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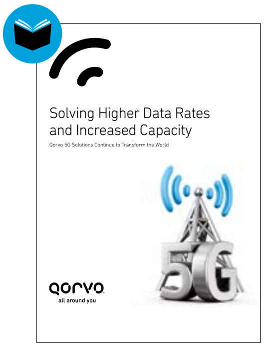

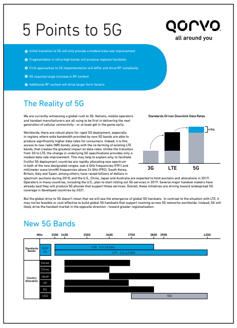

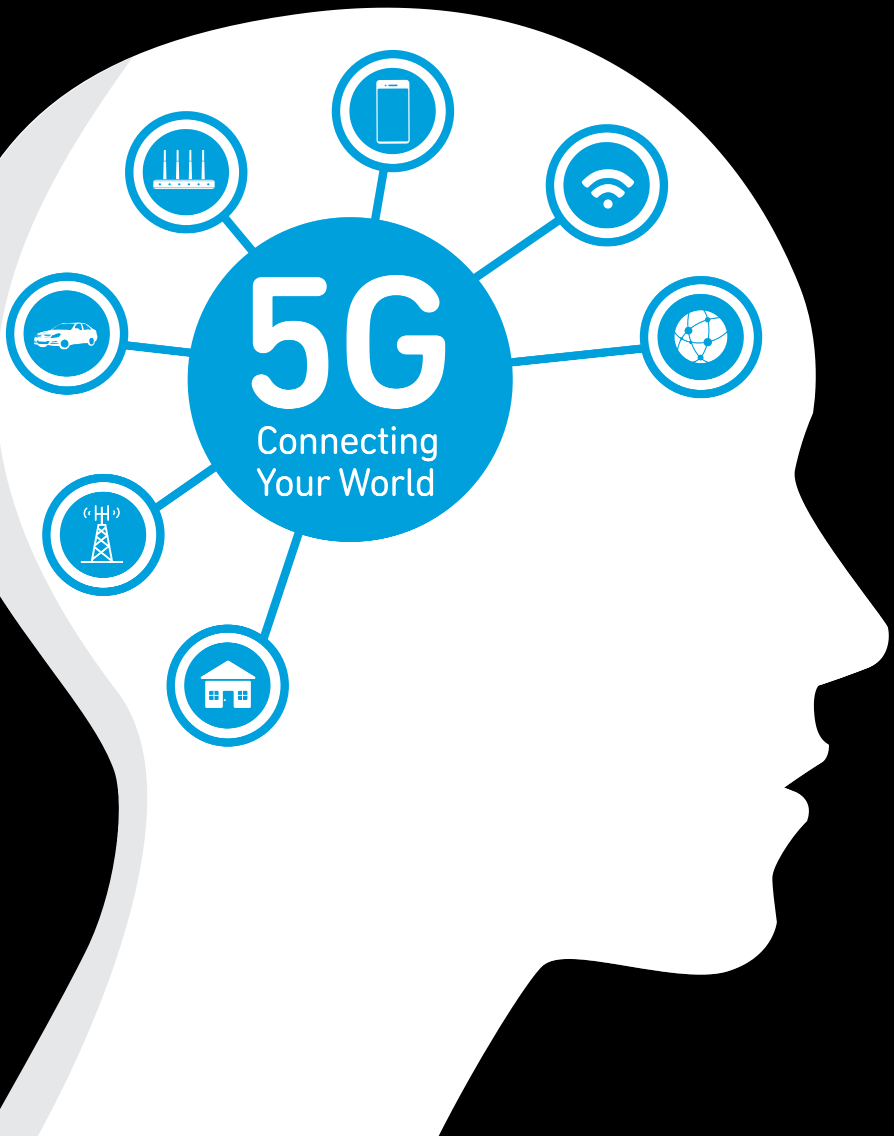

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What is 5G?

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 ultra efficient

For streaming data, taking full advantage of carrier aggregation and massive MIMO.

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.

5G Complements the 4G LTE Network

- 5G will start as an overlay of the 4G LTE network.
- The 5G radio specification (called 5G NR for "new radio") will have both non-standalone (NSA) and standalone (SA) operation.
- NSA is an evolutionary step for carriers to offer 5G services without building out a 5G core network, until they add the full SA 5G core later.
- Starting in 2019, 5G will encompass major new capabilities.

5G is wireless infrastructure

Using beam steering and high-power GaN, based on the technologies in phased-array antennas for defense.

