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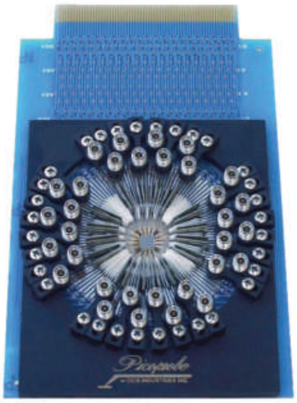

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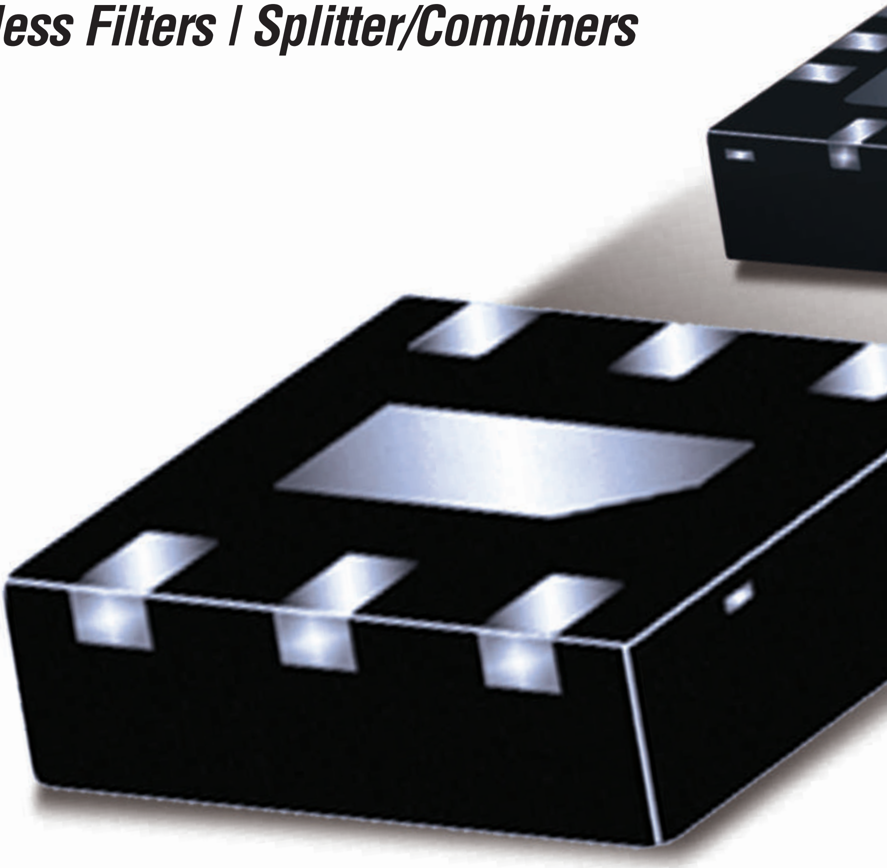

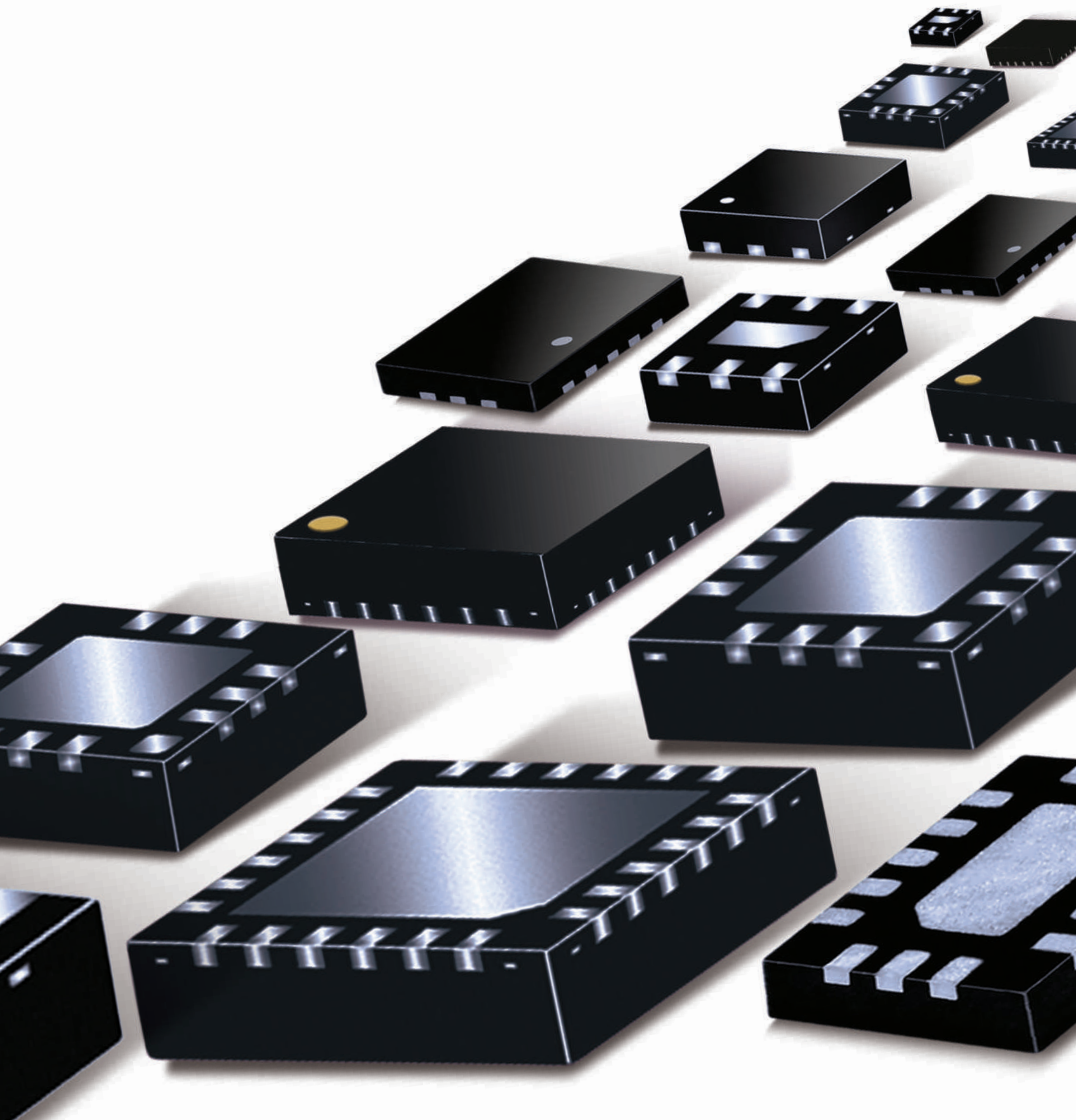

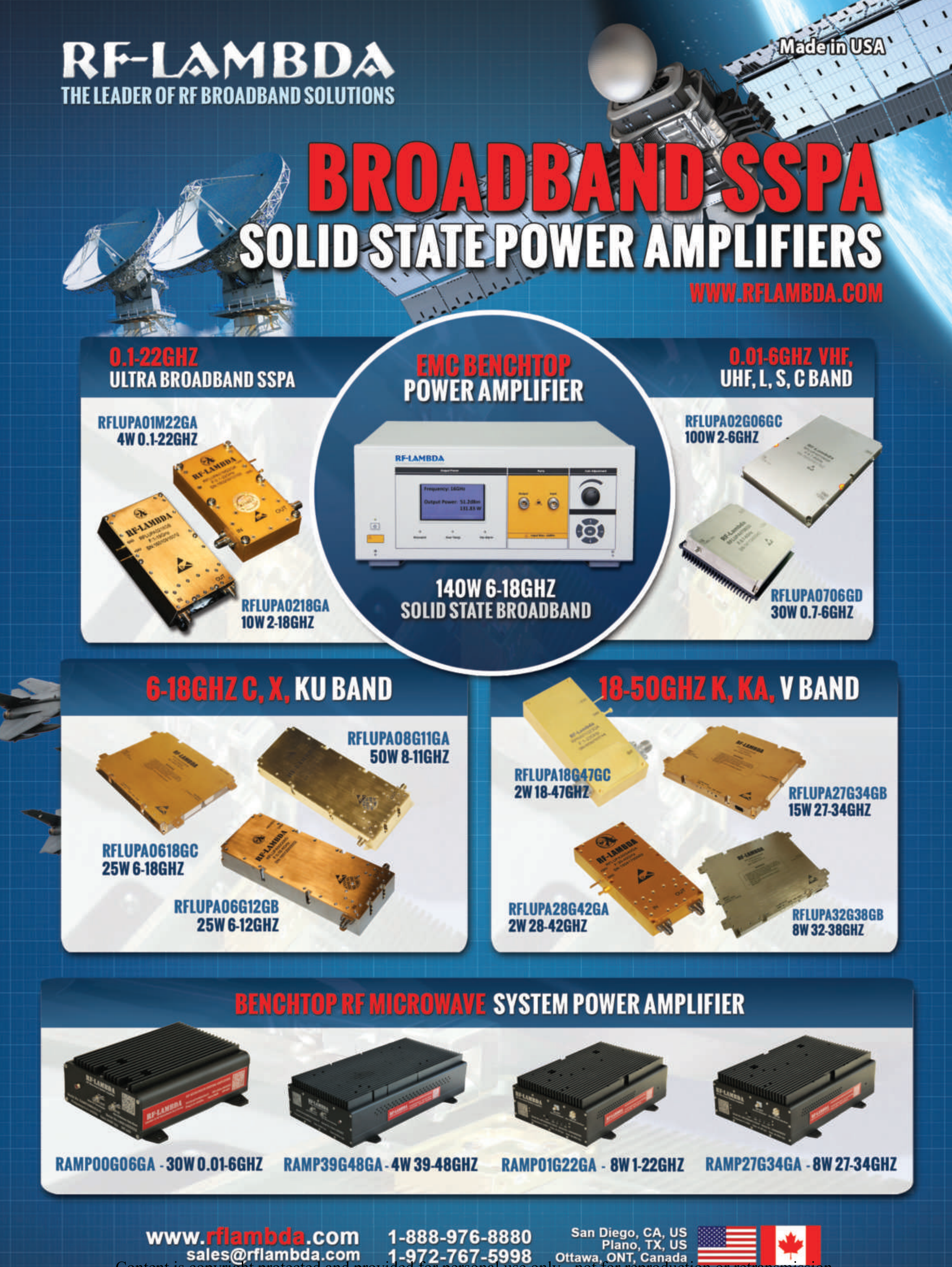
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CONTENTS

February 2019
Vol. 62 • No. 2
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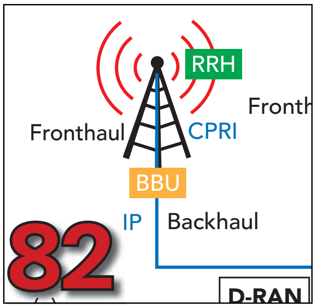

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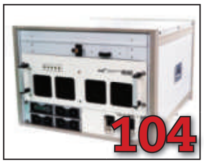

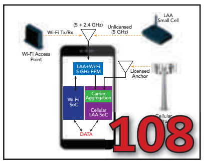

Product Features

Tech Briefs

Departments

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Executive Interview

Bob Donahue, CEO of **Anokiwave**, discusses the company's strategy to develop mmWave silicon ICs and enable a new generation of active phased arrays for commercial markets such as 5G infrastructure and satellite terminals.

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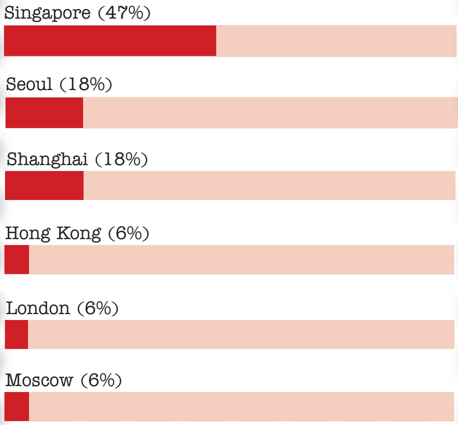

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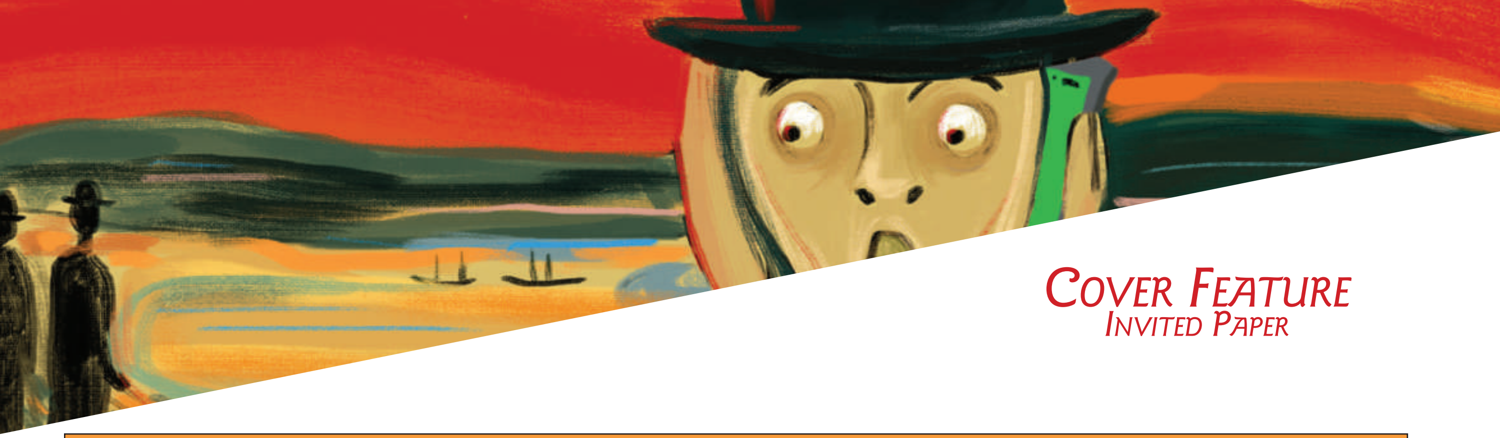

COVER FEATURE
INVITED PAPER

Editor's Note: Timed for the upcoming Mobile World Congress (MWC Barcelona), where the theme will be 5G, this issue of Microwave Journal *features two articles exploring new antenna front-end architectures being developed for 5G. The first, by Gapwaves, describes an active phased array for mmWave infrastructure based on the novel Gapwaves waveguide, which promises high performance, producibility and the capability to integrate mmWave front-end modules—even GaN with its high-power density. The second article, by MACOM, presents a design approach for a sub-6 GHz massive MIMO base station, addressing the size, weight, power dissipation and thermal challenges imposed by capacity, coverage, digital processing and siting constraints.*

Gapwaves Platform Integrates 5G mmWave Arrays

Carlo Bencivenni, Thomas Emanuelsson and Magnus Gustafsson
Gapwaves AB, Gothenburg, Sweden

mmWave systems will have a key role supporting the massive data rates planned for 5G networks. However, unfavorable propagation and technical limitations challenge the feasibility and adoption of such systems. Addressing these challenges, Gapwaves is developing waveguide technology with superior performance over conventional printed circuit board (PCB) solutions, including exceptional efficiency, routing, subarray partitioning, filtering, isolation and thermal handling. With improvements in performance, range, number of components and power consumption, the hardware, deployment and operating costs can be significantly reduced. This article discusses the design principles and results of Gapwaves' demonstration platform, including both passive and active measurements, and the integration of high-power GaN semiconductors to further enable the vision of high performance and cost-effective mmWave systems.

5G, the next-generation mobile network, has a large set of ambitious objectives, leveraging multiple technologies for several different application scenarios.[1] Within those, the 100× increase in network capacity compared to the current 4G network will be the most visible to the consumer. Traditional sub-6 GHz frequencies will continue to be the backbone for ubiquitous connectivity, with a boost in capacity from additional bands and advances in coding. However, such a dramatic increase in data rates heavily depends on massive amount of spectrum: GHz of bandwidth available in the mmWave region at a lower cost per Hz. Regulatory bodies have identified several bands for this, mostly between 24 and 60 GHz.

Moving to the mmWave region raises technical issues. The coverage from a base station is considerably less than that of existing systems, due to large propagation losses and severe shadowing and penetration effects from obstructions by buildings, trees and people. mmWave active components generate low output power with low efficiency, with smaller size creating problems with component and power density. This results in limited transmit power, high power consumption and expensive components. Typically, all components suffer from increased losses with frequency, which can become onerous for planar technologies at high frequencies. Also, satellite and backhaul services coexist in the mmWave region, requiring RF filters to prevent interference, which increases system losses.

Deployment of 5G mmWave systems will be driven by household fixed wireless access (FWA) first, with mobile access later. The success of the former depends on base station coverage; to strengthen the business case in suburban areas, higher inter-site distance (ISD) and equivalent isotropic radiated power (EIRP)

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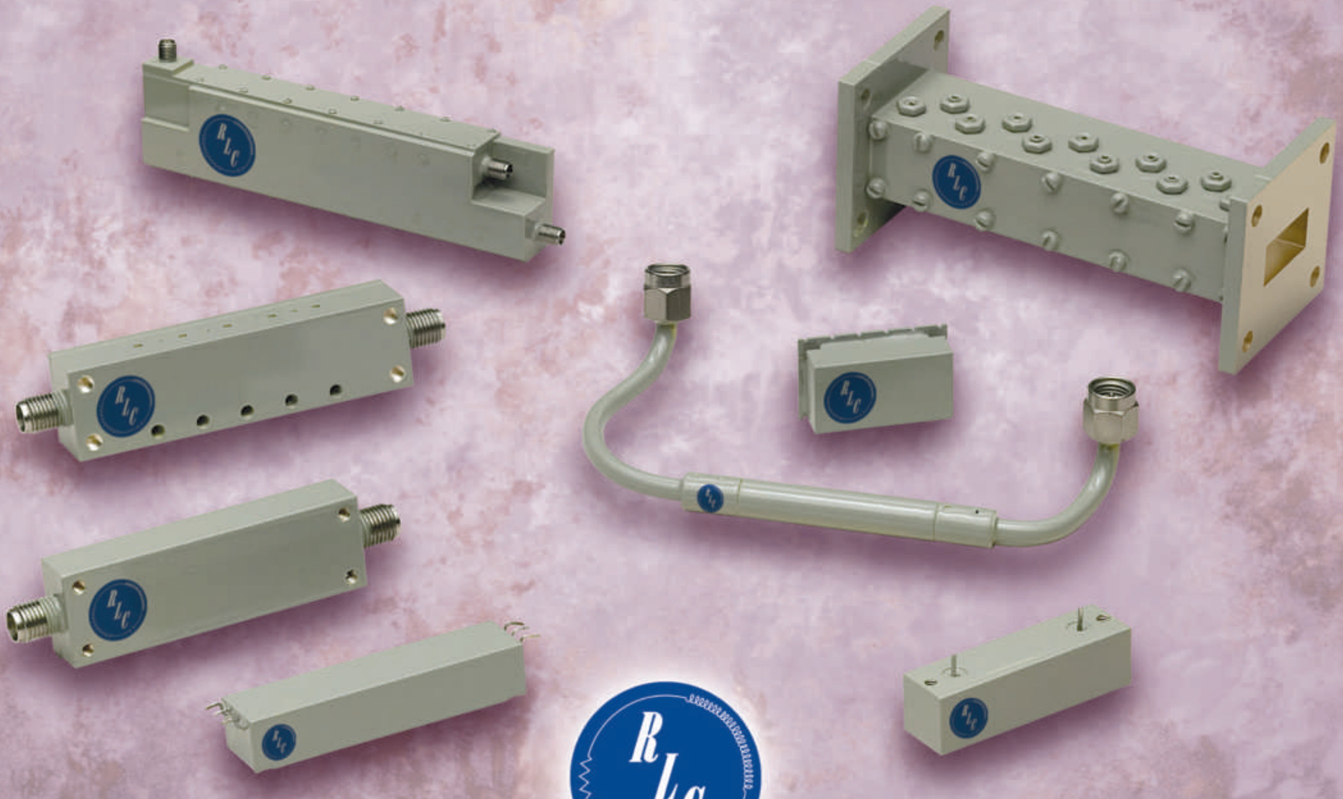

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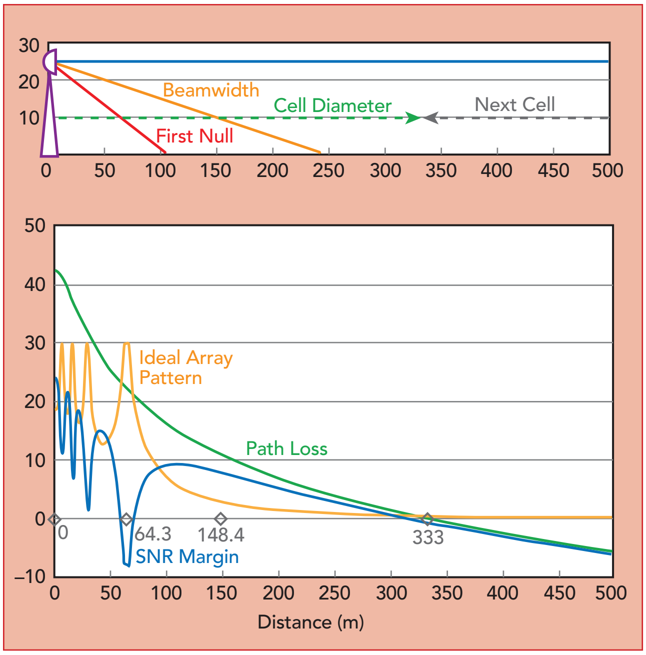

Fig. 1 SNR margin relative to the cell edge for an 8-element vertical subarray with no downtilt and 333 m cell radius.

are needed.[2] Higher EIRP increases capacity in systems with hybrid and digital beamforming, where the additional power can be shared across multiple beams and users.

mmWAVE APPLICATIONS

The industry response to the above challenges has mainly been planning small cell, high capacity coverage. However, while a denser deployment will be unavoidable, the economic feasibility and widespread availability depends on the technical solutions and associated cost. The number of base stations per area determines the cost for equipment, deployment and operation.

Recently, the first demonstration products were released by major telecommunications equipment manufacturers.[3] Most of the current systems are based on integrated PCB antennas, typically with a patch array on the front of the board and active components on the back side. Losses are minimized by vertically routing through the PCB in a one-feed-per-antenna configuration, at the expense of low gain. As a result, achieving high EIRP and downlink coverage are challenging. To partially compensate, a large number of active chains are used, increasing the cost of the system and the power consumption. However, the increased power at the base station, as opposed to the gain, does not help the uplink, which is the hardest leg. The tight integration and high power consumption in a very limited space of a multilayered PCB create thermal handling and complexity issues. Another challenge is integrating filters and their impact on performance, which is substantial at these frequencies. All these limitations ultimately result in poorer performance, reduced range, higher power consumption and increased cost. The solution by some suppliers is to increase the system size, resulting in a large number of expensive components.

Taking a different approach, Gapwaves is focusing on maximizing antenna gain and minimizing feed and filtering losses, to increase system range and performance and increasing component output power. Most importantly, low loss subarrays can be used to increase gain, with the trade-off of reduced elevation coverage, as the beam narrows and grating lobes appear. In real scenarios, however, a user's angular distribution in elevation is extremely limited, especially for suburban FWA with low buildings. As shown in ***Figure 1***, even an 8-element, vertical subarray with no downtilt or elevation scanning provides adequate signal level at all distances for a 500 m ISD (333 m cell radius), despite an elevation beamwidth of about 12 degrees. This is valid as long as no deep notches are present in the elevation pattern.

WAVEGUIDE REVISITED

The primary transmission technologies for microwave applications are metal waveguide and substrate-based PCBs. While the former offers unmatched performance, its bulkiness, cost and complexity have limited applications to niche, high-end markets such as satellite and military. PCBs offer planar, robust, cost-effective solutions with satisfactory performance and, for these reasons, have long been the standard for commercial solutions.

However, both technologies face severe challenges at mmWave frequencies. PCB losses are substantial: at 30 GHz, conventional PCB microstrip lines with high frequency substrates suffer losses in the 10s of dB/m, compared to fractions of dB/m for waveguide. PCB designers must compensate by using premium substrates and minimizing trace lengths; however, as frequencies increase, the losses become overwhelming. Waveguide suffers from increasingly impractical manu-

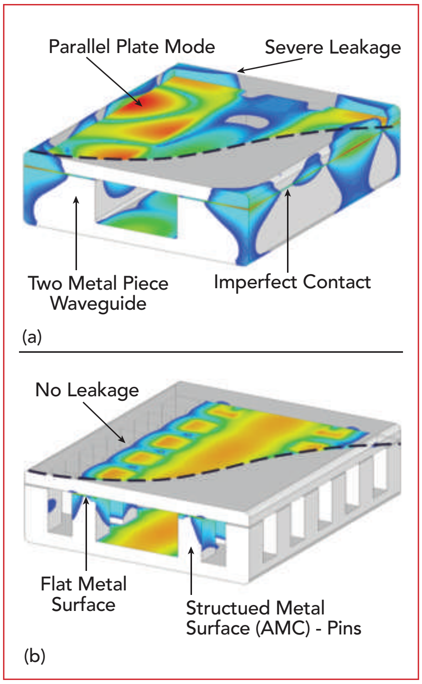

Fig. 2 Imperfect joints in standard waveguide cause leakage and spurious modes (a) compared to the fields in a Gapwaves waveguide (b).

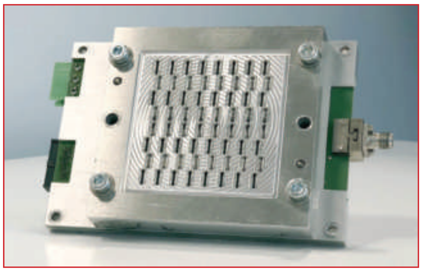

Fig. 3 Gapwaves 28 GHz demonstration array.

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facturing tolerances as frequencies increase. A rectangular waveguide with a joining defect on the order of micrometers between its two parts suffers catastrophic leakage (see ***Figure 2a***). Split-block design best practices and high quality joining processes improve performance but are not suitable for mass manufacturing.

A solution is offered by Gapwaves, a robust and low loss technology developed at Chalmers University of Technology by Professor Per-Simon Kildal and his research group.[4] By using an artificial magnetic conductor surface, typically realized with a bed of pins, robust waveguide-like transmission lines and components can be created without needing electrical contact between the layers. As shown in ***Figure 2b***, the equivalent Gapwaves waveguide performs flawlessly with a gap present, containing the fields within a few rows of pin and with comparable losses. No joining process is necessary. This key aspect enables a waveguide to achieve both premium performance and cost-effective manufacturing for consumer markets. Gapwaves AB was founded in 2011 with the objective of developing and commercializing Gapwaves waveguide solutions.

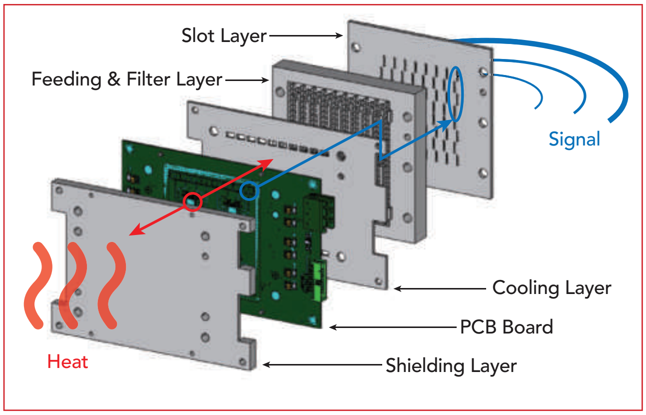

Fig. 4 Exploded view of the Gapwaves waveguide array.

GAPWAVES WAVEGUIDE 5G ANTENNA

To demonstrate the advantages of Gapwaves waveguide, we have developed a demonstration platform

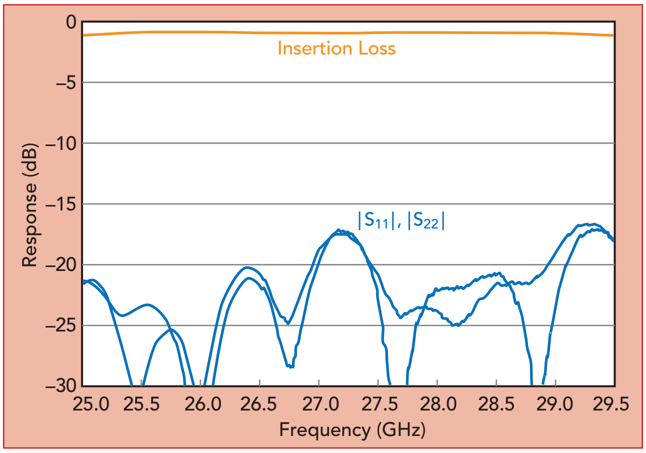

Fig. 5 Back-to-back measurement of the transition through a four-layer FR4 board.

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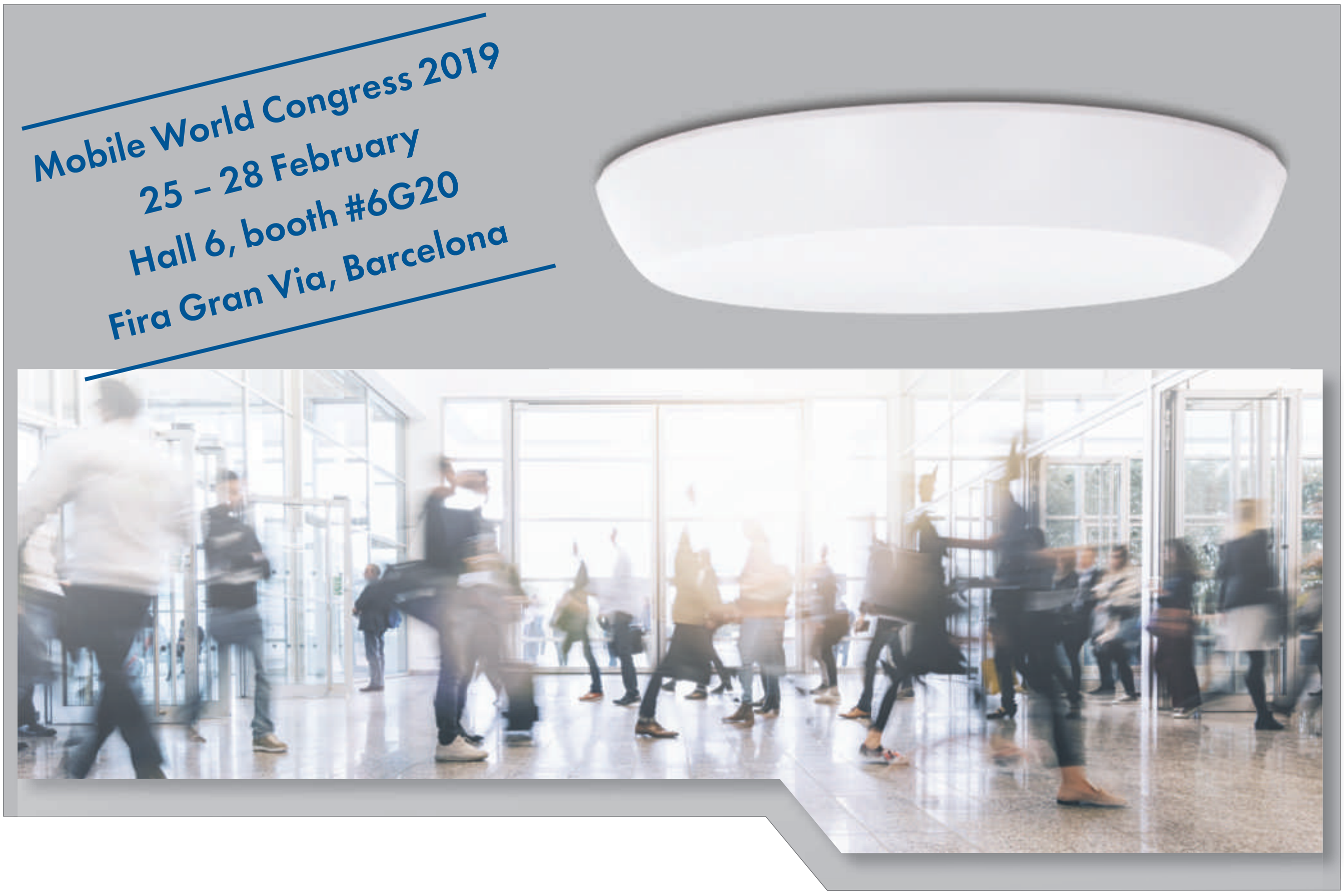

SENCITY® Occhio

Smart 5G-ready indoor antenna

Reliable, fast coverage, extended capacity and simplistic installation processes are vital factors and top priorities for operators as they look for the best technology on the market to support their journeys to 5G.

This antenna is the key to indoor connectivity, which ensures access to extended bandwidth and reliable availability with an innovative „smart connect" system that guarantees a simplified and efficient installation process - in an industry-preferred design. Thanks to its multiband capability between 1.7-6 GHz and 2x2/4x4 MIMO configurations, the SENCITY Occhio antenna ideally fulfils the multiple requirements of the 5G standard and equally meets current 4G applications.

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HUBER+SUHNER AG 9100 Herisau/Switzerland including the key passive and active components, although the focus is on the antenna and RF performance (see ***Figure 3***). Typical requirements have been considered; as a result, the design is not tailored for any specific application.

The center frequency is 28 GHz, in line with U.S. 5G trials, and the target bandwidth is greater than 13 percent to accommodate current 5G bands. A 1.2 GHz filter is integrated in each subarray feed to support analog, digital and hybrid beamforming and the typical instantaneous bandwidths. Full scanning is provided in azimuth and reduced in elevation. A spacing of λ/2, approximately 5.5 mm, and 4-element vertical subarrays were adopted to guarantee ±45 and ±10 degree scanning in azimuth and elevation, respectively. The demonstration antenna is an 8×8 array. Although a smaller size, it is sufficient to fully characterize the system and extrapolate to larger sizes without unnecessary complexity. Due to the subarrays, 16 feeds are present. SiGe front-ends are used, which provide a total EIRP of 44 dBm based on typical SiGe RFIC performance.

