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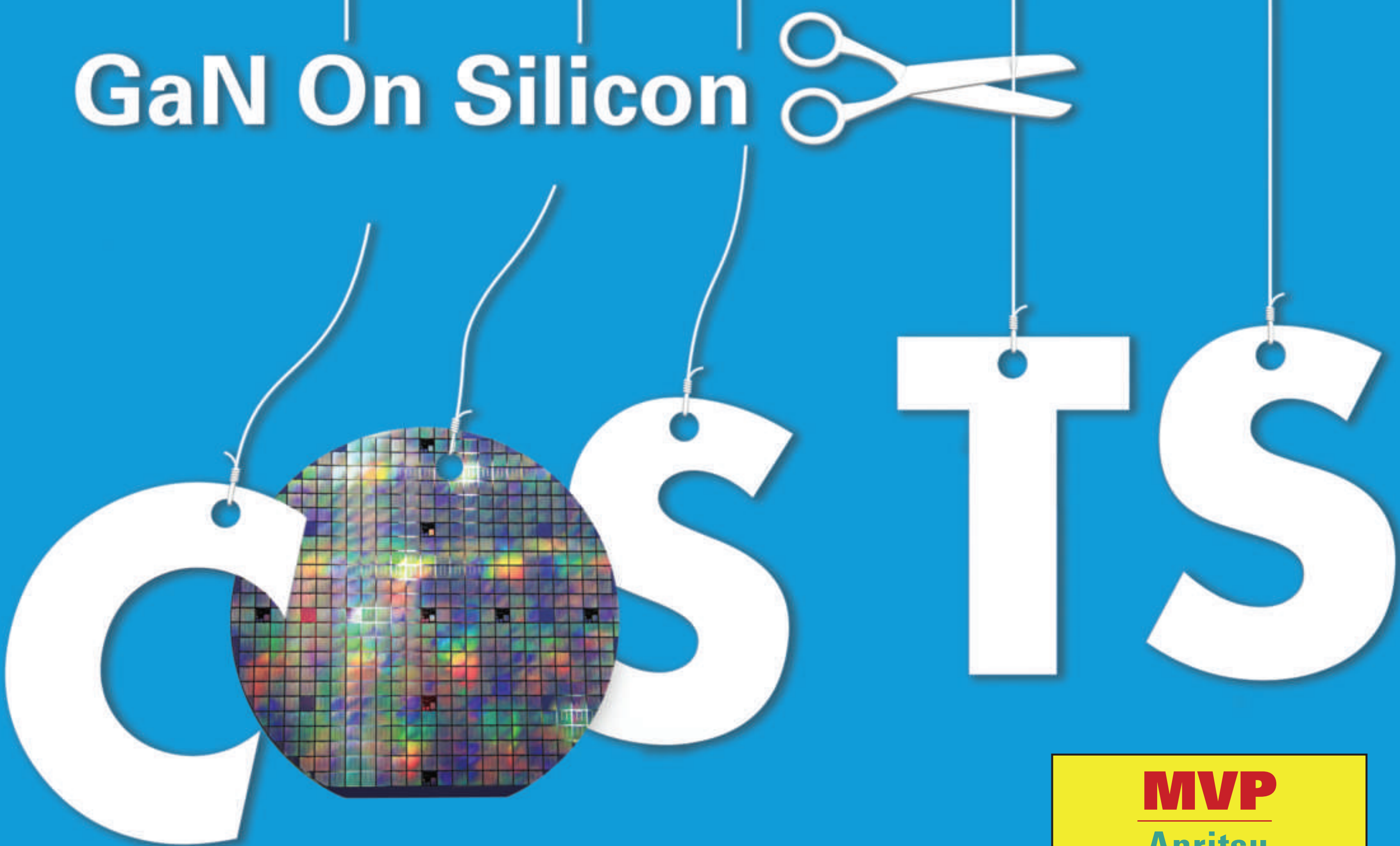
Microwave Journal



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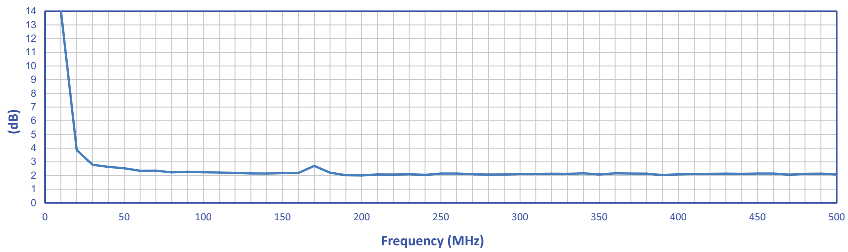
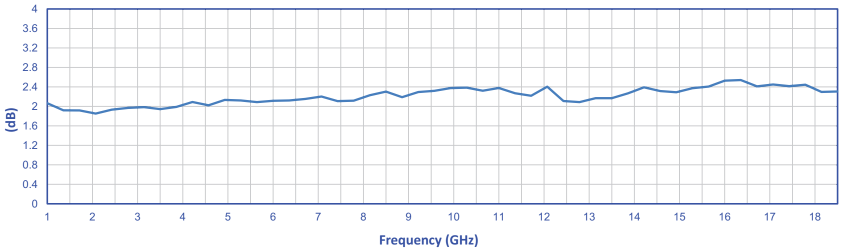
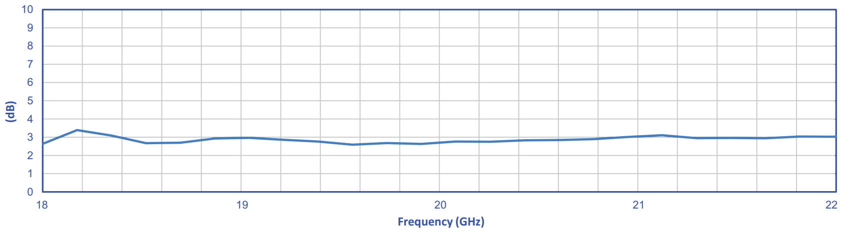
Noise Figure 10 MHz to 0.5 GHz



Noise Figure 0.5 to 18 GHz



Noise Figure 18 to 22 GHz



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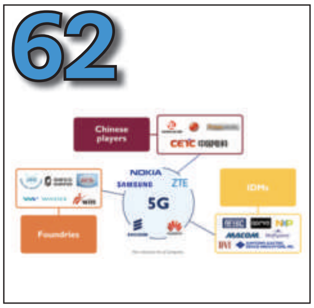

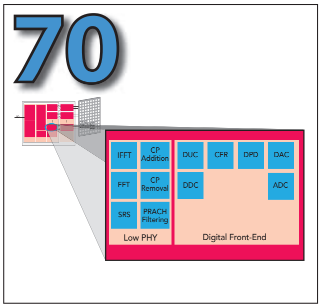

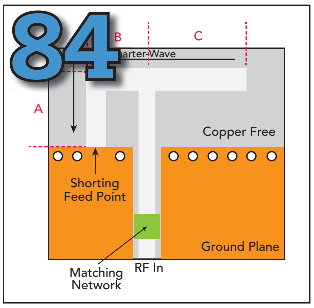

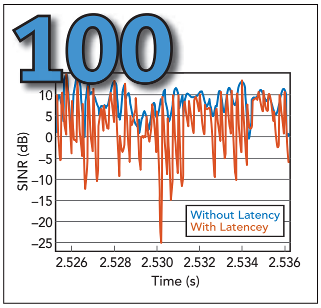

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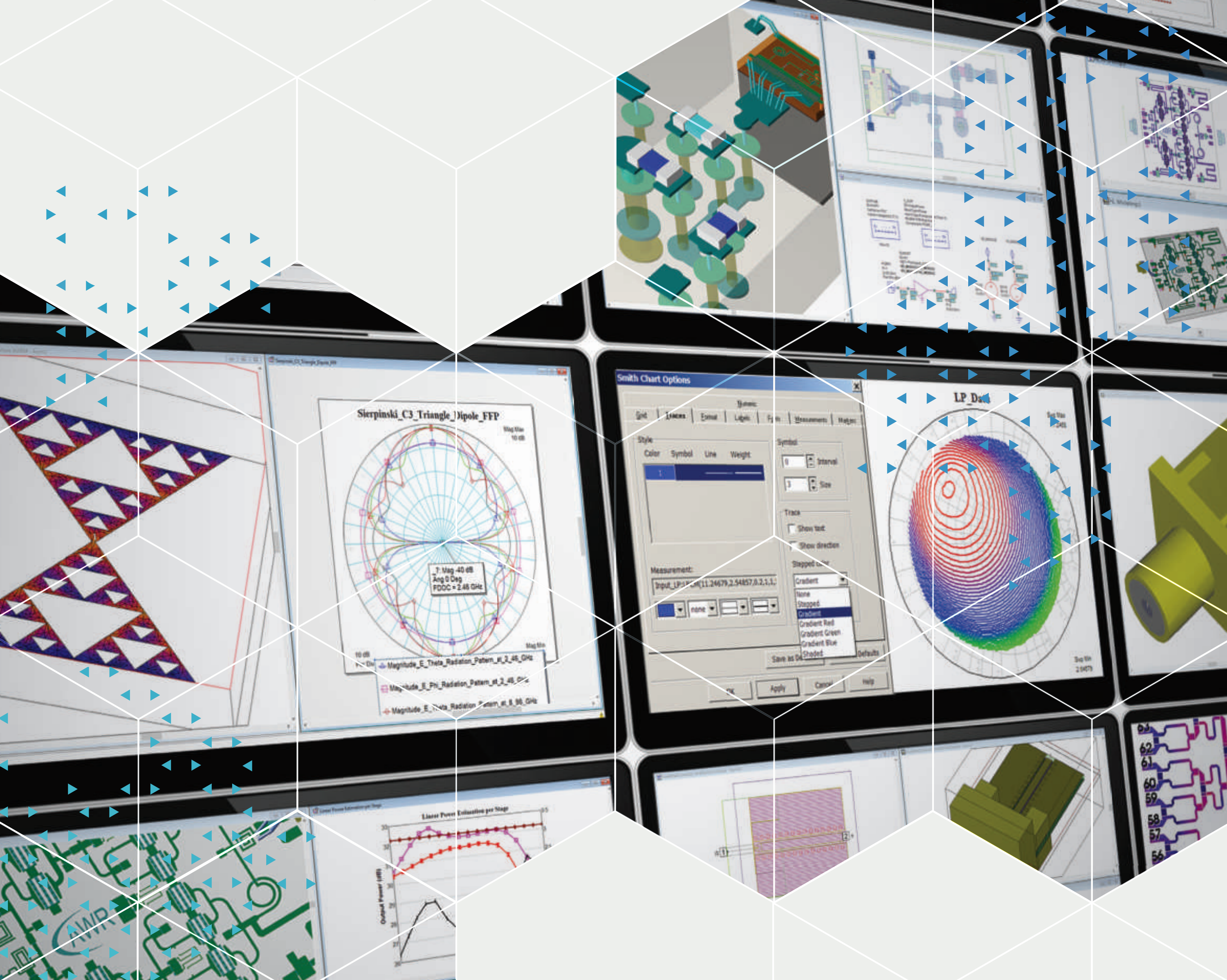

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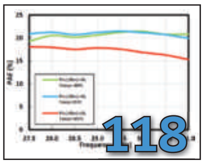

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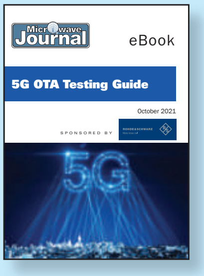

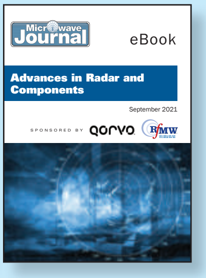

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RF GaN on Silicon: The Best of Two Worlds

Ismail Nasr
Infineon Technologies, Neubiberg, Germany

While the world continues to strive for higher speed connections paired with low latency and high reliability, the energy consumption for information communications technology continues to soar. These market requirements not only position 5G for many critical applications, they also set constraints on energy efficiency and performance. 5G network performance targets impose a new set of requirements for the underlying semiconductor components, increasing the demand for highly reliable RF front-end solutions, with improved energy efficiency, larger bandwidth, higher operating frequency and smaller footprint. As the number of semiconductor devices in base station radios increases drastically, driven by the trend toward massive MIMO (mMIMO) systems, the pressure on mobile network operators to profitably deploy scarce CAPEX and OPEX resources is even more severe. Hence, limiting equipment cost and power consumption is of paramount importance for the installation and operation of an efficient 5G network.

The RF power amplifiers (PA) deployed in modern 5G radio architectures play a major role in meeting the apparently contradictory needs for ever-higher performance and lower cost. While LDMOS technology dominated the RF PAs for radio access networks in previous cellular standards, this is changing with the implementation of 5G. GaN, with superior RF characteristics and significantly lower power consumption, is a contender. There is one caveat to this storyline, however: GaN on SiC, which is predominantly being used for new 5G active antenna radios, remains one of the most expensive RF semiconductor technologies because of its non-mainstream semiconductor processing. This limits its potential for large economy of scale. GaN on Si, in contrast, combines the best of both worlds: competitive performance paired with large economies of scale, enabled by its integration into standard semiconductor process flows. In this article, we explain how advances in GaN on Si positions the technology as a very strong contender for the RF PAs in 5G radios.

5G REQUIREMENTS

The surge of digital social media, data hungry video calls and severe internet usage on mobile devices are increasing the demand for high performance 5G radio networks to provide sufficient coverage and quality of service. This trend intensified during the COVID pandemic and, consequently, operators are pushing for a sub-6 GHz 5G roll-out as an efficient way to cope with this exponentially growing data consumption. The push for higher data rates has, however, a huge impact on the global energy bill, where it is expected that information and communication technology will grow to 21 percent of global energy consumption.[1]

From an RF radio perspective, new 5G features translate into more challenging RF characteristics: Higher carrier frequencies to 7 GHz, instantaneous bandwidth greater than 400 MHz, higher order modulation, increased channel numbers and mMIMO antenna configuration are a few.[2] Furthermore, as radios become more complex, the need to keep weight and power consumption to a minimum was never more

important, with both factors demanding higher energy efficiency to save the costs of energy and cooling equipment. The RF PA stages remain mission-critical devices in 5G mMIMO radios, the last active block before air transmission, where up to 50 percent of the base station's energy in consumed.[3] Modern semiconductor technologies for RF PAs need to meet certain harsh prerequisites to fulfill the requirements of 5G and pave the way to future generations.

In this context, GaN has established itself as the leading high-power RF PA technology for 5G mMIMO radios because of its superior RF performance. However, current implementations are cost prohibitive: GaN grown on expensive SiC wafers in III/V fabs with expensive lithography, resulting in extraordinarily high production cost compared to Si-based technologies. Initial attempts to grow GaN on Si carriers did not make it to the market because of limited performance and unfavorable cost. This is changing. In this article, we describe a new GaN on Si technology running on an eight-inch process that meets all technical requirements and offers commercially attractive economics.

RF PA TECHNOLOGIES

LDMOS — LDMOS FETs (see ***Figure 1***) were introduced in the late 1960s to early 1970s to increase the breakdown voltage of power MOSFETs.[4] The performance, ruggedness and ease-of-use of the laterally diffused structure[5,6] surpassed that of Si bipolar transistors, and LDMOS became the dominant RF power technology in the 1990s.

Over the past 30 years, LDMOS has been the standard technology for the high-power transmit stages in wireless infrastructure, achieving excellent performance to 3 GHz. With the inherent cost advantage from fabricating the devices on eight-inch Si substrates and fully compatible with standard Si process lines, LDMOS has been difficult to supplant in the wireless base station market until the advent of GaN HEMTs.

GaN on SiC — Arising from DARPA programs of the early 2000s,[7,8] which followed the successful GaAs MMIC programs of the 1970s and 1980s,[9] GaN RF devices (see ***Figure 2***) were developed to meet the demand for the higher power, wider bandwidth and higher frequency requirements of military applications, such as radar.

Compared to LDMOS, GaN has the inherent advantages of a higher critical E-field and maximum carrier density in the channel, which translates into higher power density with a higher impedance for a given output power and a lower decline in efficiency versus frequency. The attributes that make GaN attractive for military applications make GaN attractive for wireless infrastructure,[10] specifically high-power density—typically 5x that of an LDMOS transistor—combined with low parasitic capacitance, which enables the device to support wider modulation bandwidths.

The market trend toward higher frequency also favors GaN transis-

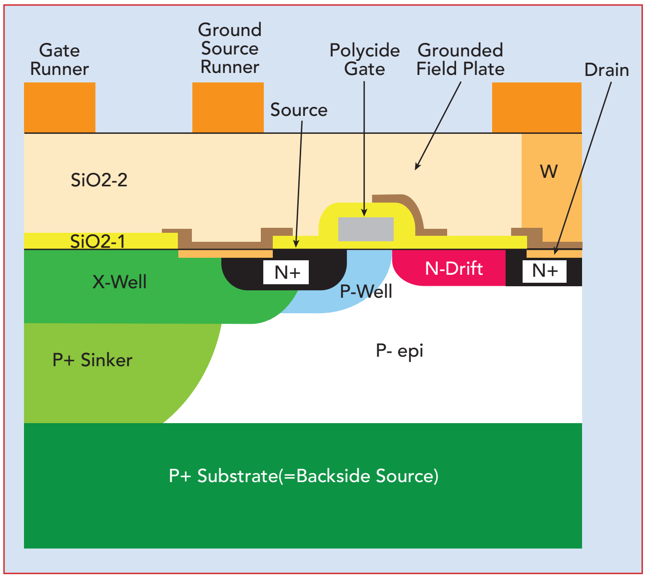


Fig. 1 **LDMOS device functional cross-section.**

tors, which maintain higher peak efficiency as the power and frequency scale. As shown in ***Figure 3***, GaN-based PAs are exceeding 80 percent efficiency, even above 2 GHz. These efficiency advantages are increasingly important for 5G and future communication systems.

GaN on Si — Cost has always been a major factor limiting the adoption of GaN in cost-sensitive applications like wireless infrastructure. This is especially true for applications at 2 GHz and lower frequencies where

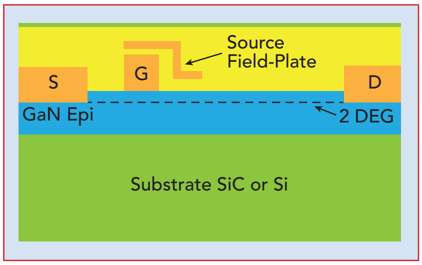


Fig. 2 **GaN HEMT device functional cross-section.**

the performance gap between LDMOS and GaN is not as significant. To address the high cost of GaN on SiC, GaN grown on Si substrates has been pursued since the early 2000s. The main challenges for performance and reliability relate to the difficulty growing high-quality GaN on Si substrates, due to lat-

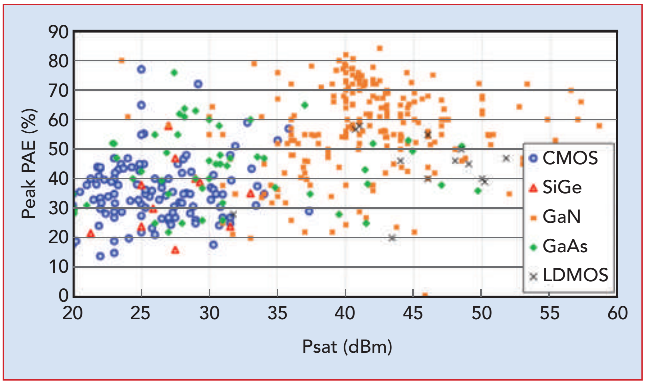
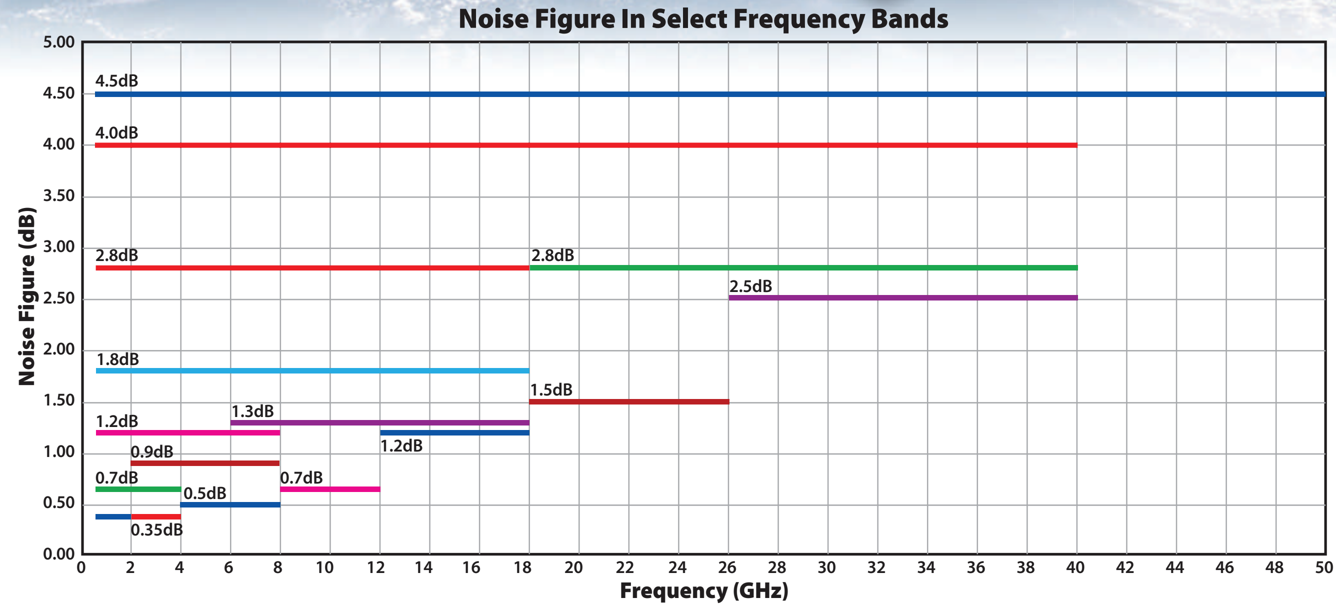


Fig. 3 **Psat vs. PAE vs. PA technology, measured over 2 to 6 GHz.**[11]

Has Amplifier Performance or Delivery Stalled Your Program?



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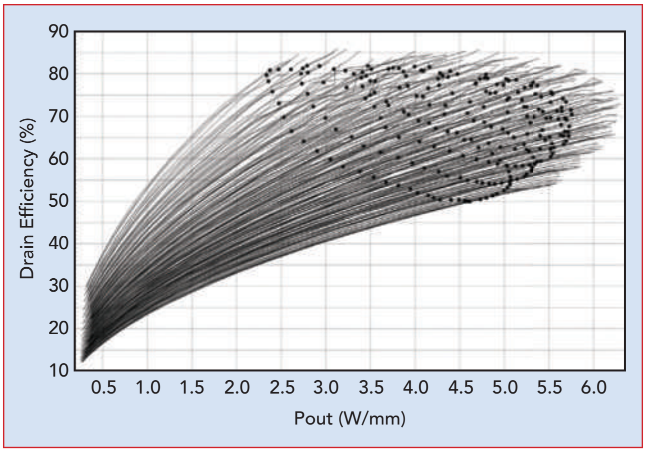

Fig. 4 **Load-pull drain efficiency vs. Pout for packaged 5.8 mm GaN on Si transistor.**

tice mismatch. A huge amount of research and development during the last 10 years, especially for power conversion applications, yielded much improved EPI quality and, subsequently, the release of many GaN on Si products, even for industrial applications.[12]

STATE OF GAN ON SI

Despite this progress, several challenges were overcome to demonstrate GaN on Si performance on par with GaN on SiC, as well as good reliability. Through this work, Infineon developed a GaN on Si technology for RF power that can reach its potential; after many years of development, GaN on Si is ready to become mainstream. The most important criteria determining maturity—performance, thermal resistance, reliability and cost—are discussed in the following paragraphs.

RF Performance — One of the most important performance parameters driving the replacement of LDMOS is RF efficiency. ***Figure 4*** shows 2.7 GHz load-pull measurements of a packaged transistor with 5.8 mm gate periphery and biased at 28 V. At 3 dB compression (P3db), indicated by the circles, the peak drain efficiencies are approximately 85 percent and the peak output power density is more than 5.5 W/mm, performance on par with GaN on SiC. The contours show fairly constant efficiency from deep back-off to near saturation—making the device technology suitable for Doherty PA applications.

Thermal Resistance — One of the fundamental differences between GaN on Si and GaN on SiC is the thermal resistance, reflecting the difference in thermal conductivity of Si and SiC substrates. GaN on SiC has better thermal conductivity. However, through wafer thinning and device layout, the same junction temperature can be achieved with a GaN on Si transistor biased at 32 V as a GaN on SiC device operated at 48 V. By extension, assuming similar failure mechanisms, a GaN on Si device operating at a lower voltage will achieve the same reliability as a GaN on SiC device.

Reliability — Device failure and drift are two con-

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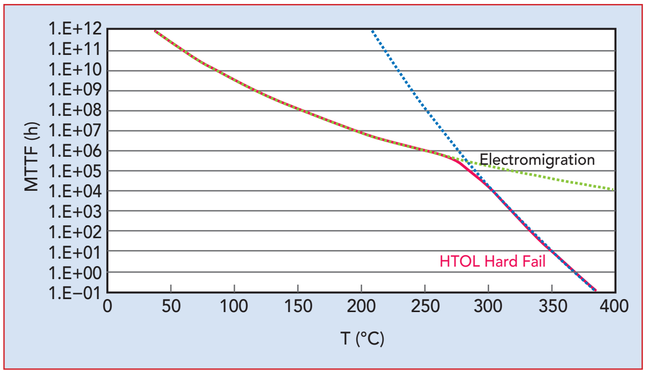

Fig. 5 GaN on Si MTTF.

siderations when assessing device reliability. The mean time to failure (MTTF) is determined by the failure mechanisms, which depend on device temperature (see ***Figure 5***). At lower temperatures, the MTTF of the GaN on Si transistor is limited by electromigration. However, electromigration is independent of the intrinsic GaN transistor, determined by the metallization and layout of the device. The MTTF due to electromigration can be extended by changing the layout. The Infineon GaN on Si device uses the same copper metallization commonly used for Si processes, which has high robustness to electromigration and achieves an MTTF of 10^8 hours at a temperature of 150°C.

Assessing the drift of the technology, ***Figure 6*** shows the Idq drift at 25°C and 100°C with the device biased at

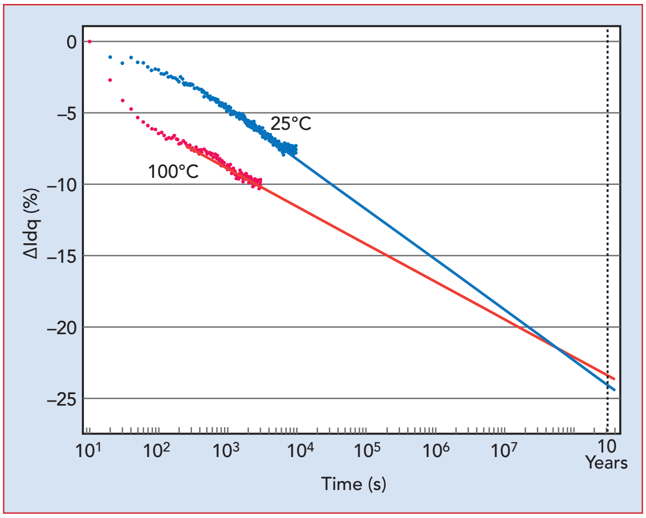

Fig. 6 GaN on Si Idg drift vs. time, 25°C and 100°C.

10 mA/mm and Vds = 28 V. Extrapolating the measurements, after 10 years the Idq drift will be less than 25 percent. ***Figure 7*** shows the degradation in output power versus time of a 20 mm packaged transistor undergoing a high temperature reverse bias (HTRB) stress test. The device is biased at Vgs = -15 V, Vds = 100 V and the temperature is 150°C. The output power degrades less than 8 percent through 1000 hours of HTRB stress.

Cost — The cost per area of a GaN on SiC device is driven by the SiC substrate and the cost of processing

typically small wafers in a III/V fab. By comparison, the Infineon GaN on Si technology runs on eight-inch wafers in a standard Si fab, since it is compatible with other silicon wafer production. The GaN on Si wafer production runs on modern, eight-inch Si production equipment, taking advantage of Si's inherent integration, performance, yield and supply chain infrastructure. RF integration leading to more complex MMICs is a longstanding trend, so the cost per area of a volume Si fab remains an important differentiator.

GAN ON SI PA MODULES

The key performance parameters for a wireless infrastructure PA module (PAM) comprise the power-added efficiency (PAE) at the nominal RF output power, the dynamic peak output power and the ability to linearize the PA in both frequency-division duplex (FDD) and time-division duplex (TDD) modes.

