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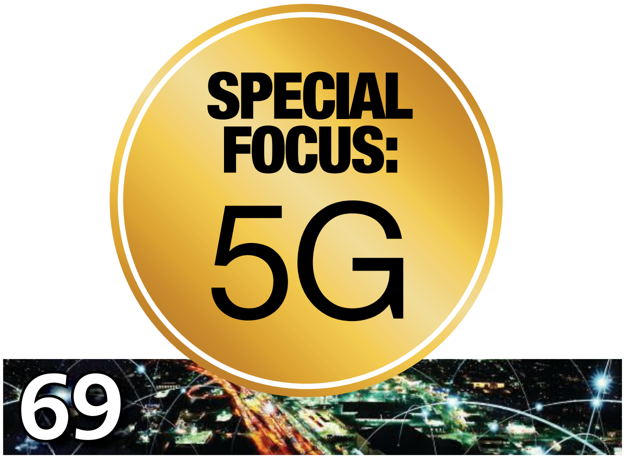

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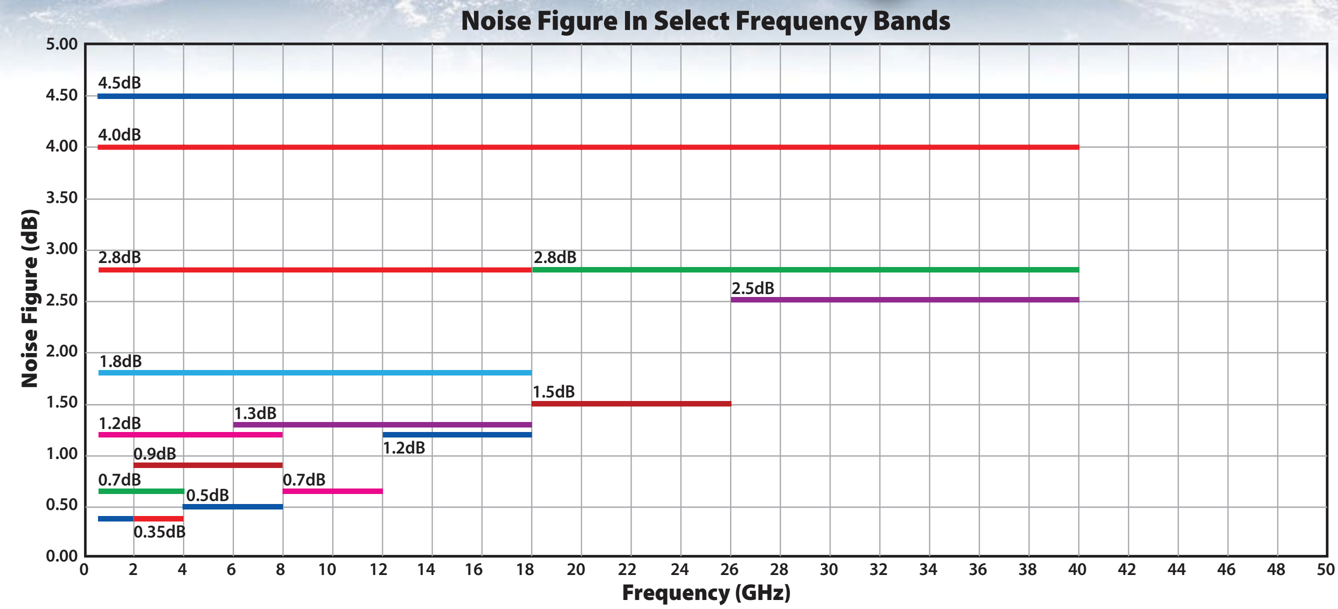

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EUROPEAN EDITORIAL OFFICE
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Aline Friedrich, R&D Engineer, and **Winfried Simon**, Technical Director from **IMST's Antennas and EM Modeling Group**, talk about what the group is focusing on for next-generation antenna development, their product portfolio and what market applications look most promising.

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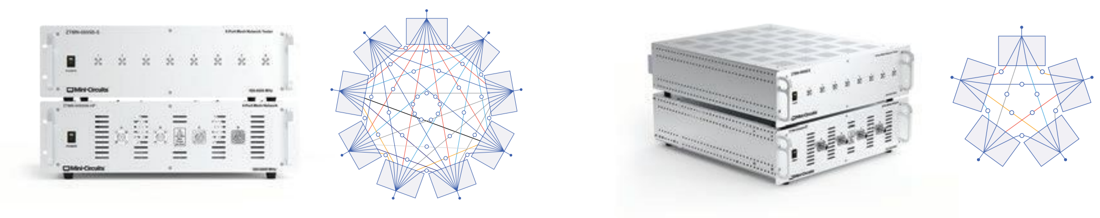

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TIME TRAVEL

Eric Higham
Microwave Journal

Francis Blake: An Unsung Hero?

The Time Travel feature highlights the early pioneers that have helped shape the trajectory of the electronics industry. Since we started this feature, we have profiled Max Planck, Nikola Tesla, Guglielmo Marconi, James Clerk Maxwell, Hedy Lamarr and Oliver Heaviside, all recognizable names. As I started thinking about the November profile, I saw that Francis Blake was granted a U.S. patent in November 1881 for the "Speaking Telephone" and thought "who?"

It turns out that Francis Blake was born in Newton, Mass., in 1850, less than 10 miles up the road from the Microwave Journal offices. He began working as a scientist with the U.S. Coast Survey at 15. In 1874, Blake married into a very wealthy family, allowing him to leave his job and pursue his passions as an inventor and later, a photographer.

This is where the story gets interesting for the electronics community. Alexander Graham Bell received a U.S. patent for the telephone in 1876, but by most accounts, the business he started was struggling. Bell's telephone received calls, but it did not transmit them very well or very loudly. At the time, Western Union was Bell's main competitor and they were using a carbon-based transmitter from Thomas Edison that performed much better.

When Blake learned of the telephone patent, he began experimenting to improve the quality of the transmitter. For the next two years, he worked with Bell employees to refine the design to correct a whole host of resonance, mounting, contact point and material issues. In 1878, satisfied that he had a viable improvement, Blake took his transmitter to the Bell offices and after thorough testing by Thomas Watson, the person who received Bell's first phone call, the Bell Company bought Blake's design. Feeling confident that they had a transmitter that was as good as or better than what Edison had developed for Western Union, the Bell Company sued Western Union for patent infringement and won. Western Union settled out of court and surrendered all its patents and telephone business to the smaller Bell Company. From these beginnings and armed with the patent and the "Blake Transmitter," as it became known, the Bell Company grew into Bell Telephone, a behemoth that had revenues of more than $400 billion with more than one million employees before it was broken up in the early 1980s.

The proceeds from the sales and licensing of the Blake Transmitter made Francis Blake independently wealthy. In 1884 he took up photography and it quickly became a passion. In 1885, Blake purchased an instantaneous shutter camera, which meant a shutter speed of about 1/300th of a second. Not satisfied, Blake designed a focal plane shutter that allowed shutter speeds of 1/1000th -1/2000th of a second. This allowed stop-action photographs of moving objects that were quite different from what was common at the time.

Francis Blake was a bit of a Renaissance person with his interests and inventions. He rubbed shoulders with the people credited with developing the U.S. phone industry, but he did not have that notoriety. His Blake Transmitter was widely used for 20 years after it was patented and it was credited with speeding up the development and deployment of telephony in the U.S. So, the answer to my question of "who?" is a man who may be the unsung hero of an industry that is currently approaching $2 trillion in revenues.


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Next-Generation Terabit Wireless Communication: Advancements Beyond 6G

V. Manimala
Builders Engineering College, Tamil Nadu, India

Dr. N. Gunavathi
National Institute of Technology, Tamil Nadu, India

As the demand for faster wireless communication continues to escalate, the advancement of next-generation terabit wireless communication technologies has become a prominent area of research. This article explores the advancements and challenges that lie beyond 6G, aiming to achieve terabit data rates in wireless networks. It presents key technological innovations, including advanced modulation schemes, ultra-dense networks, mmWave and terahertz communication, massive MIMO (mMIMO) and intelligent beamforming techniques. To do this, emerging technologies such as optical wireless communication, visible light communication and novel spectrum utilization techniques were studied. The article also addresses the fundamental challenges associated with terabit wireless communication, including channel capacity, energy efficiency, security and interference management. By presenting an overview of the advancements and potential solutions, along with some of the reference work being done in this area, this article provides valuable insights into the future of terabit wireless communication beyond 6G and offers a foundation for further research in this field.

Terabit wireless communication represents a paradigm shift in wireless connectivity, enabling transformative applications and services that demand extraordinary data rates. While the realization of terabit wireless communication is still in the research and development stage, advancements in technologies such as mmWave communications, mMIMO, beamforming and intelligent network management are paving the way for this exciting future of wireless communication.[1] ***Figure 1*** shows the concepts of spectrum administration, antenna systems and their beamforming techniques, along with the fusion of additional technologies that will facilitate 6G for THz communication.

THOUGHTS FROM THE BROADER TECHNICAL COMMUNITY

The signal-to-noise ratio (SNR) of optical wireless communications or visible light communications systems is increased by utilizing silicon photomultipliers (SiPMs) in the receiver.[2] SiPMs are highly sensitive light detectors that can detect single photons with high efficiency. They are based on silicon avalanche photodiode (APD) technology and can achieve low noise levels and high gain. By using SiPMs in the receiver, the system can capture and amplify weak optical signals more effectively, leading to an improved SNR. The higher SNR obtained with SiPMs can help reduce the bit error rate of the system. "Terabit Indoor Laser-Based Wireless Communications: LiFi 2.0 for 6G"[3] gives a detailed examination of the necessary technologies to create indoor wireless networks powered by lasers that can achieve data rates in the terabit per second range. This data


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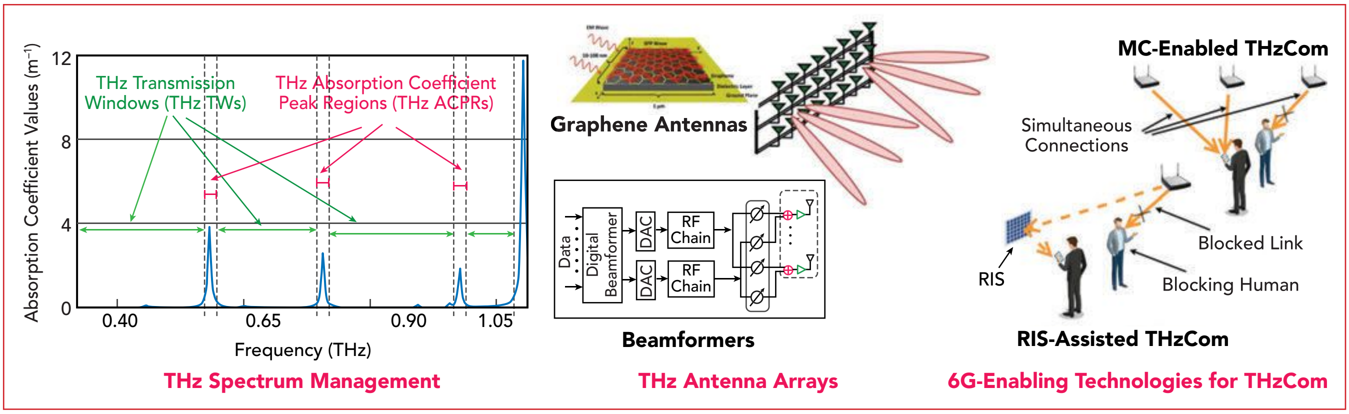

Fig. 1 Three pivotal areas for the development of end-to-end THz communications systems.[1]

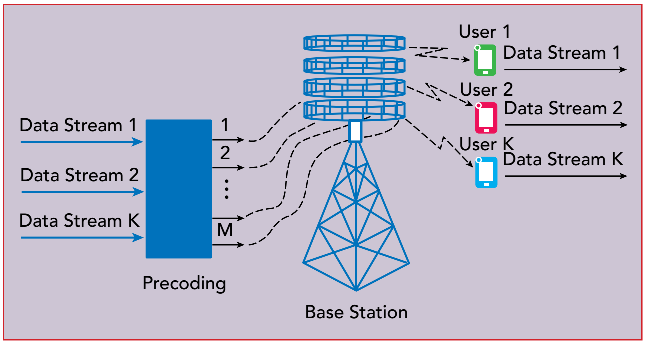

Fig. 2 Massive MIMO system model.[4]

rate is considered to be a key performance indicator for 6G wireless communication.

Another cited reference, "Precoding and Beamforming Techniques in mmWave-Massive MIMO: Performance Assessment"[4], focuses on the integration of mMIMO with mmWave frequency bands to achieve the design goals of 5G wireless communication systems that will serve as stepping stones to 6G and beyond. The integration of mmWave communications with mMIMO offers several advantages, including improved spectral and energy efficiency, enhanced mobile network capacity and significant increases in multiplexing gains. These benefits are crucial for meeting the requirements of 5G networks. The utilization of a single-cell downlink mMIMO system model facilitates the assessment and evaluation of the efficacy of mMIMO systems. A diagram of a mMIMO system is shown in ***Figure 2***.

"Demo: AI-Engine Enabled Intelligent Management in B5G/6G Networks"[5] showcases an artificial intelligence (AI) engine that incorporates multiple AI algorithms and demonstrates its potential in managing the life cycle of network slices. The AI engine solution is designed to be distributed, meaning that it can be deployed across multiple locations or devices. This distributed deployment allows the AI engine to offer customized machine learning (ML) models that are specifically designed for different use cases. The availability of a variety of ML models enables the AI engine to facilitate data analysis of network functions and intelligent applications at the edge cloud. The edge cloud refers to computing resources and services deployed closer to the network edge, enabling faster processing and reduced latency.

One of the key features of this solution is its ability to dynamically allocate computing resources to each distributed component of the AI engine. This resource allocation capability facilitates intelligent network management by allowing the system to adapt the allocation based on the requirements of each component. This flexibility enables efficient utilization of computing resources and ensures optimal performance for intelligent network management tasks.

IMPORTANT AREAS OF CONSIDERATION FOR TERABIT WIRELESS COMMUNICATION

Data rate advancements: Terabit wireless communication represents a significant leap in data rates compared to current wireless technologies. It enables faster transmission of large volumes of data to facilitate things like real-time streaming of high-resolution videos, immersive virtual reality experiences and rapid data transfer for applications like autonomous vehicles and smart cities.

Spectrum utilization: To achieve terabit data rates, efficient utilization of the RF spectrum is essential. Advanced modulation schemes are employed to maximize spectral efficiency and enable higher data rates within the available frequency bands.

mMIMO and beamforming: mMIMO systems, equipped with multiple antennas, play a crucial role in achieving terabit wireless communication. mMIMO, combined with advanced beamforming techniques, allows for spatial multiplexing, improved link reliability and interference mitigation. These techniques will all contribute to higher data rates and overall system capacity.

Intelligent network management: Terabit wireless communication necessitates intelligent network management techniques. AI and ML algorithms are employed for dynamic resource allocation, interference management and efficient utilization of network resources. Intelligent algorithms adapt to varying channel conditions and user demands, ensuring optimal performance and data rate delivery.

Fiber-like experience: Terabit wireless communication aims to deliver a fiber-like experience over wireless networks. These high data

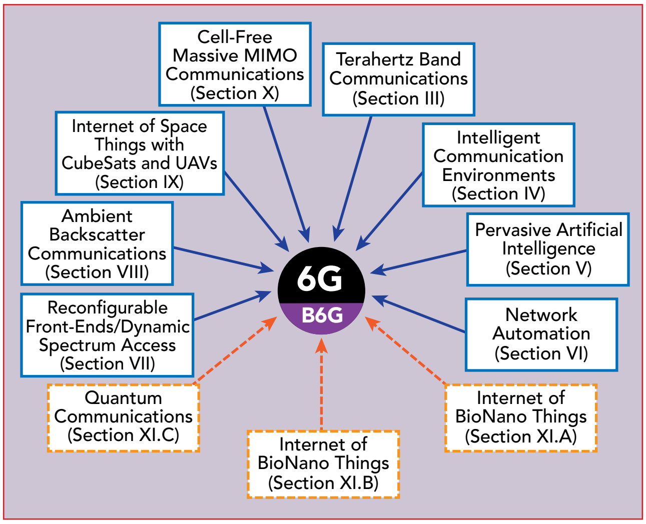

Fig. 3 Key enabling technologies envisioned for 6G and beyond wireless communications systems.[6]

rates enable users to experience seamless connectivity, fast downloads and low latency connections, similar to or exceeding the performance of wired fiber-optic networks.

Backhaul and infrastructure: Achieving terabit wireless communication requires robust backhaul infrastructure. Fiber-optic links and high capacity microwave links serve as the backbone for carrying the massive data traffic generated by terabit wireless networks. Upgrading and expanding the network infrastructure is crucial to support the high speed and high capacity demands.

BEYOND 6G

New generations of wireless communications get developed and deployed with a surprisingly repetitive cadence. If the industry is working on 6G, the next generation is not far behind. "Beyond 6G" in the title of this article refers to the future evolution of wireless communication technologies beyond the evolving 6G standard. While 6G is still in the early stages of development, researchers and industry experts are already envisioning the possibilities and potential features of communication systems that would go beyond 6G. "6G and Beyond: The Future of Wireless Communications Systems"[6] explores the applications of enabling techniques and recent advancements in 6G. It highlights various use cases, identifies open problems and proposes potential solutions. Additionally, it provides a development timeline that outlines global efforts in the realization of 6G wireless technology. The paper extensively discusses the potential impact of emerging technologies such as the Internet of NanoThings, the Internet of BioNanoThings and quantum communications on the field of wireless communications. These innovative technologies are considered promising in their early stages and have the potential to bring about substantial advancements in wireless communication systems. ***Figure 3*** shows several crucial technology enablers that need to be addressed to accomplish the objectives of the networks that will evolve from 6G.

6G will enable a multitude of critical use cases, encompassing a wide range of essential applications and services with some shown in ***Figure 4***. "5G, 6G, and Beyond: Recent Advances and Future Challenges"[7] describes some of the latest advances and developments in 5G, 6G and beyond 6G systems. The article provides an in-depth investigation into the key technological enablers and use cases associated with these advanced wireless networks.

GOALS AND TRENDS FOR BEYOND 6G COMMUNICATION

Terabit and petabit data rates: Beyond 6G aims to achieve even higher data rates compared to 6G. Terabit per second (Tbps) and petabit per second (Pbps) data rates are envisioned to support the growing demand for high speed communication, enabling applications like real-time 8K/16K video streaming,

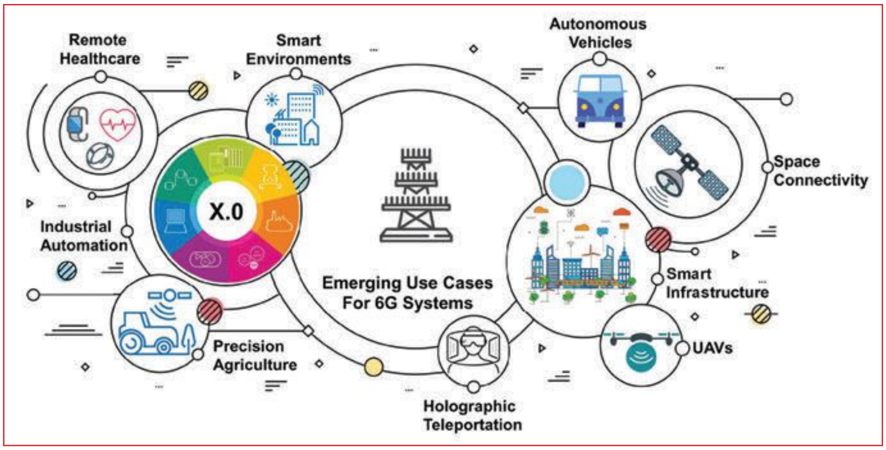

Fig. 4 Use cases best served by 6G systems.[6]

holographic communication and immersive virtual and augmented reality experiences. The article "Petabit-per-second Data Transmission using a Chip-scale Microcomb Ring Resonator Source"[8] showcases 1.84 Pbps transmission rates over a 37-core, 7.9 km fiber using 223 wavelength channels derived from a single microcomb ring resonator. This resonator generates a stabilized dark-pulse Kerr frequency comb. Additionally, the theoretical analysis suggests that a solitary, chip-scale light source has the potential to support data transmission systems with massively parallel space- and wavelength-multiplexing at a rate of 100 Pbps.

Intelligent and cognitive networks: Beyond 6G will further leverage AI and ML techniques to create intelligent and cognitive networks. These networks will be capable of self-optimization, self-healing and self-adaptation to dynamically changing network conditions, user requirements and traffic patterns. "Sixth Generation (6G) Cognitive Radio Network (CRN) Application, Requirements, Security Issues, and Key Challenges"[9] provides an overview of the forthcoming generation of cognitive radio (CR) network communication. It discusses the mandatory cases for its evolution, highlights the present technology improvement efforts and presents a detailed perspective on the future advancements in this field. ***Figure 5*** shows a potential scenario for using 6G CR in data transmission networks.

Enhanced spectrum utilization: Beyond 6G will explore innovative spectrum utilization techniques to address the growing spectrum scarcity. This may involve leveraging higher frequency bands, such as the THz range, as well as developing advanced spectrum-sharing mechanisms to efficiently allocate and utilize the available spectrum resources. "Beyond 5G: Big Data Processing for Better Spectrum Utilization"[10] highlights the immense potential of big data processing in enabling advanced user- and situation-oriented resource utilization in future wireless networks. Specifically, it explores the utilization of detailed and content-rich maps and records known as Radio Service Maps to unlock spectrum opportunities in 6G networks.

Seamless integration of physical and virtual worlds: Beyond 6G aims to close the divide between the physical and virtual realms, enabling seamless integration of digital information and physical environments. This may involve advancements in the IoT, cyber-physical systems, edge computing and the tactile Internet to create a highly interactive and immersive communication experience.

Ubiquitous and hyperconnected networks: Beyond 6G envisions hyperconnected networks that seamlessly integrate various communication technologies, including terrestrial networks, satellite networks, aerial platforms and even space-based communication systems. These networks will provide ubiquitous connectivity, enabling seamless communication anytime

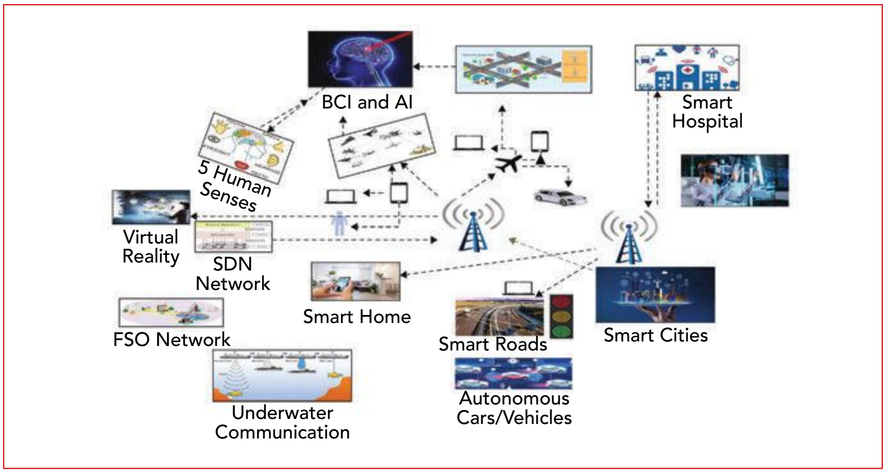

Fig. 5 A possible scenario for 6G CR network communication.[9]

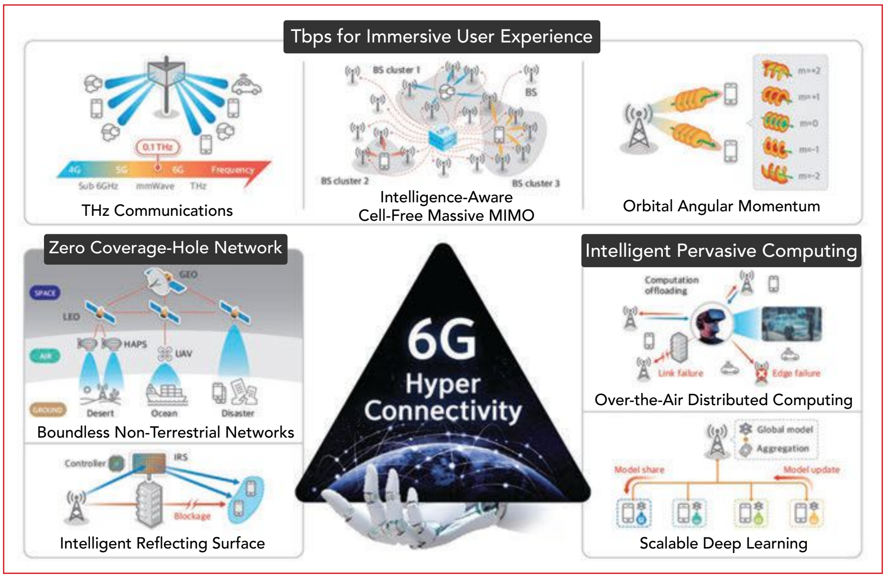

Fig. 6 Vision of 6G hyperconnectivity.[11]

and anywhere. "Towards 6G Hyper-Connectivity: Vision, Challenges, and Key Enabling Technologies"[11] provides an overview and analysis of the hyperconnected architecture of 6G networks, highlighting its key components, addressing the current challenges and exploring potential areas for future research and development. The fundamental principles of hyperconnectivity in 6G are visually depicted in ***Figure 6***.

Quantum communication: Beyond 6G may incorporate quantum communication technologies, harnessing the principles of quantum mechanics to provide secure and fast communications. Quantum key distribution (QKD) and quantum teleportation are potential applications that could enhance security and enable new communication paradigms. As cellular systems progress from 5G to 6G, there has been significant advancement in quantum information technology (QIT), particularly in quantum communications and quantum computing. QKD, for instance, can strengthen 6G security by enabling secure quantum communications. "Quantum-Enabled 6G Wireless Networks: Opportunities and Challenges"[12] offers a technology-driven and forward-thinking depiction and investigation of how QIT can be harnessed for the advancement of future 6G wireless networks. ***Figure 7*** illustrates a quantum-enabled

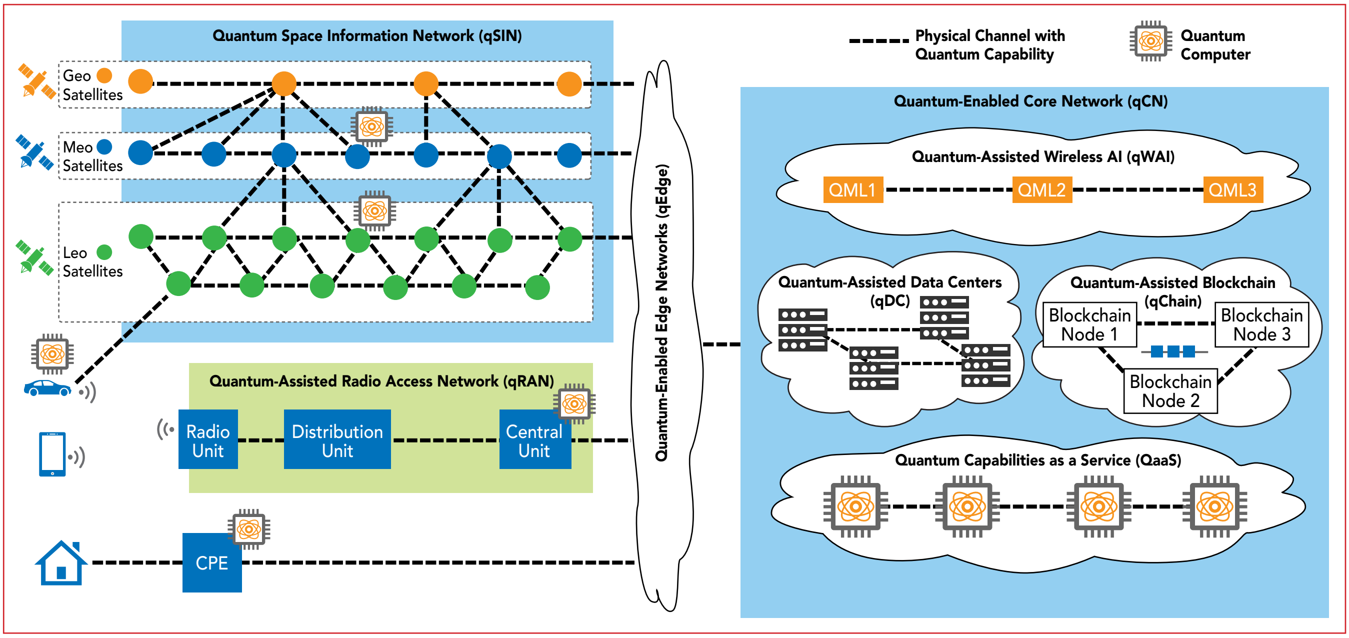

Fig. 7 A possible quantum-enabled 6G system.[12]

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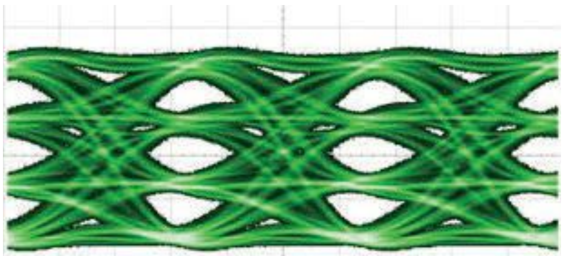

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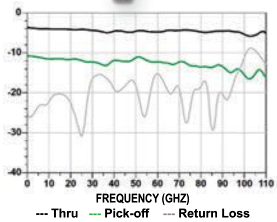

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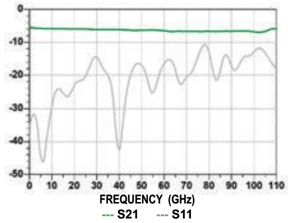

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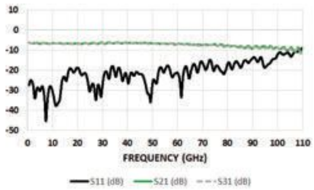

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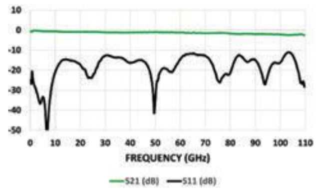

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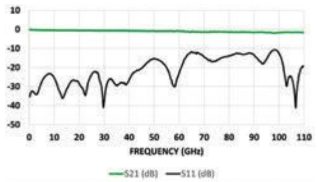

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6G system, where QIT is exploited to realize new 6G functionalities and services.

Green and sustainable networks: Energy efficiency and sustainability will continue to be important considerations in beyond 6G networks. Energy-efficient hardware designs, renewable energy integration and intelligent power management techniques will be employed to reduce the environmental impact of wireless communication systems. "Shaping Future 6G Networks: Needs, Impacts, and Technologies"[13] introduces a comprehensive approach to achieving green 6G, emphasizing the role of AI in this context. It highlights the advantages of employing AI in wireless networks, considering the energy requirements for AI training and inference.

Social and economic impact: Beyond 6G will not only focus on technological advancements but also consider the social and economic impact of communication systems. This includes addressing the digital divide, fostering inclusivity and leveraging wireless communication technologies to drive economic growth, innovation and social development.