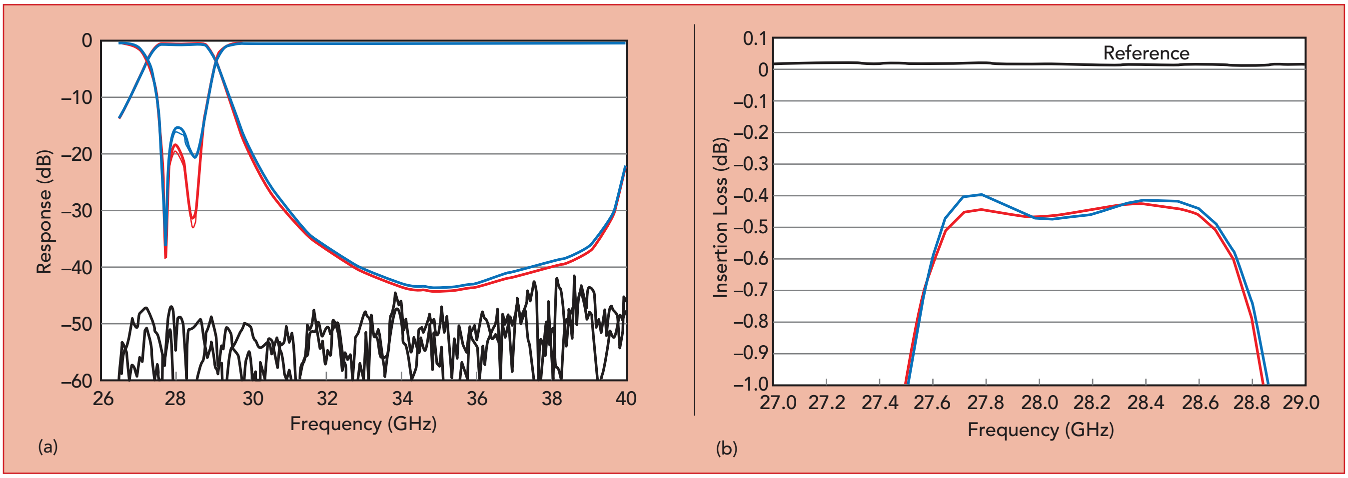

Fig. 6 **Measured performance of two 28 GHz Gapwaves waveguide bandpass filters showing wideband performance (a) and passband insertion loss (b).**

As shown in ***Figure 4***, the system is a multi-layer, largely metal assembly. The PCB, with the active components, is located between the shielding layer on the back and the cooling layer on the front. The shielding layer improves isolation and cavity mode suppression, and the cooling layer hosts the transitions to the antenna. Both layers are key to thermal performance. From the PCB, the RF is routed to the filter and distribution layer, which provides low loss routing, the subarray feeds and dedicated filters. Finally, the slot antenna is the front layer.

Fig. 7 **The single polarization Gapwaves antenna is an 8 x 8 slot array configured as 4-slot subarrays in eight columns and two rows.**

Transitions

One of the key advantages of Gapwaves waveguide technology is the low loss nature of its interconnections, typically more than 10× better than equivalent PCB solutions. It is highly desirable to transition from the PCB hosting the digital and low frequency signals to waveguide as soon as the RF signal is generated, performing high frequency functions such as filtering and routing in waveguide. The transition between PCB and waveguide should guarantee a low loss, robust and contact-less interface.

While a variety of transitions have been designed and manufactured, a through-substrate configuration has been adopted. This allows positioning the components facing backward in direct contact with the heatsink. Since the signal travels from the microstrip vertically through the substrate, different transition versions have been designed depending on the PCB stack-up. A single transition with a two-layer 10 mil

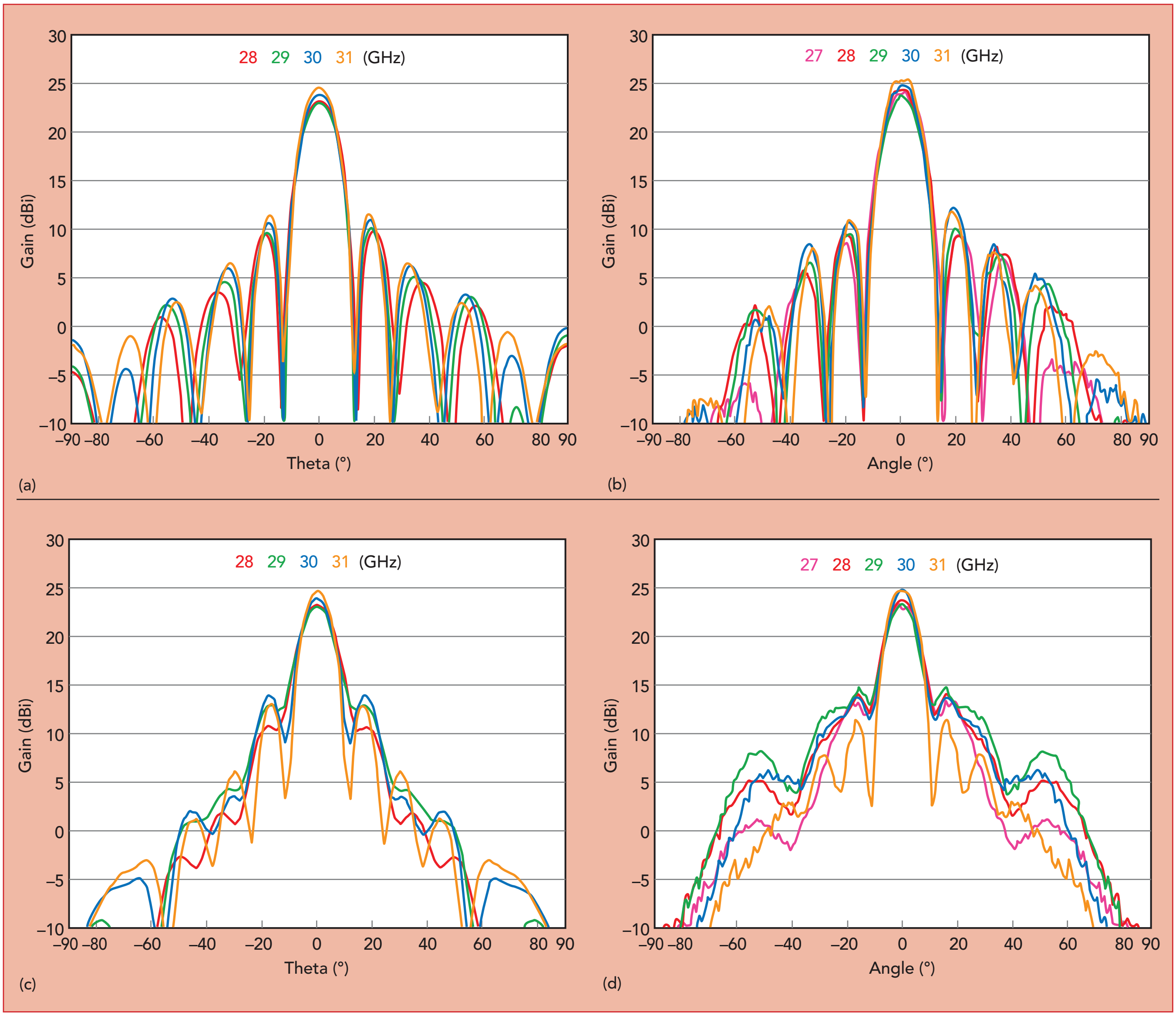

Fig. 8 **Gapwaves array antenna patterns: azimuth simulated (a) and measured (b), elevation simulated (c) and measured (d).**

Rogers RO4350 board has a measured insertion loss of 0.2 dB and return loss of 20 dB over a 20 percent bandwidth. ***Figure 5*** shows a back-to-back measurement of a four-layer board with a 10 cm waveguide line section. Tolerance analysis and repeated measurements prove the robustness of the design to assembly variations.

Filtering

RF filters are needed to protect sensitive services, such as the passive Earth Exploration Satellite Service (EESS).[5] The EESS band extends to 24 GHz, and the low end of the 5G n258 band starts at 24.25 GHz—only 1 percent frequency margin. Meeting emission limits requires sharp filter rejection or an expensive guardband. While several filter technologies could be applied, they can introduce considerable loss, use scarce PCB area and cause complicated routing.

Gapwaves waveguide technology enables waveguide filters integrated in the antenna, offering premium performance and eliminating complexity. While waveguide filters are well known and used in high performance applications, the amount and density of the filters pose the main challenges for the gap waveguide design. Achieving the filter area, constrained by the antenna element spacing to approximately $0.5\lambda \times 2\lambda$, is extremely challenging, as the area includes the division walls or pins between the subarrays and transitions between layers. Since the array will contain tens to hundreds of filters which must be functional as assembled without tuning, the design must be extremely robust to manufacturing and assembly. While the pin structure of the Gapwaves waveguide helps with the robustness, the design of the filter resonator is crucial. The design for meeting these requirements is less than about $\lambda/2$ in x, y and z.

For the demonstrator antenna array, the filter design is a third-order Chebyshev with 1.2 GHz bandwidth (20 dB return loss) centered at 28 GHz. The measured performance of two filters is shown in ***Figure 6***. The insertion loss is 0.4 dB, compared to an equivalent microstrip filter which would have losses of several dB. Although the filter fits comfortably under each subarray, for these measurements it was positioned on the auxiliary through line to characterize the filter independent of the antenna.

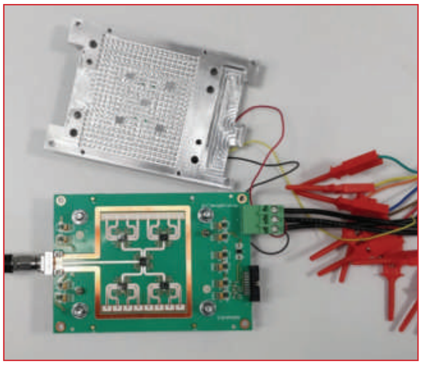

Fig. 9 Analog beamformer board.

Antenna

The demonstrator antenna is an 8×8 slot array organized as 4-slot subarrays in an eight column, two row configuration (see ***Figure 7***). As the subarray is periodic, the antenna can be extended in both horizontal and vertical directions. The $\lambda/2$ spacing and vertical grouping enable scanning without grating lobes beyond 45 degrees in azimuth and up to 10 degrees in elevation. The demonstrator antenna has a single polarization. Both vertical and horizontal versions of the antenna have been developed and tested, although this article only presents results from the single polarization antenna.

The subarray is a series, end-fed resonant slotted waveguide. The antenna covers the band from approximately 26.5 to 31 GHz, greater than 15 percent relative bandwidth. The measured and simulated array patterns show very good agreement (see ***Figure 8***), with no notches in the elevation patterns. The antenna has a total gain of 24 dBi, 12 dBi per subarray per channel. Embedded matching is better than 20 dB, isolation better than 16 dB and active matching better than 10 dB over all scan angles.

Thermal Design

Thermal handling is challenging at mmWave frequencies, where the


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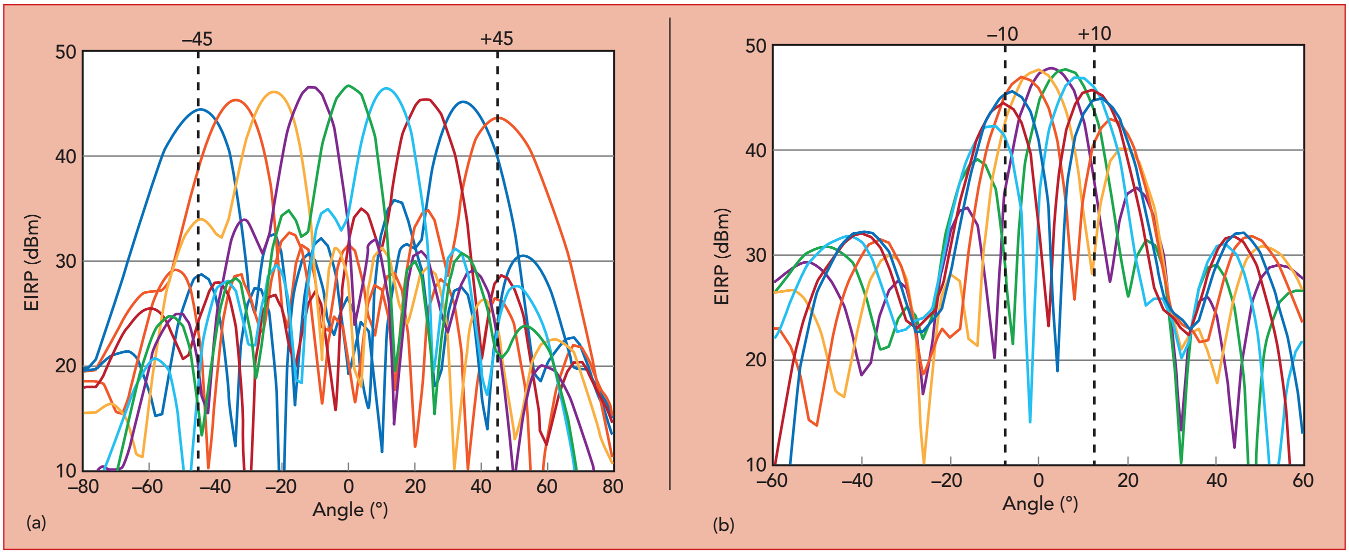

Fig. 10 Gapwaves array azimuth (a) and elevation (b) beam steering using analog beamforming.

many densely packed components create substantial heat in a limited area. High thermal handling is critical to ensure semiconductor and other components operate within their specified operating temperature ranges, assuring reliability and optimum performance. A SiGe IC solution for a mmWave, dual polarized array, for example, dissipates several W/cm^2. The thermal situation is complicated by the desire for passive cooling, which is challenging for a system dissipating more than a few hundred Watts. For even moderate heat dissipation, PCB designs rely on using thermal vias.

A Gapwaves waveguide system has excellent thermal capabilities. The all-metal antenna assembly doubles as an integrated heatsink, extracting heat from both the top and bottom sides of the components. Back-of-the-envelope calculations show that the antenna assembly can extract up to 2 W/°C from top-sided cooling of a typical 5 mm × 5 mm component area. The subarray architecture also provides benefits: for a fixed EIRP, it reduces the required power and decreases component density.

Measurements of the demonstration platform confirmed the effectiveness of the design using top-side cooling of the SiGe ICs. The steady state temperature measured by the on-chip sensors at maximum output power was only 60°C, when maximum junction temperatures are typically around 150°C.

ARRAY PERFORMANCE

The active part of the demonstration platform consists of an analog beamforming board using commercially available components (see ***Figure 9***). The 16 antenna ports are fed by four SiGe ICs, each with four Tx/Rx channels and connected to a single input/output RF connector. A fifth IC on the board serves as an optional buffer and preamplifier. The SiGe Tx/Rx chains provide 17 dBm saturated output power per channel, backed off to 8 dBm per channel to ensure good linearity.

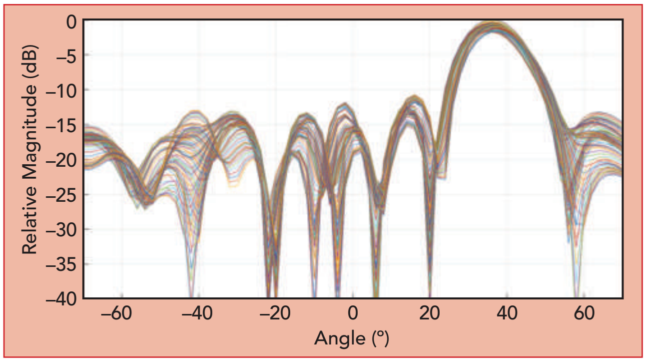

Fig. 11 Azimuth antenna pattern vs. frequency, 26.5 to 29.5 GHz, no calibration.

The amplitude and phase of each port can be independently controlled digitally, enabling full control of the beam. The total power consumption is about 13 W. The ICs operate from 26.5 to 29.5 GHz, less than the bandwidth of the antenna.

Active measurements validate the system performance in both Tx and Rx. Only the Tx results are presented here, with the measured antenna beams shown in ***Figure 10***. The beams are well behaved: scanning beyond the design requirements of ±45 degrees in azimuth and ±10 degrees in elevation and stable over frequency (see ***Figure 11***). The measured EIRP is approximately 52 dBm at saturation, backed off to 44 dBm with an error vector magnitude (EVM) of approximately 3 percent (see ***Figure 12***).

INCREASING EIRP

To increase the EIRP of mmWave arrays, a logical step is to adopt GaN on SiC in the RF front-end. Originally developed for defense applications, GaN technology has matured and the cost is becoming competitive for commercial applications.[2] Its high breakdown, electron mobility, power density and excellent thermal properties make the compound semiconductor attractive for mmWave front-ends. For Tx, GaN achieves a saturated

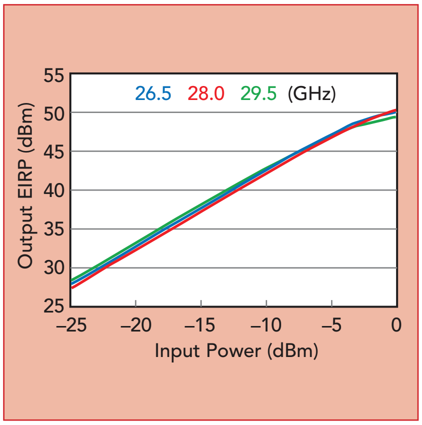

Fig. 12 Measured antenna EIRP.

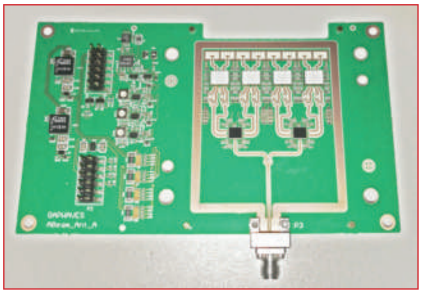

Fig. 13 Analog beamformer using GaN front-end modules.

power of 2 W with a power-added efficiency of approximately 10 percent. Backed off to an EVM of 3 percent, GaN can deliver an average output power of 24 dBm. GaN also achieves a noise figure about 1.5 dB better than SiGe, which significantly improves the uplink margin.

However, the high-power density of GaN requires considerable cooling capability in the antenna array, even though GaN's maximum rated junction temperature is about 75 degrees higher than SiGe. The Gapwaves waveguide approach offers the thermal handling needed for GaN power amplifiers. Although Gapwaves is agnostic to the choice of semiconductor technology, combining the low loss, high gain waveguide array with the high-power and high efficiency of GaN is very attractive. The combination can reduce the number of components and power consumption for a given EIRP, reducing the cost of the array. A gap waveguide antenna using a GaN front-end is being developed for the 28 GHz band (see ***Figure 13***). The subarray design contains eight slots in a single row, using analog beamforming with a GaN front-end module. Eight subarrays can be combined to form a 64-slot antenna with 24 dBi gain and 56 dBm EIRP at 9 dB back-off. The array will scan ±45 degrees in azimuth, and no elevation scan is planned. A total power consumption of about 40 W is expected.

SUMMARY

Gapwaves' demonstration platform shows the performance capabilities of the Gapwaves waveguide technology for mmWave antenna arrays. The low loss and thermal advantages of waveguide; the ability to integrate antennas, filters, radio and baseband components; and a cost-effective, producible platform position this technology as a strong contender for 5G and other mmWave systems. While the platform is agnostic to RF semiconductor technology, its thermal performance is particularly beneficial for the high-power density of GaN.■

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Sub-6 GHz mMIMO Base Stations Meet 5G's Size and Weight Challenges

Walter Honcharenko
MACOM, Lowell, Mass.

Base station deployment and site acquisition constraints require smaller, lighter 5G massive MIMO (mMIMO) radios and antennas. Improved signal processing, high efficiency devices and integration from discrete lineups to front-end modules (FEM) make it possible.

The RF and microwave industry has made considerable progress toward enabling commercial sub-6 GHz 5G wireless infrastructure, with mmWave fixed wireless trials progressing in parallel. The early excitement surrounding 5G has given way to a defined set of industry standards, and component and system manufacturers have variously aligned on practical, scalable 5G base station architectures that deliver the promise of faster data throughput and expansive capacity to serve subscriber, IoT and other applications.

The evolution from 4G to 5G—and the anticipated 100× capacity improvement required by our ever-increasing demand for data—requires a fundamental change in cellular communication RF system architecture and design. With so many users, devices, automobiles, smart meters, low-power wide-area devices and other machine-to-machine communication, the capacity of 4G cellular systems employing fixed sector antenna systems will fall short. At the highest level of communication theory, it is well known that maximizing throughput over a wireless channel requires maximizing signal-to-noise ratios (SNR) or signal-to-interference+noise ratios (SINR). High density cellular networks are typically interference limited, not noise limited, forcing the RF architecture to evolve into a system where interference is managed. Here is where mMIMO systems come into the picture. mMIMO, with many more transceivers and antenna elements than are used in 4G systems, uses beamforming signal processing to direct RF energy to users and reduce interference by dynamically steering antenna beams away from interfering sources, in both azimuth and elevation. By steering RF energy to users and away from interference, SINR, throughput and overall system capacity improve.

mMIMO CHALLENGES

With 5G antenna array and mMIMO technology coming to fruition, wireless network operators will

face deployment challenges as they make the transition from 4G LTE to 5G base stations, an incremental evolution that will see both technologies comingled for what is likely to be an extended period. Occupying similar physical footprints, 4G LTE and 5G base stations will, wherever possible, populate existing co-located cell towers and rooftop installations, configured as they are today to minimize interference and coverage gaps.

Fig. 1 Typical cell tower installation, with two tiers of radios and antennas.

As 5G base stations proliferate across existing sites, available installation space will shrink dramatically, space that is already at a premium from continued 4G LTE base station deployments in some regions. Indeed, many cell towers have already been pushed to the brink of their hosting capacities, evidenced by the increasingly and chaotically-cluttered towers dotting today's metro environments. ***Figure 1*** shows a typical tower installation with two tiers of antennas, radios, RF cables and power feed lines, which represent approximately 250 kg weight on each sector. Wind loading, ice loading and moment arms are key factors as base stations multiply on a tower, with concern for base station resilience and service continuity in poor weather conditions.

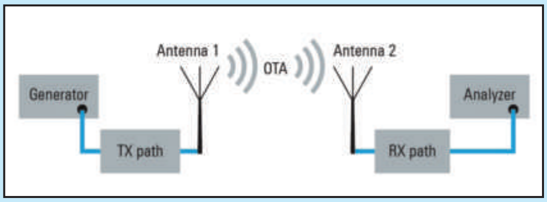
These challenges must be met with smaller, denser sub-6 GHz 5G base station designs. In parallel, base station weight and volume remain critical considerations for system designers, given the nontrivial labor and equipment costs imposed on wireless operators for installation and subsequent maintenance. Where operating costs were calculated based on just the aperture size of the antenna, tower operators have largely moved to a pricing model where charges are calculated using base station weight, aperture area and volume. Initial installation costs are also determined by the location, weight and type of installation: tower or rooftop, one or two people, crane, etc. The initial 4G systems were split into a radio head and an antenna, where the radio was often on the ground and the passive antenna mounted on the tower. In other installations, both radio and

Master the Challenges of OTA Calibration

ROHDE&SCHWARZ

Integrating antennas to the radio frequency chipset without connectors is increasingly common with both low cost IoT devices and especially in highly integrated 5G mobile communication equipment operating at mmWave frequencies. This makes testing a device under test (DUT) over the air (OTA) mandatory. To tackle the challenges of OTA testing it is key to understand the demands of antenna measurement and chamber setup.

Calibration is an important first step in the preparation for OTA testing. The measurement results of a DUT should not be setup-depended, requiring a calibration for each measurement setup. The OTA link adds a significant amount of attenuation to the measurement setup due to the free space path loss (FSPL), in addition to the losses from cables and other connected components. Unlike with cables, a stable measurement distance and perfect mechanical alignment is crucial for OTA measurement accuracy in order to avoid differences in attenuation caused by positioning errors.



Port calibration, for example by using a network analyzer, cannot be conducted to an air interface. Therefore, another type of calibration is required. Commonly, antenna gain measurements are conducted by comparing an unknown antenna to a reference antenna. Following this principle, an antenna with known gain is required to identify the calibration information of the OTA test setup and store these calibration data either on the measurement instrument or some external software controlling the measurement setup.

The high FSPL, longer cables due to the required measurement distance as well as the use of high frequencies require excellent dynamic range from the test and measurement equipment.

To address these different challenges, to calibrate OTA test setups and to carry out OTA measurements, Rohde & Schwarz has a diverse portfolio of vector network analyzers like the R&S®ZNA, vector signal generators, such as the R&S®SMW200A and signal and spectrum analyzers such as the R&S®FSW. Rohde & Schwarz also offers complete OTA test solutions, such as the R&S®ATS1000 antenna test chamber. Combined with Rohde & Schwarz test instruments, it is the ideal environment for 5G antenna characterization throughout the entire process from R&D to production for both active and passive devices.

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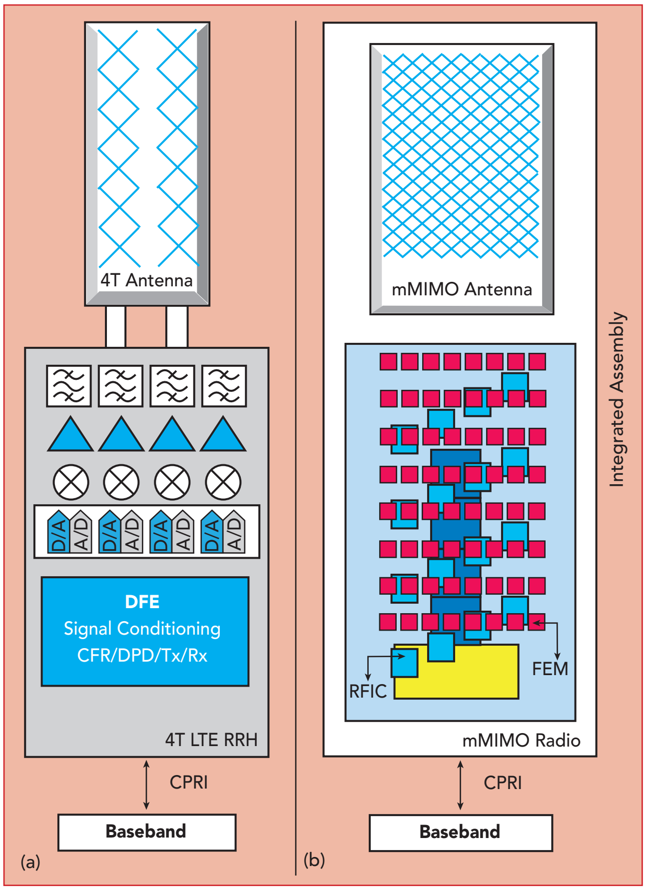
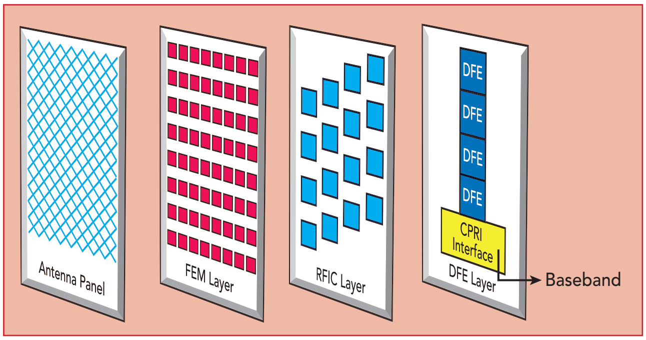


▲ Fig. 2 Architecture of a conventional 4T LTE remote radio head (a) vs. a mMIMO radio containing 192 antenna elements and 64 TRx FEMs (b).

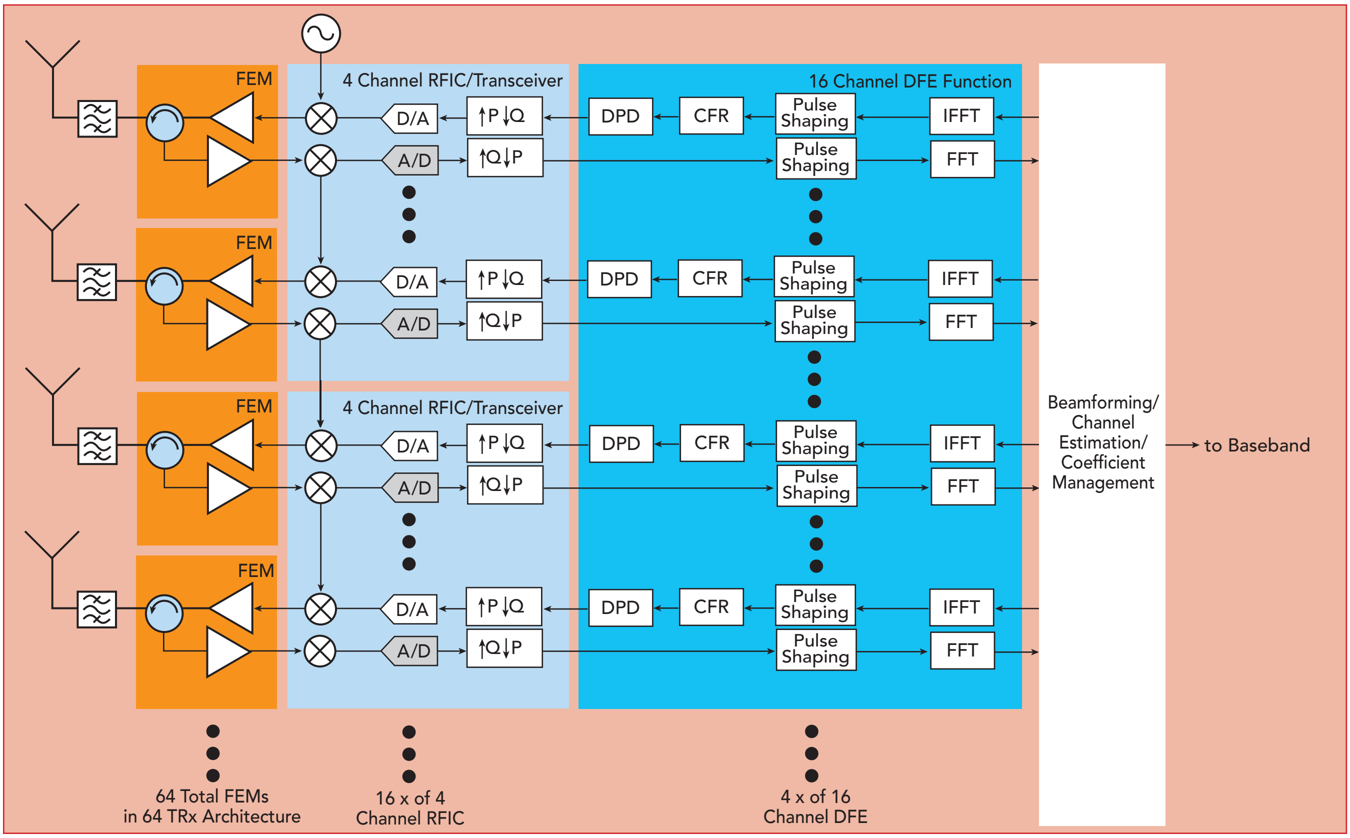
antenna were located on the tower, with commensurate costs. 5G mMIMO antennas, by definition, will position the active electronics on the tower, immediately behind the antenna, in a single integrated unit.

Of course, base station size and weight have always and will always be central concerns for RF component providers, base station designers and operators. A looming shortage of tower and rooftop real estate will only exacerbate these problems. On the path to realizing commercial-scale mmWave 5G connectivity, site acquisition will become infinitely more difficult, given the 100 m spacing between base stations that frequency and physics require for uniform coverage. mmWave base station equipment installed on lamp posts, street signs, bus stop shelters and other structures will need to be far lighter and less obtrusive than anything that has come before.

Site acquisition challenges will be compounded by concerns over the effective isotropic radiated power



▲ Fig. 3 Notional mMIMO radio stackup.



▲ Fig. 4 Typical mMIMO radio functional block diagram.

(EIRP). While 4G LTE and sub-6 GHz 5G base stations may exhibit comparable EIRP levels when accounting for beamforming gain, increasingly higher frequencies will require higher RF power to compensate for building penetration losses and boost the EIRP to achieve comparable indoor coverage. Diffraction losses, aperture efficiencies and path loss all suffer as a function of frequency (i.e., 6 to 12 dB/octave), while penetration losses increase dramatically at higher frequencies due to the skin depth and conductivity of coated glass, conductive (moist) masonry, brick faces and other materials.

Health and safety requirements dictate that EIRP emission limits (1 mW/cm^2) and exclusion zones remain within acceptable levels in the transition from 4G LTE to 5G, so raising EIRP levels will naturally introduce some placement challenges. These will be compounded with the implementation of mMIMO beamforming techniques if theoretical maximum power is used. Where conventional antennas point horizontally, beam steered antenna arrays will radiate in many directions, even down into pedestrian walkways. This health and safety concern will introduce additional constraints for acquiring urban 5G base station sites, intensifying the pressure to design smaller, lower power base stations that can be flexibly deployed while preserving safety.

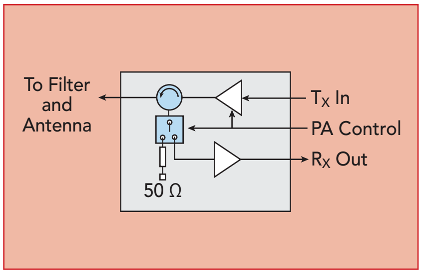


Fig. 5 Simplified FEM block diagram.

REDUCING SIZE AND WEIGHT

When it comes to optimizing sub-6 GHz base station size and weight, several design considerations must be considered, from the component to the system, with power consumption, efficiency and thermal dissipation the most important.

Antenna aperture size is wholly dependent on the number of onboard antenna elements, which depends on the desired network capacity and expected interference. Whether the array has 64, 128 or 192 elements, the physical dimension is determined by the physics of the array, scanning angle requirements, grating lobe performance and beam widths. The volume and depth of the base station, determined by the underlying electronics and heat sinking, can absolutely be optimized; here, we see plenty of room for improvement.