A trend for the RF power per antenna element in active antenna systems (AAS) is increasing the nominal linear output power of the PAM from 3 to 8 W, possibly to 12 W and higher. The frequency and antenna array scaling impose a size restriction on the PAM so it fits within the element spacing on the RF printed circuit board (PCB) to minimize the system cost. Power GaN technology supports this compact form factor because it can withstand higher junction temperatures.

To assess the capabilities of Infineon's GaN on Si technology, a single-stage Doherty amplifier PAM on a multi-layer organic laminate substrate was designed to have an average modulated linear power of 39 dBm in the 3.4 to 3.6 GHz band (see ***Figure 8***). In a Doherty design, the input signal is split between "main" and "peaking" amplifiers, and the amplifier outputs are recombined with a 90-degree phase shift in one path. Biased at 28 V and with a single-tone input signal, the gain and drain efficiency (DE) of the PAM versus output power were measured at room temperature (see ***Figure 9***). At

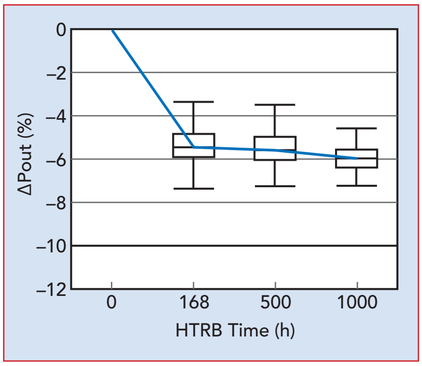

Fig. 7 GaN on Si Pout drift vs. HTRB time.

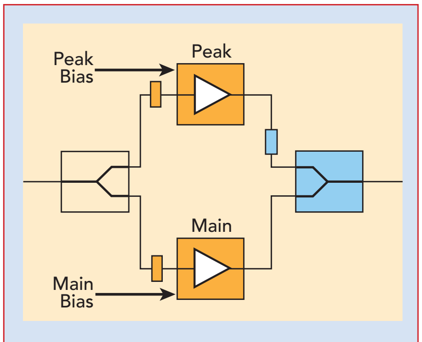

Fig. 8 Single-stage Doherty PA block diagram.

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39 dBm output, 10.5 dB power gain was achieved, including the 3 dB splitter, combiner and other passive losses. A maximum output power of 47.5 dBm was measured.

Using a clipped and filtered, modulated 5G NR waveform with 7.5 dB PAR, the nominal RF operating power of 39 dBm is predicted, with the first peak in DE expected near this point, to ensure minimal deviation of the modulated DE from the single-tone DE. The single-tone DE was 52 to 54 percent. The performance of the GaN on Si PAM is comparable to the performance reported for GaN on SiC.[13-15]

The dynamic peak power of the PAM with a modulated signal and using digital predistortion (DPD) was measured at 3.6 GHz using a spectrum analyzer (see ***Figure 10***). A peak power of 47.5 dBm was measured. The figure compares the modulated AM-AM dependency with and without DPD, showing the DPD yields excellent linear output characteristics. The capability of DPD to linearize the PAM reflects low device nonlinearity and low circuit and device memory effects. Ease of linearization using commercially available DPD engines is an important characteristic of the device technology and amplifier design.

The fielded application for this PAM is in FDD and TDD base stations. With the versatility of the 3GPP's 5G standards, the time diagram of a transmitted signal can be rather complex and irregular, with single symbol transmission possible. Thermal, charge trapping and video bandwidth determine the dynamic response of the PAM, which manifests in varying output power and error vector magnitude along the symbol sequence within a

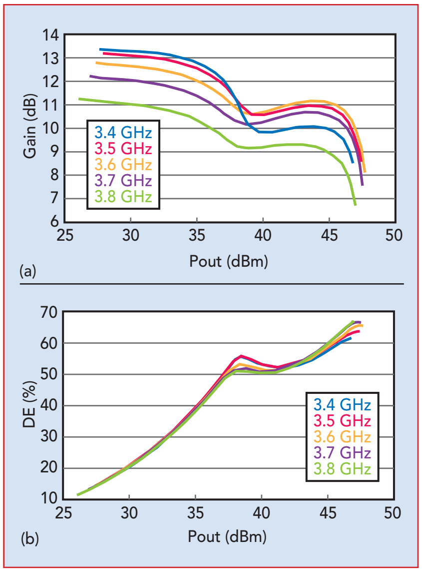

Fig. 9 Measured gain (a) and DE (b) vs. input power of a single-stage Doherty PA.

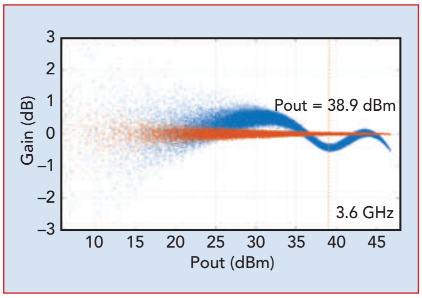

Fig. 10 Gain vs. Pout of the Doherty PA with a 3.6 GHz modulated signal, comparing the "raw" performance (blue) with DPD linearization (red).

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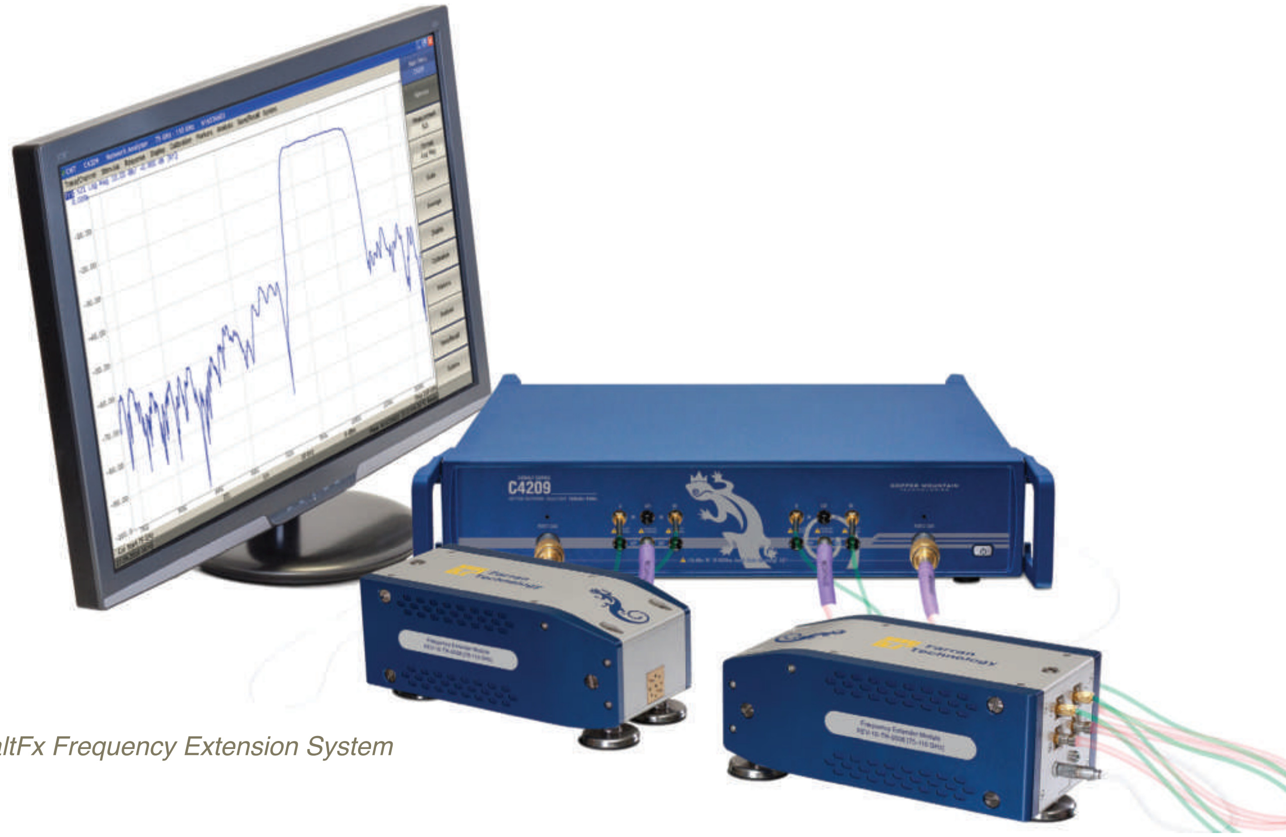

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transmitted sub-frame. To illustrate, ***Figure 11*** plots the power spectrum of the first symbol of a transmitted sequence, showing performance in FDD, mixed and TDD modes using DPD without the long-term memory model. Vc refers to the clamping voltage or off-stage gate bias. The TDD mode measurements used the following modulated signal: 3GPPD TM3.1a with a 1 × 20 MHz channel, 5G NR OFDM 256-QAM, 60 kHz SCS and 7.5 dB PAR.

TRENDS AND CHALLENGES

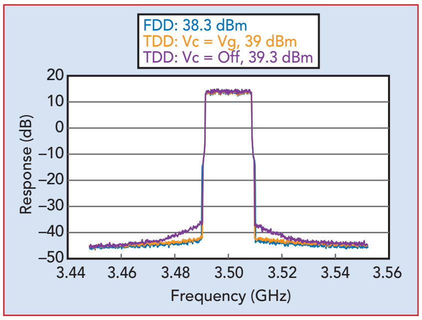
As the RF transmit power increases, heat management becomes more important. With mMIMO AAS, there are several thermal management considerations: 1) system overheating leading to component performance degradation and reduced long-term reliability, 2) higher operating cost because of lower energy efficiency and 3) passive heat removal from the radio system.

While discrete module solutions could provide better heat management through lower packaging density, they can create BOM and PCB-area bottlenecks in larger AAS, requiring significant design optimization by the system integrator. Control over die thickness, use of proper die attach techniques and high-quality soldering of the PAM onto the PCB are key to removing heat from the PAM. Maintaining near constant output power over temperature requires a smaller design margin and yields higher PAE. Infineon's GaN on Si PAM products have a -0.02 dB/°C power gain coefficient, which is comparable to GaN on SiC and LDMOS PAs.

Wider instantaneous bandwidth and use of frequency bands above 5 GHz are two additional market trends leading to more integrated PAM solutions on GaN. Infineon's GaN on Si technology has the capability for MMIC integration, which offers substantial benefits, not only for meeting the output power specifications, but also overcoming performance limitations from the parasitic effects of cascading discrete components, transistor parasitics and bond wires, which typically result in reduced bandwidth and poorer energy efficiency.

SUMMARY

This article discussed the development of an RF GaN on Si technology for wireless infrastructure that improves the cost-performance value of GaN. After many years of GaN on Si development, the technology has matured to deliver its potential, providing efficiency on par with GaN on SiC at a lower cost



▲ **Fig. 11** Measured Doherty PA spectrum in FDD and TDD modes using DPD without the long-term memory model.

based on Si wafer processing. This article has shown GaN on Si can meet the efficiency, linearization and power density requirements of 5G wireless communication systems. We believe this is the start of a longer journey, where further industry developments will push the capabilities of GaN on Si to higher frequencies and higher power levels, potentially expanding applications beyond wireless infrastructure. ■

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Most Valuable Product

Rubidium™ Signal Generators Redefine Industry Standards for Spectral Purity and Stability

Alexander Chenakin, Suresh Ojha and Sadashiv Phadnis
Anritsu Company, Morgan Hill, Calif.

Anritsu's new Rubidium signal generators address today's market demands for high performance microwave signal sources through 20 to 43.5 GHz. With innovation and quality as their driving principles, the Rubidium signal generators challenge traditional performance expectations with atomic-grade frequency stability and super clean phase noise of –140 dBc/Hz at 10 kHz offset from the 10 GHz carrier.

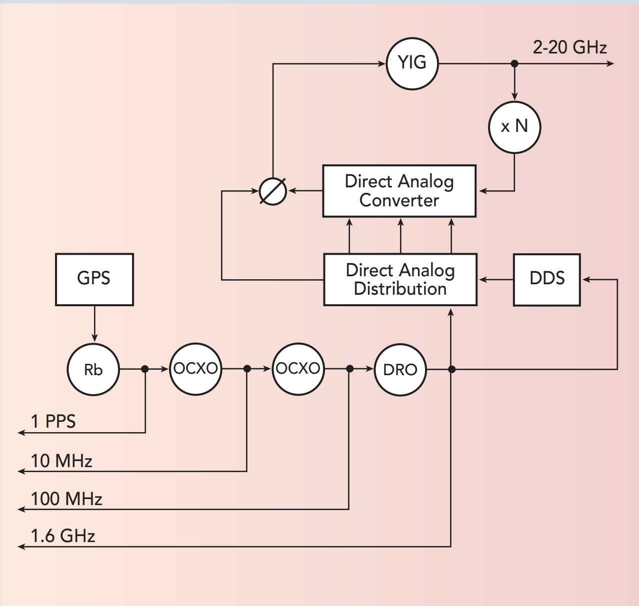
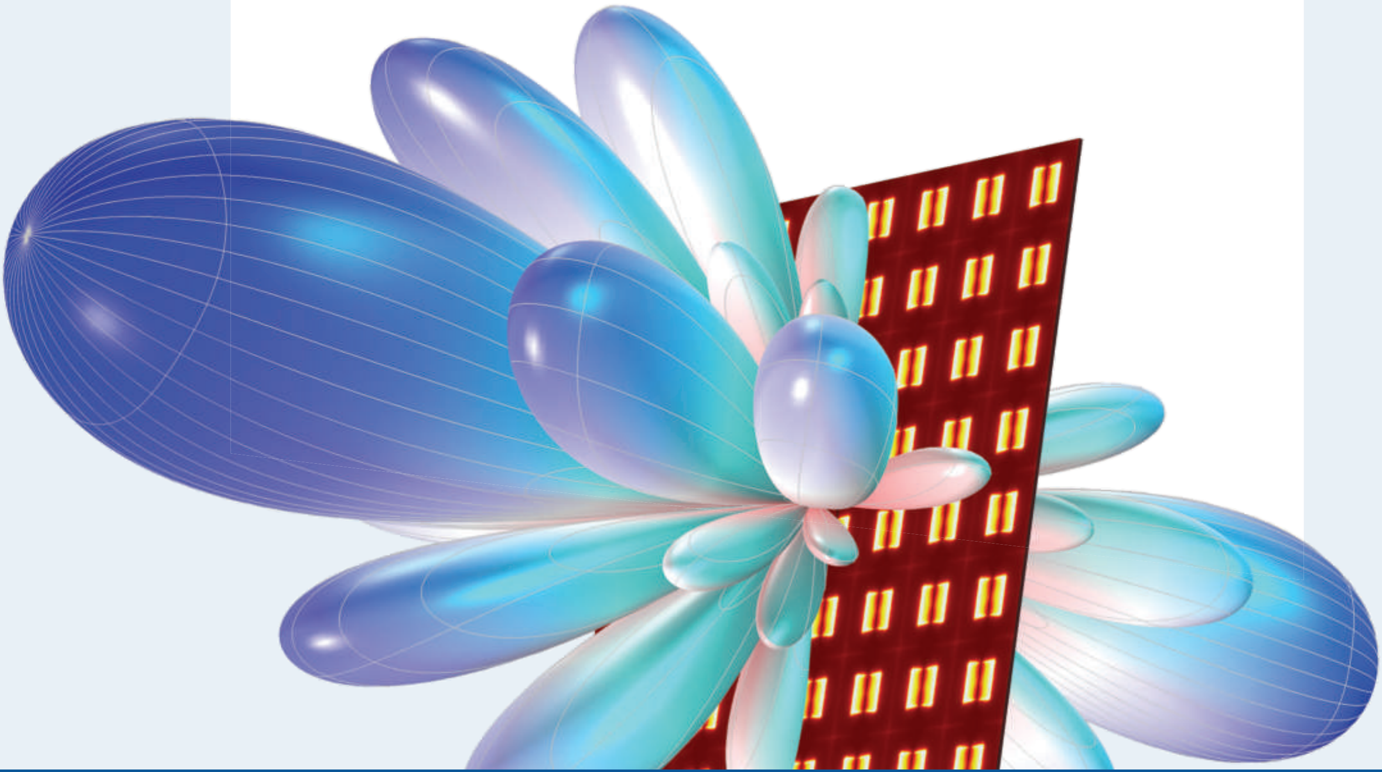


Fig. 1 A simplified block diagram of Rubidium™ synthesizer core.

Signal generators are the salt of the earth; modern technologies could not exist without them.[1,2] To address today's market requirements, Anritsu Company has introduced the Rubidium series, a new generation of microwave signal generators based on an innovative technology[3] that provides a combination of wide frequency coverage, fine resolution and high output power coupled with low phase noise and atomic-grade stability. The synthesizer core is based on a proprietary 2 to 20 GHz YIG oscillator that is locked to an internal reference extracted and distributed by direct analog means as illustrated in ***Figure 1***. The YIG native frequency coverage is further extended with a frequency multiplier and frequency divider (followed by a high-power amplifier, amplitude control and harmonic filtering) to achieve 9 kHz to 20 GHz or 43.5 GHz coverage. The YIG output signal is down-converted by a direct analog converter that eliminates any frequency divider and, therefore, phase noise degradation within the phase lock loop. A switched frequency multiplier is inserted into the loop that (a) reduces the number of frequencies generated by the direct analog distributer and (b) also provides additional residual PLL noise suppression at low frequencies.



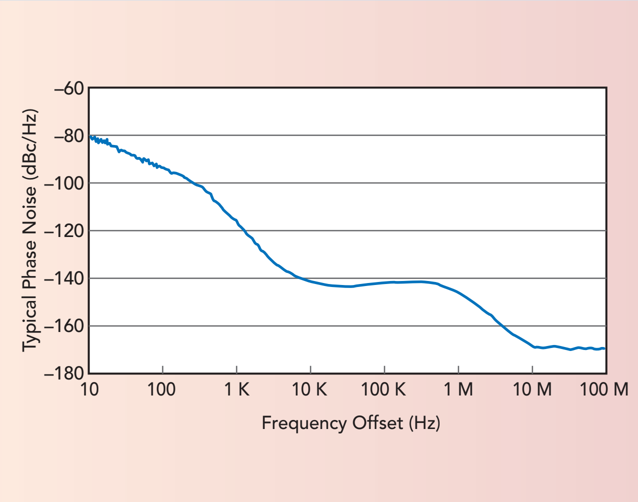


Fig. 2 Rubidium Typical Phase Noise at 10 GHz.

Fig. 3 In-field power calibration with a USB power sensor.

As a result, the presented architecture provides essentially a noiseless PLL mechanism, meaning it translates synthesizer's reference noise with no added phase noise degradation over 20logN fundamentals. A three-source combined reference is utilized to provide the lowest possible phase noise at any given frequency offset. Furthermore, the combined reference is disciplined by a rubidium atomic clock that introduces a much higher degree of stability compared to a conventional OCXO-based reference. The rubidium clock operation is based on fundamental constants rather than physical dimensions and, hence, is extremely stable. Various reference frequencies are available for instrument synchronization including a high frequency 1.6 GHz output for the highest fidelity.

The architecture of Rubidium signal generators delivers high performance in respect to spectral purity and stability. Phase noise is always a key specification for signal generators. The Rubidium signal generators offer four noise grades exhibiting exceptional -140 dBc/Hz at 10 GHz and 10 kHz offset with the premium noise option as depicted in ***Figure 2***. Another important aspect is frequency stability. Conventional signal generators normally rely on 10 MHz ovenized crystal oscillators (OCXO) showing relatively stable performance. Nonetheless, an OCXO oscillation frequency depends on the crystal mechanical resonance or—in other words—on crystal dimensions. Obviously, with a temperature change, the crystal dimensions change too, resulting in slight frequency variations. Furthermore, the crystal material itself evaporates with time, eventually leading to frequency aging. Hence, introducing an atomic standard radically improves the internal time base stability—not in multiples, but by several orders of magnitude.

IN-FIELD CALIBRATION

Precise and stable frequency and output levels are essential in a microwave signal generator. Hence, traditional signal generators require periodic calibration. This represents a certain challenge. Whether the calibration lab is across the street or across the country, sending an instrument out for calibration during a critical time is an expensive and time-consuming proposition. To reduce the total cost-of-ownership, the Rubidium signal generators offer a built-in calibration routine to adjust its internal time base as well as output power on the spot. One of the primary tasks when calibrating a signal source is to set its time base that ultimately defines the instrument's frequency accuracy. Fortunately, the Rubidium signal generators come with a rubidium time base that is considered to be a frequency standard itself. Thus, in most practical scenarios, no frequency calibration is required at all. This is very important in some sensitive applications such as aerospace and defense.

The Rubidium signal generators include a built-in global navigation system receiver that receives a signal extracted from an on-board satellite high precision atomic source circling the earth. The output of the receiver is a 1 pps pulse stream that can be used to adjust the instrument's internal time base to synchronize it with any worldwide frequency standard offered by global navigation systems. This adjustment is performed with just a mouse click, thus, eliminating a need for sending the signal generator for a factory calibration. Another valuable feature of this signal generator is that it allows connecting a USB power sensor (see ***Figure 3***). The power sensor enables measuring the power directly at the device-under-test plane, therefore, taking into account any loss introduced by external cables or other devices. Furthermore, the precision power sensor allows calibrating the instrument output power (in certain limits) as needed without sending to the factory.

Overall, the new Rubidium technology offers superior performance in comparison with traditional instruments. With excellent spectral purity and signal stability, the Rubidium series is an ideal signal source for design and manufacturing test of components and systems for a wide variety of applications—including wireless communications, aerospace and defense and consumer electronics.

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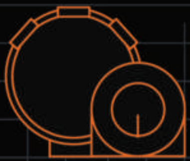

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DREAM ON

CEO Chris Marki Combines Creativity, Innovation and Hard Work to Deliver Performance Shattering Products in an Environment that Promotes Engineering Excellence

An Interview with CEO Chris Marki of Marki Microwave by JT Konstanturos

JTK: Please tell me how Marki Microwave came to be.

CM: My parents founded Marki in 1991, funded only by their own savings. It was an incredible risk, but my dad, as he tells the story today, "never had a doubt" we would succeed. My dad, who immigrated to the United States during the Hungarian Revolution, had become a world class mixer designer by this point in his career, so he was very confident that he would be able to deliver best in class performance… he was right. 30 years later, Marki Microwave still believes in dreaming big to solve the industry's toughest technical problems.

JTK: Can you tell me what is new in RF today?

CM: Actually, very little is new in RF anymore. Almost everything that we see today is a variation on a very old and well understood theme. This is not a criticism of our industry, but more of a recognition of the maturity of the field. RF technology dates to World War II when the British used radar to help with the Battle of Britain. Most of what you see in RF is a modern spin on an old concept. Marki Microwave is one such example. My father started in the field in 1971 and the technologies available to him during his career are fundamentally different than the ones we use today. But the physics are the same and the basic circuit concepts are identical. My dad is retired now, but whenever I show him a new idea or cool innovation, he instantly recognizes the underlying physics and novelty. Nothing is new—only repurposed and repackaged using modern manufacturing and technology.

JTK: When did you join the company?

CM: I joined in 2007. I had just completed a PhD in optics and realized that my dad had the best job in the world – invent stuff, build stuff and sell stuff. Coming out of grad school, that lifestyle was very appealing compared to constantly chasing research funding for questionably good ideas. My first goal was to not break anything and my second was to find new and better techniques to design and manufacture our products. We have had a good run of things and are about to move into a new factory that is six times bigger than the one I started at in 2007.

Your company states it is 100% Made in America. What does that mean to you?

CM: We aren't "Made in America" for any particular ideological reason. We are Made in America because that is how we can manage to build the best hardware in the world. Our designs and assembly techniques are highly differentiated and complex, and we carefully choose our suppliers and partners. *Nothing we do is a commodity*, so it is extremely rare to find something inside Marki that actually *could* be offshored. Beyond this, if you place your reputation on delivering best in class performance for your products, then it is important that the inventors and innovators on your technical team have close access to the people who actually build your parts. It would be impossible for me to innovate on many of our products if I had to fabricate the assembly in a distant country with a different time zone and language. The life blood of our technology is in the packaging, so it must be done domestically if we wish it to stay cutting edge.

JTK: What markets are your products designed for?

CM: I am big believer in bottom-up innovation and mostly ignore end markets. I believe that the most successful products require a "key technical insight", to steal a phrase I learned in the book *How Google Works*. My entire career in inventing and innovating products has involved ignoring specific markets or platforms and instead focusing on key technical challenges that face all our customers. This approach guarantees that we are always focused on cutting edge technology and not on wayward marketing projections. To do this, you must constantly antagonize your existing capabilities and search for new ideas to help solve hard problems.

JTK: Marki Microwave is investing in quantum computing, is that correct?

CM: Mainstream adoption of quantum computing is not an *if* but a *when*. It is truly changing the way we look at solving complex problems, but standardization is far off. Our interest in quantum is to understand how we fit into the ecosystem now and into the future, and then develop products and solutions that fit that particular space. I only recently began to appreciate that most of the big players in QC were already avid Marki customers, and many of the companies with headline grabbing announcements often use Marki hardware. My job is to listen to these incredible engineers and scientists, learn about their challenges, and position our product pipeline (to borrow a phrase from our company motto) "to shatter performance barriers."

JTK: How would you describe the Marki Microwave culture?

CM: Innovative and creative – both traits are in Marki Microwave's DNA. There is a strong artistic gene in my family. My father was a master jeweler and painter before he became an engineer. My mother was an outstanding violin player. I also have that creative instinct. When I was younger, I would watch in awe to see Stevie Ray Vaughan or Steve Vai play the guitar. They were doing things with six strings that felt magical. I have always wanted to "bottle lightening" like that, and I see a lot of similarities between the act of product design and the act of musical expression. It wouldn't surprise me if both of those came from the same part of the brain. I have always wanted to express my own technical ability through inventive and unique ideas, and in that way, I consider my designs to be like a new song or melody. The good news is that inventive creativity and the desire to write "unique music" is incredibly useful if you want to make differentiated technology. There is a reward in my field for people who can come up with clever solutions to problems, and a musical or artistic sense is correlated, in my opinion. Music is also central to my design practice. In fact, I associate certain bands and songs with specific Marki Microwave designs – I must have listened to Chris Cornell's final solo album 100 times while designing the circuits that eventually became the MM1-0626 mixer.

JTK: Are you hiring?

CM: You bet. We are looking for the best and the brightest talent who are not afraid to challenge the status quo. Some of the biggest advantages of working with a company our size is that we are small enough for you to have visibility and growth potential but large enough to provide the most up to date equipment and the expertise to support career growth. Most importantly, we have been around long enough to have earned an industry reputation for building cutting edge products you can't find anywhere else.

To view Marki Microwave's products and job openings, visit www.markimicrowave.com. For sales information, contact sales@markimicrowave.com or (408) 778-9952.

DefenseNews
Cliff Drubin, Associate Technical Editor

DoD Taking Measures to Protect Nuclear Weapons, Space Assets

The Defense Department (DoD) relies on nuclear-armed bombers, submarines and intercontinental ballistic missiles, as well as space-based sensors, to provide a strategic deterrence umbrella for the homeland and to protect deployed forces, allies and partners.

However, sensitive microelectronics used in these assets could be vulnerable to high levels of ionizing radiation caused by several factors, including cosmic rays in outer space, severe solar storms and an electromagnetic pulse caused by a high altitude nuclear detonation.

"To protect against these threats, the DoD has developed techniques to protect microelectronics used in satellites, spacecraft, the nuclear triad and the triad's command and control center," said Rich Ryan, director for international programs, nuclear forensics, resiliency and survivability in the office of the deputy assistant secretary of defense for nuclear matters. This protection, known as hardening, can consist of manufacturing chips on insulated material, redundant circuits, altering the design of circuits and placing a shield over the microelectronics. Each of the methods used undergoes rigorous radiation testing in military and government laboratories to ensure they work in hazardous conditions, he said.

Satellite (NASA Photo)

In the past, there was no central repository for identifying and accessing parts that have been certified as radiation hardened. On September 30, the DoD opened a parts library to serve the department and other agencies with requirements for radiation hardened parts, including NASA and the Department of Energy. The cloud-based library is hosted by Nimbis Services in Oro Valley, Ariz.

Known as the Trusted Silicon Stratus Distributed Transition Environment, the authority to operate this library was issued by the Strategic Radiation Hardened Electronics Council; the Air Force Research Laboratory at Wright Patterson Air Force Base, Ohio; and the Naval Surface Warfare Center Crane Division in Indiana. "The authorization comes as a clarion call to improve supply chain visibility across the nuclear enterprise. Establishing this microelectronics library is key to improving the ability to analyze key parts, their sources and to facilitate government re-use of intellectual property throughout the DoD," Ryan said.

MESA Radar Sets Sights on Airborne Battlespace

Wedgetail. Peace Eagle. Peace Eye. Known by different names, the 737 Airborne Early Warning & Control (AEW&C) system provides a long-range picture of the battlespace with its enhanced Airborne Moving Target Indication (AMTI) capability.

Perched on top of the AEW&C system is the Northrop Grumman designed and built multi-role electronically scanned array (MESA) sensor. The MESA radar electronically scans the skies around the Boeing 737-based aircraft, providing the warfighter with an unrestricted 360-degree view.

