Microwave Journal E-BOOK

5G Semiconductor Solutions - Infrastructure and Fixed Wireless Access

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5G Semiconductor Evolution

By 2023, there are 1 billion forecast subscriptions for 5G technology according to Ericsson, CCS Insight. Recent forecasts have been increasing due to the early standards release by the 3GPP and other positive market trends with announcements by leading U.S. operators AT&T, Sprint and T-Mobile that promise mobile 5G services later this year or early next year. In addition, Verizon will be launching fixed access 5G services this year.

According to a recent 5G Americas release, Cisco forecast 25 million 5G-capable devices and connections by 2021; analyst firm Ovum currently predicts 84 million by 2021; CCS Insight increased their predictions by 50 percent (over their October 2017 forecast) to 280 million 5G connections in 2021, with 60 million 5G connections expected in 2020. Ovum expects 11 million 5G connections in 2020. By 2023, both CCS and Ericsson forecast 1 billion 5G connections worldwide.

With this much growth and activity for 5G networks, we have put together this eBook covering some of the technical challenges and solutions for 5G infrastructure and fixed wireless access design along with overviews of the market. We start with an overview of the latest standards and trends related to radio components and then cover some of the semiconductor design tradeoffs and architectures for 5G fixed wireless access mmWave arrays. The next article discusses the advantages for semiconductor and measurement companies to work together to overcome 5G challenges and how to prepare for them. Then we provide a detailed look at how GaN technology can solve many of the 5G challenges for infrastructure and fixed wireless access systems that require higher efficiency, broad bandwidths, higher linearity and small size. The last article covers how mmWave links will perform and how to properly characterize and measure them.

We hope this eBook on 5G Semiconductor Solutions covering infrastructure and fixed wireless access helps engineers understand the tradeoffs and measurements needed to design better 5G solutions. A better understanding radio link characteristics and semiconductor capabilities should result in better designs and reduce time to market.

Pat Hindle, Microwave Journal Editor

5G Update: Standards Emerge, Accelerating 5G Deployment

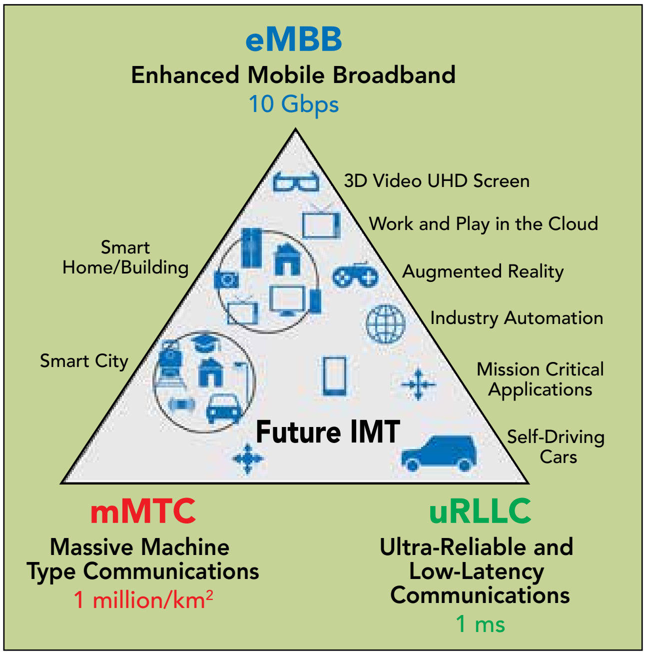
Pasternack
Irvine, Calif.

5G technologies and standards have recently emerged from buzz and corporate blustering to real and rapidly paced definitions and development. When 5G visions were first announced, many considered the performance targets in these predictions to be pipe dreams. However, corporate initiatives to develop 5G technology with real 5G radio and networking platforms and international collaboration on 5G standards has proceeded at a pace few could predict. If this progress means to meet performance targets for 5G, manufacturers must accelerate their timetables and their supply chains to meet the demands of new and competitive 5G hardware and systems.

The race to capture the global business for upcoming 5G solutions—consumer, commercial and government—is starting to resemble the historic space race between Russia and the U.S. The major difference is this goes far beyond a race between two sovereign superpowers, with many international companies and countries in the competition. True 5G solutions require many layers of national and international regulation, as well. Major international telecommunications companies and manufacturers are all competing to demonstrate 5G capabilities and features, while simultaneously paving the way for viable mmWave radio access unit and radio access network (RAN) technology. With spectrum, radio and network standards solidifying ahead of schedule, the pioneering aspects of 5G—mainly the expansion into many more verticals or slices than mobile broadband—are gaining focus and investment.

EARLY 5G FEATURES AND USE CASES

Though the expected features and use cases for 5G are diverse and extensive, the start of the 5G rollout will likely address only a few of the featured use cases: enhanced mobile broadband (eMBB), ultra-reliable low latency communications (URLLC) and massive Internet of Things (mIoT) or massive machine-type communications (mMTC), as illustrated in ***Figure 1***. These provide increased throughput and performance for user equipment (UE), while offering a mobile network designed to support the massive number of new IoT, or Industry 4.0, applications. Interestingly, these early 5G features will likely be implemented at sub-6 GHz frequencies (current cellular bands, ≤ 1, 3.5 and 3.7 to 4.2 GHz and various combinations based on country) before 2020, offering opportunities in the vehicle and broadcast market, infrastructure and, primarily, mobile.



▲ **Fig. 1 The primary use cases for 5G. Source: Werner Mohr, The 5G Infrastructure Association.**

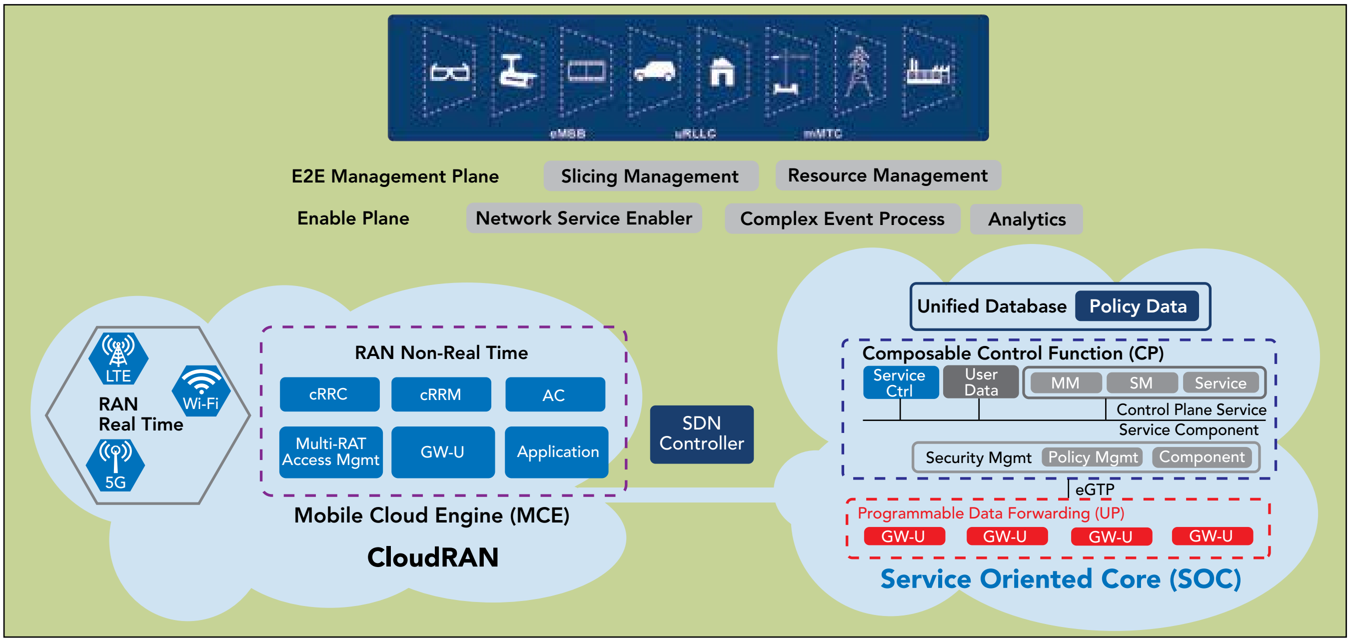
EARLY 5G FACTORS AND INFLUENCERS

The main 5G standards bodies and organizations are consistent with past generations of mobile wireless, i.e., 3GPP, GSMA, ITU and each country's spectrum regulatory agency. Importantly, the heads of industry-leading companies are driving these organizations' focus and standards developments. Other industry consortiums and alliances, such as the Next Generation Mobile Networks (NGMN) alliance and TM Forum, are also contributing and advising in the development of 5G standards and specifications.

With the forecast increase in competition for 5G services, and the need to provide lower cost data services now, there is a general impetus to hurry along the advent of 5G. With so many companies and countries taking the initiative with announcements of 5G deployments, these industry and international consortiums have been moving quickly with specifications, standards and spectrum allocation.

Referencing the Verizon 5G Technical Forum (V5GTF), companies feeling the pressure to commercialize more rapidly are even creating new forums to accelerate the development of 5G technologies. Another example of carrier-led efforts to advance 5G is the merger of the xRAN forum and C-RAN Alliance, with the focus of evolving RAN technology from hardware-defined to virtualized and software-driven. Industry forums in market verticals other than mobile are also forming to accelerate adoption and standardization. For example, the 5G Automotive Association encourages collaboration among telecommunication and automotive companies.

Some explanation for this rapid pace could be the concern that collaboration-based organizations have for early adopting companies and countries developing their own regional standards to meet the demand ahead of the competition. For example, some companies, namely AT&T and Verizon, have already claimed they will provide 5G services in select cities in 2018. These 5G services will not necessarily meet all 3GPP 5G specifications, but will likely provide superior throughput to current 4G services and be readily upgraded, most likely through software, to the final 5G specifications. Without 5G capable handsets, either sub-6 GHz or mmWave, it is likely that these companies will offer either hotspot or fixed wireless access (FWA) services instead.[1-2] While the UE may not yet be available, 5G base station and terminal equipment is; Huawei recently announced 5G end-to-end solutions.[3] These offer sub-3 GHz, C-Band and mmWave operation with massive MIMO technology and are reportedly fully 3GPP 5G compliant. In a demonstration with Telus in Canada,



▲ **Fig. 2 A new virtualized cloud radio access network architecture will enable operators to serve the multiple use cases envisioned for 5G. Source: Huawei.**

a 5G wireless to the home trial using Huawei equipment reportedly demonstrated 2 Gbps, single-user download speeds.[4]

With a lack of a standardized infrastructure in market verticals other than mobile wireless, however, the standardization and specification for vehicle and industrial applications may take far longer than anticipated. This could explain, somewhat, the additional focus of telecommunication service providers on 5G applications in the broadcast and home internet services markets. FWA using sub-6 GHz and mmWave 5G capabilities could provide gigabit internet speeds to homes without expensive fiber installation and even undercut the cable television and home phone service giants.

5G STANDARDS AND SPECIFICATIONS

The GSMA recently released a report, "Mobile Economy," which claims that two-thirds of the world's mobile connections will be running on 4G and 5G services by 2025, with 4G accounting for over half of the global connections and 5G accounting for approximately 14 percent.[5] Not surprisingly, the demand has caused standards and specification organizations to step up their timetables, and market pressures are solidifying 5G radio specifications earlier than expected.[6] However, the "5G precursor" specifications being released now are not the finalized 5G specifications and standards, rather evolutionary steps from 4G specifications that will be compatible with the future 5G specifications.

The latest 3GPP specification defines the non-standalone 5G new radio (NSA 5G NR),[7] which requires an LTE anchor and 5G NR cell. The LTE anchor provides the control plane and control plane communications, while the 5G NR will provide enhanced data capacity. The NSA 5G NR specification currently only covers frequency range 1 (FR1), between 450 and 6000 MHz. These bands are designated in Table 5.2-1 in the 3GPP specification document 38101-1,[8] and are subject to modification when Release 15 is issued in June 2018. The maximum bandwidth for FR1 NR bands is 100 MHz, of which only n41, n50, n77, n78 and n79 are capable. These bands are also designated as time-division duplex (TDD) bands, for which carrier aggregation (CA) should enable greater than 100 MHz functional bandwidth.

Also in this release are the descriptions of new RAN architecture options. The new architecture is built around a network virtualization strategy, where the control and user planes are separated. Referred to as network function virtualization (NFV) and software-defined networking (SDN), these features are designed to enable future network flexibility and a variety of applications. This methodology is meant to continue providing enhanced mobile telecommunications, while adding diversity of services—hence, independent network slicing.[9]

Future 5G "Cloud RAN" capabilities (see ***Figure 2***) are meant to support multiple RANs, standards and operators using the same physical infrastructure or core network. Such an adaptable RAN would allow for various applications and industries to rely on the same hardware and network assets, physical infrastructure to pave the way for future opportunities. The system to provide capabilities for service-level agreements for a collection of devices is dubbed "network slicing" by 3GPP.

The future 5G standard, what will be concluded in the complete 3GPP Release 15, or 5G Phase 1, will be finalized in June 2018 (see ***Figure 3***). Before the end of 2019, 3GPP will provide updates to Release 15, and a clearer vision of Release 16, or 5G Phase 2, will become available in December 2019. Currently, there is little information on how 5G rollouts will occur and what industries, outside of mobile wireless, will begin adopting the capabilities of 5G. Though trials have been performed and early 5G network and radio access hardware is available, UEs have yet to be released, and operators have virtually no experience and limited understanding or expectations of 5G. Furthermore, mmWave hardware is not yet widely available and, without this valu-

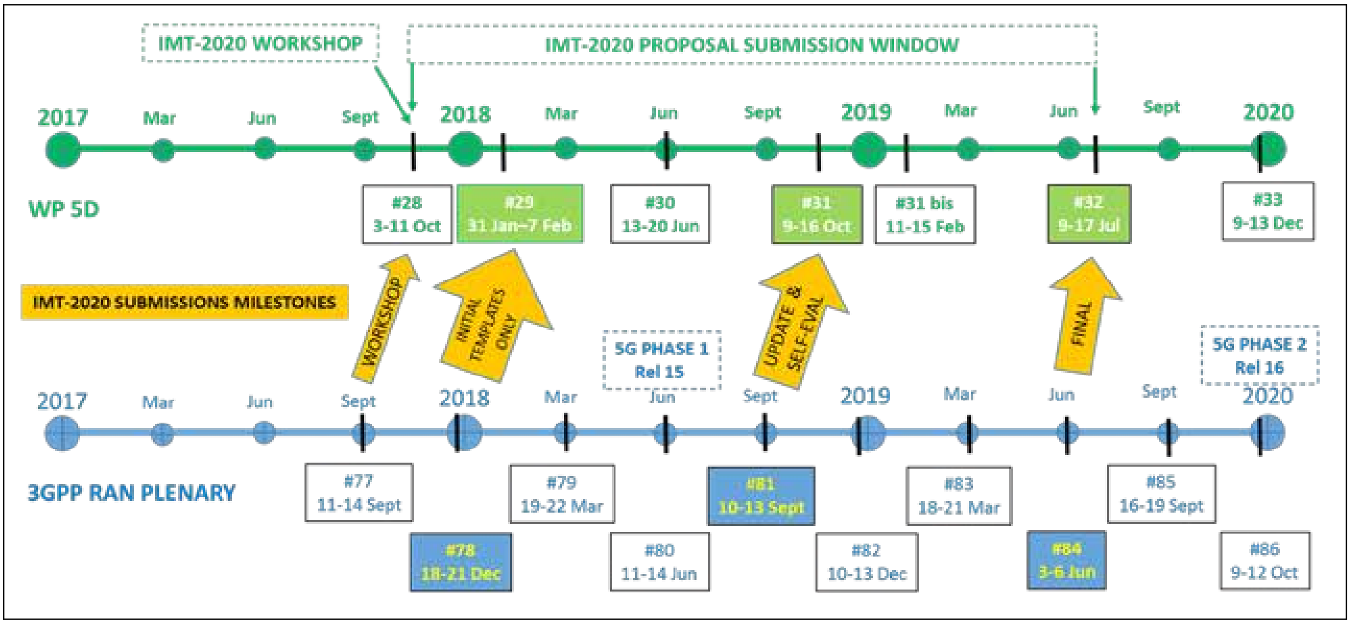


Fig. 3 3GPP timeline for 5G specifications. Source: 3GPP.

able experience, solidifying 5G mmWave specifications is impractical. The mmWave frequency designations for 5G will not be identified for the ITU until WRC-2019, in time for IMT-2020.

