them less reliant on scarce components. For example, some companies now use diverse types of materials, such as aluminum, instead of copper. They're also investing in new technologies, e.g., 3D printing, to improve manufacturing efficiency and reduce reliance on traditional supply chains.

Fortunately, one issue the industry doesn't have to deal with is the increasing demand for devices like GPUs, which data centers require to keep pace with the massive amounts of data they must process. Their requirements are increasing exponentially thanks to artificial intelligence, which has gone from something likely to appear in the future to a global frenzy.

Need Outweighs Concerns

Although supply-chain problems are expected to continue well into 2024, what's most remarkable for the RF and microwave industry is that despite supply-chain disruptions, the market has nevertheless been proliferating and is almost certain to continue to do so for as long as market forecasters care to predict *(see chart above)*.

After all, 5G must meet expectations, and the propagation challenges of the millimeter-wave region still must be solved. Combine the auto industry's need for connectivity, the proliferation of IoT devices, and the lessons learned from the supply disruption, and the future for the industry appears rosy. ■

bojanp_29819112 | Dreamstime

Harnessing the Power of 5G
for Better Indoor Connectivity

Growing adoption of 5G mobile technology is disrupting connectivity. But what does this mean for in-building communications, where approximately 80% of all mobile voice and data traffic occurs?

By ***Slavko Djukic,*** *VP of Product Line Management and Technology, SOLiD Americas*

SINCE MOBILE NETWORK OPERATORS (MNOs) started rolling out the first 5G networks roughly five years ago, this latest mobile technology continues to experience a meteoric rise. In fact, 5G is on record as scaling faster than any previous generation of mobile wireless technology.

In North America, 5G connections already account for a market penetration of 36% of the population, and worldwide 5G networks are on track to add nearly a billion new connections each year to reach 6.8 billion by the end of 2027.

Despite this obvious success—or perhaps in part because of it—5G technology is still facing several hurdles to be overcome and challenges to be addressed. This is particularly true when it comes to mobile communications that either originate or terminate indoors.

The Rise of 5G

For the most part, the unprecedented scale and impact of 5G is due to the disruptive nature of this technology. Thanks to the ability to deliver higher capacity, faster data speeds, and lower-latency connectivity, 5G enables a wide array of new capabilities, such as:

- *Enhanced Mobile Broadband (eMBB):* More throughput at faster speeds for enhanced data rates, expanded coverage, and improved data-sharing efficiency.
- *Ultra-Reliable, Low-Latency Connections (URLLC):* Near real-time interaction and controls allow the network to support new use cases in manufacturing, healthcare, and military applications.

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1255 Armour Blvd.,
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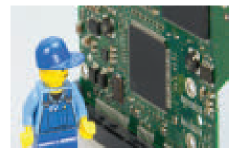
JQL Technologies specializes in the design and manufacture of ferrites and filters, up to 110 GHz. Ferrite devices include isolators, circulators, waveguides and microstrip devices in various topologies. RF and microwave filters include bandpass, lowpass, highpass, cavity, duplexers, triplexers, multiplexers and subassemblies of ceramic, cavity, waveguide and ceramic waveguide filters. JQL supplies for many of today's most significant military, commercial and homeland security programs around the world. Applications include satellite communications and space, radar, radio communications, fire control radars, telemetry applications, missile guidance systems, mobile radio base stations, public safety systems and air traffic control and communications. ***JQL is one of the world leaders for Surface Mount*** isolators and circulators for 5G applications. Surface Mount devices come in microstrip and in PCB mount topologies.

JQL, an ISO 9001 and AS9100 certified company, has significant global presence with manufacturing in USA, Italy, Malaysia & China. JQL acquired Dorado, established in 1979 and a leader in RF, Microwave & Millimeter wave components in 2016. Later, JQL acquired Ferrocom RF Corporation, also established in 1979, and a key player in the Military and Satcom markets. To strengthen the European operation, JQL acquired TEBO Spa in Italy in October 2023, a leader in EMS with over 40 years in the field of electronics, serving telecommunication, defense, automotive & medical.

JQL's combined engineering strength, along with a vast array of microwave test equipment, has placed the corporation on a solid base to provide customized solutions to the Military, Aerospace, Space and Satcom markets. Since 2018, JQL has successfully participated in global space programs, supplying microstrip and surface mount devices to reputed organizations.



JQL is one of the pioneers in surface mount devices for LEO, MEO & GEO satellite programs. JQL is totally committed to provide their customers with high quality products. The RF filters offered by JQL are subjected to undergo rigorous inspection and tests per MIL STD before being launched. Equipped with "state of the art" machine shop and testing labs in a sprawling 150,000 square foot facility, JQL is extremely confident of meeting the specifications of the customers and deliver a totally compliant product. The brand JQL is a mark of excellence in terms of quality and customer service.

JQL manufacturers a range of filters from 30 MHz up to 40 GHz in various topologies. The current output is approximately 5000 filters a month which includes global commercial and military market. Ceramic and ceramic waveguide filters consume nearly 70% of the capacity.

- *Massive IoT and M2M Communications:* The ability to support many more devices per unit of area than 4G/ LTE while enabling longer battery life in connected devices.
- *Network Slicing:* Virtual logical networks, or "network slices," within a single physical network allow for segregation of targeted use cases with varying levels of service and security.

These capabilities, in turn, enable mobile network operators (MNOs), enterprises, and manufacturers to develop innovative services with the power to revolutionize nearly every industry—from healthcare, industrial manufacturing, and retail to logistics, real estate, hospitality, and education.

With 5G eMBB capabilities, virtual-reality (VR) and augmented-reality (AR) technologies can be leveraged to create immersive experiences for telehealth, scientific research, education, and premier guest experiences in the hospitality industry and throughout event venues.

Likewise, capabilities such as massive IoT connectivity, network slicing, and intelligent positioning enable realization of mission-critical Industry 4.0 use cases, including predictive maintenance, manufacturing automation, real-time asset tracking, and occupational health and safety, implemented with high accuracy and low latency.

These 5G advances are due to fundamental network architecture changes made as the technology evolves from 4G, as specified in the 3GPP standards. Although these evolutionary transformations enable significant improvements in mobile network speed, quality, latency, and reliability, they also affect how 5G networks perform indoors.

Indoor 5G Access

As more consumers and businesses worldwide adopt 5G, there are mounting expectations of seamless 5G connectivity everywhere, all the time. This includes indoors where roughly 80% of all mobile voice and data traffic occurs. Whether in an office building, hospital, airport, subway, hotel, or stadium, subscribers demand always-on mobile service in today's hyper-connected world.

Moreover, 5G data connectivity has become essential to day-to-day business for many organizations. For example, a growing number of healthcare facilities have adopted a bring-your-own-device (BYOD) policy. This means that to reliably access electronic healthcare records and application data, physicians and staff need secure and reliable connectivity to at least three of the major MNO networks. And in offices or other commercial properties, building owners rely on 5G and the IoT to automatically control building systems such as security cameras, lighting, and smart thermostats.

Yet, even before the evolution to 5G, legacy mobile network service was typically unreliable inside most modern buildings. Energy-efficient Leadership in Energy and Environmental Design (LEED) building materials, congested network traffic, and nearby obstructions that block radio-frequency (RF) transmissions all contribute to spotty in-building coverage and dropped calls.

To address these connectivity issues, many building owners and network operators have traditionally installed distributed antenna system (DAS) platforms to deliver and amplify mobile network signals throughout buildings and campuses. Now the transition to next-generation 5G is creating new in-building connectivity challenges.

5G Connectivity Complexity

As demand for mobile data capacity escalates, the Federal Communications Commission (FCC) continues to make new RF spectrum available to alleviate bottlenecks, including both frequency 1 (FR1) bands below 6 GHz, and frequency 2 (FR2) bands above 6 GHz. However, many of the new frequencies used for 5G are even less capable of penetrating buildings than previous spectrum deployed for 3G and 4G/ LTE networks.

Initial allocations of FR2 mmWave frequencies between 24 and 40 GHz didn't provide an economical solution for wide-area 5G deployment. Because these high-band frequencies offer such poor propagation over long distances, MNOs need to build very dense networks to avoid coverage gaps, making these frequencies impractical outside densely populated urban areas.

However, the 5G mmWave frequencies are also easily blocked by most objects and building materials, including energy-efficient glass. Thus, service can be unreliable both indoors and outdoors in built-up city neighborhoods.

More recently, the FCC made available new mid-band spectrum for 5G, including the C-band (3.7 to 3.98 GHz), Citizens Broadband Radio Service (CBRS, 3.55 to 3.7 GHz), and the spectrum dubbed "Auction 110" by the FCC (3.45 to 3.55 GHz), which is also known as Lower n77. These mid-band frequencies offer an optimal mix of speed, capacity, and coverage.

In turn, most MNOs are taking advantage of them to build out their networks

Challenges	AWS	C-Band	Difference
Pilot Power	LTE 20 MHz -30.8dB	NR 100 MHz -35.2dB	4.4dB
Pathloss	58dB at 30 Feet	63dB at 30 Feet	5dB
Cable Loss	100' ½" Superflex 3.1dB	100' ½" Superflex 4.4dB	1.3dB/100'

1. When upgrading DAS platforms from legacy AWS bands to C-band, overall signal loss can be as much as 20 dB due to channel size, clutter, free-space path loss, and other factors, although these values will vary according to each building configuration. SOLiD Americas more cost-effectively and enhance wide-area 5G capacity and speed for a better user experience. Plus, because the CBRS spectrum includes some general authorized access (GAA) channels that are unlicensed, other organizations are also using this spectrum to build private 5G networks for a range of enterprise and industrial applications.

Nonetheless, this new mid-band spectrum occupies a higher frequency range than traditional mobile network spectrum, limiting transmission distance and signal strength. As a result, although Tier 1 MNOs are rolling out more wide-area 5G networks using mid-band frequencies across the U.S., these frequencies still can't penetrate building materials, leaving many building tenants, visitors, and employees without ready access to 5G services indoors.

Building Out In-Building Coverage

As network managers and building owners plan their in-building 5G strategy, the first step is to identify whether existing DAS platforms can be upgraded. With a modular, multi-band DAS, support for the new 5G frequencies can be easily added to legacy systems without requiring complete infrastructure replacement.

However, the RF characteristics of new mid-band spectrum should be carefully considered when planning upgraded deployments. This may require RF benchmarks, site surveys, updated network designs, and approval from the local mobile service providers.

Mid-band signals tend to be attenuated by metal, concrete, low-emissivity glass, and other building materials. So, not only are these frequencies less likely to provide in-building service from outside networks, but these transmissions also can be impeded by interior walls and furniture.

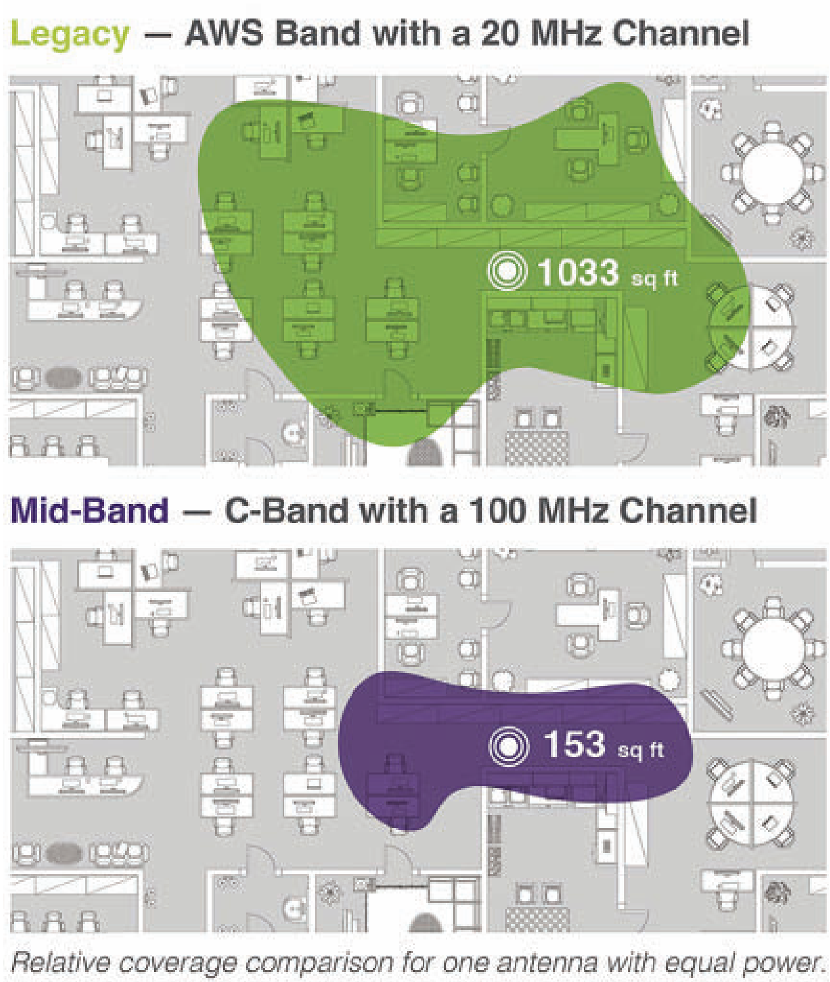
The C-band, for example, offers just one-fourth the signal propagation characteristics of legacy mobile communications bands. *(Fig. 1)* This means that additional reconfiguration of existing in-building network infrastructure is needed to provide sufficient coverage and capacity indoors with mid-band 5G spectrum.