Near-peer adversaries have been developing sophisticated advancements in platforms and system capabilities that threaten the warfighters' advantage in the battlespace. The MESA radar for the AEW&C system provides critical domain awareness for warfighters and allows them to see farther and make accelerated and informed decisions to meet mission objectives.

MESA provides the ability to dynamically adjust to each unique or emerging tactical situation. The radar can extend its detection range without having to fly closer to a threat situation. By targeting its energy to the threat, the sensor can nearly double its detection range in the emphasis location, all while maintaining a full background of the entire battlespace. Compared to other surveillance radars, MESA also has higher update rates for enhanced tracking, bringing battle management to the edge of the radar surveillance envelope.

The system enables tracking of airborne and maritime targets simultaneously, including the ability to revisit high profile targets at rapid rates. At the same time, MESA provides a fully integrated, long-range Identification, Friend or Foe (IFF) capability to maintain continuous surveillance of the operational area.

MESA Radar (Source: Northrop Grumman)

Modern jamming threats can jeopardize the warfighters' understanding of the environment. With MESA's multiple channels and independent receivers, the sensor uses modern electronic protection techniques to adapt to jamming and electronic attack threats, while simultaneously maintaining situational awareness. No matter the threat, it ensures the warfighter retains a constant view of the battlespace.

For More Information Visit mwjournal.com for more defense news.

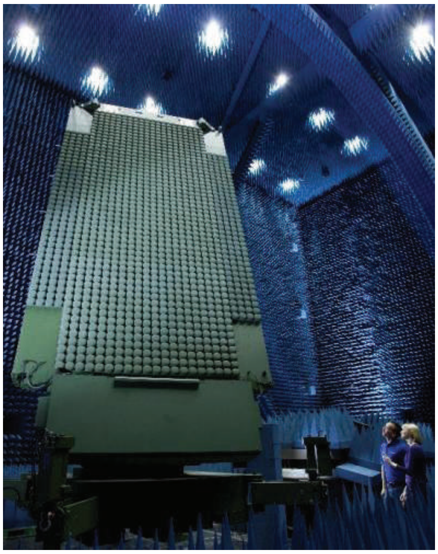
TPY-4 Radar Setting New Standard in Airspace Threat Detection

Lockheed Martin's TPY-4 has received its official U.S. Government nomenclature—AN/TPY-4(V)1—officially marking the radar's maturity and its ability to deliver fully digital technology, therefore setting a new standard for the future of radars.

TPY-4 offers multi-mission capabilities, such as early warning, situational awareness, tactical ballistic missile surveillance and air defense. It also integrates the latest mature commercial technologies to create a revolutionary radar architecture.

The first TPY-4 is well ahead of any competition and already in production to be unveiled by the end of this year. The radar's production sub-assemblies are passing environmental and performance tests, attributed to the foundation built and validated under Lockheed Martin's investment and the commonality with the U.S. Army's Sentinel A4 radar. The radar's test results continue to surpass model predictions, as validated by open air testing.

TPY-4 is an internationally available, transportable, multi-mission radar that can operate in contested RF environments and provide the warfighter an ability to detect and track threats better than any previous radar available today. It accomplishes this with a fully digital, software-defined sensor architecture, allowing users to maintain ongoing surveillance throughout the mission.


TPY-4 (Source: Lockheed Martin)

That is because TPY-4 radar users are not locked by the system's hardware. Users can transmit and receive digitally, allowing for more enhanced target identification and classification. Earlier radars may have some level of digitization, but Lockheed Martin's software-defined TPY-4 radar is digital at every element and across the entire architecture. Users do not have to account for downtime for time-consuming actions, like hardware upgrades or manual data transfers.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The Last Drone Standing: First Responder UAS Endurance Challenge

Picture this: A person is lost in the desert. Local first responders initiate a search and rescue operation. As they conduct the search, they're faced with a problem: loss of broadband signal.

This isn't a made-up scenario. First responders often work in conditions where communication networks are weak or not available. One possible solution is to use drones to deploy broadband networks, making signals available anywhere. But today's drones often can't provide adequate support to first responders. The equipment is too heavy for drones to carry for very long.

To help solve the largest challenges facing the first responder community, NIST often turns to private companies, academic researchers, hobbyists and others via open innovation prize challenges. This time, the First Responder Unmanned Aircraft System (UAS) Endurance Challenge addressed the obstacle of extending the flight time for drones that carry heavy payloads. The objective for challenge participants was to design, build and fly a UAS that could carry a 10-pound (4.5-kg) communications device to deploy broadband coverage for as long as possible to transfer critical data files to the first responders. And as part of the challenge, participants were tasked with overcoming difficult technical requirements including weight restrictions, vertical takeoff and landing, an ignition kill system and an appropriate fuel system, all while ensuring cost-effectiveness.

Forty-three teams entered the competition, of which five final competitors spent a total of 14 months designing and building lightweight drones that go beyond today's technical capabilities by flying continuously for 90 minutes or longer with heavy payloads. The prize challenge competitors built their systems with the intention of providing broadband service to boots-on-the-ground first responders when they lack network or bandwidth. This includes servicing areas with a lack of cellular network coverage or where cellular infrastructure has been compromised due to a natural disaster or areas with limited backhaul connectivity, which links the main network to remote locations.

The competition's top prize went to Team Advanced Aircraft Company (AAC), which received $100K for its six-rotor drone with propellers on each arm. AAC is a veteran-owned company based in Hampton, Va., that specializes in building American-made drones that enable longer flights through their hybrid-electric propulsion system. The company builds UAS devices that are quick to set up and easy to use for its customers, including members of the public safety community. Unlike some other prize challenge competitors, AAC's drone is not a prototype but a product it currently is selling.

The other top teams in the competition included Team Intelligent Energy, which received second place and $40K for its six-rotor drone with a hydrogen fuel system, long endurance and lifting capabilities. Team Autonomous Robotics Competition Club, from Pennsylvania State University, took third place and received $20K for its multirotor, gas-electric hybrid drone. Team Endure Air also contributed to the UAS competition with its single-rotor helicopter drone.

Global 5G Connections Are Growing Rapidly

Subscriber adoption of 5G has increased significantly, as global wireless 5G connections for the second quarter of 2021 reached 429 million, according to data from Omdia, said 5G Americas.

Chris Pearson, president of 5G Americas said, "5G is progressing at a very rapid pace. Yet, the pace of subscriber uptake is only the beginning. 5G will be foundational for a new era of technology innovation throughout the world."

According to Omdia, the world added 124 million 5G connections between Q1 and Q2 of 2021, increasing 41 percent from 305 million to 429 million. 5G remains on pace to triple the number of connections in 2020 and is forecast to reach 692 million globally by the end of the calendar year.

Additionally, ten 5G commercial networks went live globally in Q2 2021, bringing the global total up to 182 networks, according to data from TeleGeography. That number is expected to reach 220 by the end of 2021 and 323 by the end of 2023.

Forward projections for 5G and 4G LTE from Omdia remain healthy, with estimates of global 5G connections reaching 4.7 billion in 2026. Of that, 512 million is expected to come from North America and 277 million in Latin America and the Caribbean.

In its first year of commercial availability in Latin America and the Caribbean, 5G connections reached 15,706. LTE remains the dominant wireless cellular technology in the sub-region with 454.8 million connections, an addition of 71 million new LTE subscriptions year over year, representing 18.4 percent annual growth.

According to Jose Otero, vice president of Caribbean and Latin America for 5G Americas, "The ongoing geographic expansion of enhanced mobile broadband networks together with the wider availability of handsets supporting this technology is driving 4G adoption in markets such as Brazil, Colombia and Mexico. However, at the other end of the spectrum, 2G and 3G continue to lose subscribers as operators start planning their disconnection and prepare for the impending mass-market demand of 5G services, expected to start in 2024."

For More Information
Visit mwjournal.com for more commercial market news.

Challenges of Integrating Antennas into IoT Devices

By 2025, 7.2 billion antennas will be shipped for IoT devices—nearly threefold of what it is today. With new product launches and evolution of existing devices requiring multiple radios, smaller form factors and greater device breadth, OEMs are increasingly challenged both at the design phase and when getting their products to market. A new white paper from ABI Research highlights the challenges created by the small, yet critical, antenna component and the real-life impact it has on all IoT product design and certification processes.

Increasingly, antenna vendors are required to work more collaboratively with their customers to limit the potential pitfalls of the process. The antenna is less and less seen as a standalone component, but as one that functions as part of a broader system. Offering software and services on top of the antenna component itself presents significant emerging opportunities for traditional component vendors, as RF engineering gains complexity from expanding network standards and accessible radio spectrum.

One antenna vendor taking a different approach to its incumbent competitors is Ignion, a Spanish company responsible for creating the Virtual Antenna, which has shipped over 25 million units through 2020. These wideband antennas work on all frequencies between 698 and 10,500 MHz and are tuned purely through the matching network. This technology shifts the focus of antenna integration from the antenna component itself to the comparatively simple matching network, which can significantly reduce complexity, antenna selection and integration time for IoT devices. Ignion's technology addresses the critical concerns of OEMs regarding RF design in IoT products.

> The antenna is less viewed as a standalone component, but as one that functions as part of a broader system.

IoT designs are evolving to incorporate more radios, to miniaturize devices and to reduce power consumption. There are a huge number of OEMs operating in the space, with many getting to large volumes while many others experiment with smaller-scale products. Simplifying the job of RF design in these conditions becomes critical, meaning there are significant opportunities for antenna vendors willing to modify how they interact with customers.


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Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

Maury Microwave Inc., a pioneering leader in RF calibration, measurement and modeling solutions backed by **Artemis Capital Partners,** announced that it has completed the acquisition of **dBm Corp. Inc**. dBm expands Maury's test and measurement technology portfolio into the emulation market. They complement and strengthen Maury's heritage in mission-critical defense and commercial satellite communications programs of record. dBm will continue to operate from its existing headquarters in Oakland, N.J., as a division of Maury and continue to be led by its founding team of Dale Sydnor (president), Bill Pastor (vice president of Engineering) and Mike Cagney (vice president of Sales & Marketing).

dB Control, an international defense electronics manufacturer and subsidiary of **HEICO Corp**., has acquired 100 percent of **Paciwave Inc.** for cash paid at closing. The acquisition will add specialized RF and microwave components—as well as integrated microwave subsystems—to dB Control's existing product line for military organizations, major defense contractors and commercial OEMs. These new products will be designed and manufactured specifically for defense and complex electronics applications that require PIN diode switches, PIN attenuators, PIN limiters, switching assemblies and integrated subsystems. Sunnyvale, Calif.-based Paciwave is a specialized designer and manufacturer of RF and microwave components and integrated assemblies.

Antares Defence Systems announced the addition of **Scimitar Technology Ltd.** to their stable of defence and security related companies. This acquisition will develop their presence beyond RF subsystems into tactical situational awareness equipment for use in utilities, first responders, police, training and military environments. Building on the fantastic work already completed over the last five years they wish departing CEO Caius Hawkins the best of luck with his new ventures. Technical Director Ross Nicholls is staying on in the same role, continuing the growth of the product suite and they look forward to developing their customer offering rapidly during the coming year.

Rogers Corp. has announced its acquisition of **Silicone Engineering Ltd.**, a leading European manufacturer of silicone material solutions based in Lancashire, UK. Silicone Engineering expands Rogers' existing advanced silicones platform and provides Rogers a European Center of Excellence to service customers requiring premium silicone solutions for applications in the EV/HEV, Industrial, Medical and other markets. Rogers' expects the transaction to be accretive to 2022 earnings per share. Trailing twelve-month revenues for Silicone Engineering were approximately £30 million, and Silicone Engineering's profitability is comparable to that of the Elastomeric Material Solutions business unit.

COLLABORATIONS

Rohde & Schwarz and **Vector Informatik** are collaborating on closed-loop scenario testing of automotive radar sensors for advanced driver assistance systems (ADAS) and autonomous driving. Coupling the DYNA4 virtual test drive simulation platform from Vector with the latest Rohde & Schwarz radar moving object stimulation system enables powerful verification of safety-critical ADAS functions. These include emergency braking in an integrated hardware-in-the-loop (HiL) environment. HiL testing is a technique used to accelerate the development of complex real-time embedded systems such as ADAS in situations where using a fully assembled vehicle is not possible or too costly, time-consuming or dangerous. Instead, the operation and behavior of supporting systems are electronically simulated.

Apple collaborated with **Ansys** to launch the first-of-its-kind RF safety testing simulation solution for Apple's MagSafe module technology developers. The novel technology eliminates the need for physical prototypes and expensive RF safety certification software—reducing costs while simultaneously accelerating the certification process for developers MagSafe chargers use magnets in newer iPhone models to connect to accessories that also have magnets built inside, including chargers, cases and docks. Apple's MFi Program offers developers the technical specifications and resources for creating MagSafe accessories that communicate with Apple devices using MFi technologies and components.

COMSovereign Holding Corp. announced that its **Innovation Digital LLC** unit and **IQ-Analog** entered into a strategic development alliance targeted at "beyond 5G" wireless communication. As part of the strategic alliance, IQ-Analog will incorporate Innovation Digital's patented digital signal processing algorithms and architectures into its next generation of application specific integrated circuits designed for future commercial and military markets.

NEW STARTS

Ferrite Microwave Technologies launched a new website with a special focus on circulators, isolators and other high-power components. The new website offers visitors fresh content, new product data and the latest information about FMT's products and capabilities. With a new and improved look, FMT's world-class components have individual pages for device applications, technical data and renderings for each component. This includes dedicated pages for: circulators, isolators, loads, duplexers, windows, phase shifters and much more. Ferrite has a design tool library of 1400+ devices, and this expansive line of high-power microwave components is now on full display.

For More Information For up-to-date news briefs, visit mwjournal.com

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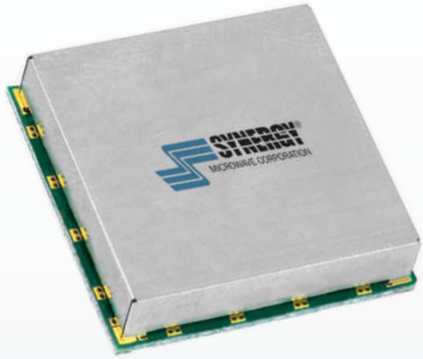

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HFSO2000-5L	2000	0.5 - 12	+5 VDC @ 100 mA	-133
HFSO1600-5	1600	0.5 - 12	+5 VDC @ 100 mA	-137
HFSO1600-5L	1600	0.5 - 12	+5 VDC @ 100 mA	-133
HFSO1500-5	1500	0.5 - 12	+5 VDC @ 100 mA	-140
HFSO1200-5	1200	0.5 - 12	+5 VDC @ 100 mA	-142
HFSO1000-5	1000	0.5 - 12	+5 VDC @ 35 mA	-141
HFSO1000-5H	1000	0.5 - 12	+5 VDC @ 35 mA	-144
HFSO1000-5L	1000	0.5 - 12	+5 VDC @ 35 mA	-137
MSO1000-3	1000	0.5 - 14	+3 VDC @ 35 mA	-138
HFSO800-5	800	0.5 - 12	+5 VDC @ 20 mA	-146
HFSO800-5H	800	0.5 - 12	+5 VDC @ 20 mA	-150
HFSO800-5L	800	0.5 - 12	+5 VDC @ 20 mA	-142

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ACHIEVEMENTS

Movandi released test drive results showing how 5G mmWave can deliver exceptional performance in a moving automobile when Movandi BeamXR powered smart repeater with Movandi BeamX cloud software control, machine learning (ML) and artificial intelligence (AI) are combined. This landmark test in a moving vehicle demonstrated the ability of these high frequencies and cloud intelligence to deliver high quality of service and multi-gigabit per second downlink speeds in difficult mobile environments. Movandi mounted a prototype mmWave repeater behind the windshield in the car and measured downlink and uplink speeds on a smartphone with and without the repeater. It was conducted at speeds up to 28 MPH using Verizon's 28 GHz ultra-wideband network over a 3-mile (5-km) route along DeAnza Boulevard, one of the busiest corridors in Silicon Valley near Apple's corporate headquarters in Cupertino, Calif.

OneWeb confirmed the next successful launch of 34 satellites by **Arianespace** from the Baikonur Cosmodrome. The launch follows the successful completion of OneWeb's 'Five to 50' mission and highlights the momentum of the business as it prepares to both introduce commercial service and focus on scaling to global service. This latest successful launch brings OneWeb's total in-orbit constellation to 288 satellites. These will form part of OneWeb's 648 LEO satellite fleet that will deliver high speed, low latency global connectivity. Lift-off occurred on August 21 at 11:13 BST. OneWeb's satellites separated from the rocket and were dispensed in nine batches over a period of 3 hours 45 minutes with signal acquisition on all 34 satellites confirmed.

CONTRACTS

Amentum, a contractor to U.S. federal and allied governments, has been awarded a $90 million contract to support the Program Executive Office Integrated Warfare Systems Above Water Sensors (PEO IWS 2.0) and the Naval Surface Warfare Center, Crane Division (NSWC Crane) with systems engineering services. Amentum was awarded the contract under the **Department of Defense Information Analysis Center'**s (DoD IAC) multiple-award contract (MAC) vehicle. These DoD IAC MAC task orders are awarded by the U.S. Air Force's 774th Enterprise Sourcing Squadron to develop and create new knowledge for the enhancement of the Defense Technical Information Center repository and the R&D and S&T community.

Citadel Defense has been awarded a sole-source contract for $6 million from a classified **U.S. Department of Defense** customer to build and deploy an AI-powered counter-drone solution. The system will be deployed at sensitive government locations and effectively operated by non-specialist military personnel and first responders. The solution is designed to autonomously detect, classify, track, and defeat unwanted unmanned aerial systems using state-of-the-art AI, ML and sensor fusion. Mission Microwave Technologies has received follow-on orders from a government contractor to provide Ku- and Ka-Band block upconverters as components of complex satcom transportable terminals in support of the U.S. Army.

Smiths Interconnect announced a six-year contract to deliver a highly integrated multi-channel subsystem to support **General Atomics Aeronautical Systems**' Lynx® Multi-Mode Radar in ground and maritime missions. The Lynx radar pinpoints time-sensitive targets and produces high-resolution photographic imagery on a wide field-of-view coverage for manned and unmanned aircraft systems. Smiths Interconnect's subsystem contributes to the accuracy of the Ground/Dismount Moving Target Indicator technology and enables the Lynx radar system to distinguish slow moving targets from stationary clutter. Smiths Interconnect's extensive experience in the design and manufacture of highly integrated subsystems was instrumental in the choice of the supplier for the Lynx system.

Julia Computing has been awarded funding by the **U.S Department of Defense Advanced Research Projects Agency (DARPA)** to bring Julia's advanced AI and ML capabilities to the field of fully digital phased array systems. Funding was awarded as part of DARPA's Tensors for Reprogrammable Intelligent Array Demonstrations (TRIAD) program. This project is a further step in Julia Computing's extensive ML research program. Julia Computing is partnering with RF expert Professor Miguel Bazdresch at the Rochester Institute of Technology to demonstrate these capabilities on purpose-built phased array testbeds, constructed from low-cost MIMO software-defined radios and NVIDIA GPUs.

Comtech Telecommunications Corp. announced that during its first quarter of fiscal 2022, it was awarded $4.6 million of funding from the U.S. Army to provide ongoing system refurbishments, sustainment services and baseband equipment. This most recent order continues its sustainment of the U.S. Army's family of ground satellite terminals including providing spare parts, repairs, upgrades, refurbishments, logistics and engineering services and training. Comtech Telecommunications Corp. is a leading global provider of next-generation 911 emergency systems and secure wireless communications technologies to commercial and government customers around the world.

PEOPLE

Mercury Systems Inc. announced that **Mitch Stevison** has joined the company as executive vice president and chief growth officer, effective immediately. Reporting to Mark Aslett, Mercury's president and chief executive officer, Dr. Stevison will drive and align the company's growth strategy across the enterprise to achieve its growth objectives. Dr. Stevison, a 20-year U.S. Army veteran, brings to Mercury more than 16 years of global experience in the aerospace and defense industry. He comes to Mercury from Raytheon Missiles & Defense, where he served as vice president of Strategy.

Infinite Electronics Inc. has appointed **Matthias Norweg** to the position of senior vice president of

Executive Interviews

mwjournal.com

Maryam Rofougaran, co-founder and CEO of Movandi, describes the company's strategy to improve the coverage and speed the deployment of mmWave networks for 5G and how Movandi is unique in the industry.

Jessen Wehrwein, vice president of marketing at **Quantic Electronics**, talks about the company's strategy in acquiring a number of RF companies this year and the synergy of putting them under one umbrella.

Corporate Development. In this role, Norweg will lead Infinite's global mergers and acquisitions, including target identification, due diligence, deal negotiation and working with the broader Infinite team on integration planning. Norweg comes to Infinite with 20 years of experience in corporate development, investment banking and venture capital. Immediately prior to Infinite, he served as senior vice president of Corporate Development and treasurer at Synchronoss Technologies.

Gowanda Electronics announced that the company's CEO, **Donald McElheny**, retired at the end of August 2021 after 24 years with the company. McElheny joined Gowanda Electronics in 1997 as New Product Development manager. Initially he oversaw the exploration and development of new electronic components for Gowanda but he took on increasing responsibility in subsequent years, being named COO in 2006. McElheny became CEO in 2011.

Modelithics Inc. welcomed **Dr. Ali Boudiaf** to the company as director of Lab Operations. Dr. Boudiaf comes to Modelithics with 30 years of experience in the RF, microwave and mmWave engineering arena. In his new role at Modelithics, his responsibilities include managing all aspects of lab operations as well as advancing Modelithics microwave and mmWave test system capabilities. Prior to joining Modelithics, Dr. Boudiaf was the CEO and co-founder of Smart MedTech. He also previously worked at ERZIA Technologies as director of Amplifier Systems. Dr. Boudiaf's prior experience also includes positions with Maury Microwave, Focus Microwaves, Agilent Technologies and ATN Microwave.

▲ *Ali Boudiaf*

REP APPOINTMENTS

AGC Multi Material America Inc. announced that effective immediately, they will be partnering with **Tritek Circuit Products**. Tritek will become the West Coast distributor for AGC Multi Material America's digital laminate and prepreg materials. Tritek Circuit Products is a customer centric, full-service distributor to the PCB fabricators in the region. Tritek is in its 30th year of doing business with the same mission of bringing world-class products and expert level technical service to their customers. AGC Multi Material America Inc. develops and manufactures high speed digital and RF/microwave materials for the automotive, telecommunications and internet infrastructure, enterprise and military/aerospace markets.

Arralis Technologies Ltd., an advanced mmWave communications solution provider, has signed a technology, sales and distribution agreement with **TXMission**, an advanced new space and airborne communications systems provider. The companies will jointly develop a

suite of communication products for smallsat, HAPS, UAV and airborne applications that require high performance and extremely low size, weight and power. Development will initially focus on a range of advanced Ka-Band transceivers with integrated gigabit software-defined radios, satellite terminals, phased array antennas and network management systems.

MCS Test, a consultant and supplier of EMC, wireless, avionics, RF & microwave and mobile radio test equipment, is now an authorized distributor for **Keysight Technologies** in the U.K.

RFMW and **CML Microcircuits Inc.** announced the expansion of their already-successful business relationship. Their existing distribution agreement has now been widened to include global marketing and sales of the CML product portfolio. This partnership is poised to build on the success of CML's new SµRF range of high frequency, high bandwidth ICs targeting RF and mmWave markets. The SµRF range is a perfect fit for the RFMW distribution product line and presents an exciting opportunity to distribute and promote these products on a global scale.

SV Microwave announced that they have signed a distribution agreement with **Master Electronics Inc.** who is currently stocking several of their top-selling products. Master Electronics Inc. is based in Phoenix, Ariz., and is a global authorized distributor of electronic components. Master Electronics thrives on collaborating with its customers and suppliers to design creative solutions to their purchasing, supply chain and business challenges.

PLACES

pSemi® Corp., a Murata company focused on semiconductor integration, announced the opening of a branch office in Taipei City, Taiwan. Murata established its presence in Taiwan more than 40 years ago, taking into consideration the nation's semiconductor manufacturing ecosystem, geographic proximity to other Asian countries and talent pool. Sharing space with Murata, pSemi's Taiwan office is located at Rm. 1503, 15F., No. 88, Section 2, Zhongxiao E. Road, Taipei, 10050. It is in close proximity to Murata Electronics' factory in Taichung, enabling pSemi to leverage Murata's manufacturing footprint and to facilitate joint IC and module development.

UL, the global safety science leader, announced that it will open expanded electromagnetic compatibility (EMC) and wireless laboratory in Carugate, Italy. The enhanced facility will feature an end-to-end service solution for EMC and wireless testing for a wide range of industries, including consumer electronics, information technology equipment, telecommunications, medical, industrial, lighting and small and large appliances. UL's EMC-Wireless laboratory expansion will allow for an increase in testing capabilities for wireless professional appliances, connected industrial devices as well as connected consumer medical and in vitro diagnostic devices. It will also increase testing capacity and speed, thanks to multiple equipment and facility upgrades.

Anritsu's new Rubidium™ low-noise RF/microwave signal generator redefines signal purity and stability.

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INVITED PAPER

The RF GaN Device Market: A Roller-Coaster Ride

Poshun Chiu and Ezgi Dogmus
Yole Développement (Yole), Lyon-Villeurbanne, France

In as little as five years, analysts at Yole Développement (Yole) predict the already mighty RF GaN device market will mushroom from some $900 million to $2.4 billion (see ***Figure 1***). Three decades of investment from defense organizations around the world has placed this high power density, high efficiency material firmly on the compound semiconductor map, with GaN devices routinely used in military radar and electronic warfare. As defense agencies look to commercial applications to pay back their billion-dollar investments, 5G/LTE telecoms applications are already providing a return on the investment. At least for now.

BASE STATION ADOPTION

China's Huawei started using GaN RF devices in its 4G LTE remote radio heads (RRH) in 2014. The telecom behemoth had decided to trade low-cost Si LDMOS for GaN's high power density and wide

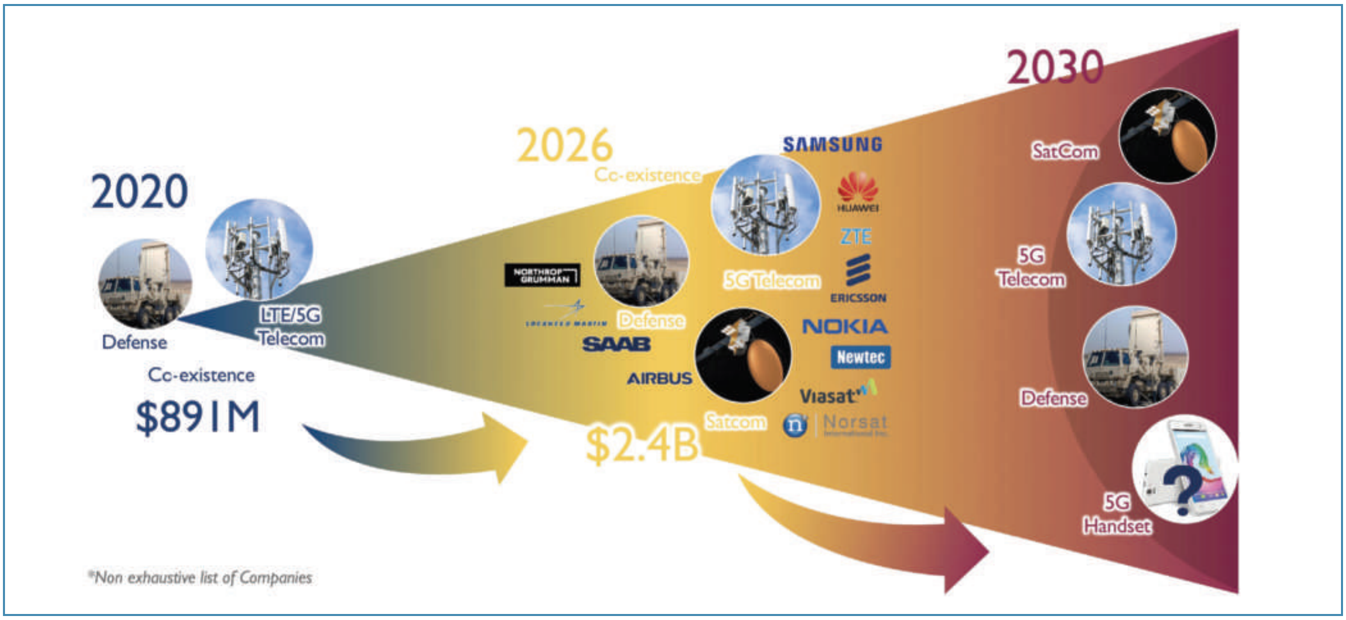
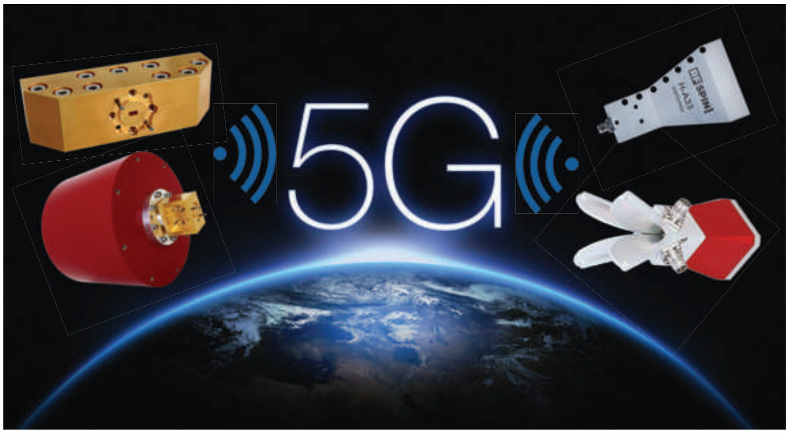


Fig. 1 GaN RF device market evolution from 2020 to 2030. Source: GaN RF Market: Applications, Players, Technology, and Substrates 2021 report, Yole Développement, 2021

THE FUTURE OF COMMUNICATION

For those who have noticed slow video streaming or download rates for their large digital files on their smartphone or other mobile communications device working on 4G LTE, 5G is the answer. It operates within many of the frequency ranges as 3G and 4G LTE, but it provides much-needed bandwidth for growing numbers of worldwide wireless users and their applications. 5G can be implemented in low-band, mid-band or high-band millimeter-wave 24 GHz up to 54 GHz.