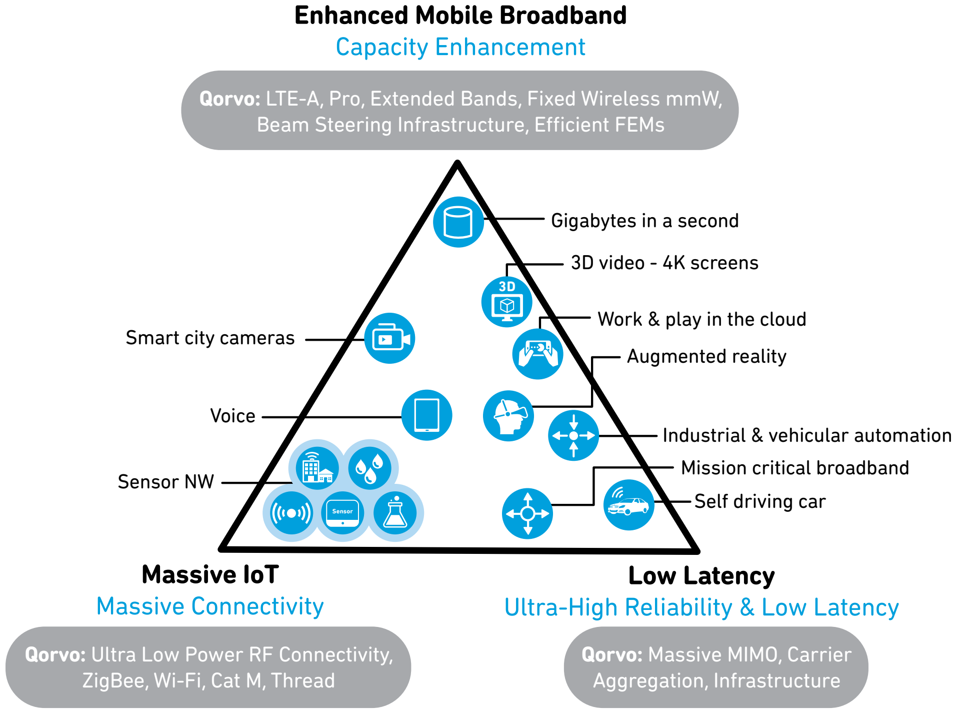
5G is low-latency

For real-time connections enabling autonomous vehicles and augmented/virtual reality.

Qorvo is the standard setter – participating in standards bodies and partnering with wireless carriers – to define 5G RF for the future.

Connecting the Uses of 5G

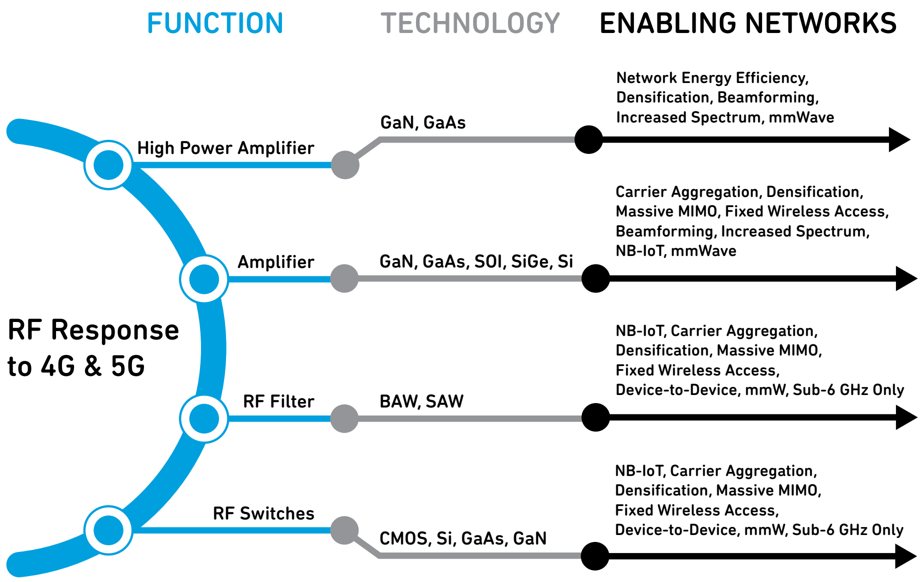
Qorvo connects RF for all 5G use cases — more than just cellular and Wi-Fi.



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

RF Communication Technologies By Use Case

5G will overlay the 4G LTE network in the coming years. The RF function, frequency band, power level and other performance requirements determine which semiconductor technology is the best fit.



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

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.

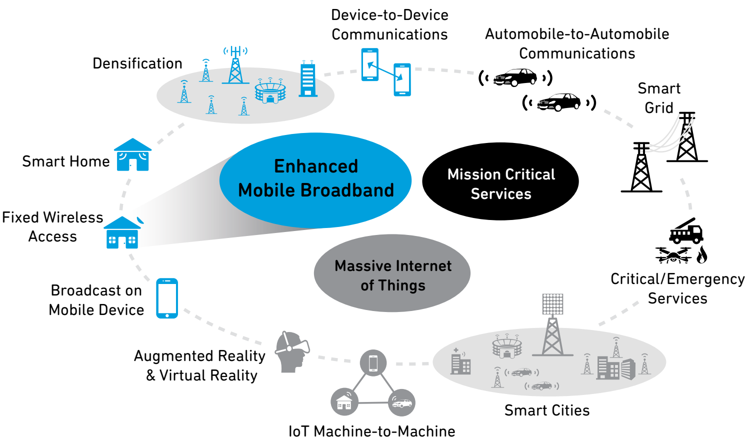


Figure 1 5G use case.

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 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.

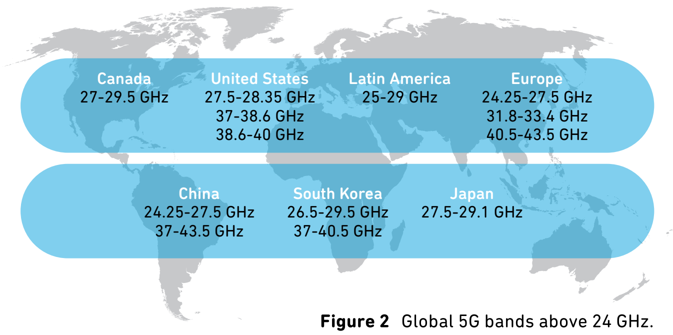


Figure 2 Global 5G bands above 24 GHz.

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.

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.

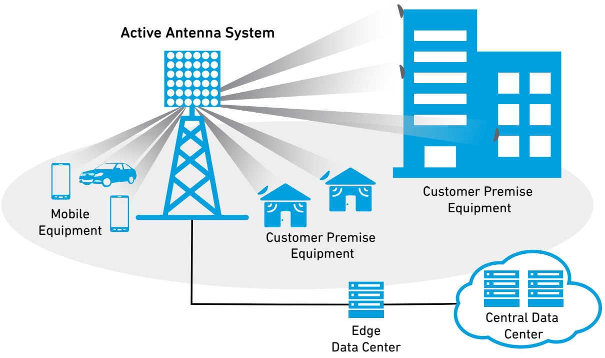
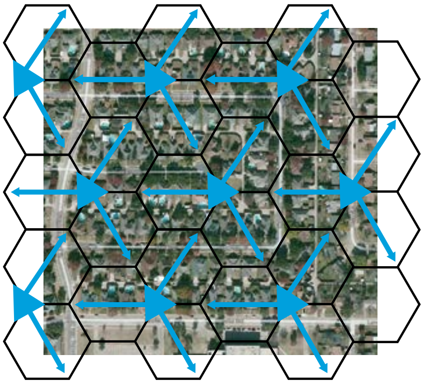


Figure 3 End–to–end FWA network.