5G Phase 1 is still based on OFDM waveforms, though there are a variety of candidate waveforms which may eventually supersede OFDM. Specifically, 5G phase 1 leverages cyclic prefix OFDM (CP-OFDM) for the downlink, and both CP-OFDM and discrete Fourier transform spread OFDM-based (DFT-S-OFDM) waveforms for the uplink. 5G Phase 1 allows for flexible subcarrier spacing, where the subcarriers can be spaced at 15 kHz $\times$ 2^n to a maximum of 240 kHz with a 400 MHz carrier bandwidth. Up to two uplink and four downlink carriers can be used, for a combined uplink bandwidth of 200 MHz and downlink bandwidth of 400 MHz.

CURRENT 5G HARDWARE

For the past few years, many telcos and hardware/platform manufacturers have been engaging in a game of 5G one-upmanship. Early demonstrations included mmWave throughput, mMIMO, CA and a variety of software and hardware examples. Many of the latest 5G trials and demonstrations involved technology more aligned with the upcoming 3GPP Release 15, capable of being updated by software to meet the final 5G Phase 1 specification and future updates.

Hence, many of the recently released and announced 5G modems and transceivers are able to be updated via software, and offer throughput handling capabilities that account for greater bandwidth availability at currently unavailable mmWave frequencies. Many leading hardware manufacturers and telecommunication companies are continuing to push to advance 5G trials and deployments by 2019, well ahead of a final specification, by leveraging NSA 5G NR and technology that can be modified to meet the finalized specifications.[10] Given the nature of the race to commercialize 5G, and the likelihood of future 5G specifications adjusting to the findings of early trials and deployments, programmability and flexibility of both the software and hardware of 5G radios and core networks are essential.

Another factor to consider with 5G hardware is not only backward compatibility, but dual connectivity of 4G LTE and 5G systems. Similar to how prior generations of mobile wireless were eventually integrated into the latest specifications, it is likely that current 4G LTE rollouts will be merged into future 5G specifications. Supporting dual connectivity, backward compatibility and future 5G specifications will require highly adaptable RF hardware that can allocate resources based on the actual environment, not just preprogrammed scenarios.[11-12]

As the finalized 5G mmWave spectrum and radio hardware is not yet determined, and extensive mobility trials with mmWave frequencies are still underway, the first round of 5G mmWave technology will provide fixed wireless service (FWA). This approach minimizes many of the challenges associated with a complete 5G solution, including mmWave mobility concerns around non-line-of-sight and antenna beam tracking with moving UEs. Also, FWA 5G modems and transceiver chips can be larger, use more power and cost more than modem and transceiver chips for UE.

Available 5G modems, typically with integrated 5G transceivers, are offered by Samsung, Qualcomm, Intel, Huawei and others. Some of these early 5G chipsets are reportedly capable of 2 Gbps data rates and mmWave transceiver operation at 28 GHz. Common features include NSA 5G NR compatibility, with a variety of beamforming techniques, antenna switching, 3D frequency planning tools and virtualized RAN.[13-14]

Currently, device and network hardware manufacturers, with associated telecommunications service providers and test and measurement manufacturers, are engaging in 5G NR trials with simulated UEs. Samsung and National Instruments, as well as Datang Mobile and Keysight Technologies, demonstrated what will likely be commercial 5G base station hardware and 5G UE emulation systems at Mobile World Congress 2018.[15-16] It is likely that 5G UE chipsets will become available in 2019, although it is unknown if these UE will leverage mmWave technology or just the sub-6 GHz 5G FR1 frequencies.

The latest commercially available 5G hardware solutions are typically RF front-end (RFFE) modules designed to account for the new NSA 5G NR frequencies, which can be included with other RFFE hardware to offer a complete solution. These RFFEs include power amplifiers (PA), low noise amplifiers (LNA), switches and filters and differ somewhat from 4G RFFEs. As the power Class 2 specification for higher output power (26 dBm at the antenna) is available for 5G hardware, PAs may be higher power than with 4G, necessary to overcome increased propagation losses at higher frequencies through the atmosphere and common building materials.

With 100 MHz of available Tx bandwidth, techniques like envelope tracking—which currently only supports up to 40 MHz of bandwidth—may not be viable; less efficient techniques, such as average power tracking are more likely for early 5G systems. These early 5G RFFE modules will likely be wideband, requiring additional filtering for the new sub-6 GHz 5G bands, as well as the legacy and still necessary 4G bands. These multi-band filters are currently more complex combinations of surface acoustic wave (SAW), bulk acoustic wave (BAW) and film bulk acoustic wave (FBAR) filter banks and integrated modules.

RF HARDWARE AND TEST SYSTEMS

Given the inclusion of new sub-6 GHz frequency bands in NSA 5G NR, new RF hardware is needed to support these new frequencies—specifically n77, n78 and n79—which were not previously used for mobile wireless. Though not determined in NSA 5G NR, frequency bands below 600 MHz may eventually be supported by 5G for massive low power connectivity such as IoT, Industry 4.0/Industrial IoT and other machine-type communications. The additional subcarrier channel spacing, bandwidth, CA and 4 x 4 MIMO specifications result in the need for large numbers of filters, antennas, LNAs,

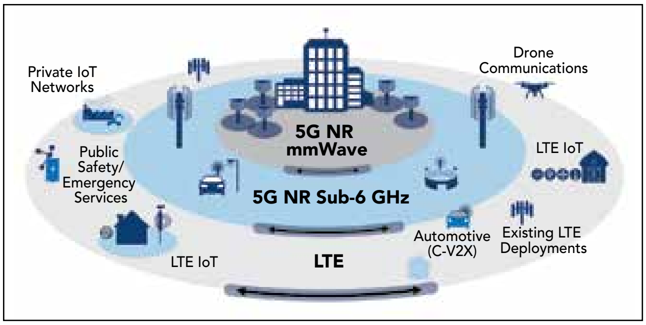


Fig. 4 Once deployed, standalone 5G services, operating at sub-6 GHz and mmWave frequencies, will need to coexist with LTE. Source: AndroidAuthority.com; used with permission.

PAs and switches, with accompanying NSA 5G NR modems and RF transceivers.

The early 5G modems and transceivers do not necessarily need to contend with these challenges, as these commercial devices can operate on select bands. However, 5G base stations for eMBB and future industrial and vehicle applications will require forward and backward compatibility. This means that 5G RF hardware will need to service all current mobile frequency bands, as well as 5G FR1 and 5G mmWave FR2 frequencies (see ***Figure 4***). This is a particularly troublesome hardware challenge, as the hardware for many of the existing cellular frequencies may interfere with the NSA 5G NR bands, as dual connectivity is necessary to meet the throughput specifications. Also, the new NSA 5G NR frequency bands surround the ISM bands for Wi-Fi, Bluetooth and other wireless equipment operating in the unlicensed bands.

With such closely packed bands and extremely wideband radios, the performance degradation from receiver desensitization is likely with inadequate filtering, PA linearity and harmonic suppression. New NSA 5G NR transmitters can operate with higher output power and higher peak-to-average power ratios for maximum throughput, which may cause problems with co-located 5G receivers in the same base station or nearby 5G devices.

Real estate for RF hardware, especially antennas, is already small in UEs, and 5G specifications may require 4 x 4 MIMO for the downlink and 2 x 2 MIMO for the uplink, meaning six independent RF pathways. 5G antenna tuning technologies will be critical to maximize antenna radiation efficiency over wide bandwidths. These RF pathways must also be much wider than 4G LTE pathways, as NSA 5G NR now supports 100 MHz bandwidth on a single carrier, with more CA options (up to 600 new combinations with Release 15). NSA 5G NR also allows for 200 MHz combined uplink and 400 MHz combined downlink bandwidth. This results in a substantial amount of data to process, challenging for energy efficient UEs and base stations.

It is probable that the RF hardware for UEs will be increasingly integrated, with filter banks, high density switches, antenna tuning, LNAs and PAs integrated into RFFEs with systems on chip (SoC) technologies. 5G UE antennas may also be integrated solutions, possibly with antenna tuning and some pre-filtering and beamforming features included. This level of integration is also plausible to achieve the cost targets to ensure handsets are affordable and meet phone form factors.[17-19] With the increased complexity of 5G and the need for dense RF solutions, it is no surprise that many UE manufacturers are attracted to 5G modem-to-antenna solutions for faster development and deployment.

Many current 4G UEs and base stations rely on LDMOS, GaAs and SiGe PAs, with GaN a recent entry into the base station PA market. As the frequency is extended to sub-6 GHz, LDMOS, which struggle beyond 3 GHz, is less likely to meet 5G specifications, while GaN PAs—and possibly LNAs—are likely to be used in the infrastructure. GaAs and SiGe amplifiers will compete for amplifier and switching functions in the sub-6 GHz 5G applications. To maintain lower cost and smaller form factors than current mmWave PA, LNA and switch solutions provide, highly integrated RF silicon on insulator (SOI) technologies are likely to be used for 5G mmWave applications. Future RFFEs may use RF SOI, SiGe BiCMOS or RF CMOS SoCs that integrate the PA, LNA, switches and control functions to operate mmWave phased array beamforming antenna systems (see ***Figure 5***). It is possible that future RF silicon technologies can be further integrated or combined with other technologies to include filtering and the digital hardware required to enable hybrid beamforming modules. Future variations of RF SOI or RF CMOS may even be integrated with more advanced digital hardware, such as FPGAs, memory and processors. Baseband processing and accessory DSP functions could be implemented in the package, as well, for compact 5G mmWave solutions.

As frequency routing and filtering is essential for 5G CA and back compatibility with prior mobile generations, integrated SAW, BAW, FBAR and other integrated resonators and filter technologies are essential for UEs and even compact small cells. With the potential for interference and design complexity, 5G modules for UEs will also likely incorporate Wi-Fi and Bluetooth

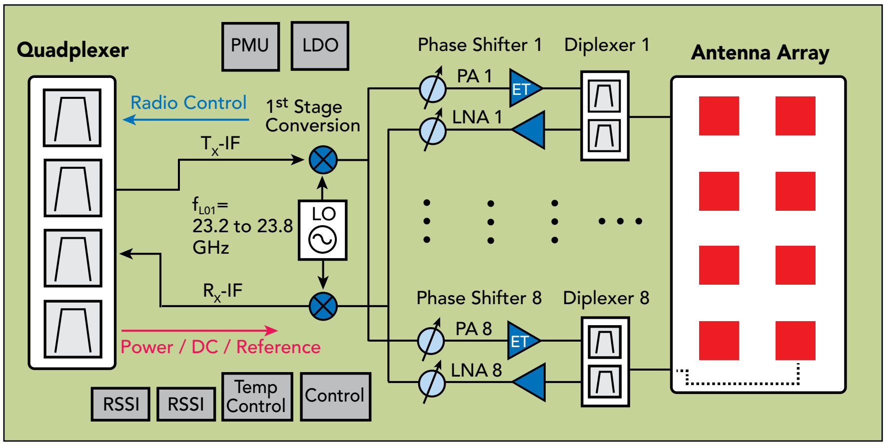


Fig. 5 5G FDD beamforming module architecture. Source: arXiv:1704.02540v3 [cs.IT].

modules, further increasing the filtering and frequency routing complexity. Other integration-capable technologies, such as RF SOI, may be employed for 5G RFFEs, as recent advances in RF SOI enable filter and amplifier co-integration. It may be several years before SOI filters are used for sub-6 GHz 5G applications, although it may be sooner for mmWave systems, as amplifier and switch integration possible with SOI technologies make this an attractive next step.

CONCLUSION

The rapid progression of 5G specifications and the rush of mobile wireless manufacturers and service providers to start 5G trials and deployments has led to a plethora of early 5G demonstrations and interim 5G specifications. In just the past few months, modem, transceiver and RF hardware manufacturers have been announcing 3GPP-compliant 5G solutions, which rely on heavy integration and software reprogrammability to meet current demand and provide future-proofing. This deep level of integration and soon-to-come 5G deployments will require flexible test and measurement systems which can be readily adapted to the changing standards and lessons learned from early trials.[20] Access to 5G accessories and interconnect technologies, especially 28 GHz and other mmWave components and devices, will be essential to prevent delays in trials and deployments.■

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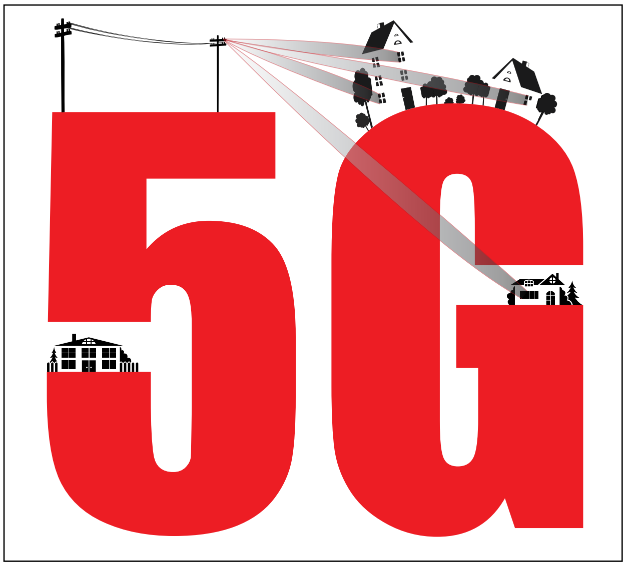


Editor's Note: At the end of December, the 3GPP approved the 5G non-standalone new radio (NSA NR) specification, which defines how enhanced broadband services can be deployed using a 5G NR leveraging the existing LTE network. This NSA architecture will first be fielded—later this year—for fixed wireless access (FWA) services using mmWave spectrum, i.e., 28 and 39 GHz.

Qorvo and Anokiwave are two companies leading the development of the mmWave front-end technology for the active phased arrays that will power these FWA services. Each company has analyzed the system requirements and defined a unique approach to meeting them. Qorvo has chosen GaN, Anokiwave silicon. We are fortunate that this issue of *Microwave Journal* features articles from both, each stating the case for its technology choice. Regardless of which argument you favor, no doubt you will agree that both companies are doing excellent technology and product development, a key step to making 5G viable.

5G Fixed Wireless Access Array and RF Front-End Trade-Offs

Bror Peterson and David Schnaufer
Qorvo, Greensboro, N.C.

The vision of next-generation 5G networks is to deliver an order-of-magnitude improvement in capacity, coverage and connectivity compared to existing 4G networks, all at substantially lower cost per bit to carriers and consumers. The many use cases and services enabled by 5G technology and networks are shown in ***Figure 1***. In this first phase of 5G new radio (NR) standardization, the primary focus has been on defining a radio access technology (RAT) that takes advantage of new wideband frequency allocations, both sub-6 GHz and above 24 GHz, to achieve the huge peak throughputs and low latencies proposed by the International Mobile Telecommunications vision for 2020 and beyond.[1]

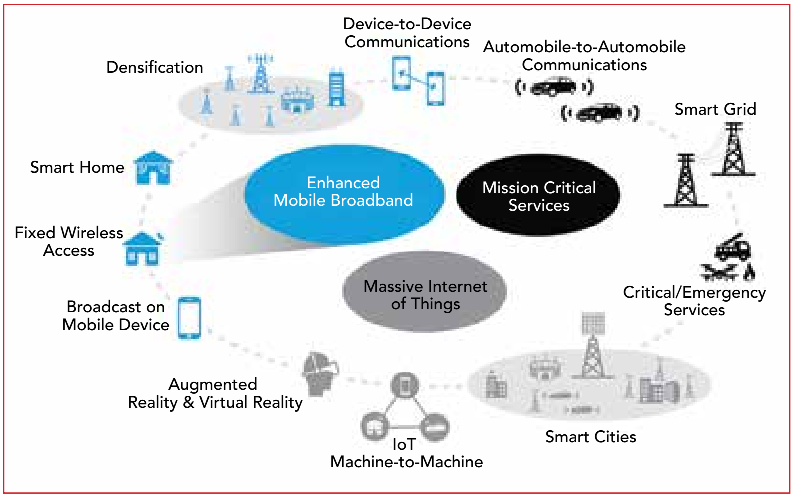


Fig. 1 **5G use cases.**

Mobile network operators are capitalizing on the improvements introduced by NR RAT, particularly in the mmWave bands, to deliver gigabit fixed wireless access (FWA) services to houses, apartments and businesses, in a fraction of the time and cost of traditional cable and fiber to the home installations. Carriers are also using FWA as the testbed toward a truly mobile broadband experience. Not surprisingly, Verizon, AT&T and other carriers are aggressively trialing FWA, with the goal of full commercialization in 2019.

