all around you

Defining What's Possible

The Path to 5G

5G: The Future of RF

Beyond Smartphones to Smart Everything

At Qorvo, we aim to improve lives, solve problems and simplify. We help customers at the center of communication - building solutions that meet the growing demands of a connected world. We're helping shape the global 5G standard as a platform for a new era of connectivity. We deliver core RF technologies and innovative products that will enable 5G end to end, from wireless infrastructure to mobile devices. Partnering with customers, carriers and standards bodies, we'll bring the vision to life.

What 5G Is

5G is massively broadband reaching into frequencies never previously thought of for mobile wireless - above 3.4 GHz, and even to 30 GHz and beyond.

5G is wireless infrastructure using beam steering and high-power GaN, based on the technologies in phased-array antennas for defense.

5G is ultra efficient for streaming data, taking full advantage of carrier aggregation and massive MIMO.

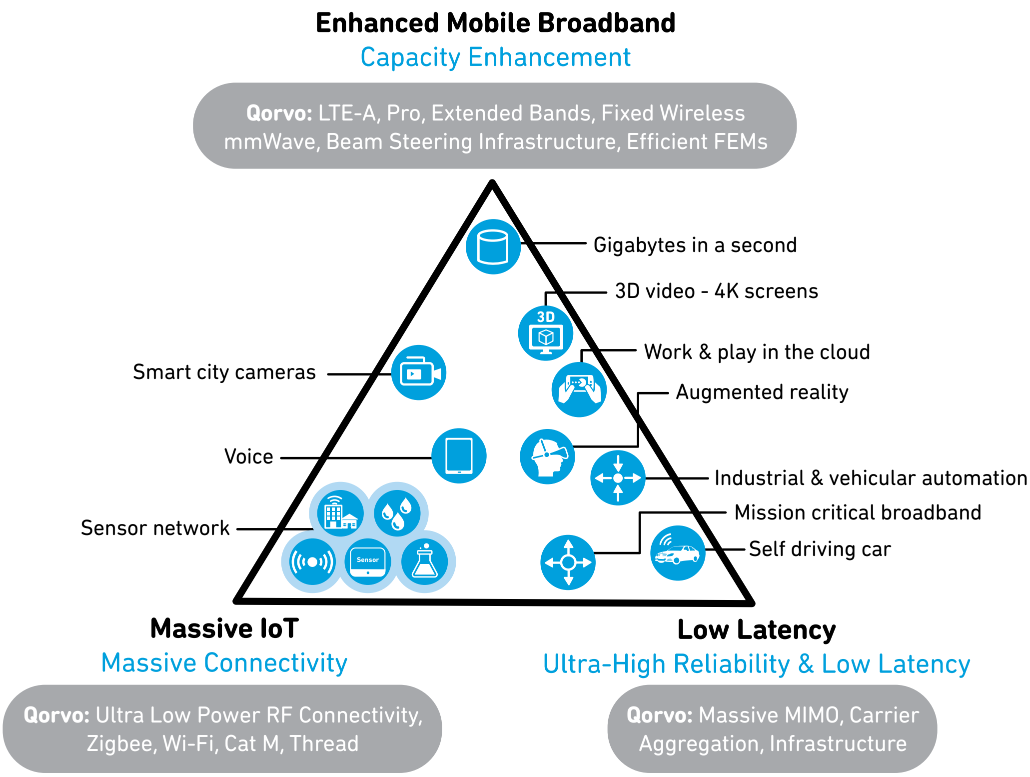
5G is low-latency for real-time connections enabling autonomous vehicles and augmented/virtual reality.

5G is fixed wireless giving more choices to get 1 Gb/s connections to your home and business.

5G is the backbone of the Internet of Things connecting more than a trillion devices to the internet in the next 10 years.

Connecting the Uses of 5G

Qorvo connects RF for all 5G use cases - more than just cellular and Wi-Fi.



(Source: Qorvo, Inc., from ITU-R IMT 2020 requirements)

Gallium Nitride (GaN): 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.