Moreover, although the C-band spectrum offers much greater capacity due to increased channel sizes up to 100 MHz, the wider channels consume more radio power, which drastically reduces the effective coverage area. In fact, indoor C-band coverage per antenna is roughly 15% of what's possible with previous frequencies at the same power level.

That means an antenna providing around 1,000 square feet of coverage for a 4G 20-MHz channel in the legacy Advanced Wireless Service (AWS) band would only cover a little more than 150 square feet with a 100-MHz channel in the C-band, assuming a typical office environment with sheetrock walls *(Fig. 2)*.

As a result, achieving the same indoor coverage with C-band requires a higher effective output power from the antenna, versus legacy mobile communications frequencies. To overcome these obstacles, most existing 4G systems will need amplifiers that provide 4X to 10X more output power for mid-band 5G to match the existing footprint.

Yet, a higher-power configuration may not be feasible if the legacy system already uses high-output power amplifiers. If this is the case, the best practice may be to



2. Relative in-building coverage with C-band is roughly 15% of what's possible with the legacy AWS band, requiring a higher effective antenna output power. SOLiD Americas

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EMAIL | inquiry@kyocera-avx.com
TEL | 864-967-2150

One AVX Boulevard
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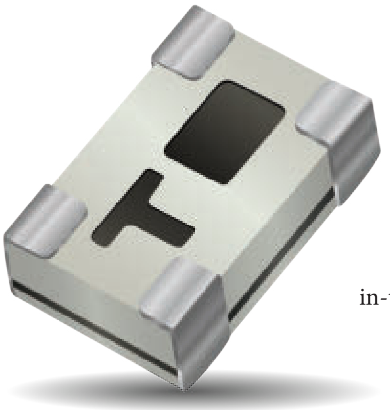
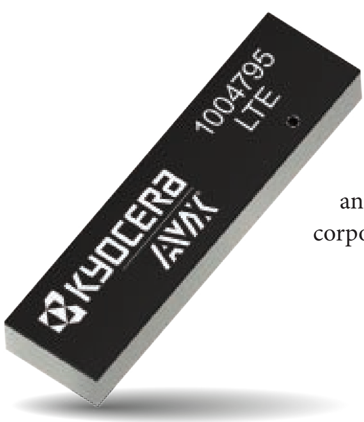


KYOCERA AVX is a leading international manufacturer and supplier of a vast portfolio of advanced electronic components, including capacitors, inductors, filters, resistors, couplers, diodes, and circuit protection devices, as well as a broad range of innovative sensor, control, interconnect and antenna solutions. With 33 research, design, manufacturing, and customer support facilities in 16 countries around the world, **KYOCERA AVX** offers significant competitive advantages, including delivery and production capabilities optimized to suit each customer's just-in-time inventory requirements, and global engineering teams experienced in developing new-to-market product solutions specially designed to fulfill customer's unique application requirements.

KYOCERA AVX has successfully served the automotive, industrial, medical, military, consumer electronics, communications, and transportation markets for nearly 50 years. In the automotive sector, **KYOCERA AVX** actively contributes to developing new safety, engine control, infotainment, and chassis control technologies. In the medical sector, advanced **KYOCERA AVX** products provide critical support for a wide range of implantable, life-supporting, treatment, imaging, and diagnostic devices, including pacemakers that regulate patients' heartbeats, cochlear implants that provide audio input for the hearing-impaired, and diagnostic equipment that helps medical professionals identify and cure patients' ailments. Finally, our accomplished research and development (R&D) teams regularly anticipate needs in the communications sector and adapt and innovate products to support the explosive growth of next-generation technologies spanning smartphones and tablets to networks and data centers.

Backed by decades of in-depth R&D, **KYOCERA AVX** products also provide critical enabling support for a wide variety of green technologies designed to conserve existing energy resources and create dependable, affordable electronic systems capable of effectively harnessing renewable energy sources, such as wind, solar, and hydroelectric power. High-reliability **KYOCERA AVX** components are at the forefront of countless products that are helping to ensure that both this generation and generations to come will benefit from cleaner, greener technologies designed to preserve and protect the environment, ranging from clean power generation and conversion systems to hybrid and electric vehicles in the personal and commercial vehicle and mass transportation markets, including cars, trucks, trams, and trains.



KYOCERA AVX has an abundance of patents, continues to invest heavily in R&D, and submits several new patent applications every year to further expand the company's strong technology base with newly innovated, next-generation product solutions.

KYOCERA AVX is also committed to consistently exceeding customer expectations and continuously satisfying that goal through successfully implementing the company's corporate mission and vision statements.

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install a fiber-to-the-edge overlay system to support specific coverage requirements of the new 5G frequencies. In this way, fiber-to-the-edge technology carries voice and data transmissions to the edge of the DAS network, enabling faster speeds, higher bandwidth, and lower latency at each access endpoint throughout a building or campus.

Plus, as technology convergence drives more fiber throughout the entire communications network, a common, end-to-end fiber infrastructure offers a scalable evolution path to support more secure and efficient building management systems or IoT applications, such as security monitoring, energy management, smart locks, or motion-activated lighting.

This installed fiber also facilitates future communications technology upgrades. These include additional DAS capacity overlays to enable support for future frequency bands as the FCC releases more spectrum and MNOs turn off previous mobile generations.

Sophisticated link-budget analysis tools and experienced DAS professionals can help network managers weigh the various factors unique to each in-building deployment to enable optimized 5G coverage and capacity. Recommendations to ensure high quality for maximum service availability might include adjusting power output, deploying fiber-to-the-edge, or replacing existing antennas and coaxial splitters.

Timing is Everything

In addition to signal propagation considerations of new 5G frequencies, changes in radio-access-network (RAN) architecture complicate the delivery of 5G connectivity indoors. One of the most substantial transformations from 4G LTE networks is the introduction of the 5G New Radio (NR) air interface standard, designed to enable high-capacity throughput for significantly faster and more responsive 5G mobile experiences.

The 5G NR air interface supports high-bandwidth applications such as streaming video and VR, low-bandwidth massive IoT connectivity and M2M communications, and mission-critical use cases like vehicle-to-everything (V2X) communications and VR-assisted telemedicine, requiring very-low-latency transmissions.

To bring about greater capacity and lower latency, this new air interface enables 5G networks to support a combination of FR1 and FR2 frequency bands, whereas traditional mobile communications traffic primarily used the FR1 bands. Most of these new 5G frequency bands employ time-division duplexing (TDD), rather than frequency-division duplexing (FDD), to provide more contiguous spectrum and support larger channel widths.

Sophisticated link-budget analysis tools and experienced DAS professionals can help network managers weigh the various factors unique to each in-building deployment to enable optimized 5G coverage and capacity.

The introduction of TDD means that timing synchronization is critical in 5G networks to avoid interference between uplink (UL) and downlink (DL) transmissions. Moreover, because 5G devices can only identify and connect to mobile networks within 3GPP standards-defined delay windows, delay management becomes a key consideration as well.

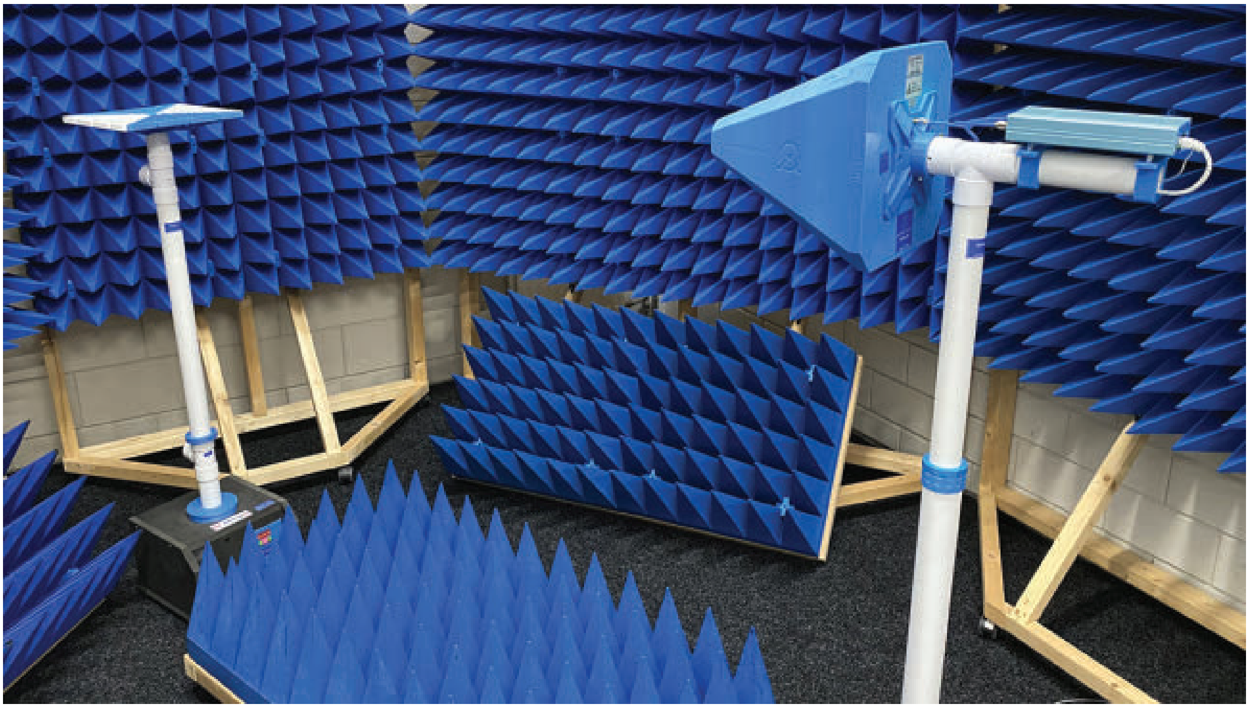
Consequently, when it comes to managing DAS platforms to support 5G service, failure to properly synchronize timing and minimize delays will result in poor in-building network performance and user experience. On the plus side, the increased scheduling flexibility enabled by TDD bands means that more slots can be assigned for either UL or DL transmissions per channel. This allows network managers to configure the in-building 5G network to meet the specific needs of a venue or service.

Promise of the 5G Future

As 5G adoption continues to accelerate, this disruptive technology is empowering an array of exciting new capabilities. Innovative 5G services are revolutionizing industrial and manufacturing processes, healthcare procedures, scientific research, business practices, and our day-to-day lives.

And the frenetic pace of mobile network evolution doesn't appear to be slowing down anytime soon. In some regions, 5G is just starting to gain momentum, while MNOs in other parts of the world are demonstrating 5G Advanced and 6G technologies. The common denominator is that consumers and businesses alike expect ubiquitous, always-on connectivity everywhere.

New mid-band spectrum presents an ideal blend of frequency characteristics to enhance wide-area network coverage, capacity, and speed, helping to fulfill 5G's true potential. But when planning in-building DAS deployments, be sure to consider how the new 5G RAN architecture and frequency allocations will impact the effective coverage reach and capacity to ensure optimized quality of service for an ideal 5G experience. ■



By Oscar Appelman, *Founder, Aptab*

An Investigation into **Wireless Signal Propagation**

Explore the intricacies of wireless signal propagation in indoor environments through detailed measurements and insightful observations.

1. Shown (on left) is the MegiQ VNA-0460e, used to excite the transmitting antennas during the measurements in this article (Ref. 2). Images courtesy of Aptab

IN A WORLD where wireless devices have become an integral part of daily life, the guarantee of reliable wireless networks is more crucial than ever. Accurately predicting the propagation characteristics of wireless signals is highly desirable.

However, due to the complex nature of wireless signal propagation in volatile environments, simulating such scenarios is notoriously difficult and lacks accuracy.[1]

As a result, characterizing wireless signal propagation is often neglected and wireless networks are set up based on intuition and simple measurements.