In this article, we analyze the architecture, semiconductor technology and RF front-end (RFFE) design needed to deliver these new

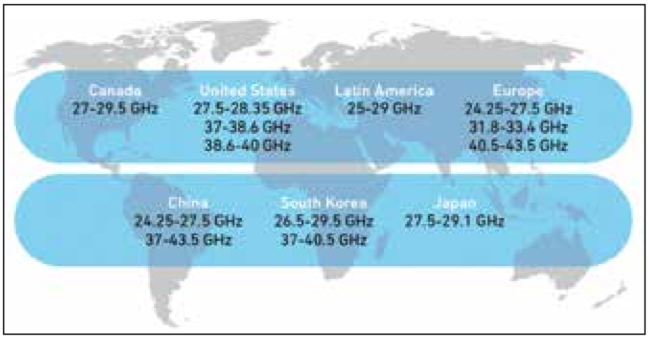


Fig. 2 Global 5G bands above 24 GHz.

TABLE 1

FCC POWER LIMITS FOR 28 AND 39 GHz BANDS

Equipment Class	Power (EIRP)
Base Station	75 dBm/100 MHz
Mobile Station	43 dBm
Transportable Station	55 dBm

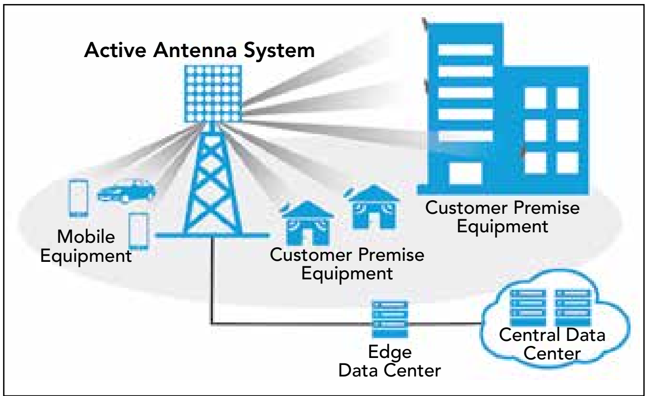


Fig. 3 End–to–end FWA network.

mmWave FWA services. We discuss the link budget requirements and walk through an example of suburban deployment. We address the traits and trade-offs of hybrid beamforming versus all-digital beamforming for the base transceiver station (BTS) and analyze the semiconductor technology and RFFE components that enable each. Finally, we discuss the design of a GaN-on-SiC front-end module (FEM) designed specifically for the 5G FWA market.

FWA DEPLOYMENT

A clear advantage of using mmWave is the availability of underutilized contiguous spectrum at low cost. These bands allow wide component carrier bandwidths up to 400 MHz and commercial BTSs are being designed with carrier aggregation supporting up to 1.2 GHz of instantaneous bandwidth. Customer premise equipment (CPE) will support peak rates over 2 Gbps and come in several form factors: all outdoor, split-mount and all indoor desktop and dongle-type units. Mobile-handset form factors will follow.

Global mmWave spectrum availability is shown in ***Figure 2***. In the U.S., most trials are in the old block A LMDS band between 27.5 and 28.35 GHz, but the plan-of-record of carriers is to deploy nationwide in the wider 39 GHz band, which is licensed on a larger economic area basis. These candidate bands have been assigned by 3GPP and, except for 28 GHz, are being harmonized globally by the International Telecommunications Union.[2]

FWA describes a wireless connection between a centralized sectorized BTS and numerous fixed or nomadic users (see ***Figure 3***). Systems are being designed to leverage existing tower sites and support a low-cost, self-install CPE build-out. Both are critical to keeping initial deployment investment low while the business case for FWA is validated. Early deployments will be mostly outdoor-to-outdoor and use professional roof-level installations that maximize range, ensure initial customer satisfaction and allow time for BTS and CPE equipment to reach the needed cost and performance targets.

Large coverage is essential to the success of the FWA business case. To illustrate this, consider a suburban deployment with 800 homes/km^2, as shown in ***Figure 4***. For BTS inter-site distance (ISD) of 500 m, we need at least 20 sectors, each covering 35 houses from nine cell sites. Assuming 33 percent of the customers sign up for 1 Gbps service and a 5x network oversubscription ratio, an average aggregate BTS capacity of 3 Gbps/sector is needed. This capacity is achieved with a 400 MHz bandwidth, assuming an average spectral efficiency of 2 bps/Hz and four layers of spatial multiplexing. If customers pay $100 per month, the annual revenue will be $280,000/km^2/year. Of course, without accounting for recurring costs, it is not clear FWA is a good business, but we can conclude that as ISD increases, the business case improves. To that end, carriers are driving equipment vendors to build BTS and CPE equipment that operate up to regulatory limits to maximize coverage and profitability.

In the U.S., the Federal Communications Commission has defined very high effective isotropic radiated power (EIRP) limits for the 28 and 39 GHz bands,[3] shown in ***Table 1***. The challenge becomes building systems that meet these tar-

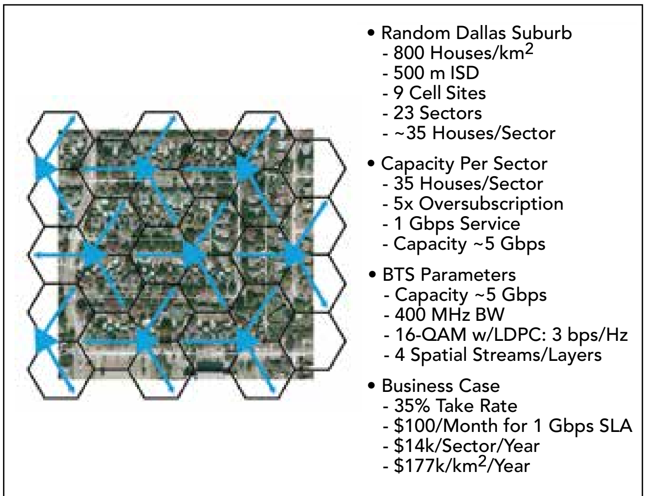


Fig. 4 FWA in a suburban environment.

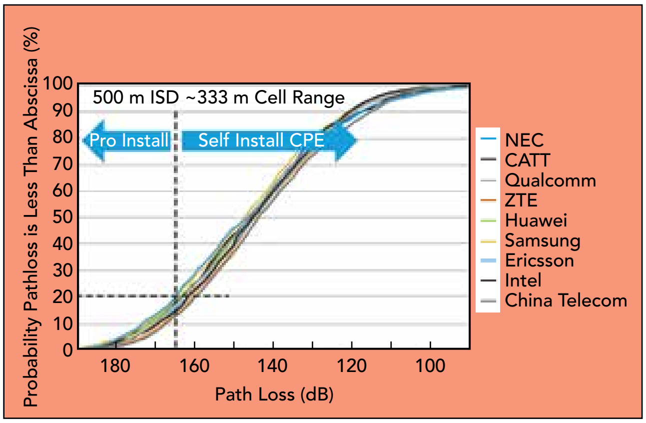


Fig. 5 Statistical path loss simulation for urban-macro environment with 500 m ISD.

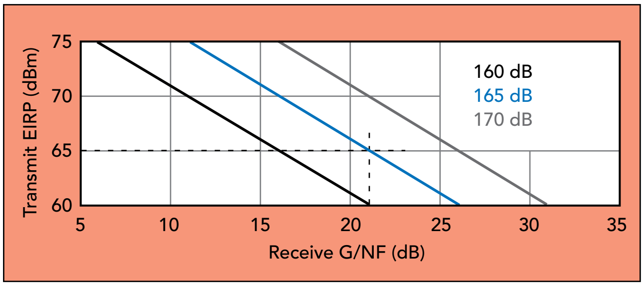


Fig. 6 Transmit EIRP and receive G/NF vs. path-loss for 1 Gbps edge-of-coverage throughput.

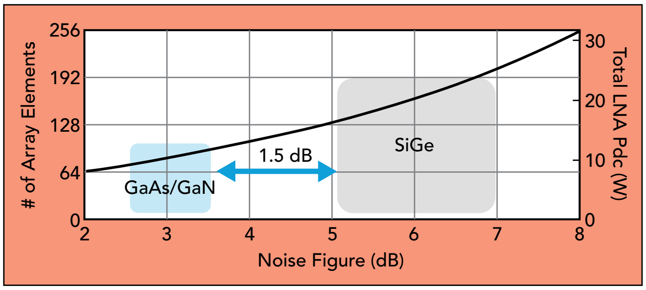


Fig. 7 Array size vs. front-end NF and power consumption for G/NF = 21 dB.

gets within the cost, size, weight and power budgets expected by carriers. Selecting the proper front-end architecture and RF semiconductor technology are key to getting there.

FWA Link Budget

The standards community has been busy defining the performance requirements and evaluating use cases over a broad range of mmWave frequencies. The urban-macro scenario is the best representation of a typical FWA deployment: having large ISD of 300 to 500 m and providing large path-loss budgets that overcome many of the propagation challenges at mmWave frequencies. To understand the needed link budget, consider a statistical path-loss simulation using detailed large-scale channel models that account for non-line-of-site conditions and outdoor-to-indoor penetration, like those defined by 3GPP.[4] ***Figure 5*** shows the result for a 500 m ISD urban-macro environment performed by equipment vendors and operators. For this simulation, 28 GHz channel models were used with 80 percent of the randomly dropped users falling indoors and 20 percent outdoors. Of the indoor users, 50 percent were subject to high penetration-loss models and 50 percent lower loss. Long-term, carriers desire at least 80 percent of their potential users to be self-installable to minimize more expensive professional roof-level installations. The distribution curve shows the maximum system path loss to be 165 dB.

Closing the link depends on many variables, including transmit EIRP, receive antenna gain, receiver noise figure (NF) and minimum edge-of-coverage throughput. To avoid overdesign of the cost-sensitive CPE equipment and shift the burden toward the BTS, the link design begins at the CPE receiver and works backward to arrive at the BTS transmitter requirements. In lieu of the conventional G/T (the ratio of antenna gain to system noise temperature) figure-of-merit (FOM), we define a more convenient G/NF FOM: the peak antenna gain (including beamforming gain) normalized by the NF of the receiver. ***Figure 6*** illustrates the required EIRP for the range of receive G/NF to overcome a targeted path loss delivering an edge-of-coverage throughput of 1 Gbps, assuming the modulation spectral efficiency is effectively 2 bps/Hz and demodulation SNR is 8 dB. From the graph, the BTS EIRP for a range of CPE receiver's G/NF can be determined. For example, 65 dBm BTS EIRP will be needed to sustain a 1 Gbps link at 165 dB of path loss when the CPE receiver G/NF is ≥ 21 dBi.

Next, we consider the impact of receiver NF by plotting the minimum number of array elements needed to achieve G/NF of 21 dB (see ***Figure 7***). We also plot the total low noise amplifier (LNA) power consumption. By adjusting the axis range, we can overlap the two and see the impact NF has on array size, complexity and power. For this example, each LNA consumes 40 mW, which is typical for phased arrays. The NFs of RFFEs, including the T/R switch losses, are shown for 130 nm SiGe BiCMOS, 90 nm GaAs PHEMT and 150 nm GaN HEMT at 30 GHz. The compound semiconductor technology provides ≥ 1.5 dB advantage, translating to a 30 percent savings in array size, power and, ultimately, CPE cost.

To explore architecture trades that are key to technology selection and design of the RFFE components, we start by understanding the antenna scanning requirements. We highlight the circuit density and packaging impact for integrated, dual-polarization receive/transmit arrays. Finally, we investigate all-digital beamforming and hybrid RF beamforming architectures and the requirements for each.

1D or 2D Scanning

The number of active channels in the array depends on many things. Let's start by first understanding the azimuth and elevation scanning requirements and whether two-dimensional beamforming is required for a typical FWA deployment or if a lower complexity, one-dimensional (azimuth only) beamforming array is sufficient. This decision impacts the power amplifier (PA). ***Figure 8*** shows two FWA deployment scenarios. In the suburban deployment, the tower heights range from 15 to 25 m

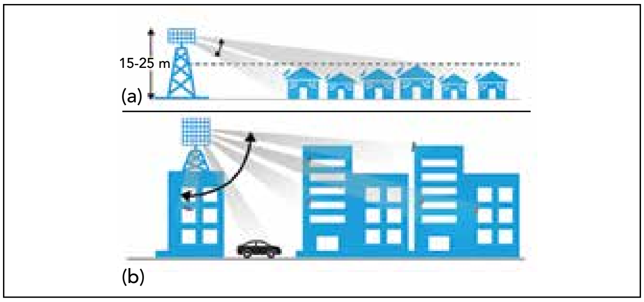


Fig. 8 Array complexity depends on the scanning range needed for the deployment: suburban (a) or urban (b).

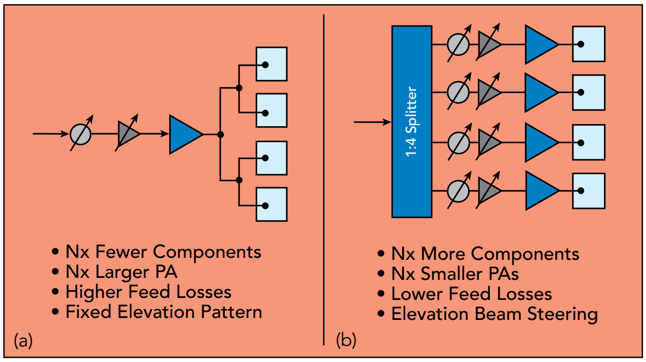


Fig. 9 Column-fed (a) and per-element (b) active arrays.

and the cell radius is 500 to 1000 m, with an average house height of 10 m. Just as with traditional macro cellular systems, there is no need for fully adaptive elevation scanning. The elevation beam can be focused down by corporately feeding several passive antenna elements, as shown in ***Figure 9a***. This vertically stacked column of radiating elements is designed to minimize radiation above the houses and fill in any nulls along the ground. Further, the gain pattern is designed to increase at relatively the same rate as the path loss. This provides more uniform coverage for both near and far users. The nominal half-power beamwidth can be approximated as $102°/N_{ANT}$ and the array gain by $10\log_{10}(N_{ANT}) + 5$ dBi. With passively combined antennas, the elevation beam pattern is focused and the fixed antenna gain increases, as shown in ***Table 2***. For the suburban FWA deployment, a 13 to 26 degree beamwidth is sufficient, with the passively combined column array from four to eight elements. In the urban scenario, however, the elevation scanning requirements are greater, and systems will be limited to one or two passive elements.

Figure 9b illustrates the per-element active array. Both the per-element and column-fed array architectures have the same antenna gain, but the column-fed array has a fixed elevation beam pattern. The per-element array supports wider scan angles but needs 4x as many PAs, phase shifters and variable gain components for an antenna with four elements. To achieve the same EIRP, the PA driving a column-fed array with four antennas will need to provide at least 4x the output power, which can easily change the semiconductor selection. It is reasonable to assume a suburban BTS will use antennas with 6 to 9 dB higher passive antenna gain compared to an urban deployment. As a result, the phased array needs far fewer active channels to achieve the same EIRP, significantly reducing active component count and integration complexity.

TABLE 2

APPROXIMATE PERFORMANCE FOR CORPORATELY FED ELEMENTS

Column Array Size	Beamwidth (°)	Gain (dB)
Single Element	102	5
2-Element	51	8
4-Element	26	11
8-Element	13	14

Array Front-End Density

Early mmWave FWA BTS designs used separate, single-polarization transmit and receive antenna arrays, which allowed significantly more board area for components. These designs avoided the additional insertion loss and linearity challenges of a T/R switch. However, a major architecture trend is integrated T/R, dual-polarization arrays (see ***Figure 10***), which is driving RFFE density. The key reason is spatial correlation. Adaptive beamforming performance depends on the ability to calibrate the receive and transmit arrays relative to one another. As such, it is important to integrate the transmit and receive channels for both polarizations, so the array shares a common set of antenna elements and RF paths. The net result is a requirement for the RFFE to have 4x the circuit density of earlier systems.

At mmWave frequencies, the lattice spacing between phased-array elements becomes small, e.g., 3.75 mm at 39 GHz. To minimize feed loss, it is important to locate the front-end components close to the radiating elements. Therefore, it is necessary to shrink the RFFE footprint and integrate multiple functions, either monolithically on the die or within the package, using a multi-chip module. Tiling all these functions in a small area requires either very small PAs, requiring a many-fold increase in array size, or using high-power density technologies like GaN. Further, it is critical to use a semiconductor technology that can withstand high junction temperatures. The reliability of SiGe degrades rapidly above 150°C, but GaN on SiC is rated to 225°C. This 75°C advantage in junction temperature has a large impact on the thermal design, especially for outdoor, passively-cooled phased arrays.