GaN's Superior Properties

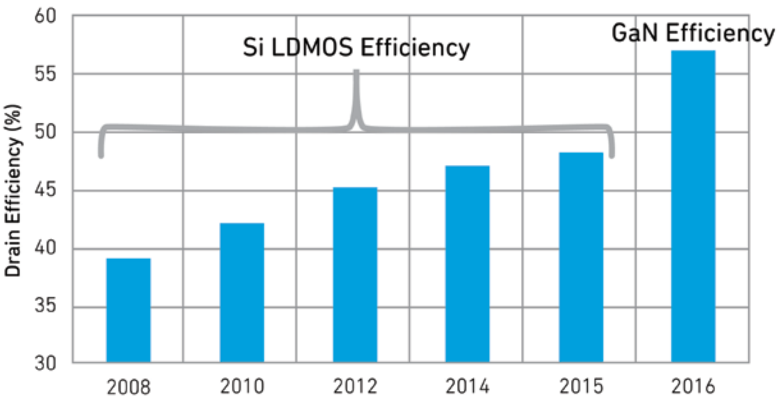
In our last quarterly article, we discussed ways in which the telecom industry is focused on energy efficiency for 'green' communications. We explored how MIMO, beamforming, and small cells increase efficiency, making a telecom network that's more environmentally friendly overall. We also highlighted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

Doherty Power Amp Efficiency at 8dB of Back Off



The entrance of GaN in the base station market space increases efficiency. This translates to a large savings of Watts and energy.

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.

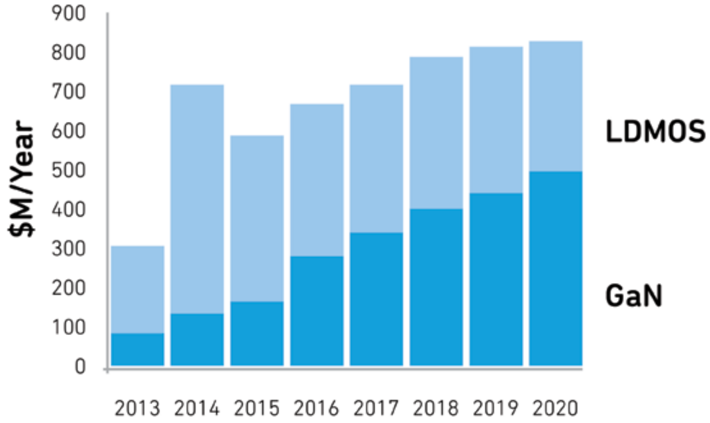
Early 5G trials began in 2013, and data from these and more recent experiments are now frequently published.

Key technologies offering promising results in millimeter wave (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.

GaN is Heavily Used in Base Stations



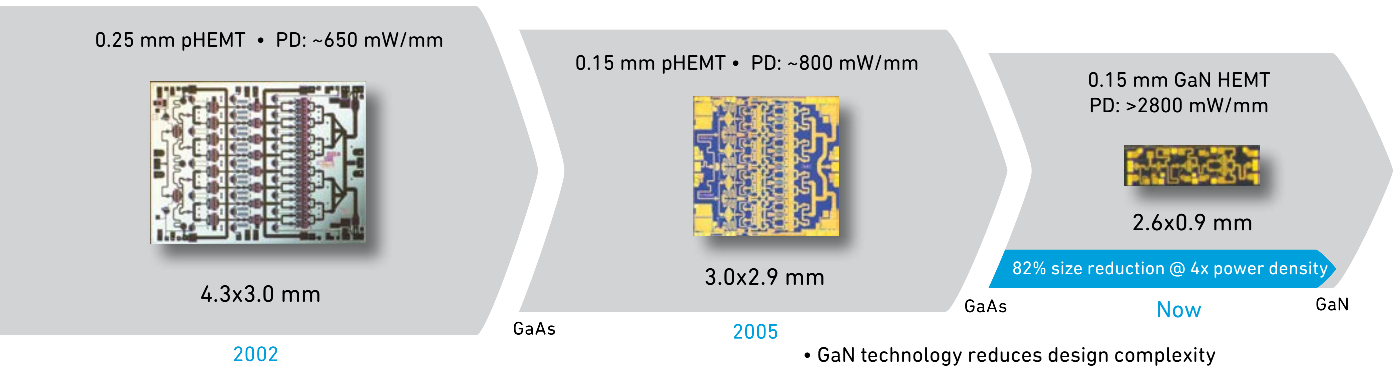
Source: Compound Semiconductor

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.