- Random Dallas Suburb
  - 800 houses/km2
  - 500m ISD
  - 9 cell sites
  - 23 sectors
  - ~35 houses/sector
- Capacity Per Sector
  - 35 houses/sector
  - 5x oversubscription
  - 1 Gbps service
  - Capacity ~5 Gbps
- BTS Parameters
  - Capacity ~5 Gbps
  - 400 MHz BW
  - QAM16 w/LDPC: 3bps/Hz
  - 4 spatial streams/layers
- Business Case
  - 33% take rate
  - $100/month for 1 Gbps SLA
  - $14k/sector/year
  - $177k/sq-km/year

Figure 4 FWA in a suburban environment.

Large coverage is essential to the success of the FWA business case. To illustrate this, consider a suburban deployment with 800 homes/km2, 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 over subscription 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/km2/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, shown in **Table 1**. The challenge becomes building systems that meet these targets 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.

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

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.

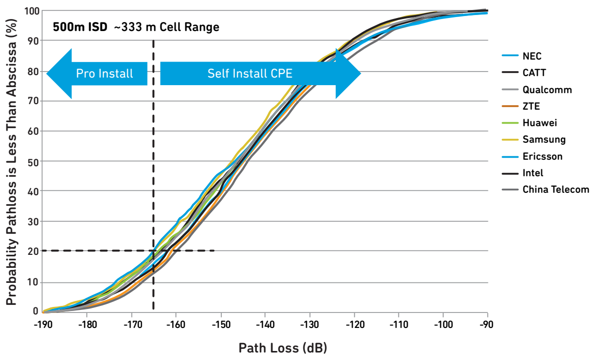


Figure 5 Statistical path loss simulation for urban-macro environment with 500 m ISD.

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.

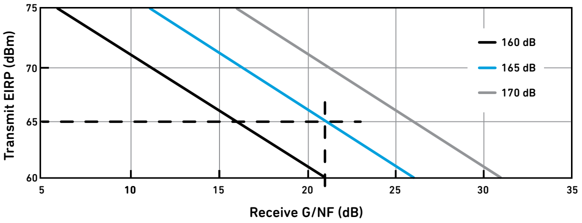


Figure 6 Transmit EIRP and receive G/NF vs. path-loss for 1 Gbps edge-of-coverage throughput.

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.

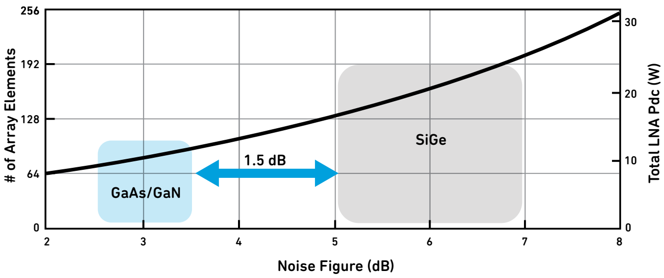


Figure 7 Array size vs. front-end NF and power consumption for G/NF = 21 dB.

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.

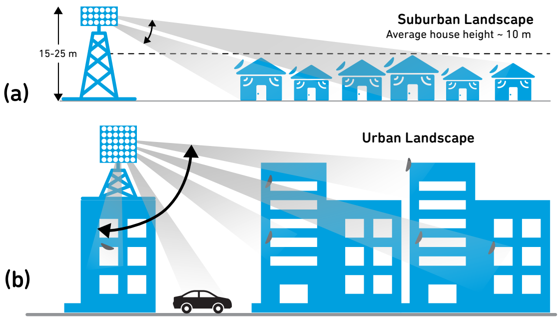


Figure 8 Array complexity depends on the scanning range needed for the deployment: suburban (a) or urban (b).

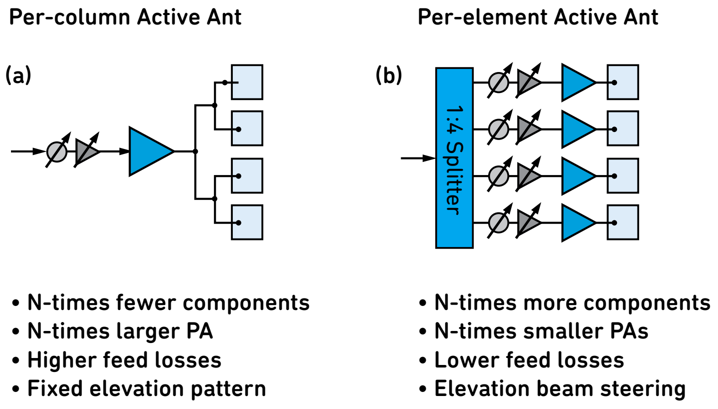


Figure 9 Column-fed (a) and per-element (b) active arrays.

In the suburban deployment, the tower heights range from 15 to 25 m 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°/NANT and the array gain by 10log10(NANT) + 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.