CONCLUSION

While specific standards and technologies for beyond 6G are yet to be defined, this article and its references provide a glimpse into the potential directions and aspirations for future wireless communication systems beyond the anticipated 6G era. Terabit wireless communication aims to provide a fiber-like experience over wireless networks, offering seamless connectivity, fast downloads and low latency connections. This creates opportunities for real-time streaming of high-resolution videos, immersive virtual reality experiences and rapid data transfer for applications like autonomous vehicles and smart cities. In conclusion, next-generation terabit wireless communication advancements beyond 6G hold tremendous promise for revolutionizing the ways to connect, communicate and experience the digital world. The realization of terabit wireless communication will bring all closer to a fully connected world where data flows seamlessly, enabling new possibilities and transformative applications across various sectors. ■

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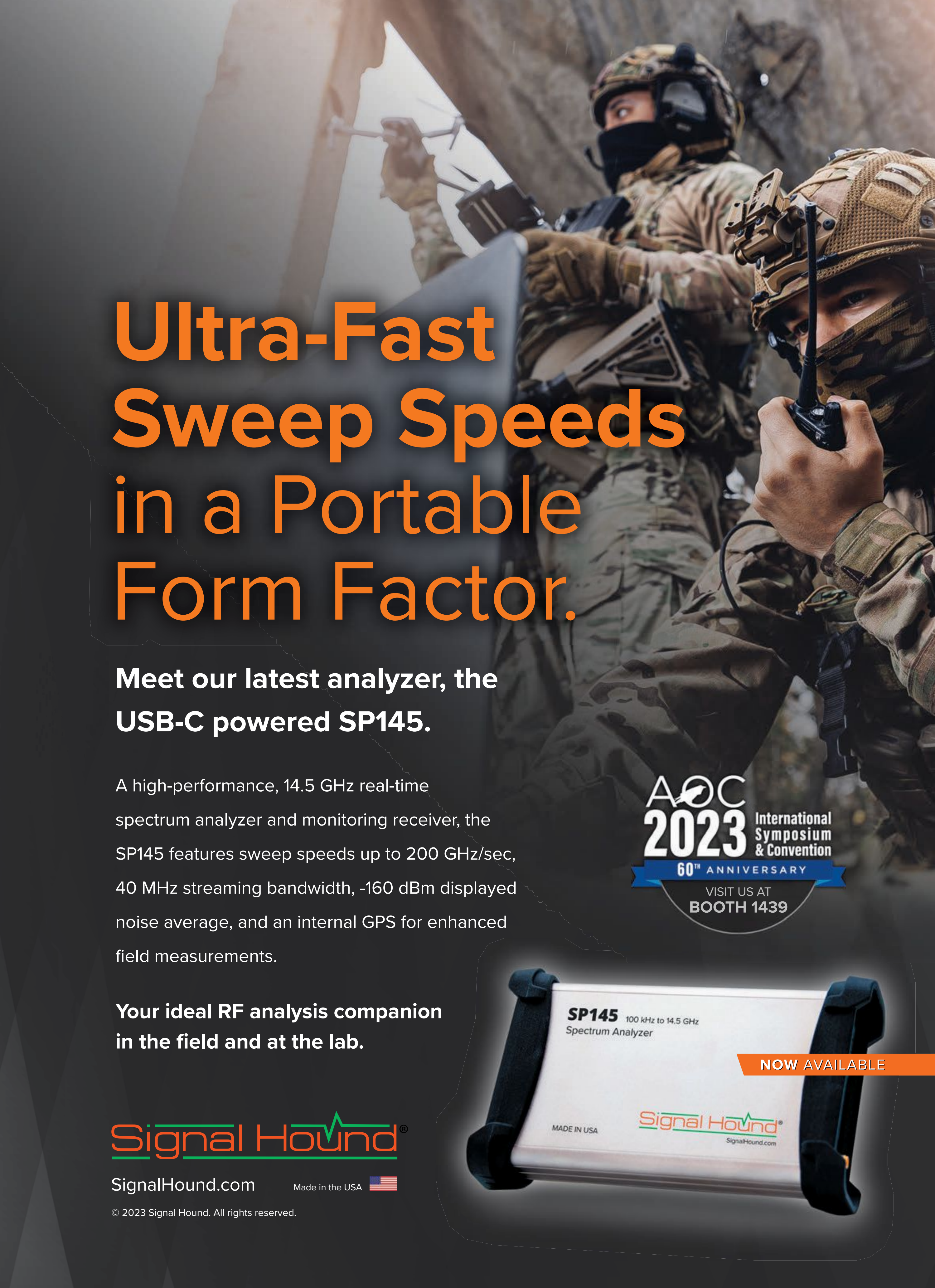
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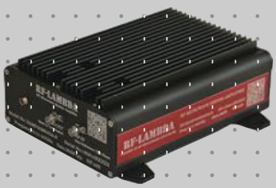

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INVITED PAPER

5G Non-Terrestrial Networks Take Flight With New Radio and IoT Applications

Reiner Stuhlfauth
Rohde & Schwarz, Munich, Germany

Non-terrestrial networks (NTNs) present a plethora of connection possibilities in emerging 5G networks. These connectivity solutions range from satellite-based communications via airborne stations to scenarios that consider air-to-ground communications and uncrewed aerial vehicles (UAVs) flight control. These scenarios are also intended to be dynamic, taking advantage of the benefits of satellites in different orbital planes and with different coverage footprints. This article will present a technological overview of these different networks.

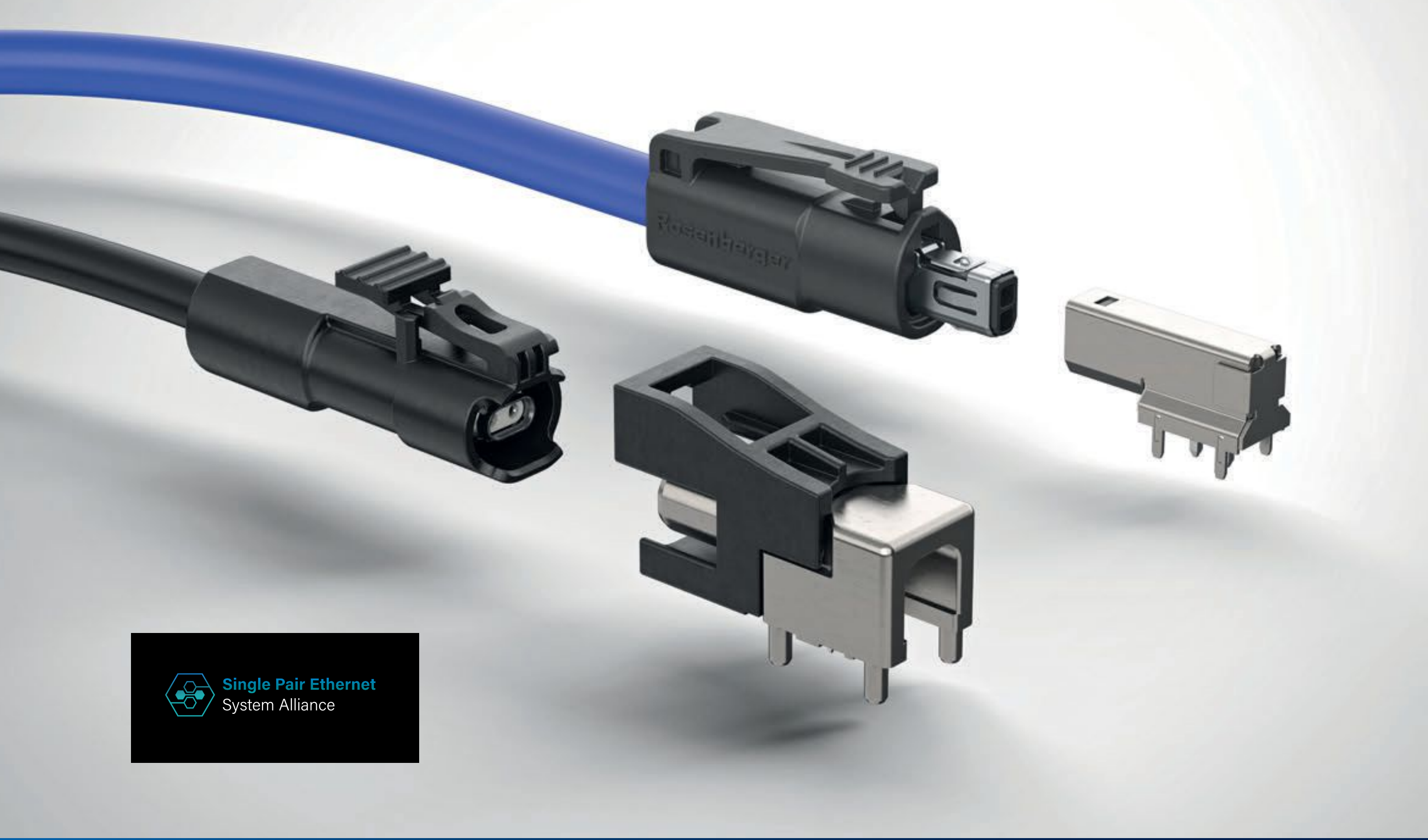
LAYING THE GROUNDWORK

To begin addressing the challenges of incorporating NTNs, 3GPP launched a Release 15 study, identified as TR 38.811, that addresses channel models and deployment scenarios. There is also a follow-up Release 16 study, TR 38.821, that proposes solutions for adapting 5G New Radio (NR) to support NTN. The main objective of these studies is to identify a feature set that enables NTN within the 5G system while minimizing the impact on the existing 5G system. The aim is to enable NTN without waiting until the final network environment is perfect. Release 17 addresses the technical specification of NTN. These specifications affect all the layers within a 5G system, ranging from the physical layer via the protocol stack to the network architecture enhancements. Considering this as the basic technology framework, Release 18 will continue to foster the NTN evolution with additional spectrum, protocol layer enhancements and service proliferation.

The major motivation to foster NTN communications is the desire to provide ubiquitous connections all over the globe. According to publicly available market statistics, wireless communications technologies covered more than 80 percent of the world's population, but less than 40 percent of the world's landmass in 2020. NTN satellite-based communications are well-suited to tackle this challenge and focus on worldwide ubiquitous coverage in maritime, remote and polar areas.

The first 5G NTN deployments will focus on ubiquitous connectivity and coverage. They will do this by separating the technology into NR-based NTN (NR-NTN) and IoT-based NTN (IoT-NTN). NR-NTN can be considered the enhanced mobile broadband (eMBB) equivalent of terrestrial 5G, enabling satellite-based connectivity focusing mainly on coverage and outdoor applications.

IoT-NTN is the extension of terrestrial IoT technologies like NB-IoT, LTE-M or 5G RedCap, in the future, but using satellite resources for connectivity. Satellite networks will have performance constraints, so NTN 5G will not compete with terrestrial 5G. Rather, 5G NTN will complement terrestrial 5G systems to provide



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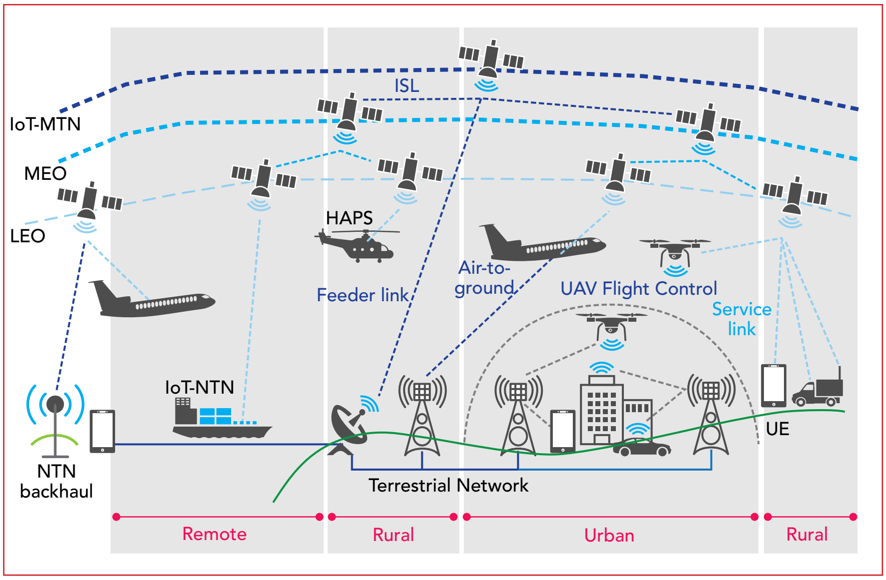
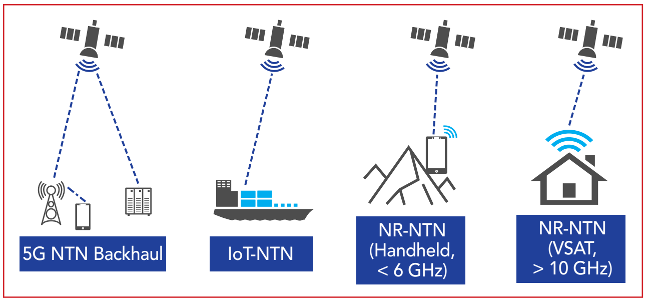


▲ Fig. 1 **The role of NTN in connectivity networks.** ***Source:*** **Rohde & Schwarz.**



▲ Fig. 2 **NTN prospective use cases.**

connectivity in underserved regions as a means toward the goal of ubiquitous connectivity. The diagram in ***Figure 1*** shows an overview of the role satellites may play in this goal of global connectivity.

NTN USE CASES

Two major thrusts have become apparent in the current evolution of NTN. The first is enhancing 5G NR specifications and hardware to allow NTN communications to be incorporated within the entire 5G network. NR-NTN focuses on providing eMBB services via airborne stations or satellites and this represents the long-term evolution of 5G into the sky. In Phase 1, the focus is on basic internet connectivity to provide voice, web browsing and text messaging services. These services will use sub-6 GHz spectrum and operate primarily on handheld devices. Phase 2 and beyond envision VSAT user equipment (UE) with enhanced RX capability using higher frequency ranges and offering much higher data rates. In the first phase, the architecture will be a transparent payload, but Release 19 is assumed to incorporate a regenerative payload architecture that will enable the NTN system to support fixed satellite services (FSS), broadcast satellite services (BSS) and mobile satellite services (MSS) as a transition to the capabilities envisioned in Phase 2 and beyond.

As described earlier, a major focus of NTN is ubiquitous coverage. However, 3GPP NTN focuses on more than underserved area coverage. At a higher level, these four use cases are categorized as follows in TR 22.822:

Service continuity: Providing radio access technology (RAT) coverage where it is not feasible with terrestrial networks like maritime or remote areas. TR 22.822 supports service continuity between land-based 5G access and satellite-based access networks owned by the same operator or by operator agreements.

Service ubiquity: Motivated by mission-critical communications and aims at permanent system availability, especially for public protection disaster relief use cases leading to outage or destruction of terrestrial network architectures. System availability can be resumed and obtained in a short time using NTN connections.

Service scalability: Follows the general aspect of traffic management strategies. Enhancements of traffic steering like the offloading of traffic from terrestrial to non-terrestrial communications provide better system efficiency, especially when considering the wide NTN gNB coverage range.

5G system backhaul services: Represent situations where UE are still connected to terrestrial RATs but the NTN connection serves as a backhaul connection to the core network.

The second major thrust involves incorporating the terrestrial IoT network into NTN. IoT-NTN proposes the adaptation of NB-IoT or enhanced machine-type communication (eMTC) for NTN connections. This implies reducing device and satellite complexity, along with accepting a lack of or reduced quality of service support. IoT-NTN communications will be on a best-effort approach, like latency-tolerant applications, but energy efficiency and power saving will play a pivotal role compared to NR-NTN. Release 17 prioritizes standalone deployment, applying a transparent bent pipe satellite architecture and assuming the UE possesses GNSS capabilities (not simultaneous operation) to precompensate time and frequency.[1] ***Figure 2*** shows a conceptual drawing of the 5G NR and IoT use cases for NTN networks.

NTN SPECTRUM

The frequency spectrum availability is the most pertinent characteristic of NTN communications. Since satellites are not restricted to one country or region, an international harmonization of frequencies is essential for global satellite communications. Currently, several frequency ranges are being discussed for NTN. The current Frequency Range 1 (FR1) bands agreed up by 3GPP for NTN are the S-Band frequency range of 1980 to 2010 MHz in the uplink (UL) and 2170 to 2200 MHz in the downlink (DL), which is band n256 and the L-Band frequencies 1525 to 1559 MHz DL together with 1626.5 to 1660.5 MHz for the

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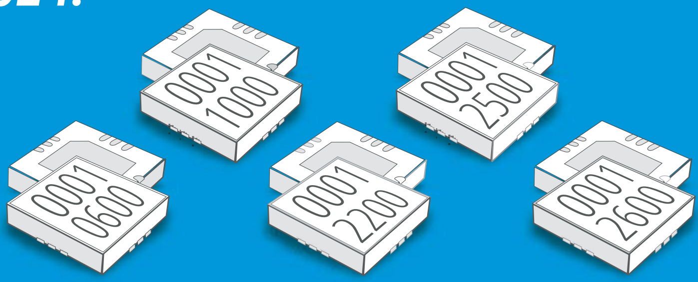

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Reflective SPDT	DC - 10GHz	0.8dB	30dB	36dBm	Chip form, BM or QFN Packging
Non-Reflective SPDT	DC - 10GHz	1.0dB	30dB	36dBm	Chip form, BM or QFN Packging
VVA	DC -10GHz	4dB	-	27dBm	20 dB variation, Chip form, BM or QFN Packging
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UL, which is band n255.

In the longer term, 3GPP is discussing NR-NTN above 10 GHz. Ka-Band is the highest priority band with a DL of 17.7 to 20.2 GHz and a UL of 27.5 to 30 GHz. Ku-Band with a DL of 10.7 to 12.75 GHz and a UL of 12.75 to 13.25 GHz and 13.75 to 14.5 GHz is also being envisaged. While these frequency bands are in use for current satellite communications, they present challenges for 5G implementations. Some of these bands fall into the spectrum gap between the 5G FR1 and FR2 bands. In addition, NTN frequencies will use frequency-division duplexing, due to the long round-trip time, as opposed to the time-division duplexing scheme that is widely used by 5G NR.

Like terrestrial communications, coexistence is relevant for NTN. A satellite cell or beam coverage area is large and often exceeds country and terrestrial cell borders. Deployments must address supplementary satellite coverage where terrestrial and non-terrestrial networks share the spectrum or different spectrum bands.

NTN ARCHITECTURES

The following architectures are relevant for current and future NTN and satellite constellations:

Low earth orbit (LEO): Satellites with an altitude between 500 km and 2000 km have a shorter round-trip time (RTT), which is typically less than 30 ms. The size of a LEO satellite is also assumed to be small, with a diameter typically < 1 m and may even be in the range of a dozen centimeters for a nanosatellite, with a weight below 500 kg. The assumption is that NTN uses a beamforming mechanism at the satellite station. The typical beam footprint of a LEO satellite ranges between 100 km and 1000 km.

Medium earth orbit (MEO): Satellites travel at a velocity of about 13,800 km/h and have an orbital period of 6 to 12 hours. The beam footprint is like a LEO constellation.

Geostationary earth orbit (GEO): Satellites operate above the equator at an altitude of 35,786 km resulting in a notional station keeping its position fixed in terms of elevation and azimuth angle with respect to a given Earth point. The beam footprint ranges from about 200 km for narrow beams, up to 4000 km in the case of large beams. Due to the larger orbit radius distance, the RTT of a GEO satellite is about 544 ms.

High altitude platform systems (HAPS) or high altitude IMT base stations (HIBS): This category includes airborne objects such as airplanes, balloons, helicopters and drones (UAVs). They operate very flexibly at altitudes from several hundred meters up to about 15 km and have beam footprints with diameters of just a few kilometers up to 100 km, on average. Operators may use HAPS/HIBS to provide additional capacity in a specific region, making dynamic deployment an advantage. A disadvantage of this architecture is the smaller coverage area. Due to the shorter distances, the RTT performance is competitive with terrestrial networks. The HAPS and HIBS use cases are differentiated by spectrum usage and use cases. HAPS networks currently focus on FSS only, due to regulations, while HIBS networks may provide MSS.

NETWORK ARCHITECTURES

The satellite covers a geographical area by forming a beam. That beam footprint is either static or moving with respect to Earth. NTN architectures need radio access from the terrestrial terminal or UE to the satellite, which is referred to as the service link. To complete this overall link, the satellite needs to be connected to a terrestrial gateway, referred to as the feeder link. LEO and GEO satellite constellations have a known or predictable trajectory, which facilitates the routing of the connection to the ground station. To facilitate NTN-capable RAN deployment, the 3GPP is discussing transparent mode and regenerative mode architectures. Release 17 deals primarily with the transparent mode architecture.

Transparent NTN NG-RAN architectures behave like a repeater or bent pipe in space. This architecture disaggregates the terrestrial base station into the satellite components, ground gateway and terrestrial gNB functions. The satellite functions implement RF filtering,

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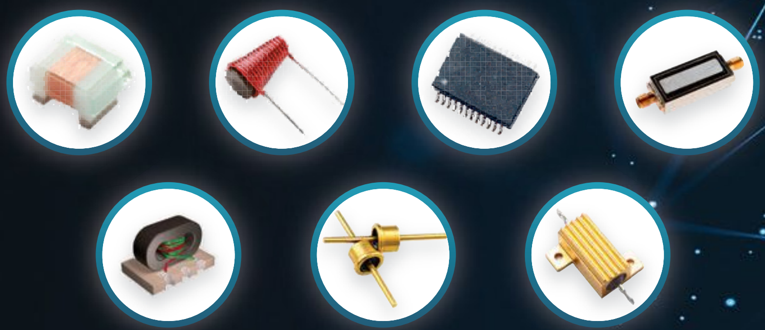

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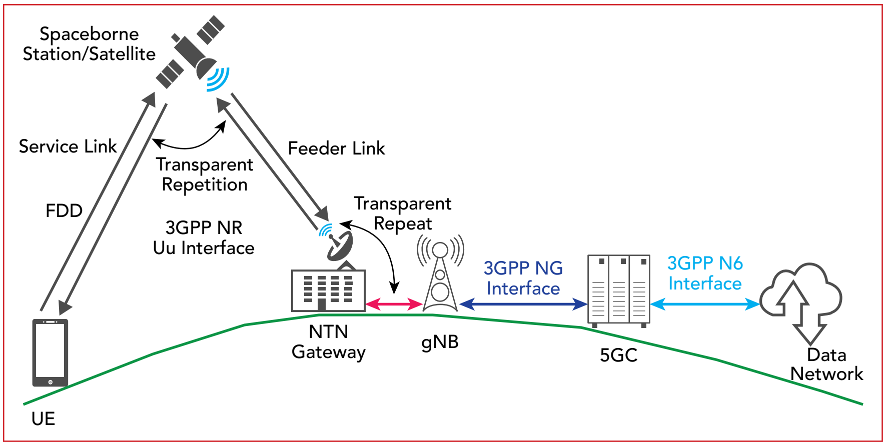

Fig. 3 **Transparent payload NTN NG-RAN architecture.** ***Source:*** **Rohde & Schwarz.**

frequency conversion, RF amplification, RF transmission and reception in the uplink as well as the downlink direction. The pivotal characteristic of this architecture is that the waveform is repeated between the service link and feeder link by an unchanged payload. The carrier undergoes a frequency change for a variety of reasons, including avoiding interference between the service and feeder links.

This architecture is independent of the radio waveform, so any changes do not require modifications in the spaceborne station. Disadvantages of this architecture include noise amplification as the satellite may not perform any channel equalization or noise cancellation, vulnerability against jamming attacks, longer overall RTT with two satellite-Earth links and the lack of inter-satellite link (ISL) connections for traffic steering.

The connection between the UE and the terrestrial gNB not only includes the service link and the feeder link but several ISLs in between these two links are possible in future extensions. 3GPP TR 38.821 states that the regenerative payload is required for the first ISL implementations. ***Figure 3*** shows a representation of this transparent NTN NR-RAN network.

Future NTN deployments that Release 19 will define will include regenerative mode architectures. The major difference from the transparent payload architecture is that gNB functions are incorporated into the satellite in regenerative mode architectures, creating faster scheduling decisions and shorter RTT. The regenerative architecture model raises satellite hardware complexity and computing power and may also incorporate multi-access edge computing (MEC) functionalities to reduce the RTT.

NTN RF CONSIDERATIONS

The distance between terrestrial UE and spaceborne stations impacts the link budget or high path attenuation, but simulation results show that the signal-to-noise ratio conditions permit communication. More critical is the long time delay or RTT, which also depends on the time and elevation angle. Satellite velocity causes a frequency carrier deviation or Doppler shift, which creates a paradigm change compared to terrestrial networks where the base station is stationary. Ionospheric radio wave propagation is also responsible for waveform polarization rotation, known as Faraday rotation.

Path Attenuation

The distance between the UE and the satellite creates high path attenuation. 3GPP discussed several link budgets and carried out studies with diverse parameters and simulation results, which are shown in TR 36.763 and TR 38.811. As the antenna technology evolves, the objective is to lessen the path loss challenge with highly directive antennas that increase antenna gain. The composite path loss is based on the basic path loss, which is mainly the free-space path loss (FSPL), attenuation due to atmospheric gases, attenuation due to atmospheric scintillation and building entry path loss. Typical assumptions are FSPL values of -160 dB for LEO and -190

dB for GEO and it is assumed that the UE RX sensitivity will be better than terrestrial networks.

RTT and Differential Time Delay

The large distance between the terrestrial UE and the satellite creates a long RTT. This creates a long latency period and it poses a challenge to low latency communication applications planned with NR-NTN. Typical one-way latency values range from 30 to 40 ms in LEO constellations and up to 544 ms in GEO constellations.

A detailed analysis of the RTT and latency aspects of satellite networks identifies two challenges. The first concerns the differential delay between the NTN gNB and all the UE in a beam footprint coverage area. The second is the time-varying latency and RTT during the entire connection period due to the nature of an elliptical flight orbit and the changing distance between the UE and the satellite. The first challenge is caused by the elliptical shape of the beam footprint and how the size of the ellipse depends on and changes with the elevation angle. This means that the satellite experiences different propagation times among the UE within the beam footprint. The second challenge is caused by the UE experiencing an RTT that varies in response to the satellite's orbital trajectory. When the satellite appears at the horizon, just above the minimum elevation angle, the distance between the UE and the gNB is the longest. This creates the largest value of RTT, but this will change with the elevation angle. This impacts the buffer management of the MAC layer and HARQ operation.

Doppler Frequency Shift

One of the most serious challenges to creating NTN connections with good quality of experience is carrier frequency deviation or Doppler shift. A moving base station or satellite, in combination with a UE potentially moving, causes a time-variant Doppler shift across the connection time. This Doppler shift depends on the relative velocity between the UE and the satellite, the carrier frequency and the angle between the velocity vector and the signal propagation direction.

Faraday Rotation in NTN and Polarization Aspects

Faraday rotation is caused by the structure of the atmosphere and it is indicated by the total amount of electrons. Faraday rotation describes the rotation of the polarization resulting from the interaction of the electromagnetic wave with the ionized medium in the Earth's magnetic field along the path. This is described in TR 38.811. Circular polarization methods may counteract this effect, but this method requires the UE to apply the same circular polarization or tolerate a 3 dB polarization loss in addition to the FSPL.

SUMMARY

The goal of 3GPP is to enable 5G NTN, satellite-based communications with the lowest impact on 5G. As communications evolve, the architecture of wireless networks must also evolve away from the cellular network concepts of previous wireless generations.[2] The anticipation is that 6G will consist of multiple dynamic and intelligent nodes with onboard computing power and MEC functionality that are interconnected and may be moving relative to each other. The terms interworking, integration and unification describe the evolution path from legacy satellite and cellular technologies to 5G NTN and eventually, 6G.

New research areas will enable an evolution toward organic networks. These organic networks will incorporate cell birth and death behavior, vagabonding network components and intelligent traffic management. Incorporating NTN into the 5G ecosystem with Release 17 signals the advent of a new technology evolution fostering and driving the worldwide proliferation of wireless communications systems. ■

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2. "5G & Non-terrestrial Networks," *5G Americas*, Whitepaper, February 2022.

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- ✓ Enhanced Coverage
- ✓ Increased Capacity
- ✓ Beamforming

Radio Specifications

Parameters	Specifications
3GPP Band	n78
DL/UL Frequency	3.55 – 3.7 GHz
Carrier Bandwidth (Max)	100 MHz
Duplex Mode	TDD
Modulation	QPSK/QAM 256/64/16
Sub-Carrier Spacing (SCS)	15, 30 KHz
DC Power @ 296°K	Single
MIMO	64T64R
EIRP	≥ +74dBm (52 dBm + Antenna Gain of 2dBi = 74 dBm)
Effective Isotropic RX Sensitivity	122 dBm

Connectivity Specifications

Parameters	Specifications
Physical	3x 25G Base-T Eth over SFP+
Interface Protocol ORAN Split	7.2x
Time & Synchronization	IEEE 1588v2, IEEE 1914.1, ITU-T G.826x, G.8275.1
Powering	-48 V
Maximum Power	< 900 W

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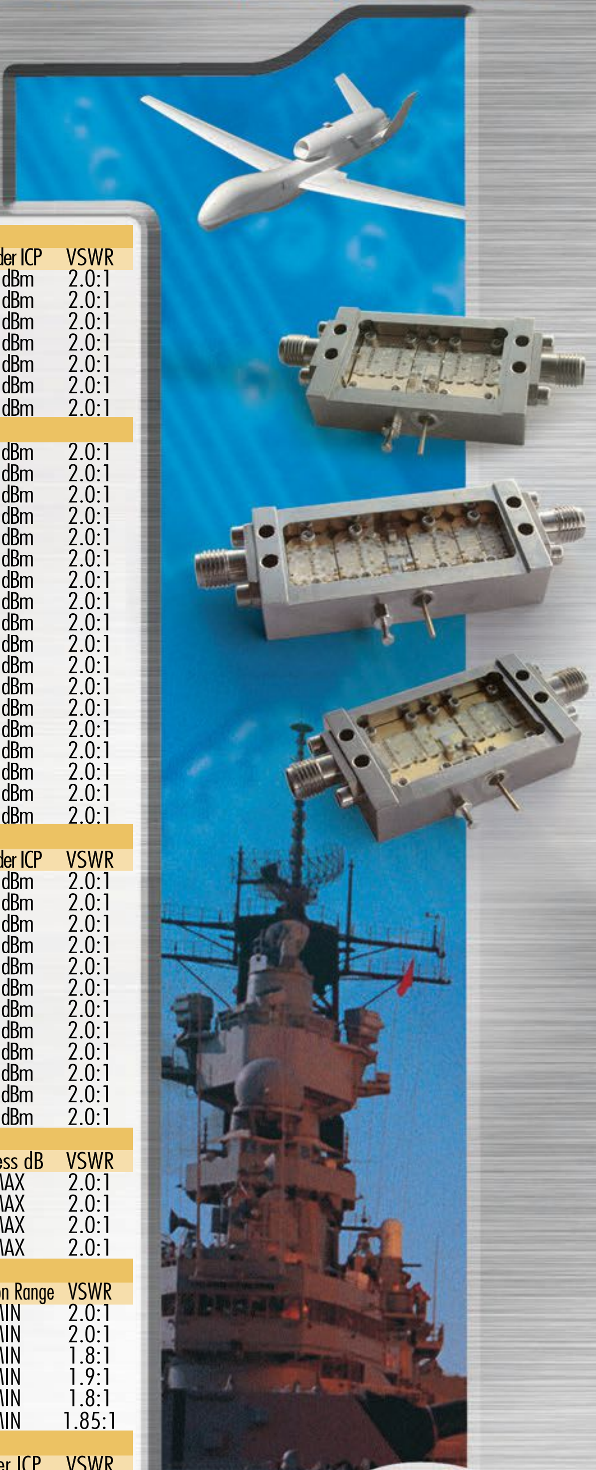

OCTAVE BAND LOW NOISE AMPLIFIERS

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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Cliff Drubin, Associate Technical Editor

Boeing to Lead Counter-Hypersonic Flight Test, Evaluation for DARPA's Glide Breaker

Boeing will develop and test technologies for a hypersonic interceptor prototype for DARPA's Glide Breaker program as part of a four-year effort. Boeing will perform computational fluid dynamics analysis, wind tunnel testing and evaluation of aerodynamic jet interaction effects during flight tests.