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 Enabling Monolithic Front-End Solution for 5G

Higher Power Density ➔ Small Size ➔ Miniaturization & Easy Integration



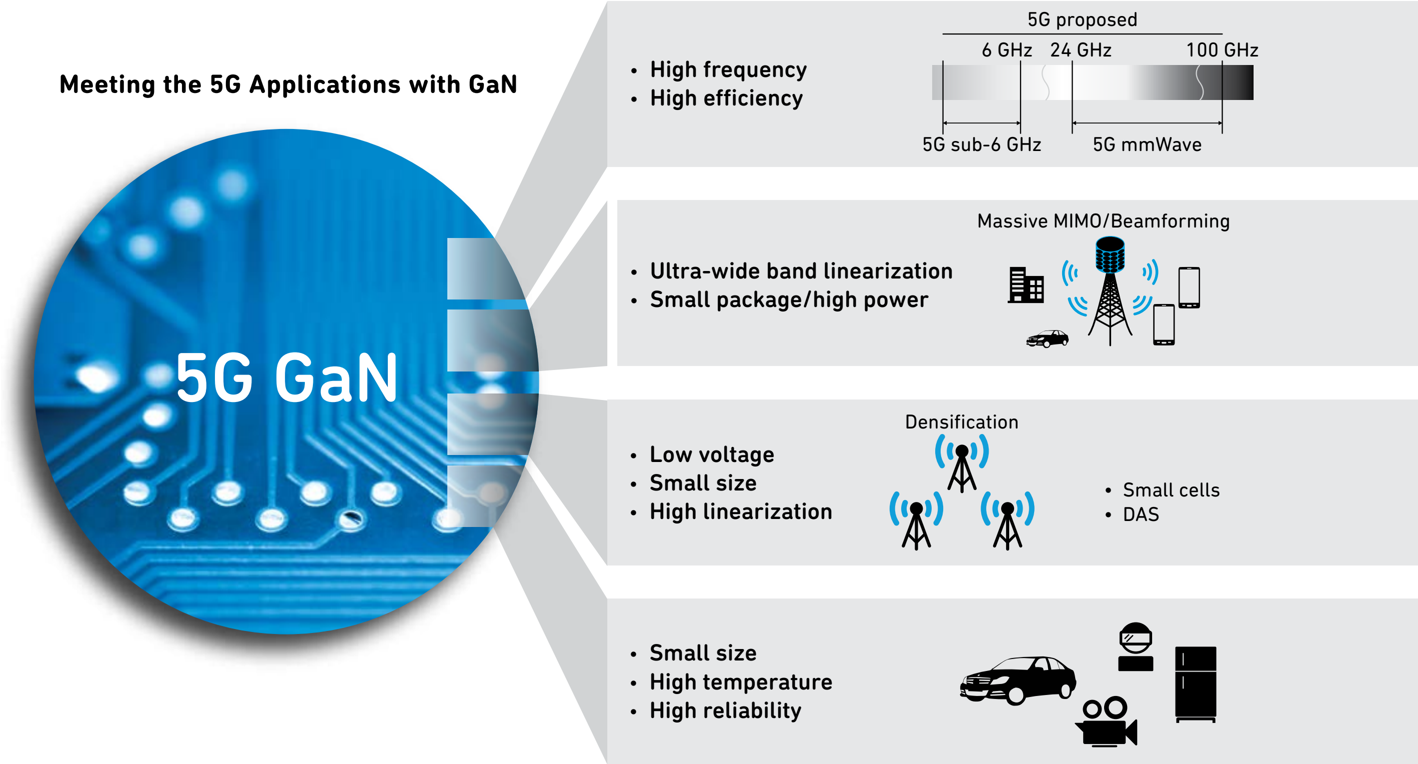
- GaN technology reduces design complexity
- Essential for success of high-frequency commercial markets

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 beamforming technology (beamforming 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.

GaN: Not Just for Defense Anymore

By Scott Vasquez, Senior Market Strategy Leader, Qorvo



Introduction

Once considered a technology solely for defense programs like electronic warfare (EW) and jammers, gallium nitride's advantages are becoming increasingly cost-effective and critical for commercial applications.