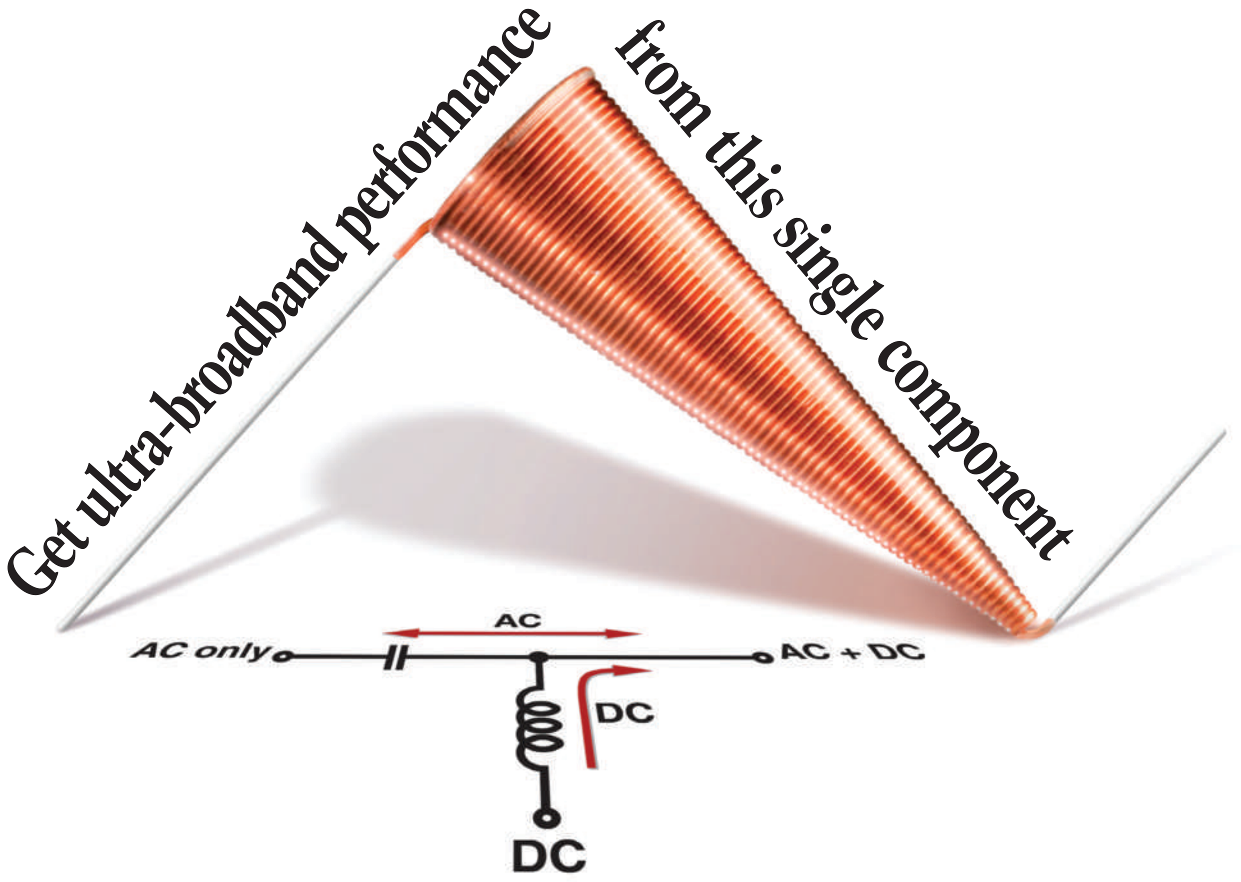
A key system size consideration frequently overlooked with 5G mMIMO is the dramatic increase in signal processing hardware required, compared to typical LTE systems. The mMIMO system may have 192 antenna elements connected to 64 transmit/receive (TRx) FEMs with 16 transceiver RFICs and four digital front-ends (DFE), a 16× increase in

digital signal processing compared to the four transceivers in a typical LTE 4T MIMO system (see ***Figure 2***). Add a 5× increase in bandwidth when moving from 20 to 100 MHz, for example, and the signal processing multiplier is staggering. The stackup in ***Figure 3*** illustrates the functions in a typical mMIMO integrated antenna and radio. The top panel contains the antenna elements, and the layers below the antenna contain the RF and digital circuitry. While the TRx FEM, RFIC and DFE layers are shown as separate boards, in practice the three functions will be combined into one or two densely packed boards to minimize interconnections.

Perhaps even more jarring than the additional hardware in a mMIMO system is the attendant impact on power consumption and heat dissipation. Previously, power amplifier (PA) power consumption was the most important factor when designing base station heat sinks and power supplies. Now, the power consumption of the signal processing electronics is approaching, and in some cases, eclipsing that of the onboard PAs.

The significant increase in signal processing hardware can be offset to an extent by optimizing the signal and waveform conditioning algorithms applied to the transmitted signals. Legacy signal conditioning algorithms such as crest factor reduction and digital predistortion (DPD) were primarily developed for macro base stations with very high-power PAs, a more complicated and taxing processing workload than is required for the smaller, lower power PAs populating mMIMO antennas. These algorithms easily consumed 75 percent of the available signal processing resources in the DFE processors, whether custom ASIC/SOCs or FPGAs. By streamlining these algorithms for 5G mMIMO architectures and redistributing the functionality across several logic blocks, a minimal set of optimized algorithms will improve signal processing efficiency, reducing overall power consumption.

To illustrate the 16× multiplier of the digital signal processing and transceivers in a mMIMO system, a functional block diagram is shown in ***Figure 4***. This architecture is typical of all mMIMO designs, with some differences in the partitioning of logic (e.g., 8- or 16-channel DFEs) or discrete component instead of integrated FEMs. This example shows, from left to right, 64 RF and transceiver paths divided among 16 transceiver RFICs driving four DFEs. The DFEs process the digital data from the 64 channels and are connected to the beamforming processor and baseband interface processor. The emergence of RF SOCs with direct sampling analog-to-digital converters (ADC) and digital-to-analog converters (DAC) capable of ~60 GSPS help to shrink the size and weight of 5G antennas by reducing the steps required for analog up- and down-conversion in conventional transceiver architectures. This reduces the overall component count and cost by elimi-



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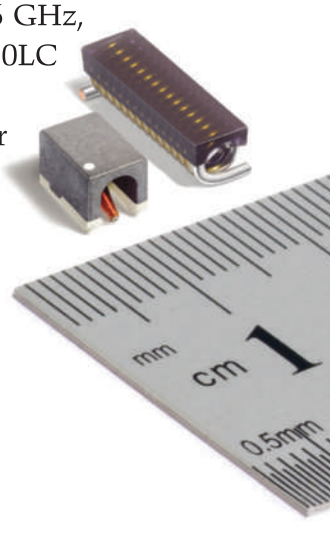

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FEM BENEFITS

The emergence of GaN on Si PAs provides wideband performance and superior power density and efficiency compared to LDMOS devices, meeting the exacting thermal specifications while preserving valuable PCB space for the tightly-clustered mMIMO antenna arrays. Space-saving multifunction MMICs and multi-chip modules (MCM) are supplanting discrete ICs and single-function devices, enabling integrated RFICs for 5G base stations. FEMs are benefiting from a similarly streamlined design approach using integrated assemblies incorporating PAs, T/R switches, matching circuits, low noise amplifiers, digital step attenuators, controllers and DPD couplers packaged in compact packages (see ***Figure 5***). With drain efficiencies approaching 60 percent

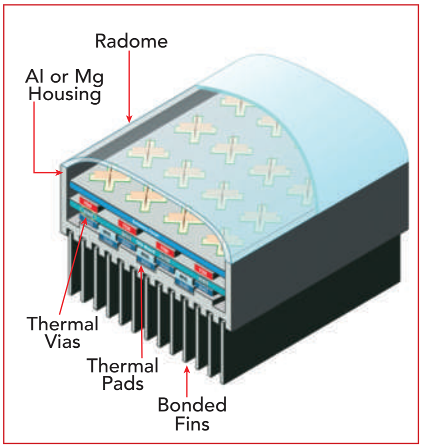

Fig. 6 **Integrated mMIMO radio.**

and optimized integration of the Tx and Rx components, as well as DPD feedback paths, using FEMs in mMIMO radios and TRx boards has many benefits:

- Reuse portions of the transceiver board layout.
- Optimize device-to-heat sink thermal management.
- Optimize power levels, feedback loops, VSWR and control circuitry.
- Manage isolation and noise within the FEM.
- Enable dynamic power saving modes.
- Improve final yields compared to discrete designs, since the integrated FEM is fully tested.

Using the FEM design approach, redesigning a mMIMO radio for a different number of antenna elements, frequency band or power level is simplified, as FEMs are "plug and play" modules, with standardized interfaces, control logic and RF levels part of the design methodology.

THERMAL DESIGN

In all mMIMO designs, where the antenna and electronics are contained in one enclosure (see ***Figure 6***), the majority of the product engineering focus is managing thermal performance. The engineering efforts for signal processing, RF design, digital design, board layout, power design are indeed complex, but ultimately the mechanical/thermal/design and product environmental requirements will determine the volume and weight. Conventional 4G radio heads are built with the radio inside the heat sink, fins surrounding the entire package. With a mMIMO design, the antenna

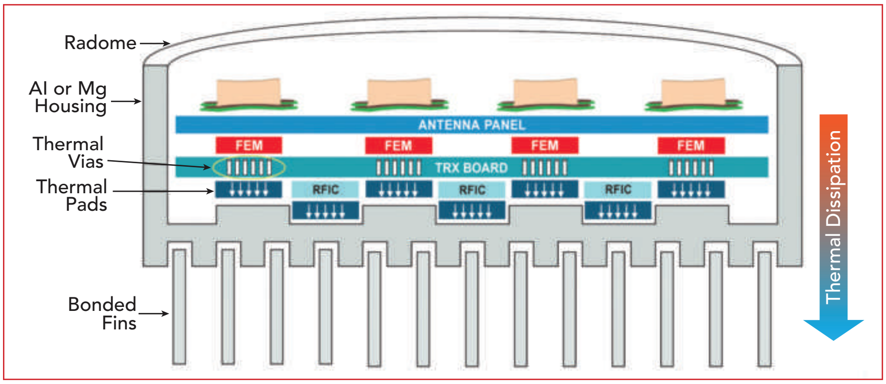

Fig. 7 Integrated mMIMO radio cross section showing layers and heat conduction paths.

and its radome are very poor conductors of heat, limiting thermal dissipation to the rear of the mMIMO radio.

By leveraging advanced packaging techniques for the MMICs and MCMs within the FEM, additional cooling and space-saving benefits can be achieved. ***Figure 7*** illustrates a simplified mMIMO design, not including the power supplies and fiber interfaces. The case housing has extruded fins bonded into the housing to save casting weight and increase thermal efficiency. The TRx board integrates the FEMs and RFICs, with the FEMs conducting heat down through thermal vias, while the heat from the RFICs conducts out through the lid. This allows heat to be dissipated in multiple directions, rather than unidirectionally from the FEMs and RFICs. Heat can be removed through the top lid and the bottom of the package through the ground vias and baseplate, distributing heat more efficiently and enabling a cooler device in a smaller footprint. Alternatively, the FEM can channel heat through both the thermal vias and the lid, to dissipate as much heat as possible.

SUMMARY

The impending proliferation of 5G base stations operating sub-6 GHz, later at mmWave, will undoubtedly strain tower and rooftop deployment flexibility and site acquisition options for the foreseeable future. By alleviating the signal processing and conversion workload and exploiting higher levels of integration, from discrete components to FEMs, significant reductions in base station size and weight can be achieved.

The expected roadmap for FEMs, SOCs and full single module solutions, from optical in to RF out, is a natural progression of technology. Integration of the optical interfaces, with direct sampling RF Tx and Rx and the required signal conditioning, will define a true SOC. These evolving capabilities will enable 5G mMIMO base stations to become ubiquitous, fitting comfortably in the contours of our metro and suburban landscapes.■

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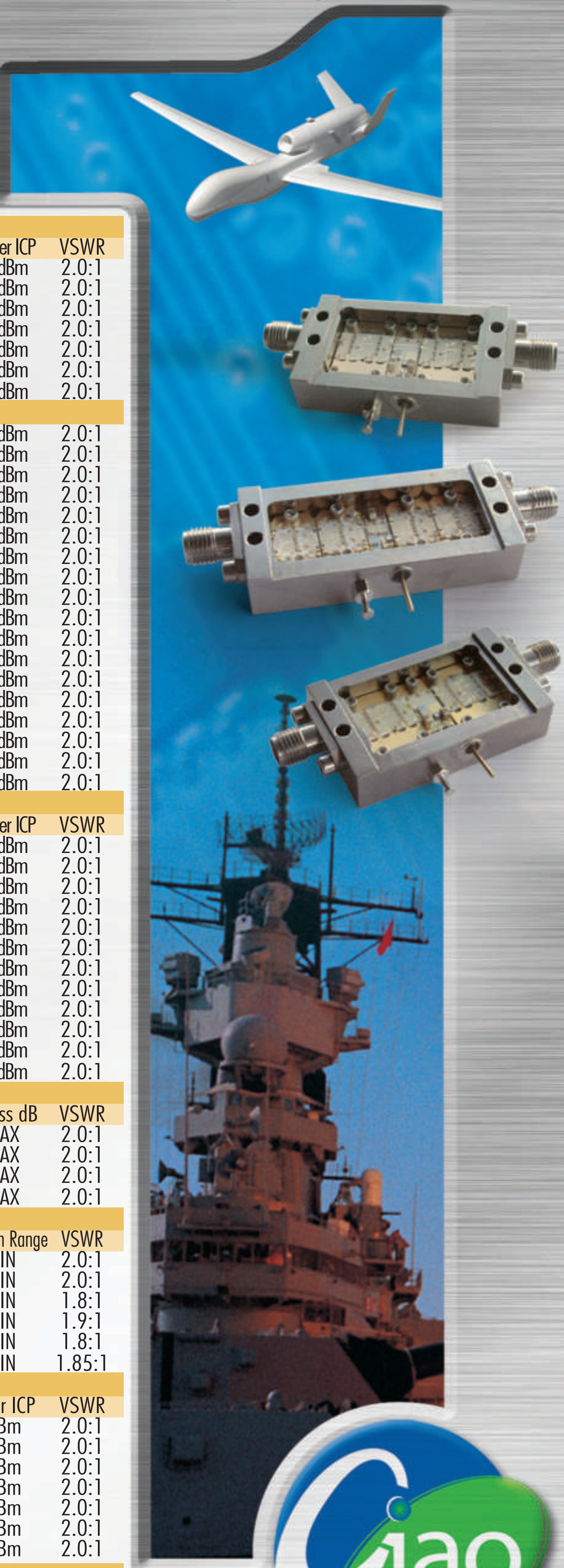

OCTAVE BAND LOW NOISE AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA01-2110	0.5-1.0	28	1.0 MAX, 0.7 TYP	+10 MIN	+20 dBm	2.0:1
CA12-2110	1.0-2.0	30	1.0 MAX, 0.7 TYP	+10 MIN	+20 dBm	2.0:1
CA24-2111	2.0-4.0	29	1.1 MAX, 0.95 TYP	+10 MIN	+20 dBm	2.0:1
CA48-2111	4.0-8.0	29	1.3 MAX, 1.0 TYP	+10 MIN	+20 dBm	2.0:1
CA812-3111	8.0-12.0	27	1.6 MAX, 1.4 TYP	+10 MIN	+20 dBm	2.0:1
CA1218-4111	12.0-18.0	25	1.9 MAX, 1.7 TYP	+10 MIN	+20 dBm	2.0:1
CA1826-2110	18.0-26.5	32	3.0 MAX, 2.5 TYP	+10 MIN	+20 dBm	2.0:1

NARROW BAND LOW NOISE AND MEDIUM POWER AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA01-2111	0.4 - 0.5	28	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA01-2113	0.8 - 1.0	28	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA12-3117	1.2 - 1.6	25	0.6 MAX, 0.4 TYP	+10 MIN	+20 dBm	2.0:1
CA23-3111	2.2 - 2.4	30	0.6 MAX, 0.45 TYP	+10 MIN	+20 dBm	2.0:1
CA23-3116	2.7 - 2.9	29	0.7 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA34-2110	3.7 - 4.2	28	1.0 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA56-3110	5.4 - 5.9	40	1.0 MAX, 0.5 TYP	+10 MIN	+20 dBm	2.0:1
CA78-4110	7.25 - 7.75	32	1.2 MAX, 1.0 TYP	+10 MIN	+20 dBm	2.0:1
CA910-3110	9.0 - 10.6	25	1.4 MAX, 1.2 TYP	+10 MIN	+20 dBm	2.0:1
CA1315-3110	13.75 - 15.4	25	1.6 MAX, 1.4 TYP	+10 MIN	+20 dBm	2.0:1
CA12-3114	1.35 - 1.85	30	4.0 MAX, 3.0 TYP	+33 MIN	+41 dBm	2.0:1
CA34-6116	3.1 - 3.5	40	4.5 MAX, 3.5 TYP	+35 MIN	+43 dBm	2.0:1
CA56-5114	5.9 - 6.4	30	5.0 MAX, 4.0 TYP	+30 MIN	+40 dBm	2.0:1
CA812-6115	8.0 - 12.0	30	4.5 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA812-6116	8.0 - 12.0	30	5.0 MAX, 4.0 TYP	+33 MIN	+41 dBm	2.0:1
CA1213-7110	12.2 - 13.25	28	6.0 MAX, 5.5 TYP	+33 MIN	+42 dBm	2.0:1
CA1415-7110	14.0 - 15.0	30	5.0 MAX, 4.0 TYP	+30 MIN	+40 dBm	2.0:1
CA1722-4110	17.0 - 22.0	25	3.5 MAX, 2.8 TYP	+21 MIN	+31 dBm	2.0:1

ULTRA-BROADBAND & MULTI-OCTAVE BAND AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	3rd Order ICP	VSWR
CA0102-3111	0.1-2.0	28	1.6 Max, 1.2 TYP	+10 MIN	+20 dBm	2.0:1
CA0106-3111	0.1-6.0	28	1.9 Max, 1.5 TYP	+10 MIN	+20 dBm	2.0:1
CA0108-3110	0.1-8.0	26	2.2 Max, 1.8 TYP	+10 MIN	+20 dBm	2.0:1
CA0108-4112	0.1-8.0	32	3.0 MAX, 1.8 TYP	+22 MIN	+32 dBm	2.0:1
CA02-3112	0.5-2.0	36	4.5 MAX, 2.5 TYP	+30 MIN	+40 dBm	2.0:1
CA26-3110	2.0-6.0	26	2.0 MAX, 1.5 TYP	+10 MIN	+20 dBm	2.0:1
CA26-4114	2.0-6.0	22	5.0 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA618-4112	6.0-18.0	25	5.0 MAX, 3.5 TYP	+23 MIN	+33 dBm	2.0:1
CA618-6114	6.0-18.0	35	5.0 MAX, 3.5 TYP	+30 MIN	+40 dBm	2.0:1
CA218-4116	2.0-18.0	30	3.5 MAX, 2.8 TYP	+10 MIN	+20 dBm	2.0:1
CA218-4110	2.0-18.0	30	5.0 MAX, 3.5 TYP	+20 MIN	+30 dBm	2.0:1
CA218-4112	2.0-18.0	29	5.0 MAX, 3.5 TYP	+24 MIN	+34 dBm	2.0:1

LIMITING AMPLIFIERS

Model No.	Freq (GHz)	Input Dynamic Range	Output Power Range Psat	Power Flatness dB	VSWR
CLA24-4001	2.0 - 4.0	-28 to +10 dBm	+7 to +11 dBm	+/- 1.5 MAX	2.0:1
CLA26-8001	2.0 - 6.0	-50 to +20 dBm	+14 to +18 dBm	+/- 1.5 MAX	2.0:1
CLA712-5001	7.0 - 12.4	-21 to +10 dBm	+14 to +19 dBm	+/- 1.5 MAX	2.0:1
CLA618-1201	6.0 - 18.0	-50 to +20 dBm	+14 to +19 dBm	+/- 1.5 MAX	2.0:1

AMPLIFIERS WITH INTEGRATED GAIN ATTENUATION

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure (dB)	Power-out @ P1-dB	Gain Attenuation Range	VSWR
CA001-2511A	0.025-0.150	21	5.0 MAX, 3.5 TYP	+12 MIN	30 dB MIN	2.0:1
CA05-3110A	0.5-5.5	23	2.5 MAX, 1.5 TYP	+18 MIN	20 dB MIN	2.0:1
CA56-3110A	5.85-6.425	28	2.5 MAX, 1.5 TYP	+16 MIN	22 dB MIN	1.8:1
CA612-4110A	6.0-12.0	24	2.5 MAX, 1.5 TYP	+12 MIN	15 dB MIN	1.9:1
CA1315-4110A	13.75-15.4	25	2.2 MAX, 1.6 TYP	+16 MIN	20 dB MIN	1.8:1
CA1518-4110A	15.0-18.0	30	3.0 MAX, 2.0 TYP	+18 MIN	20 dB MIN	1.85:1

LOW FREQUENCY AMPLIFIERS

Model No.	Freq (GHz)	Gain (dB) MIN	Noise Figure dB	Power-out @ P1-dB	3rd Order ICP	VSWR
CA001-2110	0.01-0.10	18	4.0 MAX, 2.2 TYP	+10 MIN	+20 dBm	2.0:1
CA001-2211	0.04-0.15	24	3.5 MAX, 2.2 TYP	+13 MIN	+23 dBm	2.0:1
CA001-2215	0.04-0.15	23	4.0 MAX, 2.2 TYP	+23 MIN	+33 dBm	2.0:1
CA001-3113	0.01-1.0	28	4.0 MAX, 2.8 TYP	+17 MIN	+27 dBm	2.0:1
CA002-3114	0.01-2.0	27	4.0 MAX, 2.8 TYP	+20 MIN	+30 dBm	2.0:1
CA003-3116	0.01-3.0	18	4.0 MAX, 2.8 TYP	+25 MIN	+35 dBm	2.0:1
CA004-3112	0.01-4.0	32	4.0 MAX, 2.8 TYP	+15 MIN	+25 dBm	2.0:1

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LM Receives $1.8B Contract for PAC-3 Missiles

The U.S. and allied military forces will upgrade their missile defense capabilities under a $1.8 billion contract for production and delivery of Lockheed Martin Patriot Advanced Capability-3 (PAC-3) and PAC-3 Missile Segment Enhancement (MSE) interceptors.

The contract includes deliveries for the U.S. Army and Foreign Military Sales of PAC-3 and PAC-3 MSE interceptors, launcher modification kits and associated equipment.

PAC-3 missiles are high velocity interceptors that defend against incoming threats, including tactical ballistic missiles, cruise missiles and aircraft. Thirteen nations—the U.S., Germany, Kuwait, Japan, Qatar, the Republic of Korea, Kingdom of Saudi Arabia, Taiwan, the Netherlands, United Arab Emirates, Romania, Poland and Sweden have chosen PAC-3 and PAC-3 MSE to provide missile defense capabilities.

Building on the combat-proven PAC-3, the PAC-3 MSE uses a two-pulse solid rocket motor that increases altitude and range to defend against evolving threats.

HENSOLDT Forges Ahead with Development of Eurofighter's Radar

Following a successful acceptance test, HENSOLDT has delivered the second active antenna for the Captor-E radar system. Ready for series production, manufacturing the active electronically scanned array (AESA) will begin at the HENSOLDT factory in Ulm, Germany, with delivery of the first radar system planned by mid-2019, later than the original schedule, which was the end of 2018.

The Captor-E is an upgrade to the Captor radar—a mechanically steered, pulse Doppler radar—used on the Eurofighter. The AESA combined with flexible radar resource management will improve detection and enable simultaneous multi-target tracking, missile guidance and situational awareness.

Since the Eurofighter's nose is larger than that of comparable fighters, the Captor-E antenna is larger and "more powerful" than that of competing aircraft, according to HENSOLDT. The Captor-E radar can also be mechanically rotated, increasing the detection area and the field of view, compared to other AESA radars.

A €1 billion contract to develop the Captor-E was signed on November 19, 2014. The radar is being developed by the Euroradar consortium, comprising Leonardo, Indra and HENSOLDT. The consortium has produced more than 400 of the current-generation Captor radars.

During the spring of 2018, the Captor-E successfully completed two flight campaigns at British Aerospace Systems in Warton and at Airbus Defence and Space in Manching, meeting the requirements of the Critical Design Review (CDR).

A German Ministry of Defense report issued in March 2018 said the development program was 13 months late, with a "very high risk" that it would miss the initial delivery scheduled for late 2018. At the time, the Euroradar consortium disagreed with the report, saying the program was on schedule.

Eurofighter (Photo: HENSOLDT)

Kratos Receives $65M in Recent Space and SATCOM Contract Awards

Kratos Defense & Security Solutions Inc. recently announced that it has received recent space and SATCOM contract awards and options on existing contracts totaling approximately $65 million. Work performed under these contract awards will be performed at secure Kratos manufacturing facilities and customer locations and is expected to be substantially completed over the next 12 months.

The awards include Kratos' products and services across technology application domains that are critical to defending space operations and assuring global SATCOM for the U.S. and its allies, as well as certain other operations that are essential to national security. Under the contract awards, Kratos will provide solutions for satellite command & control, signal monitoring, end-to-end service assurance, cloud-enabled architectures and other applications. Kratos products support more than 85 percent of U.S. space missions, and are used by more than 75 percent of global satellite operators. Kratos owns and operates the largest global, commercial network of space-focused RF sensors employed to help customers identify, locate and mitigate interference challenges. The company recently announced it has begun leveraging this network to offer new Space Situational Awareness (SSA) services to bring additional clarity and insight to operations in the space environment for its customers.

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Phil Carrai, president of Kratos' Space, Cybersecurity and Training business, said, "The Space sector is experiencing a technology renaissance, and much of that advancement is occurring in the ground segment solutions that Kratos specializes in: those which assure the availability, reliability, security and operational goals of these missions. The range of space missions enabled by these awards and renewals is extremely broad, and Kratos is one of the only companies that can support that breadth with industry-leading COTS products, as well as cloud operations enablement, mission-specific applications and tailored waveforms."

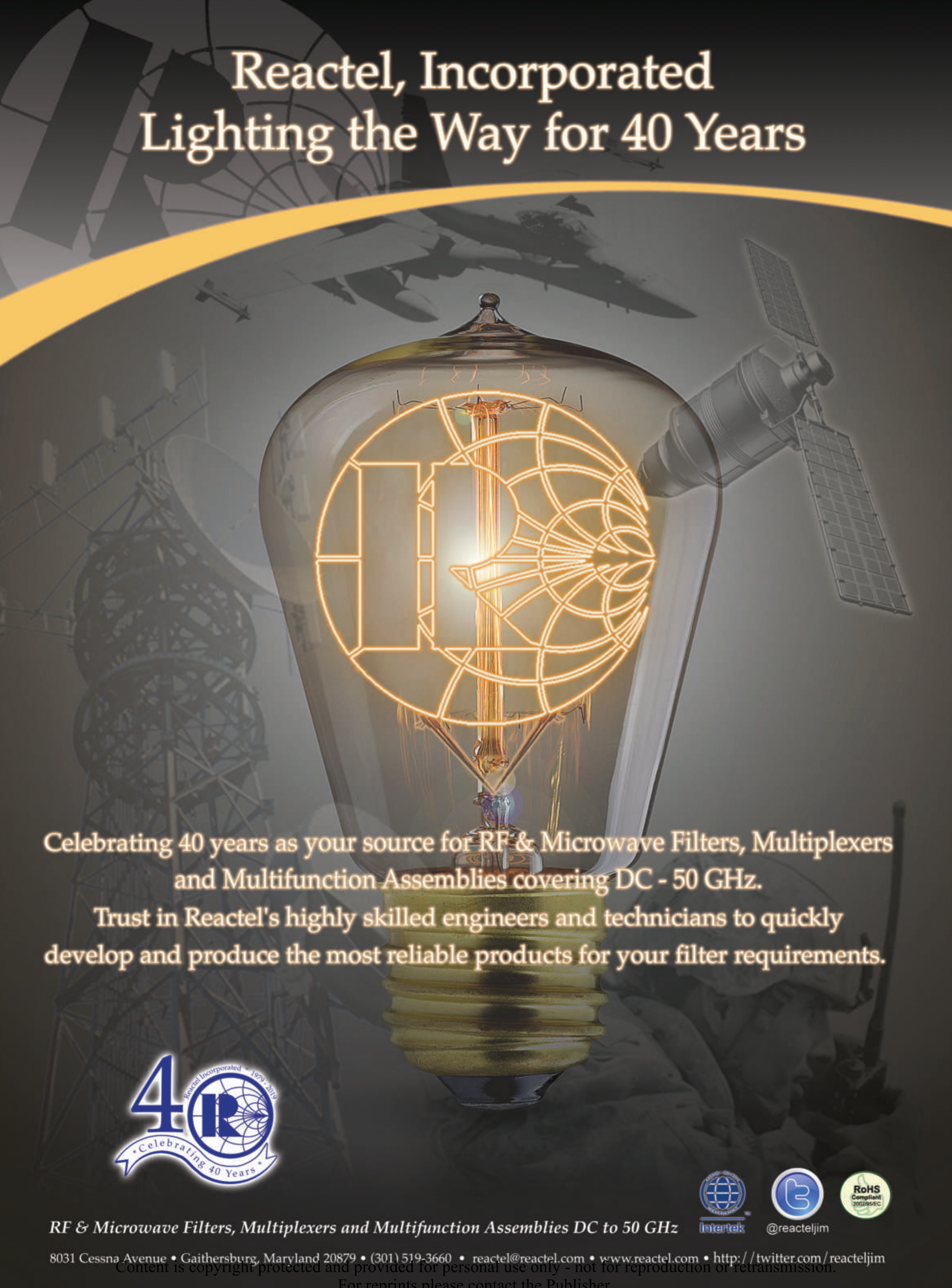
Leonardo DRS, RAFAEL to Provide Additional TROPHY Protection Systems

Leonardo DRS Inc. recently announced that it has been awarded an undefinitized contract action initially worth $79.6 million to provide the U.S. Army and Marine Corps with additional TROPHY active protection systems, bringing the total funded value of the program to over $200 million. Developed by long-time partner Rafael Advanced Defense Systems Ltd., TROPHY provides combat-proven protection against anti-armor rocket and missile threats, while at the same time locating and reporting the origin of the hostile fire for immediate response.

TROPHY VPS (Source: Leonardo DRS)

The DRS and RAFAEL team led a successful demonstration featuring a new, lighter "TROPHY VPS" variant on a Bradley Fighting Vehicle in Israel during August 2018. The team will also participate in the Army's Stryker Expedited APS demonstration "rodeo" in February.

"TROPHY VPS provides the same capabilities and performance as TROPHY in a significantly smaller package," said Moshe Elazar, executive VP and head of Rafael's Land and Naval Division. "We are also leveraging our global leadership in both active protection (close to 1,500 TROPHY systems) and medium-caliber remote weapons systems (over 1,000 systems), to offer the mature, reliable, lightweight Samson turret, which combines both capabilities. Given our wide customer base and existing production lines for both, this is a capable, affordable, low risk solution for the U.S. Army's next-generation combat vehicles and other programs in Israel and other markets."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Cliff Drubin, Associate Technical Editor

Improved Hardware, 5G, Cloud and Enhanced Dev Tools Set to Accelerate AR Market to $116B by 2023

This past year was significant for augmented reality (AR), with new entrants in the market, new smart glasses launched, new and improved platforms and portfolios and generally more enthusiasm and curiosity from the public to explore the technology. Despite that technical challenges and budget limitations remain an issue for near future mass adoption, the total AR market will be worth $116 billion by 2023, finds ABI Research. Technological advancements, the growth of mobile AR, more proof of concept use cases and audience acceptance are the main factors that will lead to this booming growth.

"New entrances across hardware and software, along with expanding incumbents, are reshaping the AR landscape, providing more opportunities for customers and developers," said Eleftheria Kouri, research analyst at ABI Research. "For example, Magic Leap's initial hardware offering, as well as updated devices from Vuzix and others, are met with market conversations spanning outside of just hardware. Magic Leap is working with AT&T to trial 5G AR, connectivity players such as Huawei are pushing for cloud AR/VR and development tools such as AWS Sumerian and Unity continue to grow in capability."

> After the initial hype, a more grounded market outlook for augmented reality is taking hold.

These factors combine to spur the expected significant growth across the AR market. AR providers highlight the importance and numerous advantages of AR solutions in business strategy and employee efficiency while more and more focus on strong collaborations with other related technologies such as IoT data, 5G and artificial intelligence (AI). With 29 million AR smart glasses shipments in 2023, the ballooning install base of head-worn AR combined with hundreds of millions of AR-enabled mobile devices in the same timeframe will make these partnerships a requirement to maintain AR quality of experience while still providing the efficiency and safety increases promised with the technology.

"Allowing time for maturation, combined with ongoing audience education, is key to ensuring a successful AR business story," says Eric Abbruzzese, principal analyst at ABI Research. "Proving value to potential customers in the enterprise with specific, targeted and realistic metrics will win business over the next few years as the addressable market grows. While the consumer market is vastly different from the enterprise market, the basic approach of proving realistic value remains the same. After a few years in the hype cycle, a more grounded market outlook has taken hold. The fact that the potential value and usefulness of AR has not changed as a result points to its revolutionary potential."

10B Global Mobile Connections by 2023, Including 1.3B 5G Connections

Industry trade organization 5G Americas recently announced that global mobile connections will total 10 billion by 2023, according to forecasts provided by Ovum. Also, by the end of 2023, global 5G connections are expected to reach 1.3 billion.

Latin America and the Caribbean continue steady growth of LTE connections and is forecast to reach more than half a billion LTE subscriptions by 2022. Meanwhile, North America's strong leadership in LTE will be replaced with early 5G connections building in 2019, and is forecast to reach 186 million 5G connections by 2023 for a 32 percent share of market.

> Growth of LTE unabated while 5G is beginning to trend upward.

"Growth of LTE is unabated, as LTE added 239 million connections worldwide in the third quarter of 2018," stated Kristin Paulin, senior analyst at Ovum. "Ovum forecasts that LTE will continue to grow well into 2022, and we will see a decline in subscriptions beginning around 2023 due to 5G growth. Regardless, GSM (Global System for Mobile Communications), HSPA (High Speed Packet Access) and LTE (Long Term Evolution) will still be deployed worldwide in 2023."

Forecasts for LTE continue to show very positive growth, with milestones of nearly 4 billion at end of 2018; more than 5 billion by 2020; and about 6 billion in 2022, at which time LTE growth will decline due to the mass market growth of 5G. In 2023, LTE connections will decline to 5.7 billion, when nearly 1 billion GSM connections and 2 billion HSPA connections will remain.