This article employs measurements to describe the impact of environmental factors on wireless signal propagation and strives to offer insights into the requirements for an optimal implementation of wireless networks.

Measurements and Equipment

The measurements in this article were conducted to examine the effect of distance and objects on the signal reception of a wireless device. At one specific location in a building, the received signal-strength indicator (RSSI) was determined for six different transmitter locations.

A MegiQ VNA-0460e *(Fig. 1)* was employed for signal transmission and a MegiQ RMS-0460 Antenna Radiation Measurement System *(Fig. 2)* for signal reception.[2] A comparison between RSSI values provides insights into the behavior of wireless signals in a typical indoor scenario.

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Founded 1986

WEB | www.nickc.com
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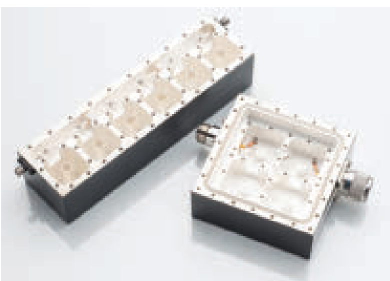
Networks International Corp. (NIC) is a leading manufacturer of radio-frequency and microwave filters and assemblies that provides custom solutions for advanced communications systems. For over 35 years, NIC has partnered with its customers to transfer value through superior engineering design, manufacturing, and continuous support. NIC is a small business that serves the Military, Space, and Commercial markets. The company's heritage lies in the military market where precision, high reliability, and repeatability are mission-critical.



Typical applications for NIC's products include communications, navigation, guidance, surveillance, point-to point and multi-point radio systems, radar systems, and satellite systems.

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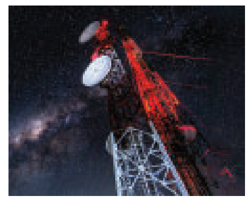

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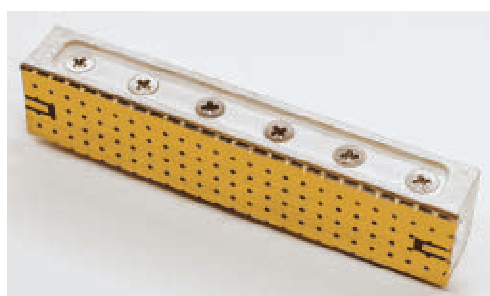

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2. The MegiQ RMS-0460 received the transmitted signals during the measurements in this article (Ref. 2).

Antenna Characterization

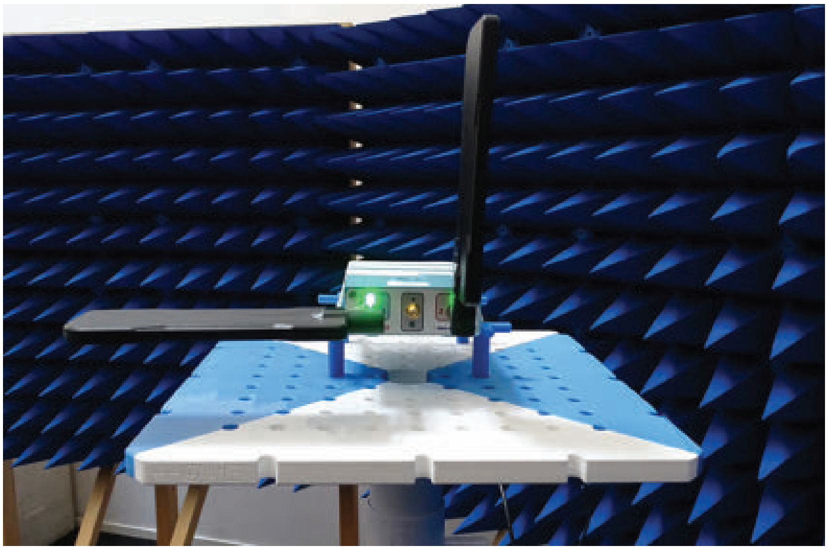
The antennas used in the measurement setup are linearly polarized wideband paddle antennas from Summit Electronics, provided by Top Electronics *(Fig. 3)*.[3] A full characterization of the RF impedance of these antennas was conducted using the MegiQ VNA for frequencies between 400 MHz and 6 GHz *(Fig. 4)*.

The wireless signal propagation of these antennas was characterized using the MegiQ RMS. RMS measurements include, but are not limited to, the field strength, antenna gain, effective isotropic radiated power (EIRP), and total radiated power (TRP) for frequencies between 370 MHz and 6 GHz. To obtain 3D electromagnetic radiation patterns of the antennas, a full scan over three antenna rotations was performed in a matter of minutes for the entire frequency range of the MegiQ RMS. The resulting radiation patterns for a horizontally polarized transmitting antenna at a frequency of 2.4 GHz are illustrated in *Figure 5*.

Figure 6 represents the return loss (RL) and total isotropic gain (TIG) of the antennas, measured by the MegiQ VNA and MegiQ RMS, respectively. A comparison between the RL and TIG illustrates their

The measurements in this article were conducted to examine the effect of distance and objects on the signal reception of a wireless device.

3. The wideband paddle antenna used for the measurements in this article is from Summit Electronics and was provided by Top Electronics.



4. The MegiQ VNA-0460e with wideband paddle antennas is connected to port 1 and port 2. This setup characterized the RF impedance of the antennas and transmitted horizontal and vertical linearly polarized waves from port 1 and port 2, respectively.

inversely proportional behavior. A change in RL indicates a change in power reflection and thus in impedance matching. It would therefore be expected that the TIG responds inversely to the RL, i.e., when one increases, the other tends to decrease.

To determine the correlation between these two properties, the MegiQ VNA software can translate the RL to the forward loss (FL), representing the amount of power that's accepted by the antenna. *Figure 7* represents both the FL and TIG.

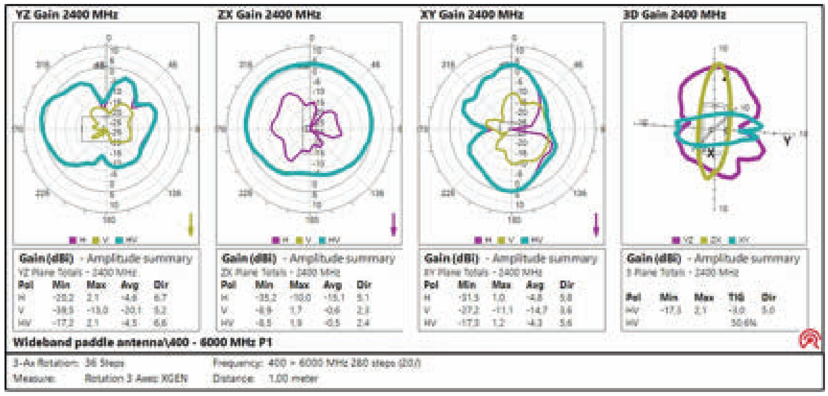
In an ideal situation, the FL and TIG should be equal if all accepted power is transmitted by the antenna. The deviation between them therefore reveals the importance of wireless signal propagation measurements. The TIG includes all antenna losses and environmental effects, which aren't detected with the VNA impedance measurements.

RSSI Measurement Setup

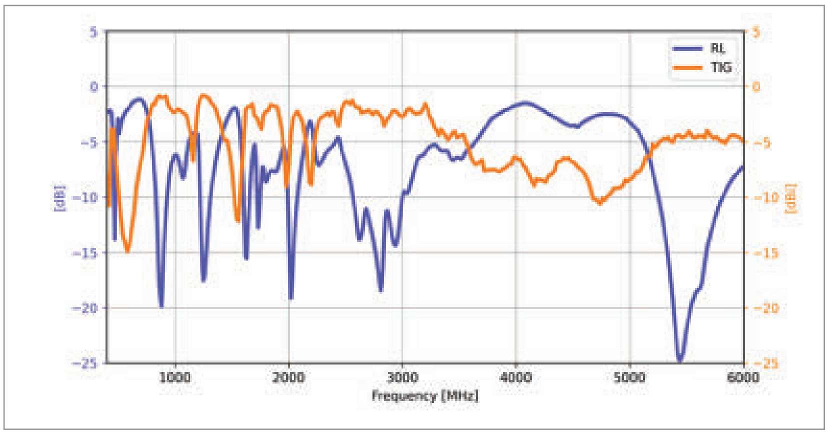
During all RSSI measurements, the paddle antennas were connected to the MegiQ VNA to excite them at an accurately controlled power level. The MegiQ RMS then measured the RSSI using the same paddle antennas, as this represents a realistic scenario in which two similar devices are communicating. The antennas were oriented such that both a horizontal and a vertical linearly polarized electromagnetic field were transmitted and received. *Figure 8* shows the measurement setup.

To measure the RSSI for different transmitter locations, the turntable of the MegiQ RMS had to be positioned at these locations as well. Due to the versatility of the MegiQ RMS, this was achieved by controlling the turntable wirelessly using a Silex DS-600 Network USB Server. After connecting the turntable to the Silex DS-600, the RMS software was able to control it without the need for a wired connection between the RMS and the turntable.

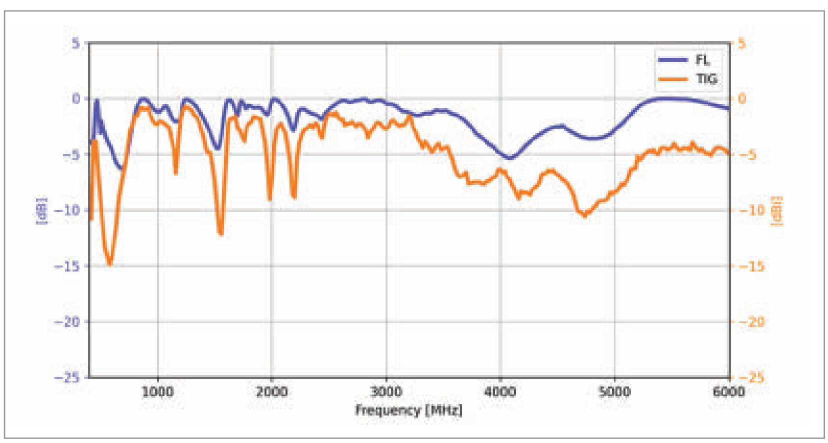
The affordability, high accuracy, and versatility of the MegiQ VNA and MegiQ RMS rendered them the ideal equipment for the measurements conducted in this article.



5. Here are the radiation patterns of the horizontally polarized wideband paddle antenna as shown in Figure 3, visualized for a frequency of 2.4 GHz. Next to the 3D radiation pattern, the figure represents the YZ, ZX, and XY rotation separately. "H," "V," and "HV" denote the received horizontally, vertically, and combined polarized fields, respectively.



6. This shows the return loss (RL) and total isotropic gain (TIG) of the wideband paddle antenna as illustrated in Figure 3. The comparison between the RL and TIG indicates their inversely proportional behavior.



7. This is a visual representation of the forward loss (FL) and total isotropic gain (TIG) of the wideband paddle antenna as shown in Figure 3. FL is defined as the amount of power that's accepted by the antenna. The comparison between the FL and TIG illustrates their directly proportional behavior.