This is particularly true for telecom networks and the ever-increasing demands to deliver more data, faster, and to more places.

GaN is a III/V direct bandgap semiconductor commonly used in RF amplifiers, switches, low noise amplifiers, and power electronics. GaN has become the technology of choice for high-RF power applications that require the transmission of signals over long distances such as EW, radar, base stations, satellite communications, and more.

GaN on silicon carbide (SiC) has many advantages including increased power density, efficiency, and improved thermal properties that enable higher reliability and operating temperature. But until recently, GaN was out of reach for most outside the government and defense sphere.

Plastic Packaging

Device packaging technology has been a key factor in helping bring GaN costs in line with market volumes over the last few years. Making high-power GaN MMIC power amplifiers available in small, lightweight plastic packages improves the size, weight, and power (SWaP) performance for a range of commercial applications - optimizing system performance at a competitive price point. HAST compliance of GaN die makes plastic packaging practical.

In broadband cable, GaN is already being used in DOCSIS 3.1 upgrades. Multi-system operators (MSOs) can leverage GaN packaging and integration innovations to upgrade equipment within existing product footprints, saving installation time and cost while enhancing performance.

But GaN with advanced packaging technologies is also being deployed in commercial wireless infrastructure applications, such as small cell and cellular base stations. And it appears GaN is poised to be a critical technology for 5G and next-generation mobile.

Positioned to Deliver All Elements to Fully Address 5G RF

Scheduled for commercial launch in 2020, 5G is expected to offer significant advantages, including higher capacity and efficiency, lower latency, and ubiquitous connectivity. In telecom networks, much of the network energy consumption comes from the RF chain. GaN's superior properties of high power density, power added efficiency (PAE), gain and ease in impedance-matching improve overall efficiency in the RF chain.

Must Address All Bands	Must Have Carrier Aggregation, Higher Modulation, Massive MIMO	Must Be Engaged With Standards	Must Have Infrastructure
Only Qorvo covers low, mid and high bands with complete solutions	Only Qorvo has filters, high-efficiency PAs, multiplexers and high-performance antenna switching	Qorvo is active in 3GPP and China Mobile 5G Center of Innovation defining standards	Only Qorvo combines experience in defense and mobile for GaN power and beam steering needed for wireless infrastructure

RF complexity is only increasing - Qorvo is the smart partner

Handsets

Smartphones and phablets are already the hub of our connected lives, indispensable as a means of consuming enhanced entertainment and connecting us with mobile services and managing our smart homes from afar. That means mobile devices will have to handle more RF bands in the same or smaller space with greater range, reliable connectivity, and better battery life - and without getting hot in our hands.

GaN inherently has higher efficiencies than other competing technologies, thus resulting in a reduction in system power consumption. Maximizing the reduction in power consumption decreases thermal management challenges which could ultimately lead to improved battery life and overall device performance of user equipment such as smartphones or phablets.

Other 5G Applications

Besides operating in high-temperature environments, GaN is well-suited for many different applications, from passively-cooled, all-outdoor tower-top base station electronics, to automobile applications, to cable boxes. Having a wide array of GaN technology choices will mean more applications being serviced throughout the world.

The superior performance of GaN is driving its adoption in base stations. Strategy Analytics currently forecasts cellular infrastructure as the largest commercial segment for GaN in the next four years. And now, 5G is poised to continue the spread of GaN into commercial communications systems.

Small Cells Help Keep 5G Connected

By Tuan Nguyen, Product Line Director of Wireless Infrastructure, Qorvo

Key to the success of small cells, which boost quality of service in wireless networks, is their high-frequency components that draw upon a number of different technologies.

As more users tap into wireless communications services, the demand on wireless network capacity intensifies in both indoor and outdoor locations. Such network density or densification further pressures wireless carriers to keep pace with the increased consumption of frequency bandwidth via voice, video, and data. It also drives those carriers to expand their cellular/wireless infrastructure with minimum increases in cost or disruption of service to wireless customers. Thus, many are turning to small cells as a solution.