Waveguide transmission lines not only handle more power with much less loss at millimeter-wave frequencies than coaxial cables, but when interconnected to waveguide horn antennas they can combine for the high gain, typically 25 dBi or more at mid-band for even "standard-gain" waveguide horn antennas, and the outstanding directivity needed to maintain line-of-sight (LOS) links at millimeter wave frequencies. Moreover, waveguide horns are also physically small enough to be total unobtrusive within the many indoor 5G infrastructure setups.

When 5G links require even more gain, top component suppliers such as **Impulse Technologies** are ready with high-gain waveguide horn antennas from innovative developers such as Anteral and RF Spin. With waveguide horn antennas, millimeter waves will be the future of 5G.

57%

5G Network technology is projected to cover 57% of the market worldwide by 2025.

3 BILLION

By 2025, there is projected to be 3 billion 5G mobile subscriptions.

Anteral releases a High Performance Diplexer for 5G E-band Backhaul Systems with point-to-point radio links at 71/76 GHz and 81/86 GHz and can deliver up to 10 Gbps in a dense radio environment. The technology used makes it less sensitive to manufacturing tolerances, which is perfect for mass production. Its fabrication robustness makes this diplexer ideal for industrial applications. Anteral also provides a Dual Polarized Lens Horn Antenna for 5G & 6G (E & D-Band) Backhaul Systems ideal for High-Gain Lens Horn Antennas.

RF Spin offers the QRH50E antenna, which is an enhanced version of the broadband bestseller that helps hundreds of the world's leading players develop, test, and deploy 5G networks. This is an advanced antenna with exceptional technical parameters and excellent design in aluminum alloy with a frequency range of 5 GHz to 50 GHz. As part of their ongoing efforts to provide cutting-edge tools for the development, testing and implementation of advanced 5G networks, RF Spin launches a pyramidal horn antenna (H-A33) with a frequency range of 22 GHz to 33 GHz.

Impulse Technologies will provide you with the most innovative components and the latest technology to keep you up to speed. To learn more please contact **mleone@impulse-tech.com.**

ANTERAL IMPULSE TECHNOLOGIES INC. AN INTERNATIONAL PROCUREMENT COMPANY RF SPIN

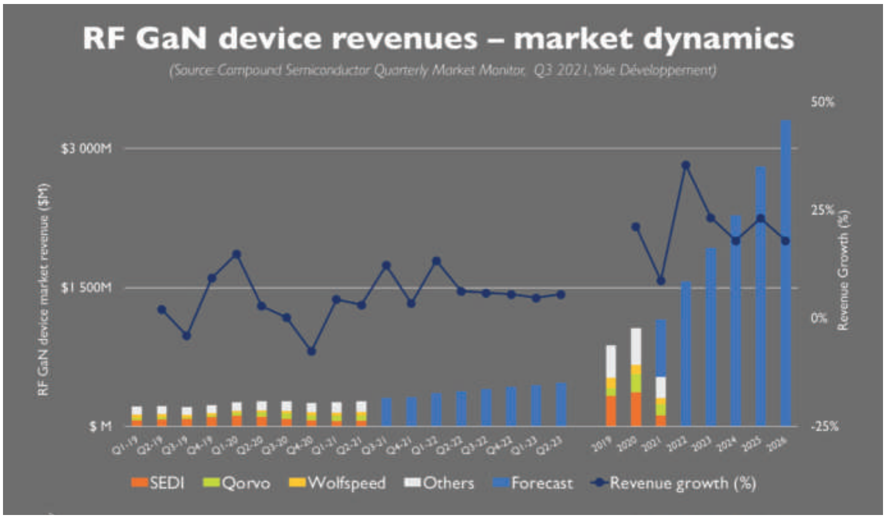


Fig. 2 Historic GaN RF device revenue and forecast growth. Source: Compound Semiconductor Quarterly Market monitor, Q3 2021, Yole Développement

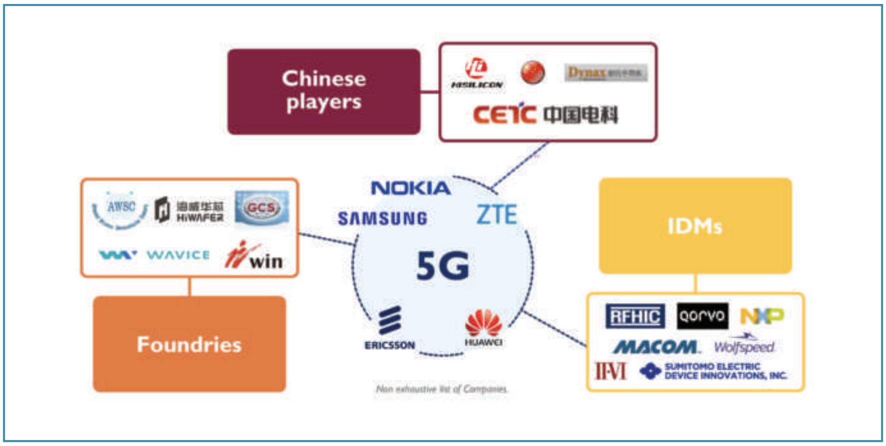


Fig. 3 Global GaN RF device suppliers. Source: GaN RF Market: Applications, Players, Technology, and Substrates 2021 report, Yole Développement, 2021

bandwidth and other OEMs followed. Today, the power of GaN is being harnessed by the 5G infrastructure market. Tried-and-tested GaN on SiC technology is widely used in 5G sub-6 GHz RRH base stations and is expected to maintain its stronghold for some time.

In part due to the monumental 5G network sharing deal between operators in China, the technology is also being adopted in 5G sub-6 GHz active antenna systems (AASs). To deploy more efficient antenna types, the Chinese operators ditched cheaper LDMOS transistors for higher performing GaN on SiC devices in these sub-6 GHz AAS deployments, a decision that kick-started GaN adoption elsewhere. Today, other OEMs have realized the value that GaN can bring to 5G wireless infrastructure and are moving to six-inch GaN on SiC wafer production in a bid to reduce the technology's high price tag.

In 2020, NXP, the Netherlands-based semiconductor manufacturer and key LDMOS player, opened a six-inch GaN on SiC facility in Arizona, signaling strong customer interest in GaN RF devices for a cost-effective price. This year, longtime GaN on SiC partners, Sumitomo Electric Device Innovations (SEDI) of Japan and U.S. semiconductor manufacturer, II-VI, opened a six-inch fab in New Jersey to churn out power transistors for 5G base stations at a more cost-competitive price. As NXP and SEDI/II-VI ramp up production, U.S. semiconductor makers Wolfspeed, Qorvo and other fabs are acting to transition to six-inch GaN on SiC production—clear signs the technology is set to

capture market share from LDMOS (see ***Figure 2***).

INTERNATIONAL TENSIONS

But what about the ongoing trade conflict between the U.S. and China? How is this affecting the GaN RF device market? Like the U.S., the Chinese government is determined to make the most of its GaN investments and grow commercial 5G applications. While U.S. sanctions have stymied China's progress, the restrictions have also pushed the government to encourage development of a homegrown, internal GaN ecosystem.

At the beginning of the tensions, Huawei and ZTE stockpiled devices so they could continue to build base stations and other network infrastructure. Since, many organizations up and down the supply chain have been funneling investments into GaN. Examples include wafer manufacturers and foundries SICC and HiWafer, integrated device manufacturers (IDM) CETC and Dynax and Huawei's own design house, HiSilicon (see ***Figure 3***). Importantly for China, industry feedback indicates that tier one suppliers are now producing quality systems with Chinese components. Given this, the rest of the world is monitoring China's progress very closely.

GAN HANDSET PAS?

There's more to come for GaN. In the longer term, 5G handsets could also harbor many opportunities for the GaN RF device market.

Today, GaAs is the leading power amplifier (PA) technology in smartphones, such as the iPhone 13, and will retain its dominance particularly in sub-6 GHz handsets. But industry trends are changing. The move to large bandwidth, higher power density and efficiency and greater integration, to save space in the handset's RF front-end, mean GaN is beginning to appeal to OEMs, especially for the mmWave bands. Indeed, at least one major semiconductor player is qualifying 5G handset PAs designed with GaN for several OEMs. In the coming years, the industry may see the first adoption of a GaN PA in luxury phones that use the increasingly popular n77 to n79 C-Band, as an alternative to mmWave and the traditional sub-6 GHz cellular bands.

What might happen next? If more OEMs around the world demand GaN PAs, more foundries will fabricate the technology and the momentum will build. If GaN PAs are widely adopted for mmWave front-ends in handsets, the technology's success is likely sealed.

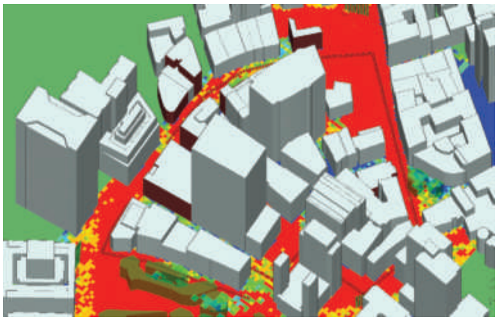
SIC OR SI?

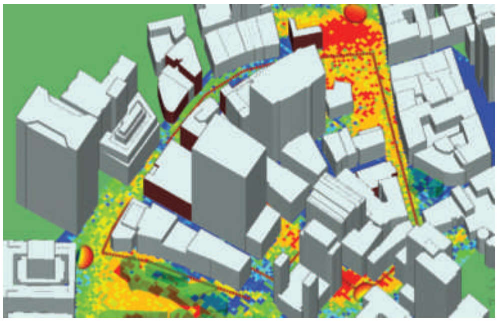
Along the way, the rivalry between GaN on SiC and GaN on Si wafers will play out. With cheap, large diameter Si substrates, GaN on Si presents a bright opportunity for OEMS to develop relatively cheap GaN-based devices and systems built on the foundation of an established, scalable wafer supply. Keen to explore this opportunity, MACOM and STMicroelectronics joined forces to develop a GaN on Si platform in 2018. Infineon is also developing GaN on Si for RF applications. Earlier this year, U.S. defense giant Raytheon and Global Foundries announced a collaboration to transfer Raytheon's GaN on CMOS process to Global Foundries for commercialization.

While these are significant industry developments and GaN on Si may deliver the cheaper PAs that high volume, cost-sensitive 5G handsets will demand, the technology does not benefit from the billion-dollar defense investments awarded to GaN on SiC. Consequently, the GaN on Si supply chain is not yet developed, and technology development spans from epitaxy to modules. Still, the pros and cons of GaN on Si and GaN on SiC are becoming clearer for the industry; for now, the technology choice depends on the OEM's strategy and view of the trade-offs.

TO THE SKIES

Satellite communication (satcom) offers another promising avenue for GaN. While destined to be a niche, low volume market, satcom has been attracting many industry players keen to apply GaN to applications such as very small aperture terminal (VSAT) satellite broadband. Here, GaN PAs from Qorvo, Wolfspeed and others have





been replacing traveling wave tube amplifiers, improving reliability and lowering the system costs of transmit-receive ground stations. Myriad large-scale projects have been springing up across the U.S. and Europe, driving the development of solid-state GaN PAs for VSAT and other applications.

In the future, GaN's radiation hardness and its high power efficiency and power density will see the technology increasingly used in satellites. Key industry players including Canada's Norsat International, the European Space Agency and GaN device manufacturers UMS, Qorvo and OMMIC are all investigating GaN for satellites.

STALWART DEFENSE

Space aside, the reliable defense market will be a strong supporter of GaN for many years. Billion-dollar projects from U.S. government agencies and prime contractors such as Northrop Grumman, Lockheed and Raytheon, as well as defense semiconductor suppliers Wolfspeed and Qorvo, will continue to fund technology development and insertion in programs. These efforts will require a secure and robust supply chain that will benefit the commercial telecom and other markets to follow. Similar scenarios are playing out in Asia and Europe, where organizations such as Thales, SAAB and BAE Systems are all working on GaN technologies that will also feed the commercial telecoms markets.

MANY QUESTIONS

While the future of the GaN RF device market is bright, the level of success hinges on yet-to-be determined dynamics. For GaN on SiC, the smooth transition to six-inch wafers will be important for its near-term success. As NXP, SEDI/II-VI and other players make the transition, will the production of quality wafers proceed as planned? If not, will this dampen GaN on SiC's adoption by 5G? Meanwhile will handset manufacturers opt for GaN on Si PAs in their 5G devices? What happens if these industry players abandon both GaN options and retain GaAs or adopt alternative technologies, such as SOI, which offer sufficient performance? What will be the impact of the deepening tensions between the U.S. and China?

Only time will reveal how the RF GaN roller-coaster ride ends. Throughout the ride, Yole Développement will scrutinize market developments, analyze the strategic questions and share our view of the likely outcomes. ■

INVITED PAPER

The Open RAN System Architecture and mMIMO

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Xilinx, Dresden, Germany

Open radio access networks (O-RAN) are transforming mobile networks. O-RAN is about the disaggregation of the traditional RAN system into the radio unit (RU), distributed unit (DU) and centralized unit (CU) components and their hardware and software platforms.[1] O-RAN fosters innovation by involving more manufacturers in the development of the RAN infrastructure, enabling new entrants to compete and disrupt the market if they can offer a competitive edge. Ideally, the O-RAN standards will create a broad RAN supplier ecosystem, where operators can pick and choose components from different suppliers and not be bound to a single company. The disaggregation of hardware and software enables virtualization, meaning large parts of the network functions become virtualized and can be run on commercial off-the-shelf hardware or general purpose processors. Virtualization also enables "cloudification," where many functions are hosted by multiple servers, typically bundled in one or more data centers.

For O-RAN networks to succeed and become accepted, the standardization of interfaces and proven interoperability are the keys to success. 3GPP has investigated different functional split options between the CU and DU (see ***Figure 1***).[2] The O-RAN Alliance has chosen 3GPP split option 2 for the interface between the CU and DU and split option 7 as the DU to RU interface. The centralization of the packet data convergence protocol (PDCP) layer enables scaling with the user plane traffic load. The O-RAN Alliance has chosen the so-called split option 2-2, enabling the separation of the U-plane from the other planes, while having a centralized radio resource controller and radio resource manager. For the interface between DU and RU, the O-RAN Alliance has chosen an intra-physical layer (PHY) split, i.e., between the low PHY and high PHY.

The high-level functional partitioning into the CU, DU and RU is shown in ***Figure 2***. The link between the RU and DU is referred to as the fronthaul, and the link

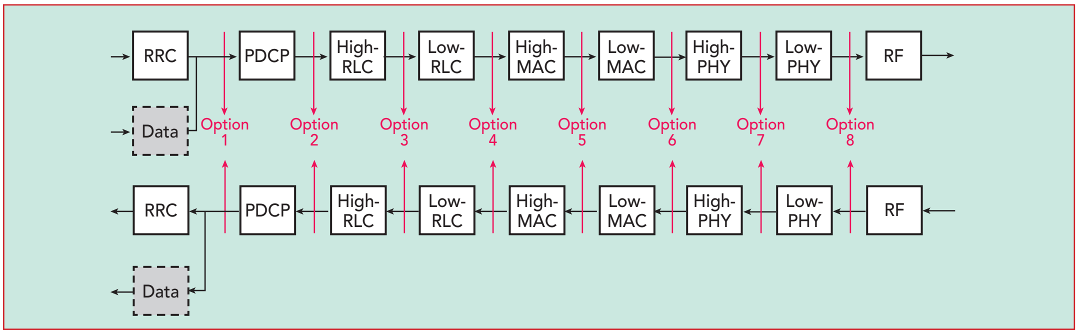

Fig. 1 **Functional split between the CU and DU.**


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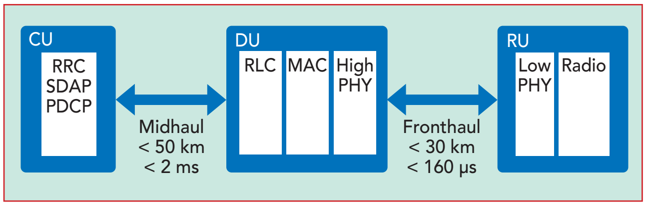

Fig. 2 Network function partitioning into the CU, DU and RU.

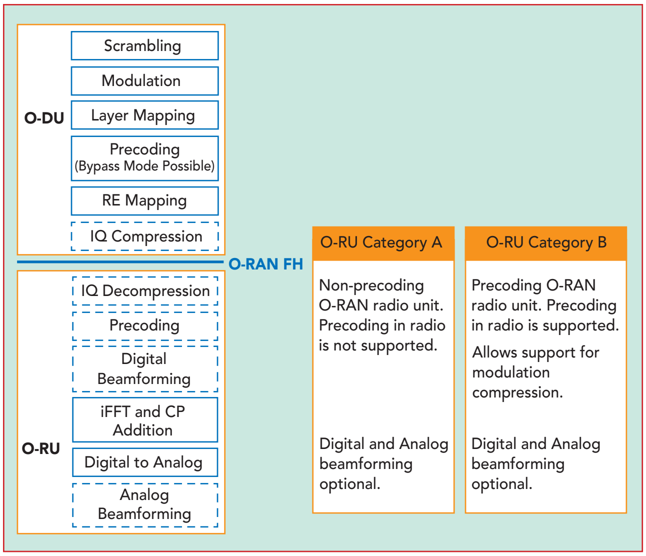

Fig. 3 O-RAN architecture. *Source:* O-RAN Fronthaul Working Group.[3]

between the CU and DU is referred to as the midhaul. Due to the various control loops within the system, different latencies can be tolerated. The most critical interface is the fronthaul, which typically tolerates latencies up to 160 µs. If a point-to-point connection is used to connect the RU to the DU, a distance between the RU and DU of up to 30 km can be supported.

As this article's focus is the RU, the discussion is more on the O-RAN fronthaul interface and the corresponding architectural split. When selecting the fronthaul interface, the following aspects must be considered:

Transport Bandwidth — Referring to Figure 1, the required data rate reduces from the right (the option 8 interface between the PHY and RF) to the left. The chosen split provides a good compromise between flexibility and algorithmic differentiation, with a modest demand on the data rate.

Architecture Split — The split must reflect the intention of an O-RAN architecture: vendor neutral hardware and software. The radio's performance is defined not only by the radio hardware, but also by the way the signals are processed. To be accepted by the market, an O-RAN system must deliver comparable performance to conventional single-vendor systems. The architectural split enables innovation and stimulates differentiation and, if possible, should not stipulate certain processing algorithms or preclude alternative processing techniques. The O-RAN Alliance has chosen an interface that defines the radio hardware with clearly defined and understandable processing functions tightly controlled by the DU and its software.

Interoperability — Interoperability between different vendor systems is key for O-RAN to be adopted by the market. Therefore, the architectural split must provide an interface easily understood by any implementer, clearly described with no room for interpretation and rigorously tested for interoperability.

The O-RAN Alliance has defined an interface referred to as the 7.2x split.[3] In the 7.2x split, the O-RAN fronthaul interface resides between the resource element mapping in the DU and the time-frequency conversion in the RU, i.e., the inverse FFT (iFFT) and cyclic prefix (CP) addition in the downlink and CP removal and FFT computation in the uplink, respectively (see ***Figure 3***). The dotted processing blocks in the figure are not mandatory for all RU categories. Precoding for certain RU categories can be done within the RU, in which case precoding in the DU is bypassed. For mMIMO radios, the interface foresees digital beamforming on the RU side.

Digital beamforming is omitted for conventional radios, which typically have only a small number of transceivers. Additionally, the O-RAN Alliance distinguishes between category A and B type O-RUs. The category B architecture supports MIMO precoding in the O-RU; category A does not. The category B O-RU provides support for modulation compression, a technique to reduce the fronthaul bandwidth by moving the modulation function to the O-RU.

In addition to the user traffic handled by the so-called U-plane of the fronthaul interface, O-RAN defines three other planes: the M-plane for handling management control data, the C-plane for handling near real-time control data and the S-plane for handling synchronization (frequency and time). The M-plane is primarily used for configuring the RU, reading out status information and handling errors and alarms.[4] It is entirely based on the NETCONF protocol, an XML-based protocol to set and query the operation of a network device. It uses YANG as its data modeling language. Typical configuration data includes

- Setting up the carrier (e.g., the center frequency, bandwidth and power)
- Mapping the antenna layers
- Fully resetting the software of the RU
- Updating the O-RU software, as the M-plane supports downloading entire software images.

Typical parameters that can be queried concerning the O-RU state and general information are

- Physical structure of the antenna radiating panel
- Clock synchronization state
- Fronthaul interface version and information about supported C- and U-plane section types and extensions
- Boot state
- O-RU alarms and performance counters, such as the number of packets received AND number of U-plane data packets received on time, late or corrupt.

The radiating panel is modeled as a rectangular array of equally distributed and independently controlled radiating elements. This information is useful for the O-DU to compute the beamforming weights used to form the desired beams. The beamforming weights determine the direction and shape of the beam. Especially in mMIMO systems, a different set of beamforming weights is typically used for every time transmission interval; however, changes can occur as often as every OFDM symbol.

As mentioned, the O-RAN Alliance supports the vision of disaggregated hardware and software. Therefore, it has defined the radio (O-RU) to be directed by the O-DU, where the algorithms for channel estimation, weight computations and near real-time user scheduling reside. The traffic associated with the provision of beamforming weights can be substantial and may be the same order of magnitude as the user plane traffic. Hence, different means of reducing the traffic are defined in the O-RAN standard.

For a cellular network to work properly, the radio units must be synchronized with an accuracy of ±25 ppb in frequency and ±1.5 µs in time. The O-RAN standard defines several means of synchronizing the RUs to the network, with the predominant method for synchronization the IEEE 1588 protocol, also referred to as precision time protocol (PTP). PTP is based on measuring the time of arrival of IP packets. However, since the IP traffic may be subject to jitter, a relatively long observation time is needed to achieve the desired frequency accuracy. Therefore, O-RAN provides the option to make use of SyncE, which uses the line rate to convey the clock from the source (e.g., the O-DU or a switch) to the O-RU. IEEE 1588 has additionally defined hardware functions built into switches and routers that enable adjusting time stamps due to latencies introduced by those network functions. Since not all network elements may be equipped with such a function, the latencies may be difficult to estimate.

In some cases, the packet delay jitter introduced by the network may not be tolerable. O-RAN provides another methodology, to synchronize the O-RUs using GPS.

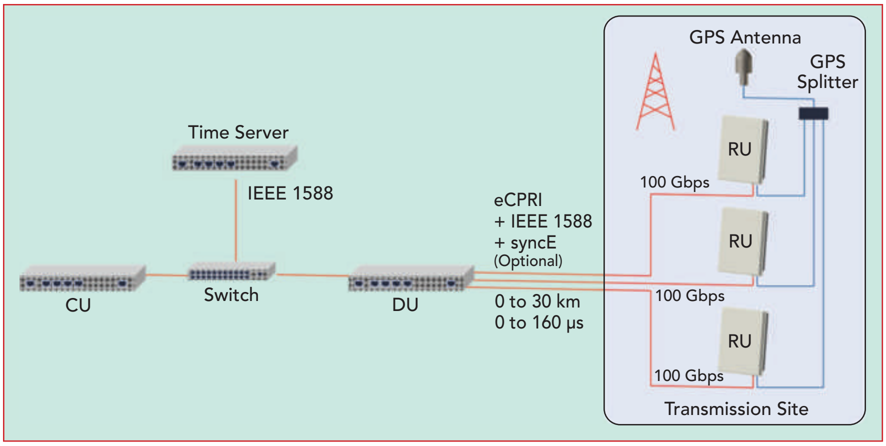

Fig. 4 **System using GPS at the RU.**

In this case, the O-RU has a built-in GPS receiver to synchronize the O-RU to the accurate GPS clock and time (see ***Figure 4***). Multiple RUs at a site receive the GPS signal from a common active antenna, and each O-RU has a GPS receiver. The O-RUs are connected to an O-DU that may be located at the site or up to 30 km away, e.g., in a data center, and the O-DU receives its time synchronization through the network from an external time server. Alternatively, it may be equipped with its own GPS receiver. As an alternative to GPS or as a fallback in the case of GPS synchronization failure, the O-DU may provide frequency and time synchronization to the O-RUs.

In some cases, cross-licensing agreements allow operators to use the spectrum of another operator to offer a joint service. This is referred to as multi-operator RAN (MORAN). From the O-RU perspective, two fundamental sharing architectures exist: If each operator uses its own O-DU, the O-RU must act as two independent RUs to the DU. If not, only the O-RU and the O-DU are shared between operators. MO-RAN is transparent to the RU. Such an architecture brings restrictions, such as time-division duplex (TDD) downlink and uplink transmission periods aligned over both operators' networks, which must be carefully handled to avoid conflicts.

RADIO ARCHITECTURE FOR MMIMO

The O-RAN fronthaul interface supports both conventional radios, with two or four transceivers, or mMIMO radios. MIMO is a means to increase the capacity of a mobile network by using the spatial domain, where the "multiple input, multiple output" refers to the radio channel. Signals sent by multiple transmitters are received by multiple receivers. Assuming propagation conditions permit, advanced channel coding methods and signal processing algorithms enable separating the transmit signals from the receive signals. mMIMO applies when the number of single antenna terminals (i.e., number of users) transmitting at a given frequency and time is much less than the number of base station antennas receiving. TDD, reference sequences and feedback from the terminals to the base station help apply the same principles to the downlink.

In general, the more transceivers in a mMIMO system, the more users can be served over the same communication channel, assuming the propagation characteristics support user discrimination. The 3GPP standards provide up to 256 transceivers. However, as the cost and power consumption increase with the number of transceivers, practical configurations for a mMIMO base station range between 16 transmitters and 16 receivers (16T16R) and 64 transmitters and 64 receivers (64T64R).

The antennas in a mMIMO system are arranged in an array, where each antenna may consist of a subarray of antenna elements. A typical arrangement for a 64T64R panel is shown in ***Figure 5***, a 12

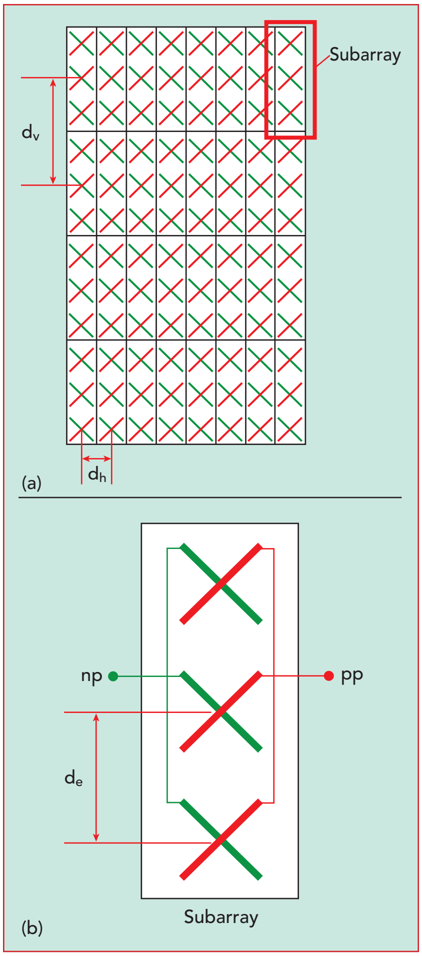

Fig. 5 **Typical mMIMO antenna: full array (a) and subarray (b).**

× 8 antenna array (see Figure 5a) comprising 32 polarized subarrays. Each subarray is made of six antenna elements, where three antenna elements radiate with a negative polarization, indicated by "np," and the other three antenna elements with a positive polarization, indicated by "pp" (see Figure 5b).