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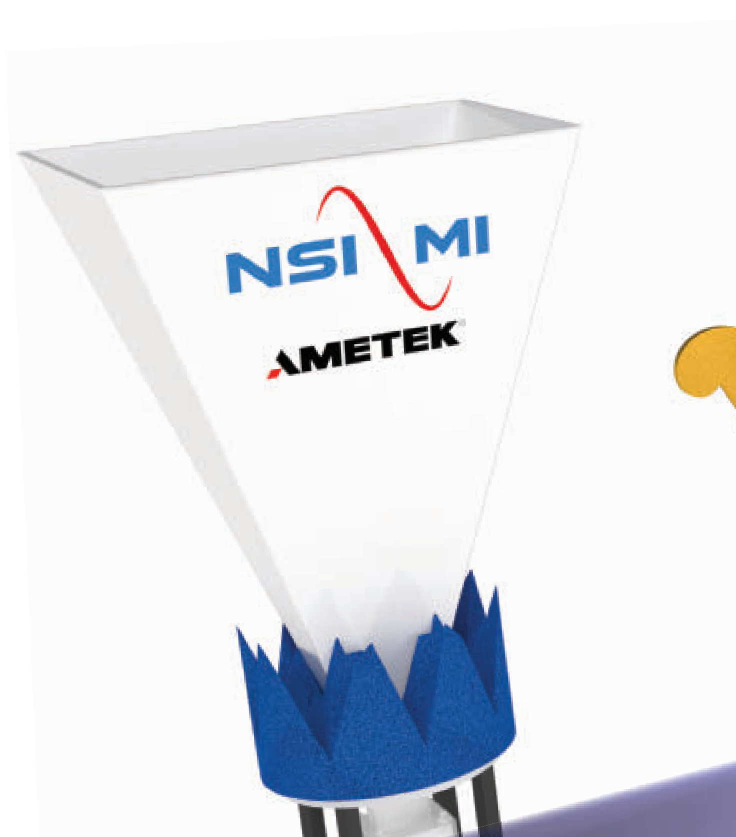
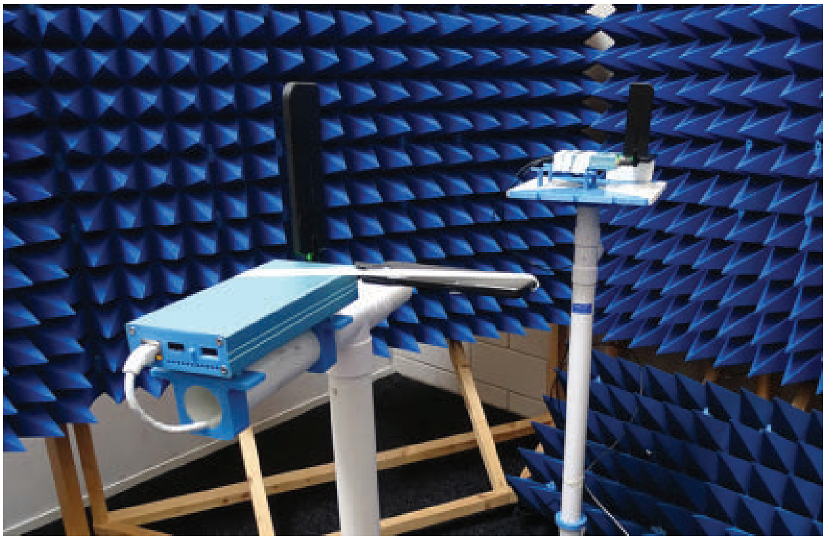




8. Here's the adjusted MegiQ RMS measurement setup for the RSSI measurements conducted in this article. Shown are the RMS receiver (left) and the VNA (right).

Despite their advantages, higher-frequency signals clearly also have their disadvantages. To mitigate these and ensure reliable wireless networks, it's crucial to consider wireless signal propagation not only during the design of wireless products, but during the construction of buildings and setup of wireless networks as well.

RSSI Variability Due to Frequency and Transmitter Location

Figures 9 and 10 illustrate the measured RSSI for different transmitter locations on a floorplan, with values averaged over the transmitted horizontal and vertical linearly polarized electromagnetic fields. This consideration is significant as many wireless devices are often used in varying orientations, randomizing the direction of polarization.

The receiver antenna is positioned on the ground floor and indicated with a cross. The locations of transmitter antennas are indicated with black dots. The bar charts visualize the measured RSSI for the different transmitter locations, where the grey part represents the noise, the light-colored part represents the minimum RSSI, and the dark colored part the average RSSI.

Figures 9 and 10 represent a selection of six frequencies:

- 450 MHz due to its various applications, like Amateur Television (ATV) and smart meters.
- 868 MHz is used for LoRa, Zigbee, Thread, and RFID.
- 1.9 GHz is a commonly used frequency for 3G and 4G wireless communication.
- 2.4 GHz is popular for Wi-Fi, Bluetooth, and Thread.
- 3.4 GHz is commonly used for 5G communication.
- 5.8 GHz is a popular Wi-Fi frequency as well, but it's also used for dedicated short-range communications (DSRC).

As expected, the bar charts indicate that the RSSI decreases as the distance between the transmitter and receiver increases. Furthermore, they show that this rate of decrease is larger for higher frequencies, which can be explained by the Friis transmission equation for free space, defined by:[4]

$$P_r = \frac{P_t G_t G_r c^2}{(4\pi R f)^2}$$

where:

- P_r = Received power
- P_t = Transmitted power
- G_t = Transmitter antenna gain
- G_r = Receiver antenna gain
- c = Speed of light
- R = Distance between transmitter and receiver
- f = Frequency

For higher frequencies (f), an increase in distance between the transmitter and receiver (R) results in a lower received power (P_r) than for lower frequencies.

In addition, this effect is amplified by the objects in the environment. Due to the smaller wavelength of signals with a higher frequency, these signals tend to observe more details in objects. As a result, they're more likely to interact with, for example, the metal grid in reinforced concrete, metal components in furniture, and even the coatings in insulated windows.

Despite their advantages, higher-frequency signals clearly also have their disadvantages. To mitigate these and ensure reliable wireless networks, it's crucial to consider wireless signal propagation not only during the design of wireless products, but during the construction of buildings and setup of wireless networks as well.

Wireless Signal Disturbances

Moving the antennas to different locations tends to change the measured radiation pattern. As *Figure 11* indicates with RSSI measurements at a frequency of 915 MHz, the orientation, shape, and distribution of electromagnetic polarization differ across the radiation patterns obtained from various transmitter locations. These changes can be attributed to various phenomena, like multipath propagation, fading, and polarization alteration.[5] Some of the most significant phenomena are mentioned below.

Whenever a signal interacts with objects, it can be absorbed, reflected, transmitted, scattered, and diffracted.[5] All of these different interactions can cause changes in the signal, like its intensity, frequency, phase, polarization, and direction. Furthermore, it leads to different paths in which the signal travels to the receiver, called multipath propagation. The detected RSSI at the receiver is highly affected by all of these interactions due to the different properties of the multipath components and the receiver's sensitivity to certain properties of the signal.

9. Shown is the floorplan of the ground floor illustrating the averaged RSSI for different transmitter locations, taken over the transmitted horizontal and vertical linear electromagnetic polarization. The transmitter locations are indicated with black dots. The receiver is indicated with a cross.

10. This floorplan of the first floor illustrates the averaged RSSI for different transmitter locations, taken over the transmitted horizontal and vertical linear electromagnetic polarization. The transmitter locations are indicated with black dots. The receiver is located on the ground floor (Fig. 9).

Interactions between the individual multipath components impact the RSSI, too. This is caused by constructive and destructive interference, where the combination of signals leads to an amplification or attenuation of the signal.

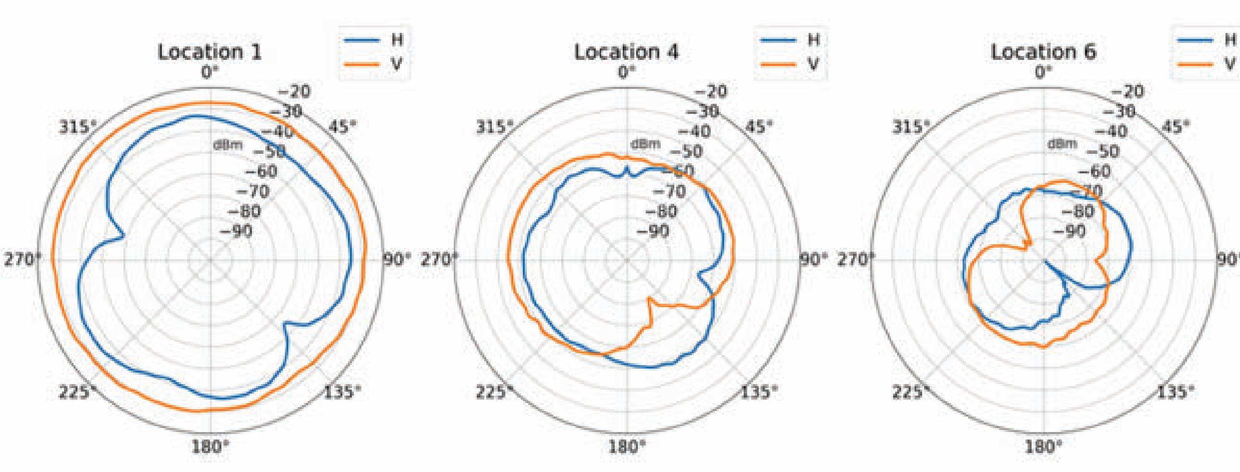
Depending on the composition and electrical properties of objects, interactions with objects potentially alter the polarization of a signal.[5] This, in turn, impacts the interaction between multipath components on the receiver side and the shape of the detected radiation patterns.

Interactions between the individual multipath components impact the RSSI, too. This is caused by constructive and destructive interference, where the combination of signals leads to an amplification or attenuation of the signal.

Figure 11 indicates the effect of multipath propagation and polarization alteration on the measured radiation patterns. Due to the multipath propagation, a change in orientation of the radiation patterns is visible.

Furthermore, *Figure 11* shows a variation in the relative distribution of horizontally and vertically polarized signals between the different locations, indicating that the polarization of these signals have changed. The polarization alteration is especially visible at approximately 150° at location 4, where the vertically polarized signal decreases in power and the horizontally polarized signal increases correspondingly.

These figures are a prime example of why antenna diversity, i.e., integrating multiple antennas with different polarization in a device, can significantly enhance the received wireless signal strength of the device.



11. This image depicts the polar radiation patterns at 915 MHz for a transmitted horizontally and vertically polarized signal, measured for three different transmitter locations. The RSSI is measured using a vertically polarized wideband paddle antenna and is represented in dBm. The locations correspond to the locations in Figures 9 and 10.

Conclusion

The reception of wireless signals propagating in an indoor environment depends strongly on the characteristics of the signal, distance between antennas, and layout of the environment. This was proven with a comparison between radiation patterns for different transmitter locations, which revealed how the RSSI and polarization can change by physically moving a wireless device within the same network.

In addition, the measurements showed that higher frequency signals suffer from more signal degradation as the distance increases between transmitter and receiver. These signals face a stronger interaction with the environment, making their wireless propagation more unpredictable and prone to distortion.

To draw clear and concise conclusions about the precise effects of objects on wireless signal propagation, a more comprehensive analysis and measurement approach is needed. Nevertheless, the research conducted in this article demonstrates that the discussed phenomena significantly affect the reception of transmitted wireless signals. It emphasizes the necessity of accounting for wireless signal propagation to ensure reliable wireless networks, not only during the design of new wireless products, but also throughout the construction of environments housing wireless devices, as well as during the setup of wireless networks. ■

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To draw clear and concise conclusions about the precise effects of objects on wireless signal propagation, a more comprehensive analysis and measurement approach is needed.

How Edge Processing Enables **Next-Gen mmWave Scanners**

This article describes how mmWave imaging hardware works and presents a chipset that uses edge processing to manage massive data loads to empower the development of walkthrough security scanning systems.

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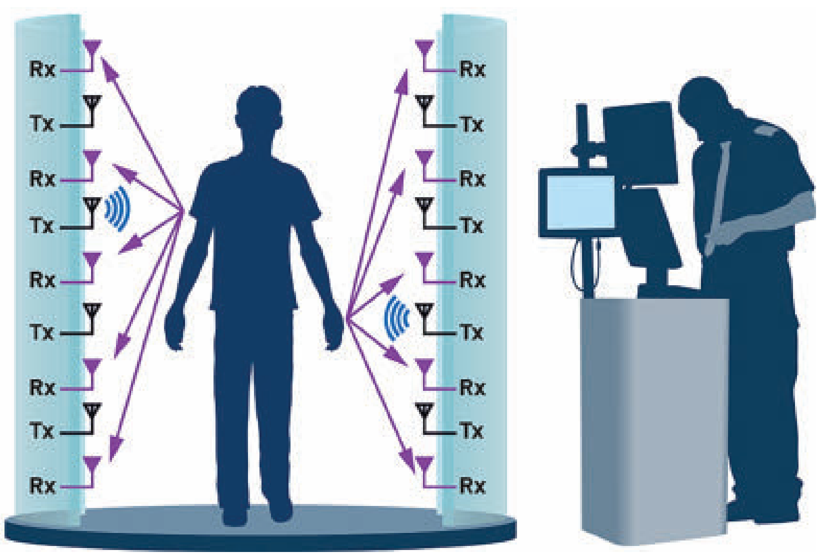

1. Operation of a mmWave security imaging system. Images courtesy Analog Devices

By ***Eamon Nash,*** *Applications Engineering Director, Analog Devices*

MILLIMETER-WAVE (mmWave) imaging has become an important part of security scanning systems in airports, public buildings, and stadia. Millimeter-wave scanners are superior to traditional metal detectors because they can identify and locate both metallic and nonmetallic threats. This article dives into the specifics of mmWave imaging hardware and looks at a chipset that uses edge processing to manage massive data loads, which is essential in the development of walkthrough security scanning systems.

How Does mmWave Imaging Work?

Figure 1 illustrates the operation of a mmWave scanner. The system consists of an array of transmitters and receivers connected to a spatially dispersed antenna array. It's analogous to a network analyzer that measures return loss or S_{11}.