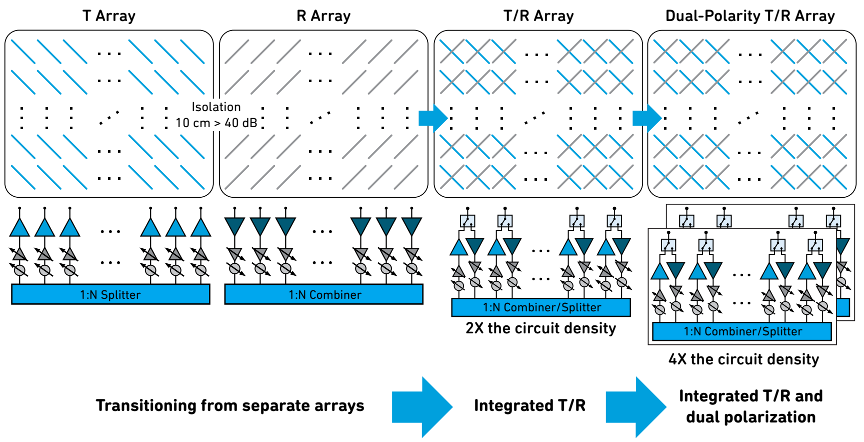


Figure 10 FWA antenna arrays are evolving from separate T and R arrays to integrated T/R arrays with dual polarization.

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, 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

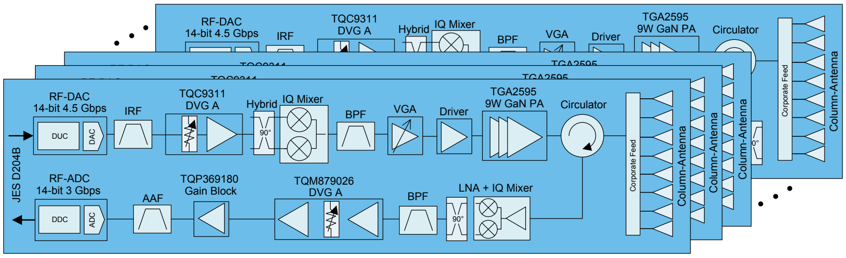


Figure 11 Array design using digital beamforming and commercial, off-the-shelf components.

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:

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

$$\mathrm{EIRP} = 10\log10(N_{COLUMNS}) + 10\log10(N_{PAS}) + G_{ANT} + P_{AVE/CHANNEL}\ (\mathrm{dBm})$$

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.

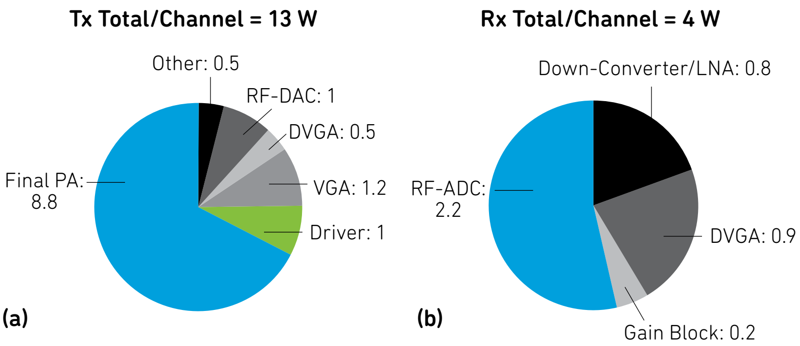


Figure 12 Power dissipation of the transmit (a) and receive (b) chains.

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 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 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.

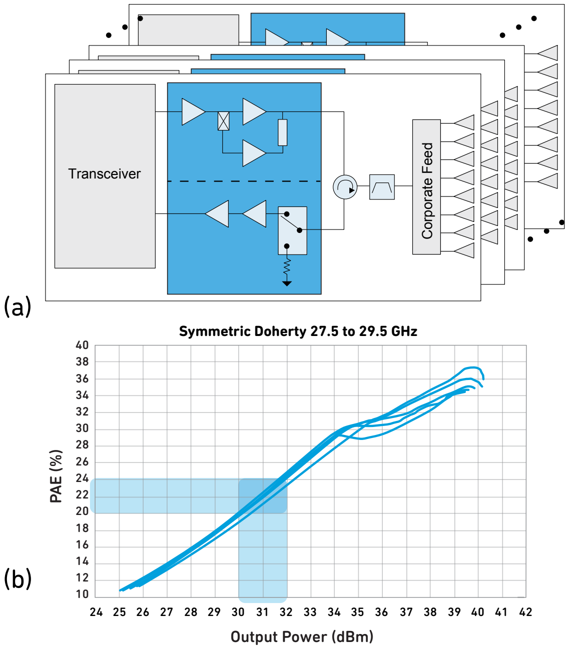


Figure 13 Integrated FEM with symmetric GaN Doherty PA and switch-LNA (a) and PA performance from 27.5 to 29.5 GHz (b).

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.

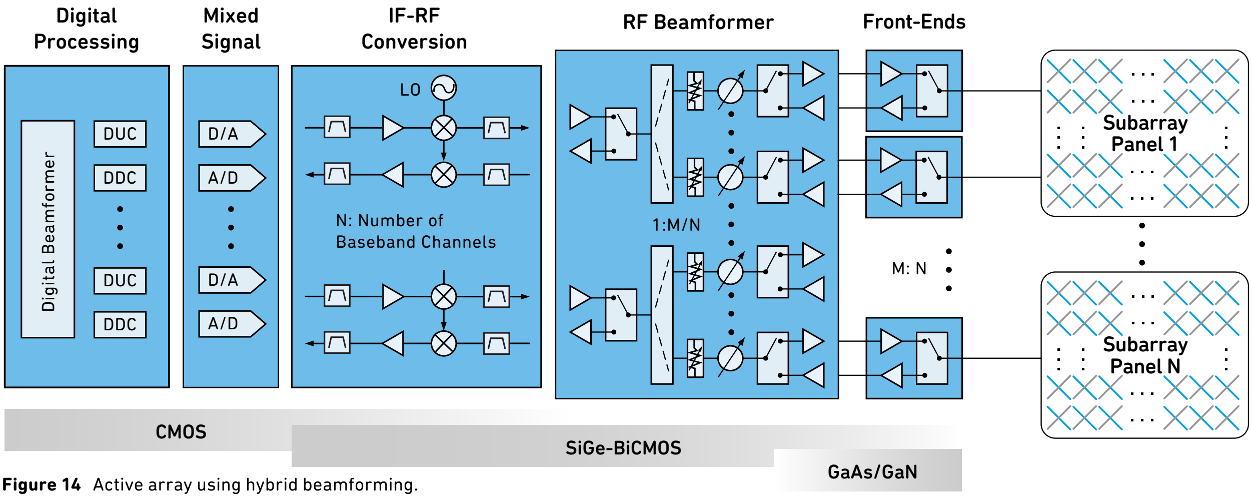


Figure 14 Active array using hybrid beamforming.