With conventional, passive base station antennas, antenna gain is an important factor. The antenna gain is defined as the ratio between the maximum radiated power at a specific angle and the power radiated by a hypothetical antenna transmitting the same total power isotropically, i.e., equally distributed over the full sphere. It is assumed that the hypothetical antenna radiates all the power without any loss between its antenna port and free space. For the same power at the antenna feed, the radiated power of a directional antenna at boresight will be greater than the corresponding isotropic antenna by the gain factor.

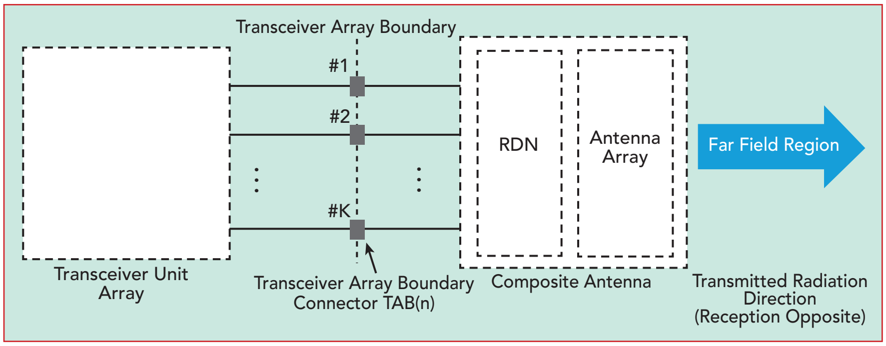

Fig. 6 **AAS radiated and conducted points of reference.** ***Source:*** **3GPP.[5]**

To enable comparison with conventional radio architectures, which have a remote radio head and a separate passive antenna, the 3GPP has defined a reference radio architecture for mMIMO. This reference architecture defines two reference points for conducted and radiated measurements,[5] assuming a transceiver unit array connected to a composite antenna (see ***Figure 6***). The transceiver unit array contains the transmitters and receivers, generates the modulated transmit signals and performs receiver combining and demodulation. The composite antenna consists of the radio distribution network and the antenna array, the interface between the transceiver unit array and the composite antenna is called the transceiver array boundary (TAB). The two points of reference defined by 3GPP are the TAB for conducted measurements and the far-field region for radiated measurements, also referred to as over-the-air measurements.

The RF output power of the transmitter limits both data rates and coverage. The output power typically refers to the power combined from all transceivers, which is the conducted power measured at the TAB. The corresponding measurement of radiated power is called the effective isotropic radiated power (EIRP), which includes the gain of the composite antenna. For example, a radio panel that provides 200 W (53 dBm) of RF power at the TAB and feeds an antenna array with 25 dBi gain at boresight will have an overall power measured at boresight of 78 dBm EIRP.

From antenna array theory, the far-field antenna array pattern of a linear array is the product of the single element pattern and the array factor (AF), assuming all antenna elements are the same kind, point in the same direction and are excited with equal power. The AF is the far-field radiation pattern of an array of isotropic radiators. Provided no coupling occurs between radiating elements, a linear array with 12 rows and eight columns and an element spacing of half-wavelength ($\lambda/2$) will have an AF of 96 (i.e., 19.8 dB). Coupling between the elements will reduce the AF and minimizing coupling can only be achieved by proper design; however, it becomes increasingly difficult when the element spacing d_e is less than a wavelength, particularly less than $\lambda/2$.

Sidelobes are another important characteristic of antenna arrays. The sidelobe level (SLL) is the maximum power from a sidelobe normalized by the strength of the main lobe. Alternatively, the inverse value, i.e., the ratio between the strength in the direction of the main lobe and the maximum sidelobe level, is often used and referred to as the sidelobe level suppression (SLS). In a mMIMO antenna, the actual beam pattern depends on the subarray radiation pattern and the amplitude and phase relationships between the subarrays, which are defined by the beamforming vector applied at the beamformer. The beamforming vector yielding the pattern with the lowest sidelobe levels typically uses different phase and amplitude values. For maximum output power, all the amplitudes need to be identical. To compare the radiation performance of different mMIMO active antenna units (AAU), only phase variations

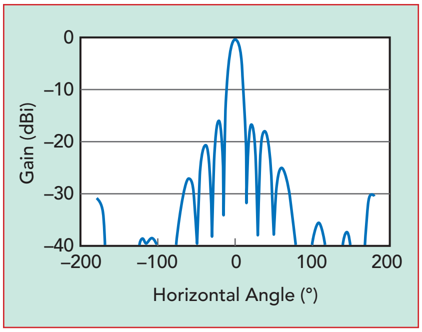

Fig. 7 Typical azimuth antenna pattern for a user beam at 0°.

are allowed in the beamforming vector; the amplitudes are forced to be the same. To illustrate, ***Figure 7*** shows a typical beam pattern with SLLs less than -16 dB.

O-RAN MMIMO ARCHITECTURES

The RU in a mMIMO AAU can be separated into its functions (see ***Figure 8***). Some are only required once, while others, like the transceivers, are used multiple times. Each transceiver serves a single polarization of a radiation panel subarray. Among the functions used only once is the fronthaul interface connecting the O-RU to the O-DU, the beamformer, clock synchronization, management and control.

The fronthaul uses an Ethernet interface and is separated into the C-, U-, S- and M-planes. The M-plane interpreter and manager connects to the O-RU controller, which sets up and oversees the overall well-being of the unit. The O-RU controller measures the power consumption, temperature, output power and relative amplitude and phase accuracies for both receive (Rx) and transmit (Tx) to let the DU exploit channel reciprocities. It hosts multiple event counters and reports statistics, warnings and errors through the M-plane to either the O-DU or directly to the management system. The O-RAN Alliance has standardized this as the service management and orchestration framework. S-plane packets following the IEEE 1588 PTP protocol are interpreted independently. PTP information is used to synchronize the O-RU clock to the network. As noted earlier, a built-in GPS receiver can be used as an alternative clock.

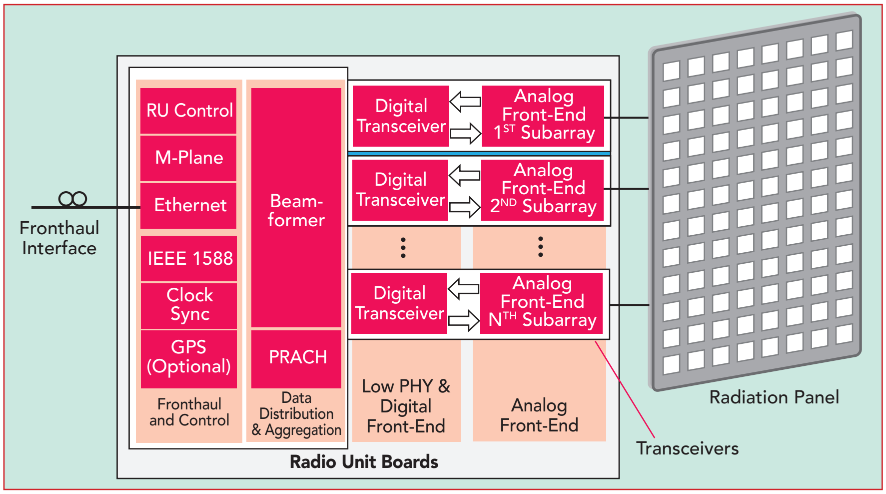

Fig. 8 Typical RU architecture for a mMIMO AAU.

The beamformer connects to N_{Tx} transmitters and N_{Rx} receivers. If $N_{Tx} = N_{Rx} = N$, which is usually the case, the beamformer is said to be connected to N transceivers, with all transceivers identical. Each transceiver consists of the digital transceiver and an analog front-end. For each layer, the beamformer performs two matrix multiplications for each subcarrier (SC). During transmit, the vector of resource blocks contained in each radio layer is multiplied by the Tx beamforming matrix to yield a vector of SCs for each transceiver. Likewise, during receive, each vector of SCs received from every transceiver is multiplied by the Rx beamformer to yield the SC vector for all layers. ***Figure 9***

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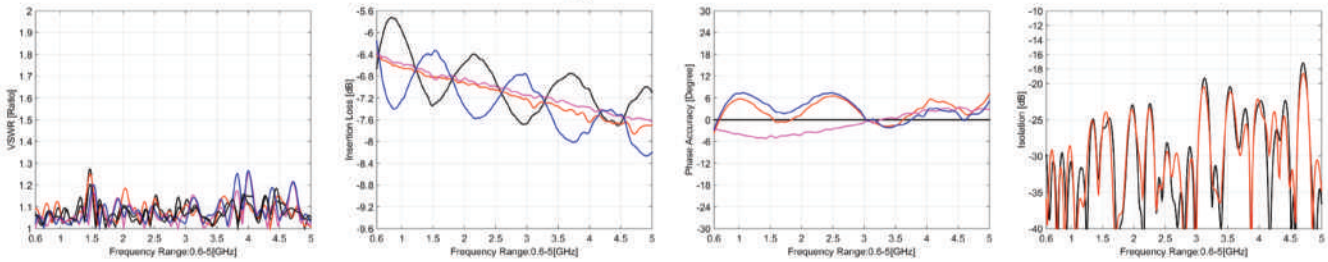
— Typical Test Curve* —



*Corresponding Channels: A1B1、A1B2、A1B3、A1B4

P/N	Freq. Range (GHz)	VSWR Max. (:1)	Insertion Loss** Max.(dB)	Amplitude Balance Max.(dB)	Amplitude Flatness Max.(dB)	Phase Accuracy Max.(Deg.)	Isolation Min.(dB)
SA-07-4B006050	0.617-0.821	1.4	8.2	±1.1	±0.8	±10	16
	0.832-0.96	1.4	8.2	±1.1	±0.7	±9	16
	1.427-1.71	1.5	8.3	±0.9	±0.7	±9	15
	1.71-2.2	1.5	8.5	±0.9	±0.8	±10	14
	2.496-2.69	1.5	8.7	±0.9	±0.7	±9	13
	3.3-4.2	1.6	8.9	±1	±0.7	±12	13
	4.4-5	1.6	9.2	±1	±0.8	±12	13

**Theoretical 6dB Included

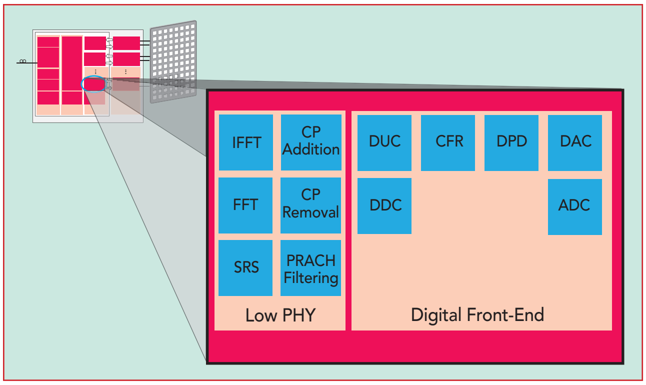


Fig. 9 **Elements of a digital transceiver.**

shows the functions of each digital transceiver, which contains the low PHY and digital front-end. The digital front-end encompasses front-end functions like filtering, gain settings and linearization in the digital domain, and the low PHY addresses time-frequency conversion and OFDM signal generation.

In the downlink direction, the SCs from the beamformer containing data in the frequency domain are transformed to the time domain within the iFFT. The OFDM signal is formed by adding a CP and passed to the digital front-end for digital up-conversion, comprising filtering, the frequency shift of the baseband signal and digital-to-analog conversion. For the downlink, the digital front-end includes crest factor reduction, which reduces the peak-to-average ratio of the OFDM signal, and digital predistortion (DPD), which linearizes the power amplifier. The uplink signals from the analog front-end are converted into the digital domain using analog-to-digital converters and digitally down-converted to baseband. With the down-converted signals, the CP is removed and the signal is converted to the frequency domain via the FFT. The OFDM symbols are then passed to the Rx beamformer. The low PHY also contains special functions for physical random access channel (PRACH) and sounding reference signal (SRS) filtering. The PRACH and SRS signals are passed to the fronthaul interface, and the O-DU post-processes the SRS and PRACH data.

The analog front-end (AFE) connects to the radiating panel and contains analog components like power amplifiers, filters, drivers and baluns and may contain switches and circulators. The AFE amplifies the Tx and Rx signals to and from the antennas. It must provide sufficient dynamic range for the Rx and Tx paths, isolate the paths and manage any noise introduced by the power amplifier stages. The radiating panel is designed to provide the required gain for the mMIMO system and the horizontal and vertical steering.

SUMMARY

This article has provided a tutorial on the architecture of the O-RAN and the approach to standardizing the interfaces between the RU, DU and CU to achieve interoperability and provide an environment for new entrants and network innovation. mMIMO is one RAN implementation to improve data capacity in areas with high mobile traffic, and the article discussed the functional architecture of a mMIMO RAN meeting O-RAN standards.

A future article will discuss the mMIMO architecture and performance parameters of the RU, applying the concepts to the design of two AAUs: for the North American band from 3.7 to 3.98 GHz and the European band from 3.3 to 3.8 GHz. ■

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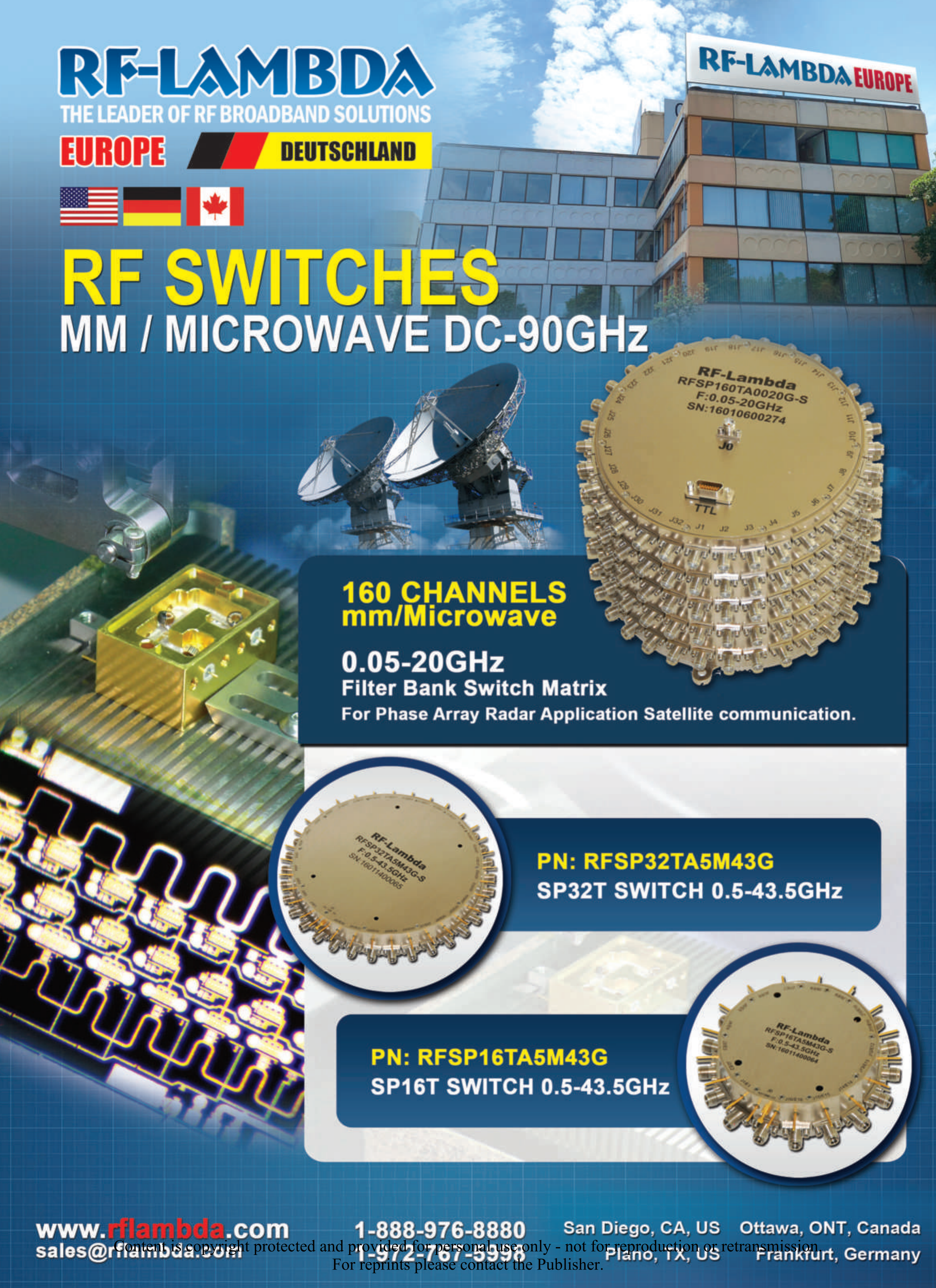
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INVITED PAPER

Embedded PCB Antennas for IoT: Design and Implementation Considerations

Kevin Hietpas
Pasternack

IoT modules are often defined by their small form factors and ability to transmit sensor data to a centralized hub via a wireless connection. While the radio modulation scheme and IoT protocol can vary, most IoT devices fall below the 6 GHz band. For these IoT applications there is a need for small planar antenna structures implemented on a common PCB platform where connection to the microcontroller unit (MCU) and processing unit of the node is accomplished often via a push-on miniaturized coaxial interface. This article examines the various PCB antenna implementations and their design considerations, with an additional discussion around the packaging and placement of IoT nodes and how this can impact their connectivity.

THE MYRIAD OF IOT DEVICE CONSIDERATIONS

Power and size constraints often cause IoT nodes to run off either a simple coin-cell battery or small form factor energy storage device for an extended period (on the order of years). To accomplish this, a low energy-consuming protocol must be employed with different "classes" and/or "power modes" to enable different levels of energy savings. For instance, a LoRa device has various current modes (i.e., transmit, receive, synthesizer, standby, idle and sleep) to enable the sensor node to extend its operating lifetime, enabling minimal maintenance and repair.

The frequency of uplink/downlinks are also particularly relevant for battery savings—scheduled uplinks and downlinks enable less latency, a higher throughput and greater reliability while asynchronous, ad-hoc transmissions can extend range and battery life at the expense of data rate and payload size.

Extensive energy harvesting techniques have often been leveraged for IoT devices, allowing for a relatively unlimited battery life without human intervention. This, however, does increase node cost and complexity.

Regardless of the industry, IoT devices often leverage cellular, Bluetooth and Wi-Fi protocols as they are prolific and therefore easy to integrate and scale with the native system for monitoring and control. Often, multi-protocol IoT platforms incorporate a more niche IoT protocol (e.g., ZigBee, LoRa, Sigfox, etc.) as well as a Bluetooth low energy (BLE), Wi-Fi or cellular module to incorporate the benefits of both. A device that leverages Wi-Fi can more readily connect to the cloud, allowing for control/configuration as well as firmware upgrades from any remote location.

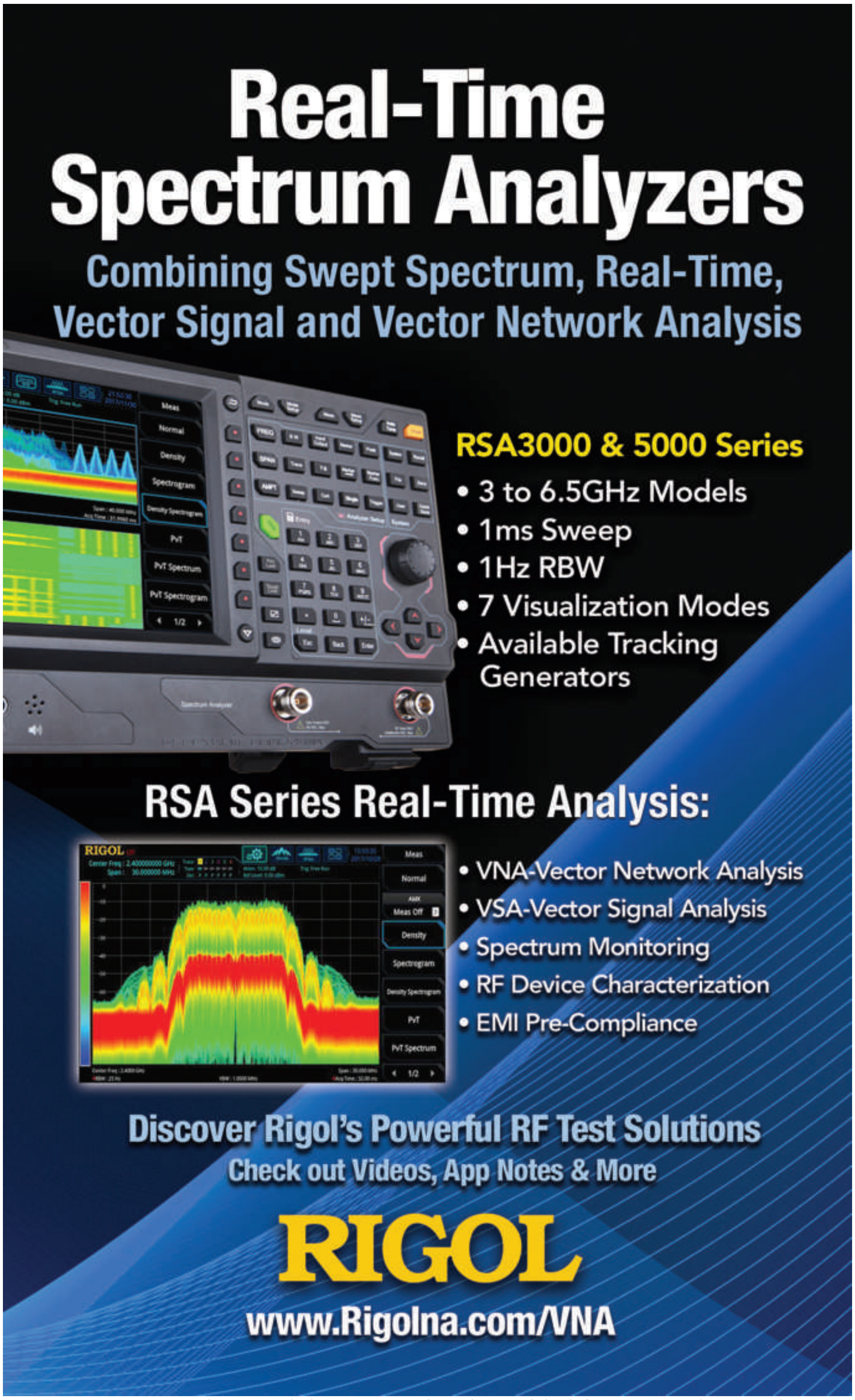
A node that includes both BLE and a sub-GHz low-power wide-area network solutions can provide Bluetooth beacons for a real-time location system while also remotely controlling a simple mechanism such as industrial lighting from a distant location. Still, there are the major considerations of test and certification that come with Bluetooth and cellular devices. Both protocols require extensive testing and proof before they can come with the required "stamp of approval" for release.

WHY CARE ABOUT THE ANTENNA?

In the massive landscape of IoT sensor technologies, protocols, vendor-specific SoCs and development boards, often over-

looked is the antenna, link budget and integrity of the wireless link between nodes. Typically defined by an omni-directional radiation pattern with a specific vertical/horizontal beamwidth, most IoT devices use either a whip, PCB or chip antenna. In cases where specific fringe devices must be connected, directional antennas (e.g. Yagi) can be used to extend range. Each antenna type has its respective benefits and considerations.

PCB antennas are particularly effective due to their balance between gain and size. The characteristic low profile of the PCB antenna allows it to be readily configured within a case as opposed to jutting out like the classic whip antenna. Unlike the chip antenna, PCB antennas can operate over relatively large bandwidths with relatively high gain. A trace antenna can even be embedded into a system-level board during the manufacturing process allowing for a smaller device form factor.



Beyond real estate considerations, antenna design and placement can come with significant link integrity considerations—radiation quality can be directly impacted by neighboring electronic components, metallic enclosure hardware and of course, environmental interference. Factors such as transmit/receive antenna gain, free space path loss at a specific carrier frequency, loss of the antenna feed, transmitter and receiver losses and miscellaneous environmental losses must be considered when attempting to expand the link budget. Regardless of the environment, however, radiation pattern, gain, VSWR and bandwidth are parameters preliminarily evaluated in the first steps of development and optimization of a wireless connection.

UNDERSTANDING COMMON TRACE ANTENNA DESIGNS

PCB antenna structures can be monopole, dipole, slot, patch and printed inverted-F (PIFA). There is a plethora of books, application notes and blogs dedicated solely to the design of each with extensive equations; the following is intended as an overview of the trace patterns used and their practical considerations.

Dipole and Monopole Antennas

A dipole antenna comprises two quarter wavelength (λ/4) long metallic strips with a total electrical length requirement of a half wavelength (λ/2) at the carrier frequency for maximum response (see ***Figure 1***). Much of the trace antenna literature is devoted to the design of antennas in the 2.4 GHz ISM band due to the use of conventional protocols such as Bluetooth and Wi-Fi. At 2.4 GHz, the length of the dipole antenna is approximately 6 cm, which could be unreasonably large for some applications. The omni-directional radiation pattern has a concentration of electromagnetic energy perpendicular to its length (z-axis) with a null in the middle (along the z-axis). This often requires it to be placed in a vertical orientation for maximum horizontal coverage—a serious consideration for designers intending to use a di-

pole (or monopole) antenna in an IoT device.

The addition of a ground plane eliminates one arm of the dipole, resulting in a structure that consists of a singular quarter wavelength conductive element with the ground plane acting as the other quarter wavelength arm. Analogous to a mirror, the ground plane generates a "virtual image" of the radiation pattern that is equal (same current flow direction and phase) to the one generated by the conductive strip. For the ground plane to function optimally, it must be considerably larger than a half wavelength. A finite ground plane results in edge diffraction of the radiated wave causing electromagnetic energy to move radially outward from the edge and leak behind the ground plane.[1]

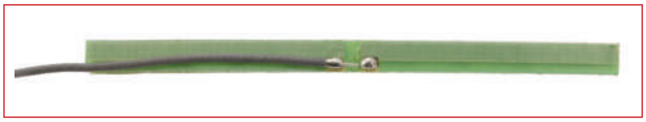


Fig. 1 This 2.4 GHz dipole trace antenna achieves 2 dBi gain.

Ideally, with a perceptually infinite ground plane, the gain of a quarter wavelength monopole antenna should be twice that of a half wavelength dipole due to reflection from the ground plane radiating exclusively toward the area above it. This results in a somewhat "lifted" pattern (see ***Figure 2***). Once again, a null is created along the length (z-axis) of the conductive quarter wavelength element revealing an ideal vertical orientation.

Bent Monopole Antennas

Bent monopole variants such as the L-shaped (or tilted whip and inverted L), planar inverted-F (PIFA) and meandered inverted-F (MIFA) structures leverage the same ground plane and conductive arm methodology with varying patterns of the conductive arm. The bend in the trace allows for a more compact size as well as decreasing the null in the radiation pattern. In these designs, however, the antenna trace typically must not run too close to ground as this can cause the antenna to act as a transmission line without any radiation.[2]

Of these variants, the PIFA is the most common due to its small PCB area and wide bandwidth performance. As shown in ***Figure 3***, it has a fold in the main resonant line that introduces a capacitance canceled out by the shorting feed point at the end of line. Impedance matching with the antenna feed is obtained by adjusting the lengths of A, B and C, where the dimensions of A and C contribute to the quarter wavelength element and B is adjusted

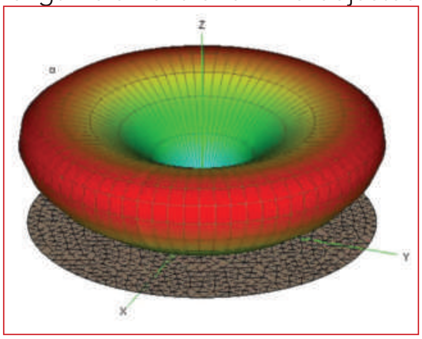


Fig. 2 Monopole antenna pattern showing ground plane effects.

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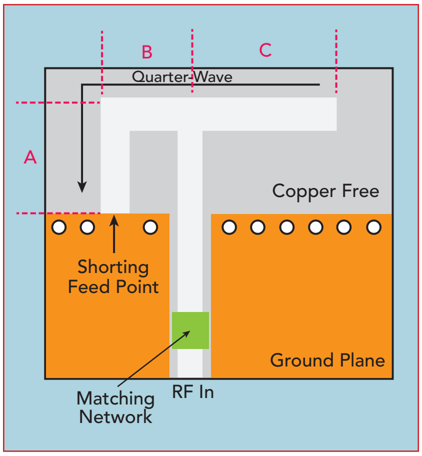

Fig. 3 **PIFA board layout.**

for an impedance match. An external matching network can also be included for additional tuning.