At any time, one antenna in the array transmits a low-power signal at a single frequency. This signal reflects off the target and generates backscatter (the illustration shows reflection from a single point on the target, but in practice the transmitted signal is omnidirectional, so there will be reflections from multiple points on the target).

The phase and amplitude of the backscatter are measured by all of the receive antennas in the array. Polarization may be used between the transmit and receive antennas to reduce direct transmit-to-

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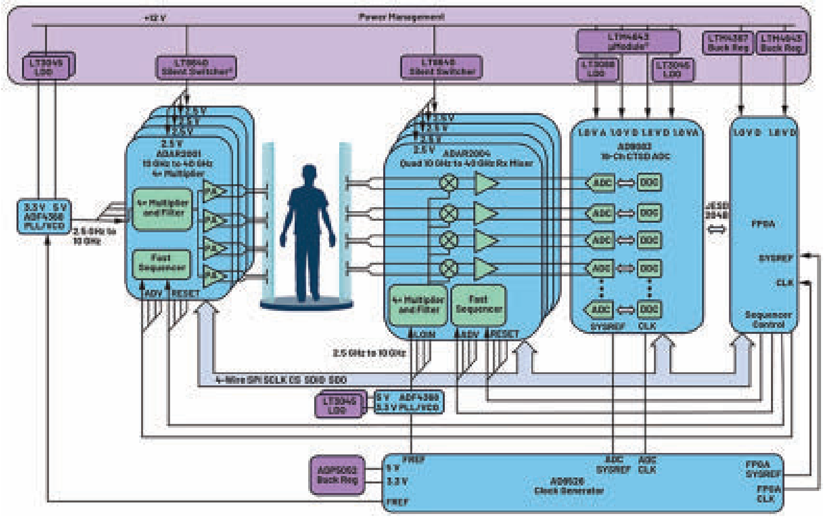


2. This diagram represents a complete mmWave imaging system.

receive leakage. Once this measurement is complete, the same signal is transmitted from another transmit antenna (operating at the same frequency) and the measurement process is repeated.

Because the depth of penetration of RF signals and the nature of the reflection vary with frequency, the scan described earlier is typically repeated at multiple frequencies, across a wide band. The resulting matrix of vectors forms a multidimensional array (vs. frequency and spatial location) that's used to create an image which can identify metallic and nonmetallic objects concealed between and under layers of clothing.

The hardware required to complete such a scan must be multichannel and have a wide operating frequency range. The 10- to 40-GHz frequency range is wide enough to differentiate the objects in a typical security scanning scenario (clothing, backpacks, weapons, and explosives).

Higher channel count systems tend to have higher resolution, giving them the ability to identify small objects. For example, while detecting a razor blade is critical in airport scanners, securing public buildings and stadia focuses more on the detection of larger items, such as weapons or explosives. In these applications, a lower channel count is typically used.

Another critical component in these systems is fast switching time. This enables the realization of scanning systems where the person being scanned need only pose for a short amount of time (typically one second or less). Next-generation walkthrough systems require faster switching times so that the person doesn't have to stop and pose.

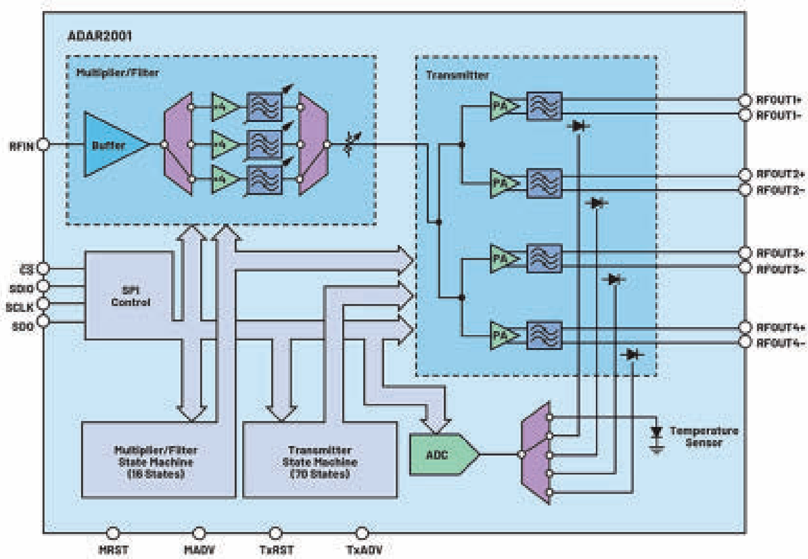
Figure 2 shows how a mmWave imaging chipset from Analog Devices can be used to implement a complete mmWave scanner. An array of transmitters (ADAR2001) is driven from a central agile frequency source. An array of receivers (ADAR2004) detects the reflected signals and down-converts them to a low intermediate frequency, at which they're IF sampled by a multichannel continuous-time sigma-delta (CTSD) converter (AD9083).

Let's now take a closer look at these components and how their functionality optimizes overall system performance.

Transmitter for mmWave Imaging Setup

As already noted, the transmitter consists of a large channel count of spatially dispersed antennas, each driven by a power amplifier. The ADAR2001 is a four-channel transmitter that connects directly to the antennas and has an output frequency range of 10 to 40 GHz. Because of the difficulty associated with distributing a 10- to 40-GHz signal in a large array, the ADAR2001 incorporates a 4× multiplier. As a result, all of the plumbing and signal distribution in front of the transmitter ICs happens in the 2.5- to 10-GHz frequency range.

The main RF elements of the ADAR2001 transmitter are an RF input buffer, a 4× frequency multiplier with integrated switchable harmonic filters, a 1:4 signal splitter, and four differential-



3. The ADAR2001 is a 10- to 40-GHz transmitter.

out power amplifiers, which are intended to drive differential antenna structures such as dipole or spiral antennas. *Figure 3* shows a detailed block diagram of the ADAR2001.

A CW RF input signal between 2.5 and 10 GHz and with a power level of at least –20 dBm is applied to the RFIN port. The broadband frequency multiplier consists of three parallel subcircuits. Each subcircuit (low band, mid band, high band) is optimized to multiply and filter a segment of the total frequency range. Switches at the input and output of the multiplier block are used to select the subcircuit for the desired frequency of operation.

The multiplier output passes through a programmable attenuator (PA) before being split into four and applied to four power amplifiers. In addition to the configurable filtering in the multiplier block, each PA contains a low-pass/notch filter that can be enabled or disabled. For output frequencies up to 20 GHz, this filter should be enabled. Above 20 GHz, it should be disabled.

The PA is used to help ensure relatively flat output power versus frequency. This attenuator has approximately 15 dB of digital step attenuation range. As the output frequency sweeps from 10 to 40 GHz, this attenuation should be decreased to maintain the desired output power flatness versus frequency. This results in a nominal PA output power of +5 dBm on each of the differential PA outputs with harmonic suppression that ranges from –20 to –30 dBc.

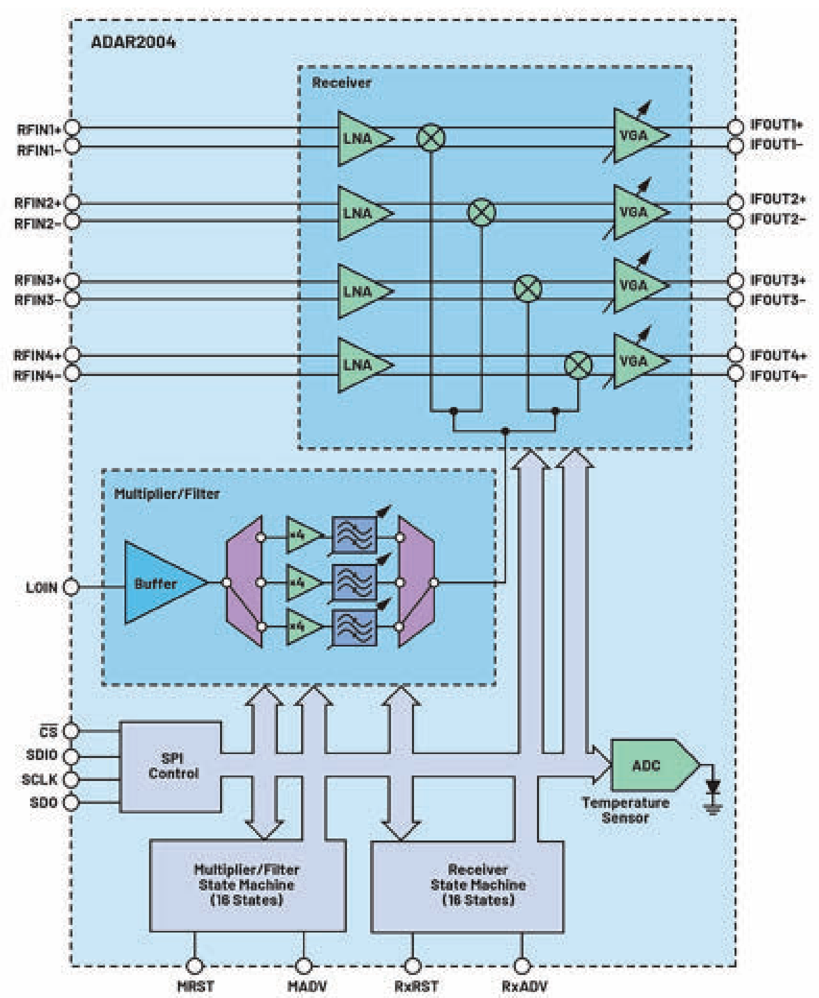
To do a complete 10- to 40-GHz frequency sweep, the multiplier/filter block settings must be adjusted seven times to ensure optimum harmonic rejection and output power. In addition, while the system is dwelling at one frequency, each transmitter channel must be successively turned on and off.

To avoid creating a bottleneck of SPI commands, the ADAR2001 includes two state machines that can be preprogrammed with up to 70 states. Once the device's RAM has been programmed, state advances can be made with a simple pulse to the device's MADV (advance) pin. These features combine to ensure a 2-ns channel switching time. This switching time is also achievable when switching between ICs (e.g., Channel 4 of Device A is switching off as Channel 1 of Device B is switching on).

Because a full scan involves a full-channel sweep at multiple frequencies, switching time is critical. For example, if the array has 500 elements and is going to sweep from 10 to 40 GHz in 50-MHz steps, it must perform a total of 300,000 channel switches to complete a full scan.

The RF output power on each channel can be monitored using individual, on-chip RF detectors. Die temperature can also be monitored by an on-chip temperature sensor. These sensors feed into a 5:1 analog multiplexer, which passes the desired signal to an on-chip 8-bit ADC.

The ADF4368 PLL/VCO provides the stimulus to the transmitter network. Its output signal will be split multiple times depending on the number of transmit channels. The ADF4368's relatively high output power of +9 dBm and the minimum input threshold of the ADAR2001 (–20 dBm) ensure that the ADF4368's output can be passively split many times before amplifier buffering is required.



4. The ADAR2004 is a 10- to 40-GHz receiver.

Receiver for the mmWave Imaging Setup

The reflections from the transmission are picked up by the receivers, which

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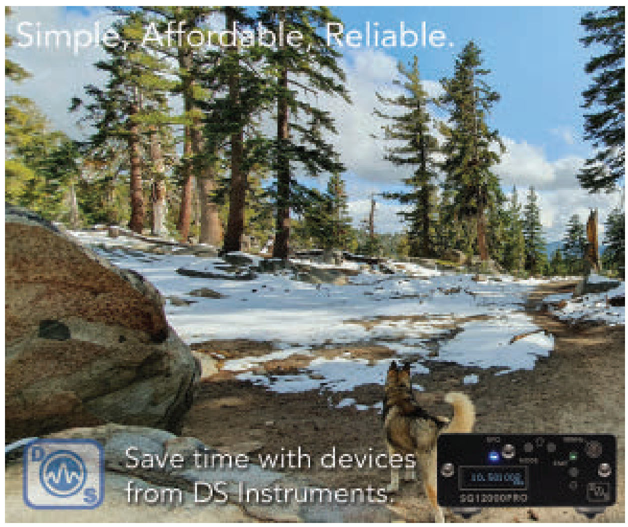

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are an array of multichannel mixers and ADCs. The ADAR2004 is a quad mixer and ADC driver with a digitally programmed gain amplifier (DGA). The LO input, which also has an internal 4× multiplier, is driven by a second phase-locked loop (PLL) whose output frequency is offset from the radio frequency so that the mixer produces a real IF output. The IF outputs of the mixers are then sampled by the AD9083, a 16-channel CTSD ADC with integrated digital downconversion.