The rollout of 5G wireless networks will address demands for increased capacity and data, but these networks are still some years away. So, a more practical answer that's in keeping with today's 4G wireless networks is to use small cells, which function as miniature base stations that are added to an existing wireless network. They operate at relatively low power levels to fill any 'holes' that exist in wireless coverage, in both indoor and outdoor locations.

As an example of the magnitude of growing wireless user demands, fans attending the National Football League's (NFL) 2016 Super Bowl championship game in Santa Clara, Calif., used more than 7 TB of data on the Verizon Wireless network alone - nearly three times as much data used at the 2015 Super Bowl game. Fans connected to the network via smartphones and many other unique wireless devices. They benefited from the generous capacity provided by 4G Long Term Evolution (LTE) technology bolstered by the use of small cells, macrocells, and mobile cell sites (as reported by Verizon Wireless in a press release dated February 8, 2016).

Small Cells + DAS Solutions

Small cells and distributed antenna systems (DAS) are being employed (Fig. 1) to achieve increased data capacity in 5G wireless networks while enhancing quality of service (QoS) in those networks. But with densification comes interference and mobility handover challenges between small cells and the macro network, requiring careful network design and management.

The Evolution of 5G

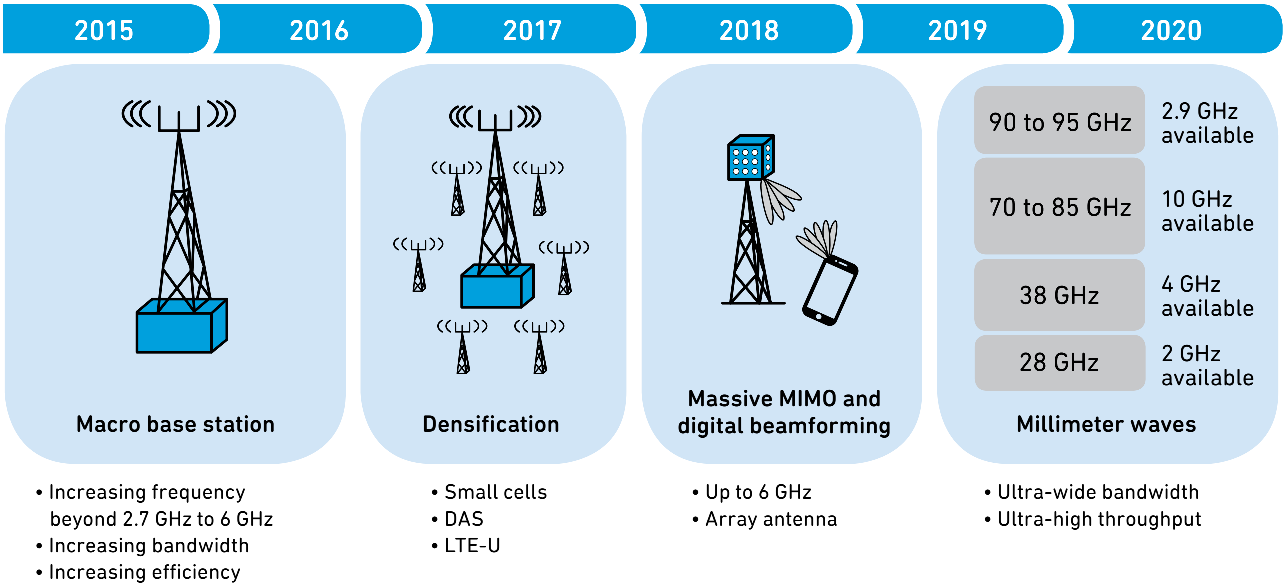


Figure 1. A number of technologies will be required to optimize performance in 5G wireless networks, including distributed antenna systems (DAS), millimeter-wave technology, and small cell base stations.

As mobile communications devices move from a macrocell environment to a small cell coverage area, the network will instantaneously switch profiles. The relatively low power levels of small cells allow mobile devices to be in close proximity to those small cells. They are able to gain network access while conserving battery life, and they needn't establish radio communications links with more distant larger cell sites at transmission levels diminished by distance. Mobile-device users will benefit from increased data speeds, mobility, and flexibility, too, since small cells and DAS solutions support multiple standards, such as third-generation (3G) and 4G cellular, and implement carrier aggregation with LTE Advanced (LTE-A) systems.