The MIFA antenna (see ***Figure 4***) is like a helical or spiral antenna, as it increases the total length and accomplishes resonance with varying orientations of trace/wire compressions. In a MIFA, horizontal and vertical lines form multiple turns. Like the PIFA, tuning is accomplished by adjusting the geometry within the meandered line. This effectively reduces the size of the antenna. However, it often comes with tradeoffs such as reducing gain and therefore shortening range, relying more on tuning and therefore exhibiting a narrower bandwidth and increasing sensitivity to interference from external sources as well as native electrical components on the board.

Dipole Antenna Variants

Printed dipole antennas face a major size disadvantage. At low frequencies this is especially relevant; here, a monopole antenna element has the advantage that it can potentially be placed on a corner of the board with the ground plane serving both as the RF ground plane/return path of the antenna and ground for the native electrical components of the IoT module. As the operating frequency increases, however, this becomes less of a concern. Moreover, like bent monopole antenna structures, different dipole patterns can be employed to increase bandwidth and decrease size.

Tapering the dipole arms is a known bandwidth enhancing technique. For example, the planar conical dipole antenna, also known as a bow tie antenna (see ***Figure 5***), behaves as a uniformly tapered transmission line. When an RF signal is applied across the feed, currents flow radially outward and form an enclosing magnetic field. However, currents are abruptly terminated at the edge of the bow tie causing more reflections and a narrower bandwidth than its 3D, biconical counterpart. Still, a relatively constant impedance and gain can be achieved over a massive frequency range relative to other dipole antennas. The antenna in Figure 5 exhibits a high gain (4.5 dBi) over a large bandwidth (4.9 to 5.9 GHz).

Fig. 4 **This 800/900 MHz MIFA antenna achieves 2 dBi gain.**

Along the same line of reasoning found in bent monopole quarter wavelength antennas, smaller form factors can be achieved by meandering the conductive arms of the dipole elements (see ***Figure 6***). As previously mentioned, this optimizes the Q but can decrease overall bandwidth and efficiency. Therefore, the use of self-resonant space-saving techniques such as the spiraling or meandering of the conductive arms comes with tradeoffs that must be considered for the application.

GENERAL PLANAR ANTENNA CONSIDERATIONS

Board Layout

There are some general design principles to consider to achieve the most benefit from the low profile form factor and potential space savings. For monopole antennas, sufficient ground planes are critical; a good quality/large ground plane enables an improved VSWR and a closer correlation with theoretical antenna behavior. For planar antennas integrated onto the module board, there is a keep out area around the antenna that requires the board to be free of copper traces or ground fill. In multi-layer designs, vias along the edge of the keep out area are necessary to connect ground planes.

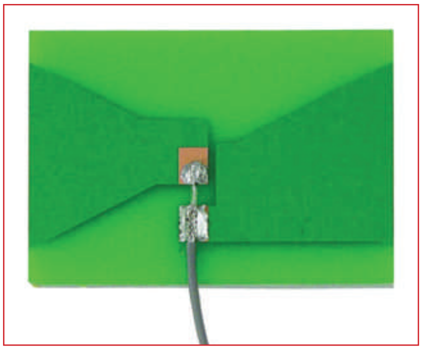

Fig. 5 **Planar conical dipole or bow tie antenna.**

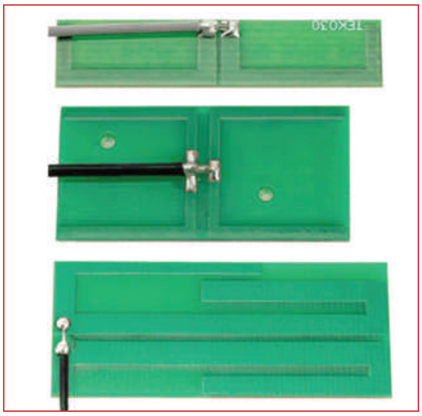

Fig. 6 **Dipole antennas using bent conductive elements to save space.**

Antenna tuning, or the minor adjustment in trace dimensions or length of the conductive arms, must be done within the enclosure and not in free space, as the enclosure and environment in which it functions affects its radiation performance. Moreover, any changes in layout often lead to changes in antenna performance and therefore must be tested.

Antennas with thicker trace widths often have broader bandwidths, as can be seen with structures such as the conical dipole antenna. Beyond trace thickness and length of the conductive elements, the relative

permittivity (ε_R) and thickness of the substrate material (e.g., FR4, flexible PCB (FPCB) and Teflon) also affect antenna performance.

Impedance Matching

Impedance mismatches cause unnecessary reflections and signal loss, so a lumped element matching network such as a pi- or T-match at the antenna feed allows for maximum power transfer. More complex matching networks enable tuning with series and shunt inductive and variable capacitive elements such as MEMS switches. Other variations include single-stub or multiple-stub tuners that provide broader bandwidth at the expense of space. These structures reduce the effects of external factors such as changes in orientation as well as the effects of obstacles and objects that are near the antenna that can cause signal degradation while matching transmission and reception bands necessary for the application.

Dipole antennas have found use in a wide array of applications due to their ability to accommodate a MIMO implementation in LTE/5G systems with relatively straightforward multi-band, dual-polarization designs (see ***Figure 7***). An integrated microstrip balun is often used to match the impedance of the antenna and transmission line. A differentially fed planar dipole antenna is also used with an integrated Marchand balun to provide a balanced transition between the antenna and its feed network. Dual-polarized planar dipole antennas have been realized through the formation of two identical elements of varying orientations while exhibiting low cross polarization.[3]

Enclosures

IoT devices and sensor nodes often come in ruggedized enclosures to prevent damage from environmental elements such as wind, precipitation, UV damage, humidity and salt water. Enclosures that are NEMA-rated and/or IP-rated can be used: however, these do not consider the effects that the various parts will have on antenna radiation patterns. Even a molded plastic enclosure can cause RF losses and should therefore be tested and characterized prior to manufacture. A polycarbonate casing will exhibit different signal loss characteristics than a thermoplastic casing and, of course, a stainless steel enclosure. Metallic components such as pads, pins, tracks and ground planes can cause the antenna to lose efficiency, gain and bandwidth while metallic casing components such as brackets, padlock, screws/studs and even an external pole mounting kit will cause signal degradation.

In some applications, the casing itself is used to adjust the antenna

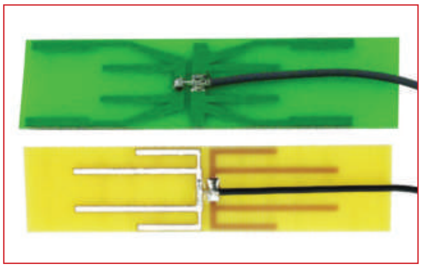

Fig. 7 Dual-band 2.4/5 GHz omnidirectional planar dipole antennas.


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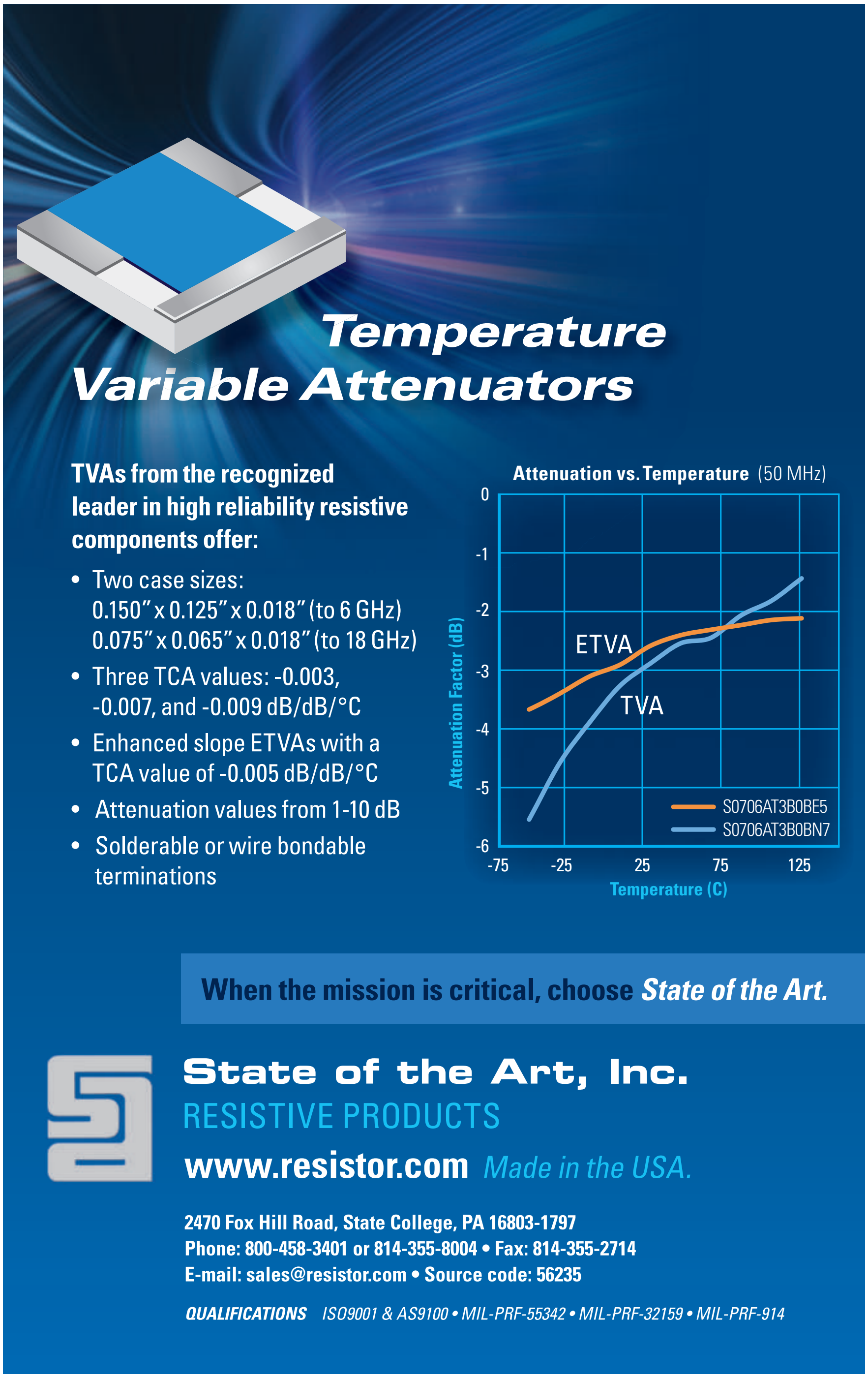
radiation pattern. For example, altering a dipole antenna radiation pattern can be accomplished via a director or reflector strip. A director strip adjusts radiation elements within the antenna to change its frequency response while the reflector strip, or metal part of the antenna casing, adjusts the antenna radiation pattern to fit an area of coverage and potentially support ceiling/wall installations. When leveraging a commercial off-the-shelf (COTS) PCB antenna, it is important to verify its performance both inside and outside of its enclosure to ensure that the structure does not negatively affect desired performance.

Certifications

IoT device certifications are an essential part of the design process from prototype to production. This is particularly true for Bluetooth and cellular devices. For example, the GSMA defines the over-the-air (OTA) testing of IoT devices using 3GPP communications (e.g., NB-IoT, LTE-M and CAT1/CATbis) in its TS.51 report.[4] Tests and performance requirements are defined for total radiated power and total radiated sensitivity. These parameters evaluate antenna performance where poor OTA performance would result in a high block error rate, as well as potential access failure. When using the unlicensed spectrum however, the most critical design consideration is typically conforming to FCC EIRP regulations.



CONCLUSION

PCB/trace antennas suit a wide range of applications with narrow single-band and multi-band options. The size and shape of the antenna can be reduced using common bending/meandering techniques however, this comes with an array of efficiency and sensitivity considerations.

A higher gain antenna will loosen the constraints on the link budget, wider traces often correspond to a larger bandwidth. Still, these come at the cost of size, and in the world of IoT the miniaturization of sensor nodes, ease of installation and scalability are serious considerations.

A COTS antenna comes with the benefits of a proven antenna structure with verified performance, but this does not ensure that the antenna will function within an enclosure of choice.

The basic structures of a simple monopole (e.g., PIFA and inverted L) and bent dipole are popular choices. Nevertheless, these antennas are only a few of the many possibilities depending upon the carrier frequency, operating bandwidth, polarization, size and cost.

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19-24 June 2022

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091521

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Authors are invited to submit technical papers describing original work and/or advanced practices on RF, microwave, mmWave, and THz theory and techniques. The deadline for submission is 7 December 2021.

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1. Full-length (20 minute) oral papers report significant contributions, advancements, or applications.
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There are four selection criteria: Originality, Quantitative Content, Clarity and Interest to MTT-S Membership.

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For the initial submission deadline, the paper length should be 3 pages. An accepted paper may be 3 or 4 pages long.

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2. Authors should adhere to the format provided in the template, which can be downloaded from the conference website.
3. The initial submission should be in PDF format, and cannot exceed 4 MB in size.
4. Authors should upload their paper by midnight Hawaii time on 7 December 2021.

Details at www.ims-ieee.org

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Papers are reviewed by IMS2022 Technical Program Subcommittees. A double-blind review process will be used to ensure anonymity for both authors and reviewers.

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Authors will be notified of the decision by 2 February 2022 via email. For accepted papers, an electronic version of the final 3-4 page manuscript along with a copyright assignment to the IEEE must be submitted by 9 March 2022. The Symposium proceedings will be recorded on electronic media and archived in IEEE Xplore.

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Authors of all papers presented at IMS2022 can submit an expanded version of their papers to a special symposium issue of the IEEE Transactions on Microwave Theory and Techniques.

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INVITED PAPER

mmWave Beamforming in Dynamic, Urban Environments

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In 5G and 6G, mmWaves bring the promise of new, high bandwidth frequency bands, supporting many of the new concepts envisioned for future applications in wireless communications. Propagation losses and fast fading due to increasingly mobile devices and short wavelengths pose challenges for many of these new concepts. mmWave MIMO beamforming technology can help solve some of these issues but must be able to adapt to dynamic channels as devices move and signals interact with people and vehicles moving through a scene. To evaluate performance, ray tracing simulations can predict the fast fading and Doppler spectra expected in an active urban environment and estimate the impact a dynamic channel has on MIMO beamforming.

To support the demand for significantly higher data rates and an ever-increasing number of connected users, wireless service providers have begun using the large expanse of spectrum available in the mmWave band; however, mmWave propagation presents unique challenges. Principal among these are increased free-space path loss and greater attenuation for diffracted beams when compared to the sub-7 GHz bands. To mitigate the increased path loss, high gain antennas for one or both ends of the link are employed. At the base station, exceptionally high gains are attained with many-element phased arrays forming massive MIMO (mMIMO) links with users. The use of such high gain antennas, in turn, demands that adaptive beam steering be used in mobile scenarios. This introduces challenges of its own.

ADAPTING TO A DYNAMIC CHANNEL

Since the channel is continuously changing, latency between the measurement of channel state information (CSI), e.g., beam selection and/or channel sounding, and use of the adapted beam for data transmission yields a throughput that is degraded relative to that achievable in a static scene. This degradation can be particularly severe for high mobility scenarios and for scenes with obstacles that can dynamically block a link, as shadow fading is particularly sharp for mmWaves. For these reasons, an accurate prediction of link performance in a mobile environment requires knowledge of the time dependent channel and an understanding of relevant latencies.

Beyond the challenges associated with adaptive beamforming, the mmWave channel is also a faster fading channel compared to sub-7 GHz channels because of the shorter wavelength. Thus, the coherence time is shorter, and the corresponding Doppler bandwidth is broader. For the orthogonal frequency division multiplexing (OFDM) waveforms used in 5G New Radio (NR), the increased Doppler bandwidth results in interference between subcarriers yielding further degradation of throughput.

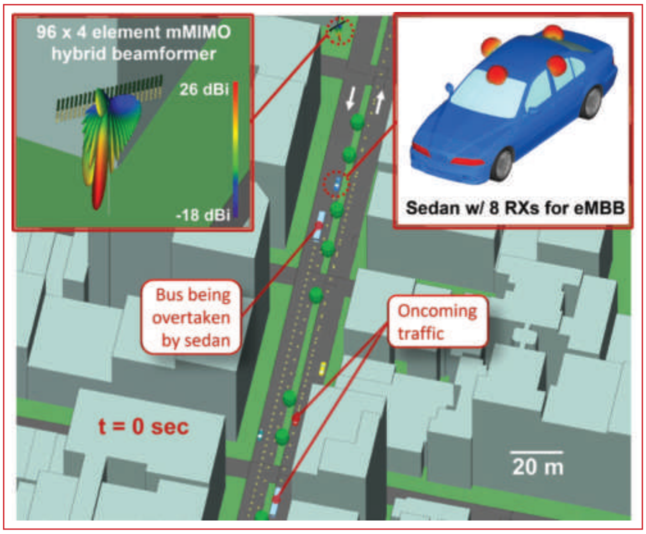


Fig. 1 **mmWave hybrid beamformer transmitting four data streams to a sedan driving in central Manhattan.**

CASE STUDY

To illustrate the impairments due to mobility, consider the use case of providing enhanced mobile broadband (eMBB) service to a moving vehicle in a dense urban environment and in the presence of other moving vehicles. Realistic predictions of the time-varying channels are made using Remcom's Wireless InSite® propagation tool[1] to perform ray tracing simulations over a series of densely-spaced time steps. Simulations show that the vehicle-mounted receivers (Rx) detect fading as the vehicle moves along its route, and illustrate an example of a Doppler spectrum that results from the motion of the vehicle receiving service and other vehicles around it. Next the degradation in the signal-to-interference-plus-noise ratio (SINR) due to latency between measuring and using the CSI for adaptive beamforming is considered. Relative to the case where mobility is ignored, this latency alone provides a degradation of 5 to 8 dB in the SINR for latency parameters suggested by the 5G NR standard.[2-4]

The specific eMBB scenario considered here is the hybrid beamforming of four data streams to a mobile vehicle. This scenario is motivated by a recent 5G NR field trial[5] where a data rate of 11 Gbps was demonstrated across four data streams and 732 MHz of aggregated bandwidth for a vehicle moving at 30 km/h and communicating with hybrid beamforming mMIMO base stations operating at 28 GHz. For an increased speed of 100 km/h, the throughput was reduced to 8 Gbps. Whereas the field trial was conducted in a pristine environment, within the context of our simulations, a similar vehicle-to-network (V2N) interface is deployed but in a dense urban environment and in the presence of additional moving vehicles (see ***Figure 1***).

The sedan which receives the eMBB service is equipped with a total of eight Rxs: two cross-polarized Rxs at each of four locations as shown in the upper right inset. Further, the sedan is equipped with four baseband RF chains so that it can decode four data streams from the four Rxs with the highest signal strength. The 5G Node B (gNB) radio base station is located at the top center of Figure 1 and shown in detail with exaggerated dimensions for visualization in the upper-left inset. The gNB is a 28 GHz hybrid beamformer consisting of four digital baseband RF chains. Each drives a 96-element phased array equipped with an analog beamformer. Each 96-element panel is a rectangular array that spans four elements in the vertical direction and 24 in the horizontal dimension with λ/2 spacing. The elements themselves are patch antennas with 6 dBi gain. Two panels are co-located but with elements having orthogonal polarizations at ±45 degrees relative to vertical. The second set of two panels are similarly co-located but positioned vertically above the first two-panel set. The four-panel assembly is angled down by 10 degrees to increase coverage to users at street level. Each panel is equipped with an analog beamformer which enables beam steering over 32 angles in the horizontal direction evenly spaced across a 120-degree span. These 32 directed beams are configured in the precoding matrix that can be requested by the user equipment (UE), i.e., the sedan receiving service. One such beam produced by a single panel is shown in the upper-left inset of Figure 1. The total RF power output by the four-panel array is 27 dBm.

Having four digital baseband RF

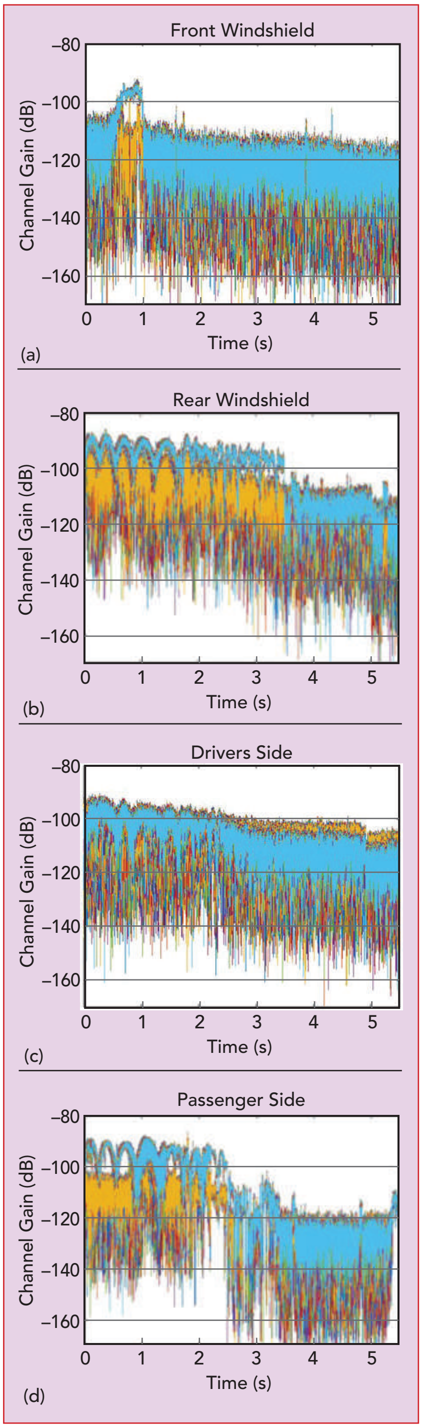


Fig. 2 **Receiver fading at the front windshield (a), rear windshield (b), driver side (c) and passenger side (d) of the moving sedan over 5.5 s.**

chains, the gNB can simultaneously transmit four data streams to the UE. The gNB does so by employing digital beamforming using one beam from each panel selected from the precoding matrix. With these four analog-formed beams, the digital beamformer employs regularized-zero-forcing (RZF)[6] to determine the optimum complex weight coefficients for transmitting each of the four data streams to an individual Rx on the UE, while simultaneously minimizing interference to the other three active Rxs not associated with a given data stream.

The UE travels along Park Avenue at a constant speed of 14.75 m/s. Along the route, it overtakes a bus moving at 7 m/s in the adjacent lane and is proximate to oncoming traffic, a car (14 m/s) and a bus (13 m/s). Figure 1 depicts the scenario at an initial time, t = 0 s, where the yellow dots which extend in front of each moving vehicle denote waypoints at equal time intervals for the given route.

DETERMINISTIC CHANNEL MODEL

Before considering the effects of latency on beamforming, first consider the general characteristics of the fading channels for the scenario described above. Remcom's Wireless InSite is used to evaluate the propagation channels by performing ray tracing for each of the 384 × 8 element pairs between the mMIMO gNB and the UE's Rxs. Ray tracing is performed at each of a dense series of time steps spaced by 2.5 ms over a time interval between t = 0 and 5.5 s.

New mobility features currently under development in the Wireless InSite propagation tool facilitate simulation of the motion of the UE along with other vehicles in the scene so that any geometry that can affect the propagation channel is accurately accounted for at each time step. Ray path trajectories which connect a transmit-receive (Tx-Rx) element pair can include up to six reflections, one diffraction and attenuation by foliage. In addition, diffuse scatter off the terrain, asphalt and nearby buildings is included. Linear interpolation of ray path parameters (e.g., path length, path loss and phase shift) between time steps allows a reliable means to reconstruct ray path properties at arbitrary times. The parameters for each ray path at an arbitrary time can then be used to calculate the complex path gain and, by coherently summing over all complex path gains, the complex channel gain for each Tx-Rx element pair.

FADING AND SHADOWING

These results are used to predict channel fading for each Tx-Rx element pair as a function of time. ***Figure 2*** shows the magnitude of the channel gains over the entire route for each of the 384 mMIMO elements to four representative Rxs on the UE:

Front Windshield (see ***Figure 2a***). For most of the time, this Rx does not have a strong path from any mMIMO element, but typically has a channel gain determined by the sum of many diffuse scatter contributions, which arrive from a multitude of directions. As a result, one observes very fast fading for much of the time with rapid fluctuations in channel gain. There is a period, however, from t ≈ 0.5 to 1.0 s, over which the channel gain is relatively large for the mMIMO elements of one polarization. This is due to a strong reflection off the slow-moving bus that the UE is gaining on which exists over this period, allowing significant power to reach the Rx.

Rear Windshield (see ***Figure 2b***). For this Rx, the characteristics of fading for the first ≈ 3.5 s are notably different from the front windshield Rx, as the gain is significantly increased and has a fading contribution that fluctuates on a slower time scale. This is because a line-of-sight (LOS) and one or more specular rays are incident on this Rx over this period. Beyond 3.5 s they are shadowed by one or both buses.

Driver and Passenger Side Rxs (see ***Figures 2c*** and ***d***). These Rxs show similar behavior to the rear

window Rx, as they also have a LOS and strong multi-path components reaching the Rxs for the initial portion of the route. The passenger side Rx is abruptly shadowed at t ≈ 2.5 s, at which point the UE is overtaking the bus on its passenger's side.

All Rxs. For all Rxs, a slow fade is observed for short to long timescales due to free-space path loss as the UE recedes from the gNB.

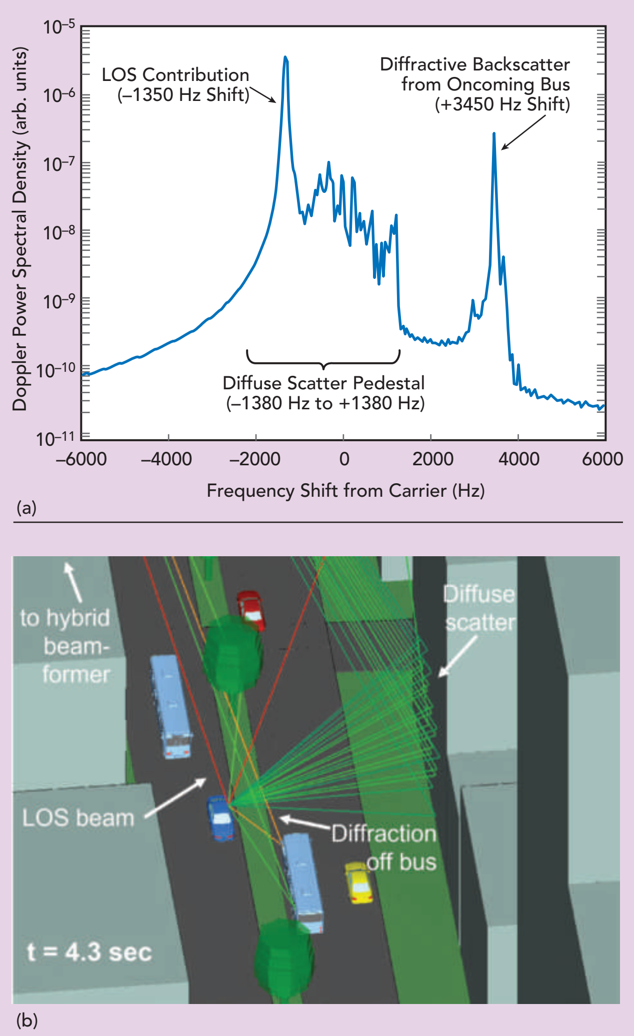
DOPPLER SHIFTS

Another quantity of interest is the distribution of frequency shifts that arise due to the Doppler effect, as such shifts introduce inter-(sub)-carrier-interference (ICI) in an OFDM waveform and thereby degrade the communication link. The power spectral density (PSD) of the Doppler frequency shifts relative to the carrier is given by the PSD of the time dependent complex channel gain over a given interval.

A typical Doppler spectrum is shown in ***Figure 3a*** where the PSD is computed over a 20 ms period at a simulation time of t = 4.3 s. The spectrum shown is the average over all mMIMO elements for a single Rx on the driver's side of the UE. There are several notable features explained with reference to ***Figure 3b***, which shows the 25 highest power (out of 500) ray paths that contribute to the received signal for a representative mMIMO element.

The dominant peak in the Doppler spectrum arises primarily from the LOS ray path, with smaller contributions from somewhat weaker reflected rays. Since the UE is moving almost directly away from the gNB with a speed $|\vec{v}|$= 14.75 m/s, the expected frequency shift for the LOS contribution is close to the maximum shift $\Delta f_{max}=|\vec{v}|/\lambda$ = 1.38 kHz. The observed shift, with a magnitude of 1.35 kHz, is reduced because the velocity of the UE is not directly away from the gNB, and the reflected rays also contribute with somewhat reduced shifts. The negative sign of the shift is expected since the UE is moving away and therefore receives a LOS signal lower in frequency than that of the carrier. This dominant peak sits on top of a broad pedestal, which extends from $-\Delta f_{max}$ to $+\Delta f_{max}$ and results from diffuse scatter contributions to the PSD, which arrive from all directions relative to the velocity, $\vec{v}$, of the UE.

Finally, the isolated peak having a frequency shift of +3.45 kHz



▲ Fig. 3 Doppler shift at the driver's side receiver (a) showing effects of diffraction from an oncoming bus (b).