ALL-DIGITAL VS. HYBRID ARRAYS

It was natural for BTS vendors to first explore extending the current, sub-6 GHz, all-digital beamforming, massive MIMO platforms to mmWave. This preserves the basic architecture and the advanced signal processing algorithms for beamformed spatial multiplexing. However, due to the dramatic increase in channel bandwidths offered by mmWave and the need for many active channels, there is a valid concern that the power dissipation and cost of such a system would be prohibitive. Therefore, vendors are exploring hybrid beamformed architectures,[5] which allows flexibility between the number of baseband channels and the number of active RF channels. This approach better balances analog beamforming gain and baseband processing. The following sections analyze the two architectures and discuss the RFFE approaches needed for each.

Digital Beamforming

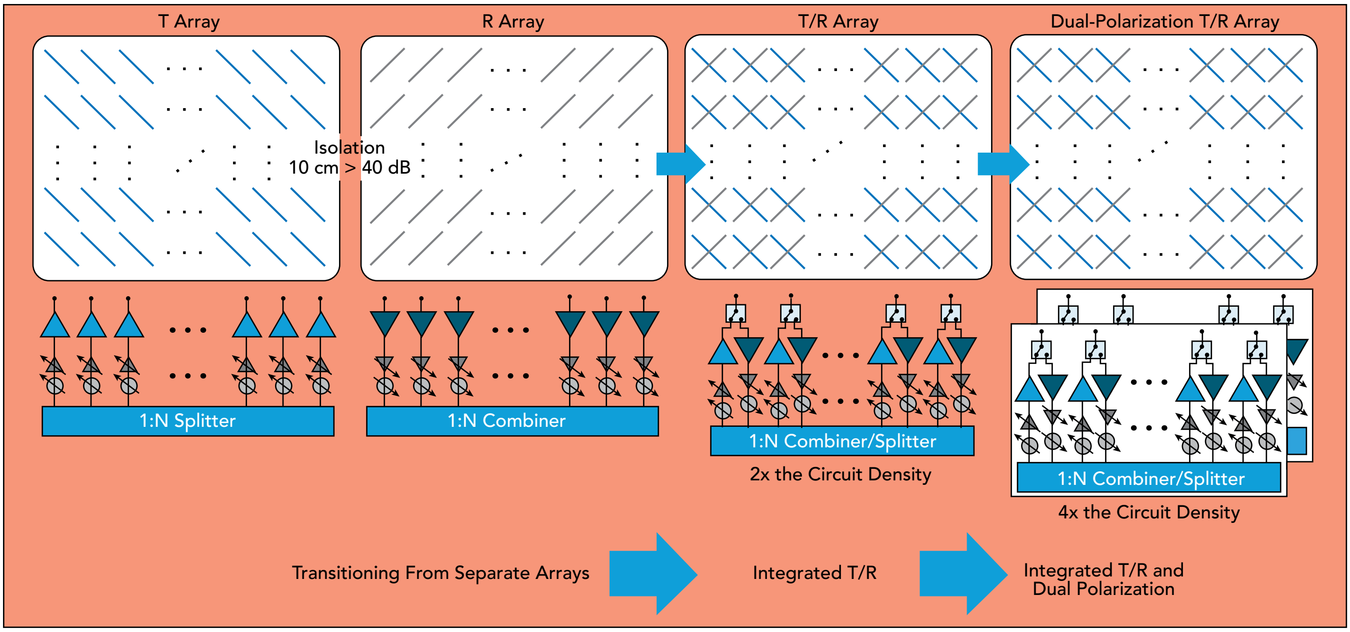
Assuming large elevation scanning is not required for suburban FWA and a well-designed, column antenna provides gain of up to 14 dBi, we start with a mmWave BTS transceiver design targeting an EIRP of 65 dBm and compute the power consumption using off-the-shelf point-to-point microwave radio components that have been available for years, including a high-power, 28 GHz GaN balanced amplifier. The multi-slat array and transceiver are shown in ***Figure 11***. Assuming circulator and feed-losses of 1.5 dB, the power at the antenna port is 27 dBm. From the following equations, achieving 65 dBm EIRP requires 16 transceivers that, combined, provide 12 dB of digital beamforming gain:

$$\mathrm{EIRP} = G_{BF}(\mathrm{dB}) + G_{ANT}(\mathrm{dBi}) + P_{AVE\_TOTAL}(\mathrm{dBm})$$

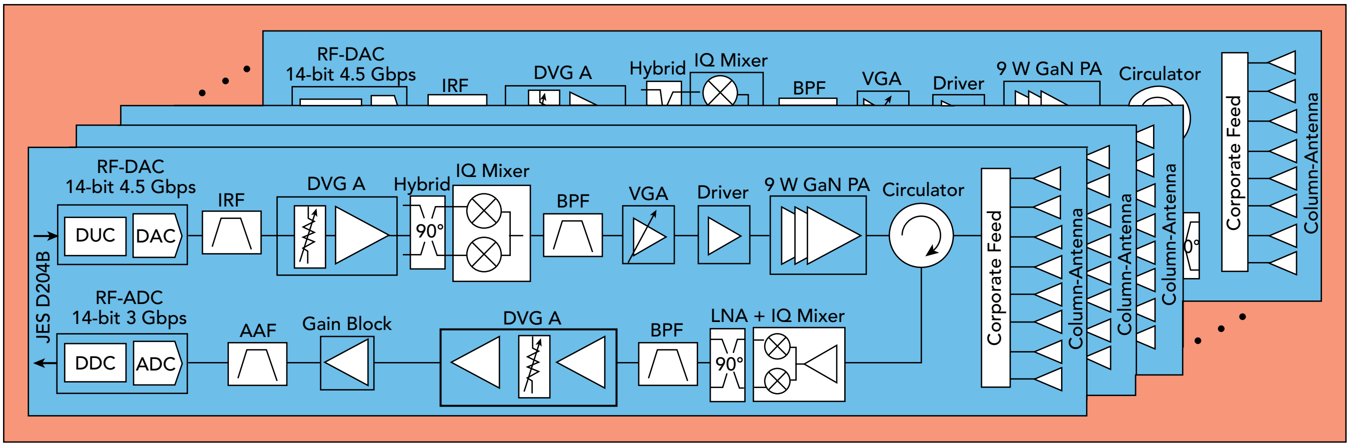
$$\mathrm{EIRP} = 10\log 10(N_{COLUMNS}) + 10\log 10(N_{PAs}) + G_{ANT} + P_{AVE/CHANNEL}(\mathrm{dBm})$$

The power consumption for each transceiver is shown in ***Figure 12***. The total power dissipation (P_{DISS}) at 80 percent transmit duty cycle for all 16 slats will be 220 W per polarization, and a dual-polarized system will require 440 W. For all outdoor tower-top electronics, where passive cooling is required, it is challenging to thermally manage more than 300 W from the RF subsystem, suggesting an all-digital beamforming architecture using today's off-the-shelf components is impractical.

However, new GaN FEMs are on the horizon to help address this. As shown in ***Figure 13***, the GaN PAs integrated in the FEM apply the tried-and-true Doherty efficiency-boosting technique to mmWave. With Doherty

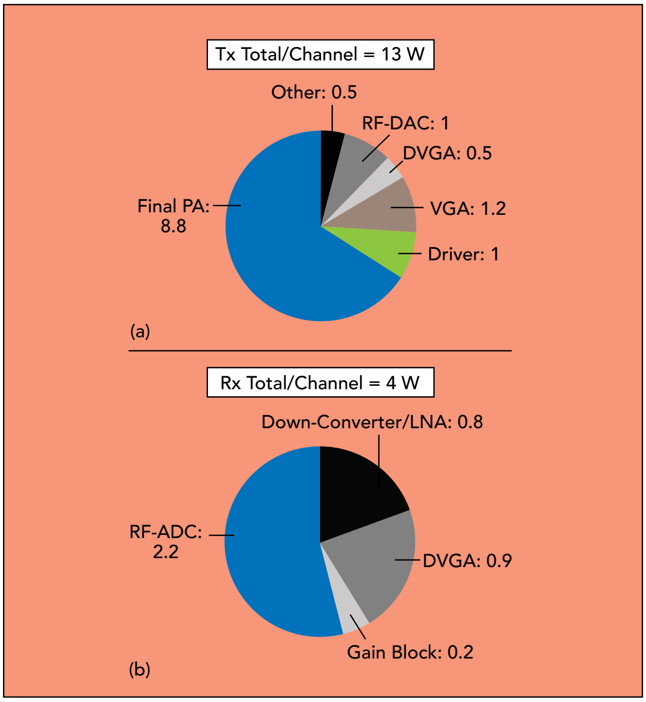


▲ **Fig. 10 FWA antenna arrays are evolving from separate T and R arrays to integrated T/R arrays with dual polarization.**

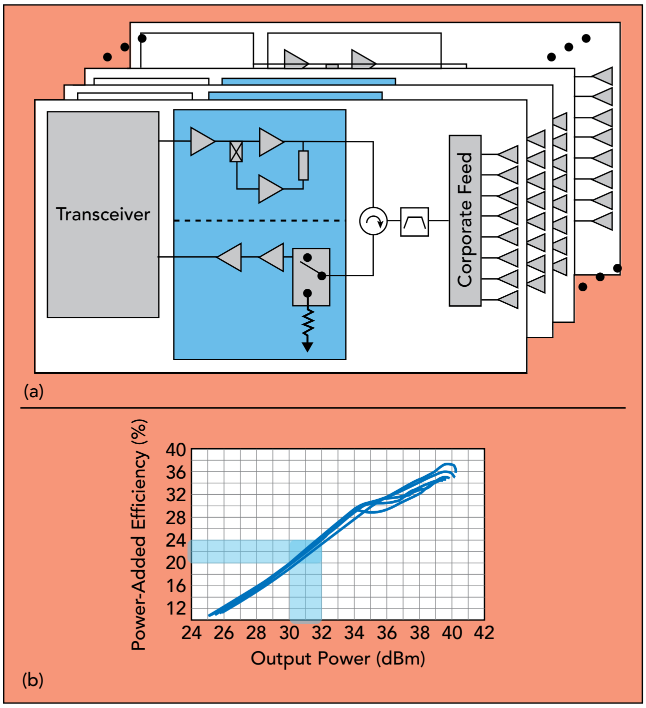


▲ **Fig. 11 Array design using digital beamforming and commercial, off-the-shelf components.**

PAs, digital pre-distortion (DPD) is needed; however, the adjacent channel power ratio (ACPR) requirements defined for mmWave bands are significantly more relaxed, enabling a much "lighter" DPD solution. The estimated power dissipation of a 40 dBm P_{SAT}, symmetric, multi-stage Doherty PA can be reduced more than 50 percent. In the above system, this improvement alone drops the total P_{DISS} below 300 W. Combined with power savings from next-generation RF-sampling



▲ **Fig. 12 Power dissipation of the transmit (a) and receive (b) chains.**



▲ **Fig. 13 Integrated FEM with symmetric GaN Doherty PA and switch-LNA (a) and PA performance from 27.5 to 29.5 GHz (b).**

digital-to-analog and analog-to-digital converters, advancement in mmWave CMOS transceivers and increased levels of small-signal integration, it will not be long before we see more all-digital beamforming solutions being deployed.

Hybrid Beamforming

The basic block diagram for a hybrid beamforming active array is shown in ***Figure 14***. Here, N baseband channels are driving RF analog beamformers, which divide the signal M-ways and provide discrete phase and amplitude control. FEMs drive each M-element subarray panel. The number of baseband paths and subarray panels is determined by the minimum number of spatial streams or beams that are needed. The number of beamformer branches and elements in each subarray panel is a function of the targeted EIRP and G/NF. While a popular design ratio is to have one baseband path for every 16 to 64 active elements, it really depends on the deployment scenario. For example, with a hot-spot small cell (or on the CPE terminal side), a 1:16 ratio single panel is appropriate. A macro BTS would have two to four subarray panels with 64 active elements, where each panel is dual-polarized, totaling four to eight baseband paths and 256 to 512 active elements. The digital and analog beamforming work together, to maximize coverage or independently, to provide spatially separated beams to multiple users.

There is an important trade unfolding, whether SiGe front-ends can provide sufficient output power and efficiency to avoid the need for higher performance III-V technology like GaAs or GaN. With good packaging and integration, both approaches can meet the tight antenna lattice-spacing requirements.

FRONT-END SEMICONDUCTOR CHOICES

The technology choice for the RFFE depends on the EIRP and G/NF requirements of the system. Both are a function of beamforming gain, which is a function of the array size. To illustrate this, ***Figure 15*** shows the average PA power (P_{AVE}) per channel needed as a function of array size and antenna gain for a uniform rectangular array delivering 65 dBm EIRP. The graph is overlaid with an indication of the power ranges best suited for each semiconductor technology. The limits were set based on benchmarks of each technology, avoiding exotic power-combining or methods that degrade component reliability or efficiency. As array size gets large (more than 512 active elements), the power per element becomes small enough to allow SiGe, which can be integrated into the core beamformer RFIC. In contrast, by using GaN for the front-end, the same EIRP can be achieved with 8 to 16x fewer channels.

System Power Dissipation

For an array delivering 64 dBm EIRP, ***Figure 16*** shows an analysis of the total P_{DISS} of the beamformer plus the front-end as a function of the number of active elements in each subarray panel. The P_{DISS} is shown for several error vector magnitude (EVM) levels, since the EVM determines the power back-off and efficiency achieved by the front-end. We assume each beamform-

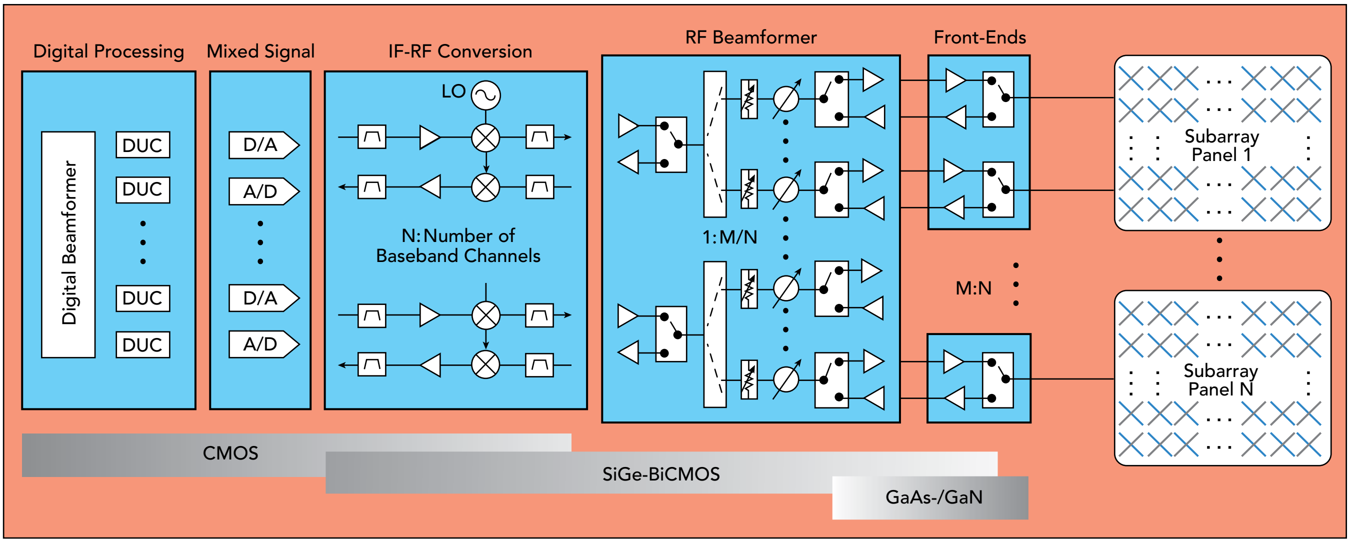


Fig. 14 Active array using hybrid beamforming.