Glide Breaker is intended to inform the design and development of future hypersonic interceptors, which could destroy a threat traveling at least 5x the speed of sound in the upper atmosphere during what is known as the "glide-phase" of flight. The development and testing will provide the foundation for future operational glide-phase interceptors capable of defending against these sophisticated and evolving hypersonic threats.

"This phase of the Glide Breaker program will determine how factors like hypersonic airflow and firing jet thrusters to guide the vehicle affect system performance at extreme speed and altitude in a representative digital environment," said Gil Griffin, executive director of Boeing Phantom Works Advanced Weapons. "We're operating on the cutting edge of what's possible in terms of intercepting an extremely fast object in an incredibly dynamic environment."

Hypersonic Intercept (Source: Boeing)

POWER Program Selects Teams to Design Power Beaming Relays

DARPA is entering the first phase of the Persistent Optical Wireless Energy Relay (POWER) program, aimed at revolutionizing energy distribution through airborne wireless power transfer. Three teams — led by RTX Corporation, Draper and BEAM Co. — will design and develop wireless optical power relays. The program goals include demonstrating the key components necessary for a resilient, speed-of-light energy network.

To support rapid development, the optical energy relays designed in POWER's phase one will be demonstrated in pods carried by existing aircraft in the project's second phase. Additionally, power beaming will enable smaller, less expensive future aircraft since fuel storage and engine volume could be dramatically reduced. This will be explored through conceptual designs in phase one. Eventually these new, small, distributed platforms could provide cost-effective aircraft with unlimited range and endurance to support military missions. Each relay design will be evaluated based on accurate and efficient energy redirection, wavefront correction for high beam quality and throttleable energy harvesting. In the third and final phase of the program, the relays will be demonstrated through an airborne optical pathway that aims to deliver 10 kW of optical energy to a ground receiver 200 km away from the ground source laser.

Energy Web Platform (Source: DARPA)

Effective relays are a critical missing component necessary for a practical, flexible and adaptive wireless energy web. These relays will overcome the unacceptable conversion losses that occur when changing from propagating waves to electricity repeatedly in a multiple-hop network. Relays also enable high altitude transmission, which is vastly more efficient than beaming power through the thick, turbulent, lower atmosphere. This high altitude optical layer will provide the long-range, high-throughput backbone for the wireless energy web.

The first phase will include benchtop demonstrations of critical technologies and is expected to last 20 months with potential for a three-month option of additional risk reduction efforts. The second phase will involve an open solicitation in early 2025 and will focus on integration of the relay technologies onto an existing platform for a low-power, airborne demonstration.

New Strike Missile Capability for Fifth-Generation Aircraft and Beyond

Northrop Grumman Corporation was recently awarded an approximately $705 million contract to deliver the Stand-in Attack Weapon (SiAW), an air-to-ground weapon that accelerates the pivot to a new generation of air power. During the next 36 months under Phase 2 development, Northrop Grumman will further develop the weapon, conduct platform integration and complete the flight test program for rapid prototyping in preparation for rapid fielding. Work will be performed at the company's Northridge, Calif., facility and its factory of the future for missile integration at Allegany Ballistics Laboratory in West Virginia.

SiAW is an air-to-ground weapon that will provide strike capability to defeat rapidly relocatable targets

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SiAW (Source: Northrop Grumman)

as part of an enemy's anti-access/area denial environment. To adapt to ever-changing threats, the missile design features open architecture interfaces that will enable rapid subsystem upgrades to field enhanced capabilities to the warfighter.

Phase 2 development is a continuation of the Air Force requirement for this first-of-its-kind middle tier acquisition large weapon program focused on digital engineering, weapon open system architecture and agility. The Air Force is targeting an initial operational capability by 2026.

Successful Firing of New Generation Exocet Missile from French Frigate

The French navy successfully fired the latest generation of MBDA's Exocet missile, Mer-Mer 40 Block 3c (MM40 B3c), at the multi-mission Alsace frigate off the coast of the DGA missile test centre of Ile du Levant on September 20, 2023.

Exocet MM40 B3c is the latest generation of MBDA's Exocet family of anti-ship missiles for integration on a wide variety of platforms including surface ships, submarines, fast jets, helicopters and coastal batteries. Previous versions of Exocet are in service with several navies around the world.

The B3c generation builds on the successive improvements made to Exocet throughout its service. MM40 B3c includes all the characteristics for which Exocet is renowned, particularly its all-weather capability and high flexibility of use. In addition, this latest missile benefits from new seeker technology and the development of new algorithms designed to meet the latest operational requirements of anti-ship warfare.

Exocet Launch (Source: MBDA)

MBDA has continued to develop Exocet since it entered service. This has enabled the missile to adapt to new battlefield conditions while maintaining its exceptional all-weather capability. The Exocet MM40 B3c is MBDA's response to new conflicts with an evolving threat spectrum, in particular high-intensity combat in complex electronic warfare environments.

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WBA Report Finds Wi-Fi 7 Will Play a Fundamental Role in Transforming How People Live, Work and Play

The Wireless Broadband Alliance (WBA) recently announced the public release of "Get Ready for Wi-Fi 7: Applying New Capabilities to the Key Use Cases," a report that explores how this new technology will transform how people worldwide live, work and play. The report is available as a free download from WBA.

Based on the IEEE 802.11be (Extreme High Throughput) standard, Wi-Fi 7 has a wide variety of advanced capabilities that will improve existing use cases or enable new ones that are not possible with existing wired and wireless technologies. The 43-page paper, led by WBA members Broadcom, CableLabs, Cisco and Intel, explores many of Wi-Fi 7's major new capabilities and applications, such as:

- Double the bandwidth and 3x the speed of Wi-Fi 6: Wi-Fi 7 supports channel widths up to 320 MHz, while Wi-Fi 5 and Wi-Fi 6 are limited to 160 MHz. It also supports 4k QAM, which is an upgrade over prior standards. With wider channels and 4K QAM capabilities, Wi-Fi 7 can deliver speeds over 3x faster than Wi-Fi 6. This is critical for enabling whole-home multi-Gigabit Wi-Fi service.
- Advanced support for latency-sensitive use cases: Wi-Fi 7 devices can use multi-link operation in the 2.4 GHz, 5 GHz and 6 GHz bands to increase throughput by aggregating multiple links or to quickly move critical applications to the optimal band using seamless switching between links. Fast link switching allows Wi-Fi 7 devices to avoid interference and access Wi-Fi channels without delaying critical traffic. This and other new features also make Wi-Fi 7 ideal for immersive extended reality, augmented reality and virtual reality, online gaming and other consumer applications that require high-throughput, low latency, minimal jitter and high reliability.

Revolutionary capabilities enable numerous use cases.

The WBA is actively collaborating with its members to conduct field trials of these technologies in real-life Wi-Fi 7 networks. These trials are open to all interested industry players and are a crucial platform for mobile device and wireless access point vendors, operators and service providers to collectively test Wi-Fi 7 capabilities in key deployment scenarios.

Tiago Rodrigues, president and CEO, WBA, said, "Get Ready for Wi-Fi 7 showcases the revolutionary capabilities that will enable Wi-Fi 7 to help bridge the digital divide and enable new use cases across consumer, business, education, government, medical, industrial, hospitality, public venues and transportation."

Competition Remains Fierce in the Wireless IoT Connectivity Market as LPWA Networks Reach 5.3B Connections in 2030

Wide area IoT connectivity vendors are fighting for space in an increasingly crowded market. According to ABI Research, low-power wide area networks (LPWAN) will reach 5.3 billion connections in 2030. LPWAN companies are competing in integral IoT applications such as smart metering, asset tracking and condition-based monitoring, with a vendor's competitive advantage often hinging on factors beyond a network's technical capabilities.

Although the market has a history of intense competition, trends in hybrid use cases suggest some IoT vendors are leaning toward collaboration.

When competing against newer technologies and other wide area networks, cellular LPWANs struggle with fractured regional deployments and higher device and connectivity costs than other LPWA technologies. But regardless of technology, LPWA solutions are increasingly confronted with complexity concerns as IoT users demand user-friendly, end-to-end IoT systems. To maintain market share, vendors must dynamically respond to these obstacles while navigating new, potentially disruptive standards and protocols such as DECT-2020 NR, MIOTY and ZETA.

Short-range wireless (SRW) technologies face a different competitive landscape than LPWANs in the IoT domain. Wi-Fi and Bluetooth are primarily used in home automation use cases but are also finding greater use in commercial IoT applications. Bluetooth Low Energy and Wi-Fi HaLow expand the technologies' place in industrial and wide area IoT deployments. Hybrid use cases, where customers deploy SRW and LPWA technologies simultaneously to optimize an IoT deployment, have further increased Bluetooth's and Wi-Fi's presence in long-range applications. Although the wireless IoT networking market has a history of intense competition, trends in hybrid use cases suggest some IoT vendors are leaning toward collaboration. The IoT connectivity landscape is broad, but some important players offering low-power connectivity technologies and driving

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innovation include the LoRa Alliance, Sierra Wireless, Texas Instruments, Nordic Semiconductor and UnaBiz.

"Competition in the wireless connectivity market continues to be fierce," said Lizzie Stokes, IoT hardware and devices and IoT networks and services analyst at ABI Research. "Vendors should attempt to carve out a unique place in the market by thoroughly understanding their client's coverage and power requirements. Vendors should cater to specific use cases and regional needs while acknowledging that customers will respond to technologies that can work well with others."

IoT and NTN Mobile Technologies are Propelling the Satellite Service Market

There will be more than 175 million non-terrestrial network (NTN) mobile connections worldwide by 2030, according to "The Ascending Satellite NTN Market", a recent white paper from ABI Research. The growing adoption of satellite services in the communication sector is driven by the deployment of satellite constellations for low latency, high-throughput network applications and extending terrestrial network coverage. By the decade's end, these shifts will translate to US$124.6 billion in annual satellite services revenue.

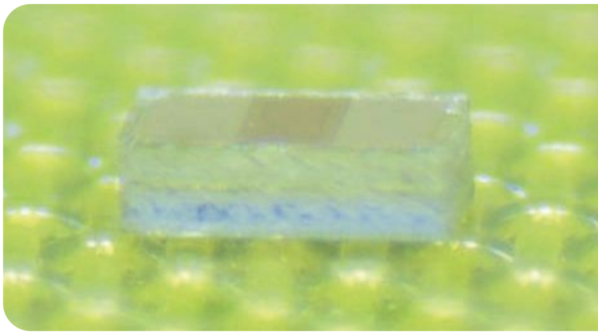
"Satellite communications (satcom) services have seen a new wave of enthusiasm and convergence with terrestrial networks looking to extend past their coverage zones and bridge the digital divide. We are witnessing a growing trend of operators leveraging software-defined satellites and multi-orbit solutions to meet the connectivity demands of the future," said Andrew Cavalier, satcom industry analyst at ABI Research.

The 3GPP initiative is having a profound impact on the satcom industry, with a wave of notable satellite operators looking to take advantage of the market opportunity being created by the convergence of satcom and terrestrial cellular networks. On the other side of the coin, smartphone manufacturers and chipset makers are making moves that highlight excitement for consumer-grade devices supporting satcom via narrowband-NTN, NTN unmodified and eventually, 5G NR-NTN.

"Much of this growth is thanks to the smaller form factor of satellites, as well as reduced launch costs by 98 percent, thanks to reusable rockets by SpaceX, and better economies of scale thanks to standardized satellite bus and payload design. All these developments make it more affordable to launch satellites into orbit and offer satcom services to a wider audience, driving further market developments," Jake Saunders, vice president of Asia Pacific at ABI Research, explained.

Dielectric Varactor

Tecdia's SMT analog varactors, made with unique voltage controlled dielectrics, are designed for controlling impedance inside analog phase shifters operational up to 100GHz.



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- Tunable Matching Networks
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Around the **Circuit**

Barbara Walsh, Multimedia Staff Editor

MERGERS & ACQUISITIONS

Infineon Technologies AG announced that Infineon has acquired the Zurich-based startup **3db Access AG**, a pioneer in secured low-power ultra-wideband (UWB) technology and already a preferred IP provider for major automotive brands. The acquisition further strengthens Infineon's portfolio for secured smart access, precise localization and enhanced sensing. Infineon now adds UWB to its connectivity range including Wi-Fi, Bluetooth/Bluetooth Low Energy and NFC solutions. The first set of IoT use cases includes secured access and authentication, accurate location tracking and indoor navigation, as well as presence detection utilizing UWB radar implementations. Infineon is acquiring 100 percent of the company's shares. The parties have agreed not to disclose the amount of the transaction.

Cadence Design Systems Inc. and **CEVA Inc.** announced that they have entered into a definitive agreement for Cadence to acquire **Intrinsix Corp.**, a wholly owned subsidiary of CEVA and a provider of design engineering solutions focused on the U.S. aerospace and defense industry. The purchase will bring Cadence a highly skilled engineering team that has expertise in advanced nodes, RF, mixed-signal and security algorithms. The acquisition is expected to be immaterial to revenue and earnings this year for Cadence and is subject to certain closing conditions.

CML Microsystems Plc, which develops mixed-signal, RF and microwave semiconductors for global markets, has completed the acquisition of **Microwave Technology Inc. (MwT)**. The acquisition expands the group's product portfolio, strengthens and enhances its support resources and increase its R&D capabilities, providing essential know-how and experience in system-level understanding, product manufacturing and packaging techniques. MwT's products are complementary to CML's existing offering and the majority of its focus and client concentration is within the U.S. The Board of CML believes there is a significant opportunity to increase its current market share by internationalizing MwT's products. The total consideration payable for the acquisition is $13.18 million.

Trexon announced that it has completed the acquisition of **C.E. Precision Assemblies Inc**. CEPA is an industry-recognized value-added manufacturer of RF/microwave build-to-print flexible and semi-rigid cable assemblies, as well as molded and braided wire harnesses. This acquisition represents Trexon's ongoing commitment to expanding its presence in the military and aerospace markets.

COLLABORATIONS

Keysight Technologies Inc. and **Synopsys Inc.** are partnering to provide IoT device makers with a comprehensive cybersecurity assessment solution to ensure consumers are protected when devices are shipped to market. Under the arrangement, the Synopsys Defensics® fuzzing tool will be embedded as an option into the Keysight IoT Security Assessment solution. The global IoT device market is experiencing notable growth due to the rise in adoption of IoT devices and is projected to reach a market value of $413.7 billion by 2031. According to Palo Alto Networks IoT Threat Report, the vulnerability of IoT devices makes them easy targets, with 57 percent of IoT devices at risk of medium- or high-severity attacks.

ERZIA Technologies and **ACST GmbH**, two pioneering leaders in the field of RF and microwave technology, are thrilled to announce their strategic partnership aimed at pushing the boundaries of frequency capabilities and addressing the challenges of the evolving RF landscape. With a focus on advancing technology to meet the demands of growing bandwidth and data capacity needs, this collaboration marks a significant step forward in the realm of terahertz frequencies. The modern world's insatiable appetite for faster and more efficient data transmission has driven the evolution of RF and microwave technology.

Skylo Technologies, a global software-defined non-terrestrial network (NTN) operator, announced a strategic partnership and ongoing collaboration with **Rohde & Schwarz**. This collaboration aims to reinforce and expand the testing capabilities for NTN, ensuring that chipsets, modules and devices using the NTN NB-IoT protocol integrate seamlessly with Skylo's network and are 3GPP Release 17 compliant. The two companies will integrate state-of-the-art testing methodologies to guarantee that Skylo's groundbreaking connectivity solutions meet the highest standards of quality and efficiency. Skylo's NTN is designed to bridge the digital divide by providing reliable and affordable connectivity to under-connected industries.

CesiumAstro SES and **Hughes** announced the successful over-the-air demonstration of a scalable Ka-Band active phased array terminal for satcom. Conducted by CesiumAstro throughout June and July in Austin, Texas, the demonstration paired the company's medium form factor terminal with the Hughes HM400 software-defined modem connecting through SES's geosynchronous orbit satellite. This news is a key milestone on CesiumAstro's roadmap to flight-qualify its Ka-Band satcom terminal on commercial and defense platforms. CesiumAstro recently announced a contract to demo its terminal aboard a U.S. Air Force MQ-9A Reaper unmanned aerial system in support of the military's need for enhanced, higher-throughput connectivity aboard airborne vehicles.

For More Information

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Around the **Circuit**

NEW STARTS

Kyocera International Inc. announced an expansion of its U.S. semiconductor and microelectronic device assembly capabilities at its manufacturing operations in San Diego, Calif., where the company has produced high performance semiconductor packaging products for more than 50 years. In response to U.S. semiconductor industry demand for domestic complex assembly capabilities that support rapidly advancing technologies, Kyocera's latest investments in San Diego have recently doubled assembly cleanroom space, tripled surface-mount component-attach capacity, added wafer laser-grooving and wafer-bumping capabilities and introduced all-new 0.3 µm placement-accuracy bonding equipment. Together, Kyocera's new capabilities in U.S.-based outsourced semiconductor assembly and testing will enable further adoption of 2.5D and 3D packaging methodologies.

Soitec inaugurated its new plant in Bernin, near Grenoble, in the presence of Thierry Breton, European Commissioner for the Internal Market and Roland Lescure, French Minister Delegate for Industry. Soitec has developed its SmartSiC™ technology as a response to vehicle electrification challenges. The technology, based on silicon carbide (SiC), sets a new standard with improved efficiency for energy conversion systems. Thanks to its reduced energy losses, better thermal management and improved power density, the material increases the range and performance of electric vehicles. Through the application of SmartCut™ technology, each SiC substrate can be used 10 times.

ACHIEVEMENTS

Richardson Electronics Ltd. announced the issuance of U.S. Patent No. 11,764,002 (the "'002 Patent"). The '002 Patent is a result of Richardson's innovative technology using ultracapacitors embedded in its ULTRAGEN3000™ generator start module (GSM). The ULTRAGEN3000™ is a compact GSM designed for installation in any orientation, allowing flexible module placement within any generator set housing. The company's patented technology enables a true drop-in replacement for lead acid batteries in engine start applications without the need to rewire or procure additional components.

Samtec has ranked number one in the 2023 Bishop and Associates European Customer Survey of the Electronic Connector Industry. This is Samtec's 12th consecutive win in the survey. From standard cataloged interconnects to unique high performance designs, Samtec's comprehensive product line supports interconnectivity needs across many industries.

Radientum, a renowned antenna design company for innovative antenna designs in automotive, wearable, IoT and other industries, has been accepted into **Nordic Semiconductor's** design partner list. Nordic Semiconductor is committed to ultra-low-power wire-

less technology that plays a key role in the realization of the wireless future. This recognition is a testament to Radientum's expertise in antenna, RF and EMC/EMI design services. The design team at Radientum specializes in developing custom antenna and RF solutions for highly integrated IoT, Industrial IoT, wearables and automotive applications with limited space.

CONTRACTS

The U.S. Department of Defense (DOD) has awarded **GlobalFoundries (GF)** a new 10-year contract for a supply of securely manufactured, U.S.-made semiconductors for use across a wide range of critical aerospace and defense applications. With an initial award of $17.3 million this month and an overall 10-year spending ceiling of $3.1 billion, the new contract provides the DOD and its contractors with access to GF's semiconductor technologies manufactured at its U.S. facilities. These GF facilities are DOD-accredited to the highest security level, Trusted Supplier Category 1A, which implements proven stringent security measures to protect sensitive information and manufacture chips with the highest levels of integrity to ensure they are uncompromised.

CACI International Inc. announced that it has been awarded a five-year contract, with a maximum ceiling value of $917 million, to continue to provide complete life cycle software and systems engineering to improve battlespace awareness for the **U.S. Air Force's Research Laboratory (AFRL)**. The contract supports the performance, research and gathering of data and information processing capabilities for the AFRL. Under the contract, CACI will implement agile and adaptable processes to develop mission software and data analysis capabilities to advance and modernize command, control, communications, computers, cyber, intelligence, surveillance and reconnaissance (C5ISR) programs. These capabilities will enhance information dissemination and decision-making across the Air Force and intelligence community, improve information security and meet program mission objectives.

Comtech announced the company was recently awarded a $48.6 million contract to deliver enterprise digital intermediate frequency multi-carrier (EDIM) modems in support of **U.S. Army** satcom digitization and modernization programs. Under the contract, Comtech will design, develop, test and deliver EDIM units and provide hardware, software and sustainment services to support performance enhancements for EDIM solutions.

Curtiss-Wright Corp. has been awarded a five-year, $34 million firm-fixed-price IDIQ contract by the **Naval Surface Warfare Center (NSWC)** to provide Modular Open Systems Approach (MOSA)-based airborne data recorder technology for use on U.S. and Australian manned and unmanned maritime aircraft.

Sensor solutions provider **HENSOLDT** has started to equip the U.S. Coast Guard's "Legend" class National

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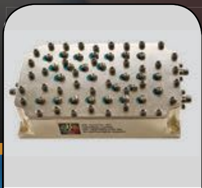

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Around the **Circuit**

Security Cutter (NSC) with its proven TRS-3D multi-mode naval radar. **The U.S. Coast Guard** awarded HENSOLDT a follow-on contract worth approximately $10 million to deliver further radar in its latest 'Baseline D' version to be installed at the Coast Guard training center (TRACEN), Petaluma, Calif. Up to now, HENSOLDT has delivered 12 radars to the U.S. Coast Guard's NSC program. Functioning within the C-Band spectrum, the TRS-3D is a multi-mode phased array radar.

BAE Systems has received a five-year contract from **Lockheed Martin** to sustain the AN/ALR-94 advanced digital electronic warfare (EW) system for the F-22 Raptor. Under the contract, BAE Systems will continue to manage EW system repairs and upgrades, supplier logistics, test equipment maintenance and provide depot-level spares and engineering support to maintain F-22 EW readiness and relevancy for today's air dominance mission. As the original manufacturer of the complex AN/ALR-94 EW system, BAE Systems has provided life cycle management of the system since the program's inception. In collaboration with Lockheed Martin and the U.S. Air Force, BAE Systems delivers innovative, cost-effective EW mission system support, enabling the F-22 warfighter to execute critical missions in contested airspace.

PEOPLE


▲ *Jerry Broz*

Delphon, a provider of engineered polymer and adhesive products for the semiconductor, photonics, medical and electronics industries, announced the appointment of **Jerry Broz, Ph.D.** as vice president, strategic marketing and business development. Dr. Broz will serve as technical lead for Delphon's new product initiatives. He will also be responsible for leading Delphon's overall business development strategy, focusing on growing market share and revenue in the semiconductor, optoelectronics, medical, defense and aerospace industries. Dr. Broz has served in numerous technical and senior leadership roles during his 30-year career in the electronics and electronic materials markets.

REP APPOINTMENT

Component Distributors Inc. (CDI) announced a new distribution contract with **BeRex**. The contract, effective immediately, signifies a strategic partnership between the two companies aimed at expanding their reach and enhancing their service to customers. The new agreement will allow CDI to distribute BeRex's cutting-edge RF semiconductor components, including high performance RF discrete components as well as highly integrated RF front-end solutions, to their broad base of customers.

INVITED PAPER

Benchmarking Seamless Sub-mmWave and Terahertz Rectangular Metallic Waveguide

James Skinner and Nick Ridler
National Physical Laboratory, Teddington, U.K.

Nathan Miller, Sam Brokenshire, Nathan Bayley and Peter Young
Flann Microwave Ltd., Bodmin, U.K.

A new range of seamless waveguide sections for sub-mmWave/terahertz (THz) frequency bands have recently been developed by Flann Microwave Ltd. Both 1 in. and 2 in. sections designed for operation at these frequencies have been manufactured using proprietary techniques. A selection of these sections in the WM-380-band (500 to 750 GHz) have been tested at the U.K.'s National Physical Laboratory (NPL) where they were measured electrically using a vector network analyzer (VNA) calibrated using NPL's primary reference standards. The results were benchmarked against measurements of equivalent devices in this waveguide size from another manufacturer representing the industry standard. They were also compared with modeled results calculated using reference values of resistivity for the waveguide conductor as a benchmark representing the "ideal" case. The results demonstrate the successful manufacture of these sub-mmWave/THz waveguides and their suitability for applications operating at these frequencies.

With the increasing uptake of THz technologies for many applications,[1,2] there is a need for high-quality, reliable electrical components operating at these frequencies to support such applications and, in turn, to enable new possibilities for these technologies. Rectangular metallic waveguide is commonly regarded as the transmission line of choice for systems operating above 110 GHz. Its relatively low loss and mechanical robustness offer advantages over other transmission media. The narrow bandwidths often considered a drawback for waveguides at microwave frequencies, do not apply to sub-mmWave/THz waveguide frequency bands. Advances in instrumentation,[3] the standardization of waveguide dimensions up to 3.3 THz,[4] the standardization of waveguide interfaces[5] and improvement in the manufacturing techniques for precision waveguides have led to a proliferation of waveguide devices, components and systems for frequencies above 110 GHz.

However, the increase in operating frequency creates challenges. Smaller waveguide aperture dimensions require tighter manufacturing tolerances; the inherent loss of higher frequency signals emphasizes the need for high conductivity materials and smooth waveguide walls, along with well-matched connection interfaces. The demands of a given application may impose further challenges such as weight reduction or resilience to environmental conditions.

Manufacturing in this field is still maturing, as is the metrology for assessing the success of this manufacturing. Until recently, the manufacture of precision sub-mmWave/THz waveguide components has been limited to the small subset of manufacturers who rely on the traditional split-block construction technique. In addition, the first inter-laboratory measurement comparisons for scattering parameters of waveguides operating in the sub-mmWave/THz bands were conducted only recently.[6,7]

Over the past year, Flann Microwave has developed a seamless design for waveguide components in sub-mmWave/THz bands.[8] This design features a seamless electroformed thin wall structure made of copper. The manufacturing process achieves an internal surface finish of less than 0.2 μm roughness average (Ra). For strength, the waveguide itself is enclosed in a stainless steel outer tube. Straight sections, bends

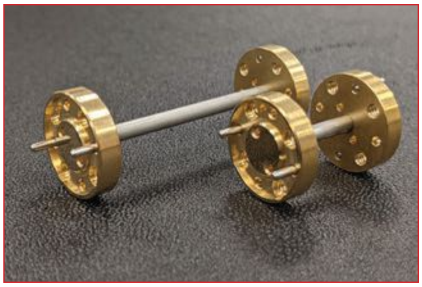

Fig. 1 Flann 1 and 2 in. seamless WM-380 waveguide sections.

and twists can be made using this technique, with expected performance comparable to precision-machined split-block waveguide. The reduced mass and bulk have the potential to provide advantages in many applications. A set of these sections for the WM-380 band is shown in ***Figure 1***. Waveguides in this band feature nominal aperture dimensions of 0.38 x 0.19 mm and are extremely challenging to manufacture successfully.

In this article, these waveguide sections are benchmarked using electrical measurements made at the NPL. Through this benchmarking exercise, the electrical performance of the sections is compared against the current state-of-the-art and the modeled "ideal" case. This allows an assessment of the success of the design and manufacture of these new waveguides, along with their suitability for use in the field of sub-mmWave/THz technology.

ELECTRICAL MEASUREMENTS

Measurement Setup and Calibration

The NPL WM-380 measurement system uses a pair of Virginia Diodes, Inc. (VDI) extender heads connected to a Keysight PNA-X VNA. This test setup is shown in ***Figure 2a***. The 2 in. Flann waveguide section is shown in more detail in ***Figure 2b***. After thermal stabilization of the system, the VNA is calibrated using the primary reference standards for the WM-380 band[9] using a 3λ/4 TRL calibration routine.[10-12] For the benchmarking exercise, the calibration was performed in 0.5 GHz steps across the 500 to 750 GHz frequency range.

Devices Under Test and the Measurement Process

The Flann seamless WM-380 sections were measured on the calibrated system. To benchmark these sections against the existing state-of-the-art, sections of equivalent length manufactured by VDI were measured. These sections are shown in ***Figure 3***.

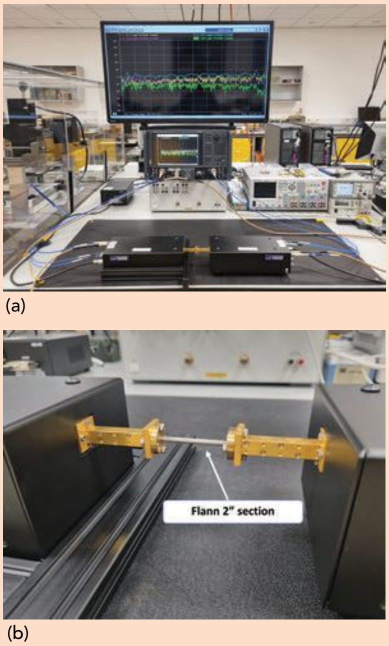

Fig. 2 (a) WM-380 measurement setup at NPL. (b) Flann 2 in. section connected to VNA during measurement.

As is evident from the figures, there are distinct differences in the section designs from the two manufacturers. In contrast to the Flann sections, the VDI sections feature square rather than circular flanges and the waveguides have a split-block construction rather than seamless. The VDI design incorporates a thick, rectangular wall structure in contrast to the thin, cylindrical design of the walls of the Flann sections. Both feature IEEE 1785.2a style flanges.[5] The devices were treated in the same way during the measurement process.

Measurements at THz frequencies are generally more prone to errors as compared with measurements at microwave frequencies. To address this, a rigorous measurement procedure was followed to achieve reliable measurements. The measurement setup and process was optimized as part of good measurement practice at these frequencies.[13] These steps include optimizing the VNA sweep settings, limiting cable movement, handling devices appropriately, using inner alignment dowels to achieve good connection alignment and using a calibrated torque driver to ensure adequate, uniform torque was applied to all screws during each flange connection.

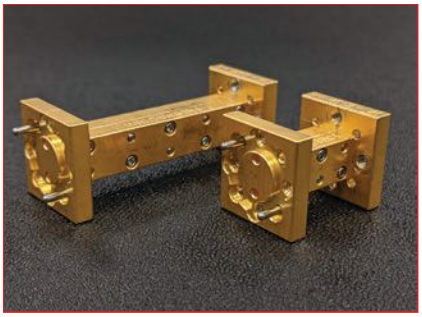

Fig. 3 VDI 1 and 2 in. reference DUTs.

COMPARISON OF ELECTRICAL MEASUREMENT RESULTS

S_{11} Reflection Coefficients

The measured $|S_{11}|$ magnitudes of both the 1 in. and 2 in. sections are shown in ***Figure 4***. As can be seen in Figure 4, all four sections produced very low reflection results, with $|S_{11}|$ measuring less than -20 dB. There is very little to distinguish the reflection performance of the Flann and VDI devices. An assessment of the $|S_{22}|$ results showed similar performance to $|S_{11}|$ for all

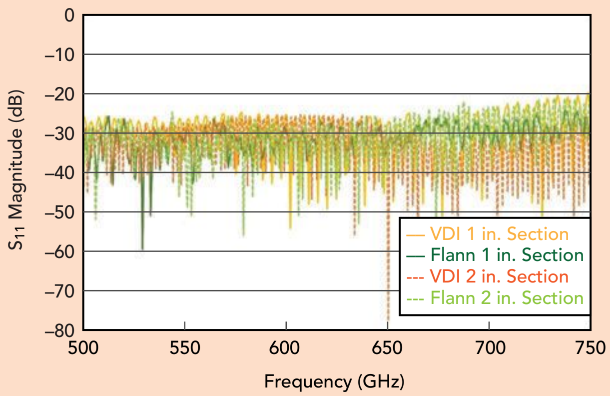

Fig. 4 Measured S_{11} reflection coefficient magnitudes for the Flann and VDI sections.

the devices. These reflection values are sufficiently small to ensure negligible impact on the transmission loss of each device.