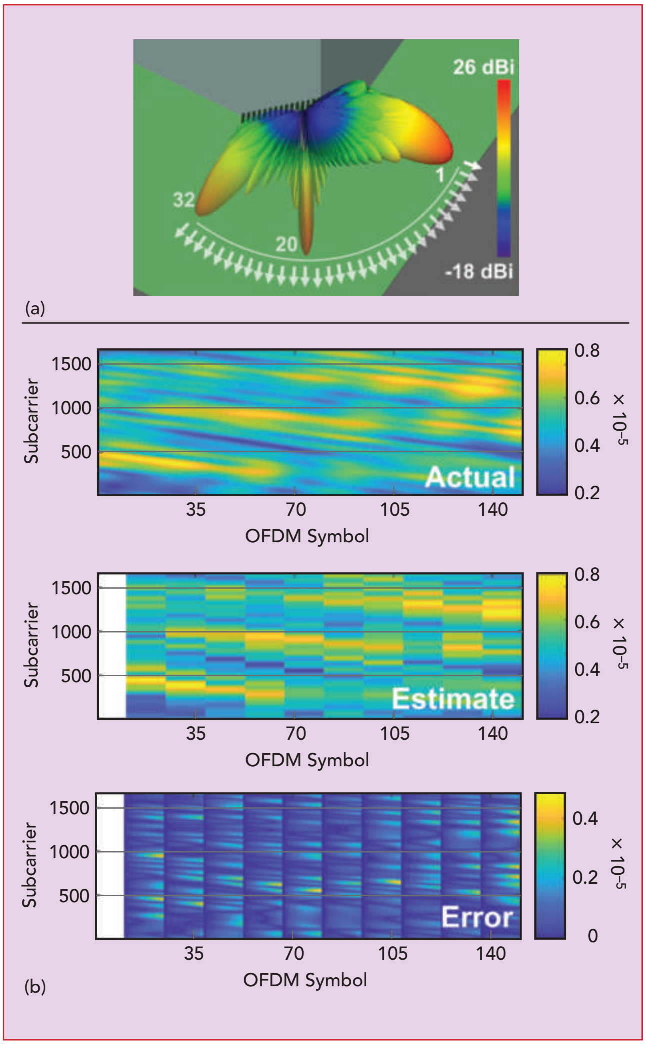


Fig. 4 **Sector scan during a signal synchronization burst (a) with channel estimation based on sounding reference signal (b).**

results from rays that first travel to the oncoming bus, diffract off the bus and, finally, travel back to the driver's side Rx. The size of this shift is reasonable. With the bus approaching the gNB at a velocity of $\vec{v}_{bus}$, and the UE and bus approaching each other with a relative velocity of $(\vec{v}_{bus} - \vec{v})$, the expected Doppler shift would be $(2|\vec{v}_{bus}| + |\vec{v}|)/\lambda$ = 3.8 kHz. Given that these objects are not moving directly toward each other, the reduced shift of 3.45 kHz is expected.

It is notable that this representative Doppler spectrum differs significantly from the often-used statistical model of Clarke[7] and Jakes,[8] which assumes a dense, uniform scattering environment and ignores strong, isolated contributions that arise from LOS or specular ray paths. The Doppler spectra for the deterministic channel simulated here, in contrast, includes contributions from LOS and specular rays which yield the dominant features in the Doppler spectrum, highlighting the value of deterministic ray tracing simulations. Further, though it is beyond the scope of this article, the time dependent ray path parameters provided by these simulations can be used to construct the time dependent channel impulse response (CIR) from which the explicit degradation of the communication link due to ICI can be determined (e.g. Wang et al.,[9] but using a deterministic rather than a statistical CIR).

BEAMFORMING DEGRADATION DUE TO LATENCY

Consider now the SINR attained for four downlink data streams to active Rxs on the UE achieved by digital RZF beamforming using four analog-formed beams, each chosen from the precoding table. Latencies which exist between channel measurement and beamforming degrade performance.

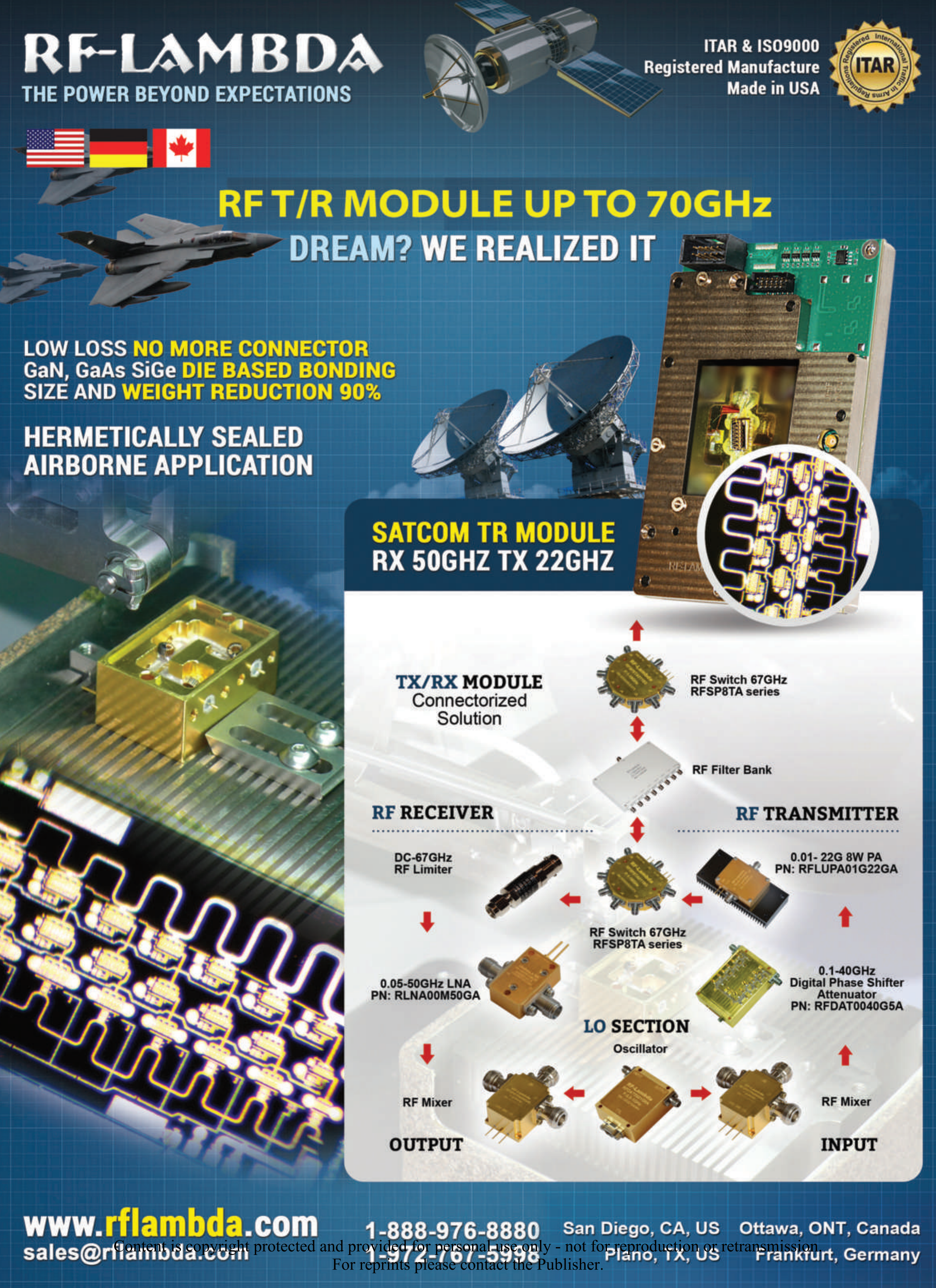
The four active Rxs (out of eight on the UE) and the precoding matrix indices (PMIs) requested by the UE are chosen following a burst of synchronization signal blocks (SSBs) which are part of the 5G NR and can be expected once every 20 ms.[4,10] During a SSB burst, the gNB scans a sector by transmitting 64 SSBs using each of the 32 analog-formed beams for each of two orthogonally polarized panels in succession (see ***Figure 4a***). During the SSB bursts, the UE determines the four Rxs out of eight that have the highest signal strength from one of the 64 SSBs.

Since the UE only has four digital RF chains, two successive SSB bursts are required to determine the four active Rxs. Thus, with a period of 40 ms, the UE chooses an active Rx set and reports to the gNB the four unique PMIs which produced the highest signal strengths. These are used to generate four beams for the analog stage of the hybrid beamforming. Next, the CSI required for the digital beamforming stage is obtained from sounding reference signals (SRSs) provided by the UE on uplink (channel reciprocity is assumed). Per the 3GPP specifications,[2] the SRS can be provided as often as once per slot; which, for a 60 kHz subcarrier spacing, is a period of 250 µs.

The latency due to both the analog and digital stages of channel estimation in beamforming degrades performance. For example, in the case of PMI set + Rx set selection, motion of the UE or other vehicles in the scene can result in abrupt shadowing of one or more active Rxs from one or more analog-formed beams. Regardless, the gNB will continue to use this compromised PMI + Rx set for beamforming until another set is chosen at a time up to 40 ms in the future despite the significant reduction in SINR over this period.

In the case of SRS-based channel estimation, discrepancies between the measured and actual CSI grow due to the channel changing continuously between SRS measurements. An example of this is shown in ***Figure 4b*** where the top panel shows the magnitude of the actual channel gain across a ≈ 100 MHz bandwidth (assuming 60 kHz subcarrier spacing) as a function of time. This CSI is sampled and stored by the gNB (middle panel) once per slot where one slot = 14 symbols = 250 µs. Over the period of one slot, the error between the stored and actual CSI grows continuously from zero. Figure 4 shows CSI for a driver's side Rx to a representative mMIMO element over a period of 40 ms starting at t = 2.5 s.

Explicit examples of degraded SINR resulting from each case considered above is readily found in the simulation. For example, ***Figure 5*** shows the SINR (red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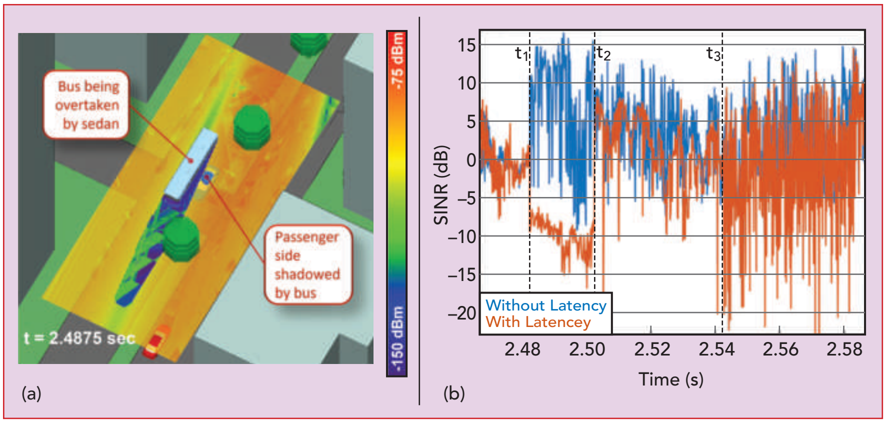
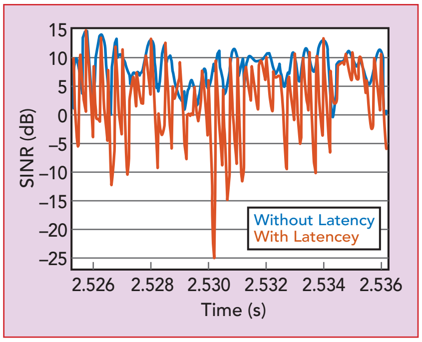


▲ **Fig. 5** **Driving scenario (a) with SINR degradation due to latency in the analog beamforming stage (b).**



▲ **Fig. 6** **SINR degradation from the latency in the digital beamforming stage.**

trace in ***Figure 5b***) for data stream #4 over a period that includes the moment (t_1 = 2.483 s) when the passenger side Rxs become rapidly shadowed by a bus. Prior to this moment, at t_0 = 2.463 s, the PMI/Rx set had been chosen to include a passenger side Rx for stream #4. When this Rx becomes shadowed at t_1, however, the SINR is significantly degraded relative to that which could be achieved if the analog and digital beams were formed based on instantaneous channel measurements (blue trace).

In this case, with latency ignored, the PMI/Rx sets chosen at t_1 switch to using driver's side Rxs for streams #3 and #4, which have direct LOS. In the realistic case, with latency considered, the gNB continues to attempt to form beams to the passenger side Rxs until the PMI/Rx sets are updated after the SSB burst at t_2 = 2.503 s (e.g., Figure 5a shows the gNB's attempt to form a beam to a passenger side Rx at a time between t_1 and t_2 even though it is shadowed). In fact, even at t_2, the updated active Rx set still includes one of the passenger side Rxs, because the signal strength recorded for that Rx was measured during the SSB burst just prior to its being shadowed at t_1. Thus, it is only when the PMI/Rx sets are updated again at t_3 = 2.543 s that both passenger side Rxs become excluded from the active Rx set.

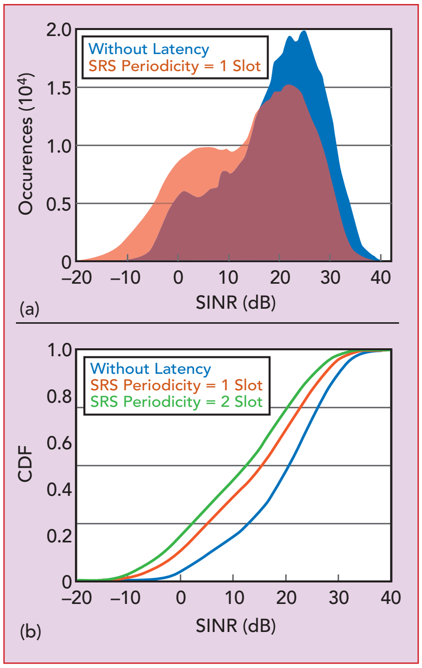
A representative time sequence demonstrating degraded SINR due to latency in SRS-based channel estimation is shown in ***Figure 6***. The red trace shows the SINR for stream #3 and associated with an Rx on the driver's side. This SINR varies periodically from a large value immediately after each SRS measurement to a low value just prior to the subsequent SRS measurement. The periodic degradation in SINR results precisely from the difference between the actual CSI and the CSI periodically captured by the gNB as depicted in Figure 4b. For comparison, the blue trace in Figure 6 shows the SINR that would be attained if the gNB used the actual CSI at all times for beamforming (i.e., ignoring latency).

COMPREHENSIVE RESULTS

To gauge the total impact latency has on beamforming for the eMBB scenario considered here, the SINR for the scenario as described above, which includes latencies based on 5G NR standards, is compared to the same scenario but with the effect of latency ignored (i.e., the PMI/Rx set selection is made and current CSI is used at each timestep for beamforming). The SINRs for both scenarios are calculated between t = 22.5

ms and 3.5 s with a 25 μs time step. Beyond the final time of 3.5 s, the UE is strongly shadowed.

A histogram of the results across all four data streams is shown in ***Figure 7a***. The corresponding cumulative distribution functions (CDFs) are shown in ***Figure 7b*** where an additional CDF result is included for a scenario where the SRS measurements are made once every two slots. The median SINR is 20.5 dB, 15.4 dB and 12.4 dB for the case which ignores latency and the cases that include all latency effects but use an SRS periodicity of one slot and two slots respectively. Thus, the combined effects of latency, including both PMI/Rx set selection and CSI measurement, act to degrade the median SINR by 5.1 dB when a one slot SRS periodicity is used and 8.1 dB for a two slot SRS periodicity.



▲ **Fig. 7** Effects of latency on beamforming: histogram across four data streams (a) and corresponding CDFs (b).

CONCLUSION

Accessing the wide bandwidths afforded by mmWaves necessitates the use of adaptive beam steering methods with degraded performance in a mobile environment due to latency. To assess the performance impact for realistic scenarios, an eMBB use case in a dynamic urban scene is employed using ray tracing simulations to provide a time dependent deterministic channel model for analysis.

The impact from latency alone, evaluated here, can be significant, resulting in a 5 to 8 dB loss in SINR for feasible parameters. The quantitative impact of other effects of mobility on the communications link, such as Doppler shifts which introduce ICI, have not been included here and will further degrade performance. All such effects, however, can be calculated deterministically using, as input, time dependent CIRs constructed from the ray tracing simulations. Ray tracing simulations can provide the foundation for the accurate evaluation of link performance in a mobile environment incorporating all effects which act to degrade service quality. ■

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EuMIC	£330	£110	£460	£150	£460	£150	£640	£210
EuRAD	£290	£100	£410	£140	£410	£140	£570	£200
2 Conferences	Standard	Student/Sr.	Standard	Student/Sr.	Standard	Student/Sr.	Standard	Student/Sr.
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EuMC + EuRAD	£570	£220	£800	£300	£800	£300	£1,120	£430
EuMIC + EuRAD	£490	£210	£690	£290	£690	£290	£970	£410
3 Conferences	Standard	Student/Sr.	Standard	Student/Sr.	Standard	Student/Sr.	Standard	Student/Sr.
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	Date	Delegates*	All Others**	Delegates*	All Others**
Automotive Forum	14th February 2022	£240	£290	£330	£390
Beyond 5G Forum	17th February 2022	£60	£70	£80	£90
Defence, Security & Space Forum	16th February 2022	£20	£60	£20	£60
European Microwave Student School	14th February 2022	£40	£40	£80	£80
Tom Brazil Doctoral School of Microwaves	14th February 2022	£40	£40	£80	£80

* those registered for EuMC, EuMIC or EuRAD   ** those not registered for a conference

Workshops and Short Courses

Despite the organiser's best efforts to ensure the availability of all listed workshops and short courses, the list below may be subject to change. Also workshop numbering is subject to change. Please refer to www.eumw2021.com at the time of registration for final workshop availability and numbering.

Sunday 13th February 2022			
WS01	EuMC	Full Day	Advances of wireless sensing in harsh and severe environments
WS02	EuMC/EuMIC	Full Day	Terahertz device, circuit and system fundamentals and applications
WS03	EuMC	Full Day	mmWave Plastic Waveguide High Data Rate Communication
WS04	EuMC	Full Day	New trends in microwave and mmWave filters
WS05	EuMC	Full Day	On-chip and scalable RF packaging solutions with integrated antennas for 5G mmWave and 6G applications
WS06	EuMC/EuMIC	Full Day	Progress and status of Gallium Nitride monolithically microwave integrated circuits
WS07	EuMC	Half Day AM	RF reliability status and challenges for 5G mmWave and 6G applications
WS08	EuMC	Full Day	Technology for RF 5G and satcom: from material to packaged demonstrators
WS09	EuMC	Full Day	Research in power and S-parameters measurements at mmWave and terahertz frequencies
SS01	EuMC	Half Day PM	Advanced non-linear characterization and design of highly efficient power amplifiers using load pull data for sub 6GHz and mmWave applications
SS02	EuMIC	Full Day	Fundamentals of microwave PA Design
SS03	EuMC	Half Day PM	5G mmWave OTA measurements – best practices for fast and reliable results
SS04	EuMC	Half Day AM	Terahertz technology, instrumentation and applications
Monday 14th February 2022			
WM01	EuMC	Half Day PM	Optimizing modulation quality measurements on wide bandwidth signals – from conformance through R&D
WM02	EuMC/EuMIC	Full Day	Advances in circuits and systems for mmWave radar and communication in silicon technologies
WM03	EuMC	Full Day	Sensing, imaging and biological tissues characterization using microwaves and mmWaves
WM04	EuMC	Full Day	RF on-wafer calibration and measurement eco-system workshop
WM05	EuMC	Half Day AM	Novel technologies for emerging on-board microwave equipment based on surface mounted electromechanical relays
WM06	EuMC	Full Day	Recent developments in wireless power transfer and energy harvesting
WM07	EuMC	Half Day AM	Beyond 5G: mmWave and terahertz techniques of 6G research
SM01	EuMC	Half Day AM	R&D trends and challenges in RFPAs for medium/high-volume products
SM02	EuMC	Half Day PM	Intuitive microwave filter design with EM simulation
SM03	EuMC	Half Day PM	Phase-noise in next-generation aerospace/defense and commercial wireless communications
SM04	EuMC	Half Day PM	Solid-state microwaves applications in industrial, scientific and medical fields
Wednesday 16th February 2022			
WW01	EuMC/EuMIC	Full Day	Technologies for 6G FEMs
WW02	EuRAD	Full Day	Virtual validation of automotive sensors
SW01	EuRAD	Half Day AM	Joint range-angle superresolution MIMO radar
SW02	EuRAD	Half Day PM	Radar design from the ground up
Thursday 17th February 2022			
WTh01	EuRAD/EuMC	Half Day AM	Advances in drone antenna measurement techniques for Satcom and RADAR applications
Friday 18th February 2022			
WF01	EuMC	Half Day AM	Advanced manufacturing and packaging
WF02	EuRAD	Half Day PM	Paradigm change in automotive mm-Wave radar applications – from technology push to demand pull
WF03	EuMC	Full Day	Innovative THz technologies for imaging, radar and communication
WF04	EuRAD	Full Day	Advanced processing and deep learning approaches for indoor sensing using short-range radars
SF01	EuMC	Half Day AM	AI techniques for microwave antenna and filter design: from theory to practice
SF02	EuMC	Half Day AM	Microwave superconductivity: applications of SQUID and Josephson junctions in microwave circuits

WORKSHOPS AND SHORT COURSES	IN COMBINATION WITH CONFERENCE REGISTRATION				WITHOUT CONFERENCE REGISTRATION			
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	Standard	Student/Sr.	Standard	Student/Sr.	Standard	Student/Sr.	Standard	Student/Sr.
Half Day	£90	£60	£110	£90	£110	£90	£150	£110
Full Day	£120	£90	£160	£120	£160	£120	£220	£160

Sidecar Module Enables RF Reliability Testing at Ka-Band

Accel-RF's mmWave Sidecar module was designed to be combined with the company's characterization platform and RF fixtures to create a single-channel, "oven-ized" RF test chamber. The Sidecar module provides frequency up-conversion, amplification and gain control for RF life testing at mmWave frequencies. Made for the Ka-Band satcom and 5G bands, the Sidecar is available in "micro" bands from 26 to 40 GHz.

Integrating the Sidecar module with Accel-RF's characterization platform yields a compact benchtop system for reliability testing, including RF measurement and thermal characterization, such as infrared or thermoreflectance. The combination provides an independent single-channel unit or it can be combined with additional units to form a multi-channel test subsystem.

Using the Accel-RF LifeTest or USBControl programs, the reliability test platform is controlled via USB to set the bias, temperature and RF input signal to a device undergoing reliability testing. The standard RF drive level is +20 dBm, with an SSPA option available to increase the drive to +35 dBm, depending on the frequency band chosen. The Sidecar has an integrated Ka-Band coupler for precise input signal monitoring and provides a gain control voltage of 0 to +10 V and ±15 V bias.

Since 2003, Accel-RF has developed RF and power semiconductor reliability test systems, recognized for its expertise with reliability testing methodologies and RF component reliability testing. Accel-RF's equipment has facilitated wide industry adoption of compound semiconductors for the space, military and commercial wireless markets, supplying reliability test systems to many semiconductor manufacturers in the U.S., Europe and Asia. Now part of STAr Technologies, Accel-RF is the only provider of fully integrated, scalable, turnkey systems for dynamic, multidimensional, RF, DC and temperature testing on a single platform. Accel-RF helps companies reduce development time, ensure reliability and reduce business risk.

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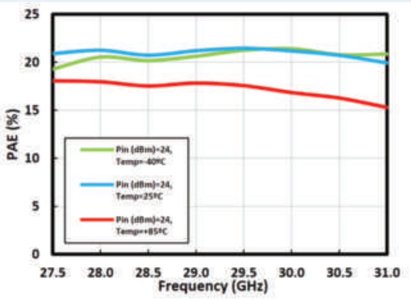

Linear, Ka-Band GaN on SiC MMIC for Satcom Terminals

Microchip Technology has released its first GaN power amplifier (PA) MMIC delivering 10 W saturated output power from 27.5 to 31 GHz. The ICP2840 MMIC was designed for commercial and defense satellite communications (satcom), 5G networks and other aerospace and defense systems operating at Ka-Band. The PA MMIC enables designers to meet high-power specifications while reducing power consumption and system weight.

Fabricated using a GaN on SiC process, the three-stage MMIC achieves 22 percent power-added efficiency at 10 W output, when biased at 24 V, and 22 dB small-signal gain. The PA supports complex modulation, such as 256-QAM, and reduces power consumption more than 30 percent compared to GaAs MMICs, capabilities particularly important for satcom equipment. Microchip's customers have confirmed the ICP2840's suitability for linear applications when backed off. The balanced architecture of the design is well-matched to 50 Ω, achieving 15 dB return loss across the band. The design integrates DC blocking capacitors at the output to simplify integrating the PA into the next higher assembly. The size of the chip is 3.0 x 3.4 x 0.10 mm.

To help with design-ins, Microchip and its distribution partners provide design support for the ICP2840, including an evaluation board and models for simulating system performance.

The ICP2840 GaN MMIC complements Microchip's portfolio of GaN on SiC transistors for radar systems, GaAs MMIC PAs, low-noise amplifiers, switches and Wi-Fi front-end modules.

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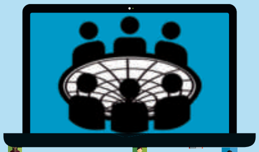

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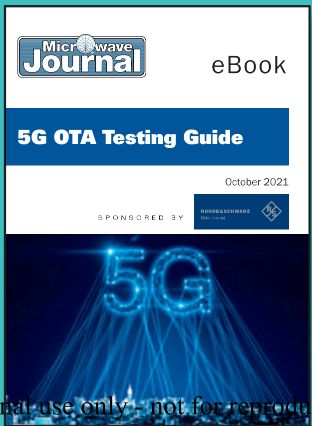

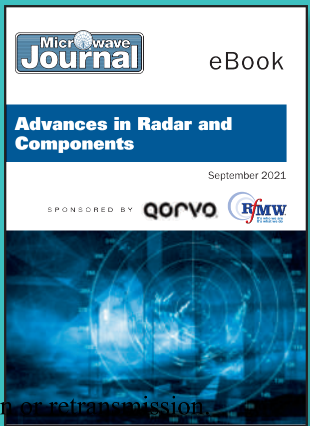

MAKING WAVES

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With the launch of the new website, users can view products by market or application, calculate mmWave array size with their array calculators and view new products and capabilities.

Anokiwave
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This blog post includes a hands-on video demonstration of APITech's new multipath emulator, enabling clients to test the functionality of Wi-Fi devices in a true multipath environment.

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Website Redesign for ET Industries

ET Industries has launched a new website that includes detailed features for broadband microwave RF power dividers, GHz directional couplers, 90- and 180-degree couplers, stripline and lumped element, MIMO antenna and a streamlined process for request for quotation.

ET Industries
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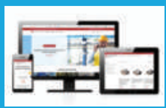

RCD Components Unveils New Logo & Website

RCD Components launched a refreshing new logo and a revamped website targeting the needs of electronic design engineers. The site offers extensive information on resistors, easy navigation and a design to enhance user experience.

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RFMW
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Spectrum M2p.7515 Digital I/O Card Video

The release of the new Digital I/O card M2p.7515 from Spectrum Instrumentation offers engineers and scientists a cost-effective way to generate and acquire fast digital signals for e.g. logic analysis or pattern generation.

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Tabor Electronics
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Reel Times: Low PIM

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Times Microwave
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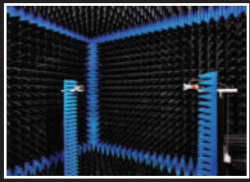
MAKING WAVES

RFspin Releases New Anechoic Chamber



Impulse announces the release of RFspin's new anechoic chamber, equipped with modern technology and absorbers ensures highly accurate measurements up to 120 GHz.

Impulse Technologies Inc. **www.impulse-tech.com**

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Menlo Micro's First Switch Summit

Menlo Micro's lead systems applications engineer, Stewart Yang, discusses how their unique IdealSwitch™ technology is critical in designing a single-slot 16-channel RF multiplexer for PXI systems, presented during Menlo's first virtual Switch Summit. All summit sessions are available to view on their website.

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Model series 352-210-XXX*, a line of 50 Ω fixed attenuators, rated 2 W average power with 1.40:1 maximum VSWR. The operating frequency range is DC to 2500 MHz, attenuation values are 1 to 40 dB, the operating temperature range is -55°C to +100°C and the RF connectors are N female/N female. Useful for analyzing harmonic signals or isolating a device under test, these attenuators reduce the amount of power delivered in a transmission line without introducing much noise or distortion.

BroadWave Technologies Inc.
www.broadwavetechnologies.com

60 dB Digital Attenuator

COMTECH PST Component Division introduced a new digital attenuator for applications in UHF band. The design operates over the 400 to 500 MHz frequency range intended for use in military or commercial applications. The attenuator provides 0 to 60 dB of range. The accuracy achieved is exceptional when changing attenuator steps. Switching speed is very fast when attenuation needs to be changed. Other frequencies, attenuation ranges and performance characteristics can be achieved for other applications.