TABLE 3

RELATIVE COST OF ALL SiGe AND SiGe BEAMFORMER WITH GaN FEM

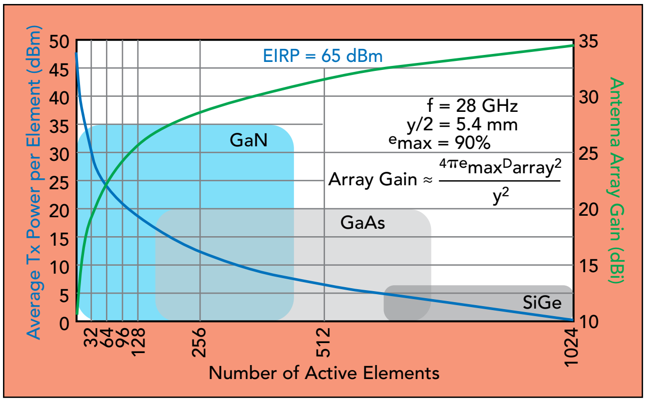
Parameter	Units	All SiGe	GaN +SiGe
Average Output Power per Channel	dBm	2	20
Power Dissipation per Channel	mW	190	1329
Antenna Element Gain	dBi	8	8
Number of Active Channels		512	64
EIRP	dBmi	64	64
Total Power Dissipation	W	97	97
Beamformer Die Area per Channel	mm^2	2.3	2.3
Front-End Die Area per Channel	mm^2	1.2	5.2
Total SiGe Die Area	mm^2	1752	144
Total GaN Die Area	mm2	0	334
	Die Cost	**Units**	**Notes**
All SiGe System Die Cost	1752	$/x	
GaN + SiGe System Die Cost (4-inch GaN)	1647	$/x	4-inch GaN = 4.5x
GaN + SiGe System Die Cost (6-inch GaN)	1146	$/x	6-inch GaN = 3x

er branch consumes 190 mW, which is the typical power consumption of core beamformers in the market.[6] The system on the far right of the figure represents an all-SiGe solution with 512 elements, with an output power per element of 2 dBm and consuming approximately 100 W. Moving left, the number of elements decreases, the P_{AVE} per channel increases and P_{DISS} is optimized to a point where beamforming gain starts to roll off sharply, and the P_{DISS} to maintain the EIRP rapidly increases. The small steps in the dissipation curves represent where the front-end transitions from a single stage to two-stage and three-stage designs to provide sufficient gain. As stages are added, the efficiency drops with the increase in power dissipation.

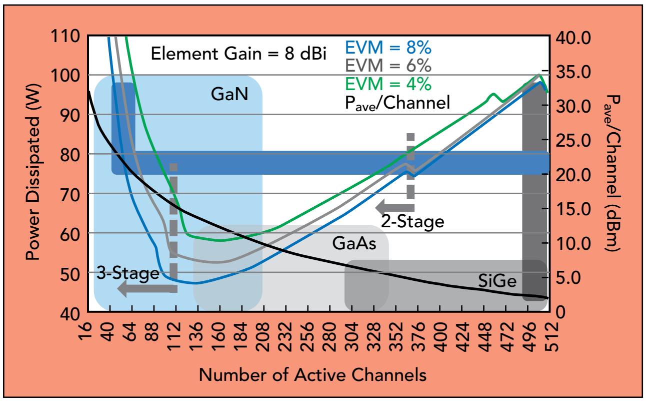
Designing to optimize system P_{DISS} without regarding complexity or cost, an array of about 128 elements with a two-stage, 14 dBm output PA (24 dBm P_{1dB}) is the best choice. However, if we strive to optimize cost, complexity and yield for a P_{DISS} budget of under 100 W, the optimum selection is the range of 48 to 64 active channels using a three-stage GaN PA with an average output power of 20 to 23 dBm, depending on the EVM target. The trends shown in Figure 16 are less a function of PA efficiency and more a function of beamformer inefficiency. In other words, the choice to increase array size 8x to allow an all-SiGe solution comes with a penalty, given that the input signal is divided many more ways and requires linearly biased, power consuming devices to amplify the signal back up.

Cost Analysis

The cost of phased arrays include the RF components, printed circuit board material and the antennas themselves. Using compound semiconductor front-ends allows an immediate 8x reduction in array size with no increase in P_{DISS}. Even with lower-cost printed antenna technology, this is a large saving in expensive antenna-quality substrate material. Considering component cost, the current die cost per mm^2 of 150 nm GaN on SiC fabricated on 4-inch wafers is only 4.5x the cost of 8-inch 130 nm SiGe. As 6-inch GaN production lines shift into high volume, the cost of GaN relative to SiGe drops to 3x. A summary of the assumptions and a cost comparison of the relative raw die cost of the two technologies is shown in ***Table 3***. Using a high-power density compound semiconductor like GaN on 6-inch wafers can save up to 35 percent in the raw die cost relative to an all-SiGe architecture. Even though the cost of silicon technologies is lower per device, the cost of the complete system is significantly higher.



▲ **Fig. 15** **Optimum RFFE technology vs. array size.**

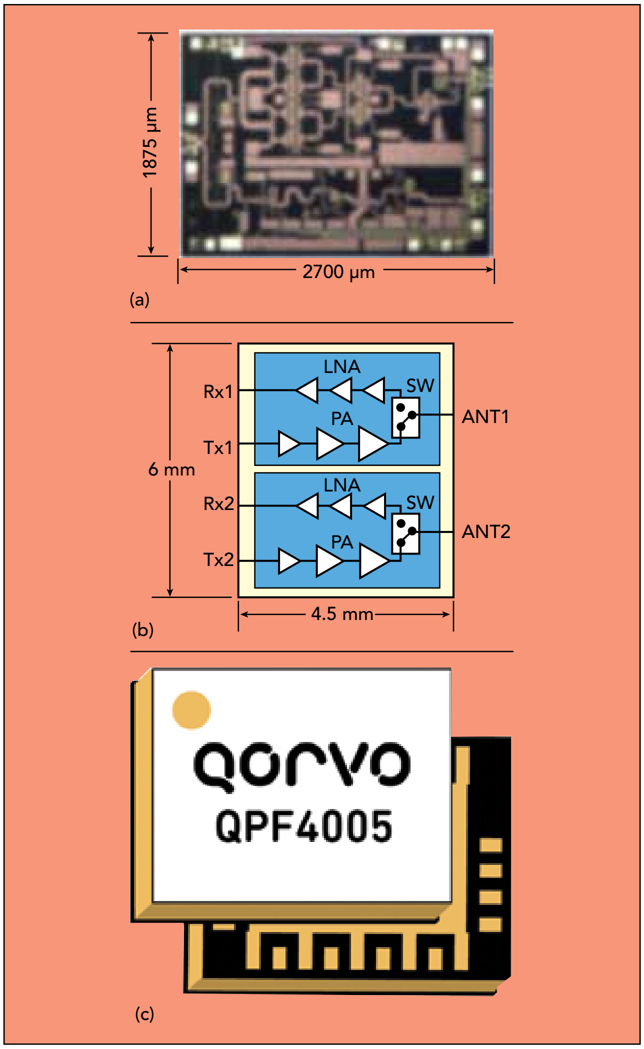


▲ **Fig. 16** **System power dissipation vs. array size and EVM for 64 dBm EIRP.**

GaN FRONT-END MODULES

To validate the concept of a GaN FEM for mmWave FWA arrays, Qorvo set out to design the highest power, lowest NF FEM for the 37 to 40 GHz band. To support the trend to integrated transmit/receive arrays, the front-end includes a PA, integrated T/R switch and a low NF LNA. The module was designed with sufficient gain to be driven by core beamformer RFICs, which have a typical drive level of 2 dBm. The FEM's P_{AVE} of 23 dBm was selected from an analysis similar to that shown in Figure 16, and the P_{SAT} was determined by analyzing the needed headroom to support a back-off linearity of ≥ 33 dBc ACPR, EVM ≤ 4 percent and a 400 MHz orthogonal frequency-division multiple access (OFDMA) waveform.

A key design decision was determining if GaAs or GaN or a combination of both were needed. The die size for a GaAs PA would not allow the FEM to meet the tight 3.75 mm lattice spacing at 39 GHz. The equivalent output power GaN PA is 4x smaller with no sacrifice in gain and a slight benefit in efficiency. Considering the LNA, the 90 nm GaAs PHEMT process was favored due to its slightly superior NF. However, the net improvement was only a few tenths of a dB once the additional bond wires and 50 Ω matching networks were considered. The trade-off analysis concluded it was better to stay with a monolithic GaN design that allowed co-matching of the PA, LNA and T/R switch. Such a design was lower risk, easier to assemble and test, and the MMIC was as compact as possible. The system thermal analysis indicated that the higher junction temperature



▲ **Fig. 17** **Integrated 39 GHz GaN front-end MMIC – intentionally blurred (a), dual-channel FEM (b) and package (c).**

offered by GaN-on-SiC was critical for passively-cooled arrays.

As shown in ***Figure 17***, the 39 GHz FEM integrates two of the multi-function GaN MMICs into an air-cavity, embedded heat-slug, surface-mount package, sized to meet the array element spacing at 39 GHz. Each of the GaN MMICs contains a three-stage linear PA, three-stage LNA and a low-loss, high-linearity SPDT switch. The FEM covers 37.1 to 40.5 GHz and provides 23 dBm average output power, which supports 256-QAM EVM levels, with 24 dB transmit gain. In receive mode, the NF is 4.1 dB, and receive gain is 16 dB. The package size is 4.5 mm × 6.0 mm × 1.8 mm.[7-8]

SUMMARY

FWA is rapidly approaching commercialization. This is due to the abundance of low-cost spectrum, early regulatory and standards work and the opportunity for operators to quickly tap a new market. The remaining challenge is the availability of equipment capable of closing the link at a reasonable cost. Both hybrid beamforming and all-digital beamforming architectures are being explored. These architectures capitalize on the respective strengths of commercial semiconductor processes. The use of GaN front-ends in either approach provides operators and manufacturers a pathway to achieving high EIRP targets while minimizing cost, complexity, size and power dissipation. To prove the feasibility, Qorvo has developed a 39 GHz FEM based on a highly integrated GaN-on-SiC T/R MMIC and is developing similar FEMs for other millimeter wave frequency bands proposed for 5G systems.■

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5G Is Coming: How T&M Manufacturers Can Prepare For and Benefit From 5G

Randy Oltman
Analog Devices Inc., Norwood, Mass.

For many, that headline is both a beacon of hope and a source of trepidation. This is especially true for test equipment manufacturers. While 5G offers the opportunity for healthy growth, there are several factors that will make reaping benefits from this generation of wireless broadband technology more challenging than it was for its predecessors.

Let's start with the current situation for electronic test and measurement (ETM) manufacturers. What generates growth in the wireless ETM business is the combination of new handset models, an increasing volume of annual handset shipments and wireless technology advancements that drive new infrastructure equipment. We have seen a reduction in the growth rate of handset shipments as annual shipment volumes have started to exceed one billion units. At the same time, mergers and acquisitions in the wireless infrastructure industry have reduced the number of customers in that segment. Finally, ETM manufacturers have also been coping with delays in the deployment of LTE-Advanced carrier aggregation in major markets. The result is a slowing market for LTE R&D and production test equipment as the industry awaits the technology shift to 5G (see ***Figure 1***).

5G IS COMING—WITH CHALLENGES

As wireless broadband technology has evolved from generation to generation—especially from feature to feature—ETM manufacturers have often been able to rely on software upgrades to adapt to changes. The move to 5G, however, is seen as a giant stride forward that will require new and far more complex solutions.

Behind the faster speed, reduced latency, increased capacity and improved reliability of 5G are new and less familiar technologies, such as mmWave, massive MIMO and adaptive beamforming—all of which will demand significantly more advanced base stations and customer devices. The most substantial change to the 5G physi-

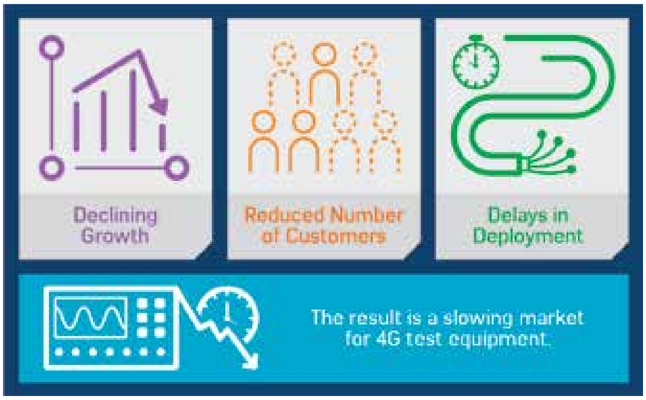


Fig. 1 A slowing market for LTE test equipment has manufacturers eagerly awaiting the acceleration of 5G.

Fig. 2 An African proverb that applies to ETM manufacturers.

cal layer is the option for mmWave transmission coupled with adaptive beamforming, requiring a large number of antenna elements. While mmWave transmission is a familiar technology for point-to-point line-of-sight wireless backhaul, using those frequencies in a cellular topology, where each cell serves hundreds or thousands of mobile users and where many antennas will be integrated into advanced device packaging, is challenging and uncharted territory. It is clear that to research, develop and test the new technologies behind 5G, ETM equipment will have to deliver far more advanced capabilities than previous generations. The ETM challenge is made more difficult by the fact that the 5G standards have not yet been finalized. And, like previous generations of wireless technology, there is the very strong desire by operators to be first with deployed networks, intensifying the need for ETM equipment early in the technology lifecycle.

Normally, this list of challenges would excite and energize an R&D group. However, the slackening growth in LTE ETM equipment has left some manufacturers with far fewer resources to devote to 5G innovation and development.

A PEEK BEHIND THE CURTAIN

While 5G introduces significant hurdles, they are not insurmountable, especially if you subscribe to the wisdom of the African proverb shown in ***Figure 2***. New levels of cooperation can be seen throughout the wireless industry. Instrumentation, wireless infrastructure, semiconductors and software organizations are working together with standards bodies, research organizations and government regulators worldwide to ensure that 5G is a unified standard addressing the many challenging performance goals, including unprecedented speed, connection density and ubiquity. Association with important wireless industry organizations such as ITU and 3GPP, and collaboration with any of the multitude of important research organizations such as NIST and any of the numerous 5G research alliances, is a first step toward greater understanding of the 5G technology trajectory. In addition, ETM manufacturers appear to be gaining a better foothold in the 5G market by forming partnerships and alliances with suppliers.

Moving supplier relationships from highly transactional to being more collaborative can bring greater effectiveness to ETM manufacturers. Knowledge sharing and close collaboration with private companies, including operators and suppliers, is essential to timely delivery of new test products with features that are best aligned with early market needs. Nondisclosure agreements and other proprietary arrangements are giving manufacturers early access to new ideas and emerging technologies, further enabling the technological breakthroughs required to deliver 5G test capabilities.

Component suppliers are providing information to optimize the performance of existing products beyond published data or are going a step further, such as creating part derivatives to meet specific needs. The right partnerships can bolster an ETM organization's strengths with early access to advanced technology. Further, by transferring design work to experienced suppliers, an ETM manufacturer can free up scarce engineering resources, allowing them to focus on their strength of delivering value-added product features.

Combined, the partnering activities outlined above are helping ETM manufacturers get the solutions they need, accelerating their own schedules and, thereby, helping them and their customers succeed.

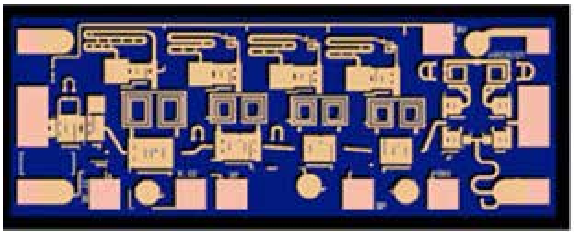
THE CHALLENGES

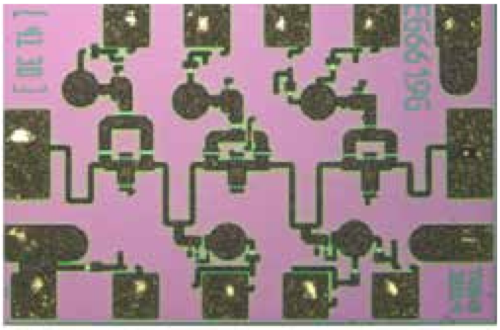
With the desire to reduce time-to-market and meet the demands of 5G, ETM manufacturers need to develop equipment prior to standards being finalized. Because 5G standards will remain in flux for the foreseeable future, working with the right supplier is giving manufacturers access to high performance solutions across the entire signal chain, from mmWave to bits. In that way, even as the 5G standard changes, there will be no need to scrap the original hardware design.

ETM manufacturers will face increased demands for greater capabilities and lower costs. As a result, test products for 5G will be far more complex than those of generations before. Looking beyond individual components to chipsets and system solutions is helping manufacturers squeeze more performance out of limited space and lower cost targets—something especially demanded of modular instrumentation. At the same time, this high level of integration, as well as the increased signal chain count required for MIMO and beamforming, is putting even greater demands on power. By working with suppliers, especially those with the broadest portfolio of products, it is becoming possible to better engineer components into complete signal chain solutions to meet the demanding performance, power, space and time-to-market requirements of tomorrow's instrumentation.