5G will trend upwards beginning in 2019 with less than 1 million global connections. By 2020, this will grow to 37 million, and then more than quadruple to 156 million in 2021. By 2022, 5G connections will exceed 500 million, and the 2023 forecast puts 5G global connections at 1.3 billion.

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- 972 million new LTE subscriptions year-over-year from 3Q 2017; 35 percent growth.
- 3.7 billion LTE connections out of a total 8.45 billion cellular connections worldwide; worldwide market share for LTE is 44 percent.
- LTE connections forecast to reach 6 billion by year-end 2022 (forecast includes M2M).
- LTE global market share forecast to reach 61percent by year end 2022.
- 5G is forecast to reach 1.3 billion connections by the end of 2023.

FCC Prepares Next mmWave Auction

The U.S. Federal Communications Commission (FCC) moved to unleash another massive tranche of mmWave spectrum for mobile service, as it approved an auction of airwaves in the 37, 39 and 47 GHz bands for the second half of 2019. Commissioner Brendan Carr declared 2019 "the year of 5G," noting the new auction plan will "result in more spectrum being auctioned in a single year than at any time in the commission's history."

The auction is the third in a series of mmWave proceedings scheduled by the FCC to open new airwaves for next-generation services. A 28 GHz auction is currently underway, with a separate 24 GHz proceeding set to follow its close. Bidding in the latest auction will be conducted in two stages: participants will make offers on general licences during an initial clock phase before vying for specific frequencies during an assignment phase.

> 3400 MHz of licensed spectrum up for grabs.

The plan also includes provisions for incumbents in the 39 GHz band, giving them the option to bid on new spectrum assignments or relinquish their licences entirely in exchange for monetary compensation.

A total of 3400 MHz of licensed spectrum will be up for grabs, offered in 100 MHz blocks. That figure includes 2400 MHz of airwaves from 37.6 to 40 GHz, which the FCC noted is the largest contiguous swathe of mmWave spectrum offered to date.

An exact date for the proceeding was not set.

Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

Accumet Engineering Inc. and **Laser Services Inc.** announced they will be merging in 2019. Both companies are considered pioneers in their industries: Accumet is known for its skill in precision lapping and polishing services; Laser Services for its custom laser cutting, drilling, marking and welding services. Together, they will provide medical device, microelectronics and military/aerospace OEMs a single source of supply for complete materials processing and assembly services. Both companies are owned by Gregory Sexton, with Sexton acquiring Accumet Engineering in 2015.

Taoglas announced the completion of its acquisition of **ThinkWireless Inc.**, an antenna provider that specializes in the design, development and production of combination antenna systems for the commercial vehicle market. The ThinkWireless brand will become ThinkWireless, a Taoglas company. ThinkWireless Founder and CEO Dr. Argy Petros and Director of RF Technology Pierre Wassom will remain. The ThinkWireless antennas will be available for purchase on the Taoglas website, through key distribution partners and through Taoglas' Antenna Builder ecommerce marketplace for custom antennas and cable assemblies.

COLLABORATIONS

Keysight Technologies Inc. announced that the company's 5G virtual drive testing (VDT) Toolset is helping **MediaTek** to accelerate end-to-end data throughput performance validation of multimode 5G New Radio (NR) Devices. Keysight's VDT Toolset enables 5G chipset and device manufacturers to bridge the gap between lab and field testing. Based on Keysight's PROPSIM F64 5G channel emulator, which emulates real-world RF network conditions, the VDT Toolset uses data captured in the field to build tests. These are then replayed in the field in a controlled laboratory environment as often as needed. This enables MediaTek to validate the performance of new 5G products under typical mobile user conditions.

One of the key use cases of 5G is ultra-reliable low-latency communication (URLLC). Important for advanced vehicle-to-everything (V2X) communication use cases, URLLC will enable automated driving in the future. In a joint project between **Huawei** and **Rohde & Schwarz**, a precision end-to-end delay measurement system for over-the-air (OTA) IP transmissions was applied to 5G V2X communication for cooperative driving applications in field tests in a moving car. A measurement accuracy below 2 μs for each transmitted IP packet was demonstrated. The transmitted data contained various IP traffic streams including video, LIDAR and control data (ITS messages) for a tele-operated vehicle.

Building on their existing partnership, **Avnet** and **Samtec** announced an extension of their distribution agreement. Avnet customers in Asia-Pacific and Japan now have access to Samtec's full product portfolio. Combined with the existing franchise in the Americas, Europe and select Asia-Pacific locations, this global agreement underscores the importance of supporting customers wherever they design and build new technology products.

Modelithics and **ANSYS** will develop the industry's first 3D electromagnetic simulation component model library that will enable customers to accelerate the design of wireless communication systems for 5G, smart devices and the industrial IoT (IIoT). The partnership creates a new industry paradigm for sharing intellectual property (IP) and increases the accuracy of the RF and microwave design process for networking equipment and mobile devices.

Analog Devices has partnered with Chinese autonomous driving technology company, **Momenta**, to develop high-definition (HD) maps for autonomous vehicles. HD maps are a critical element of autonomous driving and must deliver accurate, real-time information to help safely guide the vehicle to its destination. As part of the collaboration, Analog Devices' inertial measurement units (IMU) will be used to improve the mapping system setup and technology upgrades in Momenta's L3 freeway ramp-to-ramp solution and L4 full autonomy driving solutions.

Cree has signed a multi-year agreement to produce and supply its **Wolfspeed** SiC wafers to **STMicroelectronics**. The agreement governs the supply of a quarter billion dollars of Cree's advanced 150 mm SiC bare and epitaxial wafers to STMicroelectronics during this period of extraordinary growth and demand for silicon carbide power devices. The supply agreement enables SiC applications in the broad automotive and industrial markets.

T-Mobile, along with **Intel** and **Ericsson**, has pulled off the first 5G data call and video call using the 600 MHz band for both uplink and downlink communication on a live commercial network. During the tests, the teams generated a 5G signal capable of covering more than a thousand square miles from a single tower. T-Mobile also accomplished a tri-band 5G video call with three users on different spectrum bands—600 MHz, 28 and 39 GHz. The tests represent a step forward for the multi-band spectrum strategy the New T-Mobile will use to blanket the country with transformative next-generation 5G technology.

NEW STARTS

In conjunction with their 50th Anniversary, **AR** has unveiled a new corporate landing page. The page highlights the four divisions that make up the AR family of companies—AR RF/Microwave Instrumentation, AR Modular RF, SunAR RF Motion, AR Europe—and serves as a launching page to each of the four companies. AR RF/Microwave Instrumentation is a source for broadband high-power, solid-state, RF amplifiers and micro-

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wave amplifiers; TWT amplifiers; log periodic antennas and high-gain horn antennas; and EMC test equipment.

Laird Thermal Systems is now a fully-operational, independent business owned by **Advent International**. As a global organization, Laird Thermal Systems has the product portfolio, technical expertise, global manufacturing footprint and lifecycle services to solve complex thermal challenges and deliver optimum thermal management solutions for customers. Laird Thermal Systems works with the world's top brands in the medical, analytical, telecom, industrial and consumer markets.

ACHIEVEMENTS

Anritsu Corp. announced the successful completion of 5G Standalone (SA) connection testing between Anritsu's Radio Communication Test Station MT8000A and a mobile smartphone form-factor test device from **Qualcomm Technologies Inc.**, a subsidiary of Qualcomm Inc., including the company's 5G modem and antenna modules with integrated RF transceiver, RF front-end and antenna elements. This latest milestone follows previous successful joint integration testing of the 5G Non-Standalone (NSA) mode earlier this year. Anritsu has collaborated with Qualcomm Technologies for years on 3G and 4G technologies, helping to support its chipset development, and now delivering comprehensive 3GPP 5G NR-compliant protocol and RF measurement test solutions for the family of Qualcomm® Snapdragon™ X50 5G modems.

Nokia announced winners of **Bell Labs Prize** and **Nokia Open Innovation Challenge (NOIC)**. The Bell Labs Prize is an international competition for innovators with ideas that will significantly "change the game" in the field of information and communications technologies by a factor of 10. The winner of this year's prize is **Samory Kpotufe** for his work in developing a quantitative theoretical basis for transfer machine learning. The NOIC is a global competition that seeks innovative start-up companies with technologies, products and solutions that can change the world. The winner of this year's NOIC is **SPARK Microsystems**, which is developing a low-power wireless transceiver for the industrial IoT (IIoT) revolution.

ZTE Corp. takes the lead in completing IMT-2020 third phase 5G test for core network performance stability and security function, fully verifying the maturity of ZTE's 5G core network. The test involves the performance of the NFVI platform, the service performance of 5G core network element single/multi virtual machine deployment, as well as system capacity and stability. ZTE's system, including NFV platform and 5GC core function network elements, is deployed on the general server platform and interfaces with third party instruments in accordance with the requirement of the service model.

CONTRACTS

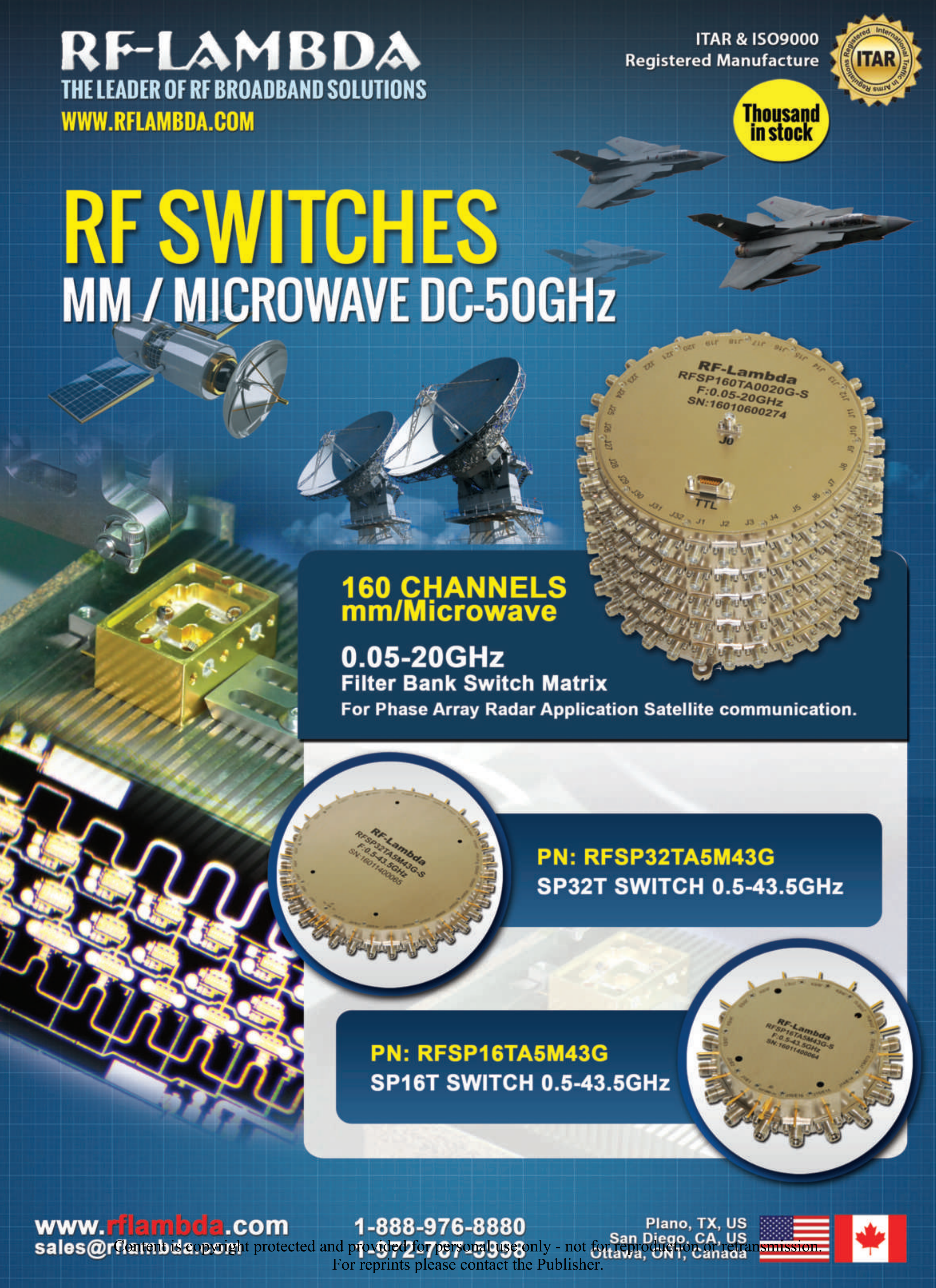
Raytheon has won a $692.9 million **U.S. Army** contract to produce Sweden's Patriot™ Integrated Air and Missile Defense System including spare parts, support and training. Previously announced by the DoD, the contract calls for Raytheon to build and deliver an undisclosed quantity of Patriot fire units and GEM-T interceptor missiles. Patriot is the backbone of Europe's defense against advanced aircraft, drones and ballistic and cruise missiles. Fifteen other nations depend on Patriot to protect their citizens and armed forces, including the U.S. and six other European nations: Germany, Greece, the Netherlands, Spain, Romania and Poland.

The **U.S. Army** has awarded **Harris Corp.** a nearly $218 million follow-on contract to support wideband satellite operations centers and management sites that deliver critical communications to warfighters around the world. The Wideband Satellite Communications Operations and Technical Support II (WSOTS-2) contract will support global networks and operations centers at 21 sites, providing operations and maintenance, life-cycle engineering, on-site technical assistance, equipment installation, depot-level repair, logistics, cybersecurity and training and sustainment. The contract leverages Harris' 30+ year legacy of providing ground systems, on-orbit assets and global communications networking to the Army and other customers, including most recently, executing the first WSOTS $160 million contract.

CACI International Inc. announced that it has been awarded a potential $125 million task order to support integrated business systems for the **U.S. Navy's Military Sealift Command (MSC)**. This five-year contract, awarded under the CIO-SP3 contract vehicle, represents both new and continuing work in CACI's Logistics and Material Readiness market area. MSC replenishes U.S. Navy ships, conducts specialized missions, strategically pre-positions combat cargo at sea and moves military cargo and supplies for deployed U.S. forces and coalition partners. Under this task order, CACI will design, develop, implement and maintain MSC's systems that provide continuous logistics support to the Navy, civilian mariners and Joint Forces.

BAE Systems has received a $78.8 million contract from the **U.S. Navy** for the maintenance and modernization of USS Shoup (DDG 86), an Arleigh Burke-class guided-missile destroyer (DDG). The value of the competitively awarded contract could reach $87.6 million if all options are exercised. Under the depot maintenance availability contract awarded, BAE Systems will dry-dock the ship, perform underwater hull preservation work, upgrade the ship's Aegis combat system and its command and control equipment and rehabilitate crew habitability spaces. The work is expected to begin in March 2019 and be completed in May 2020. The USS Shoup is the 36th ship in the Arleigh Burke class and was commissioned in June 2002.

Kratos Defense & Security Solutions Inc. announced that it has received recent space and SATCOM contract awards and options on existing contracts totaling approximately $65 million. Work performed under these contract awards will be performed at secure Kratos manufacturing facilities and customer locations and is expected to be substantially completed over the next 12 months. The awards include Kratos' products and



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services across technology application domains that are critical to defending space operations and assuring global SATCOM for the U.S. and its allies, as well as certain other operations that are essential to national security.

Intevac Inc. announced it received a contract for $6.9 million for the production of night vision cameras for the Apache Helicopter's Pilot Night Vision Sensor (PNVS) program for the **U.S. Army**. This contract for 144 cameras, from the U.S. Army's PM Apache Office in Huntsville, Ala., will provide cameras for new Apache Airframe builds, Foreign Military Sales (FMS) orders and spares. This contract vehicle enables the U.S. Army to procure additional units through May 2020 at pre-negotiated pricing. The Electronic Image Intensification camera is based on Intevac's patented EBAPS® (Electron Bombarded Active Pixel Sensor) digital imaging sensor for extreme low-light level detection.

The **U.S. Air Force** has been awarded with a $3.6 billion IDIQ contract for Large Aircraft Infrared Countermeasure (LAIRCM) systems and support. Under the contract, the Air Force may issue task or delivery order awards up to the ceiling amount specified in the contract. Work under the contract is set to conclude in 2025. The initial task order is $2.4 million for logistics support services.

Mercury Systems Inc. announced it received a $2.9 million follow-on order from a leading electronics manufacturer for state-of-the-art GPS Selective Availability Anti-Spoofing Modules (SAASM) devices for an undisclosed application. The order was booked in the company's fiscal 2019 second quarter and is expected to be shipped over the next several quarters. In addition to high performance SAASM devices, Mercury's digital microelectronics product offerings include BuiltSECURE™ high density secure memory, precision-engineered BuiltSECURE system-in-package (SiP) devices and secure solid-state storage devices in a variety of form factors. All of the company's digital microelectronics solutions are optimized for SWaP.

Tel-Instrument Electronics Corp. reported the receipt of a $1.6 million follow-on order for Mode 5 test sets from a major U.S. defense contractor. Tel-Instrument is a designer and manufacturer of avionics test & measurement solutions for the global commercial air transport, general aviation and government/military A&D markets. Tel-Instrument provides instruments to test, measure, calibrate and repair a wide range of airborne navigation and communication equipment.

PEOPLE

▲ *Ajay Poddar*

Ajay Poddar has been awarded the **MGA 2018 Innovation Award** for innovation approaches in the development of chapters and engagement of members. The MGA Awards are administered by the MGA Awards and Recognition Committee (ARC). They are awarded to those who have made sub-

Around the **Circuit**

stantial regional IEEE volunteer contributions through innovative projects, exemplary leadership, service or by fulfilling the goals as related to transnational activities.

▲ *Gary St. Onge*

Anokiwave Inc. announced the appointment of **Gary St. Onge** as VP of Business Development. In this role, St. Onge will take on additional business leadership responsibilities in the San Diego office, will increase the company's business footprint in the western U.S. and will provide strategic customer support to key accounts. St. Onge joined Anokiwave in April 2014. Prior to assuming the VP of Business Development position, he was Anokiwave's VP of Sales, where he was responsible for growing Anokiwave's worldwide business.

Vaunix Technology Corp. announced that RF/microwave designer **Anthony Capone** has joined their engineering and customer support team. Capone joins their expert wireless ATE device team in Newburyport, Mass., and will be designing and launching hardware from concept through production. He will be working on both new product development of programmable Lab Brick instruments, and on custom designs integrating synthesizers, amplifiers, switches, phase shifters and attenuators into multi-function units, such as Handover Test Systems.

▲ *Anthony Capone*

REP APPOINTMENTS

Modelithics Inc. and **Wavelength Electronics Ltd.** have recently signed a representation agreement for the support and sales of Modelithics' high frequency simulation model libraries and precision RF, microwave and mmWave measurement services in the U.K. region. Wavelength is a multi-line manufacturer's representative firm specializing in RF and passive components, offering their principal companies' products and services to support U.K. OEMs.

PLACES

MCV Microwave has announced the opening of MCV Microwave East in Laurel, Del. The new 1.23-acre facility allows MCV to expand its capabilities in advanced design engineering and production. The added internal machine shop and environmental testing ensure the company's promise to customers of quick-turn prototyping in filter development and manufacture. MCV Microwave serves Hi-Rel, space and defense, public safety, satellite and commercial wireless markets. MCV is ISO9001:2015 and AS9100D certified.

INVITED PAPER

Challenges for Effective and Realistic 5G OTA Testing

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EMITE Ingeniería S.L.

David A. Sánchez-Hernández
Universidad Politécnica de Cartagena, Spain

The path towards a realistic and cost-effective 5G over-the-air (OTA) testing scenario is not clear yet. With a tremendous pressure on 5G standards development, network deployments and device manufacturing, the realistic answers that a 5G OTA test system should provide are far from being obtained to date. This article identifies some of the challenges ahead with possible solutions.

New Radio (NR) is eagerly expected as the total solution for current wireless communications demands aiming to provide fast throughput and low latency, with a significant improvement in user's quality of service (QoS) and quality of experience (QoE). The primary concern is the need to satisfy the exponential rise in user and traffic capacity in mobile broadband communications. Global mobile traffic will experience a growth from 7,201 petabytes per month in 2016 to around 48,270 petabytes per month in 2021, an astonishing 670 percent growth.[1] NR is also expected to handle an enormous number of devices connected to IP networks, some 3× as high as the global population in 2021, raising up from 2.3 networked devices per capita in 2016 to 3.5 by 2021. To add complexity, a perceived availability of 99.999 percent and ultra-reliability are also envisioned as key features of 5G.

In the race towards satisfying the expected growth, connectivity, availability and reliability, 3GPP and CTIA have emerged as the standardization bodies that will enable adequate OTA testing of the new technologies prior to massive deployment. With the experience of 4G OTA testing standardization history in mind, there are more questions about the capabilities of consensus-driven OTA testing standardization and how it works to solve the real challenges of 5G deployment and operation. With new engineering concepts in 5G like MIMO, beamforming and the generalized use of mmWave frequencies, 5G OTA testing is clearly the challenge of the decade for wireless communications and a key milestone for 5G deployment and operational success.

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TABLE 1
3GPP 5G DUT ANTENNA CONFIGURATIONS AND OTA TEST METHODS

DUT Antenna Configuration	Description
1	Maximum one antenna panel with D ≤ 5 cm active at any one time
2	More than one antenna panel D ≤ 5 cm without phase coherency between panels active at any one time
3	Any phase coherent antenna panel of any size (e.g., sparse array)

DUT Antenna Configuration	Direct Far Field (DFF)	Indirect Far Field (IFF)	Near Field to Far Field Transform (NFTF)	Near Field without Transform (NFWOTF)	Reverberation Chamber (RC)
1	Yes	Yes	Yes	Yes	Yes
2	Yes	Yes	Yes	Yes	Yes
3	No	Yes	No	No	No
	Approved in RAN4 [3GPP TR 38.810 v2.0.0]		Approved in RAN4 [3GPP TR 38.810 v2.1.0]	Not Approved in RAN4 [3GPP TR 38.810] yet for variety of reasons	

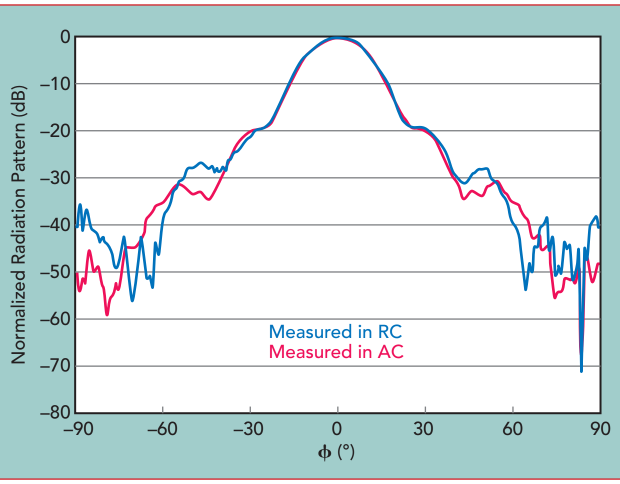
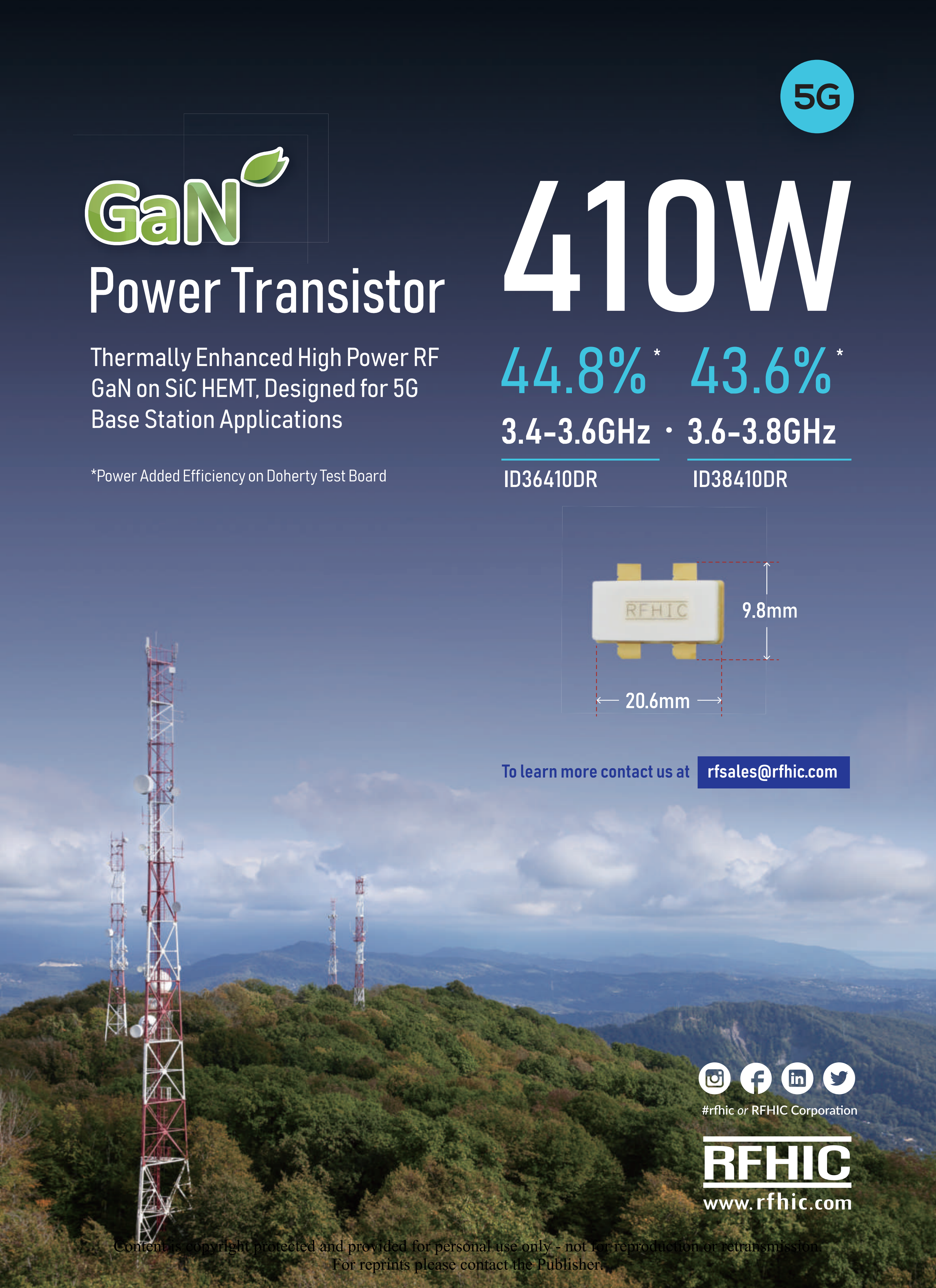


Fig. 1 AUT H-plane radiation pattern measured in RC and in AC (reproduced from Reference 2 with permission).

5G OTA TEST METHODS

Three different 5G device under test (DUT) antenna configurations and several 5G OTA test methods are being discussed within 3GPP TR 38.810, summarized in ***Table 1***. The Reverberation Chamber (RC) method can be very useful for isotropic Key Performance Indicators (KPI), particularly total radiated sensitivity (TIS) or spurious emissions, and recent progress has added the capability of directional measurements by means of either time-reversal or Doppler-discrimination effects,[2] as shown in ***Figure 1***. Non-conventional uses of RCs for 5G OTA measurements are also being explored, in particular for devices designed to function in directional-channel environments[3] and for real-time OTA testing of throughput and latency. RC-based methods have some positive aspects for 5G Non-Standalone (NSA) and Standalone (SA) OTA testing, like considerably-reduced setup cost compared to other solutions for the complex multicarrier requirements. While spatial information may be partially lost in these rich multipath systems, an average 3D isotropic emulation of delay and final throughput performance, which is after all what the user perceives in a reasonable time slot, may very well serve the purpose. Yet, little progress has been made for 5G OTA using isotropic 5G channel model emulation using RCs and with RCs lack of strong support at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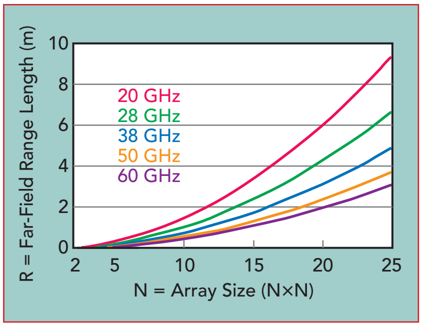
3GPP, it is not yet a 5G-standardized test method.

Extending the multiprobe anechoic (MPAC) approach to 5G implies the use of 3D channel models and mmWave operation, which makes it impractical due to the increase in complexity and the fact that too many probes would be needed, with their associated channel emulator ports, and the effect on the already-reduced quiet zone will be large. Although some simplified sectorized MPAC variations have been proposed, the additional need to operate in the far-field makes the use of MPAC for 5G OTA limited, at least at mmWave frequencies.



▲ Fig. 2 Far-field range for an N×N array of λ/2 spaced elements.

▲ Fig. 3 H300 CATR+DFF+SNF 5G OTA Test System by EMITE.

The incorporation of the Radiated Two-Stage (RTS) method into standardized 5G OTA testing is benefiting from an apparent harmonization to the MPAC method using seven 4G LTE FDD devices in single 2×2 single-carrier MIMO OTA mode, but the "Wireless Cable" is not transparent with respect to the DUT antenna characteristics, as these must be measured beforehand for the method to be applicable. In addition, the RTS method cannot yet support the user equipment (UE) beamlock test function (UBF) for 5G UEs which is clearly a limiting factor for standardized OTA testing. On the other hand, the electrical size of DUT is only limited by the size of the test chamber.

The Indirect Far Field (IFF) Compact Antenna Test Range (CATR) method can create a plane-wave field in much less space than a Direct Far Field (DFF) method by means of a reflector, and it seems ideal for 5G mmWave OTA testing, but it has difficulties providing different frequency ranges. With the options on the table, CTIA operators have recently considered the IFF method as essential for consideration during development of the CTIA 5G NSA mmWave OTA Test Plan v1.0,[4] due for release in 2Q 2019.

The Near Field to Far Field (NFTF) method relies on using a mathematical transformation to determine the KPIs in the far field from a near-field pattern scan. The NFTF method shows deficits with respect to testing during real-time operation of the device. Initially, Equivalent Isotropic Radiated Power (EIRP) and Total Radiated Power (TRP) have been reported to be measured by NFTF test systems.

The Direct Far Field (DFF) method requires Fraunhofer far-field distances and for mmWave frequencies, it is not practicable due to the space and cost requirements and the large link budget. ***Figure 2*** illustrates how the far-field range for an N×N array of half-wavelength spaced elements increases dramatically as the size of the array increases. The hybridization of DFF for use at 5G sub-6 GHz frequencies, however, it may be quite useful since other methods present drawbacks at low frequencies.

It is clear that there is no single OTA method today capable of providing answers to all the challenges of 5G testing. Several companies and institutions have called for the development of new or hybridized test methods that can provide the required answers to the numerous 5G OTA challenges presented. One good option is the recently-released

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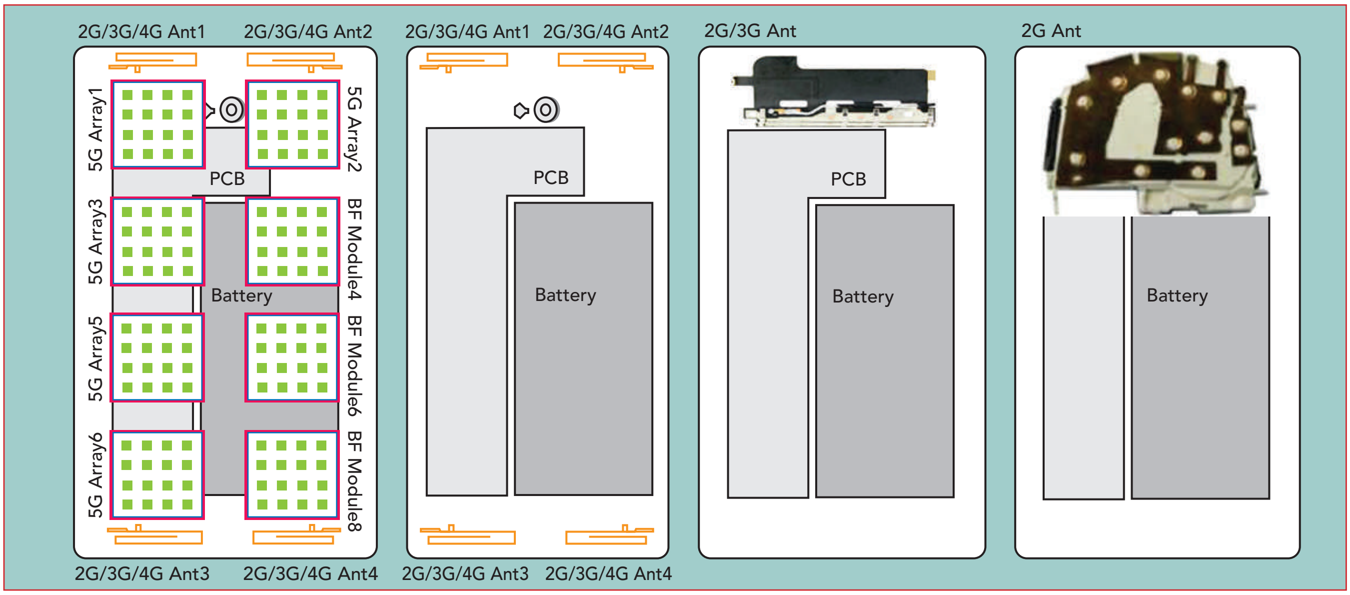

Fig. 4 The antenna layout evolution on UEs.