Antenna technologies such as multiple-user multiple-input, multiple-output (MIMO) approaches, beam steering, and phased-array techniques help provide additional wireless coverage and interoperability of multiple-band 3G and 4G systems. With massive MIMO methods, wireless network operators can increase data rates and network capacity by transmitting multiple, spatially separated data streams over the same frequency band, using multiple antennas on the base station and the user's device.

Massive MIMO base stations seek to provide from 16 to 256 channels, challenging designers of those base stations to target smaller component sizes with high energy efficiency and effective thermal management. Therefore, highly power-efficient semiconductor technologies become attractive for such base stations.

Table 1: Sizing up Small Cells

Cell Type	Output Power (W)	Cell Radius (km)	Users	Locations
Femtocell	0.001 to 0.25	0.010 to 0.1	1 to 30	Indoor
Picocell	0.25 to 1	0.1 to 0.2	30 to 100	Indoor/Outdoor
Microcell	1 to 10	0.2 to 2.0	100 to 2000	Indoor/Outdoor
Macrocell	10 to >50	8 to 30	>2000	Outdoor

High levels of semiconductor integration are also instrumental in achieving the high channel counts in these relatively small-sized base stations. Squeezing as many as 256 transmit channels into a single base station requires subsystems that package power amplifiers (PAs), low-noise amplifiers (LNAs), and switches into compact modules, and employing small-form-factor filter solutions.

Technology Potpourri

As Table 1 shows, small cells differ in output power levels, coverage areas, and number of users served. For the best performance and power efficiency, the subsystems used in small cell base stations must combine components based on different process technologies. For example, PAs may provide suitable output power and power efficiency.

Filters could require yet a third technology, especially for operating conditions that may experience extremes of temperature and humidity. Temperature-stable bulk-acoustic-wave (BAW) LowDrift™ filters from Qorvo provide a solution for filtering high-power signals while also avoiding interference from adjacent frequency bands.

Table 2: PAs for Small Cell Base Stations

PA Model	Frequency Range (MHz)	Average Output Power (dBm)
TQP9218	1805 to 1880	+24
TQP9418	1805 to 1880	+27
QPA9219	1930 to 2000	+24
QPA9419	1930 to 2000	+27
TQP9221	2010 to 2170	+24
TQP9421	2010 to 2170	+27
TQP9224	2300 to 2400	+24
TQP9424	2300 to 2400	+27

In addition to the various components required for wireless infrastructure designs, including filters, switches, and LNAs, Qorvo developed a line of highly integrated PAs for small cell base stations. The PAs do not require linearization, and feature on-chip bias control and temperature-compensation circuitry to further simplify the design of a small cell base station. They are available with +24 or +27 dBm average linear output power when driving a 20 MHz wide LTE signal (Table 2). The PAs also incorporate two stages of amplifier gain in low-cost surface mount technology (SMT) packages.

For example, model TQP9218 is a 0.25 W (+24 dBm) PA designed for small cell base stations operating from 1805 to 1880 MHz. It offers 31 dB small signal gain across its frequency range with internal impedance matching, on-chip bias control circuitry, and temperature-compensation circuitry - all packed into a 7×7 mm RoHS-compliant SMT housing. The PA achieves 16% power-added efficiency (PAE) and draws just 240 mA quiescent current from a +4.5 V dc supply.

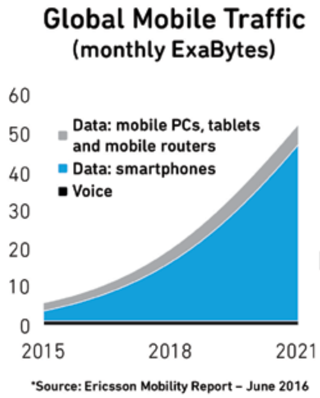
Enabling 5G with GaN Technology: Setting the Table for Success