READY OR NOT

5G is an evolutionary leap rather than a simple generational step-up. While questions still remain about what 5G will be when it arrives, there is no doubt that it is on the way. Whether 5G becomes an opportunity for ETM manufacturers will depend heavily on whether they are ready when this new technology arrives. Embracing partnerships and alliances with key suppliers will significantly help ETM manufacturers thrive in the coming 5G market. ■





WHITE PAPER

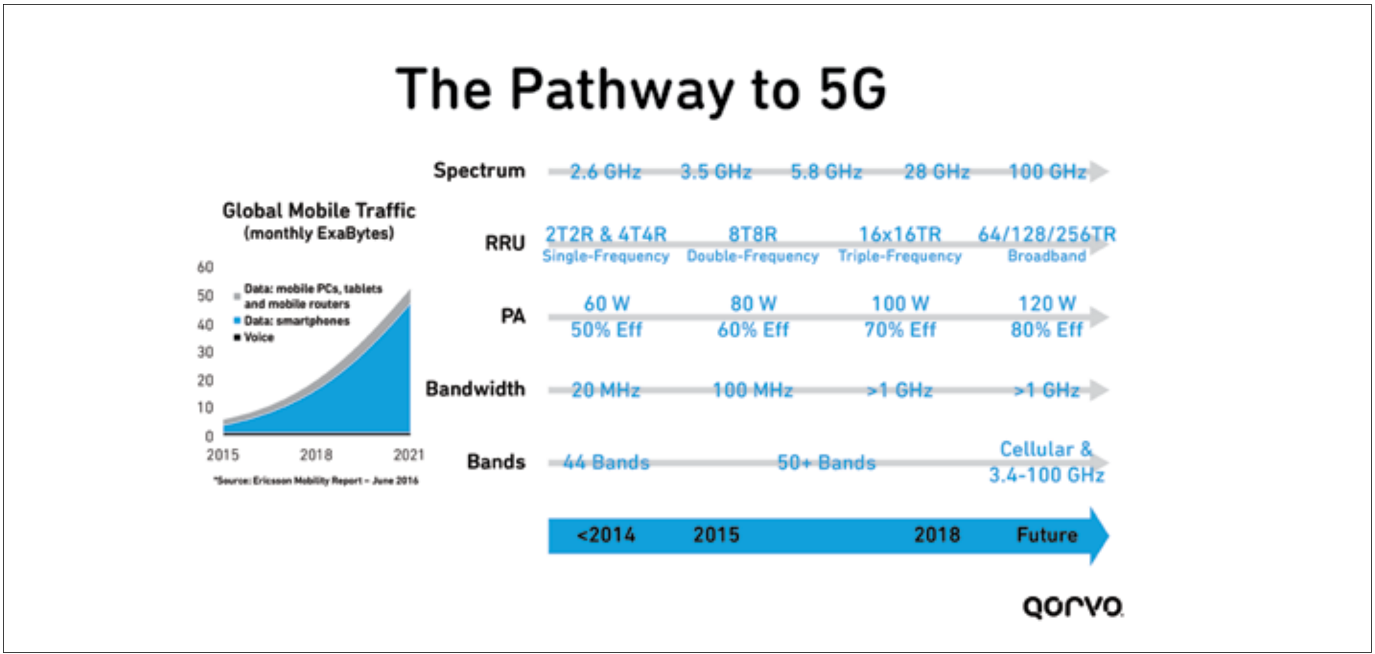
Gallium Nitride – A Critical Technology for 5G

By David Schnaufer and Bror Peterson, Qorvo

Introduction

Carrier providers talk a lot about how their individual networks provide higher capacity, lower latency, and ubiquitous connectivity. And, while today's networks certainly are better than previous generations, providers still have much to accomplish when it comes to the promises of 5G – less than 1 ms latency, 100x network energy efficiency, 20 Gbps peak data rates, and 10 Mps/m^2 area traffic capacity. Scheduled for commercial launch in 2020, 5G is expected to offer all of these significant advantages, including a more 'green' and efficient communication network.

The graph below illustrates several 5G objectives, including increased power, frequency ranges up to 100 GHz and higher efficiency. Attaining these 5G objectives requires a progression of technology and system design.

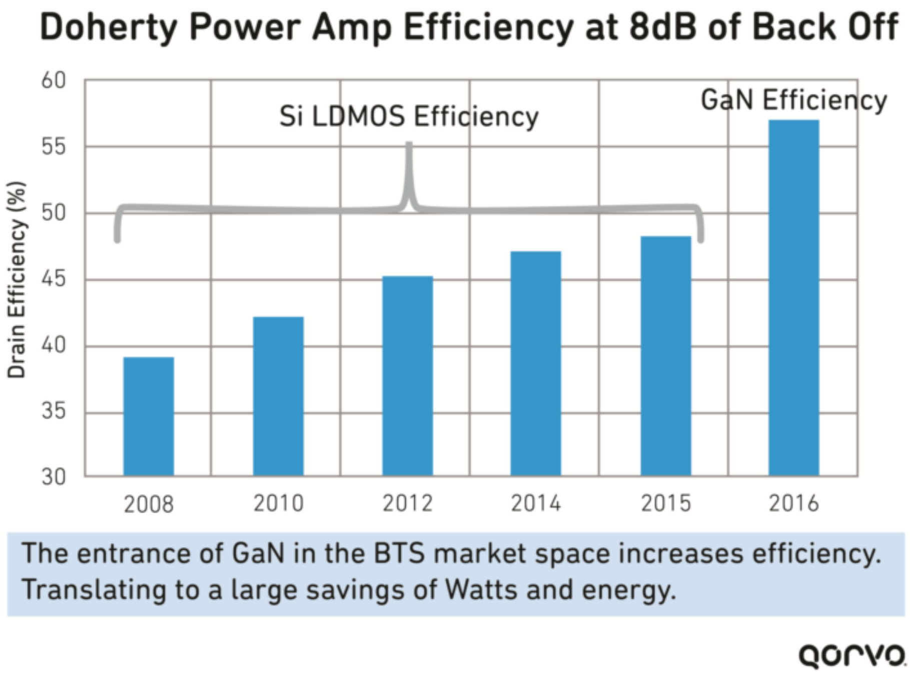


GaN's Superior Properties

In our **last quarterly article**, we discussed ways in which the telecom industry is focused on energy efficiency for 'green' communications. We explored how MIMO, beamforming, and small cells increase efficiency, making a telecom network that's more environmentally friendly overall. We also highlighted how much of the network energy consumption comes from the RF chain.

So, how do we achieve the RF chain 5G objectives and meet 'green' network goals?

Enter RF Gallium Nitride (GaN) – an efficient, wide-bandgap, reliable PA technology making year-over-year strides toward network efficiency. As displayed in the graph below, the introduction of GaN in the base transceiver station (BTS) ecosystem provides a sharp increase in front-end efficiency, making it a new go-to technology for both high- and low-power applications.



GaN offers superior properties of high power density, power added efficiency (PAE), gain, and ease in impedance matching, which improves overall efficiency in the RF chain. Like designers of Formula One race cars, wireless engineers meticulously tweak and tune their RF systems to extract every ounce of performance. By starting with a fundamentally better semiconductor technology, performance targets can be achieved at vastly improved energy efficiency.

5G and GaN

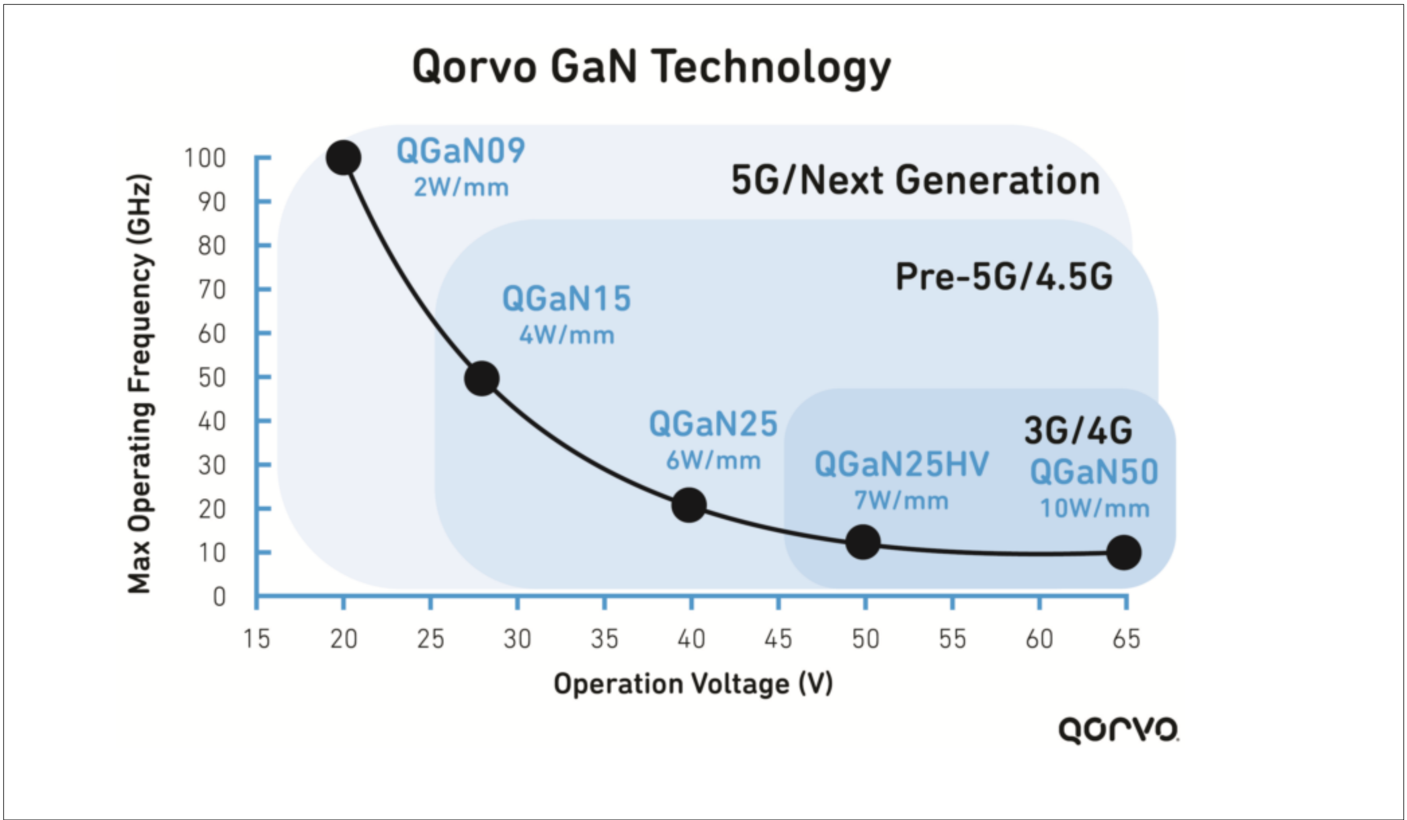
The build-out of 4G LTE networks is maturing, but there are many upgrades that will bridge the gap to 5G. We currently are in the 5G definition and proof-of-concept phase, but **companies like Verizon** are accelerating the timetable for early deployments focused on fixed-wireless access.

Early 5G trials began in 2013, and data from these and more recent experiments are now frequently published.

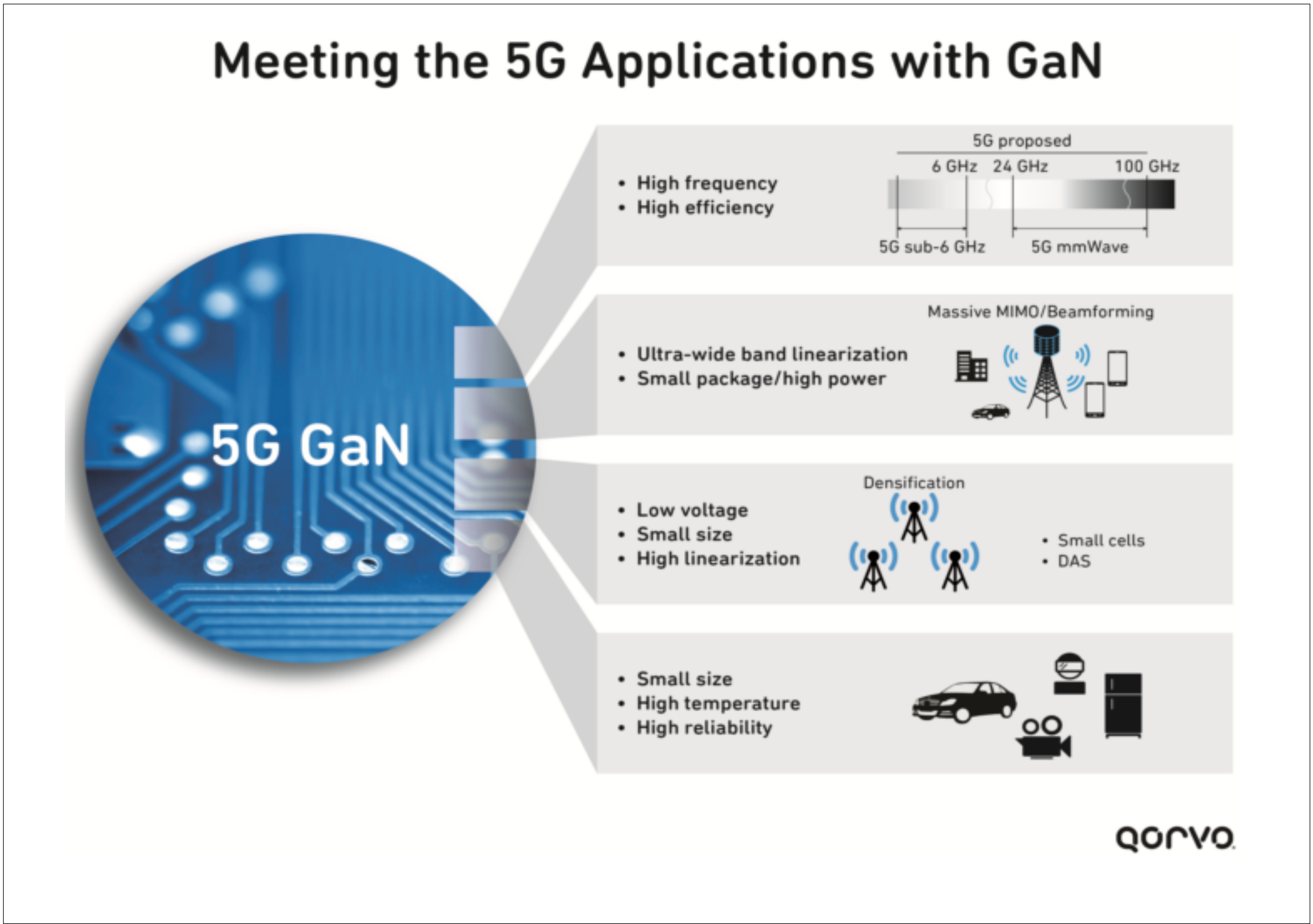
Key technologies offering promising results in mmWave, massive MIMO antenna arrays, and beamforming are already in pre-commercial development. All of the base station OEMs are in the product trial mode. Companies like Qualcomm and Intel are testing 5G-enabled modems, such as the **X50 modem**, which works in the 28 GHz band. **Qorvo and NanoSemi** have published demonstration data on ultra-wide linearization of GaN devices for massive MIMO applications.

These forward-looking companies are dialing in major 5G system architectures, frequency bands, and enabling technologies to find the proper balance of cost, performance, and complexity.