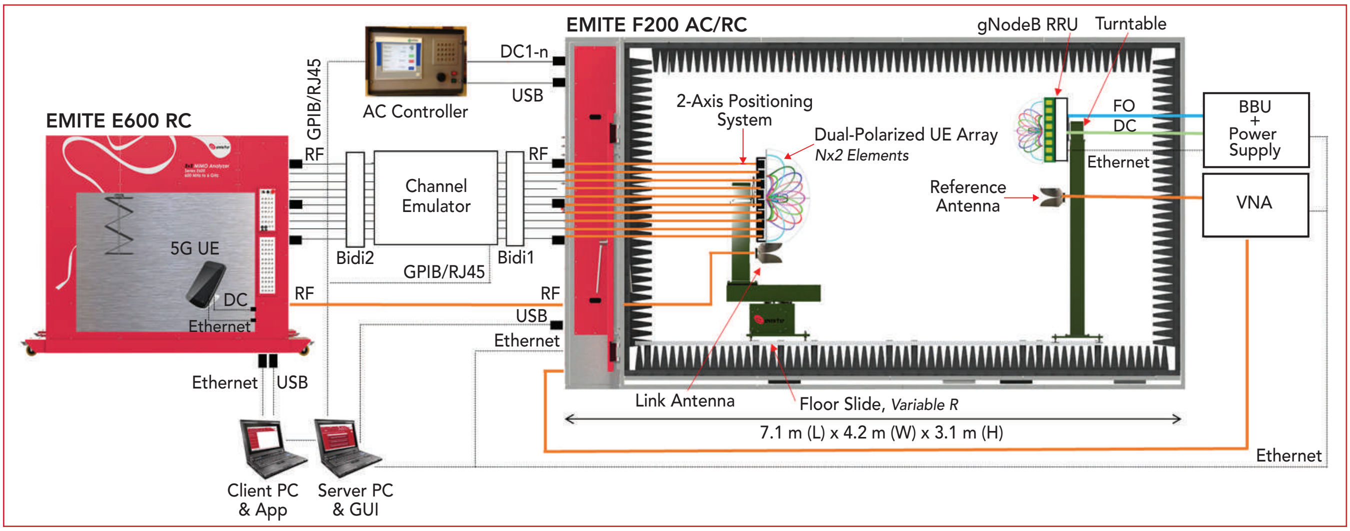

Fig. 5 gNodeB-UE E2E 5G OTA testing vs. range with two cascaded chambers.

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8SFB-250M20G-CD-SFF https://www.pmi-rf.com/product-details/8sfb-250m20g-cd-sff	0.25 - 20	8 dB Max	100 ns	10	+15 VDC @ 500 mA Typ, -15 VDC @ 100 mA Typ	1U / 19" Rack SMA Female
7SFB-950M18G-CD-SFF https://www.pmi-rf.com/product-details/7sfb-950m18g-cd-sff	0.95 - 18.05	9 dB Max	100 ns	8	+15 VDC @ 200 mA Typ, -15 VDC @ 200 mA Typ	4.33" x 5.1" x 0.98" SMA Female
5SFB-DC26G-CD-SFF https://www.pmi-rf.com/product-details/5sfb-dc26g-cd-sff	DC - 26	10 dB Max	500 ns	5	+5 VDC @ 150 mA Max, -15 VDC @ 100 mA Max	3.0" x 2.60" x 0.75" SMA Female
4SFB-2G18G-CD-SFF https://www.pmi-rf.com/product-details/4sfb-2g18g-cd-sff	0.2 - 18	8 dB Max	200 ns	4	+5 VDC @ 115 mA Max, -15 VDC @ 115 mA Max	3.0" x 2.6" x 0.75" SMA Female
2SFB-8G26G-CD-SFF Rev C https://www.pmi-rf.com/product-details/2sfb-8g26g-cd-sff-rev-c	8 - 26.5	5.5 dB Max	100 ns	2	+5V ± 5% @ 100 mA Max	1.5" x 0.8" x 0.5" 2.92mm Female
SFB-6G18G-2CH-6DB-500NS-SFF https://www.pmi-rf.com/product-details/sfb-6g18g-2ch-6db-500ns-sff	6 -18	6 dB Max	500 ns	2	+5 VDC @ 100 mA Max, -5 VDC @ 50 mA Max	2.75" x 1.75" x 1.06" SMA Female
6SFB-100M18G-1MP-MAH-TX https://www.pmi-rf.com/product-details/6sfb-100m18g-1mp-mah-tx	0.1 - 18	30 dB Gain Typ	100 ns	6	+12 VDC @ 255 mA Typ, +5 VDC @ 33 mA Typ, +3.3 VDC @ 0 mA Typ, -12 VDC @ 23 mA Typ	4.925" x 3.68" x 0.35" SMA Female

4SFB-2G18G-CD-SFF

2SFB-8G26G-CD-SFF Rev C

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CATR+DFF+SNF 5G OTA Test System shown in ***Figure 3***. A specific and optimized reflector design covers both the mmWave region (Frequency Range 2 or FR2) and part of the sub-6 GHz region (Frequency Range 1 or FR1), and a hybrid DFF/SNF tower completes the picture to provide full-range and simultaneous FR1+FR2 OTA testing.

CHALLENGES FOR 5G OTA TESTING

Fully-integrated antenna arrays

In addition to a densely antenna-populated layout, illustrated in ***Figure 4***, and unlike previous generations, 5G UE antenna arrays do not provide access to their RF ports due to small form factor and higher frequencies for some bands. Testing connector-less antenna arrays is an obvious challenge, which forces RF tests and calibrations to be performed OTA in a well-controlled environment. Phase calibration between the chains is typically required in addition to signaling performance tests and power measurements. The fact that coupling may occur and the limitations of the testing enclosure make the coherent calibration of each RF chain not necessarily leading to optimal beams. The up- or down-conversion for operating at mmWave frequencies further complicates the testing equipment.

DUT form factors

Each DUT form factor type has specific requirements and restrictions. Chipset 5G OTA measurements can be defined as the test that provides the chipset RF performance evaluation in the real SA environment.[5] It is good that chipsets are small since the mmWave wavelengths of 5G frequencies are also small, and therefore the issues with large far-field distances are minimized. The problem arises due to the fact that the chipsets usually do not have RF connectors and are also very fragile. Two other chipset-specific challenges for 5G OTA testing are the need to accurately control temperature and humidity cycling within the chamber due to the chipset being sensitive to environmental conditions and the fact that for mass production chipsets may need to be measured in the form of panels. With each panel containing a lot of similar types of chipsets, their accurate and individual 5G OTA testing becomes a very challenging task. Controlling the temperature and the humidity within any OTA test environment is also a challenging task, and only two companies have announced such feature at their test systems to date, R&S and EMITE.

5G OTA UE testing is thought to be, at least initially, compatible with legacy 4G technologies. While it has been proposed that 4G OTA methods should be attempted first for the new 5G devices, it is also clear that 5G OTA testing will further be complicated if we have to also support 4G OTA testing simultaneously.

gNodeB testing, in addition to their associated larger size, also requires phase coherency calibration, which is currently a concern due to the large number of channels. The specific OTA measurements challenges of high directivity beam performance, not only for the gNodeB end but also for the 5G UE end, deserve its own section in this technical feature.

Spatial agility

Spatial intelligence is another key performance aspect of 5G. The 3GPP has defined centered and off-center KPIs for static beams, but the beam dynamics are an inherent part of 5G. Processes such as beam searching, beam matching, beam tracking, beamforming or beam scheduling, among others, become essential when the UE moves dynamically. When the gNodeB incorporates massive MIMO, the spatial non-stationary property, the angular spreads and the 3D spatial properties cannot be ignored. Since the number of probe antennas is large, the channel between different probe antennas has a strong correlation, and removing the impact of the channel correlation across gNodeB antennas and probes remain an issue of concern.

Finally, the addition of multiuser bidirectional channels introduces yet additional challenges to the OTA test. Interestingly enough, the whole 5G gNodeB-UE end-to-end (E2E) set seems to be attracting

the most attention, as it is the pair that provides a specific user-performance. Extraordinarily complex cascaded chamber sets are being proposed for this type of testing, aiming at getting accurate and realistic KPI evaluation vs. range when using power-fix connectorless gNodeBs in one end and a moving UE on the other end. In this type of OTA test setup, shown in ***Figure 5***, for NR beam steering, beamforming or baseband beam tracking algorithms performance testing, real-time throughput, latency and mobility tests are being proposed. One chamber captures the 5G signals coming from the gNodeB and redirects them to a channel emulator and an attenuator matrix, which in turn attenuates and re-route the signals to a second chamber, an RC or AC, in which the 5G UE is located. This represents a breakthrough over previous single-chamber OTA test setups, with a lot more complexity, associated required expertise and cost.

Channel modeling

Realistic channel modeling represents yet another key aspect of 5G OTA testing. Several studies have found some extensibility of the existing 3GPP channel models to be somehow applicable at higher frequency bands up to 100 GHz. The measurements indicate that the smaller wavelengths introduce an increased sensitivity of the propagation models to the scale of the environment, which is to be expected, and show some frequency dependence of the path loss as well as increased occurrence of blockage. Furthermore, the penetration loss is highly dependent on the material and increases with increasing frequency of operation. The shadow fading and angular spread parameters are larger and the boundary between line of sight (LOS) and non-line of sight (NLOS) depends not only on antenna heights but also on the local environment. This has simplified some initial proposals, but the main drawback remains on how to model a signal that is divided into several carriers and MIMO paths which can extend from very different frequency bands. It is expected that FR1+FR2 bands will be successfully combined, providing total user throughputs in excess of tenths of Gbps and new channel modeling challenges.

CONCLUSION

5G is expected to bring significant benefits for the wireless communications industry, but it also carries the need for drastic changes in the way of how OTA testing is performed today. Performance metrics and cost-efficient ways to measure 5G equipment in a lab that is close to real world use are urgently required. This will necessarily include testing the main beam, testing in the presence of other radios in same channel and testing the communication performance against interference from different directions, evaluating also the dynamic adaptation performance of both sides—the UE and the gNodeB.

While some progress has been made, consensus-based 3GPP standardization is far from reaching the goal, and is currently limiting the scope of what can be achieved in terms of solving the existing real challenges. Failure to meet the expectations is not realistic at this stage of the process, and developing accurate and realistic OTA test methods is also the responsibility of the scientific community. We still have time, but it is rapidly running out.■

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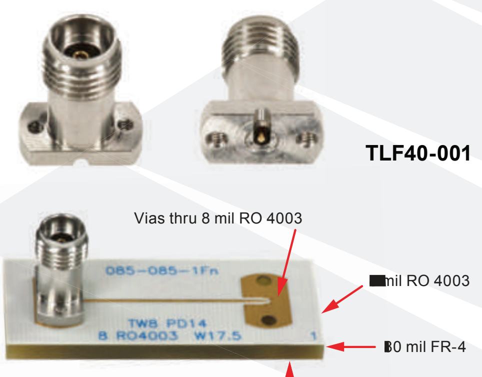

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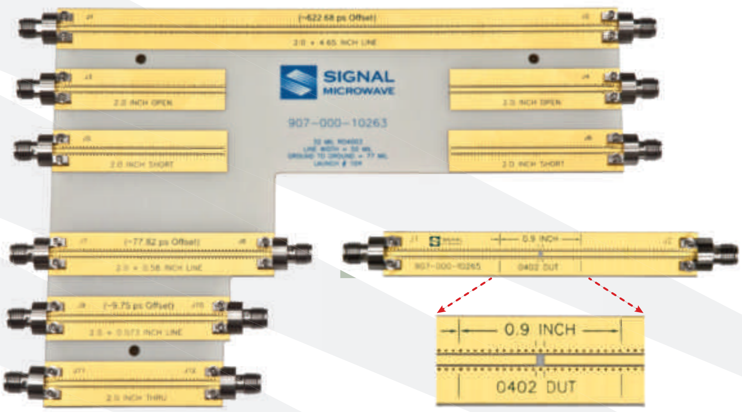

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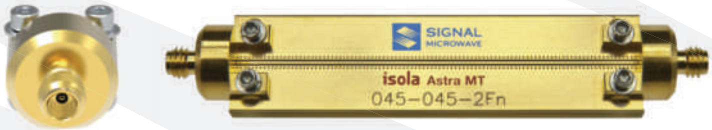

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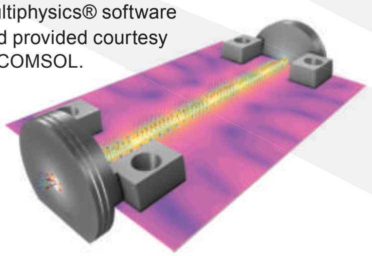

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SIGNAL MICROWAVE

INVITED PAPER

Using a COTS SDR as a 5G Development Platform

Bob Muro
Pentek Inc., Upper Saddle River, N.J.

This article is intended to familiarize radio engineers with the use of a multi-purpose commercial off-the-shelf (COTS) platform for software-defined radio (SDR) that can reduce development time for 5G.

COTS SDR has been traditionally used in military radar and communications applications for high performance and design flexibility. The latest COTS SDR products offer solutions with integrated I/O, ARM processors and large FPGAs that also include intellectual property (IP) for accessing, routing and processing digital data. These attributes, combined with superior signal integrity, phase-coherent sampling and multi-channel transceivers, make a COTS SDR system an ideal choice for a 5G development platform.

COTS SDR DEFINED

For clarity, each section of this article is divided into subsections discussing hardware, firmware and software. Hardware comprises the SDR printed circuit board (PCB) and supporting components; firmware includes the internal FPGA code for logic and digital signal processing (DSP) functions; and software is the C code that controls the FPGA with firmware and performs any additional DSP functions.

Hardware

An SDR replaces legacy analog systems consisting of RF filters, analog down-convertors (i.e., the local oscillator and mixer), bandpass filters and demodulators (see ***Figure 1a***). These fixed analog systems are limited to a specific function, such as an AM or FM radio.

An SDR exploits programmable DSP techniques to flexibly handle the increasing complexity, precision and bandwidth of today's radio traffic. To use the SDR, data conversion is required between the antenna and DSP for both receive and transmit functions.[1] An SDR receiver converts an RF signal from an antenna into digital samples with an analog-to-digital converter (ADC) and uses subsequent DSP operations to extract the required information from the signal (see ***Figure 1b***). An SDR transmitter accepts digital information to be transmitted and performs the necessary DSP operations to produce digital samples for a digital-to-analog converter (DAC), whose output drives a power amplifier for delivery to the antenna (see ***Figure 1c***). Because these radios are software-defined, they can be programmed on-the-fly in microseconds with new parameters or re-configured for different purposes by simply loading new firmware from internal or external memory.

An SDR is often implemented on a specialized PCB called a "mezzanine card." The current generation is either a switched-fabric mezzanine card (XMC) or an FPGA mezzanine card (FMC). ***Figure 2*** shows XMC and FMC mezzanine cards with their corresponding functional block diagrams. Figure 2a is an XMC card with four 200 MHz ADC channels, and Figure 2b is an FMC card with two 3 GHz ADC channels and two 2.8 GHz DAC channels. Each board includes a precision timing system with a multi-bit, fractional synthesizer for variable sampling rates, which is locked to an on-board oven-controlled crystal oscillator (OCXO) or a reference input signal. These timing systems usually accept external synchronization signals from a network time protocol server or GPS receiver for the precise timing requirements of a radar or

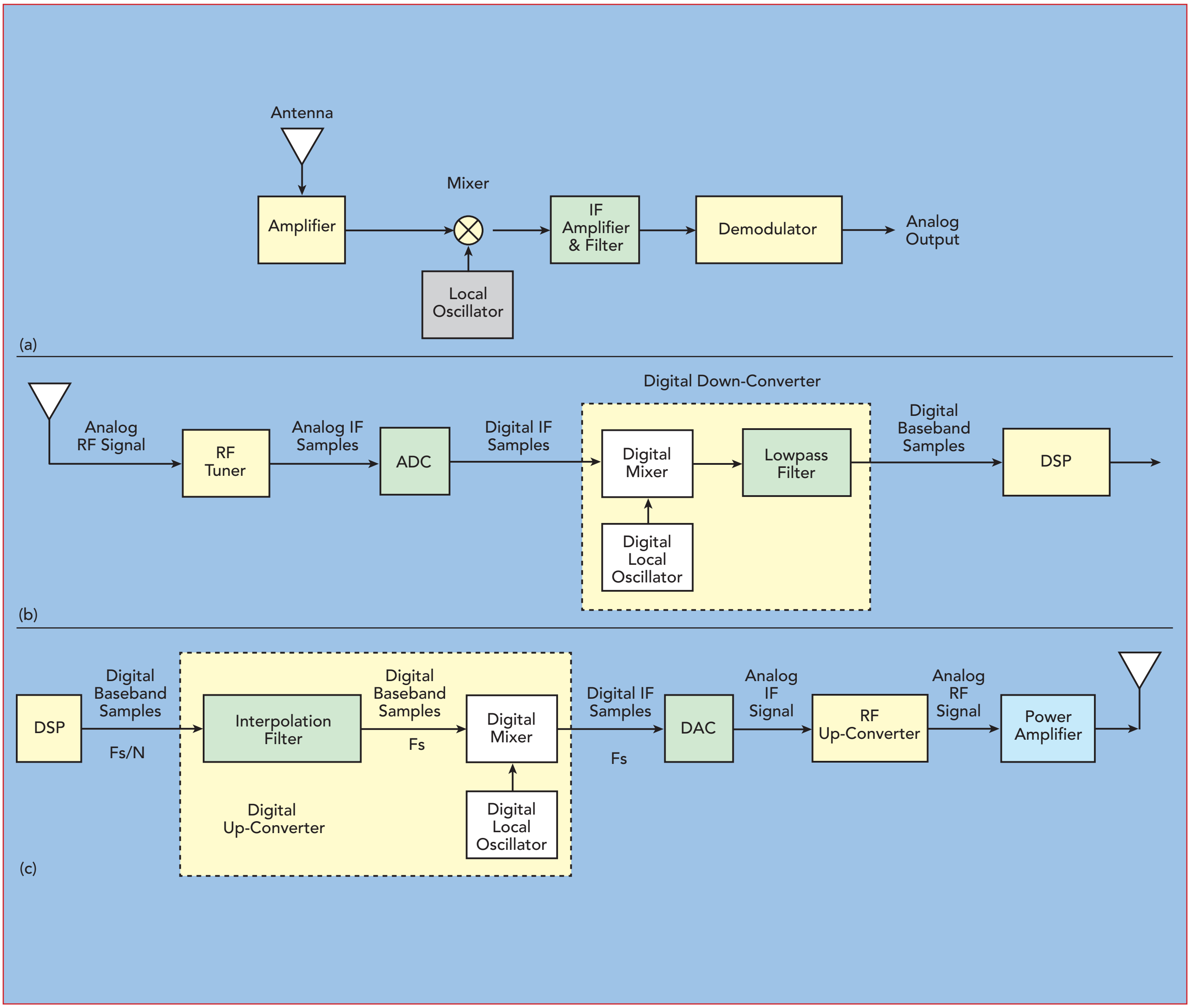

Fig. 1 **Legacy analog communications receiver (a) vs. SDR receiver (b) and SDR transmitter (c).**

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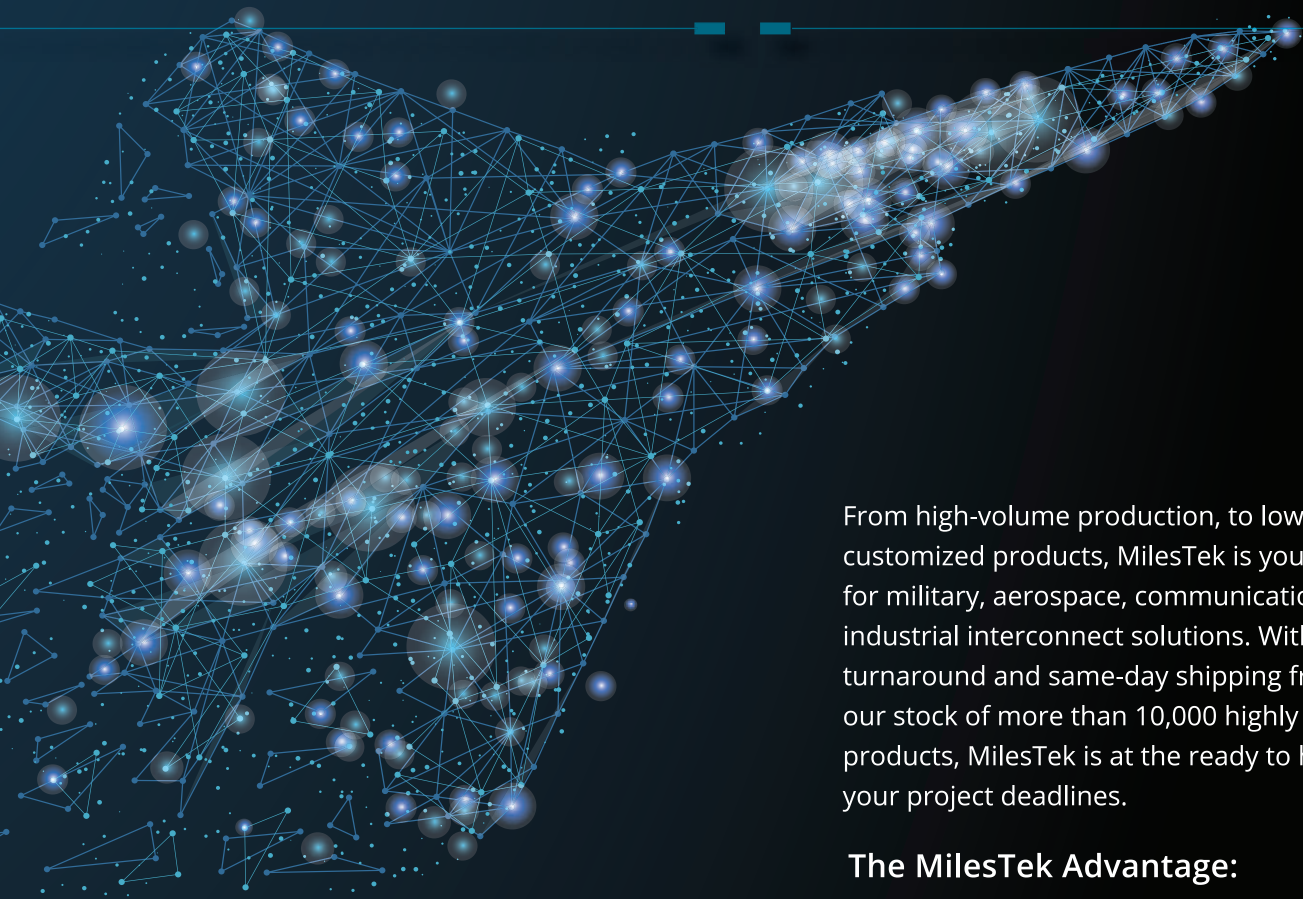

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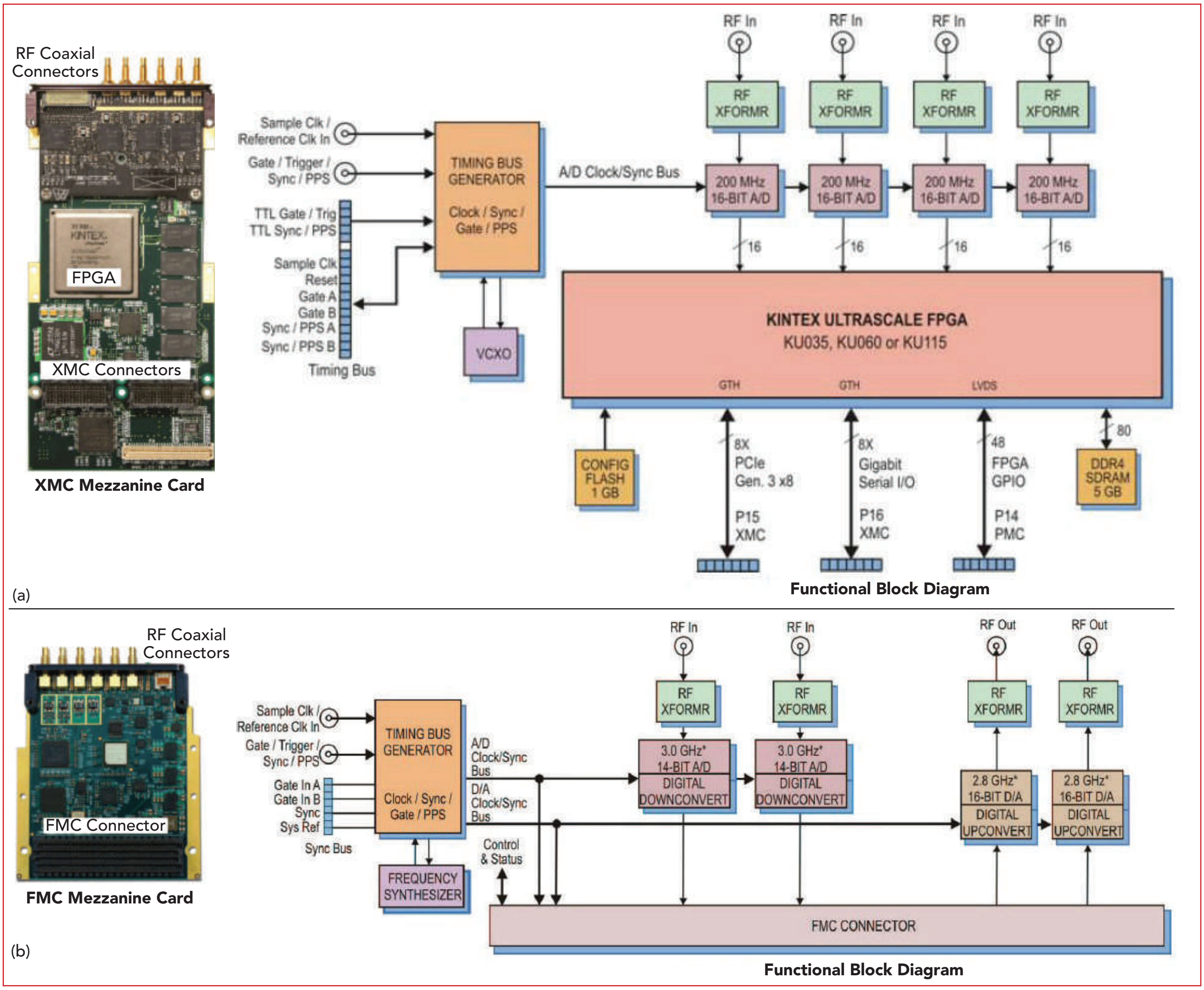
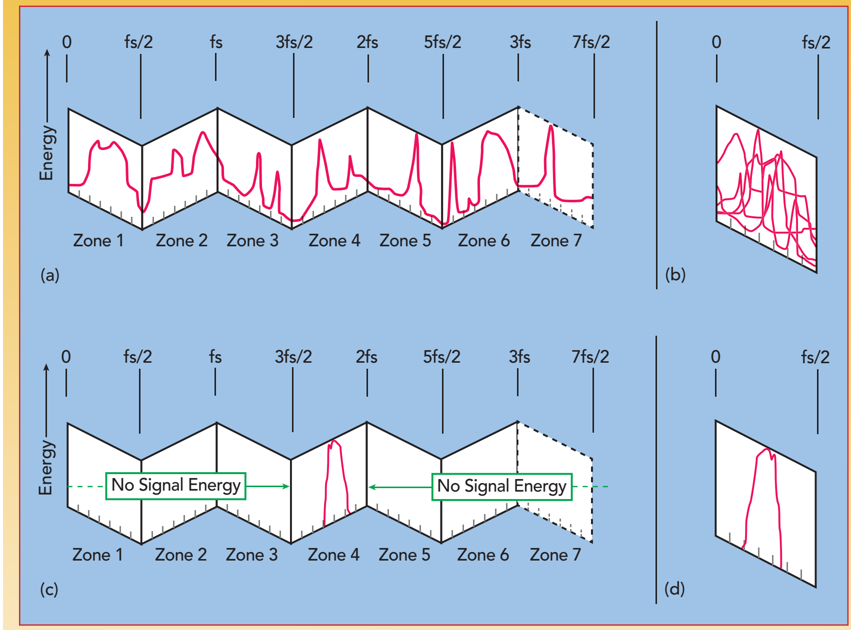


Fig. 2 XMC (a) and FMC (b) mezzanine cards and functional block diagrams.

Nyquist Zones and Undersampling



The Nyquist Theorem states: "Any signal can be represented by discrete samples if the sampling frequency is at least twice the bandwidth of the signal," where bandwidth is distinguished from frequency when explaining undersampling. Fan-fold printer paper can illustrate the concept of Nyquist zones (see **SB Figure 1a**), which are defined as multiples of half the sampling frequency, fs. If fs = 200 MHz, fs/2 = 100 MHz and successive Nyquist zones occur every 100 MHz.

All signal energy must fall within one Nyquist zone to satisfy both the bandwidth and frequency requirements of the Nyquist Theorem. The wideband signal shown in Figure S1a crosses multiple Nyquist zones and violates the "single zone" rule. Collapsing the fan-fold paper illustrates the result of sampling this wideband signal at fs: the signal energy above fs/2 will be "aliased" into the first zone, as shown in **SB Figure 1b**. Adding a lowpass filter to remove the frequencies above fs/2 before sampling will prevent aliasing.

However, aliasing can be beneficial when used on a narrowband signal that falls in an upper Nyquist zone, if the energy from the other zones is eliminated with a suitable bandpass filter (see **SB Figure 1c**). This is called undersampling.[1] In the Figure, the narrowband signal falls within Nyquist Zone 4, between 300 and 400 MHz if fs = 200 MHz. Although the signal frequency is above fs/2, the spectrum is contained within a single zone, satisfying the Nyquist Theorem. Undersampling this signal will alias it to Zone 1 (see **SB Figure 1d**) where signal processing is easier.

cellular system. Precise time alignment is also required for phase-coherent sampling of the ADCs, FPGA DSP data synchronization and DAC signal transmission.

The XMC ADC has a 200 MSPS maximum sampling rate that can capture a 100 MHz Nyquist bandwidth, excluding filtering. A common technique with digital radio is to acquire channel information or intermediate frequency (IF) bandwidth by undersampling the signal (see **Sidebar Nyquist Zones and Undersampling**). Undersampling allows an ADC with a lower sample rate and higher dynamic range to capture a narrow bandwidth signal centered at a higher frequency without loss of information. For this to work correctly, the RF input path and the ADC must accommodate these higher frequency signals.

After analog-to-digital sampling, the next stage is typically the digital down-convertor (DDC), which performs frequency translation and bandwidth reduction. The DDC is often implemented as IP firmware within the FPGA.

Firmware

An FPGA consists of unconnected logic, arithmetic and signal processing building blocks that are configured with IP firmware to perform specific functions. While ideal for extreme programming flexibility, firmware development is complex. To simplify the development process, some COTS SDR manufacturers provide FPGA IP for basic operation of their boards. This usually includes analog and digital I/O functions for acquiring and transmitting data, with DSP IP for specific radio functions like DDCs, filters, channelizers and engines to transfer data to the system.

The DDC function requires three IP building blocks: the numerically controlled oscillator (NCO) local oscillator, a complex mixer and digital filters to replace the functions of the legacy analog radio system

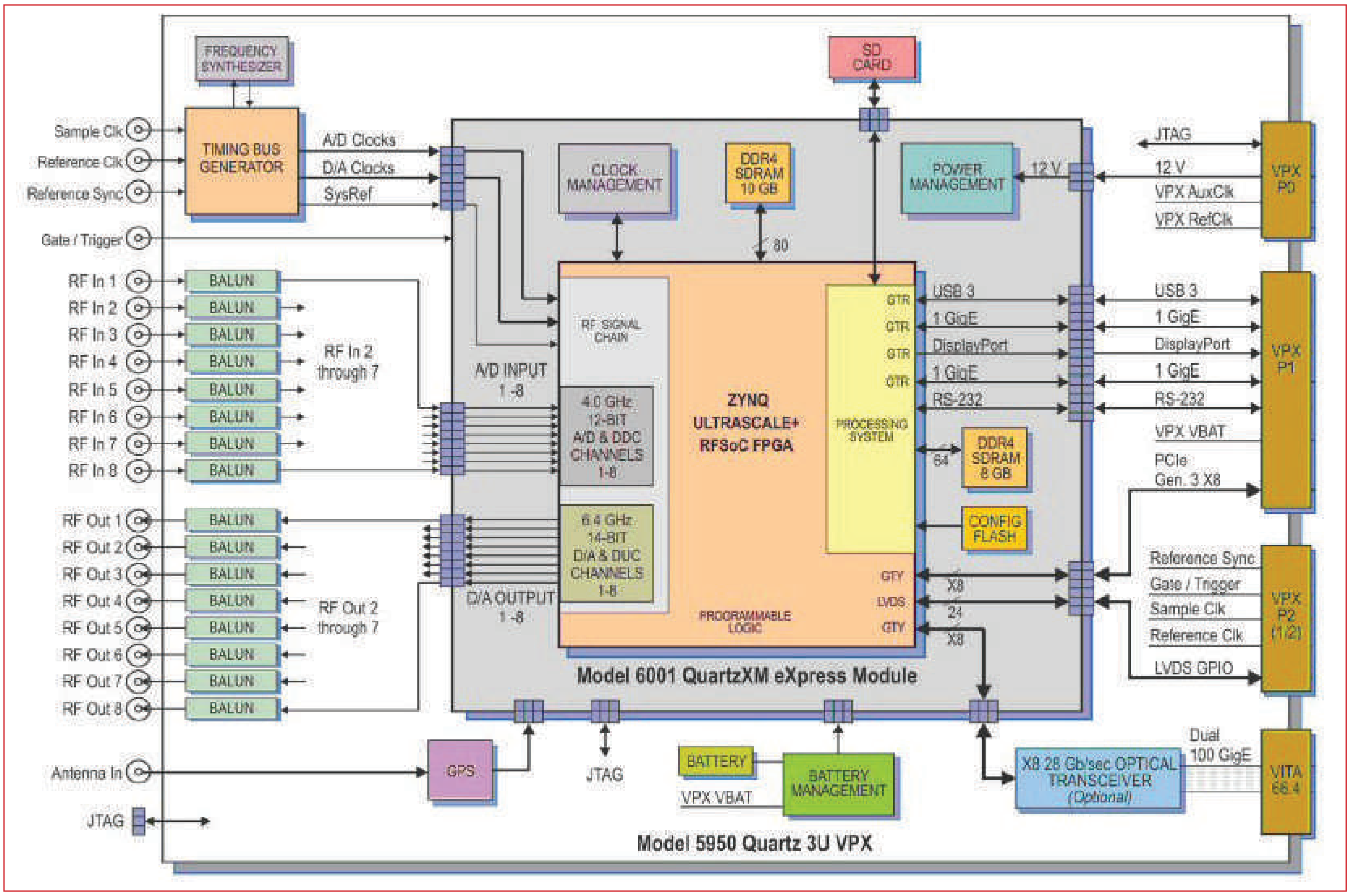


Fig. 3 **Pentek COTS SDR based on the Xilinx RFSoC.**

(see Figure 1). The tuning stage of the DDC uses a complex digital mixer to translate the frequency of interest to baseband. A pair of multipliers driven by a direct digital synthesizer (DDS) NCO allows the user to "tune" the receiver to the desired frequency. The samples are then passed through a lowpass finite impulse response (FIR) filter to decimate the signal for a finite channel bandwidth. Two key benefits of the DDC are higher signal-to-noise ratio (SNR), as a result of decimation, and the ability to tune to the narrowband center frequency of the signal (see **Sidebar Improving SNR with Digital Processing**). Decimating the signal effectively lowers the sample rate and reduces uncorrelated white noise, and the NCO enables precise digital tuning to a specific carrier frequency within a single Nyquist zone.