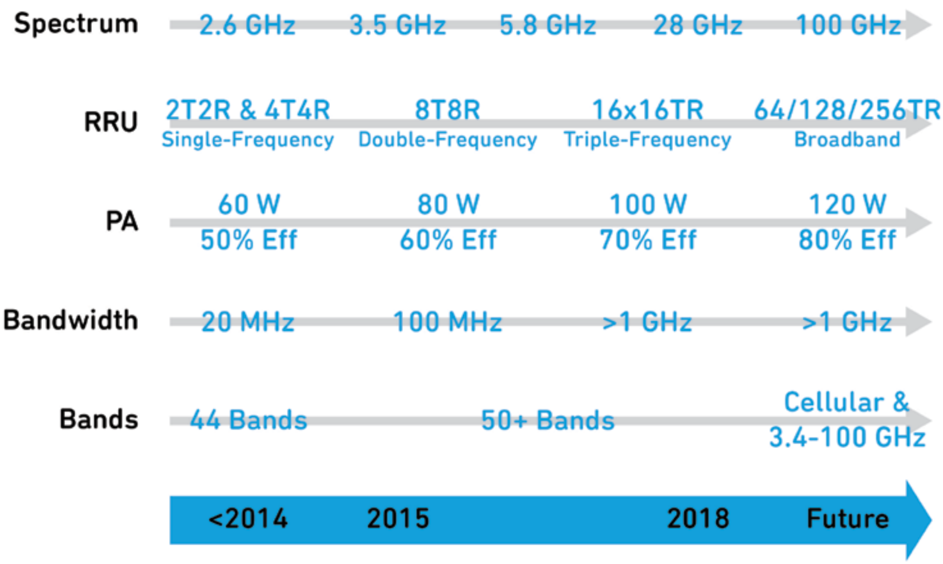
By Dr. Doug Reep, Retired Senior Director of Research, Qorvo

At Qorvo, we're closely tracking the emerging 5G standard. One thing that's particularly exciting is the likelihood that 5G includes mmWave functionality for high data-bandwidth connections. As PC board space becomes more limited and as frequencies increase in the 5G environment, GaN technology becomes even more appealing for RF applications.

The Path Toward 5G

Compared to GaAs, silicon or other traditional semiconductor materials, GaN will really start to shine in 5G network applications, such as high-frequency and size-constrained small cells. As shown in the figure below, wireless network enhancements will drive many technology advancements as the standard evolves toward 5G.





Ultimately, when we get to the emerging mmWave standards, GaN will have a clear advantage over today's technologies. GaN offers higher power density, which brings several benefits:

- Size reduction
- Lower current consumption
- Higher system efficiencies

We already see the benefits of GaN in the 4G base station arena, where GaN has begun displacing silicon LDMOS. For 5G, GaN's ability to work in the high-frequency range allows it to evolve from base stations to small cell applications and, ultimately, into mobile devices.

Going Beyond Infrastructure: Moving GaN into Mobile Handsets

The first GaN applications were developed for high-power military use such as radar or counter-IED jammers, eventually moving into commercial base stations and cable TV repeaters. Typical operating voltages for these applications range between 28 and 48 volts.

In handheld devices, however, the average voltage range is 2.7 to 5 volts. To operate GaN at these low voltage levels, we will need to work on a different class of device. We've already started to look at GaN devices in alternative materials, in order to operate efficiently at low voltage.

GaN Developments for 5G at Qorvo

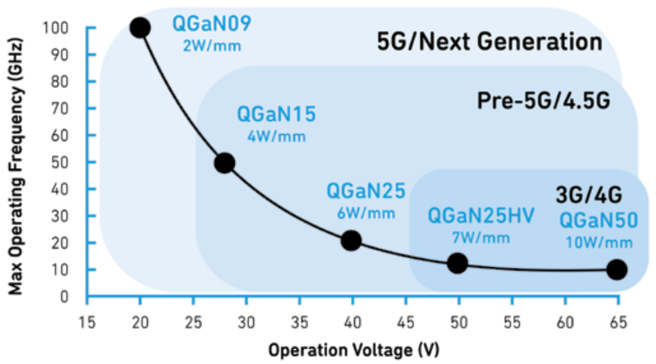
As shown in the figure below, Qorvo currently has a broad range of production-released GaN foundry processes used to enable products for 5G applications:

- Higher voltages, lower frequencies: As we move lower in frequency, we bring into play our 0.25 µm high voltage technology, or QGaN25HV. This QGaN25HV allows us to move to 48 volts with a 0.25 µm device, with high gain and power efficiency. QGaN25HV is well suited for 5G base stations as they move toward 6 GHz. At the lower 4G frequencies, between L- and S-band, our highest power density 0.5 µm technology works up to 10 watts per millimeter.