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.

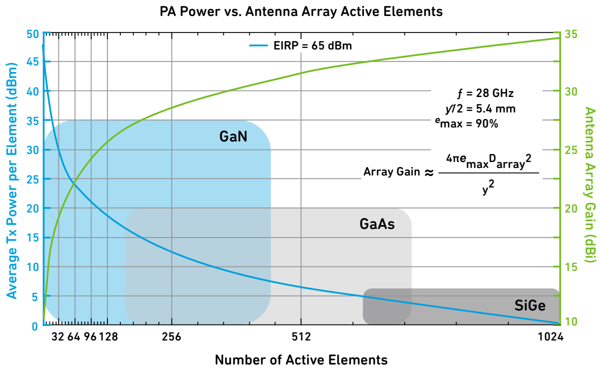


Figure 15 Optimum RFFE technology vs. array size.

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 beamformer branch consumes 190 mW, which is the typical power consumption of core beamformers in the market. 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.

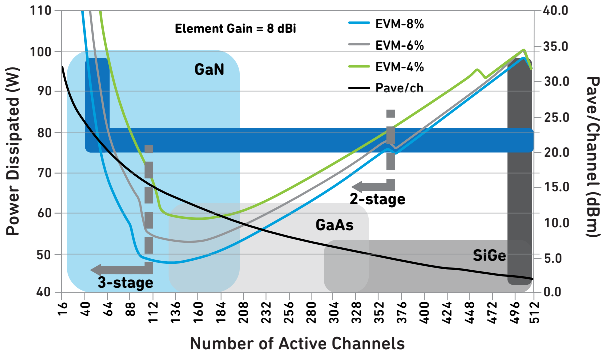


Figure 16 System power dissipation vs. array size and EVM for 64 dBm EIRP.

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 P1dB) 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 mm2 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.

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.

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	mm^2	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

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 P_{HEMT} 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 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.

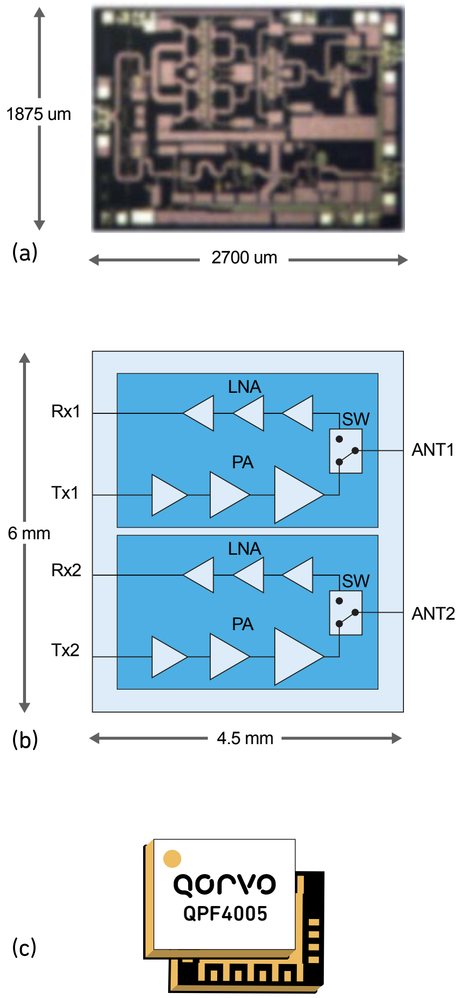


Figure 17 Integrated 39 GHz GaN front-end MMIC - intentionally blurred (a), dual-channel FEM (b) and package (c).

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.

What's Best? Wi-Fi 6 (802.11ax) or 5G?

Every time a new cellular phone standard comes out, we see new claims about the "end of Wi-Fi." When 3G was announced, the promise was that it would make Wi-Fi (802.11b) redundant, which clearly turned out to be incorrect. With 4G (LTE), this story repeated itself and claimed it would put Wi-Fi (802.11ac) in the shredder. And now the 5G message is that it will cover both the inside and outside of homes and buildings. It's almost as though Wi-Fi will soon no longer be needed.

This begs the question: What will be the impact of the next generation of Wi-Fi, Wi-Fi 6 (802.11ax)? Do we even need it in the 5G/wireless landscape? We need better questions.

Beyond the Hype

Of course, some of the messaging around 5G is just typical marketing hype, showcasing the favorable points and ignoring the less favorable ones. For example, 5G with 4 Gbps will be faster than Wi-Fi (.11ac) with 1.3 Gbps. The immediate counter argument is that Wi-Fi (.11ax) with 9.6 Gbps will be faster than 5G. But will these speeds be achieved in real life? We've seen this before, these glossy promises of high-speed access being wiped away by the hard truth of "no connection in the basement," or something similar. Cue the collective consumer yawn.

(And by the way, how good will 9.6 Gbps Wi-Fi be in the basement, if the connection to the home is 300 Mbps, or even less? What problem is this solving?)

If we want a real sense of where the developments are heading, it's probably a good idea to go a little deeper than marketing headlines. What are the real facts that can guide us? For starters, laws of physics tell us that radio waves (both Wi-Fi and 5G) have difficulties penetrating objects such as walls and foliage, and their data rates decrease with distance. Radiating more power helps a little, but it also causes unwanted noise, making equipment more expensive. In addition, there are legal maximum output power ratings to adhere to.