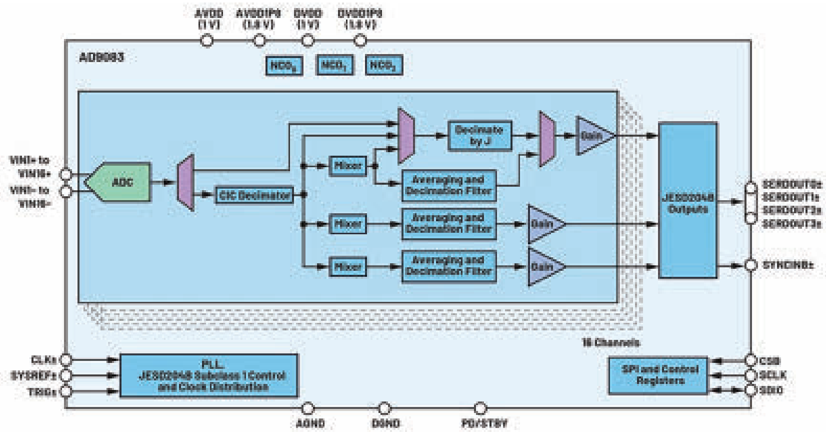
An IF sampling architecture was chosen over a zero-IF architecture to avoid DC offsets that result from LO leakage in the receiver and I/Q errors generated by imperfect quadrature balance in the LO's quadrature splitter. While these imperfections can be mitigated by calibration, calibration would be required at every input frequency because LO leakage and quadrature errors tend to vary with frequency.

Figure 4 shows a block diagram of the ADAR2004 quad mixer. The LO input is driven by a 2.5- to 10-GHz sine wave that produces 10 to 40 GHz at the output of the multiplier. The multiplier output is fed to the four mixers that have a programmable gain on their IF outputs. Like the ADAR2001 transmitter, the ADAR2004 receiver also has two on-chip state machines that can be preprogrammed.

Multichannel ADC for the mmWave Imaging Setup

Figure 5 illustrates a block diagram of the AD9083, a 16-channel CTSD ADC. The ADC inputs are designed to have the same common-mode voltage as the IF outputs of the ADAR2004. Thus, the mixer output and the ADC input can be connected directly. The absence of AC-coupling capacitors ensures that no charging/discharging transients are present when the mixer output switches abruptly (e.g., during a frequency step at the mixer input).

The use of a first-order CTSD ADC architecture with an integrated single-pole filter saves PCB space by minimizing external filtering. The architecture also enables a fast signal settling time when compared to the settling time of Nyquist-rate converters, which require highly selective antialiasing filters to eliminate noise folding. Fast settling time is a key requirement in this application because the ADC settling time must be able to keep up with the fast channel switching on the transmit side.



5. Shown is a block diagram of the AD9083 continuous-time delta-sigma ADC.

Each ADC has a signal-processing tile to filter out-of-band, shaped noise from the sigma-delta ADC and reduce the sample rate. Each tile contains a cascaded-integrator-comb (CIC) filter, a quadrature digital downconverter (DDC) with multiple finite-input-response (FIR) decimation filters (decimate by J block), or up to three quadrature DDC channels with averaging decimation filters for data gating applications. The presence of three quadrature DDC channels enables simultaneous demodulation of up to three frequencies. We'll see later how this can be used to dramatically speed up the scan time.

System Setup and Operation

The ADAR2001 and ADAR2004 were specifically designed for efficient operation in large arrays. Particular emphasis was placed on reducing wiring overhead. The RFIN and LO input ports of ADAR2001 and ADAR2004 can operate at input levels as low as –20 dBm.

Because it's desirable to drive these inputs from a common LO source (the ADF4368 in this case), this low input sensitivity allows for lots of passive fanout before amplification is required. For example, if we assume that a Wilkinson power splitter has a net loss of 1 dB, the ADF4368's output power of 9 dBm can be passively fanned out seven times and drive 128 devices (512 channels).

The advance and reset pins that drive the ADAR2001 and ADAR2004's on-chip sequencers are also designed to be driven in parallel to minimize the number of GPIOs that must be supplied by the processor or FPGA. By providing enough depth and complexity in the sequencers, it's possible to drive up to 16 ADAR2001 devices with a single set of advance and reset pulses.

Before operation, the ADAR2001 and ADAR2004's sequencers must be programmed. While it's possible to access all of the functionality of both devices using SPI commands, the associated latency would result in an unacceptably long overall scan time.

Let's consider how to set up a 64-channel system (64-transmitter, 64-receiver) for a channel-based scan. That is, we cycle through all of the transmit channels at a single frequency before incrementing the frequency and repeating the scan.

Figure 6 shows how the state machines in the 16 ADAR2001 devices are programmed to enable this sweep. A key goal of the architecture is to be able to sequence multiple devices that are doing different things from common control lines.

Notice in *Figure 6* that while each IC has 65 states, most of the ICs are programmed to be in sleep mode (SLP) the majority of the time. For instance, IC 1 is only fully active for the first four states as channels 1, 2, 3, and 4 of that IC sequentially transmit. During these four states, all other ICs are either in SLP or ready (RDY) mode.

Likewise, IC 2 is only fully active during states 5 to 8, because the other ICs are either in SLP or RDY mode. By configuring the 16 state machines in this manner, with their on cycles offset from one another, it's possible to drive the advance and reset lines of all 16 devices with parallel pulses.

Tx State	ADAR2001 IC Number																Function
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
(Reset)	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	All sleep
0																	
1	CH1	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	RDY	IC 1 transmitting
2	CH2	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	
3	CH3	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	
4	CH4	RDY	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	
5		CH1	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	IC 2 transmitting
6	SLP	CH2	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	
7	SLP	CH3	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	
8	SLP	CH4		SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	
9	SLP	RDY	CH1	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	IC 3 transmitting
•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
60	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP			
61	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP		CH1	IC 16 transmitting
62	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	CH2	
63	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	CH3	
64		SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	SLP	CH4	

6. Here, 16 ADAR2001 transmitters are programmed for a channel sweep that's driven by a single advance pulse.

Ready (RDY) Mode

The RDY mode is an intermediate state of what was developed to optimize switching time while saving power. Because most of the transmitters are inactive most of the time, the SLP mode is key to keeping down power consumption. However, the time required to switch from SLP mode to transmit mode (50 ns) is excessive from a system perspective and would result in delays during the scan.

The RDY mode is an intermediate state that can be invoked when an IC is preparing to transmit. Notice in *Figure 6* that in State 4, Channel 4 of IC 1 is transmitting, and IC 2 is being prepared for transmission by placing it in RDY mode. In the transition from transmitter states 4 to 5, IC 1 transitions from transmit mode to RDY mode, and IC 2 transitions from RDY to transmit mode. This transition takes 10 ns. The subsequent on-chip channel switches (i.e., from Channel 1 to Channel 2 to Channel 3 to Channel 4 on IC 2) have a switching time of 2 ns.

For a 1024-element array that sweeps from 10 to 40 GHz in 0.1-GHz steps, the complete scan time would be less than 20 ms. This assumes a PLL lock time of 50 µs. If two PLLs operating in ping-pong mode were used to achieve faster frequency settling, the scan time would be well below 5 ms.

The operation and sequencing of the ADAR2004 receiver are less complex because it's typical practice to configure all receiver channels to be receiving at all times. The state machines must still be sequenced so that the correct multiplier path and filter settings are chosen as the receiver sweeps in tandem with the transmitter.

As already noted, each AD9083 ADC channel can access up to three quadrature DDC channels. This means that it can simultaneously demodulate three frequencies, assuming that all three frequencies are within the input frequency range of the ADC's analog input bandwidth (125 MHz). For example, by positioning three IF tones at 50 MHz, 75 MHz, and 100 MHz, all three can be simultaneously demodulated into I and Q baseband data.

To facilitate this approach on the transmit side, three transmit PLLs must be used instead of one. The three transmit frequencies must always be directed to different physical transmit ICs (the multipliers in the ADAR2001 can't conduct multitone signals). And the three frequencies must always be different but must remain close in frequency to one another as they sweep.

For example, if one channel on one of the ADAR2001 devices is transmitting at 10 GHz, two other devices will be transmitting at 10.025 GHz and 10.050 GHz to support IF outputs at 50, 75, and 100 MHz. This scheme requires more hardware and switching infrastructure in the transmit path, but it has the benefit of reducing the overall scan time by a factor of 3.

Conclusion

The chipset consisting of the ADAR2001 quad transmitter, the ADAR2004 quad receiver, the AD9083 16-channel ADC, and the ADF4368 PLL/VCO provides the means to implement next-generation walkthrough mmWave security scanners. Integrated state machines and on-chip digital downconversion significantly offload traditional centralized processing and move it to the intelligent edge. The net result is that the central processor can worry less about controlling the system during a scan, and the data that it receives is already demodulated and decimated.

While this chipset was developed specifically for mmWave security imaging applications, the wide frequency range of the ADAR2001 transmitter and ADAR2004 receiver, as well as the level of integration of the AD9083 16-channel ADC, make this chipset an option for other applications that require high channel density and fast switching.

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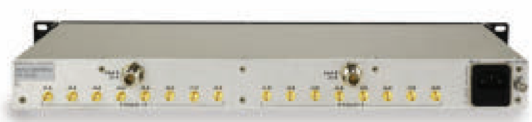

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Software-Defined Instrumentation Plus AI: A New Era in Test

The convergence of AI and flexible, software-defined instrumentation is revolutionizing the test and measurement industry, offering efficient ways to analyze data and optimize processes.

By Daniel Shaddock, Co-founder and CEO, Liquid Instruments

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THE CONVERGENCE OF artificial-intelligence tools and flexible, software-defined instrumentation has brought the test and measurement industry to the brink of a technological revolution. AI-powered solutions coupled with FPGA-based instruments enable real-time optimization, making testing faster and more adaptable across industries. However, concerns about data quality, compatibility with precision standards, and integration challenges must be addressed as the industry embraces this transformative technology.

Generative AI tools provide exciting and highly efficient new ways for scientists and engineers to analyze large data sets, detect anomalies, and optimize test processes. When coupled with next-generation test solutions built around field-programmable gate arrays (FPGAs)—which deliver an entire suite of software-defined test instruments in one reconfigurable device, from bench essentials like an oscilloscope and spectrum analyzer to advanced tools like a lock-in amplifier and software-defined radio—AI can accelerate real-time, hardware-based optimization and decision-making like never before.

While AI helps users quickly identify and respond to critical test needs, FPGA-based test solutions give them the tools they need to adapt their workflows on the fly.

Together, these dynamic technologies promise to significantly reshape the landscape of test, with rapid adoption in the aerospace and defense, semiconductor, and automotive industries driven by increased competition. As new AI- and FPGA-based, software-defined solutions propel the next generation of test at lightning speed, scientists and engineers must be ready for the new opportunities and complex challenges that come with their adoption.

Modifiable Off-the-Shelf Test Equipment

Traditional testing processes can be time-consuming and labor-intensive, with one piece of hardware often performing a single function—at an expensive price. Since most testing today requires multiple instruments, this disjointed, outdated approach leaves room for engineers, scientists, and professors to modernize testing by shifting it to a more software-centric model, which in turn makes it more flexible, affordable, integrated, and ultimately more efficient.

The reconfigurability and user programmability of FPGA-based instrumentation has given rise to a new class of modifiable off-the-shelf (MOTS) test equipment, bringing new opportunities for customization to address a range of applications. However, the barrier to program FPGAs has historically been very high, even as higher-level abstraction programming environments are deployed to help. AI and specifically large language models (LLMs) like ChatGPT are a game changer in this regard, because they enable even novices to produce, or rather request, complex deployable FPGA code with a simple prompt.

Fast and Adaptable Test Solutions

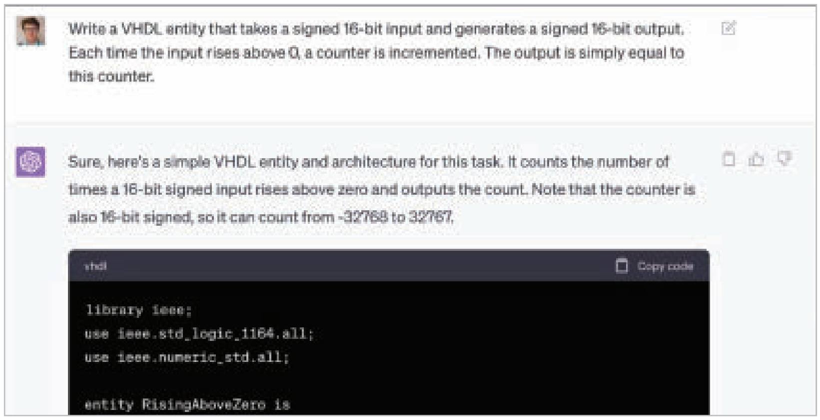
As AI and reconfigurable, FPGA-based instrumentation work together to deliver faster ways to test, and with greater flexibility, users will be able analyze massive data streams and execute complex test scenarios at a much more accelerated pace. This acceleration will translate to reduced testing times, enabling industries to get products to market much faster.