Improving SNR with Digital Processing

The calculation of the theoretical SNR of an ADC is SNR = 6.02N + 1.76 dB, where N is the number of bits in the ADC.[2] For a 200 MHz, 16-bit ADC, SNR = 6.02•16 + 1.76 dB = 98 dB. This calculation assumes the input signal is full-scale, so the actual SNR is likely lower because the gain of the front-end LNA will be reduced, "backing off" to compensate for high crest factor communication signals. The theoretical SNR will be further reduced because of ADC nonlinearity, additional noise from the LNA input and sample clock jitter. The actual measured SNR for a good quality ADC is limited to approximately 75 dB.

However, the dynamic range can be improved by reducing the bandwidth using a DDC, from the full Nyquist bandwidth to the channel bandwidth of the system. For example, the calculated SNR for a 200 MHz ADC with $f_{Nyquist} = fs/2 = 100$ MHz and a 5 MHz LTE channel bandwidth (BW) will be $SNR_{PG} = SNR_{Nyquist} + 10\log_{10}(f_{Nyquist}/BW) = 75 + 10\log10(100/5) \approx 88$ dB, a 13 dB improvement.

Software

While the vendor-provided FPGA IP might meet the specifications for a specific application, the system implementation may require controlling software to operate the radio. The FPGA IP needs operational parameters sent across the system interface from a software program, which is the function of a board support package (BSP) normally written as "C" callable routines for a Windows or Linux environment. The BSP contains library functions and precompiled example code that can be executed to test board functionality. One such function is commanding the ADC to capture and transfer data to the FPGA for further processing in the DDC. This processed data can be stored in memory or transferred to the DAC for conversion back to an analog signal and output for transmission. This is an example of a software program developed using the BSP software library functions and drivers. If any new FPGA IP is created by the user, additional control software must be written and included in the BSP package.

LATEST COTS SDR TECHNOLOGY

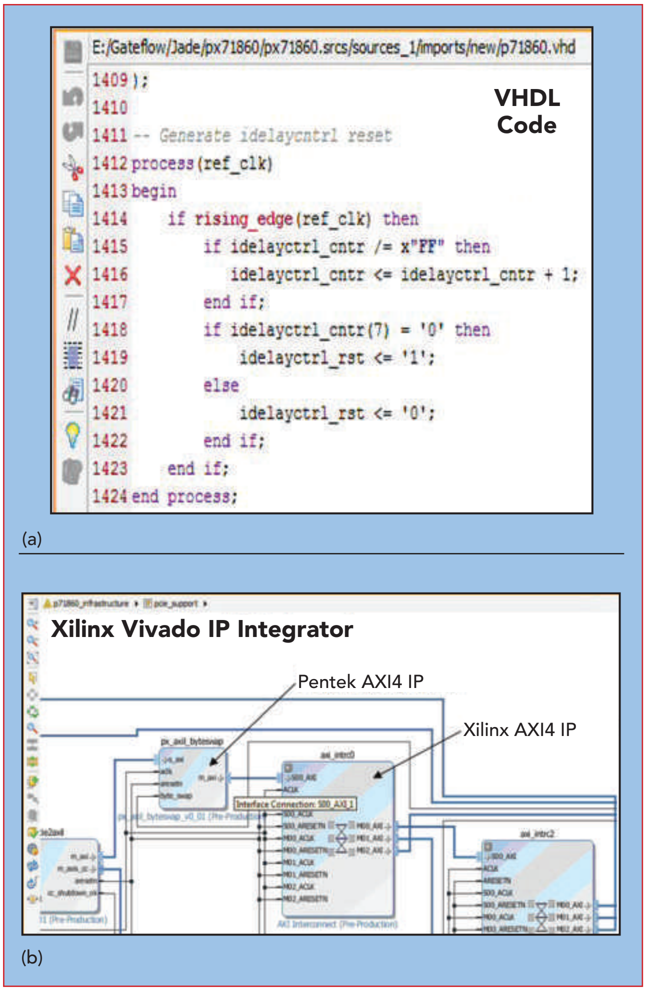
Hardware

Over the past 10 years, FPGA manufactures like Xilinx have been improving technology by reducing the size of silicon process nodes, which reduces device size, weight and power (SWaP). In late 2008, the Xilinx Virtex-6 family was constructed using a 40 nm process and averaged 2000 DSP slices per FPGA. By 2017, the Ultrascale family was on a 20 nm process, and the FPGA DSP slices increased to approximately 5,500. The latest system on a chip (SoC) from Xilinx, the RFSoC, consists of an FPGA fabric with ARM processors, ADCs and DACs, all on the same chip. The 16 nm technology has over 4,200 DSP slices; four 1.5 GHz, A53 ARM processors; two 600 MHz, R5 ARM processors; eight 4 GHz, 12-bit ADCs; and eight 6.4 GHz, 14-bit DACs per device.

Figure 3 shows a functional block diagram of one COTS implementation of the Xilinx RFSoC, the central component of the 5950 3U VPX board from Pentek. The center area including the RFSoC is a fully connectorized system on module (SoM) that plugs into a 3U VPX carrier. While this device can be controlled via a Gigabit Ethernet port, similar to the previous generation FPGA, the on-board ARM processors allow autonomous operation and the ability to communicate with, or control, devices locally or on an external network.[3]

Firmware

Previous generation FPGAs were programmed using a textual hardware description language (HDL) like VeriLog or very high speed integrated circuit description language (VHDL). The latest AXI4 compliant IP blocks are included in Vivado from Xilinx. The IP Integrator tool from Xilinx has virtual graphical blocks that represent HDL code, which can be connected to one another via drag-and-drop wiring. ***Figure 4*** shows an example of VHDL code (see Figure 4a) and the corresponding drag-and-drop graphical blocks (see Figure 4b). This more intuitive way to program allows someone new to FPGAs to wire together logical blocks representing hardware like FIR filters and DDCs to create an SDR. This programming method supports fast integration of vendor-supplied, hardware-specific IP blocks with Xilinx IP blocks to create a working SDR. Both IP block types can be combined to create a common library.



▲ Fig. 4 Xilinx IP Integrator tool, showing VHDL code (a) and intuitive "drag and drop" graphical blocks (b).

Software

These IP programming advances have provided an opportunity for COTS vendors to create a single BSP module that corresponds to one IP module with all the necessary FPGA program parameters in one location. One example is a "clock control BSP module" that corresponds directly to a "clock control IP module."

5G APPLICATION

This latest generation of SDR technology is game changing and can be used by COTS manufacturers to provide multi-channel SDR transceivers for engineers developing 5G radio products.

Figure 5 illustrates the difference between distributed and centralized radio access networks, D-RAN and C-RAN. With LTE, the traditional D-RAN cell sites were being replaced by newer C-RANs to improve data transfer efficiency and reduce radio cost. However, the mmWave massive MIMO architecture for 5G requires the separation to move the remote radio head (RRH) closer to the end user because of the increased RF path loss.

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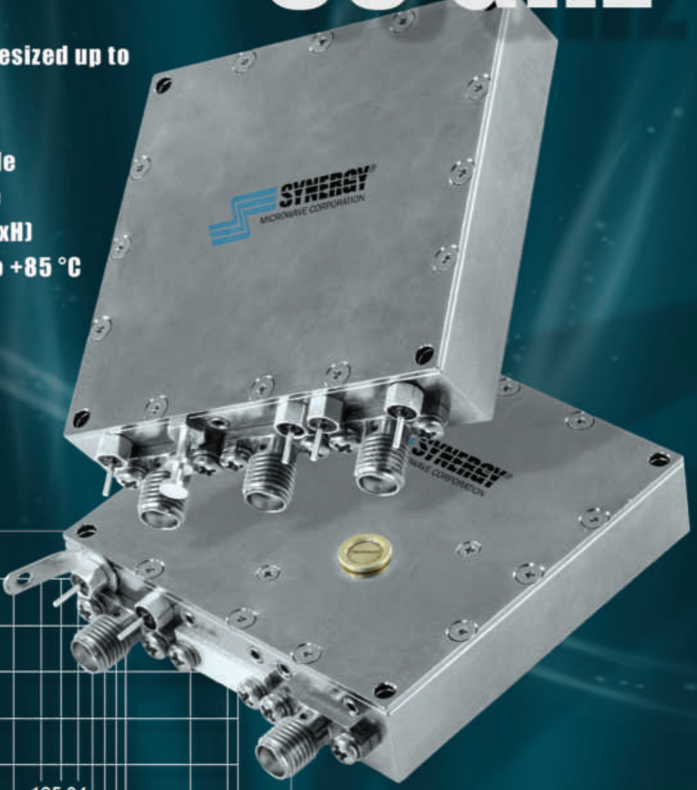

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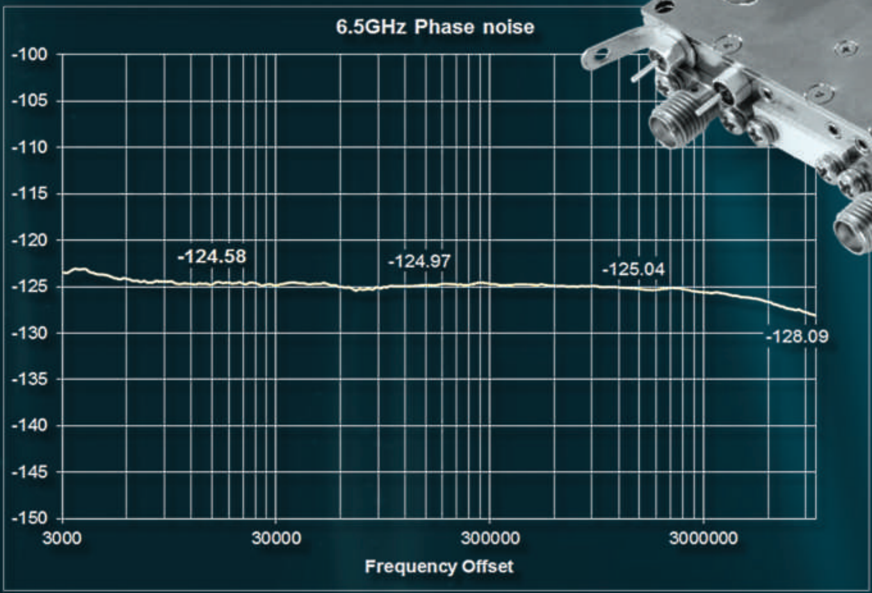

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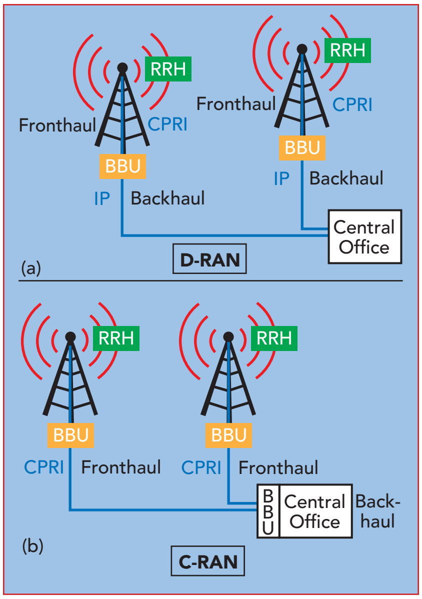

Fig. 5 Distributed (a) and centralized (b) RAN.

Figure 6 shows a functional block diagram of a C-RAN consisting of a baseband unit (BBU), RRH, GPS time/frequency reference and an interconnect module. Several of the blocks are highlighted to note possible use of COTS SDRs. The BBU is located at a central office or a virtual network "in the cloud," with access to multiple optical data lines for backhaul. The RRH is at an external location closer to the end user. The BBU and RRH in this fronthaul connection example can use a common public radio interface (CPRI), open base station architecture initiative (OBSAI) or standard Ethernet connection, depending upon system requirements. New fronthaul concepts like extensible radio access networks (xRAN) and open radio access networks (ORAN) will replace these legacy interfaces in the future.

These various transfer mode options combined with legacy cellular, Verizon 5G Technical Forum (5GTF) or the 3GPP 5G New Radio (NR) specification are configured to form a complex heterogeneous network, requiring a flexible development platform.[4-6]

Hardware

Figure 7 shows an example of using a COTS SDR board to emulate a RRH in a C-RAN architecture. A subsection of the original C-RAN with the RRH is shown in Figure 7a, with the COTS SDR RRH in Figure 7b. The encircled area in Figure 7a can be realized with the carrier card shown in Figure 7b. The custom modular carrier card contains the receive and transmit amplifiers, a GPS receiver and an optoelectronic transceiver module. The inner SoM contains the RFSoC and all connections for power management, data storage and analog/digital I/O. The incoming RF signal from the antenna is connected to the receive low noise amplifier via a duplexer, isolating it from the high power amplifier transmit levels and connecting it to one ADC channel. With the necessary IP, this SoM and custom carrier combination can emulate the original RRH.

Firmware

Once inside the FPGA fabric, the digital samples are decimated, frequency selected or tuned and filtered in the DDC. The DDC output samples can be streamed to the power meter module for measurement and sorted in the threshold detector IP module. These processed samples can be streamed to the ARM processors for crest factor reduction and digital predistortion routines before being up-converted in the digital up-converter (DUC) for re-transmission. The DUC is the reverse of the DDC, using frequency translation and interpolation instead of decimation. The digitized I/Q sample data is packetized in the digital radio for transport to the BBU via a radio data switch. Because of the variety of channels and data transfer protocols, it is necessary to understand the maximum data throughput of the signal and ensure sufficient network capacity (see **Sidebar Data Transport Requirements,** page 96).

Software

Depending on the desired level of control, BSP routines would be created for the new IP and ARM processors, or the ARM processors, in conjunction with the FPGA, can be programmed to operate autonomously.

CONCLUSION

The purpose of this article is to familiarize a traditional radio engineer with the latest hardware, firmware, software and design tools available from COTS SDR suppliers, showing

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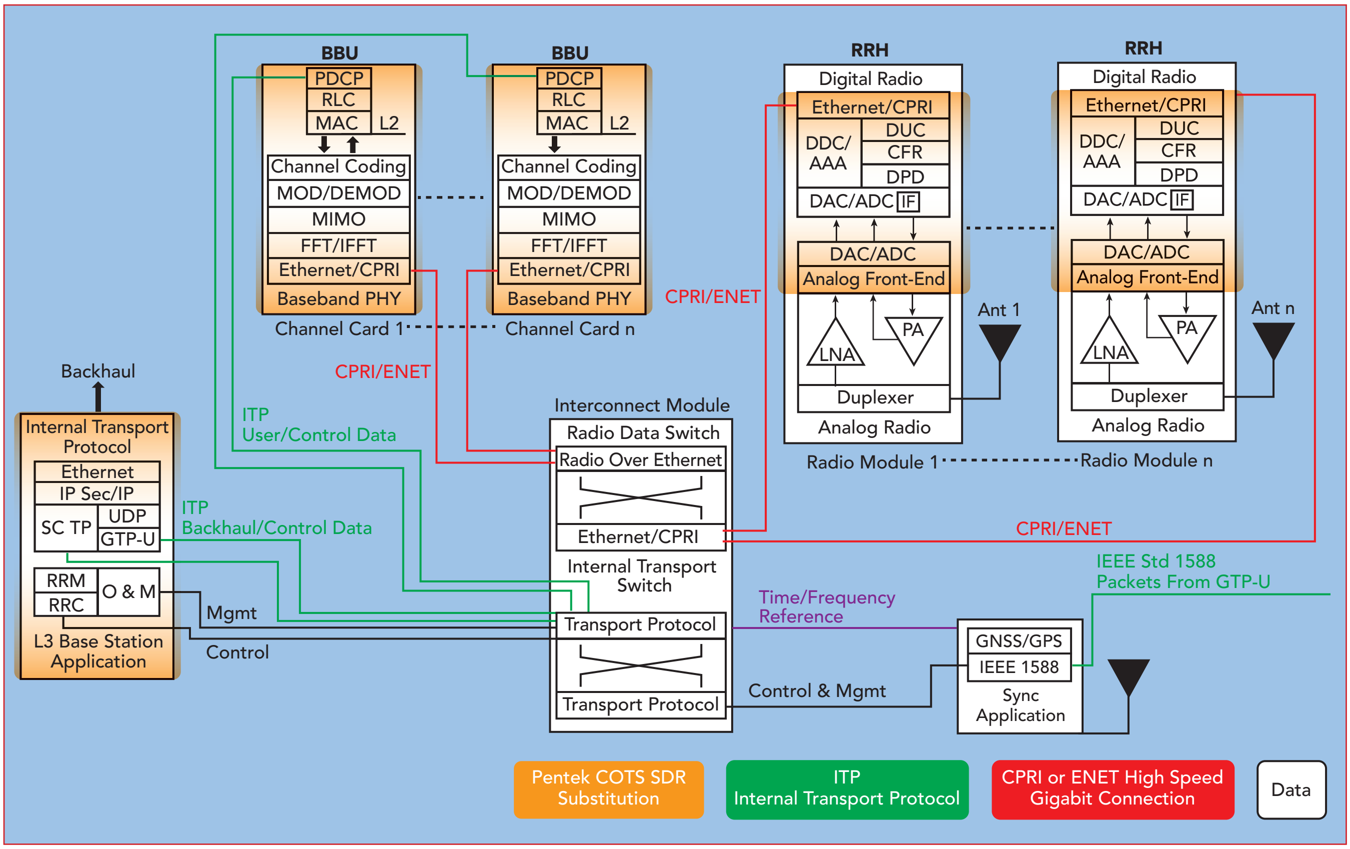

Fig. 6 C-RAN functional block diagram, showing where COTS SDR can be used.

that an SDR can be used as a 5G development platform. These SDR platforms provide superior signal integrity, high test repeatability and modular assemblies that adjust to constantly changing 5G design requirements. 5G evolution will require many development cycles for experimentation and optimization, and the use of a COTS system as a starting point will accelerate time to market.■

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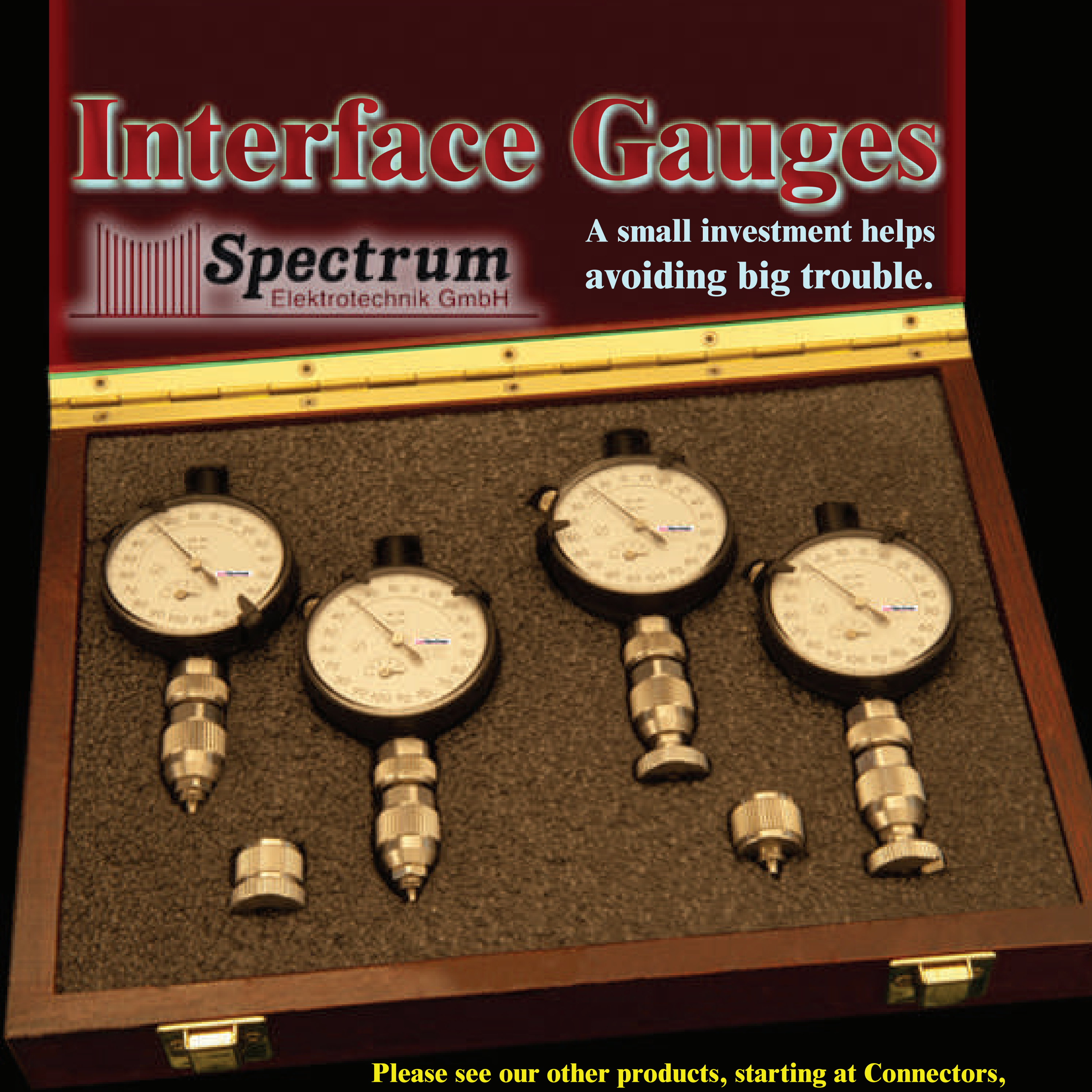
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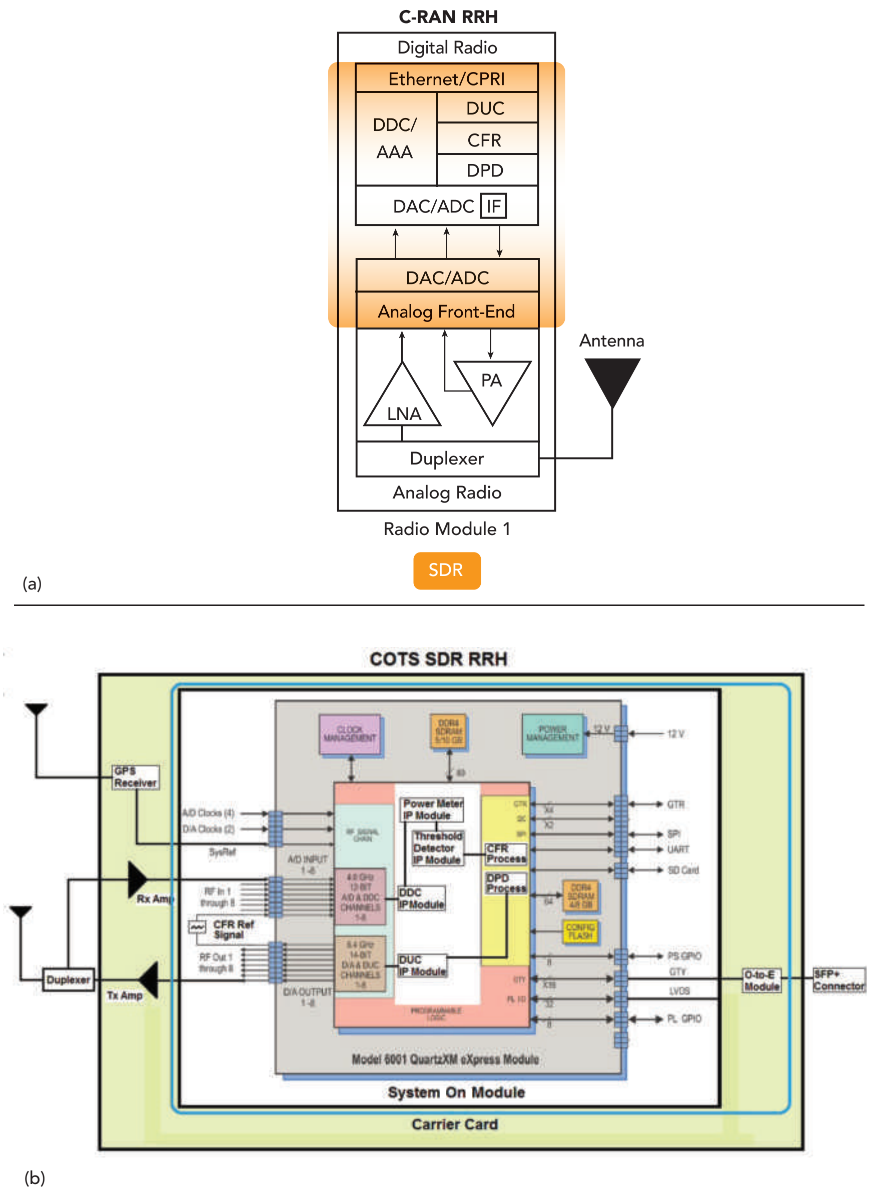
Data Transport Requirements

5G will require significantly more transport capacity than LTE.

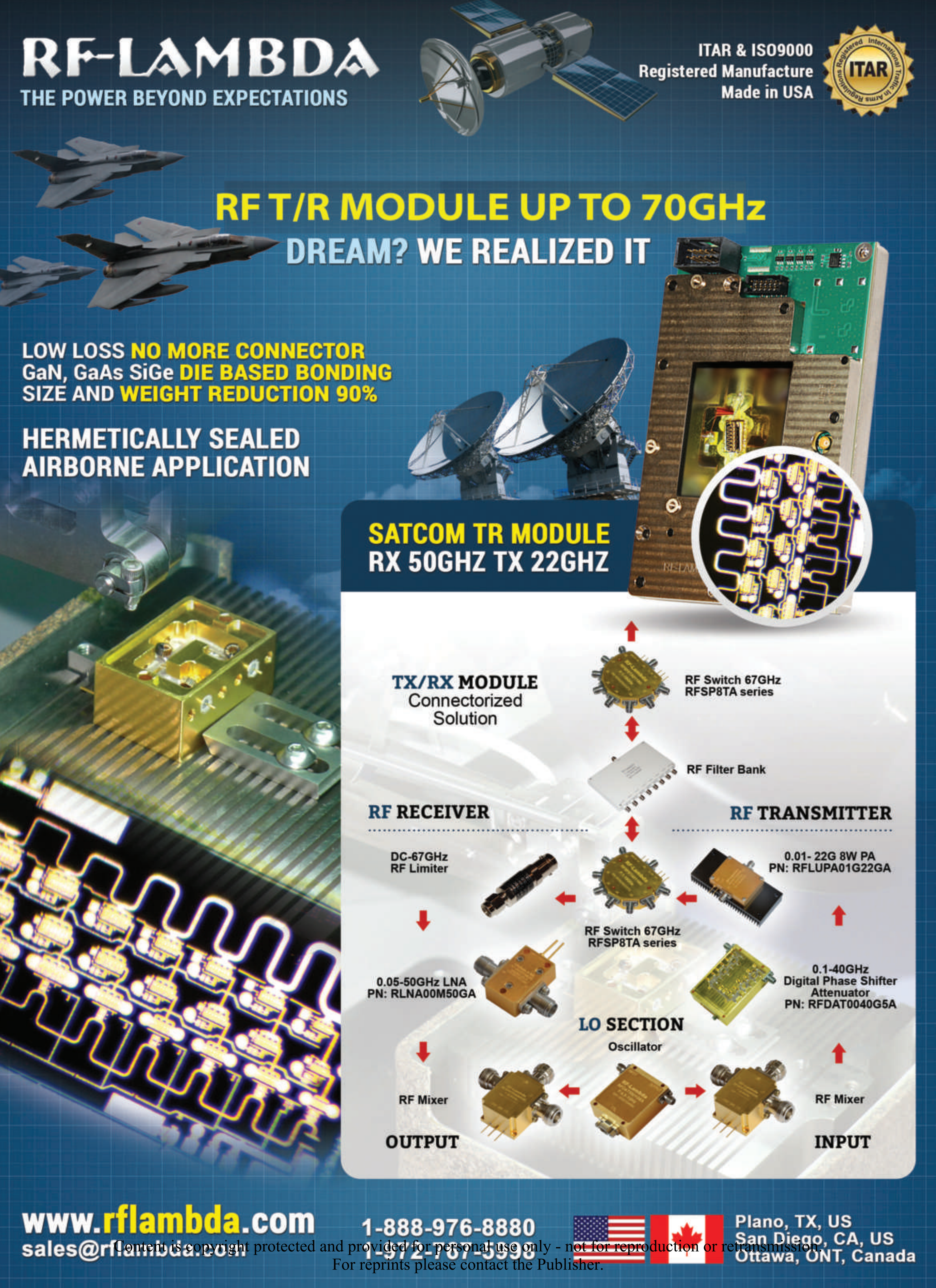
With LTE, a RRH with two antennas and 5 MHz channel bandwidth will have the following data transfer requirements: The 5 MHz channel requires at least 10 MHz sampling, or 10 MSPS, to capture the information without aliasing. With two bytes per 16-bit sample and one sample each for the I and Q data, the maximum sampling rate will be:

SR_{Max} = 10 MSPS x 2 bytes/sample x 2 for I and Q = 40 MB/s x 8 bits/byte = 320 Mbps per antenna. With two antenna inputs, the data transport will require 320 Mbps x 2 = 640 Mbps data throughput, which poses no issue for a CPRI port, which has 10 to 25 Gbps capacity.

A 5G link with a 100 MHz channel and eight antenna inputs increases the data transfer requirement to approximately 52 Gbps, which will require multiple CPRI ports. These are approximations, as the calculations ignore encoding variations.



▲ Fig. 7 RRH functional block diagram (a), showing the functions that can be implemented with a COTS SDR (b).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Global 5G Rush But No Global 5G Handsets

Ben Thomas
Qorvo, Greensboro, N.C.

We are currently witnessing a global rush to 5G. Nations, mobile operators and handset manufacturers are all vying to be the first to deliver the next-generation of cellular connectivity—or at least to get in the game early. Worldwide, there are robust plans for rapid 5G deployment, especially in regions where the wide bandwidth provided by new 5G bands can provide significantly higher data rates for consumers Indeed, it is this access to New Radio (NR) bands with the refarming of existing LTE bands that provide the greatest impact on data rates (see ***Figure 1***). Unlike the 3G to LTE transition, the change in underlying 5G specifications provides only a modest data rate improvement. This explains why, to facilitate fruitful 5G deployment, countries are rapidly allocating new spectrum in both of the newly designated ranges: sub-6 GHz (FR1) and mmWave above 24 GHz (FR2). South Korea, Britain, Italy and Spain, among others, raised billions of dollars in spectrum auctions during 2018, and the U.S., China, Japan and Australia will hold auctions and make allocations in 2019. Operators in many countries, including the U.S., plan to start rolling out 5G services in 2019, and several major handset makers have said they will produce 5G phones supporting these services. Overall, these initiatives are driving toward widespread 5G coverage in developed countries by 2021.

Yet the global drive to 5G does not mean that we will see global 5G handsets. In contrast to the situation with LTE, it may not be feasible or cost-effective to build global 5G handsets that support roaming across 5G networks worldwide. Instead, 5G will likely drive the handset market in the opposite direction—toward greater regionalization.

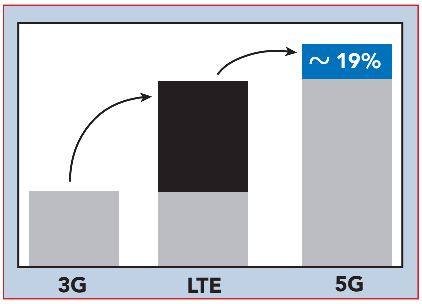


Fig. 1 5G requires added spectrum, as the specifications provide only modest data rate improvements.

5G BANDS NOT GLOBAL

First, new "global" FR1 bands (n77, n78 and n79) are, in practice, anything but global; in many cases, countries are allocating different narrow subsets of these bands (see ***Figures 2*** and ***3***). Second, FR2 mmWave allocations are following a similar pattern, multiplying the problem. Third, many operators will initially deploy Non-Standalone (NSA) 5G, which introduces complex, hard-to-manage interactions between 5G and regional LTE bands.

Those with long memories may remember the dawn of the LTE era, when bands 1 and 7 were heralded as global. Unfortunately, both were only adopted in some regions, not in others. Other bands that have been considered global candidates, such as band 41, were deployed with regional allocation differences. For example, the U.S. allocated the full available bandwidth, yet China chose only a narrow subset and, in practice, usage was even narrower, since China Mobile was only one of the three operators in China to fully deploy the allocated frequency range. Only now, many years after launch, is a more unified band 41 allocation structure being considered, with the aim of deploying 5G NR in

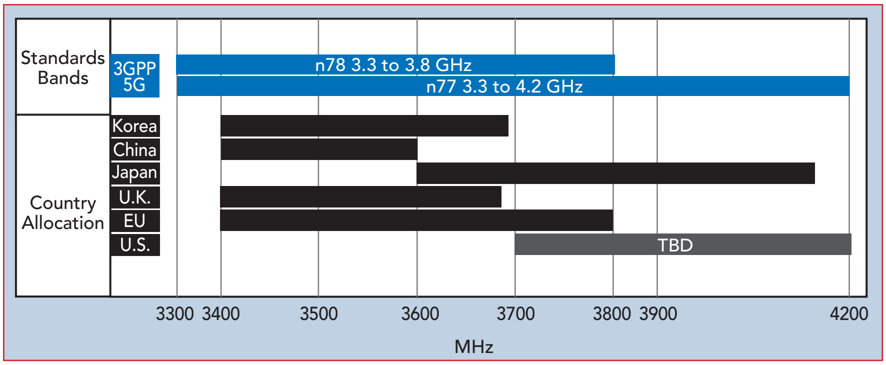


Fig. 2 Use of the "global" n77 and n78 mid-band spectrum varies by country.