There are also economic laws. Cellular (3G/4G/5G) uses licensed bands. Mobile operators (service providers) pay money to use this spectrum and need to roll out a network of (connected) base stations to cover a large area. They then need to recover this money with subscription fees. In such a service area, many users need to be served, sharing the same frequency band over multiple channels.

In contrast, Wi-Fi uses unlicensed spectrum, which is available to all for free. However, the output power is very low, so the radio signal (more or less) stays in your own house or building and has a favorable (so-called) spectral reuse. The same frequency band can be used in every house. However, to get the internet at your front door, you need to pay an internet service provider a subscription fee, including a simple router that is part of that fee. If you want, you can buy a more expensive router as well.

So, in this frequency band perspective, there's an interesting technology split between Wi-Fi and 5G, but do customers really care? Customers care about fast internet access — anywhere — at a decent price. In contrast, operators/providers care about providing good internet service everywhere (at home and around the home) and keeping costs under control. Interestingly enough, with so-called Wi-Fi off-load (where a cellular network off-loads traffic to Wi-Fi connections), the border between the two different technologies is already blurring.

A Bit of History Can Be Helpful

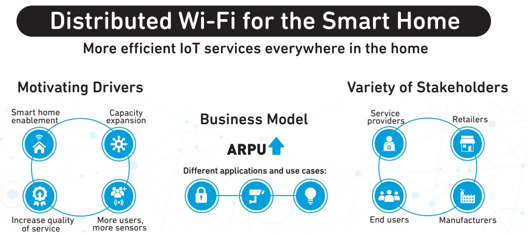
It's interesting to note that the Wi-Fi world is rooted in the commercial computer industry, while 5G is rooted in the more legislated telephone industry. So, telephone operators (now service providers) have more affinity with 5G than with Wi-Fi. When most telephone operators started to deliver internet to consumers, it was delivery to the front door. What happened inside the house was the consumer's responsibility.

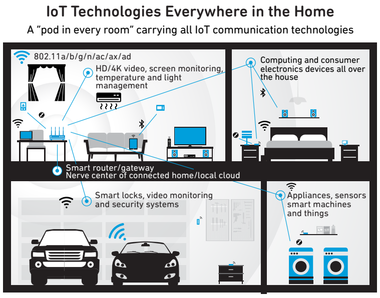
There's another distinction between cellular and Wi-Fi: a mobile phone uses a service subscription that requires a SIM card. This SIM card ensures that phones are connected to subscriptions and don't use the network illegally. But Wi-Fi doesn't need a SIM card; the frequency band is license-free. Not surprisingly, the mobile world is looking for ways to make the SIM card redundant, but initiatives like soft SIM and eSIM aren't making the desired progress because they're too cumbersome and/or are not sufficiently secure.

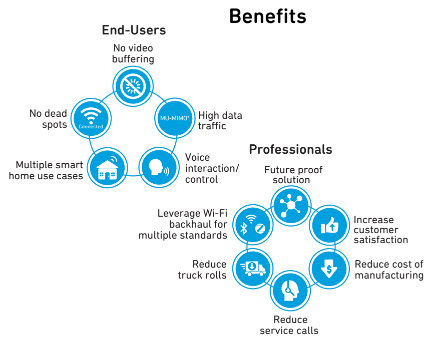
The consequence of these histories is that the consumer's internet connectivity world is split into two parts: mobile (with a subscription and SIM) and stationary (with a router at home). This scenario is now well-established. Of course, wireless internet connectivity can be troublesome, and initially telephone operators used this hassle as an opportunity to promote cellular as an alternative for Wi-Fi. The good news is this mentality is changing.

Cable operators have also entered the picture. They've found that, for many consumers, Wi-Fi coverage in the home was a major concern. Cable operators responded by extending their service to include good coverage inside the home. This is forcing cellular operators to do the same, as well as to develop a better quality of wireless indoor internet service.

Wi-Fi 6 (IEEE 802.11ax)







Better coverage inside the home is one of the key characteristics of the new generation of Wi-Fi, now called Wi-Fi 6 (based on the IEEE 802.11ax standard). The distributed concept behind this new version of the Wi-Fi standard (also called Wi-Fi mesh) helps to distribute internet to every room in the home, with the main router at the front door, and small satellite routers (also known as repeaters) on every floor and in every room. This enables internet service providers to sell and support solid internet connectivity everywhere in the home — all good news!

There are also interesting crossover products, though, and a nice example is the FRITZ!Box 6890 from German supplier AVM. This box is a traditional router, providing Wi-Fi everywhere in the home. But it doesn't use DSL, fiber or cable — it uses LTE. So, this box has a SIM card and operates the same way as if you use your mobile phone as a hotspot to connect your tablet to the internet, for example. The difference is the FRITZ!Box makes this configuration permanent in your house. The trick is to make sure you have the right subscription service (preferably unlimited data) to avoid high mobile charges for your private wireless hotspot.

A Better Way Of Looking At Things

Despite these crossovers, when talking about cellular and Wi-Fi, it still feels like two separate worlds and that we're switching back and forth between them, like a car shifting gears. Fortunately, most phones are somewhat smart, and when the Wi-Fi connection isn't working, the phone automatically switches to the cellular network. But there's a real problem if you're "on the edge of Wi-Fi" and Wi-Fi attempts to take back the connection, leaving you in limbo with a nonworking Wi-Fi and a nonworking cellular connection. In those moments, the solution is to turn off Wi-Fi to end the battle and avoid poor response times.

But wouldn't it be better if there were a good hand-off between the Wi-Fi connection and the cellular connection, so that the user always gets the best performance against the lowest cost?