AI can also uncover patterns, anomalies, and insights that humans might overlook. Bringing AI into test flows will help enhance the reliability of data and enable new ways to uncover issues that may affect product quality. In addition, AI-driven test systems are able to adapt their testing strategies based on real-time conditions and variations. By implementing one integrated, reconfigurable, FPGA-based test solution, users can leverage AI tools to centrally control and optimize the test system as a whole, rather than having to interface with and manage multiple disparate devices. This adaptability is crucial in dynamic environments where test parameters change frequently.

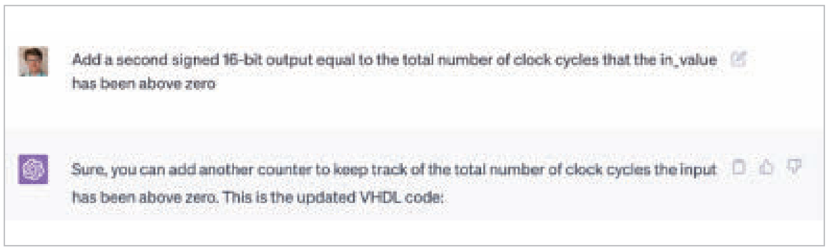
Since FPGA-based solutions enable seamless reconfiguration of instruments as needed, allowing one device to serve different test scenarios, users can turn to adaptive testing to minimize downtime while optimizing resource utilization.

With AI- and FPGA-based instrumentation, key industries can easily augment and adapt their test setups to handle a range of scenarios that would once have been deemed infeasible. They can use AI to develop signal-processing algorithms and FPGA-based instruments to deploy those algorithms to the real world—generating, analyzing, and processing signals in real-time, all from one device.

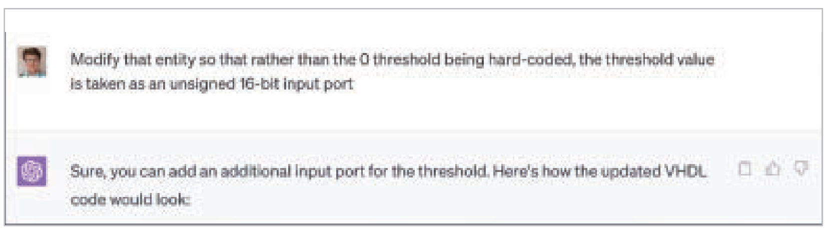
For example, when performing custom transient fault detection, engineers typically run into a tradeoff: They can either sample at a high rate but face long swaths of dead time between acquisitions, or they can sample at a very low rate with nearly continuous data. With customizable, FPGA-based test equipment and ChatGPT, a few prompts are all it takes to deploy the code to the FPGA for real-time, high-rate, dead-time-free fault detection *(Figs. 1 through 4)*.



1. Prompting ChatGPT for a VHDL-based fault counter. Images courtesy Liquid Instruments



2. Prompting ChatGPT to add a counter to the program.



3. Prompting ChatGPT to modify the entity.

Challenges of AI for the Future

The obvious problem with this new AI-based approach is its compatibility with precision measurement standards, where determinism, repeatability, and traceability are paramount.

If the algorithms used to record and process data aren't known to, let alone validated by, human operators, then how can we trust the results? Will we sacrifice this insight into our measurements and devolve into an empirical approach based on unit tests and statistical inference without really understanding what's under the hood? Is this new approach even compatible with the scientific method?

With these concerns in mind, the test industry must balance the need to obtain high-quality data while addressing the constraints of specific testing environments. Though AI thrives on data, the quality of the information used for training and inference is critical. Inaccurate or biased data can lead to flawed AI models, compromising the reliability of test

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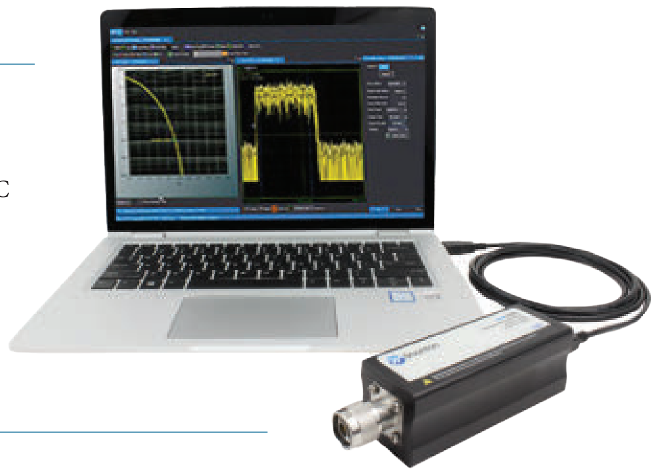

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```vhdl
library ieee;
use ieee.std_logic_1164.all;
use ieee.numeric_std.all;

entity RisingAboveZero is
    Port (
        clk: in std_logic;
        reset: in std_logic;
        in_value: in signed(15 downto 0);
        threshold: in unsigned(15 downto 0);
        out_value: out signed(15 downto 0);
        out_cycle_count: out signed(15 downto 0)
    );
end RisingAboveZero;

architecture Behavioral of RisingAboveZero is
    signal counter: signed(15 downto 0);
    signal cycle_count: signed(21 downto 0);  -- Updated to 22 bits
    signal previous_value: signed(15 downto 0);
begin
    process(clk, reset)
    begin
        if reset = '1' then
            counter <= to_signed(0, 16);
            cycle_count <= to_signed(0, 22);  -- Updated to 22 bits
            previous_value <= to_signed(0, 16);
        elsif rising_edge(clk) then
            if in_value > signed(threshold) and previous_value <= signed(thr
                counter <= counter + 1;
            end if;

            if in_value > signed(threshold) then
                cycle_count <= cycle_count + 1;
            end if;

            previous_value <= in_value;
        end if;
    end process;