S_{21} Transmission Coefficients

Transmission coefficients are a key performance parameter for these newly developed waveguides as they indicate how successfully the sections can transmit the signals. The measured $|S_{21}|$ results of both sections are shown in ***Figure 5***. Note that the drop in transmission observed around 750 GHz and more noticeably around 560 GHz is common to all the measurement results. These drops are due to atmospheric absorption peaks at these frequencies.[14] The signal loss is due to absorption by water vapor present in the air inside the waveguides. If the waveguides operate in non-atmospheric conditions, such as in space, they will not suffer from these effects. The plots shown in Figure 5 demonstrate close agreement between the Flann and VDI $|S_{21}|$ results for both the 1 in. and 2 in. sections, typically agreeing to within 0.06 dB or less.

The Flann and VDI sections' performance is close enough that the devices can be considered equivalent. This benchmarks the Flann sections successfully against the state-of-the-art. The slight differences can be attributed to factors like differing waveguide wall smoothness, mismatch levels with the test ports, waveguide conductor resistivity and the repeatability of the connections.

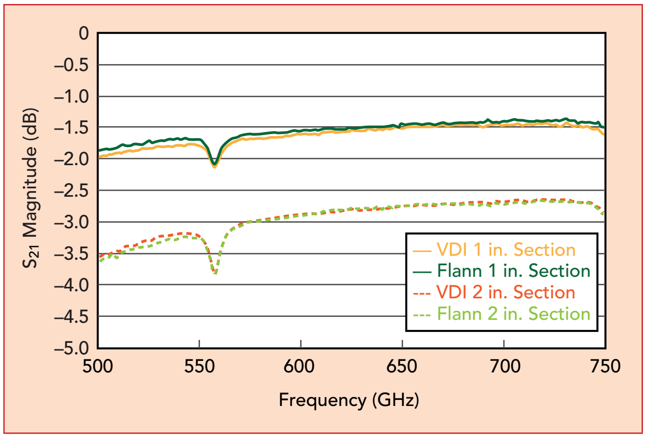

Fig. 5 **Measured $|S_{21}|$ for the Flann and VDI sections.**

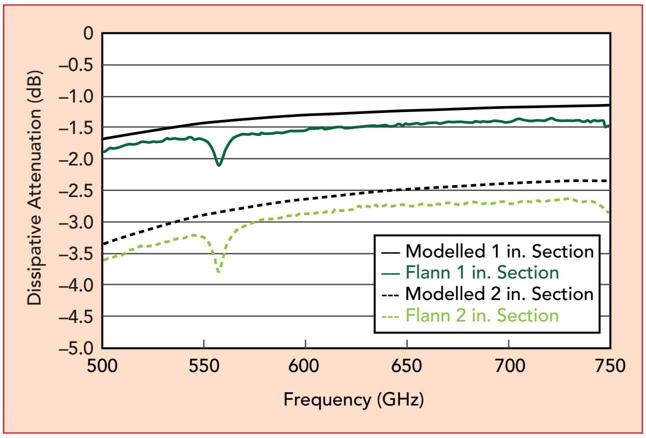

Fig. 6 **Calculated dissipative attenuation results.**

FURTHER ANALYSIS

Dissipative Attenuation

The attenuation response of a 2-port device can be divided into two components. One is associated with mismatch and the other with energy dissipation in the device.[15] Splitting the two components this way allows the losses due to conductor effects like surface roughness and finite conductivity to be isolated, removing the effects of mismatch due to imperfect flanges. This allows the results to be compared more effectively with the modeled attenuation of a waveguide section of equivalent length.

The equation used to calculate the dissipative component of attenuation is given in Equation (1):

$$\text{Dissipative attenuation} = 10\log_{10}\frac{1-|S_{11}|^2}{|S_{21}|^2} \qquad (1)$$

where S_{11} and S_{21} are expressed in linear units.

The modeled attenuation is based on the equation for attenuation constant, α, given in Equation 2:[4]

$$\alpha = 0.023273\sqrt{\frac{\rho}{\rho_0}} \times \frac{1}{b\sqrt{a}} \times \frac{\left(\frac{f}{f_c}\right)^2 + \frac{2b}{a}}{\sqrt{\frac{f}{f_c}} \times \sqrt{\left(\frac{f}{f_c}\right)^2 - 1}} \text{ dB / cm} \qquad (2)$$

where:

ρ = resistivity of the waveguide conductor

ρ_0 = reference resistivity of pure annealed copper (17.241 nΩ × m)

a and b = dimensions of the rectangular waveguide aperture in mm (a > b)

f_c = cut-off frequency (in GHz)

f = frequency at which α is calculated.

Using this equation, the loss of an "ideal" waveguide with perfectly smooth walls, perfect aperture dimensions and perfectly matched can be calculated for a section of equivalent length with the device under test and with the resistivity of gold.[4]

The dissipative attenuation was calculated for the Flann sections, with the results plotted in ***Figure 6***. Figure 6 also shows the modeled attenuation for "ideal" 1 in. and 2 in. sections. Note that the modeled attenuation does not incorporate effects due to the aforementioned atmospheric absorption.

For both sections, there is a negligible difference between the measured $|S_{21}|$ values in Figure 5 and the calculated dissipative attenuation results in Figure 6. This confirms the earlier conclusion that the reflection contribution to loss is insignificant. The results for the Flann sections trend well with the modeled results, with what appears to be a systematic offset of between 0.2 and 0.3 dB. We believe this is primarily caused by a higher resistivity for the gold conductor used on the waveguide walls, as compared to the textbook values specified for bulk material samples.[4] These values will typically differ from actual material values after the material is machined and electroplated, as often happens during the manufacturing process

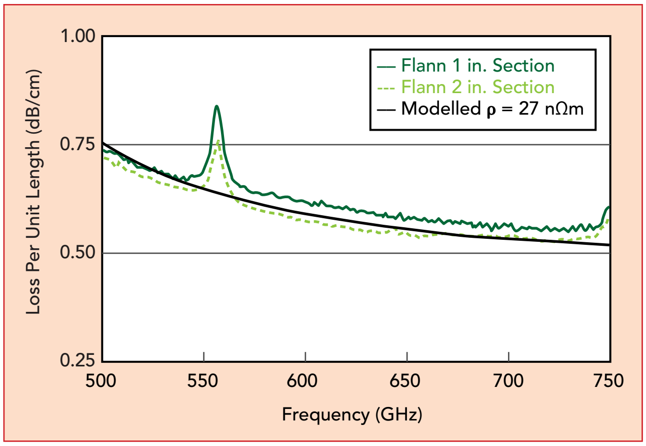

Fig. 7 **Calculated and modeled "ideal" loss per unit length results for the Flann sections.**

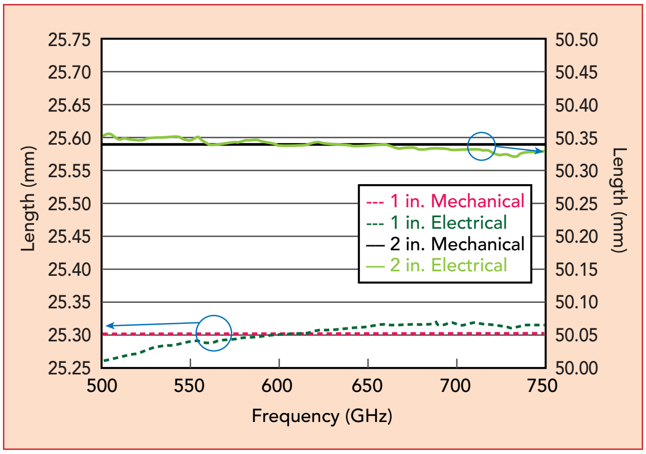

Fig. 8 **Mechanical and derived electrical lengths of the Flann sections.**

for high frequency transmission lines. The measured transmission results of the waveguides suggest a higher value of resistivity than used for the model,[16] which is also confirmed in this analysis.

Loss Per Unit Length

Loss per unit length is often used to summarize the performance of waveguides. This metric gives a good representation of the loss performance to expect from the practical use of the device. It also allows direct comparison with other waveguide sizes or with other transmission line types. It can be calculated using the mechanically measured length and electrically measured transmission coefficients.[16]

The loss per unit length results for the Flann sections are compared with modeled loss per unit length results, with the results shown in ***Figure 7***. The calculation of the modeled values was performed using Equation (2). A resistivity value of 27 nΩ x m used in this model was chosen to provide good agreement with the measured results. This value compares well with the value of 28 nΩ × m used elsewhere[16] for similar devices. The worst-case loss per unit length result for the Flann sections, approximately 0.75 dB/cm, is significantly lower than

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Distri. VSWR	1.6:1 (Max.)
Insertion Loss*	4.5 dB(Max.)
Amplitude Unbal.	±0.7 dB(Max.)
Phase Unbal.	±9 Deg.(Max.)
Isolation	16 dB(Min.)
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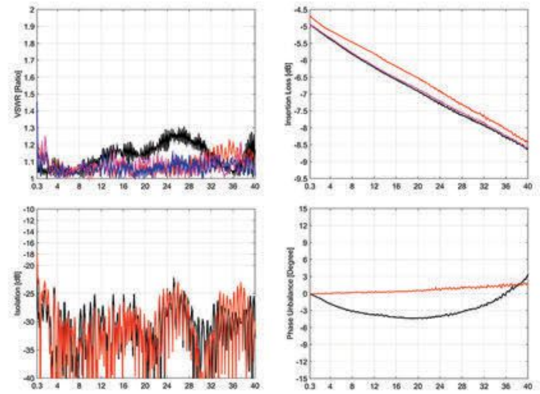
* Above Theoretical Loss 4.8dB

Test Curve



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the 1.1 dB/cm equivalent value given in the manufacturer's datasheet.[8]

Determining the Broadwall Dimension

To a large extent, the performance of a waveguide is determined by a, its broadwall dimension. Ideally, this dimension would be determined through mechanical measurement, but for sub-THz waveguides, it is not possible to measure the broadwall dimension in this way. The very small internal dimensions leave much of the length inaccessible to mechanical measurement methods. However, an estimate for an effective value of a can be determined by other means.

The electrical length, l_e, of a 2-port device can be derived from its unwrapped transmission phase response, ϕ, using Equation 3:

$$l_e = \frac{\lambda_g}{360} \cdot \phi \qquad (3)$$

where λ_g is the guide wavelength at the measurement frequency, calculated using:

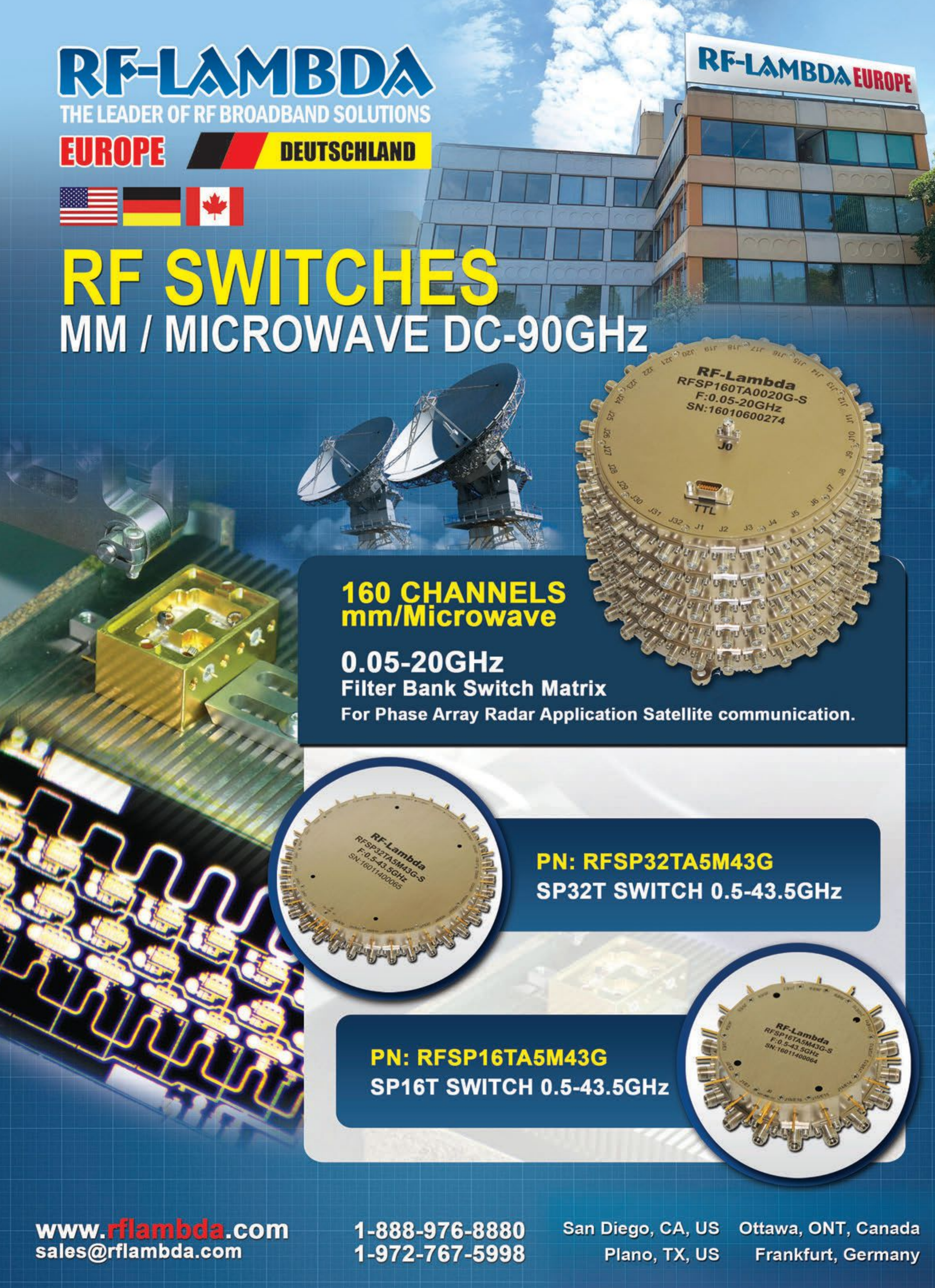
$$\lambda_g = \frac{\lambda}{\sqrt{1 - \frac{\lambda^2}{2a}}} \qquad (4)$$

where λ is the free space wavelength. The lengths of the waveguide sections were also determined mechanically, acting here as the known values of length for each waveguide section. As found in a similar investigation,[9] the results of the electrical length calculation are particularly sensitive to the assumed value of a used in the equation.[4] Use of the nominal value of a can give electrical length results that vary significantly from the mechanical length. Therefore, to perform an effective calculation of the electrical length, estimates of a for each section were obtained using a minimization technique. The electrical lengths of the sections were calculated using Equations (3) and (4), using a value of a that minimizes the difference between the electrical and mechanical results.

The outcome from this process gave a value of a = 378 µm for both the 1 in. and 2 in. sections. For the WM-380 waveguide, the nominal value for a is 380 µm. This value of a is well within the expected tolerance of this dimension, which is expected to be around 10 µm for this waveguide size. The determinations of the electrical lengths of the sections using this estimate for a are plotted in ***Figure 8*** along with the mechanical measurements of the two sections. The mean values of the electrical results agree with the mechanical results to within 10 µm. These results further indicate the successful manufacture of these THz waveguides.

CONCLUSION

Waveguide sections for the WM-380-band have been developed by Flann Microwave. They feature a seamless design and they have been benchmarked through the analysis of electrical measurements conducted at NPL. When compared with sections manufactured by VDI, the current industry standard and with modeled results, the measured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results showed very good performance. These outcomes show great promise for this design technique to be applied to straights, bends and twists for waveguide component operation up to 1.1 THz. These components are now in development. ■

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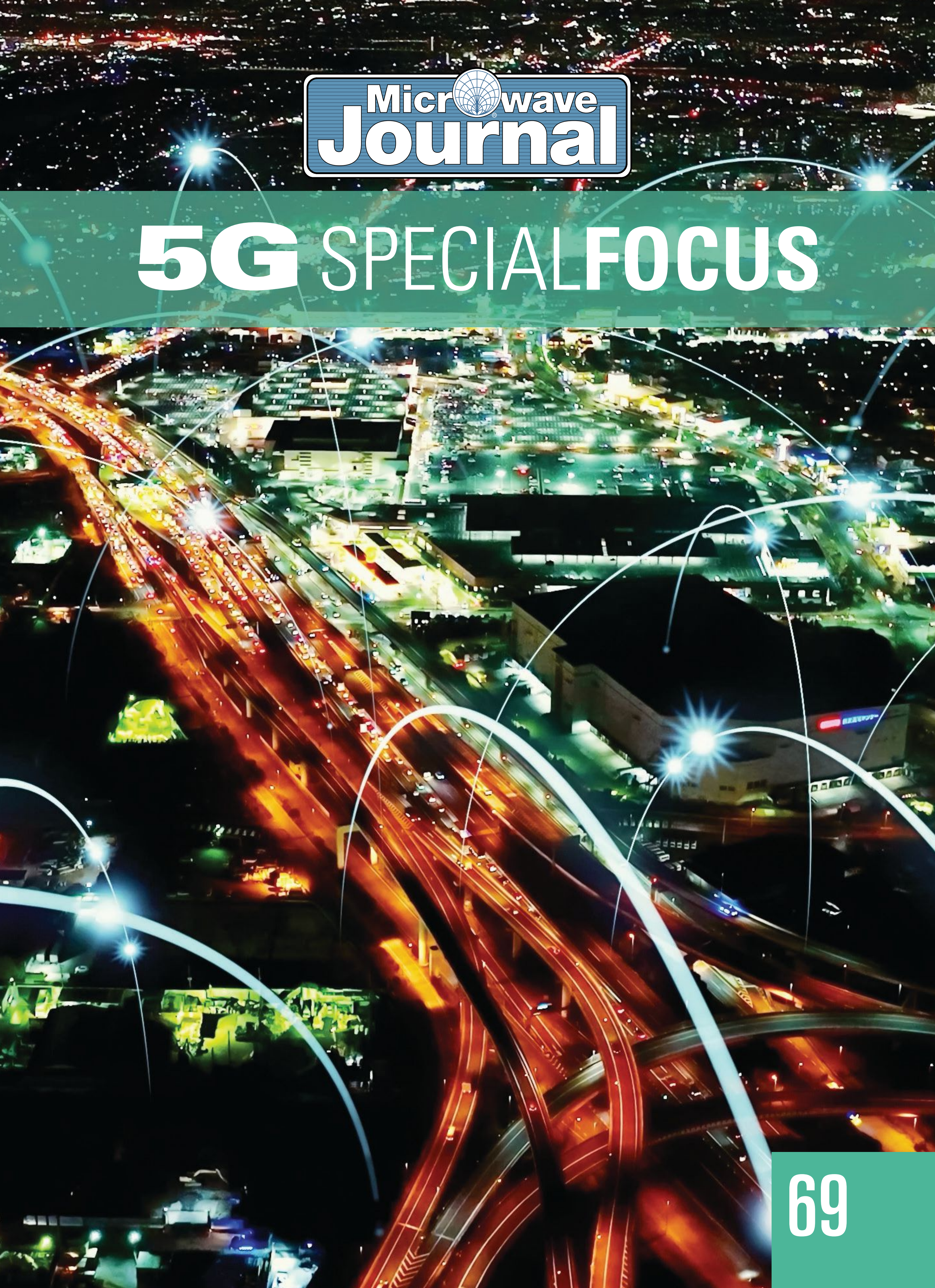

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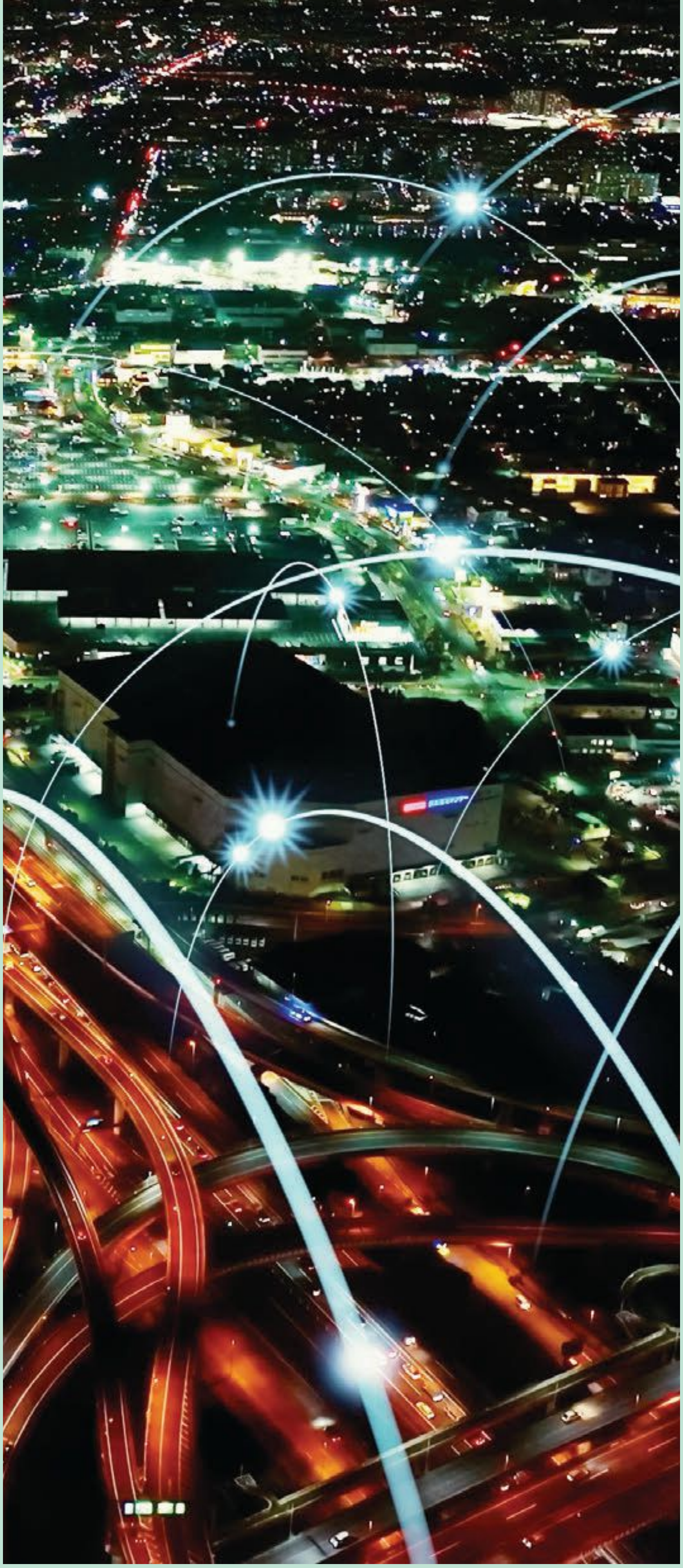

5G SPECIAL FOCUS

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The Challenges and Opportunities With Implementing V2X

Mark Fitzgerald
TechInsights, Needham, Mass.

Vehicle-to-everything (V2X) is a communication method that enables wireless information exchange between vehicles and everything else. This has come to include vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), vehicle-to-vehicle (V2V) and vehicle-to-network (V2N). Information exchanged includes data about the speed and position of surrounding vehicles and these communications promise to help avoid crashes, ease traffic congestion and improve the environment. ***Figure 1*** shows a representation of the vehicles with the networks for V2V side link (SL) and V2N applications with increasing integrated sensing and communication (ISAC) levels. ***Table 1*** shows more details on the type of network, the objects communicating and the application scenarios.

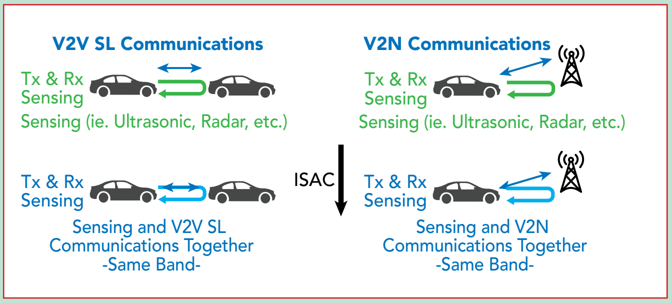

Fig. 1 **V2X integrated sensing and communication application (ISAC).** ***Source:*** **5GAA.**

TABLE 1
V2X CLASSIFICATION AND APPLICATION SCENARIOS
Source: TechInsights

	Communication Object	***Device Type***	***Main Application Scenarios***
V2V	Other Vehicles	Onboard unit (OBU)	Vehicle accident warning, forward collision warning, intersection collision warning.
V2P	Pedestrian and non-motor vehicles	Electronic devices carried by pedestrian	Non-motor vehicle approach warning, overload warning.
V2I	Infrastructure	Roadside unit (RSU)	Road information, such as congestion, accidents and construction, dangerous road section warnings, height and width limit reminders.
V2N	Network	3G/4G/5G base stations	Navigation and mapping management, vehicle remote monitoring, entertainment.

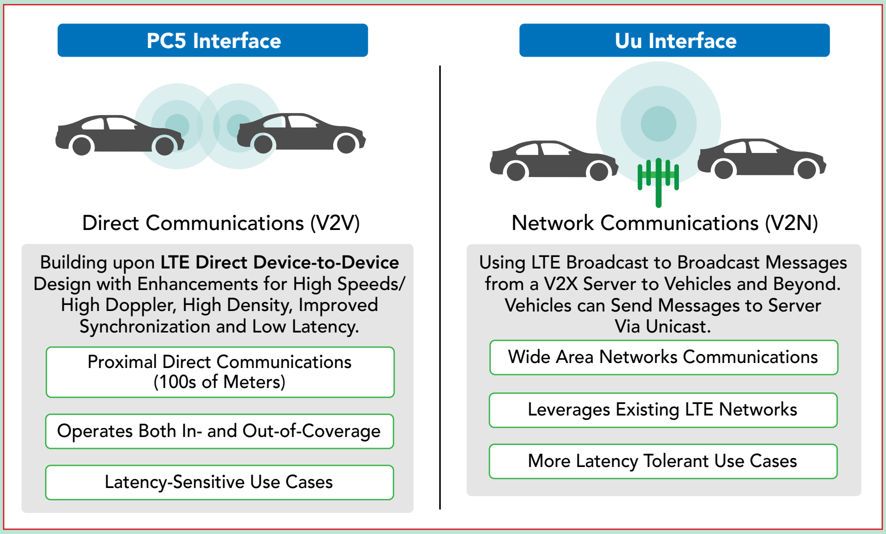

Fig. 2 C-V2X communication interfaces. *Source:* Qualcomm.

THE PROBLEM STATEMENT AND THE ORIGINS

The U.S. National Highway Traffic Safety Administration (NHTSA) estimates that safety applications enabled by V2X could eliminate or mitigate the severity of up to 80 percent of non-impaired crashes, including crashes at intersections or while changing lanes. NHTSA estimates that V2X technology can prevent 615,000 vehicle crashes and save 1,366 lives annually. This represents a significant proportion of the 42,939 lives that were lost on U.S. roads in 2021.

By 1999, the U.S. FCC had allocated 75 MHz spectrum in the 5.9 GHz (5.850 to 5.925 GHz) band for V2X. This allocation supported new safety applications. These applications were intended to alert drivers about possible collisions from other vehicles beyond the driver's sight and the field of view of advanced driver assistance systems (ADAS) sensors.

The Wi-Fi-based dedicated short-range communication (DSRC) standard, also known as ITS-G5/802.11p, WLANp and Wi-Fi-p, was approved in 2010. This has had very few original equipment manufacturer (OEM) vehicle implementations on a limited number of models. The use of cellular technologies has emerged as an alternative to DSRC, with the release of cellular V2X (C-V2X) in the 3GPP Release 14 specification in 2017.

DSRC VERSUS C-V2X

DSRC is a wireless short-range communication technology that uses 802.11p to exchange basic safety messages for collision avoidance. C-V2X is V2X delivered via Uu connectivity or the PC5 interface. Uu is a network communications interface between the user equipment (UE) and an LTE or 5G New Radio (NR) base station. The interface can be used for backhaul and/or long-range communication between the infrastructure and the vehicle. PC5 is a direct-mode communication technology operating in the globally harmonized 5.9 GHz intelligent transportation systems (ITS) band. C-V2X can be deployed as a pure Uu-based system or as a combined solution using PC5.

5G NR-V2X has lower latency, broader bandwidth and better scalability compared to LTE-V2X. From an application point of view, LTE-V2X is mainly designed to support ADAS, improve road safety and improve traffic efficiency. 5G NR-V2X, together with artificial intelligence (AI) and big data are aiming for better support of higher-level autonomous driving, overall traffic management and other new functions. In terms of technical development, 5G NR-V2X, based on the 5G air interface, is an evolutionary improvement of LTE-V2X and the two solutions complement each other.

In the device-to-device PC5 mode (V2V, V2I, V2P) operation, C-V2X does not necessarily require any cellular network infrastructure and can operate without a SIM, without network assistance and uses GNSS as its primary source of time synchronization. By not using cellular network infrastructure for every use case, C-V2X can be a cost-effective safety solution without payment network data usage and V2V and V2I applications built on C-V2X can be launched independently of 5G network rollout. Details of the interfaces in this evolutionary path are shown in ***Figure 2***.

C-V2X has the advantage of offering a clear path from 4G LTE to 5G NR. The initial C-V2X standard included in 3GPP Release 14 focused on V2V communications and fundamental modifications to PC5. The expectation was that further enhancements to support additional V2X operational scenarios would follow.

Further 3GPP releases have addressed a whole host of enhancements. These include a full set of 5G standards, multimedia priority service, V2X application layer services, 5G satellite access, LAN support in 5G, wireless and wireline convergence for 5G, terminal positioning and location, communications in vertical domains, edge computing and network automation, novel radio techniques and increased power efficiency supporting UE devices carried by vulnerable road users (VRUs) including pedestrians and cyclists. ***Figure 3*** shows a timeline for future enhancements.

V2X OPPORTUNITIES AND CHALLENGES

There are many opportunities in the C-V2X industry. These include vehicle safety for passengers and VRUs that include pedestrians and cyclists, safety, mapping, vehicle positioning, autonomous vehicle AI and computing technology. For a single vehicle, C-V2X can help collect perception-related information and send it to the vehicle to improve decision-making and route planning. There are inevitable blind spots or missed detections in the single-vehicle perception of intelligent and connected vehicles. The state information of vehicle perception blind spots such as corners and intersections provided by C-V2X roadside

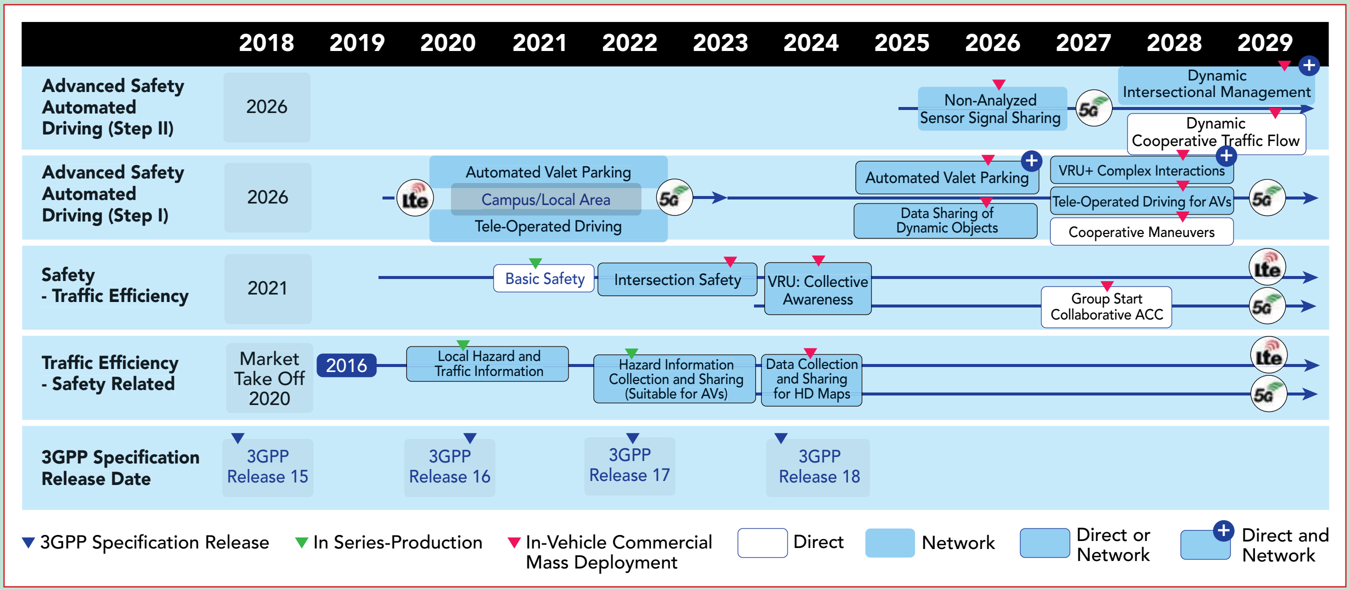

Fig. 3 **Expected timelines for mass deployment of C-V2X use cases.** ***Source:*** **5GAA.**

units (RSUs) can effectively expand the vehicle's perception range. This can improve the safety redundancy and enhance the decision-making ability of autonomous driving.