Some consumers won't care if they are connected via Wi-Fi or, in the future, 5G. The system should just provide the best connectivity, whether at home indoors, outside, or on the road. Maintaining one subscription for both home internet and cellular service — we're talking about a different way of thinking. In this scenario, a service provider (whether it's a mobile operator or a cable operator) provides the highest quality wireless internet access service, both at home and on the road. There are many initiatives underway in this area, all in the category of "Wi-Fi off-load," and in principle the technology is there. But it isn't mainstream yet, due to multiple competing and legacy interests.

The "Right" Choice

It may be clearer that the customer genuinely isn't interested in next-generation Wi-Fi or in the "next G." The consumer simply wants the best internet connection — anywhere, at any time and at the most affordable price. This is the way everyone — whether cellular providers, hotspot providers or internet service providers — can think about how to deliver the best service most efficiently to their vast subscription base.

The key is to envision 5G and Wi-Fi 6 working together to implement this, instead of playing one against the other. There should be no "right" technology choice or choosing the one best technology for a given application.

Hopefully this different way of thinking will also help to concentrate on today's real bottleneck — how to get high-speed internet to the home.

Is 5G Already a Reality?

It should come as no surprise that the pending arrival of 5G was THE big story from Mobile World Congress 2019 in Barcelona. Qorvo's Brent Dietz covered his top five takeaways from MWC19, including foldable phones and Sophia the robot — but here's a recap of Qorvo's highlights from the show.

Qorvo's 5G Mobile Portfolio Enters High-Volume Production

Most people in the industry didn't think 5G would be a reality before 2020, but one overriding message from Barcelona is that 5G is coming faster than anyone actually expected — and we could see 5G handsets in the second half of 2019.

In support of that transition, we announced at MWC 2019 that our portfolio of mobile 5G products has moved into high-volume production, helping leading smartphone manufacturers accelerate the rollout of 5G around the world. Featured products include the highly integrated front-end modules (FEMs) shown below, which support all major baseband chipsets and incorporate all the RF front-end (RFFE) functions required to support new and "refarmed" 5G bands targeted in early deployments.

Part Number	Description	5G NR Band Support
QM78203	5G Switched Power Amplifier plus Duplexer (S-PAD) Module with LNA Receive	Bands n77, n78 and n79
QM75041	5G Power Amplifier Duplexer Module (PAMiD)	Bands n41
QM77038	Multi-Mode Mid/High Band Switched Power Amplifier plus Duplexer (S-PAD) Module	Bands n41, n3

Enabling 5G Wireless Infrastructure With 100+ Million Shipped RF Devices

5G handsets won't work unless cellular infrastructure is set up to support 5G. Not only have Qorvo infrastructure products been used in dozens of 5G field trials, including the Samsung 5G multiple-input/multiple-output (MIMO) demo at the 2018 Winter Olympics, but we also announced at MWC19 that we've shipped more than 100 million 5G wireless infrastructure components since January 2018.

Our 5G infrastructure portfolio includes solutions for both the receive and transmit RF front end, enabling customers to use beamforming with massive MIMO base stations to achieve higher data capacity, wider coverage, and indoor penetration using sub-6 GHz and millimeter wave frequencies.

We were also featured in MWC press announcements from silicon-on-insulator (SOI) partner GlobalFoundries and 5G GaN partner Gapwaves. Gapwaves' 28 GHz 5G active antenna features a Qorvo integrated FEM and our GaN-on-SiC technology.

Integration Will Be Critical For 5G Handsets

One mobile industry trend showing no sign of stopping: integration of components amid tight space constraints. Indeed, integration will be even more critical for 5G handsets, as the number of RF components in the phone only continues to grow.

Qorvo's RF Fusion™ products integrate the power amplifier, switch and filter content into a single RFFE module, and we announced at MWC that our newest generation of RF Fusion products had multiple design wins from leading smartphone manufacturers.

The newest generation of RF Fusion leverages Qorvo's advanced BAW and SAW filter technologies to deliver complete coverage in low-band and mid/high-band placements, with our QM77033 and QM77031 modules. The latest design wins also include the QM17001 mid/high-band diplexer and RF8129 envelope-tracking (ET) power management module.

RF Fusion continues to evolve and add functions and features in preparation for the rollout of 5G. The latest generations add support for new and refarmed 5G bands and EN-DC operation, in a range of scalable options. You can view our full catalog of RF Fusion solutions for 4G/5G in our latest brochure on qorvo.com/brochures.

Honored For Helping To Drive The Global Adoption for 5G

Among the many highlights during MWC, Qorvo's Paul Cooper was recognized by the Global TD-LTE Initiative (GTI) as a 2019 Honorary Award recipient at its GTI Night celebration.

Paul, who is the director of carrier liaison and standards at Qorvo, has worked for several years to further the cause of the GTI 2.0 mission to establish a 5G RF front-end sub-6 GHz ecosystem, supporting member carriers in the U.S., China and Europe. The Qorvo Carrier Program team coordinated test and marketing staff to provide data in support of 3GPP new radio (NR) standards that will drive global adoption of 5G. This award was the culmination of the hard work put in by Qorvo's 3GPP RAN4 standards team and engineering teams providing lab test data.

We're proud to be among a team of experts from multiple companies, including Qorvo, Skyworks, Sprint, Qualcomm and LG, that are helping our customers' customers — the wireless carriers — address the RF challenges of 5G.

Qorvo's Paul Cooper and a cross-company collaborative team accept a GTI Honorary Award at MWC19.

Getting Ready For 5G: Antenna Tuning Is Essential

The transition to 5G will drive a significant increase in the typical number of antennas in each handset, from 4-6 in today's LTE handsets to 6-10 in 5G smartphones. At the same time, the space for those antennas is decreasing, creating problems for antenna efficiency and bandwidth.

To counteract these challenges, 5G handset designers will need to use antenna tuning to optimize the antenna. Aperture tuning is one method used today, but implementing it requires in-depth knowledge.

Visit qorvo.com to download our new **How to Implement Aperture Tuning**: **Best Practices for 4G/5G Smartphones** e-guide to learn more.