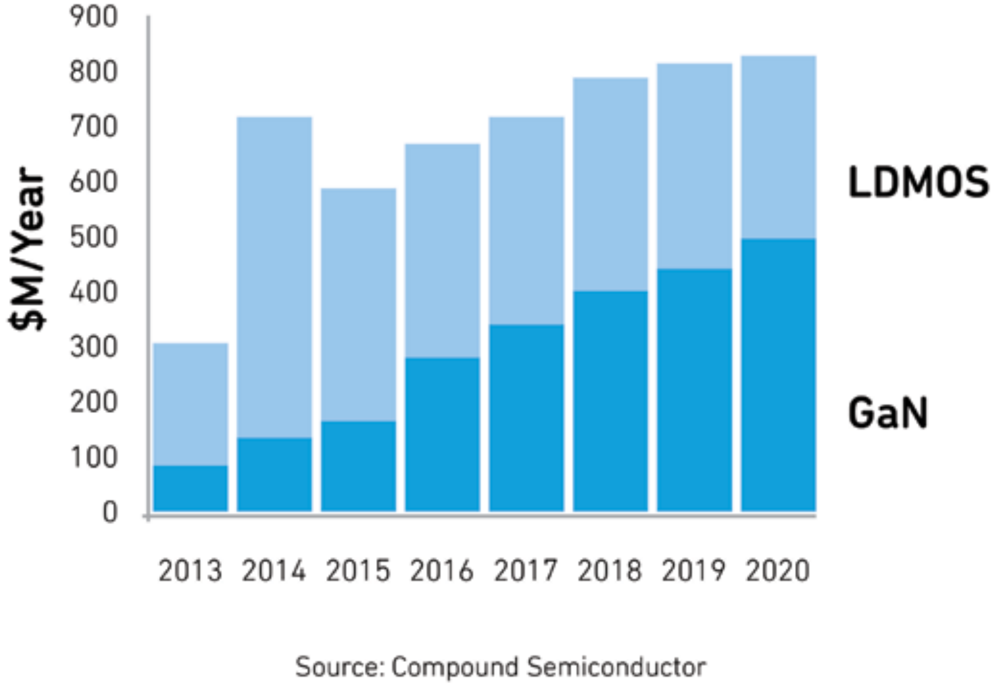
To meet the diverse set of 5G requirements, GaN manufacturers need to offer several variations that span a broad range of frequencies and power levels. With more than one GaN process to choose from, a designer can optimally match a GaN technology to an application. The graph below examines Qorvo's capabilities in this realm.



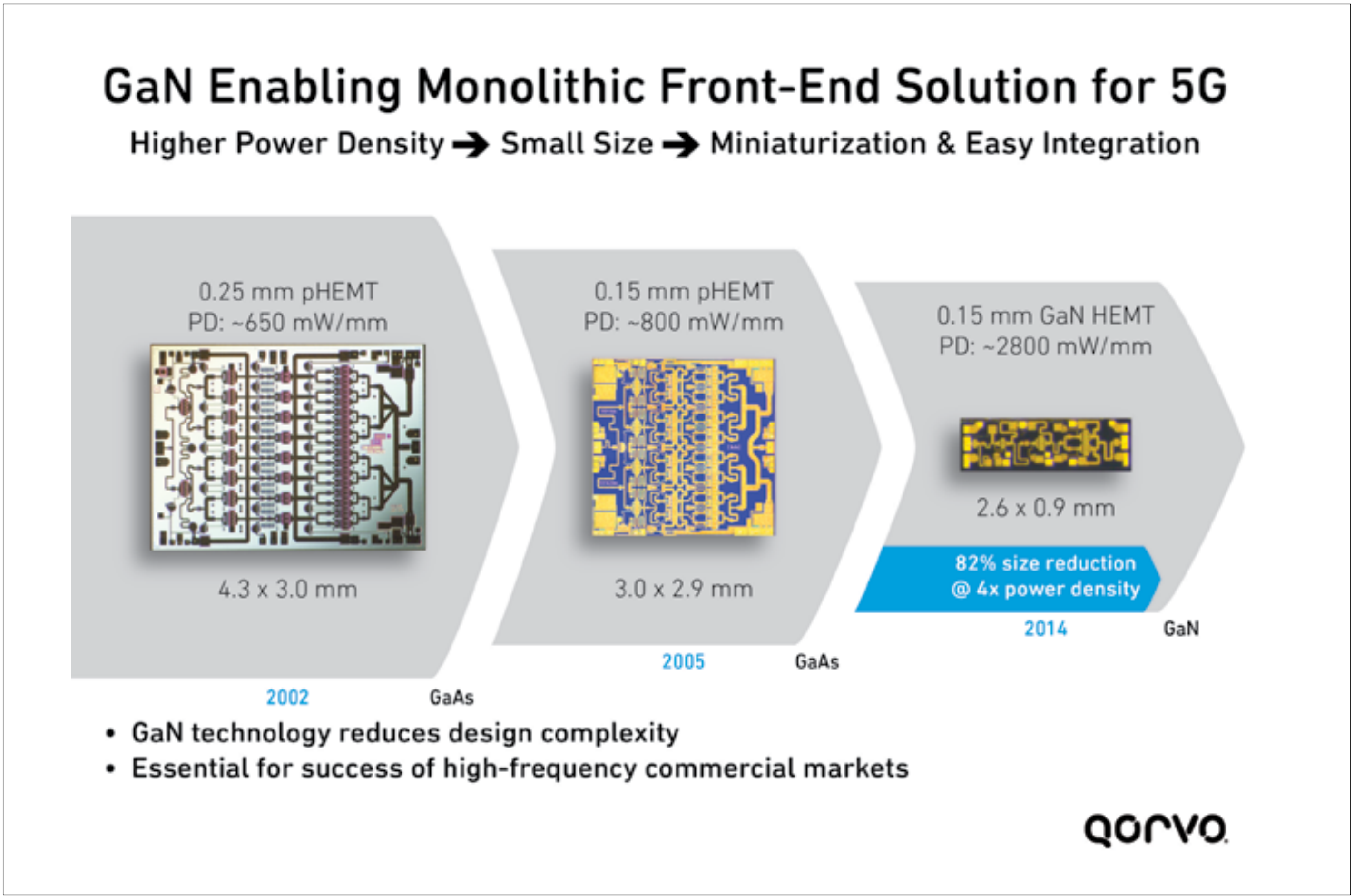
As Qorvo's Doug Reep mentioned in a **previous article**, GaN will overtake traditional semiconductor materials for 5G network applications like small cells, which require higher frequencies, tight integration, and minimal implementation cost. He also goes on to proclaim that the efficiency offered by low-voltage GaN will inevitably make its way into the mobile handset. With properties including operating in high-temperature environments, GaN is well suited for passively cooled, all-outdoor tower-top base station electronics and automobile applications. Overall, having a wide array of GaN technology choices will mean more applications being serviced.



Today, GaN is heavily used in the small cell and BTS market space and continues its upstream ascent in 2016. **GaN shipments** are estimated to reach near $300M in 2016, well above the 2015 mark of $150M. Small cell, distributed antenna system (DAS), and remote radio head network densification deployments play a big role in this trend.



The incentives of untapped spectrum, high throughput, and low latency goals are enticing developers to migrate toward higher mmWave frequency bands. The mmWave spectrum bands provide 10-30 times the bandwidth of current 4G frequency bands (<4 GHz), and network capacity is directly proportional to the available bandwidth.



GaN is well suited for both the high frequency and the wide bandwidth required in the mmWave arena. It can fulfill the performance and small size requirements, as illustrated above. Applications using mmWave frequency bands will require highly directional beam-forming technology (beam-forming focuses the radio signal into a highly directive beam, which boosts power and minimizes interference at the user device). This means that the RF subsystems will require a large number of active elements driving a relatively compact aperture. GaN is ideally suited for these applications, since powerful performance in a small package size is one of its most notable traits.

When 5G comes to fruition in 2020, we will all find out what capabilities and advantages follow. Today, the trials, initiatives, discussions, and demonstrations continue to aid in defining the 5G standard. But tomorrow, the reality of ubiquitous, sub-1-ms latency and extremely high capacities will be in our everyday lives. Whatever the outcome, it is apparent that GaN will be a critical technology in 5G applications.

About the Authors

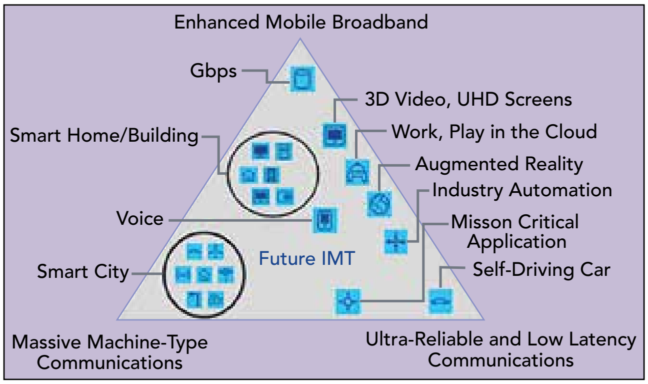
David Schnaufer
David Schnaufer is Qorvo's technical marketing communications manager. Over the last 15 years, David has worked for Qorvo. From 2013 to 2015, David served as product marketing manager for the Advanced Filters group in Qorvo. Prior to 2013, David worked as a senior manager of strategic marketing, global applications engineering, and global customer quality engineering manager. He earned an MBA in technology and business management from the University of Phoenix, a BA in business administration from Belmont Abbey College, and an electronics engineering degree.

Bror Peterson
Bror Peterson is a principle systems engineer with Qorvo Inc. located in Richardson Texas. He is currently focused on mmWave 5G base-station RF system analysis and product development. He received a Master of Science in Electrical Engineering degree from Virginia Tech in 2000. He has been involved with research, design, and development of wireless infrastructure systems for over 17 years with a broad background in communications theory and systems analysis.

Pre-5G and 5G: Will The mmWave Link Work?

Andreas Roessler
Rohde & Schwarz, Munich, Germany

Any next-generation mobile communications technology has to provide better performance than the previous generation. With the transition from 3G to 4G, for example, theoretical peak data rates spiked from around 2 Mbps to 150 Mbps. Subsequently, LTE-Advanced Pro has reached Gbps peak data rates, with 1.2 Gbps data throughput recently demonstrated.[1] In a recent survey on 5G conducted by Qualcomm Technologies and Nokia,[2] 86 percent of the participants claimed that they need or would like faster connectivity on their next-generation smartphones. The conclusion that can be drawn from this is that data rates are always a driver for technology evolution.



▲ **Fig. 1 5G application scenarios defined by IMT-2020.**

But 5G is not only targeting higher data rates. The variety of applications that can be addressed with this next generation is typically categorized into what is commonly called the "triangle of applications," shown in ***Figure 1***. The hunt for higher data rates and more system capacity is summarized as enhanced mobile broadband (eMBB). Ultra-reliable low latency communications (URLLC) is the other main driver, with an initial focus on low latency. The requested lower latency impacts the entire system architecture—the core network and protocol stack, including the physical layer. Low latency is required to enable new services and vertical markets, such as augmented/virtual reality, autonomous driving and "Industry 4.0." The triangle is completed by massive machine-type communication (mMTC); however, initial standardization efforts are focusing on eMBB and URLLC. All these applications have different requirements and prioritize their key performance indicators in different ways. This provides a challenge, as these different requirements and priorities have to be addressed simultaneously with a "one fits all" technology.

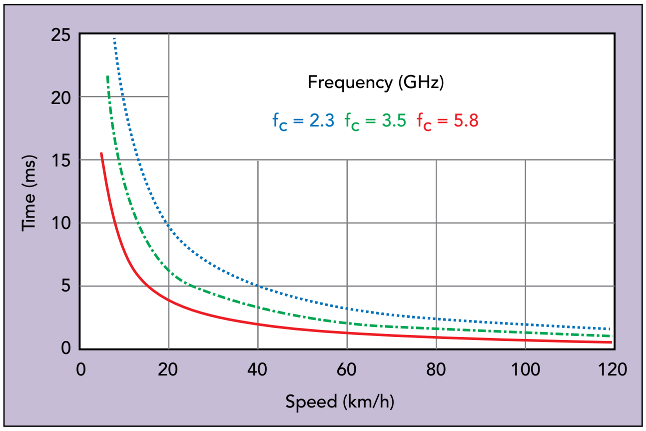


Fig. 2 Coherence time vs. speed for three carrier frequencies below 6 GHz.

PRE-5G VS. 5G

It takes quite some time to define a "one fits all" technology within a standardization body, such as the 3rd Generation Partnership Project (3GPP). Several hundred companies and organizations are contributing ideas recommending how the challenges and requirements of 5G should be addressed. The proposals are discussed and evaluated and, finally, a decision is made on how to proceed. At the beginning of defining a new technology and standard that address the radio access network, air interface and core network, the process can be quite time consuming—time that some network operators do not have.

Often, one application is addressed and, in that case, a standard is developed that targets just one scenario. LTE in unlicensed spectrum (LTE-U) is one example in 4G. The goal was to easily use the lower and upper portion of the unlicensed 5 GHz ISM band to create a wider data pipe. 3GPP followed with its own, standard-embedded approach called licensed assisted access (LAA) about 15 months later. 5G is no different. Fixed wireless access (FWA) and offering "5G services" at a global sports event like the 2018 Winter Olympic Games in Pyeongchang, South Korea are two examples within the 5G discussion. For both, custom standards were developed by the requesting network operator and its industry partners. Both these standards are based on LTE, as standardized by 3GPP with its Release 12 technical specifications, enhanced to support higher frequencies, wider bandwidths and beamforming technology.

Take the example of FWA. The network operator behind this requirement is U.S. service provider Verizon Wireless. Today's service providers do not just offer traditional landline communications and wireless services; they also supply high speed internet connections to the home and are expanding into providing content through these connections. Verizon's initial approach to bridge the famous "last mile" connection to the home was fiber to the home (FTTH). In some markets, Verizon sold that business to other service providers, such as Frontier Communications.[3] To enhance its business model, Verizon is developing its own wireless technology for high speed internet connections to the home. To be competitive and stay future proof, Gbps connections are required that outperform what is possible today with LTE-Advanced Pro.

The achievable data rates over a wireless link depend on four factors: the modulation, achievable signal-to-noise ratio (SNR), available bandwidth and whether multiple-input-multiple-output (MIMO) antenna technology is used. From the early 90s to the millennium, the wireless industry optimized its standards to improve SNR and, thus, data rates. At the turn of the century and with the success of the Internet, this was no longer acceptable; bandwidth was increased up to 5 MHz with 3G. Initially with 4G, wider bandwidth—up to 20 MHz—was introduced, as well as 2 × 2 MIMO. Today, with higher-order modulation up to 256-QAM, 8 × 8 MIMO and bundling multiple carriers in different frequency bands using carrier aggregation (CA), peak data rates have reached 1.2 Gbps. To further increase data rates, for the use case of FWA, in particular, wider bandwidths are required. This bandwidth is not available in today's sweet spot for wireless communications—between 450 MHz and 6 GHz. More bandwidth is only available at higher frequencies with centimeter and mmWave wavelengths. But there is no free lunch. Moving up in frequency has its own challenges.

HIGH FREQUENCY CHALLENGES

Analyzing the free space propagation loss (FSPL), path loss increases as frequency increases. Wavelength (λ) and frequency (f) are connected through the speed of light (c), i.e.,

$$\lambda f = c$$

and as frequency increases, wavelength increases. This has two major effects. First, with decreasing wavelength the required spacing between two antenna elements (usually λ/2) decreases, which enables the design of practical antenna arrays with multiple antenna elements. The higher the order of the array, the more the transmitted energy can be focused in a specific direction, which allows the system to overcome the higher path loss experienced at cmWave and mmWave frequencies. The second effect relates to propagation. Below 6 GHz, diffraction is typically the dominating factor affecting propagation. At higher frequencies, the wavelengths are so short that they interact more with surfaces, and scattering and reflection have a much greater effect on coverage.

mmWave frequencies also challenge mobility. Mobility is dependent on the Doppler shift, f_d, defined by the equation:

$$f_d = f_c v/c$$

where f_c is the carrier frequency and v is the desired velocity that the system supports. The Doppler effect is directly related to the coherence time, $T_{coherence}$, which may be estimated with the approximation:

$$T_{coherence} \cong 1/(2f_d)$$

Coherence time defines the time the radio channel can be assumed to be constant, i.e., its performance does not change with time. This time impacts the equalization process in the receiver. As shown in ***Figure 2***, the coherence time decreases with increasing speed. For example, to drive 100 km/h and maintain the link at a carrier frequency of 2.3 GHz, the coherence time is about 2 ms. That means the radio channel can be assumed to be constant for 2 ms. Applying the Nyquist theorem, with a time period of 2 ms, two reference symbols need to be embedded in the signal to properly reconstruct the channel. Figure 2 shows that coherence time decreases at higher frequencies. For cmWave frequencies, the Doppler shift is already 100 Hz at walking speed, and it increases with higher velocity. Thus, the coherence time decreases significantly, making the use of cmWave and mmWave frequencies in high-mobility scenarios inefficient. This is the major reason why 3GPP's initial focus standardizing the 5G new radio (5G NR) is on the so called non-standalone (NSA) mode, using LTE as the anchor technology for the exchange of control and signaling information and for mobility. With FWA, mobility is not required, so Verizon's technology approach can completely rely on mmWave frequencies, together with the exchange of control and signaling information between the network and connected device.