With the support of a V2N-enabled cloud-controlled platform and C-V2X technology, the goal is to achieve "pedestrian-vehicle-road-cloud" collaborative control at the traffic/transportation level. Achieving this means that C-V2X provides effective information for single-vehicle decision-making in addition to achieving autonomous traffic control of all road sections. This control will extend to all weather and traffic conditions for all traffic participants. A challenge to this goal is the mixed-traffic environment with vehicles of different intelligence levels. Achieving this goal will be beneficial to traffic control and management on a local and national level.

However, there are still doubts about V2X and V2I collaboration and business case realities. Continued wireless spectrum regulatory issues and the lack of government mandates for V2X technology adoption on new vehicles have stalled the widespread adoption of V2X outside of China. Some in the industry see V2X networks as a complementary technology to high-level, large-scale autonomous driving and ADAS implemented in onboard, single-vehicle intelligence. Challenges to V2X implementation include:

High cost of deploying new infrastructure: According to the U.S. DOT, the average cost of C-V2X infrastructure construction at a single intersection is $6,000 to $7,000. This includes the cost of mapping the intersection, purchasing RSUs and installing them in the field.

Onboard hardware costs: OEMs currently bear the costs for the onboard unit (OBU) and they face a difficult situation: V2V applications cannot be triggered because very few cars support V2V. Without seeing a benefit, consumers will be unwilling to pay for C-V2X functions. If the OEMs cannot make a profit they may curtail C2V investment and this will stagnate development.

Additional vehicle hardware cost: According to ITS America, the OBU cost for C-V2X within an existing telematics control unit is $160 to $170 per vehicle.

Unclear data ownership: The development of V2X technology relies on making infrastructure data, like traffic light data, open source. However, most countries and regions have not yet formed clear regulations on the ownership of various types of data. This makes it difficult for all demonstrators to obtain data outside their products and there is no unified evaluation standard for data security and credibility.

Multi-department management: V2X is a cross-industry technology involving the automobile, communications, road management, surveying and mapping industries with each having related management departments. Different authorities may have different rules, resulting in inconsistent management and complex processes, creating duplication, crossover and blind spots.

Cybersecurity: The "ISO/SAE21434 Road Vehicles – Cybersecurity Engineering" document specifies requirements for cybersecurity risk management regarding engineering for the concept, development, production, operation, maintenance and decommissioning of road vehicle electrical and electronic systems, including their components and interfaces.

Business model challenges: There is no clear business model for the commercialization of C-V2X. The PC5 transmission mode is now complimentary, meaning all messages that communicate through PC5 are free of charge. The cost of an OBU, which is an important part of C-V2X, includes development costs, testing and hardware and may include validation and certification costs in the future.

V2X DEPLOYMENT PHASES

According to the CAR 2 CAR Communication Consortium,[1] V2X will be deployed in three phases:

Day 1 Phase – Awareness Driving: Vehicles and infrastructure transmit information regarding their

status information about tolling stations from RSUs, as well as information describing unexpected events like adverse weather conditions and dangerous situations.

Day 2 Phase – Sensing Driving: The V2X system will be extended to permit vehicles and RSUs to share information about objects detected via onboard sensors such as cameras, LiDAR or radar. This phase also includes functional safety in support of semi-automated driving use cases at receiving vehicles.

Day 3+ Phase – Cooperative Driving: This deployment phase will take advantage of vehicles with increasing automated driving capabilities (SAE level 3 and level 4). All the functionalities introduced in the Day 2 Phase will be reused and applied in a stricter way to support highly automated driving use cases including cooperative merging, cooperative lane change and cooperative overtaking functionality.

CHINA LEADS V2X ADOPTION

The China Industry Innovation Alliance for the Intelligent and Connected Vehicles alliance issued the "Technology Roadmap for Intelligent and Connected Vehicles 2.0" in January 2021. The objectives include C-V2X being installed in at least 50 percent of new vehicles assembled in 2025 with a goal of most vehicles having C-V2X installed by 2030. While TechInsights does not believe that the 50 percent goal will be reached by 2025, the addition of V2X in the China New Car Assessment Program (C-NCAP) ratings will promote the adoption of V2X in the region. China has adopted the technical route of C-V2X from the very beginning on a national level. They have allocated the 5905 to 5925 MHz band to C-V2X.

STALLED V2X DEPLOYMENT IN THE U.S., KOREA AND EUROPE

In Europe, ETSI has approved the use of C-V2X as an access layer technology for ITS devices for vehicles and roadside infrastructure. Regulators in the European Union, Japan, South Korea and the U.S. are still finalizing regional and national spectrum allocation details. This will determine how the 5.9 GHz band will be used for V2X.

The NHTSA remains strongly interested in V2X technologies but they are not included in the current NCAP roadmap. They are considering various V2X deployment issues, including technological evolution and regulatory changes to the radio spectrum environment. The lack of an NHTSA mandate, or timeline for a potential mandate, along with the compressed spectrum availability for V2X in the U.S. will likely limit OEM adoption through 2024/2025. There is potential for an uptick in adoption by OEMs post-2024/2025 if wireless spectrum allocations become clearer and waivers are not needed, assuming a supportive regulatory framework is in place.

In December 2019, the U.S. FCC unanimously voted to allocate the lower 45 MHz of the previously dedicated 5.9 GHz automotive safety band to unlicensed uses such as Wi-Fi. They also allocated the upper 30 MHz for C-V2X. The FCC decision made clear that only the remaining 30 MHz would be dedicated to V2X technology and that cellular-based C-V2X was the winning protocol. The FCC's decision specified a 2024 timeframe for existing DSRC equipment to be removed from the reallocated spectrum. There is concern that the remaining 30 MHz is limited by interference and bandwidth limitations and may be limited to basic safety messaging within 20 MHz of the allocated 30 MHz.

In April of 2023, the FCC granted a waiver that allows proponents of C-V2X to use the upper 30 MHz of the 5.9 GHz band. Waiver applicants will be allowed to deploy C-V2X RSUs and OBUs ahead of the final rules. Waiver applicants include vehicle OEMs Audi, Ford and Jaguar Land Rover.

CHALLENGES FOR V2X

Unfortunately for the global automotive industry, the lifesaving promise of V2X technology remains tangled in regulatory clashes con-

cerning specification and spectrum allocation debates. China is the only region of the world that has a clear deployment strategy for V2X technology. V2X adoption continues to be hampered by wireless spectrum allocation, the lack of government mandates or NCAP rating credits and vehicle OEMs taking a wait-and-see approach to see which protocol gains favor within the industry or through mandate and if other vehicle OEMs will adopt the technology.

In the short- to medium-term, both 802.11-based DSRC/ITS-G5 and C-V2X will see market deployment. Near-term deployments of V2X will vary by region with Europe and Japan continuing DSRC efforts while China and the U.S. favor C-V2X solutions. Though DSRC/ITS-G5 and C-V2X share the same wireless spectrum, the technologies are not interoperable.

The continued rollout of 5G networks will undoubtedly help support C-V2X adoption, but applications between two suitably equipped vehicles or a vehicle and an RSU do not require 5G network coverage. V2V and V2I applications built on C-V2X can be launched independently of the 5G network rollout. The 5G Automotive Association (5GAA) foresees an important medium-term (2025 to 2027) objective aimed at confirming the 5.9 GHz spectrum configuration for mass adoption of C-V2X-direct radios for advanced driving in different regions of the world. TechInsights' latest global light vehicle V2X forecast is shown in ***Figure 4***.

This forecast includes the following assumptions:

China: C-NCAP 2023 includes V2X protocols in its rating system incentivizing OEMs to implement V2X solutions that will be scored as extra points for a five-star rating. Though not a specifically mandated requirement, these protocols can score up to 10 safety-assist points as an incentive award. C-V2X deployments have started mostly on luxury segment vehicles but will continue to gain traction on lower segments, with Ford already deploying C-V2X in the region, as NCAP points are awarded.

- V2X penetration will see more rapid growth from 2024 and reach 60 percent of vehicle production in 2030.
- Stronger points allocation and a potential mandate for V2X is possible by 2030, driving higher V2X adoption rates.

Europe: The EU remains undecided on V2X protocol adoption and a V2X NCAP mandate is stalled due to uncertainty in the industry concerning V2X protocol selection. Though the Volkswagen (VW) Group has deployed V2X, other OEMs are waiting for a clear 5.9 GHz spectrum allocation and a finalized Euro NCAP points allocation plan in 2026, along with the potential for a V2X mandate that is likely in 2029. VW has deployed DSRC-based V2X as standard equipment in its 2020 Golf model and has extended the technology to its ID. electric vehicles. The VW Group had planned

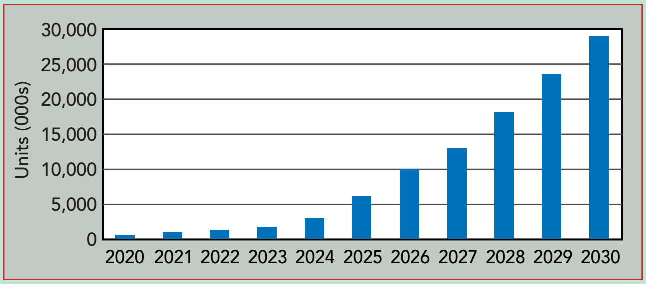

Fig. 4 Global light vehicle V2X forecast. *Source:* TechInsights.

to roll the technology out to all VW Group vehicles but this strategy seems to have stalled.

- V2X penetration will begin to expand from 2026 through 2029 due to the Euro NCAP V2X points award incentive.
- The proposed 2029 mandate will likely include a phase-in period, meaning full penetration of V2X will not occur until after 2030, which is beyond the time horizon of our latest forecast report.

North America: V2X is not one of the proposed ADAS technologies in the NHTSA's NCAP upgrade proposal that was published in March 2022.

- This lack of a mandate, or even a timeline for a potential mandate, along with the compressed spectrum availability for V2X in the U.S. will likely limit OEM adoption through 2025/2026.
- V2X deployments on vehicles produced in North America dipped considerably in 2020 as the DSRC V2X-equipped Cadillac CTS went out of production.
- V2X deployments will begin to rise again in late 2024 as Ford implements C-V2X and other automakers such as GM, Jaguar Land Rover and Toyota likely follow in subsequent years.
- Though there is some OEM interest in V2X deployment, the lack of a mandate and spectrum limitations cap V2X implementation to only 16 percent of vehicles produced in 2030 in North America.

Other regions: Deployments in Japan are mostly implemented from retrofits of 5.8 GHz DSRC OBUs for electronic toll collection (ETC) and ITS applications. The 760 MHz DSRC V2X systems have only been implemented by a handful of Toyota Group models and can only be used in Japan as the frequency band has not been standardized in other market regions.

- Demand in Japan will continue to include DSRC V2X deployment, due to its earlier implementation for ETC and ITS.
- C-V2X has been tested in Japan since 2021, but the technology remains in the experimental stage at this point.

Other emerging market regions like Brazil, India, Russia and Thailand will lag further behind as they lack the public financing to invest in ITS projects and supporting infrastructure, along with consumers not being able to afford the cost of V2X systems. ■

Reference

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5G NR Challenges and Trends in RFFE Design

Peter Bacon and Young-Taek Lee
pSemi, San Diego, Calif.

The proposed capability enhancements from 4G LTE to 5G new radio (5G NR) are a massive leap designed to boost mobile telecommunications applications and enable many more opportunities. Aside from significantly improving all major performance metrics, the 4G to 5G transition also heralds a more flexible and capable radio architecture with additional mmWave frequency spectrum on top of legacy 4G LTE-Advanced (LTE-A) and new sub-6 GHz frequency bands. 5G also intrinsically supports new use cases beyond enhanced mobile broadband (eMBB), including ultra-reliable low latency communications (uRLLC) and massive machine-type communications (mMTC). Plans also exist to further expand the 5G frequency bands to cover both licensed and unlicensed mmWave spectrum. Moreover, 5G NR allows for both frequency-division duplex (FDD) and time-division duplex (TDD) operation with wider channel bandwidths, user equipment (UE) with increased maximum power, higher-order modulation schemes and multi-antenna architectures. 5G NR RF front-end (RFFE) designers benefit from understanding these trends and aspects of the new RF hardware and technologies needed to address these new challenges.

5G NR TRENDS

The 5G NR deployment ramp up is in full swing with many organizations striving to achieve 5G NR performance goals. The performance goals for 5G, along with how they compare with 4G are shown in ***Figure 1***. ***Figure 2*** shows some of the new 5G NR spectrum allocations. The mmWave frequency ranges (FR) that are becoming known as FR2-1 and FR2-2 are of great interest for several reasons. There is a large amount of available bandwidth, these bands lack other interfering deployments and the size of the RF hardware elements and the antenna are proportionally smaller. Perhaps a bit counterintuitively, proponents are viewing the increased atmospheric attenuation at these frequencies as a benefit that can aid in mitigating interference.

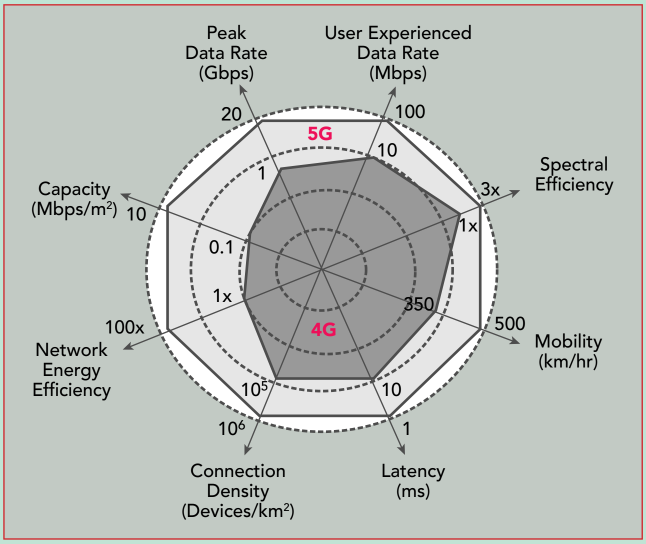
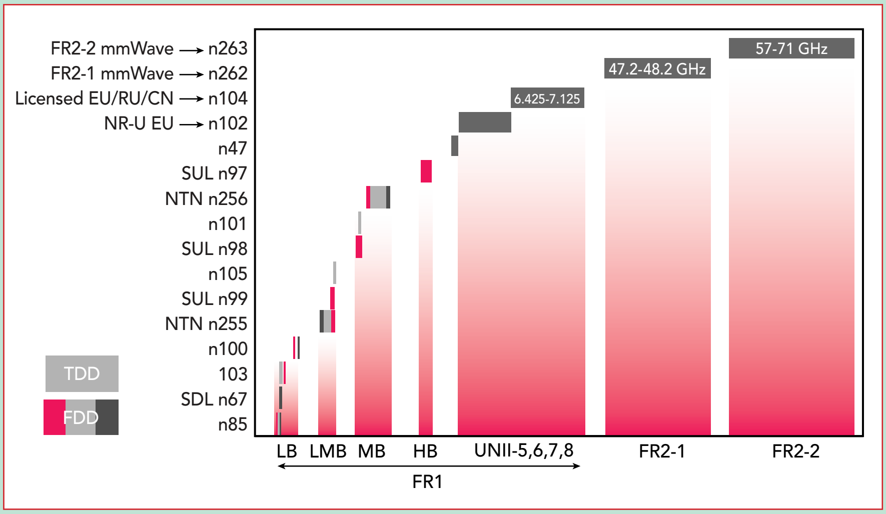


Fig. 1 Key capabilities of 5G NR compared to 4G LTE-A.[1]

FR2 mmWave technology allows for advanced/active antenna systems (AAS) that are extremely compact, along with sophisticated MIMO and beamforming systems with higher throughput compared to 4G LTE-A technologies. The 5G NR enhancement over 4G LTE-A and new frequency bands enable greater capacity, connection density, peak data rates and user-experienced data rates. 5G NR also comes with increased modulation schemes, new encoding and additional layers that support new use cases. These combined features in the 5G NR standards empower 5G to boost mobility, reduce latency, enable higher network energy efficiency and provide better spectral efficiency than 4G LTE-A.



▲ **Fig. 2 3GPP 5G NR band definitions.**

5G NR introduced the concept of a bandwidth part (BWP) as a set of contiguous resource blocks (RBs) that can be set to different transmission bandwidths. Each BWP can have its own numerology and while multiple BWPs can be defined for a given carrier component (CC), only one BWP can be active at a time in downlink (DL) and uplink (UL). The introduction of BWPs enables far more flexible use of spectrum based upon individual UE use cases.

Compared to a maximum channel bandwidth of 20 MHz per CC for 4G LTE-A, 5G NR FR1 can use a 50 MHz maximum channel bandwidth per CC with 15 kHz subcarrier spacing (SCS) and 100 MHz with 30 kHz or 60 kHz SCS. FR2-1 allows for 200 MHz when using 60 kHz SCS and up to 400 MHz when using 120 kHz SCS. The subcarrier spacings for different time slots are shown in ***Figure 3***. ***Table 1*** shows the higher SCS and maximum transmission bandwidth allotments that are being considered for the 52 to 71 GHz frequency range of FR2-2.

4G LTE-A was essentially designed for mobile broadband, though it was possible to configure 4G LTE-A to support other functions within that framework. 5G NR has additional use case features built into the standard that support new applications for cellular wireless technology. The three initial and key use cases for 5G NR are eMBB, uRLLC and mMTC. Each use case has details of the specification and features designed to support the use case in ways that would not be feasible with a one-size-fits-all solution.

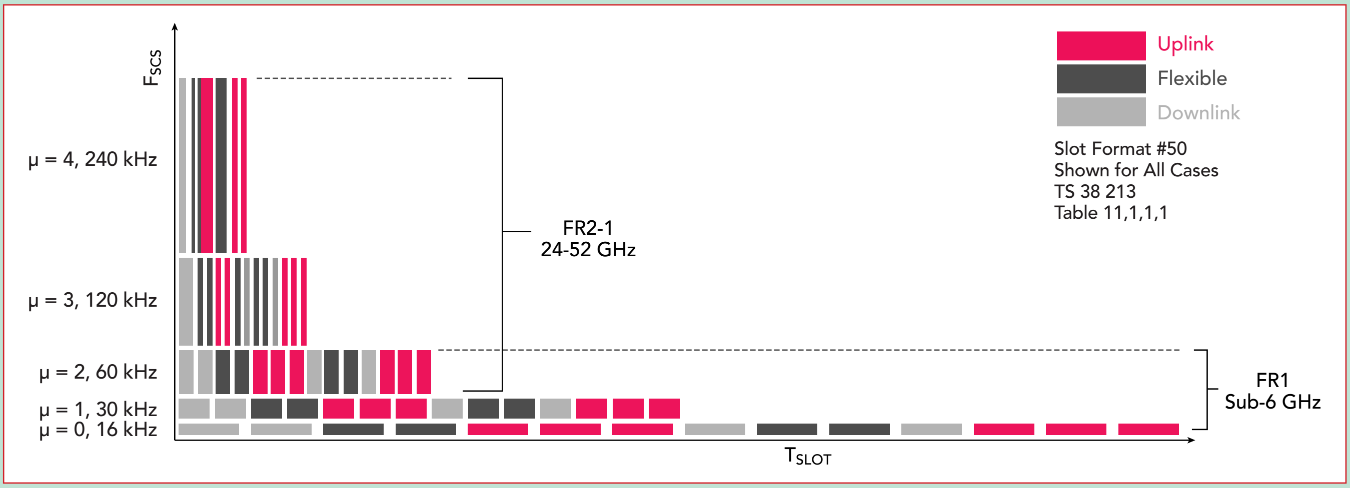
As an example, uRLLC requires much lower latency and higher mobility for vehicle-to-infrastructure (V2I) or vehicle-to-vehicle (V2V) applications for autonomous vehicles or driver safety features. However, uRLLC applications do not prioritize capacity, peak data rate, UE data rate or spectral/network efficiency as much as eMBB applications do. Similarly, mMTC use cases prioritize connection density and network efficiency over other performance metrics to better serve communications among multitudes of machine-type sensors, actuators and beacons. ***Figure 4*** shows a spider diagram of the relative importance of the 5G NR network goals to the three main use cases.

TABLE 1

MAXIMUM TRANSMISSION BANDWIDTH CONFIGURATION N_{RB}.[2]

SCS (kHz)	50 MHz	100 MHz	200 MHz	400 MHz	800 MHz	1600 MHz	2000 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}
60	66	132	264	N/A	N/A	N/A	N/A
120	32	66	132	264	N/A	N/A	N/A
480[1]	N/A	N/A	N/A	66	124	248	N/A
960[1]	N/A	N/A	N/A	33	62	124	148

Note 1: The SCS is optional in this release of the specification.



▲ **Fig. 3 5G NR FR1 and FR2-1 frequency bands and subcarrier spacing.**

5G NR RFFE DESIGN CHALLENGES

The performance and capability enhancements of 5G NR versus 4G LTE-A bring additional challenges

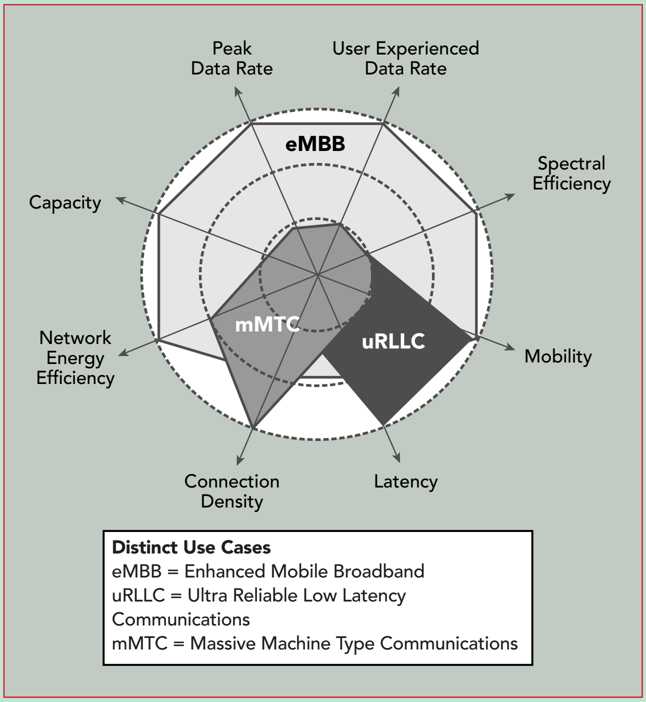


Fig. 4 The three major initial use cases for 5G NR.[1]

that RFFE designers must address. One of these challenges is TDD asynchronous inter-band operation. This becomes especially important when the transmission noise of one band falls into the receive band of a second band when they share an overlapping time slot. There are over 50 UL versus DL slot allocation formats for use in any one band and there are multiple band combinations where this overlap could occur. The significance of this potential interference and network operation is a function of the noise levels, intermodulation (IMD) products and filter rejection levels of the hardware. ***Figure 5*** shows the extent of this potential problem.

Self-Desense

The increased complexity of additional bands and uplink band combinations of 5G NR compared to previous generations leads to an increased risk for self-desense or self-interference, especially in the sub-6 GHz frequency band. Higher maximum and average power levels with 5G NR TDD, as shown in ***Figure 6***, are other

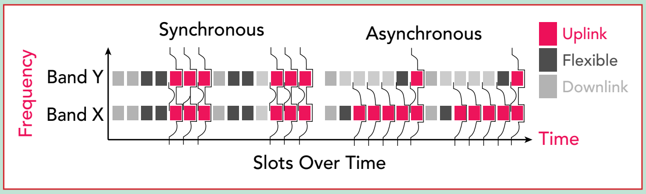


Fig. 5 Asynchronous TDD operation where Band X TX could interfere with Band Y RX.

factors to consider. 5G NR presents more than 60 FR1 band definitions with over 3500 carrier aggregation and dual-connectivity (DC) band combinations, along with the potential for asynchronous operation. This includes multi-mode operation with the UE and base stations operating LTE-A and 5G NR transceivers simultaneously (EN-DC). If any of these combinations result in substantial IMD distortion products, leakage, noise or other interference injected into the receiver, the receiver's sensitivity is reduced.

Maximum sensitivity degradation (MSD) is the metric in the 5G NR standard that defines the permissible degradation of the receiver's sensitivity for a particular band combination. MSD is the amount the RX sensitivity (REFSENS) is degraded for a particular band combination. This value depends upon parameters like maximum TX power, isolation levels, linearity, bandwidth and carrier frequency. These factors also include self-interference caused by coupling and crosstalk effects between the various functional blocks of the RFIC, RF modules, phone board and the entire RFFE.

Figure 7 provides an example of the self-desense effect between two 5G NR FR1 frequency bands. In this case, the UL transmission of Band n78 (3300 to 3800 MHz) is coupling, possibly from multiple locations in the UL signal routing, to the UL transmission of Band n3 (1710 to 1785 MHz uplink). This causes intermodulation products at the Band n3 DL receive signal chain of

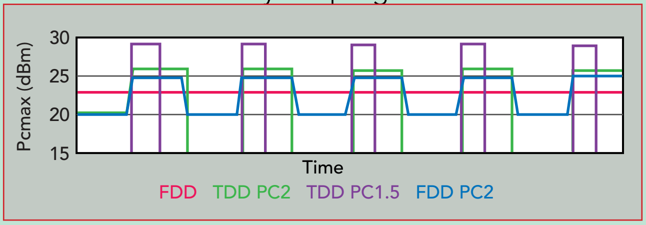


Fig. 6 **TDD with duty cycle applied to the maintain average power at 23 dBm.**

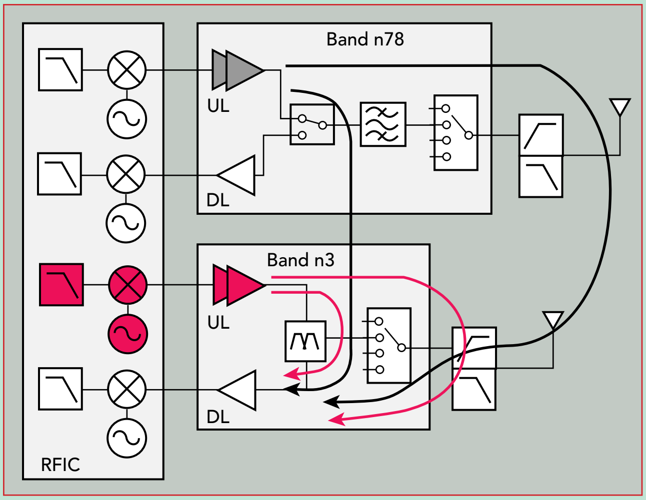


Fig. 7 **Potential self-desense/self-interference mechanism in a 5G CA transceiver.**

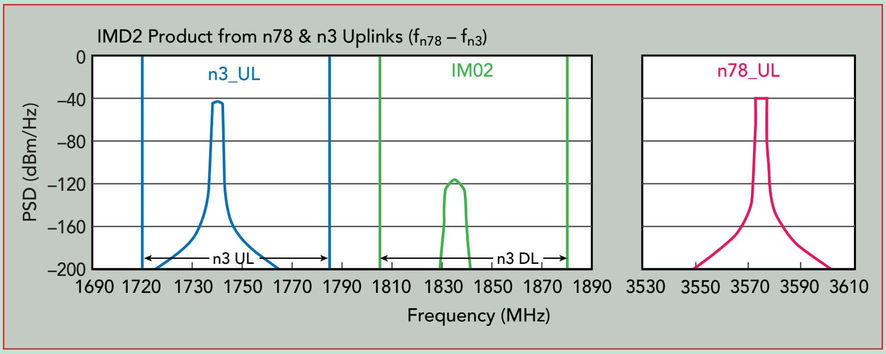


Fig. 8 **PSD in dBm/Hz versus frequency (MHz).**

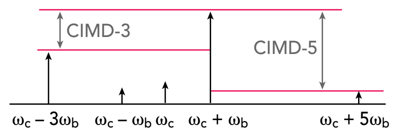


Image (dB)	CIMD-5 (dB)	Desense (dB)
–30	–60	10
–35	–70	4

Fig. 10 **IMD products and image power levels leading to DL desense.**

the RFFE (1805 to 1880 MHz). This is the case shown in ***Figure 8***. In this example, Band n78 is a TDD band while Band n3 is an FDD band, so the UL and DL of Band n3 are at different frequencies. However, the second-order intermodulation distortion products (IMD2) created by the mixing of interference coupled from the UL of Band n78 and the UL of Band n3 into the DL of Band n3 could result in high IMD products falling within the Band n3 DL. That signal may contain enough energy to desensitize the receiver in Band n3, worsening the bit-error rate due to SNR degradation and degrade throughput.

Figure 8 graphically shows the mechanism just described. It combines a plot of the power spectral density (PSD) of the 5G NR Band n3 UL, Band n78 UL and the IMD2. We see that overlapping UL signal components in the transceiver create distortion in the DL of Band n3.

Increased Channel Bandwidth RFIC Impairments Causing Desense

Increased 5G NR channel bandwidths in the sub-6 GHz FR1 bands compared to 4G LTE-A create a similar challenge. The channel bandwidth of many of the FDD LTE-A bands being used in 5G NR FR1 has increased without increasing the duplex spacing. This channel bandwidth increase creates additional opportunities for RFIC impairments to impact the transmission output signal quality. If there is coupling between the transmission and receive signal chains, these impairments could impact the receiver sensitivity. Examples of these impairments could be an image signal generated during frequency conversion because of IQ mismatch or LO leakage. The power amplifiers (PAs) in the transmitter could exacerbate the level and bandwidth of these RFIC impairments in the receive band compared to previous 4G LTE-A levels.