- High-frequency applications: Our current GaN process portfolio includes 0.15 µm, or 150 nanometer, technology for higher frequencies. Our 0.25 µm technology is well suited for applications ranging from X- through Ku-band. This 0.25 µm technology also offers highly efficient power amplifier functions.

But what about GaN processes for mobile 5G handsets? As we see the higher frequency standards emerge (Ka-band or mmWave), low-voltage GaN processes will require further development.

Qorvo GaN Technology Roadmap



Addressing Packaging and Thermal Challenges of GaN and 5G

One last piece of the puzzle to enable GaN for 5G involves advanced packaging techniques and thermal management. GaN devices for highly reliable military applications have traditionally been available in ceramic or metallic packages; however, commercial 5G network infrastructure and mobile handsets will require smaller, lower-cost, plastic overmold packaging to compete with incumbent silicon LDMOS or GaAs devices in plastic packages. Similarly, mobile handsets will focus on low-cost modules that include GaN mixed with other technologies, analogous to today's products - but they'll also need highly compact, highly efficient mmWave materials and devices.

The challenge for infrastructure will be developing packages that maintain RF performance while addressing thermal management. GaN's higher power densities - from 3 to 5 and as much as 10 times higher than GaAs - present a very tough thermal and mechanical problem to the subsystem package designer.

Our engineers always balance three requirements: RF performance, thermal management, and low cost. Qorvo has plastic overmold packages with enhanced thermal management capabilities for GaN, including thermal spreaders built into the bases of the package.

Our products in plastic packages also meet stringent environmental standards, such as JEDEC standards for temperature, humidity and bias compliance. This gives our customers assurance that our products will have long-term reliability for their 5G applications - whether high frequency, high power or low voltage.

Looking to the Future

Although 5G is still several years away, Qorvo is already working to develop the process technology and packaging techniques to enable our customers' 5G applications. GaN is sure to play a key, exciting role in the 5G landscape.

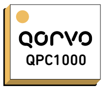
5G: A Future Technology Standard Qorvo is Enabling

Just as we did for 2G, 3G and 4G, Qorvo is collaborating with industry leaders and partnering on research efforts that will create the new 5G standard. Check out the below press releases at **qorvo.com/news** that show how we're building a new connected world through integration, technology and partnerships.

03/01/2017	Qorvo Delivers Highly Integrated Solution for Pre-5G Massive MIMO Networks
02/27/2017	Qorvo Accelerates Race to 5G with Industry's First 5G Front End
01/26/2017	Qorvo Joins China Mobile 5G Innovation Center
07/19/2016	Qorvo Powers 5G Field Trials with Industry-Leading Infrastructure Solutions
02/22/2016	Qorvo Joins 3GPP to Promote Development of 5G Standard

Qorvo 5G Product Highlights

QPF4005
Dual Channel HPA, Switch & LNA FEM
- Frequency range: 37-40.5 GHz
- Package dimensions: 4.5x6 mm



QPC1000
5-Bit Digital Phase Shifter & SPDT
- Frequency Range: 29-31 GHz
- Package Dimensions: 6x5 mm

TGA4030-SM
Medium Power Amplifier & Multiplier
- Frequency Range: 17-37 GHz
- Package Dimensions: 3x3 mm

TGA2594-HM
Packaged Power Amplifier
- Frequency Range: 27-31 GHz
- Package Dimensions: 7x7 mm

QPB9318
Highly Integrated Front-End Module
- Frequency Range: 2.3-2.7 GHz
- Package Dimensions: 5x5 mm

QPB9319
Highly Integrated Front-End Module
- Frequency Range: 1.8-4.2 GHz
- Package Dimensions: 7x7 mm

QPL9503
Flat-Gain, High-Linearity, Ultra-Low Noise Amplifier
- Frequency range: 0.6-6 GHz
- Package dimensions: 2x2 mm

Visit **www.qorvo.com/5G** for our latest products.

At Qorvo, what we do matters. Developing solutions today, for a better, more connected tomorrow.

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