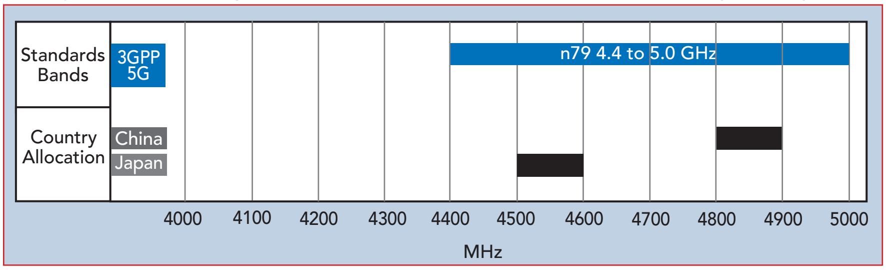


Fig. 3 China and Japan plan to use small and different portions of the n79 band.

the refarmed band n41.

The same fragmentation is occurring with the new "global" ultra-high bands n77, n78 and n79 and for the same reason. Little has changed in the way countries and regions allocate spectrum or auction it to mobile operators.

HANDSET WOES

The resulting differences in regional allocations have big implications for handset manufacturers, who must figure out how to support conflicting desires. Operators generally want handsets optimized for the subset of a band used in their respective regions. However, handset manufacturers want to sell devices globally, or at least regionally, supporting the different bandwidths and carrier aggregation (CA) combinations used in all their target markets.

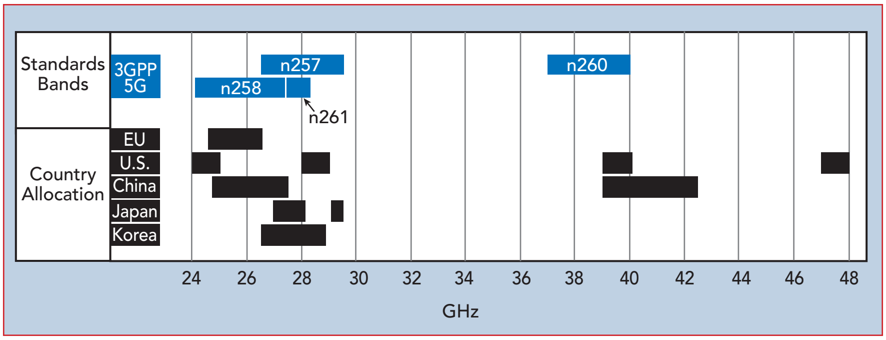
Further, leading manufacturers have chosen to participate in the Global Certification Forum's (GCF) interoperability certification, which provides benefits for roaming with LTE handsets. The common GCF practice is to certify operation over the full bandwidth of the designated band, which begs the question: what happens when an operator, or group of operators, has only deployed subsets of the allocated band?

Consider the case of n77, which covers 3.3 to 4.2 GHz. In theory, a single n77 solution would support worldwide use in all regions using this band. In practice, operators want solutions optimized for the subset of spectrum allocated in their respective regions—in some cases, as narrow as 100 MHz. If n77 will not work as a global solution, how about n78, which has a narrower 3.3 to 3.8 GHz allocation? Think again. So far, only a few operators intend to deploy the 3.3 to 3.4 GHz portion of either n77 or n78. Should a handset manufacturer be required to enable operation in a frequency range that is not even deployed? Operators vying for the best operation certainly will not demand it.

Implementing a more regional solution could deliver performance benefits, largely because handset manufacturers can tailor filtering and optimize power and low noise amplifier tuning for subsets of the bands. For example, at initial launch, the majority, if not all, of the front-end modules for n77 will use a non-acoustic filter, which provides good performance for the very wide 900 MHz of spectrum—much wider than any LTE band today. When a much narrower subset of n78 is used, say 400 MHz, a bulk acoustic wave (BAW) filter with steep filter skirts offers better performance, providing improved rejection of out-of-band frequencies and lower insertion loss at the band edges. This is one example of the tradeoff for handset manufacturers. Focusing on the regional solution would improve performance for a few targeted mobile operators, while losing the capability for true global roaming—or at least reducing the number of SKUs to service the global 5G market.

A similar dilemma exists for band n79 (4.4 to 5 GHz). China favors the 4.8 to 4.9 GHz portion of the band, while Japan is considering 4.5 to 4.6 GHz. A solution that supports the entire band would work in both countries, but it would not be optimized for either of the narrower allocations. If you were an operator in one of those countries, would you choose the global n79 solution or the one that provides better performance for the users in your country? On the other hand, as a manufacturer, would you want to build separate SKUs for China and Japan or have a single handset to cover both? These decisions trade off more than performance.

Regional allocations of FR2 spectrum make the fragmentation problem even more challenging, with differences between regions and among the operators within each region (see ***Figure 4***). Handset RF implementations for mmWave are perhaps more frequency dependent than sub-6 GHz implementations, considering the antennas. If the phone must support multiple, widely spaced mmWave frequency ranges, it may require multiple antenna arrays or, at the very least, a more complex and lossy antenna. This could be a requirement even within regions, where multiple mmWave frequency bands are being allocated. Adding to the challenge, it is likely that mmWave front-ends will be implemented in multiple placements in the handset, each consuming precious real estate within an already space-challenged form factor. This is a difficult proposition considering handset size is approaching the practical limit for maintaining portability.



▲ Fig. 4 Use of the mmWave 5G bands will also be fragmented by country.

NSA, SA AND LTE

Regions vary in their initial approaches to implementing 5G. In many areas of the world, operators are planning to accelerate 5G deployment by employing NSA 5G. NSA uses an LTE anchor band for control and a wider, 5G band to achieve higher data rates. This approach allows operators to deliver 5G sooner, by leveraging their existing LTE networks and not building out a new 5G core. However, some China operators plan to quickly transition from NSA to Standalone (SA) 5G or, in some regions, directly from LTE to SA 5G. SA removes the need for an LTE anchor, requiring a full 5G network buildout, yet easing the implementation of multi-band CA combinations, particularly on the uplink (UL).

Although NSA helps operators deliver 5G speeds sooner, it introduces considerable RF complexity: requiring dual LTE and 5G connectivity. In many cases, operators will add a 5G band to the existing regional CA combinations of multiple FDD LTE bands, with one LTE band serving as the anchor. The NSA specification requires the handset to transmit on one or more of these LTE bands while receiving on a higher frequency 5G band. This increases the likelihood of interactions between the LTE and 5G bands, with harmonics of the LTE transmit frequencies potentially desensing the 5G receiver.

To illustrate, consider the NSA combination of 5G band n78 with LTE anchor bands 3 or 66. Harmonic frequencies generated during transmission on the LTE band fall in the n78 band, potentially reducing receive sensitivity. To alleviate the possibility, additional filtering could be applied to the band 3 path, which will increase the losses on band 3. This presents problems in handsets designed for global use, particularly in regions where 5G is not yet available or with operators without n78 spectrum. In those locations, band 3 would be a main data path, and the added losses would penalize handset performance without providing any benefit to the user.

For some 5G bands, the global picture is even more complex, due to the need to support SA and NSA operation. For example, LTE band 41 is being refarmed as 5G band n41, which will provide much greater single-channel bandwidth than the 60 MHz LTE limit. North American handsets will need to support dual-transmit NSA operation using LTE band 41 together with 5G n41. This extra 5G bandwidth comes with a penalty, however. Due to reverse intermodulation products created when simultaneously transmitting on both LTE band 41 and n41, the output power must decrease to meet emissions masks, potentially reducing coverage. In China, however, n41 can be used in wideband SA mode without supporting dual transmission. Using n41 in SA mode will allow a wider bandwidth UL while maintaining the coverage that operators have achieved with LTE on band 41, and it can be supported with a single power amplifier, reducing the size and cost of implementation.

As regions move to SA 5G, many of these problems will become simpler. However, that is not likely to happen soon. I believe 5G will be around for a decade or more before SA becomes the predominant implementation across the globe. In the race to global 5G deployment, we have to accept a long period of RF complexity caused by the NSA standard.

WILL CONSUMERS BUY GLOBAL 5G HANDSETS?

Despite all these challenges, is it possible to build a global 5G handset? Probably. However, will global roaming justify the cost and other tradeoffs?

One question is whether consumers are prepared to pay for a more expensive global 5G phone. Whether the handset is regional or global, the cost will increase because the manufacturer will have to pay 5G technology license fees, in addition to the current fees for LTE. The substantial increase in RF content to provide global 5G coverage—especially considering the regional band variations—will add cost. It may be hard to justify, even for the specialized group of high-powered busi-

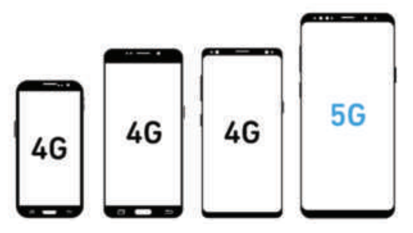


Fig. 5 The complexity of a 5G handset will require larger form factors.

ness travelers who want data roaming wherever they travel.

Recall the early days of LTE, when LTE was implemented regionally and GSM was used for roaming. When global LTE handsets emerged, quite often much of the handset LTE content was dormant. Content that adds cost yet is not used is often short lived, especially when a market matures from its infancy.

Even with a regional design, adding a single 5G band increases the RF content and cost. Additional components are required for the 5G band and to manage the signal flow through an increasingly complex signal path to antennas, due primarily to NSA and the myriad CA combinations operators have requested. Antennas are already strained to cover existing frequencies used for LTE; 5G will make the range even wider. While the challenge can be solved using antenna tuning and antenna-plexers, which maximize the number of signal connections to each antenna, both solutions add content to the handset.

5G will also mean big phones, at least initially (see ***Figure 5***). The additional RF content requires extra space, especially for mmWave coverage, which will be difficult to fit in today's handset form factors. Manufacturers do not want to reduce space allocated for batteries and other features that directly appeal to consumers. To accommodate the additional content, 5G phones may need to be "plus" devices. Even with regional 5G handsets, standard form factors may not be plausible at the outset. A quick look around will tell you that not everyone likes large form factor phones, which represent the minority of units sold. We may have to await further size-shrinking technologies before it is feasible to fit 5G into svelte 18:9 form factor phones that easily fit in a pocket.

CONCLUSION

5G is driving the market toward further regionalization of handsets. Consumers do not want to pay for RF content they will not use, and manufacturers cannot justify the cost of adding content that will be rarely used. Manufacturers may also find it difficult to squeeze the RF content into handsets while maintaining battery life and the other features consumers value. The desire to keep handset cost and complexity within reasonable limits will lead manufacturers to design regional 5G handsets, similar to the regionalization in many of today's mid-tier LTE smartphones.

To be very clear, none of these factors will slow down the impending 5G rollout. They will just fragment the market. In short, 5G handsets will be anything but global.■

5 kW GaN Transmitter for C-Band Radar

RFHIC Corp.
Anyang, South Korea

RFHIC's latest 5 kW GaN solid-state transmitter sets new standards for radar systems, offering lower operating cost and precise control. The RRT56575K0-67 operates from 5.6 to 5.7 GHz, combining four GaN power amplifiers (PA) to deliver an unprecedented output power of 5 kW (67 dBm), with harmonic performance better than 40 dBc.

Although most radar systems use magnetrons or other tube-based amplifiers as the core component of the transmitter, such systems are restricted to a low duty cycle, only transmitting 0.2 to 0.3 percent of the time. Solid-state power amplifiers (SSPA), on the other hand, transmit lower power but can operate up to 10 percent duty cycle. This enables approximately 10× higher processing gain and 2× the detection range while using less power and dissipating less heat. The RRT56575K0-67 also provides more control and precision over the RF transmit pulse, creating less spurious emissions.

The nominal input power range of the RRT56575K0-67 is between −6 dBm and 0 dBm, with a minimum gain of 67 dB at 0 dBm input drive. As the input power decreases, the RRT56575K0-67 increases the gain to maintain the output power close to 67 dBm (5 kW). Output power degradation is minimal unless the input power drops to −19 dBm (see ***Figure 1***). ***Figure 2*** shows the power consumption efficiency and the power gain versus input power. With the input power from approximately −15 to 0 dBm, the power consumption efficiency is 31 percent. The efficiency of the power supply alone is 96 percent.

COST AND RELIABILITY ADVANTAGES

The RRT56575K0-67 has an outstanding lifetime between 50,000 and 100,000 hours, depending on operating use. The extended lifetime compared to tubes results in significant cost savings. Unlike magnetrons or other tube-based systems using only one power source, the RRT56575K0-67 is configured with four stable and rugged GaN PAs, enabling the transmitter to degrade gracefully should one of the PAs fail. Another cost advantage of a SSPA is the capability to instantly go from unpowered to full power without any warm-up time.

The RRT56575K0-67 has embedded controllers to monitor the operational status of the transmitter. When an abnormal condition such as high temperature or an output

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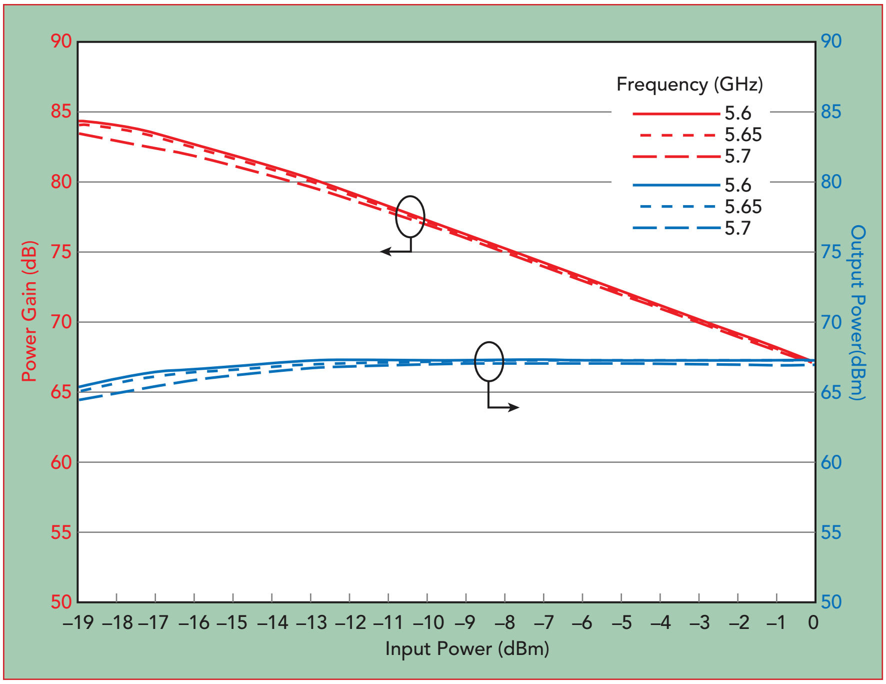
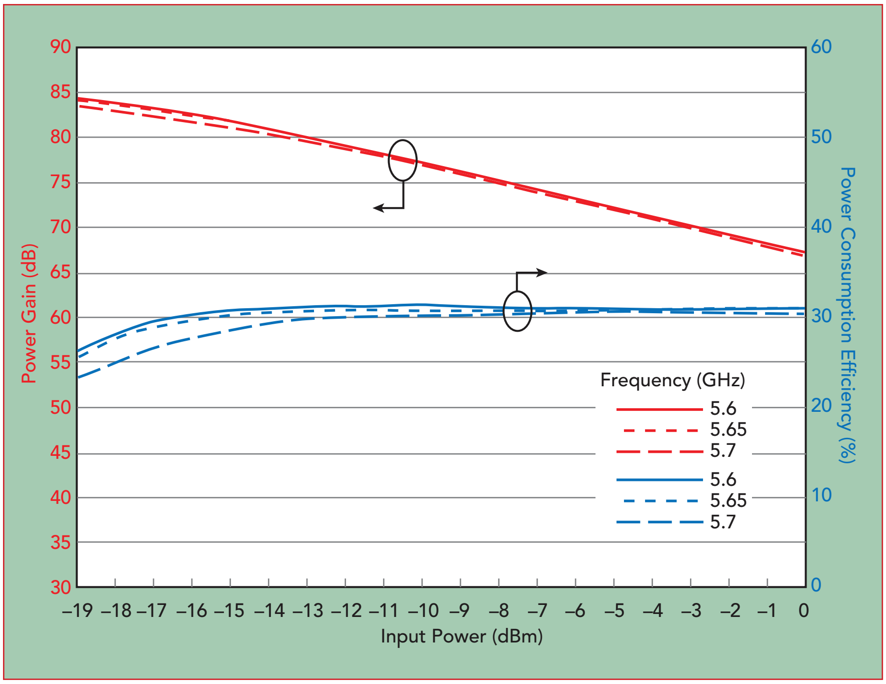


▲ Fig. 1 Output power and power gain vs. input power at 5.6, 5.65 and 5.7 GHz.



▲ Fig. 2 Power consumption efficiency and power gain vs. input power at 5.6, 5.65 and 5.7 GHz.

mismatch is detected, an alarm controlled by FPGA logic will activate and notify the user. If a critical event occurs, the system automatically shuts down. A DSUB connector in the backplane enables communication to the in-site control station or RFHIC's dedicated graphical user interface. The physical layer and protocol can be varied to meet system requirements.

MODULAR DESIGN

The RRT56575K0-67 mounts in a standard 19 in. rack and has two main shelves, the transmitter and power supply unit (PSU). The transmitter is 17.78 cm high (4U) and weighs 40 kg, while the PSU is 8.89 cm high (2U) and weighs 20 kg. The transmitter rack can be tailored to integrate the whole system, based upon user needs. The standard circular connector on the amplifier is adapted for AC power input.

Unlike other tube-based transmitters that require costly and complex water-cooling (e.g., chillers), the RRT56575K0-67 was designed to use forced air cooling to dissipate heat, even at high operating temperature. Each of the four GaN PAs is mounted on a heat sink made of an aluminum-based material, and four fans attached to the front panel ventilate hot air within the system. In the case of fan failure, the fan can easily be replaced without interrupting system operation.

The GaN PAs are biased with 50 V, and the RRT56575K0-67's power supply contains three rectifier modules designed to be load sharing, hot-swappable and n+1 redundant, meaning the SSPA will not stop transmitting RF power if one of the rectifier modules fails. Without taking the transmit system out of service, the failed module can be replaced, just as the microwave amplifier architecture is designed for soft fail redundancy. The PSU takes single phase, AC voltage between 110 and 220 V and produces the bias for the GaN transistors—typically 50 V, although the devices can operate with as high as 53 V bias.

Magnetron and other tube-based systems require high voltage power supplies inside the transmitter shelf, resulting in a dangerous operating environment compared to the RRT56575K0-67, which operates at a much safer voltage.

SOLID ROI

Upgrading to the RRT56575K0-67 will save time and money over the life of the SSPA, making RFHIC's GaN transmitter a secure and cost-effective investment, well suited to meet the needs of high-power C-Band radar. RFHIC also offers custom GaN PAs, from packaged transistors to custom rack-mount subsystems with up to 50 kW output power.

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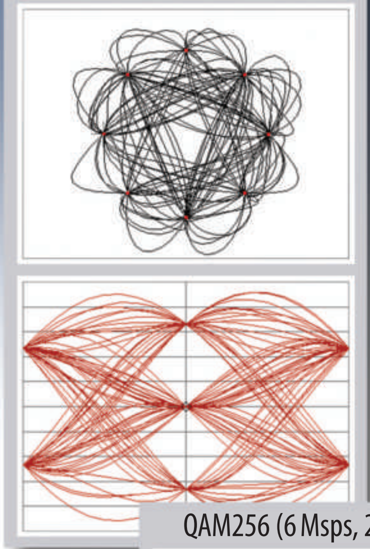
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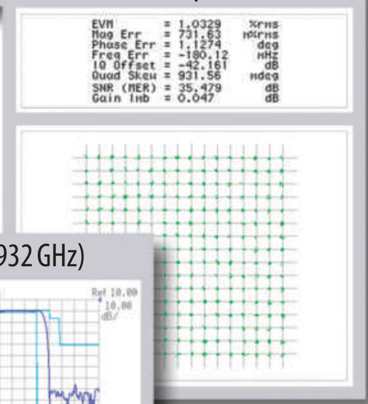

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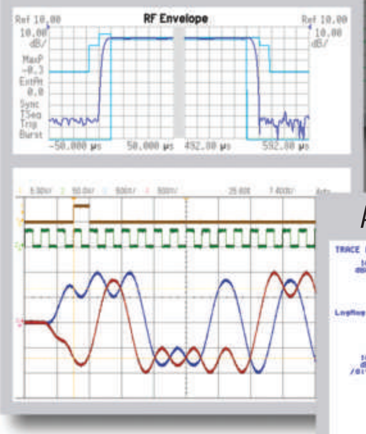

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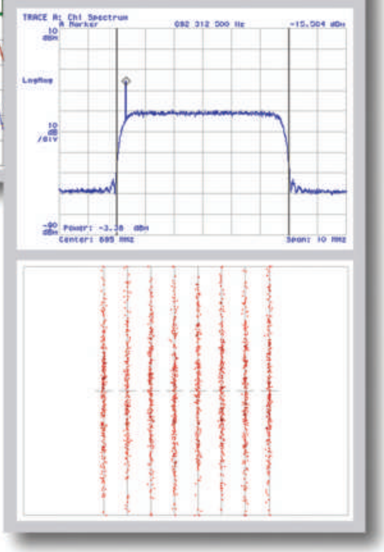
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LAA/Wi-Fi Front-End Modules for Smartphones

Skyworks Solutions, Inc.
Irvine, Calif.

Increased adoption of smartphones coupled with data-heavy applications like video streaming are creating an explosion in mobile data rate consumption. To help deliver this data to mobile users, multiple technologies are being deployed. The primary platforms today are cellular and Wi-Fi. However, to support the demand for faster data, the industry must use additional spectrum and develop more spectrum-efficient technologies. One approach is a technology known as license assisted access (LAA), which taps unlicensed spectrum to increase cellular data rates.

Two types of spectrum are available: unlicensed spectrum, used by 802.1x technologies such as Wi-Fi, Bluetooth® and Zigbee®, and licensed spectrum such as LTE and 5G, used by cellular networks. While unlicensed spectrum is free, carriers pay substantial sums to use licensed spectrum. Licensed spectrum is in short supply, the reason behind efforts to allocate more worldwide. On the other hand, a substantial amount of unlicensed spectrum is available at 2.4 and 5 GHz, with the possibility to extend unlicensed bands to 7 GHz (see ***Figure 1***).

The unlicensed spectrum available at 5 GHz is very attractive to mobile carriers, prompting the industry to develop technology to combine LTE and Wi-Fi and use both licensed and unlicensed spectrum. The 3GPP has developed a standard for LTE-LAA, enabling LTE transmission in unlicensed bands, designating LTE band 46 for LAA (shown in Figure 1). 3GPP Release 13 defines an LTE-LAA supplementary downlink to increase downlink capacity, with theoretical peak speeds up to 1 Gbps. Enhanced LAA (eLAA), defined in 3GPP Release 14, adds transmission to increase uplink capacity (see ***Figure 2***).

LAA is based on carrier aggregation to tie licensed and unlicensed bands together. An LTE carrier is the primary channel (anchor), and the unlicensed carrier in the 5 GHz band is the secondary channel, also using LTE waveforms. The 3GPP standard calls for fair sharing of the unlicensed spectrum—primarily by listening before talking—to ensure the Wi-Fi performance of nearby systems is not impacted. The 3GPP standards group and the Wi-Fi Alliance® are collaborating to ensure equitable use of the shared spectrum.

SYSTEM AND FEM DESIGN

In a smartphone and cellular network with LAA capability, the Wi-Fi system on chip (SoC) and the cellular SoC will operate at the same time to increase download data rates (see ***Figure 3***). In the phone, an LAA/Wi-Fi front-end module (FEM) will combine the functionality of a full 5 GHz Wi-Fi transmit/receive module and the 5 GHz cellular LAA receive function in a single solution (see ***Figure 4***). Skyworks is developing LAA/Wi-Fi FEMs to support LAA capability in mobile phones, incorporating three elements to optimize LAA performance.

First, the receive chain includes a high performance low noise amplifier (LNA) with multiple low noise gain states and a high linearity bypass mode. This allows the system to choose the best gain for low level signals or the bypass mode, where noise figure is not a concern but linearity limits perfor-

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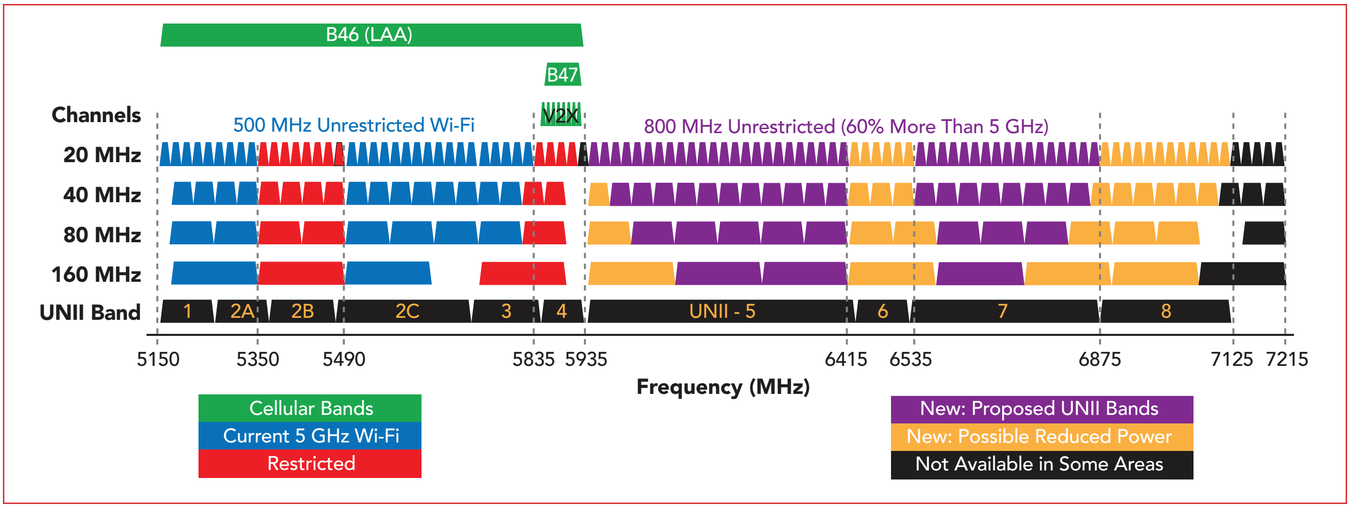


Fig. 1 Unlicensed spectrum between 5 and 7 GHz.

mance. This feature increases the input third-order intercept point (IIP3) from 6 dBm in the active state to 20 dBm in the bypass state.

Second, using a splitter after the LNA is a key differentiator, enabling the 5 GHz LAA and Wi-Fi signals to be simultaneously amplified and separately routed. In many mobile phones, the Wi-Fi and cellular radios are supplied by different manufacturers and work independently. Skyworks addresses this by integrating a splitter in the FEM, which enables the Wi-Fi and cellular signals to be routed to separate receivers, where each uses baseband frequency filtering to remove any unwanted signals. Typically, the Wi-Fi and cellular transmitters are in two different locations, which causes these signals to be at different power levels when received at the smartphone. The FEM adjusts their amplitudes to provide the optimal receive level to each transceiver. One challenge is the tradeoff between the low noise figure and high linearity states. Multiple LNA states combined with the splitter provide flexibility to make these tradeoffs.

The third section of the receive chain is the state decision control circuit. This digital block receives inputs from both the cellular SoC and the Wi-Fi SoC and synthesizes the many control signals for the FEM.

Another important function Skyworks designed into the LAA/Wi-Fi FEMs is rejection of all cellular bands below 3.8 GHz, particularly bands 40 through 43. This is important to maintain the noise figure and the signal-to-noise ratio for the desired receive signals, since LAA uses these lower cellular bands simultaneously with the 5 GHz receive channel. Unwanted signals injected into the LAA receive chain can saturate the LNA or create intermodulation distortion, degrading receiver sensitivity.

For next-generation eLAA, the FEM architecture adds a 5 GHz LAA

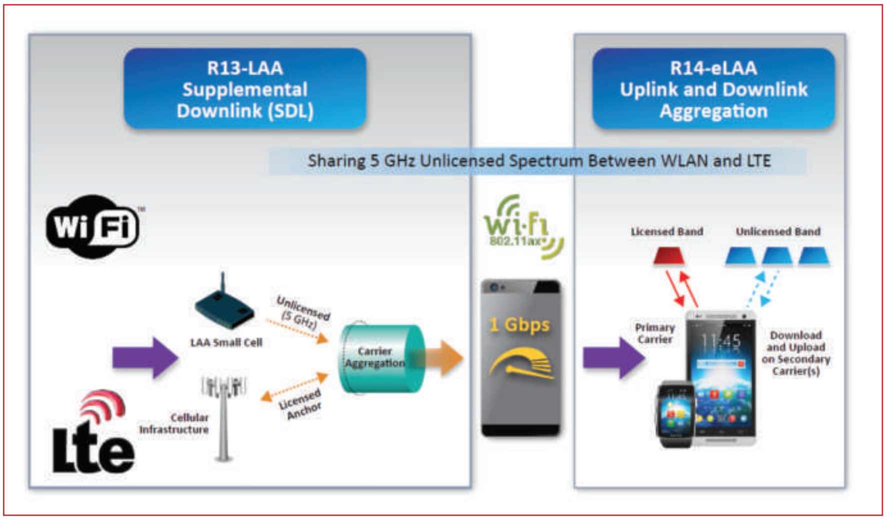


Fig. 2 LAA increases downlink capacity by tapping unlicensed spectrum, while eLAA adds access to unlicensed spectrum to increase uplink capacity.

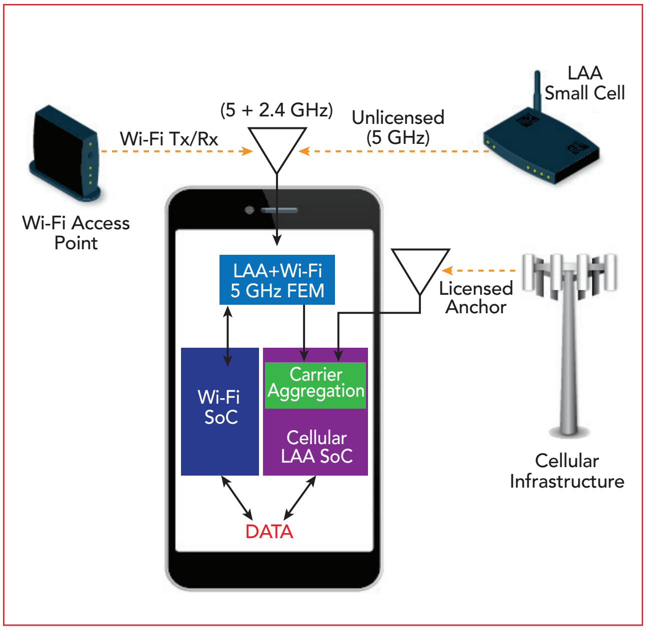


Fig. 3 Smartphone functionality for Wi-Fi and LAA.

transmit section with power amplifier (PA) paths for the cellular eLAA and Wi-Fi transmit signals. Since the PA requirements for cellular and Wi-Fi are significantly different—power control methods, modulation standards, RF metrics like error vector magnitude (EVM) and frequency mask-edge levels—the same PA cannot be used for both. eLAA FEMs will likely have two transmit ports with separate PAs, not operating simultaneously.

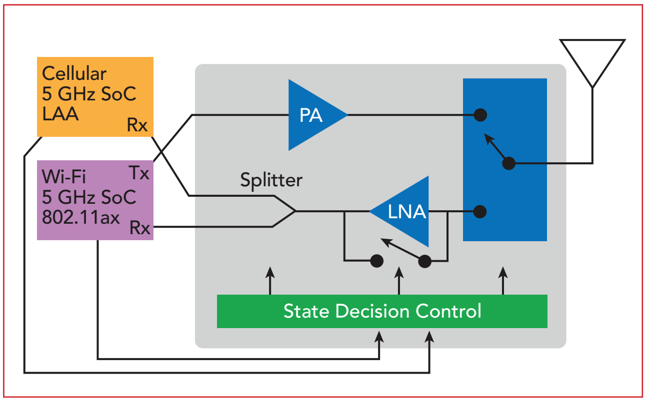


Fig. 4 Skyworks LAA/Wi-Fi FEM features.

SKYWORKS FEMs

Skyworks is sampling two integrated LAA/Wi-Fi FEMs to leading handset manufacturers. The SKY85774-11 (see ***Figure 5a***) is a 5 GHz FEM for concurrent Wi-Fi and LAA receive in a compact 2.2 mm × 3 mm footprint. The FEM also integrates a 5 GHz Wi-Fi transmit chain with a very low EVM PA for next-generation 802.11 requirements. The SKY85817-11 (see ***Figure 5b***) is an LAA/Wi-Fi FEM with both 2.4 and 5 GHz Wi-Fi functionality, integrated in a compact 3 mm × 4 mm footprint. The 5 GHz receive chain has low noise figure, high IIP3 and low LNA supply current. The 2.4 and 5 GHz Wi-Fi PAs have very low EVM, for next-generation 802.11 requirements.