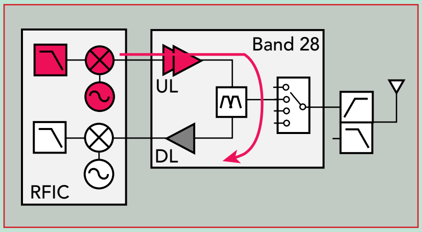


Fig. 9 **Band n28 coupling interference from the transmitter UL to the DL receive signal chain.**

As an example, consider 5G NR FR1 Band n28 with an uplink frequency range of 703 to 748 MHz and a downlink frequency range of 758 to 803 MHz. Band n28 is an FDD band with duplex spacing of 55 MHz and 5, 10, 15, 20 or 30 MHz channel bandwidths. An image sig-

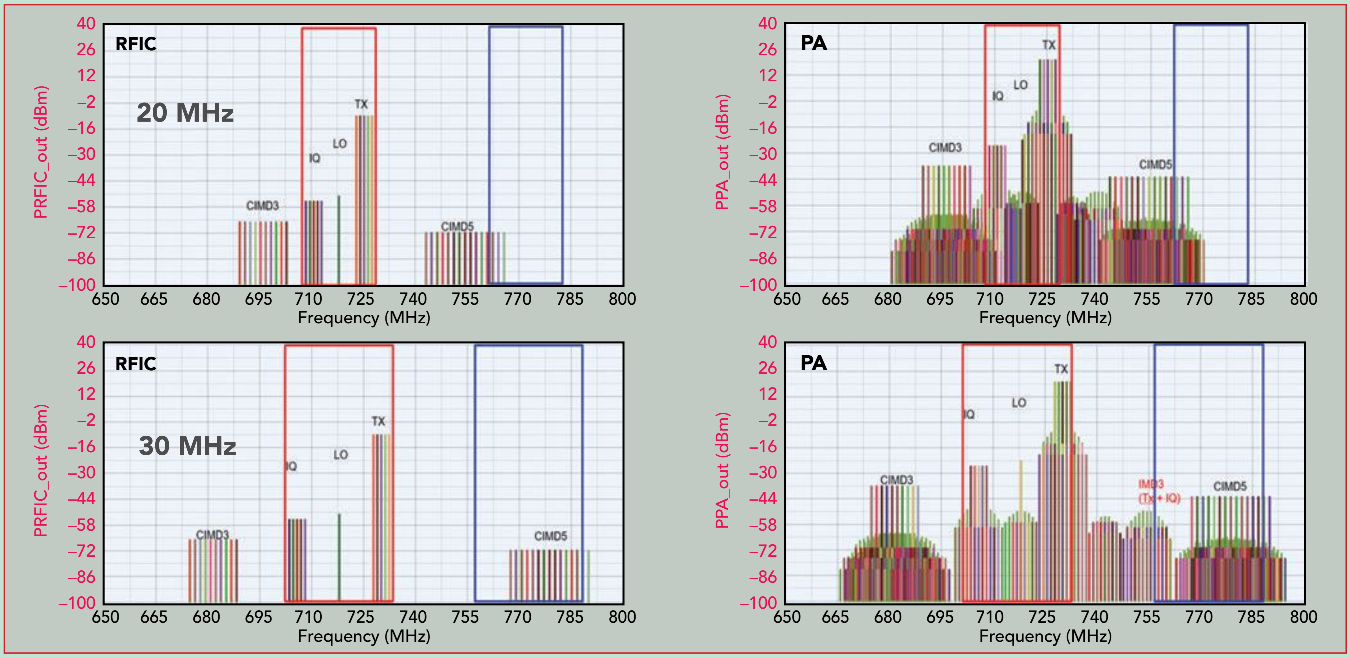


Fig. 11 **Plots of simulated RFIC and PA transmitter output.**

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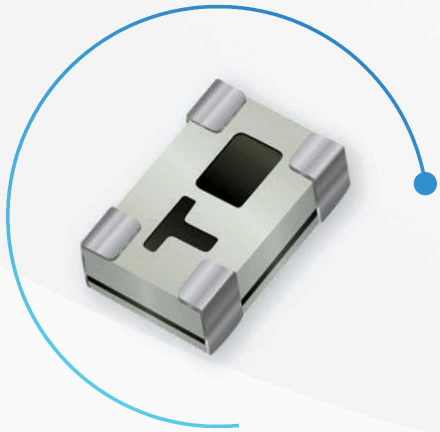

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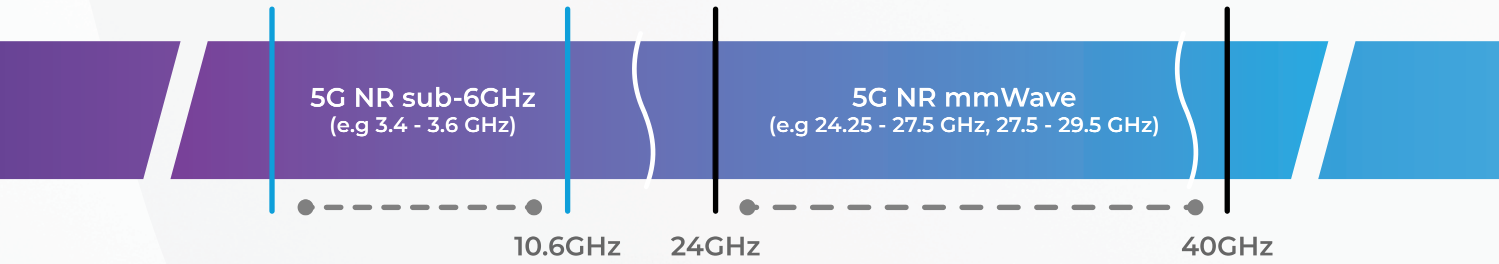

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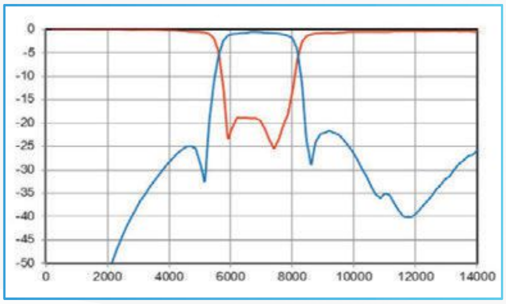

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Military | Base Stations | Test Equipment | Handheld Radios | Consumer | Active Antenna Systems | Automotive | Emergency Services nal from IQ mismatch or LO leakage may pass through a nonlinear PA resulting in distortion products that overlap the DL receiver frequency range, which leads to desense. ***Figure 9*** shows this path on an RFFE block diagram and ***Figure 10*** shows the third and fifth odd-order IMD products and image power levels, along with the potential desense of the DL receiver in 5G NR FR1 frequency bands.

As described earlier, the desense phenomenon is influenced by channel bandwidth. ***Figure 11*** shows simulated RFIC output, including impairments and non-linearities along with PA transmitter output for a 20 MHz and a 30 MHz channel bandwidth. The red rectangle represents the UL and the blue rectangle represents the DL frequency ranges for 5G NR FR1 Band n28. Figure 11 shows that a 20 MHz channel bandwidth will cause limited DL receiver desense because only a fraction of the final nonlinear products can interfere with the DL frequency range. However, with a 30 MHz channel bandwidth, a larger portion of the fifth-order IMD coming from the RFIC falls in the Band 20 DL. Both the IMD3 and IMD5 products, originating in the RFIC and amplified by the PA, are worse for the increased bandwidth case, which is enabled by 5G NR.

Increased RF Bandwidth and Channel Bandwidth Amplifier Considerations

Besides the potential for self-desense and self-interference, other challenges emerge because of increased RF and channel bandwidths. Selecting appropriate low noise amplifiers (LNAs) for the extremely wide 5G NR FR1 Bands n77 (3300 to 4200 MHz), n78 (3300 to 3800 MHz) and n79 (4400 to 5000 MHz) is a hardware consideration. Each band also supports channel bandwidths as high as 100 MHz per component carrier. There are several options for LNAs in these frequency ranges, each with its advantages and trade-offs. Common source LNAs with inductive degeneration exhibit low noise figures (NFs),

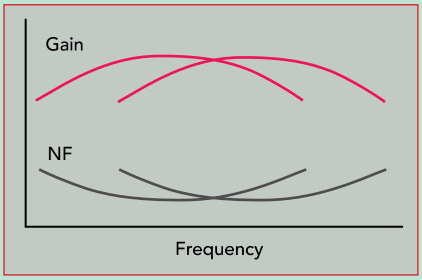

Fig. 12 **Overlapping LNA gain and NF to increase bandwidth.**

but they also have relatively narrow fractional bandwidths. The NFs of common gate LNAs with inductive degeneration are slightly inferior to common source LNAs, but they have wider fractional bandwidths. A programmable LNA is another option, though a designer would need to consider that the tuned performance of these LNAs depends on the carrier frequency. Lastly, a wideband LNA with low NF and high gain may also be suitable, though additional filtering may be necessary. Reasonable wideband gain results from combining multiple LNAs with slightly overlapping bandwidths. This technique is shown in ***Figure 12***.

There are other considerations with PAs. High efficiency is desirable and current consumption becomes a significant concern and these challenges become more difficult with wider channel bandwidths. This is especially true for Bands n77, n78 and n79. Envelope tracking (ET) is a common technique to achieve reasonable levels of efficiency. ***Figure 13*** shows a simple ET circuit, but this circuitry and design becomes more complex when channel bandwidths increase beyond 100 MHz. Additionally, it is difficult to avoid asymmetric adjacent channel power leakage ratio issues with many modern PA technologies because of memory effects in the PA.

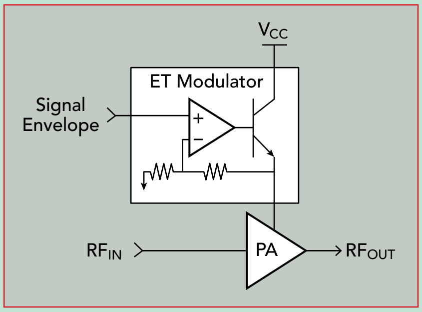

Fig. 13 **High-level schematic of an ET modulator and PA.**

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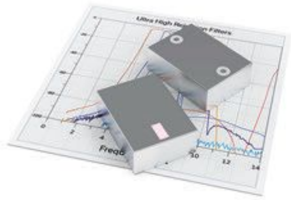

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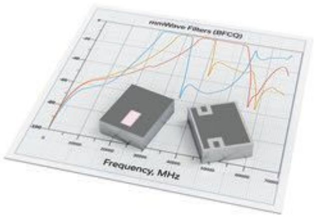

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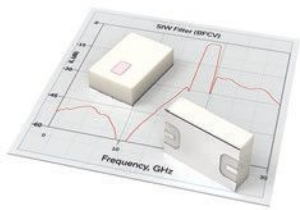

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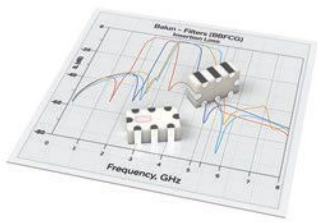

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STEPS TO TACKLE 5G NR RFFE DESIGN CHALLENGES

Some methods exist to address these RFFE design challenges and some developments are needed. One solution to tackle potential DL desense issues is to use network optimization techniques that involve spectrum allocation with RB placement. This could be part of a larger, intelligent throughput-driven spectrum allocation scheme. Using RB placement for 5G NR FR1 spectrum allocation can result in minimizing UL interactions that could desense DL receivers in the same band or nearby bands. An example of an RB placement solution for spectrum allocation to minimize DL desense occurrences with 5G NR FR1 is shown in ***Figure 14***.

RB placement can be done with relatively simple algorithms and lookup tables. However, cognitive radio techniques have also been proposed to handle real-time spectrum allocation challenges and minimize DL desense more intelligently. Using machine learning/artificial intelligence with cellular resource allocation could enable better spectrum optimization. This might allow planners to consider cellular activity and potential interference from other wireless networking technologies and noise/interference generators. This requires substantial development in cognitive radio technology and protocols for facilitating cognitive networking and cognitive radio interactions.

For specific combinations that may suffer desense or interference from IMD, the UL carrier frequency could be shifted slightly to minimize self-desense for cell-edge handsets. Referencing the example presented in ***Figure 15*** with 5G NR FR1 Band n28, a slight shift of the UL carrier frequency would shift the IMD3 product that would normally overlap with Band n28. This would also allow for increased DL channel bandwidth as shown in Figure 15.

Additional RFFE Technology Developments

To address the changes and growing expectations for 5G NR performance and capability, additional developments are needed in RFFE hardware and systems. To accommodate multi-antenna AAS technology, these developments need to be extremely compact, readily

Uplink	Downlink	n13						n5					
	Victim	(746-756)						(869-894)					
Aggressor #1	Aggressor #2	2	3	4	5	6	7	2	3	4	5	6	7
n5_A (824-829)	n13_A (777-782)								3				
n5_B (829-834)	n13_A (777-782)								3				
n5_C (834-839)	n13_A (777-782)								3				
n5_D (839-844)	n13_A (777-782)												
n5_E (844-849)	n13_A (777-782)												
n5_A (824-829)	n13_B (782-787)		3						3				
n5_B (829-834)	n13_B (782-787)								3				
n5_C (834-839)	n13_B (782-787)								3				
n5_D (839-844)	n13_B (782-787)								3				
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Fig. 14 Example of an RB placement solution for spectrum allocation.

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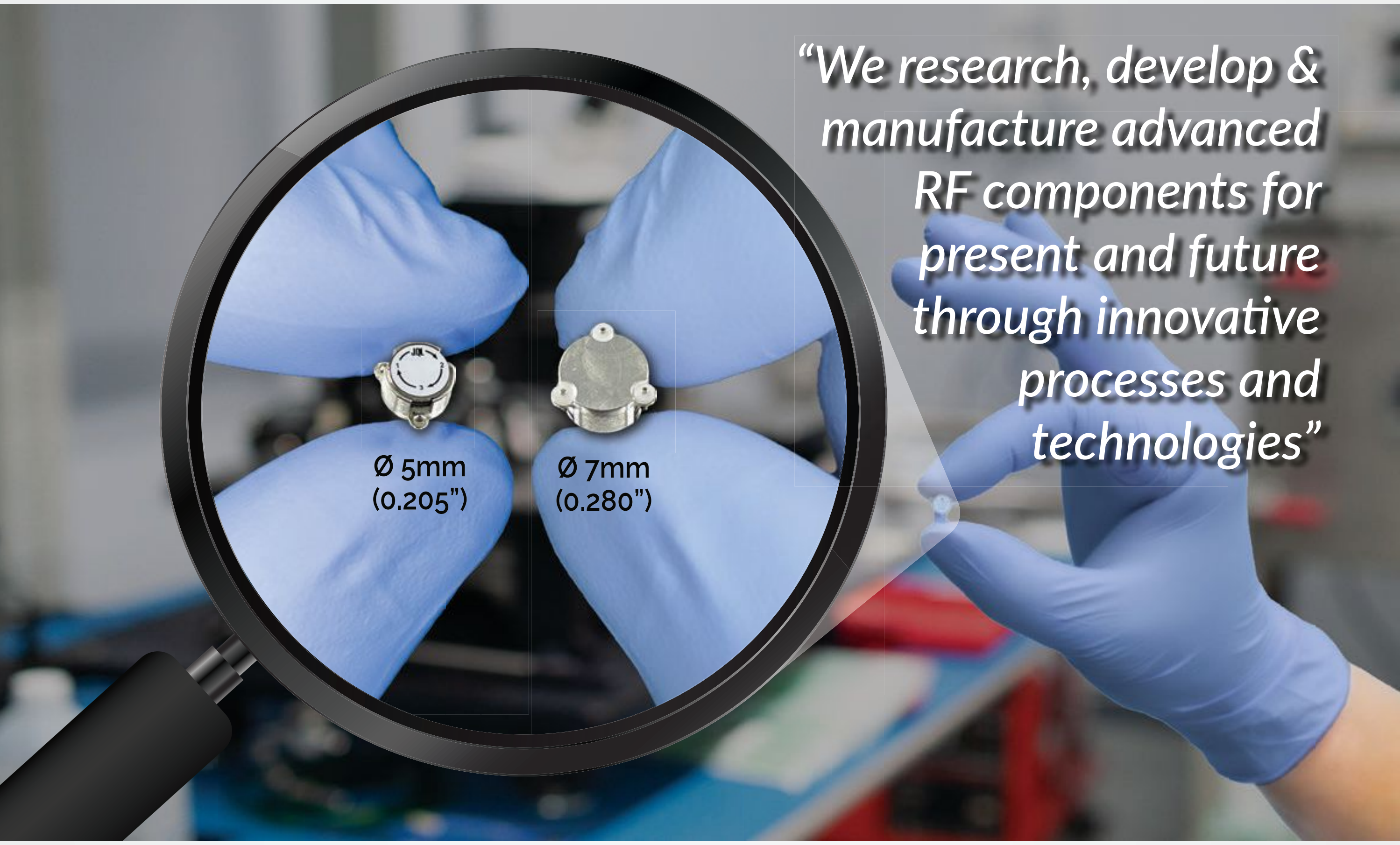

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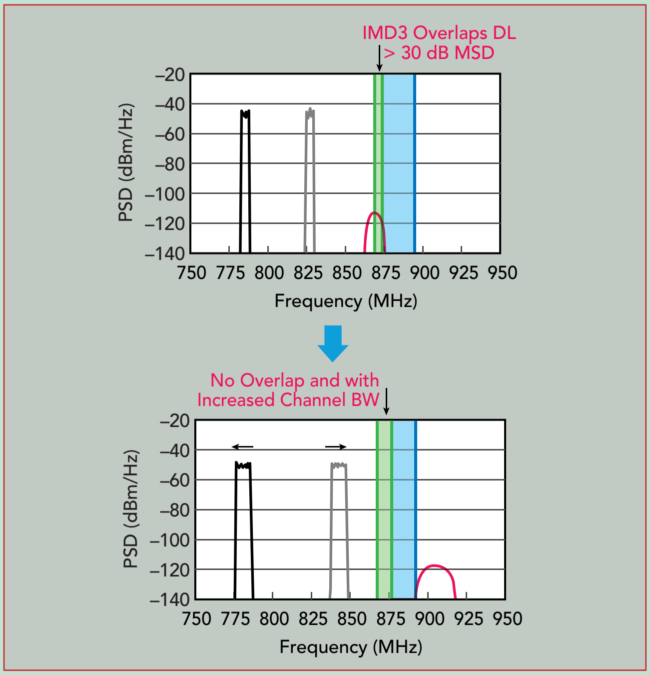

▲ **Fig. 15** **Shifting the UL carrier frequency to minimize self-desense for cell-edge handsets.**

integrated into panelized antenna solutions and more efficient. Wider bandwidth LNAs and PAs are needed to tackle the higher-channel bandwidths possible with FR1 frequency bands. Increased UL power requires high-power tolerance and high efficiency PA designs. More complex 5G NR modulation schemes increase the need for RF block designs with lower error vector magnitudes to ensure that those schemes can be successfully implemented. To reach the speeds and fidelity needed for 5G NR means linearity thresholds must increase for switches, PAs and LNAs to reduce the chance for self-desense. For 5G NR, mitigating self-desense and self-interference solely through RFFE component performance may be impossible. In the long term, the solution may involve adopting intelligent interference mitigation strategies.

CONCLUSION

The 5G NR specifications are consistently pushing the boundaries of wireless networking performance and adopting new features and use cases. These advances, though likely to continue to usher in a new age of connectivity, are also placing new burdens and creating additional challenges that RFFE designers and network optimization engineers must tackle. Ultimately, new strategies and device design/development are needed to address these challenges, but these solutions must also be extremely compact, efficient and cost-effective. ■

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Top-Side Cooling Enables 5G Active Antenna Systems

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Since the first 5G services were launched at the end of 2018, mobile network operators (MNOs) around the world have been busily deploying 5G networks and, according to the Global mobile Suppliers Association (GSA), the number of global subscribers reached 1.15 billion at the end of 2022.[1] This represented a year-on-year growth of 85.9 percent. It is still early days for 5G and MNOs globally are continuing to invest heavily in their 5G networks, primarily in the C-Band or mid-range spectrum, around 3.8 GHz.

Due to the specific propagation characteristics of higher frequency 5G signals, concerns about the end-user experience are driving MNOs to increase the density of their networks. This is particularly true in crowded urban areas where connection densities are high and the spectrum is crowded. The specifics of these urban environments bring constraints on space and access to power, meaning operators must comply with increasingly strict planning regulations when deploying 5G base stations (gNB).

Massive MIMO (mMIMO) systems are key components of the gNB and the pressures of network densification have driven a dramatic reduction in the size of the radios and antenna systems that comprise these systems. Increased levels of on-chip integration have enabled significant levels of miniaturization, contributing to this reduction in form factor, but pressure remains to continue this trend. Semiconductor manufacturers are now looking at innovations in packaging technology to achieve further reductions.

This article discusses these trends in more detail. It will explore how top-side cooling (TSC) techniques can result in smaller and lighter semiconductor devices. TSC packages are already found in several applications, such as electric motor control, but this article examines a top-side arrangement for RF radio modules, which are at the heart of mMIMO solutions.

MEETING THE 5G CHALLENGE DEMANDS INNOVATIVE TECHNOLOGIES

The design specification for 5G was drafted in response to the relentless growth in demand for wireless bandwidth and throughput. The specification contains some challenging requirements, including a step change in transmission speeds and sub-millisecond levels of latency. While previous cellular networks evolved between generations, the challenging demands of 5G require designers to adopt a transformational approach, incorporating a range of innovative techniques. These techniques include wider spectrum utilization, mMIMO and beamforming.

Wider Spectrum Utilization

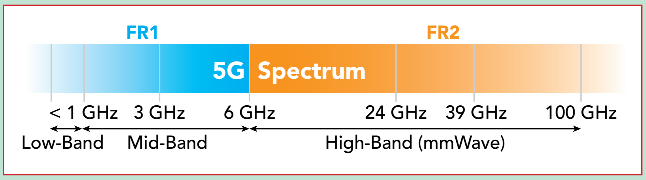
5G uses much more spectrum than previous cellular generations. It operates in two distinct frequency bands known as FR1 and FR2. A graphical representation of these two bands is shown in ***Figure 1***.

- FR1 (sub-6 GHz): 410 to 7125 MHz
- FR2 (mmWave): 24.25 to 52.6 GHz

The majority of 5G network rollouts to date have offered services in the midband region shown in Figure 1. This region, which includes the C-Band spectrum around 3.8 GHz, is becoming known as the "coverage and capacity" layer because operation in this band delivers an attractive capacity-coverage compromise. MNOs are beginning to consider the deployment of mmWave infrastructure, however, as demand grows for the higher throughput and lower latencies supported by this portion of the spectrum.

mMIMO and Beamforming

Figure 2 shows a diagram of massive MIMO combined with beamforming techniques. These are core components of 5G NR and



▲ Fig. 1 5G operates in two distinct frequency bands.[2]

together they enable 5G to support many more devices per square meter than 4G. These techniques also allow faster data transmission to more users with high precision and low latency.

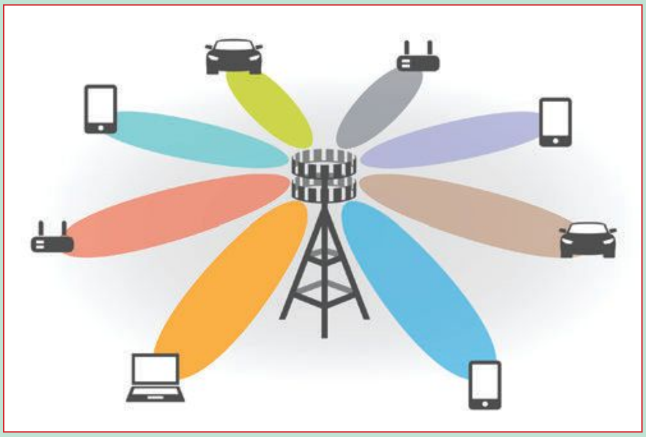
Beamforming enables the beam from the 5G base station to be directed toward the end-user mobile device, increasing special efficiency and ensuring optimum transmission levels while minimizing interference to other nearby mobile devices. mMIMO increases the number of transmit and receive paths as well as the antenna count, enabling spatial multiplexing to transmit independent and separately phased data signals, or “streams,” reusing the same time and frequency resource. At higher frequencies, the spacing between antenna elements reduces and these tightly-located antennas generate narrow beams that can be precisely focused, strengthening the received power, reducing interference and significantly increasing throughput. Spectral efficiency and capacity can be improved by adding more streams or layers until the point where power sharing and interference between users results in diminishing gains and, eventually, losses. MIMO antennas are designated by the number of transmit and receive antennas, with the most common mMIMO antenna sizes today being 32T32R and 64T64R.

NETWORK DENSIFICATION DRIVES THE MINIATURIZATION CHALLENGE

The 5G rollout is fundamentally changing the configuration of cellular networks since the higher transmission frequencies of 5G signals require denser networks. The traditional macrocells, responsible for providing wireless coverage over large areas, are being supplemented by increasing numbers of gNB. These base stations use mMIMO techniques to support higher numbers of connections while making more effective use of the spectrum.

The gNB are progressively appearing in urban areas where demand is high. These base stations are mounted in locations, like buildings and street furniture, which impose constraints on the base station design. Size and weight become important to avoid overloading of the mounting structures and to facilitate low installation costs. Low power consumption is also key since forced air cooling is not usually an option and access to local power may be limited.

The architecture of the gNB is evolving rapidly as 5G networks are rolled out with these base stations incorporating increasing levels of mMIMO to achieve the design requirements. A mMIMO deployment integrates an active transceiver array and a passive antenna array into a single hardware unit. The mMIMO system also includes the hardware and software required for the



▲ Fig. 2 Massive MIMO and beamforming representation.[3]

signal processing and the algorithms to support the execution of the mMIMO features. Shrinking transmission wavelengths are increasingly allowing the use of patch antennas and these smaller geometries enable antenna arrays with a higher number of elements.

The developments in antenna design have been enabled by significant advancements in semiconductor technology. Miniaturization techniques enable electronic components such as RF transceivers, power amplifiers (PAs), analog-to-digital converters, filters and switches to be packed into smaller ICs. These devices can fit on the back of the antenna board, significantly reducing the depth of the antenna.

THE SEMICONDUCTOR INDUSTRY RESPONDS WITH TSC

The need to fit more power into smaller spaces is not unique to the 5G gNB, as an examination of most sectors will confirm. Applications such as complex automobile control systems, wearable medical devices or the small CubeSats that increasingly support IoT connectivity, all demand more computing power in smaller and lighter enclosures. In response to this demand, the electronics industry continues to innovate. Increasing levels of on-chip integration are key enablers of small form factors and MMICs. MMICs integrate RF and digital functionality, including microwave mixing, power amplification, low noise amplification and high frequency switching onto single chips with 50 Ω inputs and outputs.

To support increasing levels of integration, circuit board and packaging techniques have also evolved rapidly. In component manufacturing, surface-mount technology has largely replaced traditional through-hole printed circuit boards (PCBs). Surface-mount devices (SMDs) enable increased manufacturing automation, which reduces cost and improves quality while enabling more components to fit on a given substrate area.

However, more components generate more heat. The RF PA is typically the most power-hungry device in a radio and an mMIMO system will contain many of these devices. Forced air cooling is often not an option in many systems, including the gNB, so thermal management is a key design consideration when

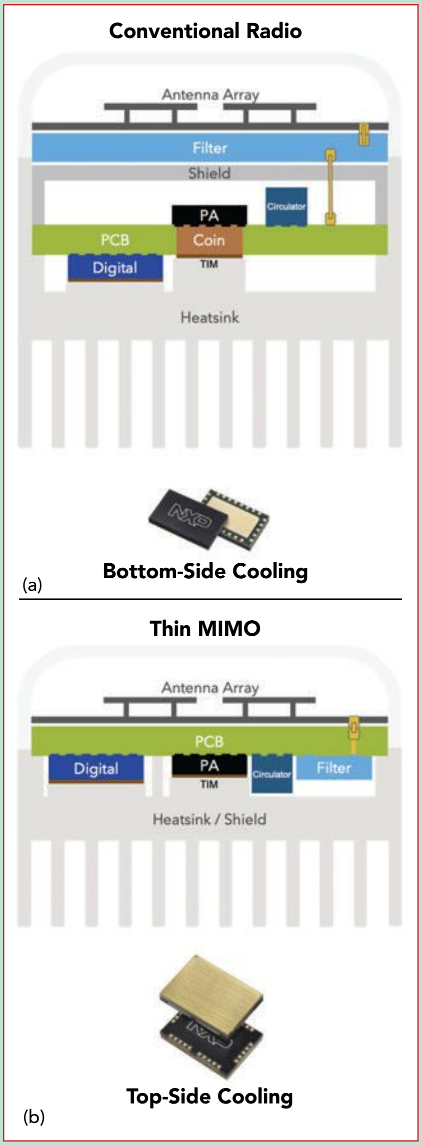


Fig. 3 (a) Conventional implementation with BSC. (b) NXP implementation with top-side cooling.

packaging electronic devices. With bottom-side cooling (BSC), thermal conduction paths transfer heat from high-power components into the PCB, which is bonded to a cold plate or heat sink. However, BSC is a compromise between thermal performance and PCB utilization since components can only be placed on one side. This constraint can significantly reduce the functional density of the board.

In response to these space and weight challenges, semiconductor manufacturers are developing packaging for their components that utilizes TSC. Different TSC implementations have been developed to meet the requirements of specific industries.

With TSC, the semiconductor chip is connected to a direct-bonded copper ceramic substrate on the top side of the package. The chip is mounted on the surface of the PCB, making a direct connection to the external heat sink. This ensures maximum power dissipation and optimizes thermal performance while eliminating the board density issues inherent in BSC mounting techniques. Semiconductor devices in SMD packages that implement TSC provide enhanced thermal performance, enable smaller form factors and increase design flexibility.

The exact implementation of TSC varies by manufacturer, driven by the needs of the application and other factors. The next section takes a closer look at the implementation of this packaging technology to better understand the benefits. Designed for 32T32R radios, this section will explore RF power modules that utilize TSC.

TSC SOLUTION REDUCES DEVICE SIZE

In 2018, NXP began producing integrated, multi-chip RF radio modules to meet customer demands for smaller and lighter RF equipment. As the 5G rollout has gathered pace, the company has responded to the requirement for even smaller radios with a new packaging technology that leverages TSC to reduce the size of a high frequency radio module. ***Figure 3a*** shows the packaging layout of a conventional radio module, using BSC. ***Figure 3b*** shows an implementation of the same radio architecture using NXP's TSC packaging technology.

On the conventional, bottom-side cooled device, the heat from the PA is conducted through a coin in the PCB to the heat sink mounted on the underside of the PCB. The RF components are mounted on the top side of the PCB and are enclosed by an electromagnetic (EM) shield. The antenna array is connected to a dielectric filter that is connected to the PCB.

To reduce the size of the radio module, the first step was to integrate the coin into the PA. This enables the coin to be moved to the other side of the PCB where it can be connected directly to the heat sink. Improvements to the circulator and the dielectric filter enable them to be mounted on this side of the PCB as well. This brings all the RF components to the same side of the PCB, creating an improved thermal path through the module. Next, integrating the EM shield into the heat sink allows the shield on the top side of the PCB to be removed, bringing the antenna array much closer to the PCB. This configuration change reduces the length of the connectors, saving cost and reducing RF losses. We estimate that the removal of the shield is responsible for much of the reduction in the thickness and weight of the new radio module.

These thinner and lighter radio units contribute to improved base station radio equipment design. Theoretically, any size reduction reduces installation cost and complexity since only one installer is required for the deployment in most cases. The goal is for the gNB to be small enough to allow a self-install process. In addition, smaller base stations are less likely to meet objections from building landlords and planning authorities and they are well-suited to indoor deployments. All these factors should be advantageous to MNOs as they add small cells to their networks.