28 GHz LINK BUDGET

As explained, the use of antenna arrays and beamforming enables the use of mmWave frequencies for wireless communication. Verizon targets the 28 GHz frequency band that was allocated by the FCC as 5G spectrum in 2016,[4] with a bandwidth up to 850 MHz. With its acquisition of XO Communications in 2015,[5] the operator gained access to 28 GHz licenses and is planning to use these for its initial roll-out of its own (Pre-)5G standard, summarized under the name 5G Technical Forum.[6]

From an operator's perspective, the viability of a new technology depends on fulfilling the business case given by the business model. The business case is governed by two main factors: the required capital expenditure (CAPEX), followed by the cost to operate and maintain the network, referred to as OPEX. CAPEX is driven by the number of cell sites deployed, which depends on the required cell edge performance (i.e., the required data rate at the cell edge) and the achievable coverage. cmWave and mmWave allows beamforming that helps overcome the higher path loss, but coverage is still limited compared to frequencies below 6 GHz, the primary spectrum being utilized for wireless communications.

To ensure adequate coverage, a link budget analysis is essential. Considering the 28 GHz band with 100 MHz carrier bandwidth, first the receiver sensitivity limit is calculated. The thermal noise level is -174 dBm/Hz and needs to be adjusted to the supported bandwidth of 100 MHz per component carrier, as defined in the 5GTF standard. In this calculation, the typical noise figure used for the receiver is 10 dB, which results in an overall receiver sensitivity limit of -84 dBm/100 MHz (see ***Table 1***). Next, the expected path loss is determined. Free space path loss is based on a line-of-sight (LOS) connection under ideal conditions. In reality, this is not the case, so extensive channel sounding measurement campaigns have been executed by various companies with the help of educational bodies, resulting in channel models describing the propagation in different environments and predicting the expected path loss. These are typically for LOS and non-LOS (NLOS) types of connections. With FWA, NLOS connections are normally used. Early on, Verizon and its industry partners used their own channel models, despite 3GPP working on a channel model for standardizing 5G NR. There are, of course, differences between these models. For the link budget analysis considered here, one of the earliest available models is used.[7]

TABLE 1

RECEIVER SENSITIVITY LIMIT

Thermal Noise Level (kT)	−174 dBm/Hz
Bandwidth Correction (100 MHz)	80 dB
Typical User Equipment Noise Figure	10 dB
Receiver Sensitivity Limit	−84 dBm

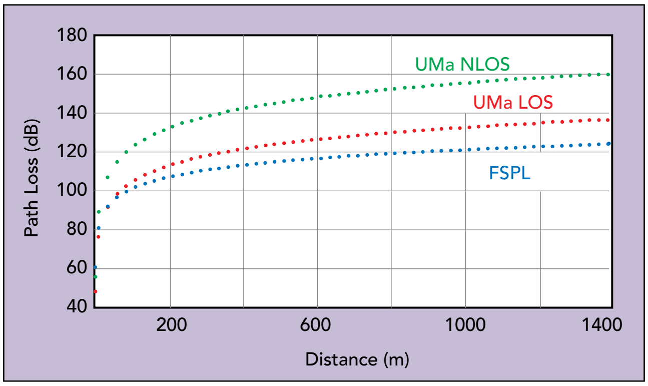


Fig. 3 28 GHz path loss vs. cell separation, comparing FSPL with LOS and NLOS for an urban macro deployment, using the ABG channel model.

Assuming an urban macro (UMa) deployment scenario, ***Figure 3*** displays the expected path loss at 28 GHz for LOS and NLOS connections compared to FSPL. From an operator's perspective, a large intercell site distance (ISD) is desired, since the higher the ISD, the fewer cell sites are required and the lower the CAPEX. However, the link budget determines the achievable ISD. Various publications show that an ISD of 1000 m is a deployment goal. Such an ISD results in a path loss of at least 133 dB for LOS and 156 dB for NLOS links using the alpha beta gamma (ABG) channel model. The next step is to decide on the required cell edge performance, i.e., the required data rate. The data rate per carrier depends on the modulation, MIMO scheme and achievable SNR. A typical requirement is, for example, to achieve a spectral efficiency of 2 bps/Hz, i.e., 200 Mbps for a 100 MHz wide channel. To achieve this, an SNR of around 8 dB is required, which increases the receiver sensitivity limit further. However, as the receiver is using an antenna array, beamforming gain is available, determined by the gain of a single antenna element and the total number of elements. A good approximation in this early stage of 5G development is 17 dBi for the total receive beamforming gain. Based on the

TABLE 2 28 GHz DOWNLINK LINK BUDGET		
Parameter	**Assumptions**	**Value**
Receiver Sensitivity Limit	100 MHz	–84 dBm
Required SNR	16-QAM, ½ FEC	8 dB
Total Array Gain	16 Elements	17 dB
Estimated Path Loss	1000 m ISD	133 to 156 dB
Required Transmit EIRP*		40 to 63 dBmi

*EIRP = Receiver Sensitivity + SNR – Rx Antenna Gain + Path Loss

TABLE 3 REQUIRED MINIMUM CONDUCTED POWER	
Required Tx EIRP	40 to 63 dBm
Array Size	64
Beamforming Array Gain	17 dB
Single Element Gain (Typically 5 to 8 dBi)	6 dBi
Minimum Conducted Power	17 to 40 dBm

TABLE 4 28 GHz UPLINK LINK BUDGET	
Total Tx EIRP	40 dBm
Path Loss	133 to 156 dB
Bandwidth	100 MHz
Thermal Noise	–94 dBm
Rx Noise Figure	6 dB
Minimum Detectable Signal	–88 dBm
Required SNR with QPSK and ½ FEC	5 dB
Total Rx Beamforming Gain	24 dBi
100 MHz Rx Signal Bandwidth	–107 dBm
Link Margin*	–9 to +14 dB

*Link Margin = Total Tx EIRP – Path Loss – Rx Signal

estimated path loss, the required total equivalent isotropic radiated power (EIRP) and the required conducted transmit power can be determined. Given the above calculations, the required total EIRP for the transmit side is between 40 and 63 dBm (see ***Table 2***). It is a fair assumption that using a larger antenna array at the 5G remote radio head results in larger beamforming gain. ***Table 3*** provides an ideal calculation of what conducted power is required to provide the required EIRP (17 to 40 dBm). For mmWave components, these are high output powers, and it is a challenge to the industry to design power amplifiers and the required circuitry to drive the RF front-end and antenna arrays. As not all substrates can provide such a high output power, the industry faces a philosophy battle among companies designing these RF components. One of the challenges is to provide components with an acceptable power-added efficiency to handle the heat dissipation.

Based on this analysis, establishing a viable communication link in the downlink direction with an ISD of 1000 m is possible. However, previous generations

TABLE 5 V5GTF VS. LTE PHY COMPARISON		
PHY Parameter	***LTE Release 8-14***	***Verizon 5G TF***
Downlink (DL) Modulation	OFDM	OFDM
Uplink (UL) Modulation	DFT-S-OFDM (SC-FDMA)	OFDM
Subframe Length	1 ms	0.2 ms
Subcarrier Spacing	15 kHz	75 kHz
Sampling Rate	30.72 MHz	153.6 MHz
Bandwidth	20 MHz	100 MHz
NFFT	2048	2048
OFDM Symbol Duration, No CP	66.67 μs	13.33 μs
Frame Length	10 ms	10 ms
# of Subframes/Slots	10/20	50/100
CP Type	Normal and Extended	Normal Only
Multiplexing	FDD/TDD	Dynamic TDD
Maximum RBs	6, 15, 25, 50, 75, 100	100
DL/UL Coding	Turbo	LDPC

of wireless technologies were uplink power limited, and 5G is no exception. ***Table 4*** shows the uplink link budget assuming a maximum conducted device power of +23 dBm and the form factor of a customer premise equipment (CPE) router with a 16-element antenna array. Depending on the path loss and the assumed channel model, a link margin can be calculated that spans quite a range (i.e., -9 to +14 dB). Everything below zero indicates, of course, that the link cannot be closed. Based on these rather ideal calculations, it can be concluded that an uplink at mmWave frequencies with an ISD of 1000 m is problematic.

For that reason, 3GPP defines a 5G NR user equipment (UE) power class that allows a total EIRP of up to +55 dBm.[8] Current regulations in the U.S. allow a device with such a high EIRP but not in a mobile phone form factor.[9] However, achieving this EIRP is a technical challenge by itself and may come to the market at a much later stage. From that perspective, a service provider should consider a shorter ISD in its business case. Current literature and presentations at various conferences indicate that cell sizes of 250 m or less are being planned for the first-generation of radio equipment. Now it needs to be determined if a shorter ISD, such as 250 m, fulfills the business case for 5G mmWave FWA.

5GTF INSIGHTS

The Verizon 5G standard uses the existing framework provided by 3GPP's LTE standard. Moving up in carrier frequency and factoring the increasing phase noise at higher frequencies, wider subcarrier spacing is required to overcome the inter-carrier interference (ICI) that will be created. The Verizon standard uses 75 kHz instead of 15 kHz. A comparison of all major physical layer parameters is given in ***Table 5***.

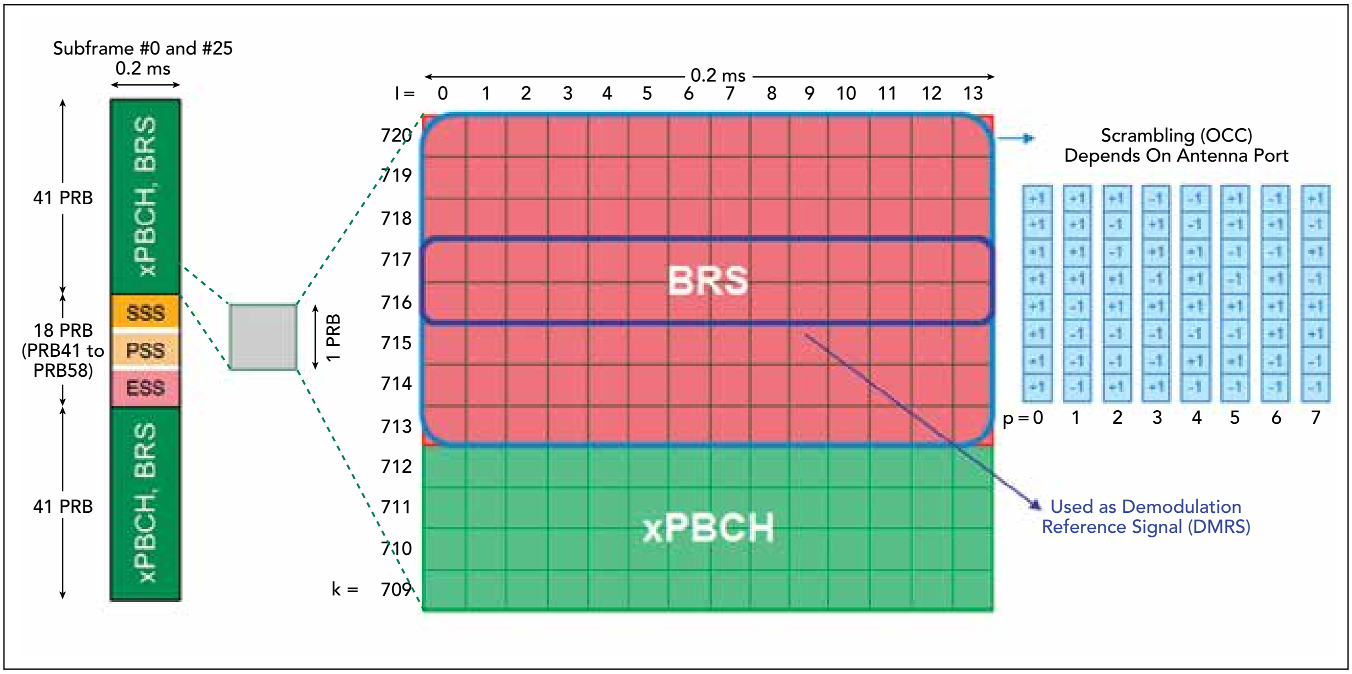


Fig. 4 5GTF synchronization and beamforming reference signals.

In determining 5G network coverage, several physical signals should be understood. Compared to LTE, the synchronization signals (PSS and SSS) are transmitted in Verizon's 5G standard in a frequency-division multiplexing (FDM) technique, versus the time-division multiplexing (TDM) approach for LTE. Also, a new synchronization signal is introduced, the extended synchronization signal (ESS) that helps to identify the orthogonal frequency-division multiplexing (OFDM) symbol timing. ***Figure 4*** shows the mapping of the synchronization signals (SSS, PSS, ESS) contained in special subframes 0 and Z5; they are surrounded by the beamforming reference signal (BRS) and extended physical broadcast channel (xPBCH).

A device uses the synchronization signals during the initial access procedure to determine which 5G base station to connect to and then uses the BRS to estimate which of the available beamformed signals to receive. The standard allows for a certain number of beams to be transmitted, the exact number depending on the BRS transmission period. This information is provided to the device via the xPBCH. In its basic form, one beam is transmitted per OFDM symbol; however the use of an orthogonal cover code (OCC) allows for up to eight beams per OFDM symbol. Depending on the selected BRS transmission period —there are four options: one slot, one, two or four subframes—multiple beams can be transmitted, on which the CPE performs signal quality measurements. Based on these BRS received signal power (BRSRP) measurements, the CPE will maintain a set of the eight strongest beams and report the four strongest ones back to the network. In general, the same principles apply as for determining coverage for existing 4G LTE technology. A receiver (network scanner) first scans the desired spectrum, in this case 28 GHz, for synchronization signals to determine the initial timing and physical cell ID that is provided by PSS and SSS. The ESS helps to identify the OFDM symbol timing. The next step is to perform quality measurements—same as a CPE would do —on the BRS to determine which has the best receive option and maintain and display the set of eight strongest received beams.

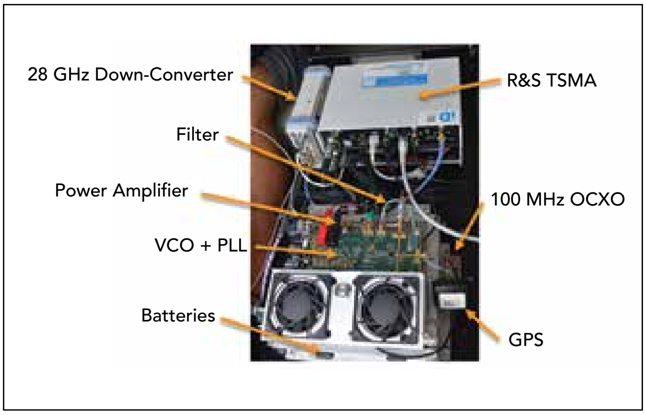


Fig. 5 R&S 5GTF coverage measurement system.

Due to the aggressive timeline for early 5G adopters, Rohde & Schwarz has designed a prototype measurement system that uses an ultra-compact drive test scanner covering the frequency bands up to 6 GHz. This frequency range is extended by using a down-conversion approach: down-converting up to eight 100 MHz wide component carriers transmitted at 28 GHz into an intermediate frequency range that can be processed by the drive test scanner. The entire solution is integrated into a battery-operated backpack, enabling coverage measurements in the field, for example, in office buildings. ***Figure 5*** shows the setup and its components, and ***Figure 6*** shows the scanner being used during a walk test in a residential neighborhood.

An example of the measurement results is shown in ***Figure 7***. In the screen to the right, the eight strongest beams for all detected carriers (PCI) are plotted, includ-

Fig. 6 Using the R&S system in the field.

ing the discovered beam index. The two values below the actual bar show the PCI (top), secondly the beam index. The beams are organized based on the best carrier-to-interference ratio (CINR) being measured for the BRS, rather than BRSRP. At the top of the screen, the user can enter a particular PCI and identify the eight strongest beams for that carrier at the actual measurement position. Also, the scanner determines the OFDM symbol the beam was transmitted in, as well as which OCC was used. Based on the measured BRS CINR, a user can predict the possible throughput at the particular measurement position. Next is the measured synchronization power and CINR for the synchronization signals. In a mobile network, based on the CINR, a device would determine if the detected cell is a cell to camp on. That is usually determined based on a threshold defined as a minimum CINR based on the synchronization signals. This is –6 dB for LTE and, for pre-5G, is being evaluated during the ongoing field trials. In Verizon's 5GTF standard, the synchronization signals are transmitted over 14 antenna ports that ultimately point these signals in certain directions. Therefore, the application measures and displays synchronization signal power, CINR and, in addition, the identified antenna port.

SUMMARY

As discussed throughout this article, the business case for using mmWave frequencies in a FWA application scenario stands or falls depending on whether the link budget can be fulfilled at an affordable ISD. When deploying 5G FWA, network equipment manufacturers and service providers will require optimization tools to determine the actual coverage before embarking on network optimization.■

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Fig. 7 Example 5GTF coverage measurements.