What's Next: How Do We Make 5G Happen Right Now?

Learn how 5G will change how we live and operate in Qorvo's series, "5G in 60" on www.qorvo.com/videos.

Eric Creviston, president of Qorvo Mobile Products, sums it up best: "We heard over and over during MWC that 5G handsets are being pulled in sooner than planned. Consumer awareness of 5G is very high and consumers want to 'future-proof' the phones they buy this year by having 5G capability, even if the network coverage is not yet in place."

We may be in the earliest stages of the 5G rollout, but it's exciting to see all the hard work and collaboration from the 3GPP standards, bodies and the industry starting to come to fruition!

News and Awards

Qorvo RF Fusion™ Wins Multiple Marquee Smartphone Designs (2/25/19)

Utilizing the newest generation of its RF Fusion RF front-end modules, Qorvo now supports marquee product releases across leading smartphone manufacturers with highly integrated mid-high band module solutions. In addition, Qorvo can now leverage their unique capabilities to deliver enhanced performance in a small solution size and reduced footprint.

As the industry begins its transition to 5G, manufacturers can accommodate complex RF content in handsets and accelerate delivery of next-generation LTE, LTE-A, 5G and IoT products. This helps smartphone manufacturers reduce time to market, optimize their handset portfolio and improve manufacturing yields.

The latest design wins also include the QM17001 mid-high band diplexer and RF8129 envelope-tracking (ET) power management module.

Qorvo and National Instruments Demonstrate First 5G RF Front-end Module (2/27/18)

In early 2018, Qorvo partnered with National Instruments to test the first commercially available 5G RF front-end module. Testing demonstrations were held during the 20th GTI Workshop in London.

Qorvo's QM19000 5G FEM, which combines a power amplifier and low noise amplifier into a single package, is targeted for mobile devices operating in the 3.4 GHz spectrum.

The FEM was tested with the advanced NI PXI system, as part of an ongoing effort to help customers design and test 5G technology for early deployments of 5G in mobile devices.

Paul Cooper, director of Carrier Liaison and Standards, Qorvo Mobile Products, stated "The wide bandwidth, excellent RF performance, and flexibility of NI's PXI test system were critical in helping us introduce the industry's first commercially available 5G FEM. Qorvo's focus on innovation was clearly demonstrated at the 20th GTI Workshop in London."

To learn more about Qorvo's news, visit

www.qorvo.com/news

Qorvo Wins Prestigious GTI Award for 5G RF Front End Module

Qorvo's QM19000, the world's first 5G front-end and recipient of the GTI 2017 Award for "Innovative Breakthrough in Mobile Technology" offers a robust and reliable platform to accelerate 5G testing and deployment.

The award-winning front-end has been a key element of 5G tests and demonstrations by operators and ecosystem partners across the world.

The QM19000 meets the challenging requirements of 5G non-standalone (NSA) and standalone (SA) deployments for advanced applications such as high-definition mobile video and virtual reality.

To learn more about Qorvo's awards, visit

www.qorvo.com/awards

Qorvo 5G Product Highlights

RECENTLY RELEASED

QPF4001
GaN single channel FEM
- Frequency: 28 GHz
- Package dimensions: 5x4 mm

QPF4005
GaN dual channel FEM
- Frequency range: 37-40.5 GHz
- Package dimensions: 4.5x6x1.8 mm

QPB9337
Dual channel switch LNA module
- Frequency range: 2.3-3.8 GHz
- Package dimensions: 6x6 mm

QPA3503
3.4-3.6 GHz GaN PA module
- 3W, 28V
- Package dimensions: 6x10 mm

TGA2224
GaN power amplifier
- Frequency range: 32-38 GHz
- Package dimensions: 3.4x1.4 mm

QPQ1270
Band 7 BAW duplexer
- Frequency range: 30 dBm
- Package dimensions: 2x2.5 mm

QPF4002
GaN dual channel FEM
- Frequency: 28 GHz
- Package dimensions: 5x8 mm

QPF4006
GaN single channel FEM
- Frequency range: 37-40.5 GHz
- Package dimensions: 4.5x4x1.8 mm

QPQ6108
SAW duplexer
- High input power: 29 dBm on DL
- Package dimensions: 2.5x2 mm

QPA9908
High-efficiency PA
- 5V, 4W
- Package dimensions: 5x5 mm

QPA9903
1805-1880 MHz 0.5 W high-efficiency amplifier
- 5V, 4W
- Package dimensions: 5x5 mm

QPA9940
High-efficiency PA
- 5V, 4W
- Package dimensions: 5x5 mm

QPA9942
High-efficiency PA
- 5V, 4W
- Package dimensions: 5x5 mm

QPA9120
Wideband driver amplifier
- Frequency range: 1.8-5 GHz
- Package dimensions: 3x3 mm

QPB9329
Dual-channel switch LNA module
- Frequency range: 3.8-5 GHz
- Package dimensions: 7x7 mm

QPL9503
LNA
- Frequency range: 0.6-6 GHz
- Package dimensions: 2x2 mm

QPA4501
GaN PA module
- Frequency range: 4.4-5 GHz
- Package dimensions: 6x10 mm

QPD0020
DC-6 GHz GaN power transistor
- 35W, 48V
- Package dimensions: 4x3 mm

QPD0030
DC-4 GHz GaN RF power transistor
- 45W, 48V
- Package dimensions: 4x3 mm

QPD0050
DC-3.6 GHz GaN transistor
- 75W, 48V
- Package dimensions: 7.2x6.6 mm

QPA3506
3.4-3.6 GHz GaN PA module
- 5W, 28V
- Package dimensions: 6x10 mm

QM19000
5G RFFE for wireless mobile devices
GTI 2017 Award
Innovative breakthrough in mobile technology

At Qorvo, we are developing RF solutions today, for a better, more connected tomorrow.
Visit **www.qorvo.com/5G** for our latest products.

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