The gNB is just one of many applications that can benefit from packaging using TSC techniques. Other verticals, such as automotive and aerospace, face similar challenges as more power is packed into smaller spaces. NXP expects that a growing range of packaging utilizing TSC will emerge to enable all these market applications. ■

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					1GHz	2GHz	6GHz	18GHz	1GHz	2GHz	6GHz	18GHz
C02	Flexible .141	4.20	N Male	≤-155 dBc	1.15:1	1.15:1	1.20:1	1.35:1	0.5	0.8	1.4	2.6
C29H	Ultra Low Loss Flexible .086	2.57	SMA Male	≤-140 dBc	1.15:1	1.15:1	1.20:1	1.30:1	0.7	1.0	1.7	3.0
F02J	Hand Formable .141	4.20	N Male	≤-155 dBc	1.15:1	1.15:1	1.20:1	1.35:1	0.6	0.8	1.4	2.6
IM03	Hand Formable .250	6.90	N Male	≤-160 dBc	1.15:1	1.15:1	1.20:1	1.35:1	0.4	0.6	1.0	1.9
			L29 Male	≤-160 dBc	1.15:1	1.20:1	1.30:1	-	0.4	0.6	1.0	-
IM04	1/4"Corrugated Cable, Superflex	7.50	N Male	≤-160 dBc	1.15:1	1.15:1	1.25:1	1.35:1	0.3	0.5	0.8	1.5
			L29 Male	≤-163 dBc	1.15:1	1.20:1	1.30:1	-	0.3	0.5	0.8	-
G02	3/8"Corrugated Cable, Superflex	10.20	N Male	≤-160 dBc	1.15:1	1.15:1	1.30:1	-	0.3	0.4	0.8	-
			4.3/10 Male	≤-165 dBc	1.15:1	1.20:1	1.25:1	-	0.3	0.4	0.8	-
			L29 Male	≤-165 dBc	1.15:1	1.20:1	1.30:1	-	0.3	0.4	0.8	-
G04	1/2"Corrugated Cable	15.70	N Male	≤-160 dBc	1.15:1	1.15:1	1.30:1	-	0.2	0.3	0.5	-
G06	1/2"Corrugated Cable, Superflex	13.40	N Male	≤-160 dBc	1.15:1	1.15:1	1.30:1	-	0.3	0.4	0.6	-
			L29 Male	≤-168 dBc	1.15:1	1.20:1	1.30:1	-	0.3	0.4	0.6	-

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Beamforming and System Gain Make NLoS Communications Possible at 60 GHz

David Sumi
Airvine Scientific, Inc. Santa Clara, Calif.

For those seeking the highest bits-per-second transmission rates in the wireless domain, the 60 GHz band has been a gleam in the eye of the wireless community for years. The band has a whopping 14 GHz of spectrum, which is more spectrum than all the sub-6 up to 42 GHz bands combined. There is no doubt that the 60 GHz band offers plenty of bandwidth to achieve multi-gigabit rates. The relative channel bandwidths for these bands are shown in ***Figure 1***.

However, the promise of multi-gigabit systems in this frequency band came with one critical restriction; all operations had to be line-of-sight (LoS), with no obstacles in the transmission path. In addition, any services in this band were and are limited to comparatively shorter-range applications, with link budgets of approximately 1000 m or less. But now, advances in system gain performance and the application of beamforming techniques have solved the LoS problem in interior environments and have resulted in true non-LoS (NLoS) connectivity. The link budget restrictions remain the same, but

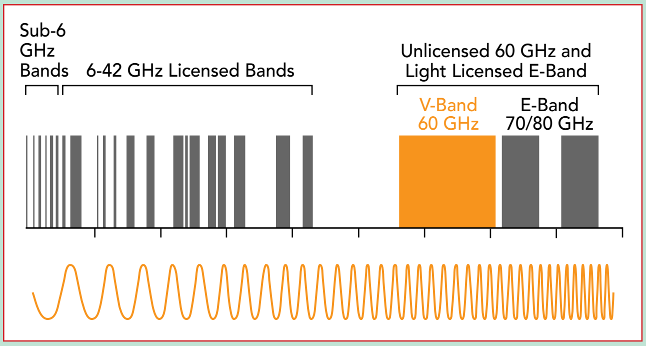


Fig. 1 Channel bandwidths for the various communications bands up to 80 GHz. *Source:* Airvine.

Fig. 2 Robotic inventory and assembly envisioned in Industry 4.0.

these restrictions are moot in these environments, as transmission paths rarely exceed 100 m.

This development opens a whole new market for services in the 60 GHz band, which comes just in time to address applications with burgeoning bandwidth requirements. Industry 4.0 applications aim to address artificial intelligence- and machine learning-based factory operations and backbone or backhaul connectivity for private 5G networks, large data centers and other large interior settings such as conference centers and MDUs are all feeding the need for increased bandwidth and data traffic. This article provides an overview of some of the efforts to develop a market for 60 GHz services. Some Industry 4.0 applications benefiting from high data rate capabilities are shown in ***Figure 2***.

THE BEGINNING

Over the years, there have been several attempts to introduce 60 GHz gear and adopt 60 GHz standards, with mixed results. The WiGig Alliance was founded in 2009 and introduced 60 GHz to the IEEE with the 802.11ad standard in 2012. In 2014, the Wi-Fi Alliance adopted WiGig 802.11ad, as an industry standard certifying WLAN equipment and began a program of interoperability testing.

These efforts failed. The requirement for strict LoS operation in an indoor environment was too restrictive in the home or business environment. Simply walking in between a client and an 802.11ad access point (AP) broke the connection. In addition, APs with built-in WiGig chips were much more expensive than a standard 2.4/5 GHz AP with the cost difference being on the order of hundreds of dollars.

TAKE TWO

The next time 60 GHz appeared on the market was just a few years later with the introduction of IEEE 802.11ay in 2019. The IEEE 802.11ay standard was a significant improvement over 802.11ad in efficiency, range and other characteristics. However, the standard was better suited for short-range applications and the dominant market application that adopted this standard attempted to use it outdoors at ranges of up to 1800 m. The rationale was that if the links had to be LoS, it was easier to do outdoors where devices can be mounted high up on buildings, towers or streetlights. However, this deployment model just served to introduce tension and compromises between the users and the suppliers. Further complicating the situation, this band suffers from oxygen absorption, a phenomenon where O_2 molecules in the atmosphere resonate at 60 GHz, absorbing the radio waves, which further attenuates the signals and reduces transmission range. The spectrum is best suited to support applications with links at short distances that meet the LoS requirement. The use case wound up being like trying to fit a square peg into a round hole.

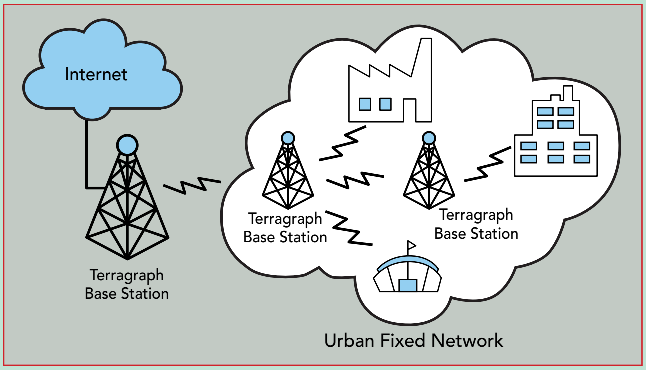


Fig. 3 **The Terragraph network concept.**

The 802.11ay standard served as the foundation for the Terragraph Project, which was launched by Meta, Facebook at the time, to establish a viable ecosystem for outdoor 60 GHz services. This goal was to address residential broadband and particularly, the "digital divide." As part of this effort, Qualcomm introduced a complete 60 GHz reference design, which included the modem, front-end and antenna. The goal of the project was to reduce total cost and speed time to market for vendors. ***Figure 3*** shows a conceptual block diagram of the Terragraph network.

These systems were point-to-multipoint, meaning the AP or base station had to implement beam steering to overcome the drop in antenna gain caused by 90 sectors in the antenna. This approach served in stark contrast to the very narrow high gain antenna used in point-to-point communications. To improve the business case, broadband wireless access systems relied on increasing the range to cover more clients per base station. This meant pushing these systems to the limits of their capabilities. Since 60 GHz is a short-range frequency with the added obstacle of oxygen absorption, using the band in longer-range deployments was challenging. The Terragraph Project has not achieved the "mass deployment" expectations and Meta stepped away from Terragraph in 2022.

THE SWEET SPOT FOR 60 GHZ

Using 60 GHz indoors matches the inherent short-range performance of these systems to applications that are also short-range. There are no indoor requirements for a one-mile link. It is rare to have a link exceeding 100 m and these links usually range from 25 to 50 m. However, the LoS restriction existed until it became possible to penetrate interior walls and go around corners with beams that can be

steered at angles of more than 90 degrees. These new beamforming and system gain capabilities have changed the whole calculus of using 60 GHz and have created a market for indoor cable extension. Using the 14 GHz of available spectrum, it is now possible to realize capacities of 10 to 20 Gbps full duplex.

GETTING BEAMFORMING RIGHT IN THE 60 GHZ BAND

Beamforming involves precise phase shifting the elements of an antenna array to generate a narrow beam focused in a specific direction. The narrow beam increases the gain to the intended receiver, while also reducing interference to other devices nearby. This is useful in sub-6 GHz applications, but the real value comes in the mmWave bands where the additional gain helps overcome high free space path loss and oxygen absorption that occur at 60 GHz.

Beamforming is a foundational enabling technique for all mmWave communications. There are two parts to any radio system: the digital baseband modem and the RF subsystem consisting of the RFIC and the antenna array. Each has a role to play in the beamforming process. The next section presents a high-level overview of the different beamforming techniques currently being used. This will lead to a discussion of MIMO technology, which is a form of spatial multiplexing that leverages beamforming technology.

Analog Beamforming

In systems using analog beamforming, a single data stream is sent from the digital baseband through a radio chain that creates an analog signal in the mmWave band. That signal is then sent through an array of phase shifters to create a narrow beam with high gain. Depending on the design, this antenna gain may be as high as 30 dBi for a large array.

These arrays typically use patch antenna elements that are each about 2 mm^2 when operating at 60 GHz. It is possible to have as many as 256 of these elements in an array. By precisely altering the phase and amplitude of each patch antenna element, it is possible to create a narrow beam focused in a specific direction. Since power, as defined by effective isotropic radiated power (EIRP) is limited by regulation, the narrower the beam, the greater the gain as seen by the receiver. As a result, analog beamforming, when used correctly, can create a very high gain antenna.

Digital Beamforming

In this approach, all the phase shifting is done in the digital baseband. This enables precise RF beams and nulls, but this approach does not scale well since a full radio chain is needed for each antenna element. A typical implementation might include 16 data streams flowing through 16 radio chains and then into 16 antenna elements. An attractive feature of digital beamforming is that the technique supports multi-user MIMO (MU-MIMO), which makes it possible to communicate with multiple users over the same RF channel at the same time.

To limit interference, MU-MIMO requires a narrow beam focused on each intended user, with nulls focused on everyone else. Beamforming at mmWave bands is best done with a large number of antenna elements. However, this implementation in the digital domain is cost- and power-prohibitive. A compelling alternative combines the large array capability of analog beamforming with the MU-MIMO capabilities of digital beamforming. This technique is known as hybrid beamforming.

Hybrid Beamforming

This combination of MU-MIMO and analog beamforming is often referred to as massive MIMO. Each beam is structured to deliver maximum energy to the intended user, while also generating nulls aimed at all other users. As users move around in the coverage area, the digital baseband recalculates the

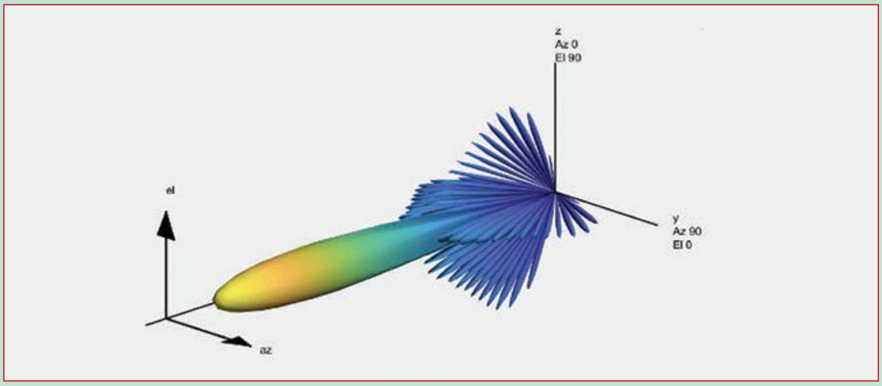


Fig. 4 Representative modeled antenna beam pattern.

necessary changes to phase and amplitude shifts. An advantage of the 60 GHz band is that antenna elements, even for a large array, can easily fit on a PCB of less than 20 cm^2. This approach is ideal for access networks that are being deployed in heavily congested areas like stadiums, city centers, convention centers and airports, where it is necessary to connect large numbers of people in a confined area.

RECEIVE BEAMFORMING

Most discussions of beamforming focus on the transmit side of the equation, but the receive side must also be considered. Not only is the RF signal phase shifted across all transmit patch antenna elements, but it must also be phase shifted across the receive side. This allows the receive signals to be properly aligned so that they will add constructively to get a strong signal. This concept is most easily explained by considering a transmitter to the left of the receiver. The receiver antenna elements on the left side of the antenna will see the signal before the elements on the right. These signals must be phased properly to add constructively.

Side Lobes

The creation of RF side lobes is an inevitable part of the beamforming process. There will always be some extraneous RF energy that is not part of the primary beam. These lobes appear as interference to other users in the operating area and they siphon energy from the primary beam that is directed at the intended user. The goal is to minimize this energy to the extent possible. A general objective in any mmWave design is to target side lobe suppression of at least 20 dB. Beamforming is well-suited for mmWave bands. The transceiver and antenna hardware are small and the technique helps counteract the free space path loss challenge while also limiting co-channel interference. The output of a modeled multi-element antenna beam at 60 GHz, with the main lobe and the sidelobes is shown in ***Figure 4***.

TABLE 1

ATTENUATION PROPERTIES OF TYPICAL WALL MATERIALS

Material	Attenuation (dB/cm)	Attenuation (dB/in)	Wall Attenuation (dB typical)
Drywall	0.09	0.23	0.29
Drywall with semigloss paint	0.60	1.52	1.91
Drywall with flat paint	0.09	0.23	0.29
Ceiling tile	1.12	2.84	2.84
Wood	1.30	3.30	4.13
Glass	4.30	10.92	
Cavity cinder block	11.30	28.70	229.62

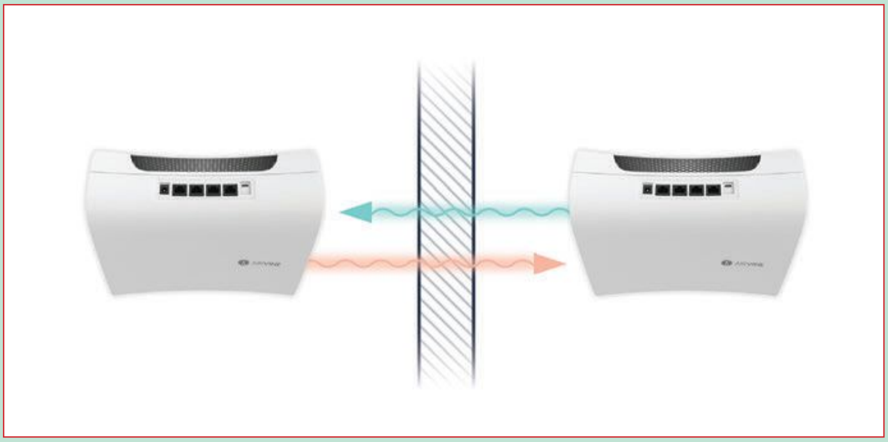


Fig. 5 Airvine WaveTunnel node communication through a wall.

System Gain Considerations

Another big contributor to achieving NLoS connectivity at 60 GHz pertains to improvements in system gain performance. As the operating frequency increases, signal propagation distance decreases. Ultimately, the maximum distance is set when the link performance drops below a specified bit error rate, packet error rate or availability rate. To achieve this NLoS connectivity indoors, penetrating obstacles such as walls is a big challenge, especially since the attenuation of wall materials increases with frequency. For 60 GHz, the attenuation of common indoor walls is well known. ***Table 1*** shows typical attenuation values for various common wall materials and the large variation in loss for these walls is evident.

Range and obstacle penetration performance depends heavily on system gain. This means simultaneously maximizing transmit EIRP (power output plus antenna gain) and receiver sensitivity while getting as much antenna gain as you can fit into a given mechanical limitation. In addition, the FCC and other regulatory agencies have mandated a maximum EIRP of 40 dBm in the indoor 60 GHz application.

The challenge becomes the best way to maximize the allowed system gain plus the receiver gain. Airvine has accomplished this by optimizing the front-end and the antenna to put as much of the EIRP in the antenna. This means narrowing the transmit beam, while at the same time reducing side lobes and other undesired artifacts. The result, in effect, tunes the entire wireless data chain from the modem to the RF transceiver to the antenna, making NLoS connectivity possible in the 60 GHz band. These techniques are the basis for Airvine's WaveTunnel™ nodes shown in ***Figure 5***. The nodes, coupled with Airvine's VineSuite control and monitoring software can be configured into a network providing gigabit per second connectivity at 60 GHz in NLoS applications requiring high data rate transmission.

CONCLUSION

The future of 60 GHz is not just bright, it is brilliant. Airvine has not violated the laws of physics, particularly the reality that higher frequencies mean shorter ranges. Instead, they have taken a fresh look at the notion that any device operating at a frequency above 6 GHz must be LoS. With careful system-level design, the Airvine WaveTunnel nodes show that NLoS links at 60 GHz are indeed possible. This development is timely as LANs are being pushed to do more and provide a foundation of connectivity for more devices and applications. Most future enterprise and residential applications, along with device use will be indoors, often with a broadband wireless connection. That connection could be Wi-Fi, private 5G or another technology and wireless multi-gigabit backhaul from the AP is now possible. ■

Phase Noise Analysis in OFDM Radar and Satellite Communication Systems

Russell J. Hoppenstein
Texas Instruments, Dallas, Texas

Although orthogonal frequency-division multiplexing (OFDM) modulation schemes offer improved spectral efficiency in aerospace and defense applications, phase noise degrades their performance integrity. This article will provide calculations to measure phase noise variance or jitter within user-specified frequency offset limits. These calculations will allow users to determine the impact on the system error vector magnitude (EVM) across several constellation schemes. The phase noise calculations also provide insight into the impact of phase noise shape over frequency offset and how the shape affects overall EVM performance for a variety of bandwidth and subcarrier configurations. The measured performance of the Texas Instruments LMX2820 RF synthesizer provides empirical data on performance metrics when used as a sample clock for an RF-sampling transceiver.

Aerospace and defense applications such as high capacity low earth orbit satellite constellations and high security, small-resolution radar systems are growing. New modulation schemes efficiently use the available frequency spectrum while still providing a secure and reliable channel. An OFDM modulation scheme for aerospace and defense applications provides a wide dynamic range and immunity from interferers or jammers.

An OFDM signal contains multiple subcarriers, each providing a subset of the entire signal transmission. Losing one or more of the subcarriers from channel interference or multipath fading does not destroy the entire message. For radar applications, the subcarriers in the OFDM signal offer multiple phase references and frequency diversity to ascertain range and radial velocity more accurately than a simple linear frequency-modulated signal. For communication applications, the subcarriers allow more users in the same frequency space without interfering with each other.

The overall signal bandwidth and number of subcarriers determine the frequency spacing between subcarriers, according to Equation 1:

$$F_{Spacing} = \frac{BW}{N_{subcarriers}} \quad (1)$$

Each subcarrier is a pulsed signal in the time domain. The signal transforms into a SINC function in the frequency domain. The zero

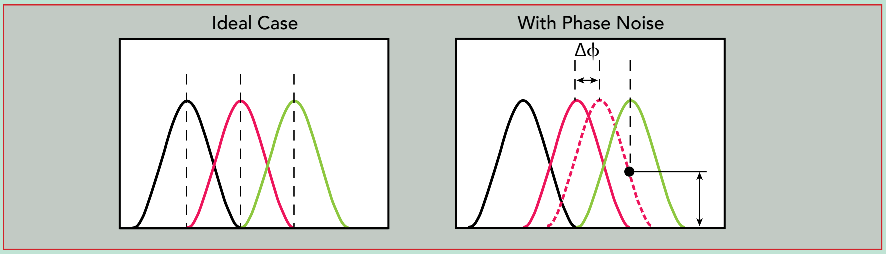


Fig. 1 OFDM subcarriers: ideal and with phase noise error.

crossings of the subcarriers line up with the peaks of adjacent carriers, indicating that all signals are orthogonal and do not interfere with one another. In a real channel, phase noise impairments shift the zero crossings slightly and cause the subcarriers to interfere with one another slightly; this is called intercarrier interference (ICI).

Figure 1 illustrates OFDM subcarriers. The ideal case diagram shows the ideal distribution of the subcarriers while the with phase noise diagram shows how a phase noise-shifted subcarrier begins to affect its neighbor. The statistical variance of phase noise within a specified frequency window determines the amount of degradation.

PHASE NOISE CALCULATIONS

Integrating the frequency response, L(f), between two frequency limits calculates the phase noise variance. When using empirical measurements, calculating the area under the curve is not so easy because the response is typically measured on a log-log scale. It is possible to use online tools to determine the results, but those inputs are usually limited to a handful of frequency points and do not provide the granularity necessary for more accurate integration across arbitrary limits. The fundamental equations provide flexibility to modify the limits of integration for different OFDM configurations.

Break any arbitrary phase noise curve into small line segments where the response and frequency are on a log scale according to Equation 2:

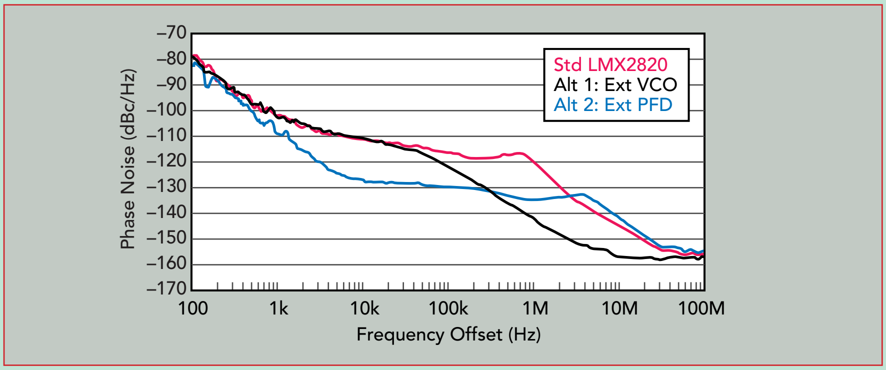
$$\log\left(L\left(f\right)\right) = m\log\left(f\right) + b \qquad (2)$$

Equation 3a gives the slope, m, while Equation 3b gives the constant, b, where k represents the index of the data in a discrete array:

$$m\left(k\right) = \frac{L_{k+1} - L_k}{10\left(\log\left(f_{k+1}\right) - \log\left(f_k\right)\right)} \qquad (3a)$$

$$b\left(k\right) = \frac{\log\left(f_{k+1}\right)L_k - \log\left(f_k\right) - L_{k+1}}{10\left(\log\left(f_{k+1}\right) - \log\left(f_k\right)\right)} \qquad (3b)$$

Equation 4 converts the phase noise response to the linear domain:



▲ **Fig. 2** **LMX2820 phase noise response with alternative configurations.**

$$L\left(f\left(k\right)\right) = 10^{\left(m\left(k\right)\log\left(f\left(k\right)\right)+b\left(k\right)\right)} = \qquad (4)$$

$$10^{\left(\log\left(f\left(k\right)^{m\left(k\right)}\right)\right)}10^{b\left(k\right)} =$$

$$f\left(k\right)^{m\left(k\right)}10^{b\left(k\right)}$$

Integrating over two frequency points yields the area under one curve segment, expressed by Equation 5:

$$A\left(k\right) = \int_{f_1}^{f_2} L\left(f\right)df = \qquad (5)$$

$$10^{b\left(k\right)}\int_{f_1}^{f_2} f^{m\left(k\right)} =$$

$$10^{b\left(k\right)}\frac{f_2^{\;m\left(k\right)+1} - f_1^{\;m\left(k\right)+1}}{m\left(k\right)+1}$$

There is the possibility of an indeterminant function with a divide by zero if the slope is 10 dB over a frequency decade corresponding to an m value of -1. You can remedy this indeterminant function by taking the limit of the overall function, or simply perturbing the denominator with a small error value for the calculation. Summing each individual subsection per Equation 6a across the frequency limits of interest will calculate the phase noise variance. The factor of two compensates for the single-sideband nature of the phase noise plot. The variables r_0 and r_1 represent the index of the array that corresponds to the lower and upper frequency limits of integration. Convert the variance to jitter using Equation 6b at a specific measured frequency.

$$\sigma^2\left(r_0, r_1\right) = 2 \times \sum_{k=r_0}^{r_1} A\left(k\right)\left[rad^2\right] \qquad (6a)$$

$$\tau_j = \frac{\sigma\left(r_0, r_1\right)}{2\pi f_0}\left[sec\right] \qquad (6b)$$

PHASE NOISE IMPACT ON EVM

The phase noise of each subcarrier interferes with all others within the signal. For any given subcarrier, its closest neighbors are most heavily affected; those farthest away are affected the least. The overall impact involves summing the error contributions from the variance of the phase noise of each subcarrier to all of its neighbors.

If the phase noise error is small, then the composite performance breaks down to an intended signal plus an error term, which includes an average phase shift that equally affects all subcarriers. The judicious use of a pilot signal to calibrate the average error will eliminate the error term. The remaining error term is the phase noise impact from each subcarrier that impairs all of the others. This error is the ICI that is responsible for the loss of orthogonality.

There are a few options to characterize the degradation of the system caused by noise. Common methods examine the bit error rate, signal-to-noise ratio (SNR) degradation or EVM degradation. Equation 7 shows the EVM degradation as a function of phase noise variance and energy per bit over noise (Eb/No). The parameter M designates the number of bits per symbol. Other factors related to quadrature mismatch, frequency error and linearity degradation do affect EVM performance; however, this analysis focuses on just the phase noise impact on the system.

$$\Delta EVM_{dB} = 10\log\left(1 + \sigma^2 \times M \times \frac{E_b}{N_0}\right) \quad (7)$$

HOW CLOCK OPTIONS AFFECT INTEGRATED PHASE NOISE

For an RF-sampling transceiver solution, the modulated signal is directly output to the RF band; the high frequency sample clock introduces phase noise error into the system. To test the effect of clock options, we used the Texas Instruments LMX2820 integrated RF synthesizer in standard mode using its internal voltage-controlled oscillator (VCO), along with two alternative configurations. The first alternative substitutes the internal VCO with a lower phase noise external dielectric resonator VCO. The second alternative substitutes the internal N-divider with an external mixer to generate a phase frequency detector tone. ***Figure 2*** shows the measured phase noise response of the three alternatives operating at 9 GHz.

BW, the OFDM signal bandwidth and number of carriers, N, determine the proper limits of phase noise integration according to Equations 8a and 8b:

$$f_1 = \frac{1}{2} \times \frac{BW}{N} \quad (8a)$$

$$f_2 = \frac{1}{2} \times BW \quad (8b)$$

Figure 3 shows the EVM degradation as a function of Eb/No over the variance of the standard LMX2820 phase noise across constellations ranging from quadrature phase shift keying to 4096-ary (M = 2 to 12) using a 20 MHz wide LTE-like OFDM signal with 1200 subcarriers. The limits of integration are 7.5 kHz and 10 MHz. The phase noise performance becomes more important as the SNR requirement increases and the constellation of points grows. Since the inherent performance is already quite good, the degradation only becomes apparent at high constellation rates with stringent SNR requirements.

The alternative LMX2820 configurations both have improved phase noise performance compared to the standard mode, but each has a different shape across frequency. It is possible to exploit these differences when operating with a real world OFDM signal. The combination of bandwidths and number of carriers is infinite. This analysis centers on cases with 1000 subcarriers and the bandwidth varying from 10 to 100 MHz, which corresponds to a subcarrier frequency spacing ranging from 10 to 100 kHz.

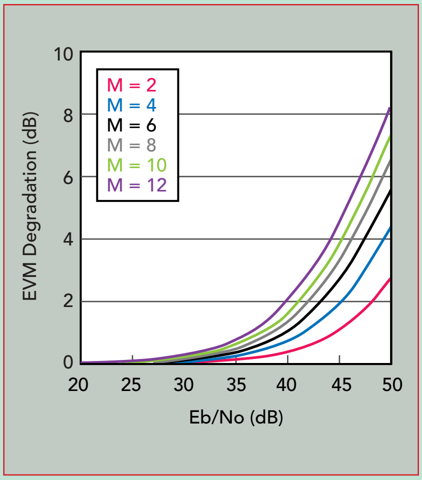


Fig. 3 **Error vector magnitude degradation vs. Eb/No over M.**

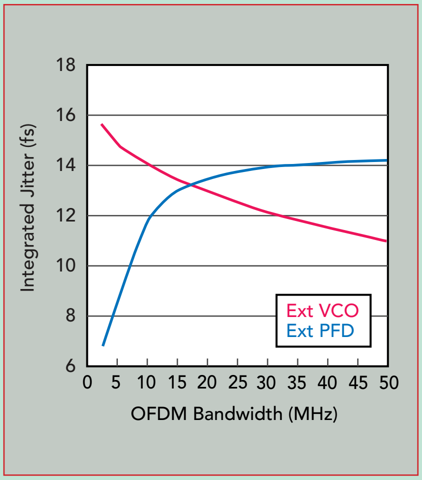


Fig. 4 **Integrated jitter vs. OFDM bandwidth using 1000 subcarriers at 9 GHz.**

Figure 4 shows the phase noise jitter calculated at 9 GHz across the OFDM bandwidth over the two alternative configurations. The first alternative provides better phase noise performance for signals with wider bandwidth and larger spacing, given the improved phase noise performance of the VCO at higher frequency offsets. The second alternative offers better performance for narrow bandwidth signals and tighter frequency spacing from the improved phase noise at close-in offsets. Applying the proper integration limits for a given OFDM configuration offers insight into the best clock topology to yield the least EVM degradation.

CONCLUSION

The phase noise analysis properly determines the impact of a specific clock source on the overall performance integrity of an arbitrary OFDM radar or communication system. The OFDM bandwidth and number of subcarriers set the proper frequency limits of integration of the clock phase noise response. The calculated phase noise variance determines the expected EVM degradation.

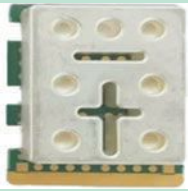
The clocking device options presented here have very low phase noise and introduce minimal error. Lower-performing clock sources have a more profound effect. Understanding specifically how the phase noise response translates to the phase noise variance for a given OFDM configuration enhances flexibility when determining the clock specifications. ■

Additional Resources

1. A. G. Armada and Miguel Calvo, "Phase Noise and Sub-Carrier Spacing Effects on the Performance of an OFDM Communication System," *IEEE Communications Letters 2*, No. 1, January 1998, pp. 11–13.
2. A. G. Armada, "Understanding the Effects of Phase Noise in Orthogonal Frequency Division Multiplexing (OFDM)," *IEEE Transactions on Broadcasting 47*, No. 2, June 2001, pp. 153–159.
3. G. Lellouch, "Waveform Design and Processing Techniques in OFDM Radar," *Ph.D. Dissertation*, University of Cape Town, 2015.
4. T. Pollet, M. Van Bladel and M. Moeneclaey, "BER Sensitivity of OFDM Systems to Carrier Frequency Offset and Wiener Phase Noise," *IEEE Transactions on Communications 43*, No. 2, February 1995, pp. 191–193.
5. V. Fialho, F. Azevedo, F. Fortes and M. Vieir, "OFDM Inter-Carrier Interference Due to Radio Frequency Synthesizer Phase Noise," *Conference on Electronics, Telecommunications and Computers (CETC)*, December 2013, pp. 608–616.
6. R. Hoppenstein, "LMX2820 RF Synthesizer Phase Noise Improvement with Alternative Topologies," *Texas Instruments*, 2022.