    out_value <= counter;
    out_cycle_count <= cycle_count(21 downto 6);  -- Output the 16 most sig
end Behavioral;
```

4. The final VHDL code to enable custom transient fault detection on FPGA-based test equipment.

outcomes. Moreover, gathering sufficient data for training AI algorithms can be challenging in certain niches such as optics and photonics.

On top of that, deploying AI for test and measurement applications is often intricate. Integrating AI- and FPGA-based hardware seamlessly into existing test setups can be a formidable task. Complex models may require significant computational resources, potentially leading to latency issues.

Ensuring compatibility and interoperability between diverse components—such as software, AI models, and FPGA boards—requires careful design and implementation. A standardized framework for integration would help facilitate the adoption of AI- and FPGA-based solutions across various applications.

The Way Forward

ChatGPT and other instruction-following AI tools like Dolly 2.0 bring tremendous value when it comes to brainstorming, catalyzing human creativity, and completing simple tasks. In industrial test and measurement, use cases range from prototyping control systems to debugging code to post-processing large amounts of data for tasks like anomaly detection. ChatGPT's ability to generate code in any language is a definitive turning point, offering engineers a huge opportunity for efficiency gains.

Of course, all data and processes must be reliable and verifiable. To be considered dependable, teams need to know that their measurements were made with well-defined variables, especially when breaking down complex engineering projects into smaller, bite-size pieces. AI doesn't currently have this ability.

For example, when engineers typically write VHDL code, they break it into modules and review it in kind. If an AI tool creates a large string of unconventionally structured code, it's harder to confirm it on a granular level, which can put greater pressure on test engineers when verifying accuracy.

To start with, AI tools could be used in noncritical ways, providing hints and insights to engineers who will ultimately need to independently validate the code. At present, these AI tools aren't compatible with standard systems engineering principles, so it's time to design new protocols and methodologies to evaluate AI outputs. It's an exciting evolution, but the industry should proceed with caution.

Launching the Next Generation of Test

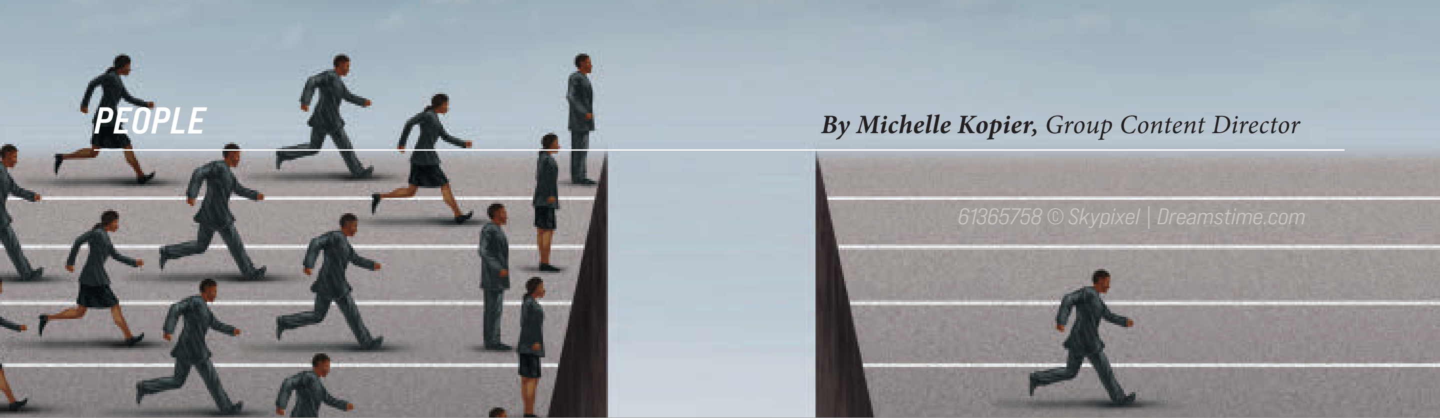
To deliver maximum benefit, AI- and FPGA-based solutions will require the support of test professionals from various disciplines, including electronics, computer science, and data analysis. Collaborative initiatives that encourage knowledge sharing and cross-disciplinary training will accelerate the adoption and advancement of these technologies.

This is perhaps easier now than at any time in the past, as scientists and engineers newly entering the workforce are much more likely to have been exposed to software engineering and computer science principles as part of their general education. Creating standardized protocols and best practices for integrating AI- and FPGA-based solutions will facilitate smoother adoption across different industries. These guidelines should encompass data collection, algorithm development, validation methodologies, and cross-functional integration.

Looking ahead, the advancement of AI and software-defined instrumentation promises to usher in an exciting new era for test. While significant challenges exist, the opportunities presented by enhanced test efficiency, data-driven insights, flexible testing, and the ability to support the development of new technologies that deliver critical benefits to humankind must be embraced.

By addressing challenges head-on through collaboration, research, and standardization efforts, critical industries can quickly maximize the potential of AI- and FPGA-based instrumentation, launching a future of faster, more accurate, and highly adaptable test and measurement workflows. In turn, it will accelerate the development of the next generation of innovative technology. ■

By Michelle Kopier, *Group Content Director*



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Innovators in Microwaves & RF

Technology is always at the forefront of our coverage at Microwaves & RF and *www.mwrf.com*, but for the 2024 Innovators in Microwaves & RF issue, we wanted to also take a moment to highlight some of the people behind the technology.

WOMEN IN SCIENCE & ENGINEERING:

Christina Gessner, EVP Test & Measurement, Rohde & Schwarz

ON OCTOBER 1, 2023, CHRISTINA GESSNER took over as Executive Vice President of the Test & Measurement Division at Rohde & Schwarz and is now a member of the company's Corporate Management. With Christina Gessner's appointment, Rohde & Schwarz again recruited a longstanding and experienced manager from within.

Christina Gessner joined Rohde & Schwarz as a technology manager in 2004. In 2011, she became Head of Product Management for Spectrum and Network Analyzers. In the following years, she held several leadership roles before being appointed Vice President of Spectrum & Network Analyzers, EMC and Antenna Test Equipment in 2018.

Throughout her career at Rohde & Schwarz, Christina Gessner successfully contributed to establishing the company's market-leading position in spectrum analysis. Her efforts included pushing the development of the first 5G measurement applications, where the company cooperated with key customers in the early phase of development and standardization.

This trailblazing work continued under her leadership, branching out into early 6G research activities across Europe, Asia, and the U.S., where Rohde & Schwarz is now actively involved. For example, as a result of this research, the first off-the-shelf test equipment is already available from her product division, which supports early 6G research in the sub-THz range.

Christina Gessner started her career at Siemens mobile communications, representing the company as a delegate to the 3GPP standardization process for UMTS and GSM/EDGE from 1998 to 2004. Christina holds a degree in RF engineering from the University of Hannover, Germany. She is author of the book *Long Term Evolution: A concise introduction to LTE and its measurement requirements* and holds numerous patents in the area of mobile communications.

Her predecessor as Executive Vice President T&M, Andreas Pauly, who is now Chief Technology Officer (CTO), has full confidence in his successor: "Christina Gessner has an entrepreneurial mindset, drives innovation, and focuses on customer needs. She has demonstrated this in several management functions and especially in her role as Vice President. That is exactly what is needed to take the Test & Measurement Division to the next level."

Christina Gessner welcomes the challenge: "I'm delighted with the trust shown to me. The Test & Measurement Division, with its highly qualified employees, has played an essential role in the company's success for years. In my new role, I will continue on this path and ensure that our customers can still rely on T&M solutions from Rohde & Schwarz in the future."

Throughout her career, Christina Gessner has demonstrated an entrepreneurial mindset, driven innovation, and focused on customer needs. Rohde & Schwarz

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OVER 25 YEARS SERVING CUSTOMERS WORLDWIDE

Since Pulsar Microwave's formation in 1987, its engineering design group has developed a broad product line of microwave and rf passive products used in both commercial and military environments. Depending on frequency and size requirements, our circuits utilize lumped elements, microstrip, air-line or strip-line technologies, and are available in surface mount, flatpack and connectorized outlines. Quality is emphasized throughout the entire assembly process and has resulted in negligible incoming test rejections and field failures.

Because of the large library of designs, totaling almost 5000 standard products, our customers have many options in choosing parts for their systems without incurring NRE charges or lengthy delivery times. At present, the product line covers rf and microwave passive components from DC to 85 GHz.

DC-70 GHZ COUPLERS AND POWER DIVIDERS

Pulsar's couplers and power dividers couplers range in frequency from DC to 70 GHz. Lumped elements are used for multi-octave requirements from DC to about 3 GHz with power levels up to 2.5 KW to optimize bandwidth and size. Microstrip circuits are used for frequencies from 250-6000 MHz to obtain low loss, moderate bandwidths and power levels up to a few hundred watts, and air-line is used for power levels up to 600 watts. For multi-octave bandwidths up to 70 GHz, strip-line configurations yield optimum performance. So many designs are available that a customer can easily find one that either fits or that we can modify to fit the application.

NEW 4-WAY 15-60 GHZ POWER DIVIDER

Our new wide band PS4-53-454/4S covers the frequency range of 15-60 GHz with 5.0 dB of insertion loss and 10 dB isolation. Amplitude balance is +/- 1.5 dB and phase balance is 15 degrees. VSWR is 2.00:1, Power handling is 10 watts, and the outline dimensions are 2.3 X 0.75 X 0.40 inches with 1.85mm female connectors.

PULSAR MICROWAVE CORPORATION

Ginel Hill was the technical lead for SiTime's TempFlat MEMS technology, which enabled a 30X improvement in temperature stability over temperature, as well as SiTime's market-making 32-kHz temperature-compensated oscillators (TCXOs). SiTime

WOMEN IN SCIENCE & ENGINEERING:

Ginel Hill, MEMS Engineering Director, SiTime

GINEL HILL'S OUTSTANDING contributions as the technical lead at SiTime have propelled both the company and the broader timing industry forward, demonstrating exceptional innovation and technical mastery.

Her work on SiTime's TempFlat MEMS technology was a groundbreaking achievement, delivering a 30X improvement in temperature stability. This technology development was much more than a marginal gain; it was a major leap forward that set new standards for timing performance and reliability across the industry.

Under Ginel's leadership, SiTime has not only kept pace with the evolving demands of time measurement—from seconds to milliseconds and down to nanoseconds—but has actively driven this evolution, ensuring that the company's precision timing technology is ahead of its time. Her ability to consistently deliver innovations that disrupt established norms and transform markets has set a high bar of achievement in the timing industry.

The 32-kHz temperature-compensated crystal oscillators (TCXOs) are a testament to her technical acumen, as they have played a critical role in positioning SiTime as a market-maker, solidifying the company's leadership position in the timing industry.

Ginel's dedication to innovation did not stop with the TempFlat MEMS. She skillfully incubated the ApexMEMS process, guiding it from its initial stages of development to the production of working samples. This initiative led to yet another 30X improvement, this time in power efficiency for high-performance resonators, further solidifying SiTime's reputation as an industry pioneer.

Her relentless pursuit of excellence and commitment to pushing the boundaries of what's possible has been instrumental in building SiTime's reputation as the leading supplier of MEMS-based precision timing products.

SiTime stands today at the forefront of the timing industry, redefining what's possible with silicon MEMS technology. In doing so, the company is disrupting a 100-year-old industry based on quartz resonator technology and is transforming the future of the $10 billion timing market.

Ginel has played a pivotal role in this technology-driven transformation. Her innovations have permeated every facet of SiTime's operations, from product development to market strategy, ensuring that the company is well-positioned to lead the timing industry in the connected intelligence revolution.

In a world where accurate timekeeping has become an indispensable component of all electronic devices, Ginel's contributions ensure that SiTime's products are synonymous with quality, reliability, and cutting-edge performance. Her work has set a new standard of excellence for the industry, ensuring that the precision timing products are not only an ideal fit for today's demanding applications, but are also resilient against the temperature, electrical, and mechanical stressors that are an inevitable part of electronic operations.

Ginel Hill's exceptional talent, innovative spirit, and unwavering dedication to advancing the state of the art in precision timing make her a standout nominee for this recognition. In addition to contributing to SiTime's market success, she has played a pivotal role in redefining an entire industry, ensuring that the company remains at the vanguard of innovation in timing technology for decades to come.

Steve is driving development of cutting edge cryogenic interconnects for quantum computing as well as leading development in RF and microwave components. Intelliconnect Group

TRAILBLAZER:

Steve Groves, Sales Director, Intelliconnect Group

STEVE GROVES HAS LED the growth and expansion of Intelliconnect, established for over 20 years as a manufacturer of RF and microwave connectors and cable assemblies, into new markets and cutting-edge technologies. With manufacturing facilities in the U.K. and North America, its products are sold worldwide. Notable success in medical equipment, both wearable and diagnostic, and solder-free connectors have kept the company at the forefront of wireless connectivity.

Steve has led Intelliconnect into the new world of cryogenic electronic systems. The company now provides high-density cryogenic connectors for quantum computing, as well as connectors and cable assemblies for cryogenic medical and research markets. Intelliconnect is now established as the supplier of choice for many of the leading American and European defense, medical, and marine OEMs.

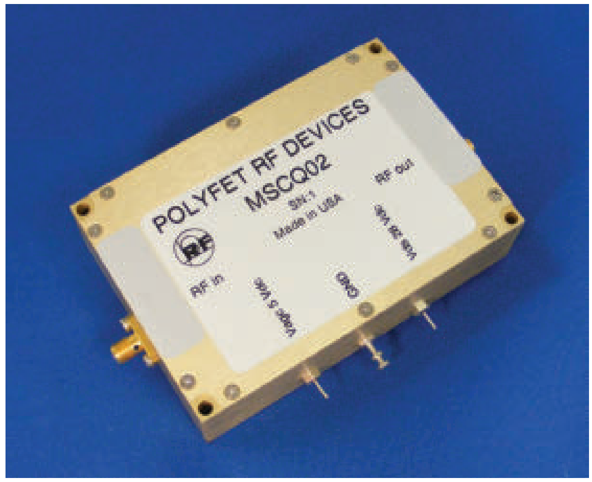
AD INDEX

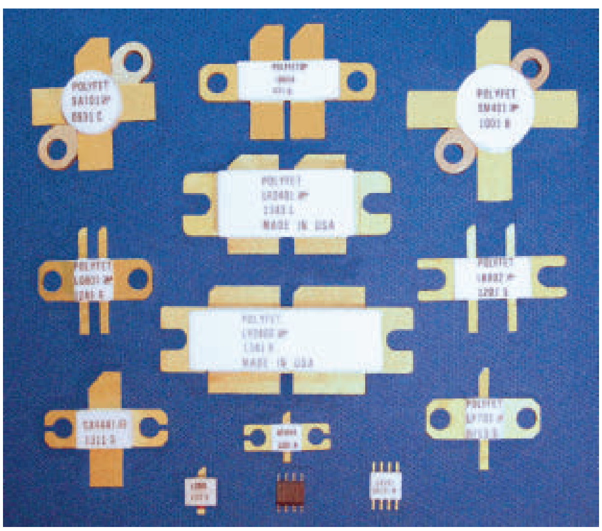
POLYFET RF DEVICES

WEB | www.polyfet.com
EMAIL | jerome@polyfet.com
TEL | 805-484-4210
FAX | 805-484-3393

1110 Avenida Acaso
Camarillo, CA 93012

Polyfet RF Devices is an ISO9001:2015 certified manufacturer of broad band RF power transistors and power modules. We are a private corporation, founded in 1987, and located in Ventura County California. Our products utilize GaN, LDMOS, and VDMOS technologies and are manufactured in the US. In 1995, Polyfet was one of the first companies to develop LDMOS power transistors. Today we are one of the few companies that manufactures devices from a broad range of technologies including both 28VDC and 48VDC RF power GaN transistors. Our technical staff is employed to provide extensive technical support to our customers ranging from device line-up suggestions to amplifier design assistance. Also available to our customers is access to a wide range of product demonstration amplifiers. Our commitment to long-term production support is welcomed by military contractors who use our products where obsolescence is a concern. Furthermore, we manufacture transistors that are proven to be suitable replacements to others in the industry that have seen EOL.





polyfet rf devices

A WIDE RANGE OF PRODUCTS

Being one of the few companies who manufacture GaN, LDMOS, and VDMOS transistors and modules, Polyfet has a wide range of products to offer. The maximum operating conditions for our products are 50VDC, or 3GHz, or 2,000W. Some of the applications our products are used for are military communications, EW, Broadcast, ATM, and NMR. Our transistors are offered in several different package types such as ceramic, plastic, single-ended, push-pull, flanged, and surface-mount. We are one of the few to offer LDMOS devices in compact, push-pull packages. Our power modules are offered in various case sizes and are internally matched to 50 ohms. In Q2 2023 we released additional 50V LDMOS devices that reach 2.0kW across HF, FM, and low VHF bands.

RF POWER SOLUTIONS

When it comes to providing discrete transistor or module solutions for RF power applications, Polyfet RF Devices is a company to consider. Given that we manufacture vast lines of transistors and modules, the chances are we have a solution for you. We have a long history of manufacturing these products and continue to develop new ones. Thank you to all our customers for using our products.

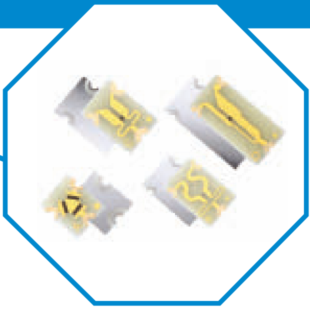
smiths interconnect

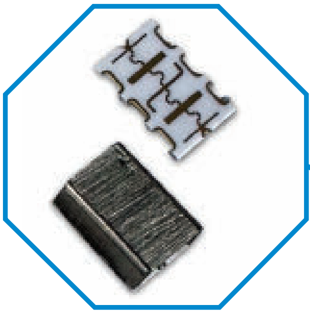
Cutting-edge Connectivity

High-Performance RF & MW Solutions

Resistive and Wilkinson Power Dividers

- Configurable design approach providing optimized solutions for dividing and combining
- Broadband frequency DC-50 GHz, surface mountable, thin film processing technology



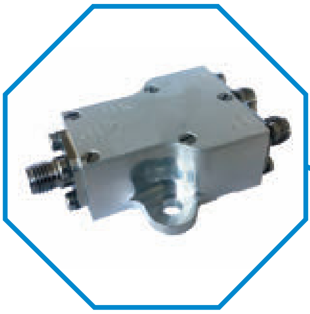


Planar X Series - Thin Film RF Filters

- Light weight – reducing overall system mass in critical space and defense applications
- Surface mountable – ideal for pick-and-place applications

SpaceNXT™ QT Cable Assemblies

- Offered with standardized testing sequences, reducing delivery times and overall cost of ownership
- Mode free performance up to 50 GHz for high frequency applications



Coaxial Couplers - UHF to Ku-Band

- Broad range of space qualified coaxial couplers for proven reliability applications
- Frequencies from UHF to Ku-Band supporting a wide array of markets and applications

more > smithsinterconnect.com