COMTECH PST
www.comtechpst.com

Power Dividers

Electromagnetic Technologies Industries Inc. (ETI) offers advanced power dividers and combiners for all microwave engineering needs. These power dividers have frequencies that range from 0.3 GHz up to 67 GHz with high isolation and low insertion loss. Design package can support SMA, K, 2.4 mm, 1.85 mm and N-type connectors. Power dividers are available in: 2-way/3-way/4-way/6-way/8-way/12-way/16-way/64-way/128-way. Please contact sales1@etiworld.com for more information.

Electromagnetic Technologies Industries, Inc.
www.etiworld.com

EM Switches

VENDORVIEW

Fairview Microwave Inc. has debuted a new line of micro-sized, surface-mount, single pole, double-throw, electromechanical relay switches with broadband performance that are ideal for a wide range of applications involving high-power, switch matrices and test and measurement systems. Fairview Microwave's new series of SPDT electromechanical relay switches includes six models with popular latching actuators in micro-size surface-mount packages. These switches deliver impressive performance with low insertion loss, high isolation and excellent repeatability.

Fairview Microwave Inc.
www.fairviewmicrowave.com

Butler Matrices

MIcable's 0.6 to 5 GHz and 2 to 8 GHz 4×4 and 8×8 wideband butler matrices cover 5G NR (FR1) and Wi-Fi 6E, the whole frequency band application in one unit respectively. Because the high performance passive components and cables are used inside, the system has super phase accuracy, amplitude balance, stability and repeatability and can produce the accurate beamforming. The applications include 5G NR (FR1), Wi-Fi, IoT, UWB, etc., chips, modules and system test.

Fujian MIcable Electronic Technology Group Co. Ltd.
www.micable.cn

mmWave Controlled Components

General Microwave Corp. is a key partner with major OEMs and primes, having been chosen for their broad and comprehensive understanding of mmWave controlled components. General Microwave offers a wide range of mmWave products operating in the 18 to 40 GHz frequency range including catalog attenuators, switches and phase shifters as well as integrated microwave assemblies. If it's a standard catalog unit or a highly customized mmWave product designed specifically for high performance, General Microwave can provide products to support your requirements.

Kratos/General Microwave Corp.
www.kratosmed.com

Digital Attenuator

VENDORVIEW

Mini-Circuits' model ZX76-50G-30-V+ is a 50 Ω digital step attenuator with attenuation range of 0 to 31.5 dB from 0.1 to 50.0 GHz. Its 6-b parallel control adjusts attenuation in 0.5 dB steps with typical switching speed of 330 ns. The attenuator operates with single (+3.3 V) or dual (+3.3, -3.0 V) power supplies and typical VSWR of 1.50:1. The RoHS-compliant attenuator is equipped with female 2.4 mm connectors and can handle input power levels as high as +28 dBm. It is well suited for communications, electronic warfare and test systems.

Mini-Circuits
www.minicircuits.com

Custom Capacitor Assemblies

Passive Plus Inc. (PPI) offers custom capacitor assemblies for high power requirements. Typical assemblies are configured in series and/or parallel combinations, producing higher voltage/current handling capabilities, extended capacitance range and tighter tolerances. PPI works with requesting engineers to determine best assembly for their applications. All assembly components receive 100 percent partial discharge and 100 percent sonoscan for internal defects prior to assembly. Final assemblies then receive 100-hour burn-in, assuring highest quality and reliability.

Passive Plus Inc.
www.passiveplus.com

Ultra-Broadband Dividers

Response Microwave Inc. announced the availability of its new broad band 2-way power divider for use in ATE and production 5G applications. The new RMPD2.1-40.292f covers the 1 to 40 GHz band offering typical electrical performance of 1.2 dB maximum insertion loss, VSWR of 1.70:1 maximum and minimum directivity of 15 dB. Power handling is 20 W and the unit is operational over the -55°C to +125°C range.

Response Microwave Inc.
www.responsemicrowave.com

NewProducts

Miniature Coaxial Switches

This RLC Electronics' miniature coaxial switch is a single pole, two position type. The switch provides extremely high reliability, long life and excellent electrical performance characteristics over the frequency range of DC to 65 GHz. The miniature package utilizes high density packaging techniques, hence the overall volume of the switch is less than 3/4 cubic inch.

RLC Electronics
www.rlcelectronics.com

TSX Fixed Chip Attenuators

VENDORVIEW

Smiths Interconnect announced the release of its new TSX Series of fixed chip attenuators optimized to combine high frequency and power in a small package. The new TSX Series is designed to offer excellent broadband performance up to 50 GHz, while delivering increased power handling in a small 0604 surface-mount package. It allows wider coverage than traditional components while providing optimized return loss for multiple frequency ranges.

Smiths Interconnect
www.smithsinterconnect.com

QUAD Band Combiner

Tamagawa announced the new quad band combiner support GSM/WCDMA/LTE systems including 700/900/1800/2600 MHz. In the indoor base station system, usually additional ports from RRU/RRH are required to implement new frequencies. Quad band combiner is an antenna, and its duplexer shares four frequencies with high isolation band to band. This product is equipped with one output port and four input ports in a 19-inch 1U rack air-cooled.

Tamagawa Electronics Vietnam Co. Ltd.
www.tmeleus.com

Automotive Grade IHLP® Inductor

Vishay Intertechnology Inc. expanded its offering of high temperature automotive grade IHLP® low profile, high current inductors with a new device in the 2020 case size. The Vishay Dale IHLP-2020CZ-8A combines a high continuous operating temperature to +180°C with a low profile of 3 mm to save space in under the hood automotive applications. The AEC-Q200 qualified device is optimized for energy storage in DC/DC converters up to 2 MHz.

Vishay Intertechnology Inc.
www.vishay.com

CABLES & CONNECTORS

Coax Cable Assemblies

NAI, a designer and manufacturer of custom interconnect solutions which deliver power and signals to monitor data, connect people and keep equipment operating, continues its introduction of new standard interconnect products under the STEADY LINK™ brand with the launch of a new line of Series-C LMR* 240 and 400 coaxial cable assemblies. Series-C coax jumpers are designed to address the dramatic increase in the use of mobile devices by providing interconnect solutions to service 4G LTE and 5G wireless and industrial network applications.

NAI Group
www.nai-group.com

Low-PIM Cable

VENDORVIEW

Pasternack has recently expanded its ever-growing line of low-PIM coaxial cable assemblies using Pasternack's Super Flex cables, as well as popular cable offerings from Times Microwave that are ideal for use in wireless infrastructure installations, distributed antenna systems and other low-PIM applications. These new

cables are available in standard and custom lengths with same-day delivery. Pasternack's expanded offering of low-PIM coaxial cable assemblies consists of over 400 unique configurations that boast PIM levels of less than -160 dBc.
Pasternack
www.pasternack.com

AMPLIFIERS

Wideband LDMOS Transistors

Ampleon has further strengthened its portfolio of advanced yet cost-effective RF power amplifier solutions by announcing the availability of two new wideband amplifier series: the 32 V-rated BLP15M-9Sxxx and the 50 V-rated BLP15H9Sxxx devices. Both families, BLP15M9Sxxx and BLP15H9Sxxx, are based on the company's ninth generation LDMOS and high voltage LDMOS technologies, respectively, and support frequencies of up to 2 GHz. They are capable of both continuous wave and pulsed signal operation, exhibiting elevated levels of stability.
Ampleon
www.ampleon.com

Amplifiers

VENDOR**VIEW**

Exodus AMP2030D-LC, ideal for broadband EMI-Lab, communication and electronic warfare applications. Class A/AB linear design for all modulations and industry standards. Covers 1 to 6 GHz, producing 600 W minimum, 400 W P1dB and 58 dB minimum gain. Excellent flatness, optional monitoring parameters for forward/reflected power, VSWR, voltage, current and temperature sensing for superb reliability and ruggedness. Integrated in a compact 10U chassis weighing approximately 50 kg.
Exodus Advanced Communications
www.exoduscomm.com

Multiband Cellular Power Amplifier

thinkRF H1000A is a discrete, rugged (IP66 rated), portable RF power amplifier for public safety and emergency comms applications. H1000A has +20 W maximum power output and an adjustable gain up to 43 dB. It simultaneously covers mobile wireless frequency bands that occur between 715 MHz to 2.7 GHz. H1000A is a smart RF amplifier. You can monitor and know the true health of the unit and avoid any unexpected issues while conducting your critical mission.
thinkRF
www.thinkrf.com

SOURCES

Dielectric Resonator Oscillator

VENDOR**VIEW**

PMI Model No. TCDRO-12G-CD-1 is a temperature compensated dielectric resonator oscillator with a center frequency of 12 GHz. This model provides a minimum output power of +18 dBm with all spurs held to -60 dBc and harmonics held to -25 dBc. The mechanical tuning frequency is ±10 MHz and the unit has a phase noise of -95 dBc/Hz. The unit requires +15 VDC with a maximum current draw of 200 mA and is supplied with SMA female connectors in a housing that measures 1.80" × 1.00" × 0.50".
Planar Monolithics Industries
www.pmi-rf.com

SOFTWARE

COMPLETE Library™ v21.5

VENDOR**VIEW**

Modelithics announced the release of the latest version, v21.5, of the Modelithics COMPLETE Library for use with Keysight Technologies' PathWave Advanced Design System (ADS). The Modelithics COMPLETE Library now contains over 800 highly scalable Microwave Global Models™, behavioral models, complex equivalent

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	(2) Mailed In-County Paid Subscriptions Stated on PS Form 3541 (include paid distribution above nominal rate, advertiser's proof copies and exchange copies)	0	0
	(3) Paid Distribution Outside the Mails Including Sales Through Dealers and Carriers, Street Vendors, Counter Sales, and Other Paid Distribution Outside USPS®	6,300	6,326
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	(2) Free or Nominal Rate In-Country Copies Included on PS Form 3541	0	0
	(3) Paid Distribution Outside the Mails Including Sales Through Dealers and Carriers, Street Vendors, Counter Sales, and Other Paid Distribution Outside USPS®	0	0
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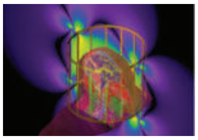
IPS Form 3526, September 2007 (Page 2 of 3)

circuit models and advanced non-linear models that represent over 24,000 passive and active components. Designers everywhere can take advantage of this extensive collection of simulation models for RF/microwave devices that includes surface-mount RLC components, diodes transistors, amplifiers, attenuators, filters, couplers and more.

Modelithics
www.modelithics.com

Transient EM/Circuit Co-Simulation

VENDORVIEW



Remcom announced an update to XFdtd® 3D EM Simulation Software, with transient EM/circuit co-simulation for electrostatic discharge (ESD) testing and support for transient voltage suppressor diodes and spark gaps. XFdtd contains a number of features for simulating the ESD testing process, allowing engineers to pinpoint components susceptible to ESD damage and optimize ESD mitigation prior to trial-and-error testing on a physical prototype.

Remcom Inc.
www.remcom.com

ANTENNAS

uRAD with 3D Printed Lens

Impulse Technologies is supplying U.S. customers with Anteral's new product for the industrial market. The product consists of a PLA 3D printed lens that fits directly over the uRAD Industrial PCB product. With the added lens, it achieves a reduction of the field of view from 160 degrees to less than 10 degrees, which makes it ideal for frontal detection applications. The application range is huge: from altimeter use to level sensor. The specific software is also included with the purchase.

Impulse Technologies Inc.
www.impulse-tech.com

Half Wave Dipole Antenna

VENDORVIEW

RFMW announced design and sales support for a Southwest Antennas' omni-directional antenna. The 1001-259 half wave dipole operates from 1.4 to 1.6 GHz with a peak gain of 2.0 dBi. Identical to the existing 1001-078 fixed based antenna, the 1001-259 adds an integrated, flexible, coil spring base which provides strain relief and impact deflection capability, thereby reducing the risk of damage if struck by another object. Both the antenna and mated RF radio connectors are protected.

RFMW
www.rfmw.com

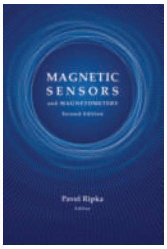
TEST & MEASUREMENT

Avionics Testing

VENDORVIEW

Spectrum Instrumentation has an exciting new application note that explains how to use the company's 200+ products for testing avionics. Learn about the way multi-channel data acquisition and signal generation instruments can be used to check and troubleshoot an aircraft's data communications, power distribution and RF processing systems. Modular instruments, be they PCIe, PXIe or LXI, offer many advantages for testing the essential data and power buses in commercial and military aircraft.

Spectrum Instrumentation
www.spectrum-instrumentation.com



Magnetic Sensors and Magnetometers, Second Edition

Pavel Ripka

This second edition of an *Artech House* classic covers industrial, space and biomedical applications of magnetic sensors and magnetometers. With advances in smart grids, renewable energy resources and electric vehicles, the importance of electric current sensors has increased, and the new edition reflects these changes. Integrated fluxgate single-chip magnetometers are presented. GMR sensors in the automotive market, especially for end-of-shaft angular sensors, are included, as well as linear TMR sensors. Vertical Hall sensors and sensors with integrated ferromagnetic concentrators are two competing technologies, which enable three-axial single-chip Hall ICs, are considered. Digital fluxgate magnetometers for both satellite and ground-based applications are discussed. All-optical resonant magnetometers, based on the coherent population trapping effect, have been approved for space applications and are covered in this new edition.

Whether you're an expert or novice, this unique resource offers you a thorough overview of the principles and design of magnetic sensors and magnetometers, as well as guidance on applying specific devices in the real world. The book covers both multichannel and gradiometric magnetometer systems, addresses special problems such as crosstalk and cross-field sensitivity, and compares different sensors and magnetometers for various applications. Miniaturization and the use of new materials in magnetic sensors are also discussed. A comprehensive list of references to journal articles, books, proceedings and webpages helps you find additional information quickly.

To order this book, contact

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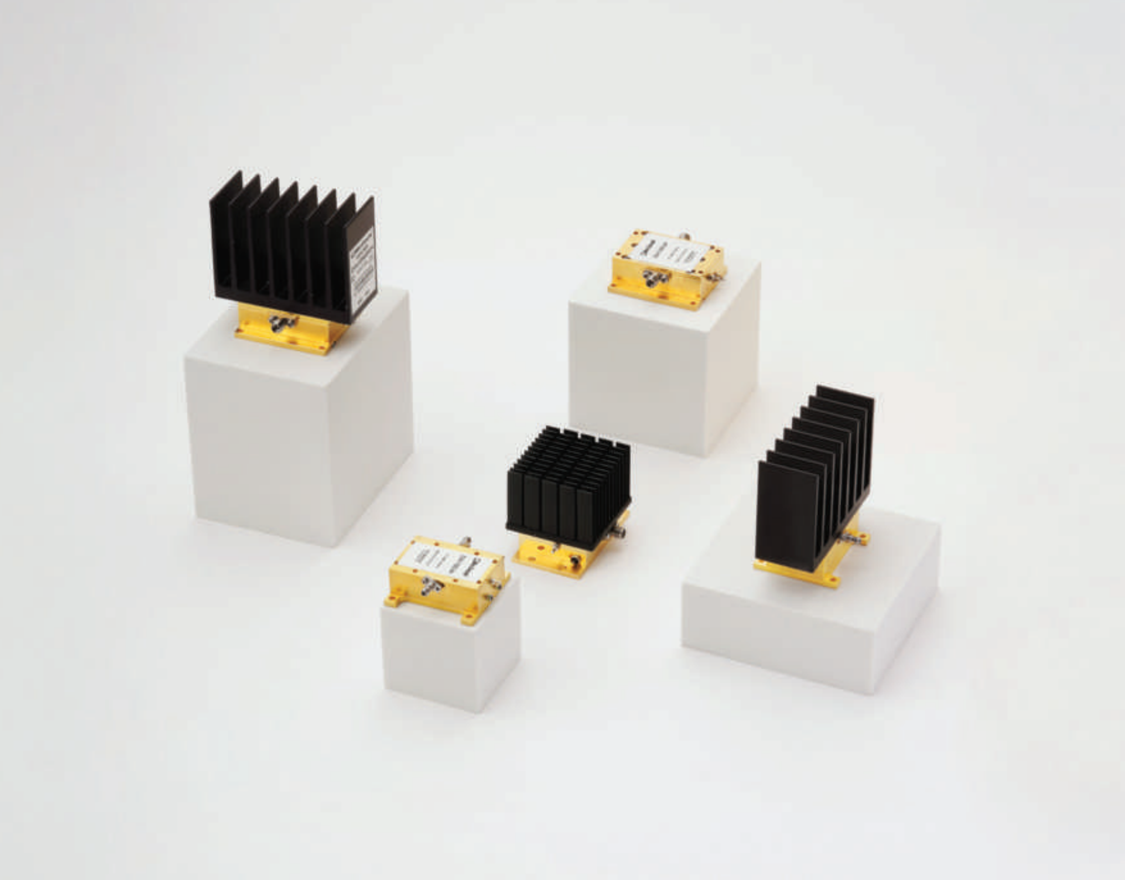


FABS and LABS

Filtronic's Salisbury Site Adds Capacity and Capability for Domestic Production of RF Products for Critical Communications

Filtronic is a company with a strong commitment to in-house manufacturing, and its Salisbury, Md., facility is no exception. The Filtronic site in Salisbury recently expanded production capacity to meet a growing demand for its public safety products, in addition to steady business for the range of filters and combiners it was already making, which operate up to 18 GHz. The Maryland area has a considerable pool of RF expertise, home to both the Goddard Space Flight Center and the Naval Research Center in Chesapeake Bay, as well as other local communications experts. Filtronic's site was well-placed to recruit staff to support the growth in output.

The 16,000 square-foot facility had ample space to accommodate the extra warehousing and assembly area to produce additional products. Of this floor area, 5,000 square feet is devoted to handling ESD sensitive components, all temperature-controlled. The on-site services include assembly and test, repair, equipment build up (rack, stack and commissioning) and drop-shipping.

The expansion was largely prompted by U.S. equipment manufacturers shortening supply chains to make them more resilient in the wake of the COVID-19 pandemic. Where possible, these companies are choosing domestic suppliers for products they previous imported from or manufactured offshore. The trend for supply chain rationalization has provided a competitive advantage for Filtronic, which successfully "re-shored" from China the manufacturing of a critical communications product, helping a leading client in the public safety market meet its supply chain goals.

The need to bring critical product assembly to Salisbury from the offshore facility, to reduce equipment lead-times in the face of the changing geopolitical landscape, was a challenge requiring a rapid response from Filtronic. Using the company's technical knowhow, local knowledge and a cloud-based manufacturing execution system, Filtronic managed this complex transition smoothly and efficiently, meeting the customer's six-month schedule.

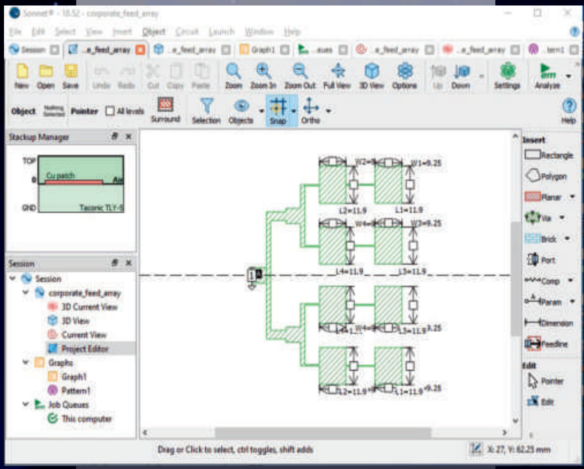
As well as realigning its operational facilities and processes, Filtronic was able to recruit local personnel who had previous experience with public safety product assembly. Additional equipment was procured and re-allocated to quickly replicate the production line at the former facility. While doing so, it was also possible to make product and process improvements, including the workflow and logistics, which yielded a significant reduction in lead time for these critical communications products.

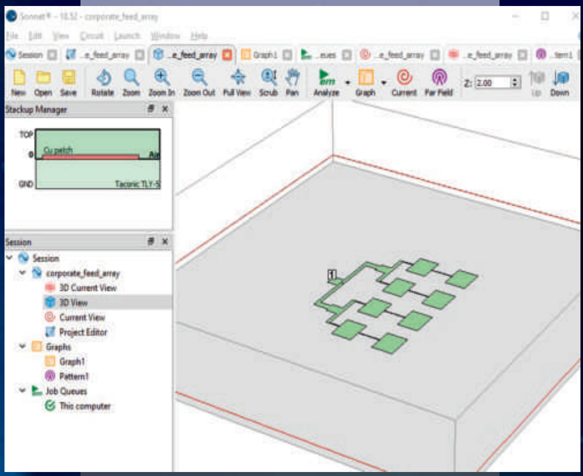
The transition was smooth, rapid and met the customer's quality standards, passing an extensive and rigorous customer audit, which enabled timely re-certification. Filtronic's customer met its country-of-origin targets without any drop in production.

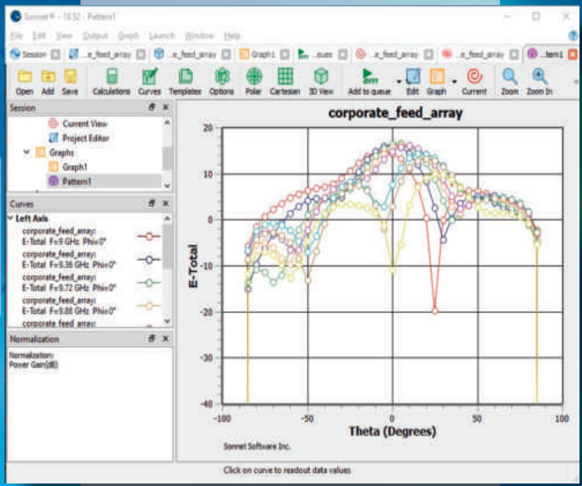
Another recent achievement for Filtronic was successfully developing a customized tower top amplifier (TTA) system. Manufactured in Salisbury, this project exceeded the customer's expectations for both performance and time to completion, as well as reducing the order-to-shipment time by 50 percent.

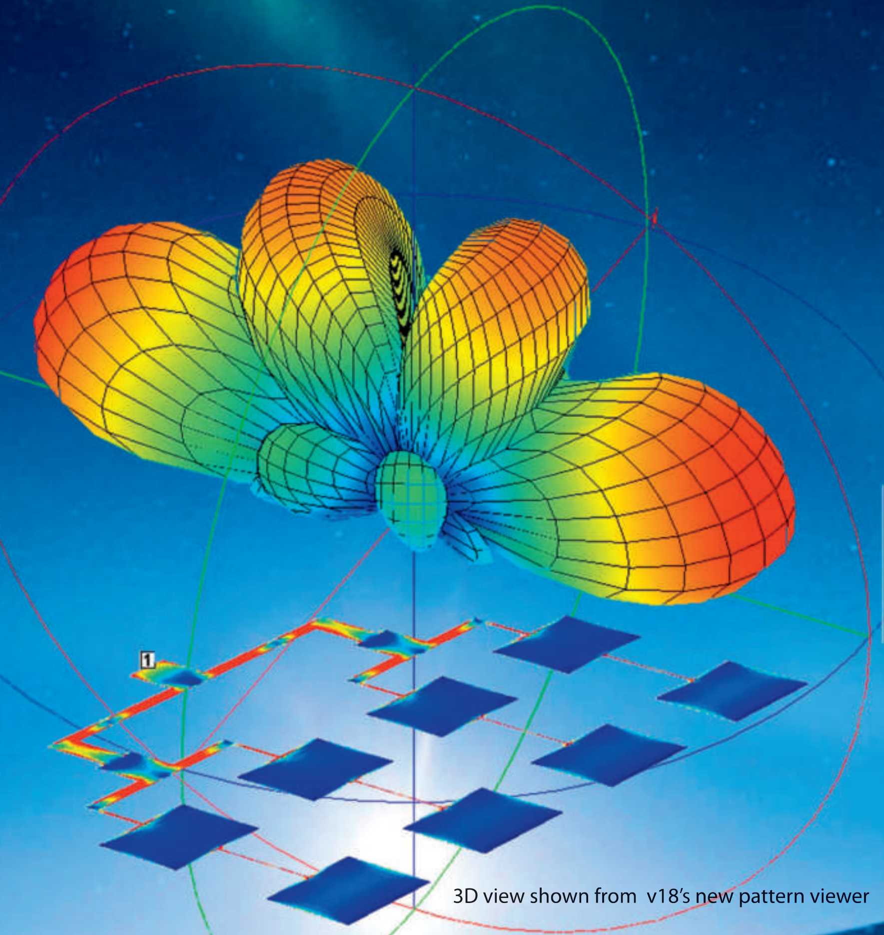
Because of product obsolescence and technological advancements, Filtronic's customer needed a new domestic supplier for TTAs, as its existing supply chain was unable to meet the challenging specification. It turned to Filtronic due to its experience supplying Tower Mounted Amplifiers for commercial telecoms. The project included product enhancements, such as more consistent performance between sites and simpler installation. It was completed—from inception through product qualification—in less than six months. The new TTA meets the existing specification and delivers all the desired performance improvements, including smart redundancy. The client's goals of reducing inventory and the order-to-shipment time to two weeks—compared to the industry standard of four weeks—were also met.

www.filtronic.com







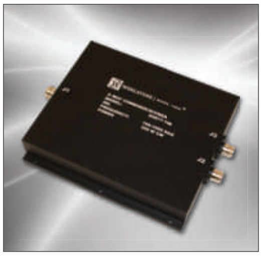


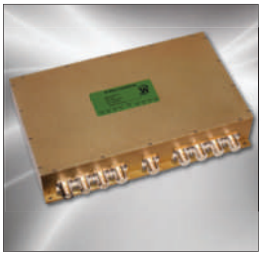
3D view shown from v18's new pattern viewer

WERLATONE®

Mobile Communications ✦ MRI / NMR ✦ Satellite Radio ✦ In-Building DAS

- **Werlatone Offers a Full line of RF Combiners, Dividers & Directional Couplers.**
- **Werlatone specializes in Commercial Transit Communication Systems.**
- **Our Solutions Cover Multiple Carrier Frequency Bands between 80 and 2400 MHz.**
- **Designed to Tolerate Extreme Environmental Conditions with IP-65 ratings.**





Even Isolated & Non-Isolated Combiners/Dividers

Model	Type	Frequency (MHz)	Power (W CW)	Isolation (dB)	Insertion Loss (dB)	Connectors	Size (inches)
D5875	4-Way	80-1000	150	Non-Isolated	0.80	N-Female	8.5 x 7.5 x 1.5
D7142W	2-Way	100-500	100	20	0.40	N-Female	4.4 x 4.3 x 1.29
D2542	2-Way	120-470	100	Non-Isolated	0.30	N-Female	2.5 x 1.75 x 1.5
D6295	2-Way	150-500	100	Non-Isolated	0.30	N-Female	1.75 x 1.75 x 1.5
D5877	2-Way	150-1000	350	Non-Isolated	0.50	N-Female	8.38 x 7.55 x 1.5
D5876	3-Way	150-1000	350	Non-Isolated	0.65	N-Female	8.38 x 7.55 x 1.5
D5944	4-Way	150-1000	350	Non-Isolated	0.70	N-Female	8.38 x 7.55 x 1.5
D5543	3-Way	400-470	100	Non-Isolated	0.20	N-Female	4.75 x 2.0 x 1.88
D6748	4-Way	470-860	250	18	0.35	N-Female	6.0 x 5.0 x 2.0
D5906	4-Way	470-860	500	15	0.40	N-Female	6.0 x 5.0 x 2.0

Uneven Splitters (Taps) & Directional Couplers

Model	Type	Frequency (MHz)	Power (W CW)	Coupling (dB)	Insertion Loss (dB)	Connectors	Size (inches)
C7141W	Uni	100-500	100	6	0.30	N-Female	7.0 x 5.0 x 1.8
C9270W	Uni	100-1000	100	6	0.60	N-Female	7.05 x 3.3 x 1.2
C8163W	Uni	100-1000	200	6	0.40	N-Female	7.0 x 5.0 x 1.8
C9534	Uni	100-1000	350	6	0.40	N-Female	6.75 x 3.0 x 1.2
C9271W	Uni	100-1000	100	10	0.50	N-Female	7.05 x 3.3 x 1.2
C2541	Tap	120-470	100	10 (Split)	0.75	N-Female	2.5 x 1.75 x 1.5
C6149	Tap	120-470	100	6 (Split)	0.75	N-Female	2.5 x 1.75 x 1.5
C5541	Tap	400-470	100	6 (Split)	0.20	N-Female	4.75 x 2.0 x 1.88
C6755	Dual	470-860	250	40	0.20	N-Female	3.0 x 3.0 x 1.09
C5560	Dual	470-860	500	40	0.10	N-Female	3.0 x 3.0 x 1.09
C6756	Dual	470-860	1000	40	0.20	N-Female	3.0 x 3.0 x 1.09

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