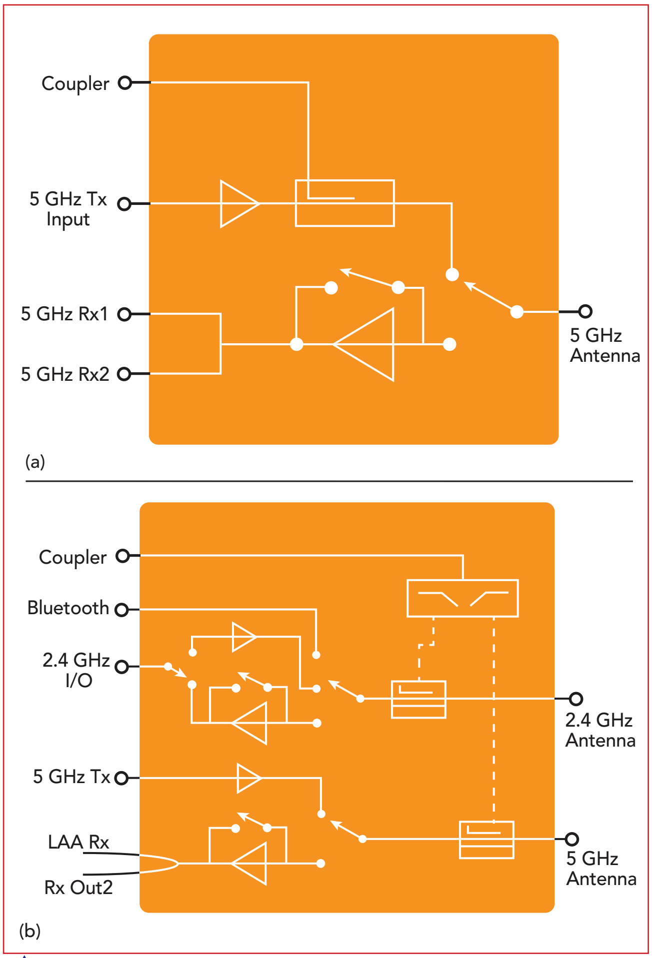


Fig. 5 SKY85774-11 LAA FEM with 5 GHz Wi-Fi transmit chain (a) and SKY85817-11 LAA FEM with 2.4 and 5 GHz Wi-Fi transmit chains (b).

LAA is being deployed by AT&T and T-Mobile, with ongoing trials at multiple carriers, such as China Mobile, SK Telecom and Verizon. Skyworks' integrated LAA/Wi-Fi FEMs will provide handset manufacturers with the functionality to adopt LAA, to increase data rates and improve user satisfaction.

VENDORVIEW

Skyworks Solutions, Inc.
Irvine, Calif.
www.skyworksinc.com

3 to 10 W Solid-State Power Amplifiers for K- and Ka-Band

To support the development of 5G, SATCOM and other applications at K- and Ka-Band, Exodus Advanced Communications offers four solid-state power amplifiers (PA) with 3 to 10 W output at 1 dB compression and 37 to 40 dB power gain. All are class A/AB designs using GaAs FETs.

The AMP4065LC-2 delivers 10 W minimum across 18 to 26.5 GHz. At rated power, the two-tone intermodulation products are −30 dBc typical, harmonics −20 dBc maximum and spurious better than −60 dBc. The 3U rack-mountable unit is cooled with forced air. Liquid cooling is an option, yielding a smaller and quieter amplifier.

The AMP4066-2 delivers 10 W at 1 dB compression across 26.5 to 40 GHz, with similar harmonic and spurious performance. The standard amplifier is also housed in a 3U, 19 in. rack chassis and cooled with forced air, with liquid cooling an option.

The AMP4047 and AMP4047A provide 3 W at 1 dB compression across 18 to 26.5 GHz and 26.5 to 40 GHz, respectively. Intermodulation, harmonic and spurious are similar to the AMP4065LC-2. This PA is housed in a 2U benchtop chassis and uses fan cooling.

The AMP4065LC-2 and AMP4066-2 models include a color touch screen and controller supporting Ethernet TCP/IP, USB, RS422 or RS485 interfaces; GPIB and Bluetooth are options. The AMP4047 does not have the touch screen, since it was developed as a basic benchtop PA for applications not requiring remote control.

The 10 W PAs can replace TWTAs for EMI/RFI susceptibility, communications and test systems. Exodus Advanced Communications offers other power levels within these families, as well as amplifiers from 10 kHz to 51 GHz—70 GHz being developed—and power levels to multi-kW, depending on frequency.

VENDORVIEW

Exodus Advanced Communications
Las Vegas, Nev.
www.exoduscomm.com

1.8 m Commercial Drive-Away Antenna

Responding to the surge in demand for high performance, customizable, drive-away satellite terminals for commercial, broadcast and corporate applications, Norsat developed the WAYFARER™ series to provide reliable, easy to deploy mobile communications. The series includes two ultra-portable commercial fly-away satellite terminals, an easy to deploy commercial drive-away antenna system and a commercial fixed terminal solution.

The 1.8 m drive-away is one of the most popular products. Solid and low weight, it deploys easily, enabling fast and reliable satellite acquisition and tracking. Norsat developed the drive-away product with a customer-focused approach, responding to the market's need for flexibility, auto-acquisition and quality reflectors. Whether mounted on an emergency mobile command center or a broadcast van, users can count on this drive-away for broadband communications capability. The terminal is ideal for mobile offices, satellite news gathering, broadcasting and government applications, such as first responders and emergency mobile headquarters.

The WAYFARER commercial drive-away antenna is flexible and equipped with an easy, one-button auto-acquire feature, getting the satellite terminal up and running in under four minutes. The rugged 1.8 m composite reflector with a low height vehicle room mount (38 cm stowed) supports DVB-S1 and DVB-S2 and is available with Ku-Band block up-converter (BUC) options of 4, 8 or 16 W.

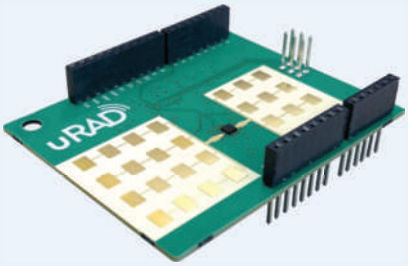
This commercial platform is an easily deployable mobile solution for SATCOM and backhaul in challenging locations and environments. The drive-away terminal is designed to offer unparalleled communications-on-the-pause (COTP) performance, ensuring high quality transmission of vital data, no matter the conditions. A complete satellite solution, the WAYFARER 1.8 m drive-away includes everything needed for mobile communications.

VENDORVIEW

Norsat International
Richmond, British Columbia
www.norsat.com
sales@norsat.com

TechBrief

24 GHz Radar Works With Arduino and Raspberry Pi



uRAD, the radar and sensing section of Anteral S.L., develops high performance radar technology for innovative applications. The latest product is an RF board that mates with the Arduino and Raspberry Pi microcontrollers (MCU) and transforms them into completely functional microwave radars. The radar operates within the 24 GHz ISM frequency band with an EIRP below +20 dBm. Two patch antenna arrays, one for transmit and one for receive, provide a field of view of 30 x 21 degrees.

Using a powerful MCU, the RF board performs the waveform generation, signal conditioning and data processing, while the Arduino or Raspberry Pi MCU is only used for the interface between the user and radar, making for easy programming and control. The Arduino or Raspberry Pi supplies +5 V bias for the radar, which consumes only 0.85 W.

The uRAD radar can detect up to five separate targets within a 0.45 to 100 m range, with an accuracy of the maximum of ±0.04 m or 0.3 percent of the measured range. It can detect the target's velocity from 0 to ±75 m/s with an accuracy of ±0.05 m/s. The radar also provides the signal-to-noise ratio of the detected target and the raw in-phase and quadrature components of the total received signal, enabling the user to access the detected signal and perform post-processing.

Four different modes—Doppler and three frequency modulated CW (FMCW) options—are easily programmed with the Arduino IDE or Python. uRAD provides the necessary libraries to configure, control and get results, as well as examples of use cases and a plug-and-play tutorial. Using the Windows, Mac or Linux graphical user interface enables the user to visualize the I/Q signals, FFT or other data and change the configuration in real-time.

The uRAD radar is a powerful tool for learning radar technology and applying it to numerous scenarios.

uRAD
Navarra, Spain
www.urad.es

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The effects of RF and MW on Biological Tissues

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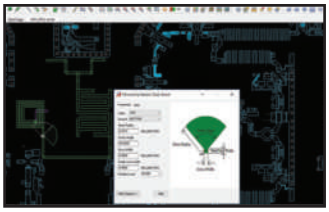
IEEE Israel

Software and Mobile Apps

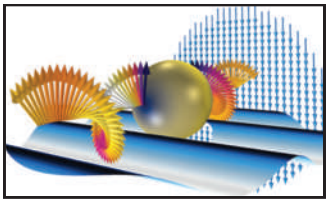
Mixed-Signal PCB Design Environment



The Allegro PCB Designer Analog/RF Option offers a mixed-signal design environment, from schematic to layout with back annotation, proven to increase RF design productivity up to 50 percent. It allows engineers to create, integrate and update analog/RF/microwave circuits with digital/analog circuits in the Allegro PCB Design environment. With its rich layout capability and powerful bi-directional interfaces with RF simulation tools, it allows engineers to design and validate RF circuits on a PCB design.

Cadence
www.cadence.com/

Model & Simulate Electromagnetics Designs & Devices



COMSOL Multiphysics® is an integrated software environment for creating physics-based models and simulation applications. A particular strength is its ability to account for coupled phenomena such as microwave heating. Add-on products expand the software for electromagnetics, structural, acoustics, fluid flow, heat transfer and chemical modeling. Interfacing tools enable its integration with all major technical computing and CAD tools. Simulation experts rely on COMSOL Compiler™ and COMSOL Server™ to deploy applications to their design teams, manufacturing departments and customers throughout the world.

COMSOL
www.comsol.com/products

Custom RF Cable Creator Tool

Fairview Microwave Inc. has introduced a new online custom cable creator tool that allows engineers and buyers to design, customize and purchase hundreds of different combinations of custom RF cable assemblies. Fairview Microwave's RF Cable Designer™ allows engineers and buyers to quickly and easily create customized RF cable assemblies from a wide selection of connectors and cable types offered by the company. Customers can choose from a multitude of connector and coaxial cable types to construct cable assemblies that address their specific application requirements.

Fairview Microwave Inc.
www.fairviewmicrowave.com

Filter Wizard®

K&L Microwave's Filter Wizard® synthesis and selection tool streamlines identification of RF and microwave filters meeting customer requirements across a large portion of K&L's standard product offerings. Filter Wizard® accelerates user progress from specification to RFQ over an ever-increasing range of response types, bandwidths and unloaded Q values. Provide the application with desired specifications, and the software returns a list of products that match, placing response graphs, outline drawings and downloadable S-parameters at your fingertips.

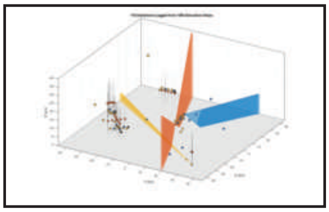
K&L Microwave
www.klfilterwizard.com

PIM Finder

Kaelus, a supplier of high-quality, PIM test & measurement instruments and RF conditioning solutions, has debuted PIM Finder, software designed to accurately identify and locate external PIM sources outside antenna infrastructure. Used in combination with the Kaelus iVA Cable & Antenna analyzer and the iPA portable PIM analyzer, PIM Finder is a software option available through Kaelus Unify, used to pinpoint and detect external PIM sources such as loose mounting and cable brackets, fasteners, parapet walls and more, while allowing for the elimination of key causes of PIM interference.

Kaelus
www.kaelus.com

Sensor Fusion & Tracking Toolbox



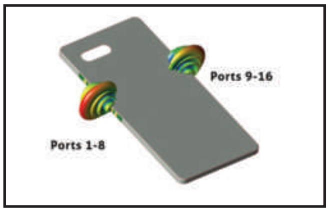
MathWorks has introduced Sensor Fusion and Tracking Toolbox, which is now available as part of Release 2018b. The new toolbox equips engineers working on autonomous systems in aerospace & defense, automotive, consumer electronics and other industries with algorithms and tools to maintain position, orientation and situational awareness. The toolbox extends MATLAB based workflows to help engineers develop accurate perception algorithms for autonomous systems.

MathWorks
www.mathworks.com/products/sensor-fusion-and-tracking.html

Software and Mobile Apps

New 5G Antenna Array Design Features

VENDORVIEW



Remcom has added 5G antenna array design features in the latest release of XFdtd® 3D EM Simulation Software, including workflow enhancements for modeling complex devices at mmWave frequencies. XFdtd provides performance metrics for beam steering applications by simulating the radiation pattern for different array or subarray phasing conditions used to steer a beam. By considering the optimal gain levels of the various beam steering scenarios, XFdtd plots the cumulative distribution function (CDF) of the effective isotropic radiated power (EIRP) of the array as a whole.

Remcom
www.remcom.com/xfdtd-3d-em-simulation-software

High Performance 3D EM Software Package

VENDORVIEW

CST Studio Suite® is a high performance 3D electromagnetic (EM) software package from SIMULIA, a Dassault Systèmes brand. Leading companies gain considerable product to market advantages by using the EM and multiphysics simulation tools in CST Studio Suite in the design of components, and the analysis and optimization of entire systems. Further information is available at www.3ds.com/products-services/simulia/products/cst-studio-suite/.

SIMULIA, Dassault Systèmes
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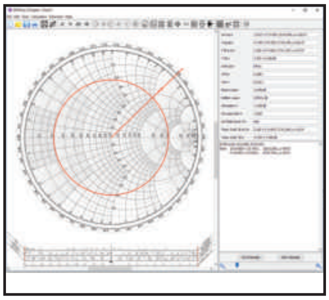
Smith Chart Software & RF Design Tool



RFOffice® V3.0 is a powerful and easy-to-use Smith chart software and RF design tool. You can import the SnP files to the interactive Smith chart. RFOffice® also provides other robust functions for RF engineers. You can draw/mark points and observe the real-time detail information as you move your cursor on the chart. Functions include drawing SWR circles, drawing curves with impedance or admittance values, transmission line design, microstrip line filter design and more.

Wave-Dimension
www.wave-dimension.com

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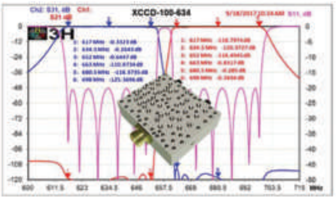
COMPONENTS

5G, Low PIM, Band Duplexer



3H's 5G Band 71 Duplexer offers < 1 dB passband insertion loss and > 100 dB co-channel isolation. The duplexer is rated for 200 W average with a PIM > 160 dBc with two 20 W tones applied at the Tx frequency band and measured at the Rx band typical. Package size is 9.85 in. × 8.85 in. × 3 in.
3H Communication Systems
www.3Hcommunicationsystems.com

Flexible Waveguide Models

Fairview Microwave Inc. has unveiled a new line of seamless and twistable flexible waveguides covering 10 frequency bands from WR-137 to WR-22 and operating in the 5.85 GHz to 50 GHz range. Typical applications include base stations, DAS systems, antennas and test instrumentation. Fairview Microwave's new line of flexible waveguides consists of 78 models—39 seamless and 39 twistable, all operating in the same wide range of frequencies.
Fairview Microwave Inc.
www.fairviewmicrowave.com

5G Ready mmWave Products

VENDORVIEW

MECA offers a family of components covering the various proposed bands for 5G and mmWave bands. Featuring power divider and couplers covering 6 to 40 and 10 to 50 GHz with 2.92 and 2.4 mm interfaces. Available in 2019, 40 to 50 and 26 to 65 GHz models. Also available are attenuators, terminations, bias tees, DC blocks and adapters. Additionally octave and multi-octave models covering MHz to GHz with SMA interfaces all built by J-Standard certified assemblers and technicians. Made in U.S. with a 36 month warranty.
MECA Electronics Inc.
www.e-MECA.com

Coaxial Ultra-Wideband Directional Coupler

VENDORVIEW

Mini-Circuits' ZCDC10-K5R44W+ is a coaxial directional coupler with an operating frequency range from 0.5 to 40 GHz. This model provides 10 dB nominal coupling with ±0.9 dB flatness over the full band. It can handle up to 15 W RF input power and achieves low mainline loss (1.3 dB at 18 GHz and 2.1 dB at 40 GHz), 15 dB return loss and 22 dB directivity up to 40 GHz.

Mini-Circuits
www.minicircuits.com

Satellite Terminal

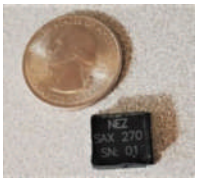
The GLOBETrekker™ 2.0 is the world's most intelligent fly-away satellite terminal. With a modular architecture that enables easy component swapping in the field, a simple one touch interface and intelligent LinkControl™ software for automatic satellite acquisition, it is both powerful and easy to use. Built to military specifications, with a suite of integrated modems, video encoders and lightweight packaging compact enough for airline check-in, operators rely on the GLOBETrekker for mission critical communications anywhere on the planet.
Norsat International
www.norsat.com

Coaxial RF Lightning and Surge Protectors

VENDORVIEW

Pasternack has just launched a new series of coaxial surge protectors that are designed to guard valuable communications equipment from power surges and indirect lightning strikes. Pasternack's 46 new coaxial lightning and surge protectors are perfect for use in cellular base stations, public safety systems, Wi-Fi networks, active antenna systems and GPS system applications. The new surge protectors are available with 7/16 DIN, Type-N and 4.3-10 connectors and feature VSWR as low as 1.1:1, max power as high as 2 kW, multi-strike capability and low insertion loss.
Pasternack
www.pasternack.com

Tunable Bandpass Filter



Richardson RFPD Inc. announced the availability and full design support capabilities for a new tunable bandpass filter from NewEdge Signal Solutions Inc. The SAX270 electronically-tunable bandpass filter is designed for the extended UHF band in tactical communications applications. NewEdge has used a breakthrough approach to achieve the filter's extremely small size and over-molded plastic packaging.
Richardson RFPD Inc.
www.richardsonrfpd.com

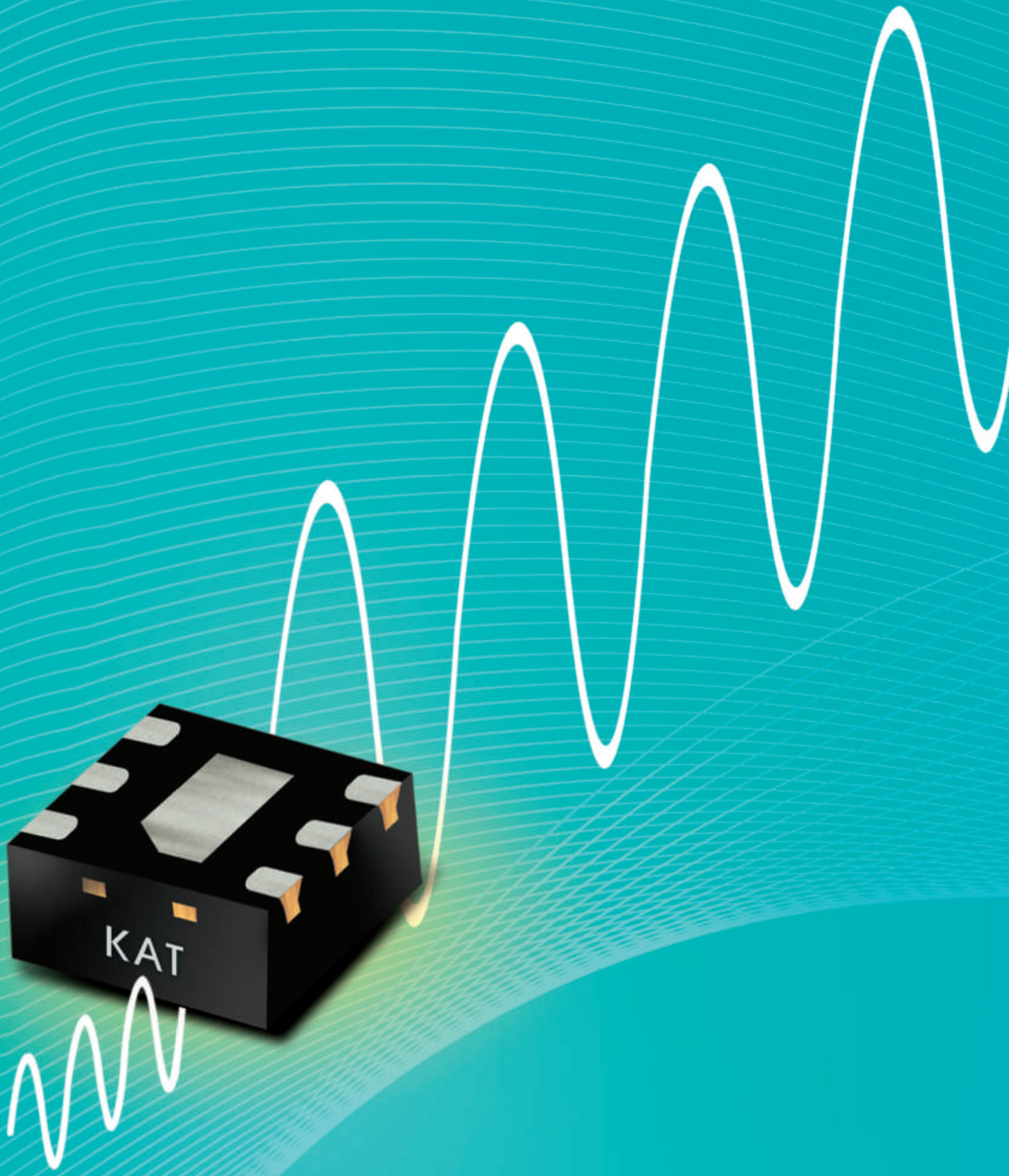
High-Power Directional Couplers

RLC Electronics' high-power directional couplers offer accurate coupling (±1 dB), low insertion loss (0.1 to 0.35 dB max) and high directivity (> 14 dB at 18 GHz) in a compact package. These high-power couplers are offered with 500 to 1000 W average power handling up to 18 GHz, as well as 100 W versions up to 40 GHz. The standard units are optimized for 2 octave bandwidths and are available with a choice of coupling values (30, 40 or 50 dB) low intermodulation products.
RLC Electronics Inc.
www.rlcelectronics.com

SpaceNXT™ Ku Series of Band Circulators & Loads

VENDORVIEW

Smiths Interconnect announced the release of the SpaceNXT™ Ku Series of high-power WR75 circulators and loads. The newly released Ku-Band family of passive waveguide components is part of an overarching initiative to create a broad range of readily accessible space qualified waveguide isolators, circulators, terminations, transitions, hybrids and couplers operating in assigned frequency bands from X- to V-Band.
Smiths Interconnect
www.smithsinterconnect.com


KAT

NewProducts

2-Way Power Divider

The SD-1 is a 2-way power divider operating in the frequency range of 2 to 300 MHz. This device combines small size and wide bandwidth performance packaged in a lead free RoHS surface mount package measuring 0.31 in. × 0.25 in. × 0.205 in. and operates over a temperature range of −40°C to 85°C. This device can handle 1 W of maximum input power in splitter mode with an insertion loss of 0.8 dB (typ.)/1 dB (max).

Synergy Microwave Corp.
www.synergymwave.com

CABLES & CONNECTORS

Dual-Use Waterproof Ethernet Cables

MilesTek's IP67, dual-use waterproof cables can be used with IP-rated receptacles for a watertight seal or with standard RJ45 jacks. This design eliminates the need to custom order specialized cables that are IP-rated on one end and have a standard RJ45 connector on the other end. This dual functionality is accomplished by a waterproof shroud that can be pulled back to mate with standard RJ45 jacks. These cable assemblies feature a CMX outdoor burn rating, foil shield to protect against EMI/RFI interference and a tethered dustproof shroud cap.

MilesTek
www.milestek.com

Waveguide to Coaxial Adapter Assembly

The M Wave Design Corp. 284CA1208, WR284 (CPRF flange) to 7/8 in. EIA waveguide to coaxial adapter assembly is rated at 100 Kw peak/3 Kw average with a 1.1:1 typical VSWR and 0.05 dB typical insertion loss. M Wave Design Corp. has a large library of heritage adapter designs along with the ability to produce new configurations quickly, covering 2 to 40 GHz range.

M Wave Design Corp.
www.mwavedesign.com

Miniature Phase Adjusters

Spectrum Elektrotechnik GmbH offers a new line of miniature phase adjusters, operating in the frequency range DC to 40 GHz (2.92 mm), DC to 50 GHz (2.4 mm) and DC to 63 GHz (1.85 mm). The products, as the standard units, which start at 2 GHz, are designed for constant impedance of 50 Ohms over the whole adjustment range. The precision mechanical mechanism guarantees continuous adjustment over the entire frequency range and a locking mechanism ensures stability of the desired position during vibration.

Spectrum Elektrotechnik GmbH
www.spectrum-et.com

AMPLIFIERS

Low Noise Amplifier

VENDORVIEW

PMI Model No. PE2-15-2R018R0-4R5-15-12-SFF is a 2 to 18 GHz low noise amplifier which provides 15 dB of gain while maintaining a gain flatness of ±1.25 dB max over the operating frequency. The noise figure is 4.5 dB typical and offers a typical OP1dB of 15 dBm. The amplifier requires +12 to +15 VDC and the current draw is 85 mA typical. The unit is supplied with SMA female connectors in their standard PE2 housing.

Planar Monolithics Industries
www.pmi-rf.com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Get the entire pulse of the Microwave and RF industry in just a few days:
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• Over 75 technical sessions, workshops and panel sessions
• RF Bootcamp, a special course designed specifically for newcomers to the micro-wave world
• 5G Summit featuring experts from industry, government and academia
• Student forums such as design competitions, paper competition, PhD Initiative and Project Connect
• Special interest groups such as Women in Microwaves and Young Professionals
• Countless networking opportunities
• Special focus on startup companies with the first ever Startup pavilion, Startup panel session and Next Top Startup competition
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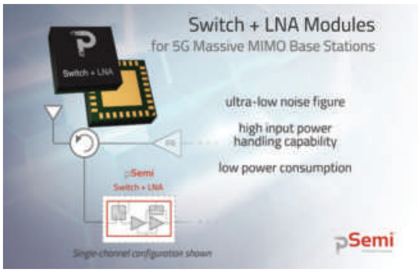
NewProducts

Switch + LNA Modules



pSemi's family of switch + low noise amplifier (LNA) modules for 5G massive MIMO base stations are now available in volume production. With an ultra-low noise figure and excellent input power handling, the PE53111, PE53211, PE53110 and PE53210 are ideal for protecting remote radio units that operate in the sub-6 GHz frequency bands. The PE53111 and the PE53211 cover a frequency range from 2.3 to 2.7 GHz (bands 40, 41, n7, n38, n41), while the PE53110 and PE53210 extend from 3.3 to 3.8 GHz (bands 42, 43, 48, 49, n78).
pSemi
www.psemi.com

Amplifier Systems

VENDORVIEW

The 9100 series amplifier systems cover the 0.8 to 40 GHz frequency ranges and comes available with continuous wave or pulsed power. The 9100 series amplifier systems have been in use for over 20 years with most of these amplifiers still in use today. As with all Quarterwave products, these amplifiers feature an ultra-low noise output, a wide range of stable voltage adjustment and modular designs that are easily adjustable to accommodate specific project requirements.
Quarterwave
www.quarterwave.com

Power Amplifier

VENDORVIEW

Skyworks announced its latest cellular infrastructure innovation, the SKY66313-11, a wide instantaneous bandwidth power amplifier with industry-leading efficiency for FDD/TDD 4G LTE and 5G applications. This breakthrough solution is utilized in small cell and massive MIMO base stations to deliver higher data rates and enhanced network efficiency that result in improved carrier capacity and greater coverage for data-intensive, multimedia and IoT devices. The amplifier's highly efficient design boasts fully-matched input/output and high gain for best-in-class operation.
Skyworks
www.skyworksinc.com

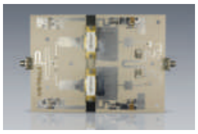
5000 MHz, 10 W Power Amplifier

The TA4002R utilizes the lastest GaN technology to provide 10 W of power in the C-1 and C-2 bands. The unit is designed to be integrated in any system that requires high-power, high efficiency and high linearity in the entire 4400 to 5000 MHz band. The amplifier provides 23 dB of small signal gain and can produce over 2 W of 64-QAM OFDM power. The compact unit measures only 2.73 in. × 2.53 in. × 1.31 in. and maintains a low operating temperature due to its built-in heat sink.
Triad RF Systems
www.triadrf.com

SOURCES

L-Band Power Module

VENDORVIEW



Designed to solve various SWaP-C in high performance L-Band avionic systems, IGN-P1011L2400 is a new high-power GaN on SiC RF power module/pallet, designed specifically for IFF/SSR systems operating under either Mode S ELM or standard Mode S pulse conditions, supplying a minimum of 2200 W of peak output power, with typically > 16 dB of gain and 57 percent efficiency and operating from a 50 V supply voltage.
Integra Technologies Inc.
www.integratech.com

Micro-Transcoder™ GPS Modulator

Jackson Labs Technologies Inc.'s Micro-Transcoder™ is by a large margin the world's smallest, full-constellation, stand-alone, real-time 10-channel GPS simulator. The Micro-Transcoder™ achieves hardening of the customers' GPS equipment by splicing the unit in-between the existing antenna and the users' GPS receiver and taking the output of any secure PNT source such as INS, SAASM, M-code, Iridium STL or concurrent GNSS receiver and encoding (RF modulating) the baseband PNT and UTC timing information into a standard GPS L1 RF signal.
Jackson Labs Technologies Inc.
www.jackson-labs.com

Synthesizer

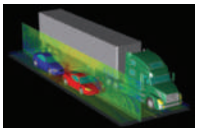
VENDORVIEW

RFE Synthesizer provides a reliable, fast tuning, microwave source covering the 11 to 15 GHz range. The design is completely designed using COT surface mount components.
RFE Inc.
www.rfe-mw.com

SOFTWARE

XFdtd Electromagnetic Simulation Software

VENDORVIEW



Remcom announced 5G antenna array design features in the latest release of XFdtd® 3D EM Simulation Software, including workflow enhancements for modeling complex devices at mmWave frequencies. The advanced antenna systems in modern devices leverage beam steering and multiple data stream transmission to meet 5G throughput requirements. XFdtd provides performance metrics for 5G beam steering applications by simulating the radiation pattern for different array or subarray phasing conditions that are used to steer a beam.

Remcom Inc.
www.remcom.com

ANTENNAS

ProLine Series Antennas

KP Performance Antennas has debuted its new ProLine antennas, a series of high performance parabolic and sector antennas that are perfectly suited for high density, point-to-point, point-to-multipoint and backhaul applications. KP's new ProLine parabolic antennas are engineered to deliver high, stable gain over wide bandwidths with side-lobe and back-lobe suppression for mitigating inter-sector interference. These 5 GHz antennas are available in 1 and 2 ft. diameters with gain performance of 24 and 29 dBi, respectively.

KP Performance Antennas
www.kpperformance.com

Ultra-Low Profile DAS Antenna

Laird Connectivity announced the CFSA35606P, the world's thinnest, ultra-low profile DAS antenna with the broadest range of frequency coverage. The CFSA3560P is a low PIM, ceiling mounted antenna with omnidirectional pattern coverage optimized for indoor DAS coverage at 350 to 520, 600 to 960, 1350 to 1550 and 1690 to 6000 MHz for the UHF, 4G LTE, 2G/3G Cellular, UMTS/AWS-3, CBRS and Wi-Fi frequency bands.

Laird Connectivity
https://connectivity.lairdtech.com

FMCW Radar Design

M. Jankiraman

"This worthwhile book is a general radar text discussing many aspects of radar design, with emphasis on practical issues. The special coverage of FMCW stems from the author's long defense experience. Recent interest in automotive radars, most of which utilize Linear FMCW, enhances the value of the book."

—Professor Nadav Levanon,
Dept. of Electrical Engineering–Systems,
Tel-Aviv University, Israel

Frequency Modulated Continuous Wave (FMCW) radars are a fast expanding area in radar technology due to their stealth features, extremely high resolutions and relatively clutter free displays. This groundbreaking resource offers engineers expert guidance in designing narrowband FMCW radars for surveillance, navigation and missile seeking. It also provides professionals with a thorough understanding of underpinnings of this burgeoning technology. Moreover, readers find detailed coverage of the RF components that form the basis of radar construction. Featuring clear examples, the book presents critical discussions on key applications.

Practitioners learn how to use time-saving MATLAB® and SystemVue design software to help them with their challenging projects in the field. Additionally, this authoritative reference shows engineers how to analyze FMCW radars of various types, including missile seekers and missile altimeters. Packed with over 600 equations, the book presents discussions on key radar algorithms and their implementation, as well as designing modern radar to meet given operational requirements.

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FABS and LABS

Cicor—Your Global Manufacturing Partner

Founded in 1966 in Lausanne, Switzerland, the Cicor Group is a solutions provider with worldwide operations and a global portfolio of electronic services and technologies ranging from prototyping to assembly to test. With over 2,000 employees at 10 production sites, the Cicor Group offers highly complex printed circuit boards (PCB) and hybrid circuits, printed electronics as well as comprehensive electronic manufacturing services (EMS), including microelectronic assembly and plastic injection molding. As your worldwide manufacturing partner, Cicor provides customized products and services from design to the finished product from one source.

The Cicor Group offers a wide range of products and services in the fields of PCB assembly, box building and system assembly, control cabinet construction, cable assembly, tool design and fabrication. Cicor offers outsourcing solutions for the development and manufacture of electronic assemblies to complete devices and systems.

Cicor has been developing and producing complex flexible, rigid-flexible and rigid PCB from concept to large scale production for many years. They have expertise in multilayer boards (MLB), multi-chip modules (MCM), high-density interconnects (HDI) and reel-to-reel technology, offering innovative and reliable solutions for demanding applications in medical, aerospace & defense, automotive and transport, communication, industrial, watch and consumer markets.

Thin film materials as well as line width and spacing down to 25 μm enable extreme miniaturization and ultra-HDI advanced solutions. Their new DenciTec® technology opens up new possibilities for innovative circuits that can be produced by combining PCB processes with thin film technology. The company offers hybrid circuits using thin film substrates with tolerances to ±2 μm. Cable lines in thick film technology can be installed in the screen printing process and then cured. For products that need high-reliability, the use of ceramic substrates ensures maximum reliability even under the hardest environmental conditions.

The new Cicor site in Arad, Romania offers manufacturing services for high quality electronic products. The site supports its clients starting in the planning stage, ensuring the ideal outsourcing solution tailored to the client's specific needs. As an EMS partner over the entire product life cycle, from hardware and software development through series production to after sales service, the facility offers complete outsourcing solutions for the manufacturing of electronic component assemblies as well as complete devices and systems.

The new Arad facility is equipped with SMT production capabilities including 18 SMD assembly machines, and six nitrogen convection reflow systems including fine pitch stenciling and automatic inspection. The facility is also equipped with through-hole technology including automatic and manual assembly, automatic cutting plus five nitrogen wave soldering systems. Coating systems are also on site for dip and silicone coating. The production also includes comprehensive testing capabilities including in-circuit, flying probe, functional and custom tests. Full optical inspection and traceability are included in the production process flow.

Companies that focus on their core business, while making effective use of external specialists such as Cicor to help design and produce their electronics, can achieve a competitive advantage in the marketplace with fast time to market at a competitive cost.

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