CERAMIC WAVEGUIDE FILTERS

VENDORVIEW



With rapid development of wireless communication technology, the requirement for filters with high Q value, low insertion loss, higher power handling capability along with higher out-of-band rejection in a smaller footprint has become the necessity. JQL has introduced a high performance ceramic waveguide filter to meet the market demand emerging from the 5G equipment manufacturers.

JQL Technologies
www.jqlelectronics.com

BANDPASS FILTER

Kyocera AVX's BP0805 bandpass filter is based on thin-film multilayer technology. The technology provides a miniature part with excellent high frequency performance and rugged construction for reliable automatic assembly. The ITF Filter is offered in a variety of frequency bands compatible with various types of high frequency wireless systems.

Kyocera AVX
www.kyocera-avx.com

RESISTOR DIVIDER

The MPDR-0070CSP2 is a DC to 70 GHz resistive divider that is packaged in an ultra-small form factor of 2.5 mm × 2.5 mm CSP. The divider (splitters) can be used as part of an analog or hybrid beamforming architecture; it allows a single RF chain to be split to support multiple beams or multiple antennas in a 5G AESA. Where loss and isolation are critical, the MPDW-0070CSP2 is a footprint-compatible Wilkinson divider.

Marki Microwave
www.markimicrowave.com

14 W HIGH POWER AMPLIFIER

Mi-Wave's 955A-29.3/40/41.5/KF/599HAC 14 W high power amplifier offers 29.3 GHz frequency with a typical small signal gain of 40 dB and Psat of 41.5 dBm. This unit is used for 5G applications. In addition, Mi-Wave offers various 955 Series 5G power amplifiers with various frequency ranges, bandwidths, gain and power outputs. All are manufactured in-house in America and fully customizable to meet your 5G and mmWave needs. Please consult with Mi-Wave for your specific RF needs.

Millimeter Wave Products
www.miwv.com

HIGH POWER AMPLIFIER

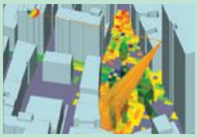
VENDORVIEW

Quantic PMI's Model PA-2G18G-43-5-40-SFF is a high power amplifier designed for a remarkably low noise figure of 3.5 dB and Psat of 40 dBm (10 W) over the 2 to 18 GHz frequency range with a high gain of 43 dB and ±1.5 dB gain flatness. Optional model PA-2G18G-43-5-40-SFF-HS is available with a heat sink and 120 Vac cooling fan. Other options available are optimized frequency bands, environmental screening and hermetic sealing.

Quantic PMI
www.quanticpmi.com

WIRELESS INSITE®

VENDORVIEW



Remcom's Wireless InSite® supports the simulation of RF interactions with engineered electromagnetic surfaces (EES), allowing modeling of passive metasurfaces designed to optimize wireless communication coverage by manipulating how signals propagate through a scene. EES artificially enhances wireless coverage at microwave and mmWave frequencies via printed conductive patterns on substrates such as plastic or glass. Wireless InSite's ray-tracing and EM path processing calculations enable the prediction of reflections, transmissions and diffractions that interact with EES placed within office buildings and urban areas.

Remcom
www.remcom.com

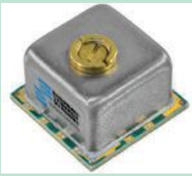
RADIOTHORIUM: 24–44 GHZ FREQUENCY CONVERTER

VENDORVIEW

The RadioThorium mmWave converter is a standalone platform for use in the 24 to 44 GHz range. The module is designed to interface directly with software-defined radios, such as those commonly implemented using Analog Devices' Mixed-Signal Front End (MxFE), or a similar software-defined radio, to obtain a complete mmWave system. Up to four modules can be combined in parallel to create complex MIMO applications.

Richardson RFPD
www.richardsonrfpd.com

DROS



Synergy Microwave introduces two new "GOLD Standard" series, surface-mount dielectric resonator oscillators (DROs) combining ultra-low phase noise with extended temperature range. These products are ideally suited for free running and phase-locked applications in 5G and 6G high data rate clocking converters, radar, military communications and test instrumentation. The GSDRO1200-8XT operates at 12 GHz and the GSDRO1500-8XT operates at 15 GHz, with typical phase noise of -123 dBc/Hz and -114 dBc/Hz, respectively, at 10 KHz offset. The operating temperature range is from -40°C to +85°C.

Synergy Microwave
www.synergymwave.com

E-Band Amplifier Supports 256-QAM With 6 W Saturated Output Power

Filtronic
Sedgefield, U.K.

To meet the needs of rapidly growing data traffic requirements from consumers, wireless transmission and backhaul systems are aggregating more channels and going higher in frequency in search of more available spectrum. One of the more attractive bands is the mmWave frequency range of E-Band. This band encompasses 71 to 76 GHz and 81 to 86 GHz and current channel bandwidths are typically 2 GHz, but can go up to 5 GHz. In addition, E-Band is "lightly licensed," meaning that it offers operators a higher degree of service assurance than an unlicensed band, while not incurring the costs of a fully licensed frequency band.

To satisfy these customer needs, Filtronic is expanding its E-Band mmWave product portfolio with the Taurus 16 (AA033) E-Band amplifier shown in ***Figure 1***. The performance of this amplifier module is shown in ***Table 1***. The Taurus 16 is capable of supporting 256-QAM system modulation schemes and it provides 6 W (typical) of saturated output power to increase the transmit range of the signal.

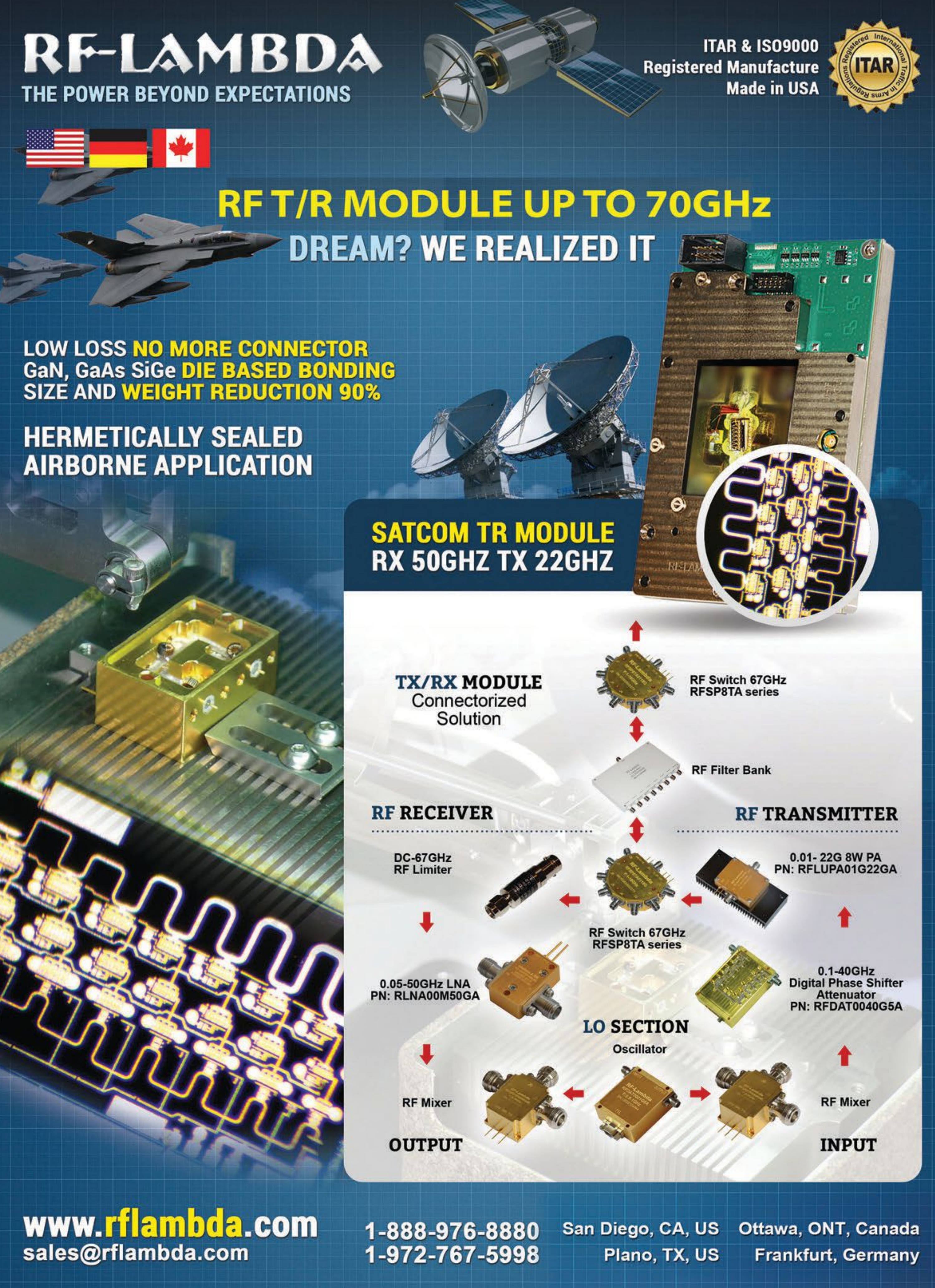
The Taurus 16 amplifier builds upon Filtronics' Cerus line of E-Band amplifiers. It does this by combining two Cerus 8 (AA022) power amplifier modules operating at 81 to 86 GHz as shown in ***Figure 2***. The Cerus line of mmWave power amplifiers is available in single to N-way configurations. Each of these configurations is available in 71 to 76 GHz and 81 to 86 GHz operating frequency versions. Each of the N-way configurations contains N Filtronic GaAs HEMT PA MMICs. These MMICs are matched and power combined in waveguide to deliver maximum power. The standard building blocks offered in the Cerus product portfolio are shown

▲ Fig. 1 **Taurus 16 (AA033) E-Band power amplifier.**

TABLE 1

TAURUS 16 PERFORMANCE CHARACTERISTICS

Parameter	Minimum	Typical	Maximum	Units
Tx Frequency	81		86	GHz
Bandwidth			5.0	GHz
Small Signal Gain		21		dB
P SAT		+38		dBm
OIP3 at +33 dBm		42		dBm
Absolute Maximum RF Input Power			+26	dBm
Supply Voltage 1	34	48	72	V
Supply Current 1		2	2.2	A
Size		111 x 81 x 40		mm
Weight		600		g
Interface	Waveguide input and output: WR12 DC connectors TFM-115-01-L-D-WT (without CTRL board)			


RF-LAMBDA
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RF RECEIVER
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PN: RFLUPA01G22GA
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Plano, TX, US
Ottawa, ONT, Canada
Frankfurt, Germany

▲ Fig. 2 Cerus 8 81 to 86 GHz power amplifier.

in *Table 2*.

The entire line of Taurus and Cerus power amplifiers contain an integrated temperature sensor that provides users with accurate amplifier temperature data and optional control circuitry that facilitates functions including mute control and alarms. The Taurus 16 and all the standard Cerus building blocks support 256-QAM modulation. The Cerus line of power amplifiers achieves 24 dB (typical) small signal gain, while the Taurus 16 amplifier checks in with 21 dB of small signal gain, because of the additional combiner loss.

Filtronic has a long heritage of supplying mmWave modules, having deployed more than 80,000 mmWave transceivers. The Cerus and Taurus power amplifiers target commercial E-Band point-to-point, high altitude platform station and satcom applications. Their size, weight and power tradeoffs make these amplifiers attractive for airborne and non-terrestrial defense applications.

TABLE 2

CERUS LINE OF POWER AMPLIFIER PRODUCTS

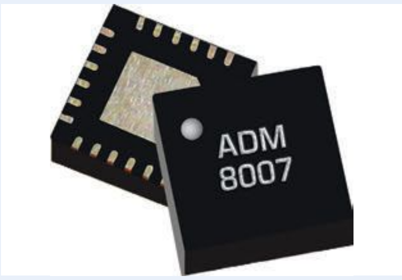
Part Number	PSat (dBm typ.)	Freq. Range (GHz)	Designation
AA025	+28	71 to 76	Cerus 1
AA026	+27	81 to 86	Cerus 1
AA023	+33	71 to 76	Cerus 4
AA024	+32	81 to 86	Cerus 4
AA021	+35	71 to 76	Cerus 8
AA022	+35	81 to 86	Cerus 8

Filtronic provides customized, high performance technologies to its core markets of telecommunications infrastructure, critical communications, space and aerospace and defense. Filtronic designs and manufactures a range of solutions from 300 MHz to 175 GHz in adjacent markets such as trackside to train, high frequency trading, test and measurement and private networks.

Filtronic
Sedgefield, U.K.
filtronic.com

Taurus product page:
filtronic.com/products/taurus

Cerus product page:
filtronic.com/products/cerus



LO Driver Amplifier Operates 2 to 40 GHz

As systems become more complex with multiple channels interfacing with digital systems in an RF system on chip (SoC), it is important to manage the design complexity while meeting aggressive design schedules. This drives requirements for small, modular RF front-end chains that can be designed once and copied across multiple channels, all while providing optimal performance and signal conditions for each channel. This is important given the relatively high cost of these RF SoCs. Optimizing the RF chains' performance will reduce the number of relatively expensive bits dedicated to error correction.

The ADM-8007 from Marki Microwave addresses this need in the RF signal chain. It is a universal LO driver that supports a frequency of operation from 2 to 40 GHz. In current systems, it is difficult to get more than 0 dBm from a passive multiplier, phase-lock loop or synthesizer. This problem is exacerbated by multiple channels, as the splitter function results in additional losses. Typically, mixers operate from 15 to 20 dBm of drive into their LO port for optimal performance and the ADM-8007 can easily support this thanks to its two-stage design. The ADM-8007 provides 23 dB of gain and a Psat of 23 dB. This means it can drive all types of mixers with different diode designs, depending on the P1dB, IP3 and spur suppression requirements of the application, with an input power of 0 to +5 dBm.

To increase its ease of use, the amplifier operates from a single 5 V supply, has internal biasing and requires no sequencing to operate. Ideal for mobile test and measurement equipment, radar, satcom and 5G transceivers, it is available as a standard 4 x 4 QFN package or in a connectorized form for laboratory testing purposes.

Marki Microwave
Morgan Hill, Calif
markimicrowave.com

Nonmagnetic Field Replaceable SMA Connectors

Signal Microwave is introducing a new line of nonmagnetic field replaceable SMA and 2.92 mm connectors that are targeting the quantum computing market. The SMA versions have a bandwidth of 27 GHz and the 2.92 mm versions have a bandwidth of 40 GHz. The first released connectors are SMA male and female field replaceable connectors that have a rear socket for 0.012 in. (0.3048 mm) launch pins or glass-to-metal 50 Ohm feedthroughs.

The connectors are made of phosphor bronze, beryllium copper, Teflon (PTFE) and Ultem. The metal components of these connectors are plated with 40 microns of gold only. Usually, a nickel barrier between the gold plating and the base metal is used for the long-term reliability of microwave connectors, especially those used in satellite applications. Nickel is magnetic, so it is not used in applications that these connectors are targeting. When the gold is plated directly over these metals without the nickel barrier, the gold and the base metals will interact and may cause corrosion over time. To manage this, the connectors can be replaced with new ones.

The 2.92 mm version may be more desirable than the SMA version, even at low frequencies, because 2.92 mm connectors do not use Teflon (PTFE) as the dielectric. The 2.92 mm connector is an air line connector developed to test SMA connectors. The air dielectric has better temperature stability than Teflon (PTFE) and it is not affected by temperature and other environmental changes.

Scheduled additions to the nonmagnetic connector product line are field replaceable SMA and 2.92 mm for 0.020 in. (0.508 mm) launch pins and glass-to-metal 50 Ohm feedthroughs, as well as nonmagnetic versions of Signal Microwave's board-mounted connectors.

Signal Microwave LLC
Tempe, Ariz.
signalmicrowave.com

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One-Stop 5G FR2 Test Solution

In the ever-evolving telecommunications and technology landscape, Aethertek is dedicated to delivering innovative solutions to address the most challenging production testing needs. The company is offering a one-stop service bundled in its FR2 test solution package. This all-inclusive approach saves users both time and expenses as they gain access to a suite of essential components necessary for successful mmWave testing. The package includes the Pluto shielding chamber, test software, horn antennas and up-down-converters. With this bundle, Aethertek hopes to increase the efficiency and precision of mmWave test solutions. Aethertek hopes that this will streamline the testing workflow and revolutionize the way testing procedures are carried out, empowering users to focus on their core objectives without needing to source and integrate multiple components from various vendors.

At the heart of Aethertek's FR2 automatic test solution is the Pluto shielding chamber, which contains nine horn antennas, a turn table and anechoic material. This chamber allows users to conduct stable and precise far-field tests on mmWave signals. The chamber facilitates precise beam steering verification, enabling researchers and engineers to fine-tune their mmWave systems.

The chamber houses up- and down-converters operating in the 24 to 30 GHz (UDCX-2430) or 37 to 40 GHz (UDCX-3740) frequency bands. These converters enable users to use existing FR1 instruments in the FR2 band. The converters also have built-in GPS functionality, allowing users to remotely calibrate and align the frequency if they are using multiple UDCX devices.

With its one-stop automatic test system, Aethertek hopes to empower users to execute tests seamlessly and efficiently, reducing manual intervention and accelerating the overall testing process. To explore more about FR2 testing solutions, please visit the Aethertek website.

Aethertek
Taipei City, Taiwan
www.aether-tek.com

Leading millimeter-wave | every year since 1999

As Anokiwave enters its 25th year of business, they are taking the time to reflect on their founding principles that made the company successful and the amazing pace of technology advancements, both in the industry and at Anokiwave.

Anokiwave
www.anokiwave.com/media/blog/articles/anokiwave_25years.html

Keysight EDA 2024

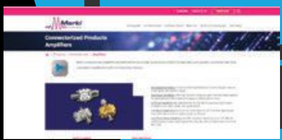
Keysight Technologies, Inc. introduces Keysight EDA 2024, a tightly integrated suite of electronic design automation (EDA) software tools that ensures first pass success. This new integrated EDA software facilitates a "shift left" approach to increase productivity for engineers developing high speed, high frequency products in multiple applications.

Keysight Technologies, Inc.
www.keysight.com

Marki Microwave Launches New Website

Marki Microwave's brand-new website delivers an enhanced user experience with its robust knowledge base, optimized search functionality and expanded library of resources and technical tools.

Marki Microwave
www.markimicrowave.com



A Primer on Quadrature Amplitude Modulation

Learn how data in the digital domain translates into analog waveforms through QAM modulation in this Mini-Circuits technical article.

Mini-Circuits
hubs.ly/Q023Cqxx0

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Pasternack's RF calculators and conversions provide engineers with valuable and easy-to-use tools ranging from complex mathematical formulas to simple conversions.

Pasternack
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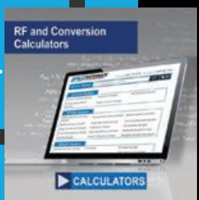

Samtec Opens New Manufacturing Facility

Samtec Inc. opened a new manufacturing facility in Royersford, Pa. The facility will specialize in the production of coaxial cables and RF connectors, servicing industries such as aerospace/defense, medical device, datacom, automotive, computer semiconductor, instrumentation and consumer electronics.

Samtec
www.samtec.com

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DEVICES/ COMPONENTS/MODULES

RF Filter

American Microwave Corp. offers model number SM-8T-818 OPTION A8429468-1, an 8.2 to 10.34 GHz bandpass RF filter. The RF filter has a frequency range of 8.2 to 10.34 GHz with an insertion loss of 2.0 dB maximum. This module has a VSWR of 1.5:1 maximum, minimum power rating of 200 mW CW, RF input connector type SMA female, RF output connector type SMA male and an operating temperature range of -54°C to +70°C. The size is 4.0 in. × 1.5 in. × 0.75 in.

American Microwave Corporation
www.americanmic.com

Ultra-Compact Module
VENDORVIEW

Exodus Advanced Communications introduces their ultra-compact 1.0 to 6.0 GHz lightweight module. This module produces 25 W minimum, 30 W nominal power. The minimum power gain is 44 dB with -20 dBc harmonics. Included are current and temperature sensing and built-in protection circuits for optimum reliability and ruggedness for all applications. The nominal weight is 450 g and dimensions of 75 mm × 105 mm x 30 mm.

Exodus Advanced Communications
www.exoduscomm.com

Waveguide Switch

Introducing Flann's new design of a waveguide switch. The new 337 series is a range of compact, low mass, low inertia, high-power switches with low insertion loss, high isolation and minimal PIM. Easily adaptable to many applications including test and measurement, aerospace and spaceflight. The H-plane structure allows easy integration with other components, giving the potential to create an entire switching network to include multiple switches, combiners, filters, etc. Models are available up to 330 GHz.

Flann Microwave
www.flann.com

High-Power Filter
VENDORVIEW

Mini-Circuits' model ZLSS252-100W-S+ is a coaxial lowpass filter with passband of DC to 2.5 GHz and stopband extending to 9 GHz. Based on suspended-substrate-stripline technology, the filter handles as much as 100 W input power. Ideal for ISM band applications, it has typical passband insertion loss of 0.2 dB and typical return loss of 24 dB. Typical rejection is 35 dB from 3.9 to 4.7 GHz, 55 dB from 4.7 to 6.0 GHz and 90 dB from 6.0 to 9.0 GHz.

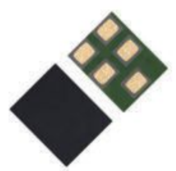
Mini-Circuits
www.minicircuits.com

Double-Ridge Couplers
VENDORVIEW

Pasternack has announced the launch of double-ridge waveguide couplers showcasing integrated coaxial connectors for seamless transitions in various applications. The new double-ridge waveguide couplers boast superior VSWR performance, offering ratios as low as 1.25:1. This is an unparalleled feature that ensures efficient power transmission and reduced reflection, aiding in the maintenance of signal integrity. Additionally, the broadwall and loop coupler designs in this line set new standards for broadband performance and efficiency in the industry.

Pasternack
www.pasternack.com

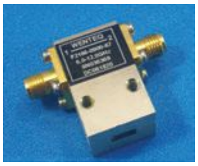
RSF Series of SAW Filters



Raltron announces specific SAW filters for GNSS navigation systems that optimize performance and provide a viable second source alternative for other mainstream suppliers. The RSF Series of SAW filters is specifically designed for GPS, GLONASS, Galileo, Compass (BeiDou) and soon NavIC systems. Developed to assist system engineers optimize performance in GNSS applications, the RSF SAW filters minimize insertion losses and ripple and provide superior signal attenuation outside the useful bandwidths with competitive temperature behavior. The RSF SAW filters can be used to efficiently separate or combine signals of different frequencies, enabling the receiver to operate with various satellite signals simultaneously.

Raltron
www.raltron.com

Octave Band 6.0 to 12.0 Coaxial Isolator



Model F2166-0900-67 is an octave band SMA connectorized isolator covering the 6.0 to 12.0 GHz frequency range. It features 0.6 dB maximum insertion loss, 18 dB minimum reverse isolation, and 1.4:1 maximum VSWR. The forward power handling is rated to 10 W.

Wenteq Microwave
www.wenteq.com

MICRO-ADS

NewProducts

CABLES & CONNECTORS

VITA 67 Cable Assemblies

VENDORVIEW

Fairview Microwave announced the rollout of VITA 67 mini-SMP (SMPM) cable assemblies. They are designed to address the critical needs of industries such as aerospace and defense, ground communication systems, radar systems and avionics. One of the standout features of the VITA 67 cable assemblies is their impressive DC to 65 GHz frequency range, setting a new industry standard for signal transmission.

Fairview Microwave
www.fairviewmicrowave.com

Test Cables

VENDORVIEW

The T26 series SMA-RA test cables utilize SMA internally swept right-angled connectors with T26 ultra-flexible and durable cable. These cables have excellent amplitude and phase stability, as well as good electrical performance in VSWR and insertion loss in a frequency range from DC to 26.5 GHz, even after 150K strict bending cycles. They are ideal for volume production, lab, 5G over-the-air and phase array antenna testing.

MIcable Electronic Technology Group
www.micable.cn

United States Postal Service

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Publisher (Name and complete mailing address)
Name: Carl S. Sheffres
Addr 1: Horizon House Publications, Inc.
Addr 2: 685 Canton St.
City, State ZIP: Norwood, MA 02062-2610

Editor (Name and complete mailing address)
Name: Patrick Hindle
Addr 1: Horizon House Publications, Inc.
Addr 2: 685 Canton St.
City, State ZIP: Norwood, MA 02062-2610

Managing Editor (Name and complete mailing address)
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PS Form 3526, July 2014

NewProducts

SOURCES

AXTAL Ultra-Low Noise OCXOs

Q-Tech Corporation announced the availability of the AXIOM line of ultra-low noise (ULN) oven-controlled crystal oscillators (OCXOs) designed and manufactured by the company's German affiliate, AXTAL. Ultra-low close-in phase noise and noise floor enable higher resolution for radar systems, better quality and more transmissible information in communications systems and higher accuracy and lower measurement limits in RF measurement systems. Customized versions are available, offering specific frequencies and modules with multiple outputs. The AXIOM145ULN is well suited for communications systems and RF measurement systems that typically require 10 MHz OCXOs.

Q-Tech Corporation
www.q-tech.com

TEST & MEASUREMENT

High-Resolution Oscilloscopes

RIGOL Technologies has added to its line-up of high-resolution oscilloscopes with the introduction of the DHO800/900 series. These new oscilloscopes have a compact, portable design that is flexible to use for both on-site and desktop testing. DHO800/900 oscilloscopes feature true 12-bit resolution with low noise for excellent signal fidelity and analysis. DHO800/DHO900 oscilloscopes are available in 125 to 250 MHz bandwidths, four channels, 1.25 GSa/sec sampling, 1,000,000 wfms/s waveform capture rate and 50 MPts of memory standard.

Rigol Technologies
www.rigolna.com

Reviewed by: Reena Dahl

Bookend

Wideband Microwave Materials Characterization

By John W. Schultz

This book offers a unique and comprehensive overview of the different methods for characterizing microwave materials. It starts off with a much-needed introduction to the physical mechanisms behind material properties, including dispersion and anisotropy. The theory and practice of traditional and novel wideband, non-resonant electromagnetic characterization methods of materials is presented in a thorough manner along with the necessary equations for implementing these methods. The author uses his background in academia and industry to provide a great resource for anyone looking to characterize microwave materials both in a laboratory or manufacturing environment.

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Tel: (831) 426-4143
Cell: (831) 713-9085
blandy@mwjournal.com

International Sales
Carl Sheffres
Group Director
Tel:+1(781) 619-1949
Cell: +1(781) 363-0554
csheffres@horizonhouse.com

Germany, Austria, and Switzerland (German-speaking)
WMS.Werbe- und Media Service
Brigitte Beranek
Tel: +49 7125 407 31 18
bberanek@horizonhouse.com

France
Gaston Traboulsi
Tel: +44 207 596 8742
gtraboulsi@horizonhouse.com

Korea
Jaeho Chinn
JES MEDIA, INC.
Tel: +82 2 481-3411
corres1@jesmedia.com

China
Shanghai
Linda Li
ACT International
Tel: +86 136 7154 0807
lindal@actintl.com.hk

Hatter Yao
ACT International
Tel: +86 139 1771 3422
hattery@actintl.com.hk

Wuhan
Phoebe Yin
ACT International
Tel: +86 134 7707 0600
phoebey@actintl.com.hk

Shenzhen
Floyd Chun
ACT International
Tel: +86 137 2429 8335
floydc@actintl.com.hk

Beijing
Cecily Bian
ACT International
Tel: +86 135 5262 1310
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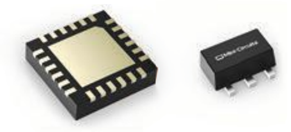
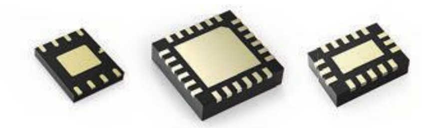


Supporting DOCSIS® 3.1 and 4.0 requirements

Dual Matched



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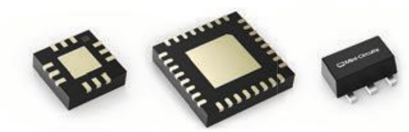
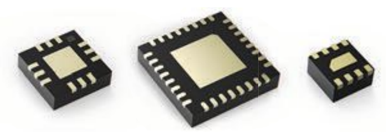


High dynamic range over wide bandwidths up to 45 GHz

Low Noise



NF as low as 0.38 dB for sensitive receiver applications

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RF Transistors

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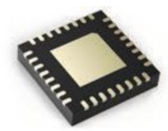
Variable Gain



Up to 31.5 dB digital gain control

Wideband Gain Blocks

Flat gain for broadband and multi-band use

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FABS and LABS

DigiKey: We Get Technical

DigiKey was founded by Dr. Ron Stordahl in 1972, but the seed for the company was planted while Ron was in college. Ron was an avid ham radio enthusiast, assembling and selling digital electronic keyer kits to other ham radio operators. After obtaining his Ph.D. in Electrical Engineering, Dr. Stordahl returned to his hometown of Thief River Falls, Minn. Dr. Stordahl would go on to complete pioneering work on digital keyers for Morse code and his love of putting together these digital keyer kits gave rise to a small mail-order company with the name of DigiKey Electronics.

DigiKey still maintains its headquarters in Thief River Falls, but from these humble beginnings, they have grown to become one of the largest and most well-known distributors of electronic components and related products in the world. Serving engineers, hobbyists, manufacturers and designers with an array of electronic components for their projects and production needs, the company has amassed some impressive metrics. They report over $5 billion in annual sales and have nearly 15 million available products. More than 5000 employees generate this revenue from more than three million square feet of facilities. They process more than 6.5 million orders, answering more than 3.2 million calls every year.

The sheer volume means that DigiKey must pay close attention to logistics. As part of their company culture, they pride themselves on their commitment to providing excellent customer service. They offer technical support, an efficient order fulfillment process and prompt shipping, with 99.9 percent of orders shipped on the same day. Customers can access resources like tutorials, videos and articles on their website to enhance their understanding of components and applications.

Their extensive range of components includes semiconductors, passive components, interconnects, electromechanical components, tools, test equipment and much more for a wide variety of applications. Engineers and designers can easily browse, search and order components and get detailed specifications, datasheets and pricing information for each product. Their website allows you to access products from more than 2400 suppliers in the "DigiKey Marketplace." This platform allows customers to access a wider range of products from fully authorized trusted partners, expanding the product selection beyond DigiKey's traditional offerings.

The core products are stored, packed and shipped from the product distribution center at the headquarters, but DigiKey maintains a global footprint. They have support centers in Europe, the Middle East and Asia and they ship to more than 170 countries. They provide multiple language options and customer support in various languages, making it easier for a diverse range of customers to navigate and utilize their services.

Earlier this year, after 50 years of service to the engineering and electrical component community, DigiKey Electronics rebranded and changed its logo. Going forward as DigiKey, the company hopes to convey a sense of design flexibility across digital platforms while maintaining an engineered feel. The update was designed to emphasize progress while underscoring the connection with suppliers and customers to reflect DigiKey's digital-first, forward-looking perspective. The company's commitment to innovation, exceptional customer service and a vast inventory has solidified its position as a trusted partner for anyone seeking electronic components and related products. DigiKey has established itself as a go-to distributor for electronic components, with an expansive product range, user-friendly online platform, exceptional customer service and dedication to meeting the diverse needs of the electronics industry and yes, they get technical.

www.digikey.com

WERLATONE

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





Even Isolated & Non-Isolated Combiners/Dividers

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

Uneven Splitters (Taps) & Directional Couplers

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

Werlatone, Inc. 17 Jon Barrett Road Patterson, NY 12563 845-278-2220 sales@werlatone.com www.werlatone.com