Microwave Journal

eBook

Design Ideas and Tradeoffs for 5G Infrastructure

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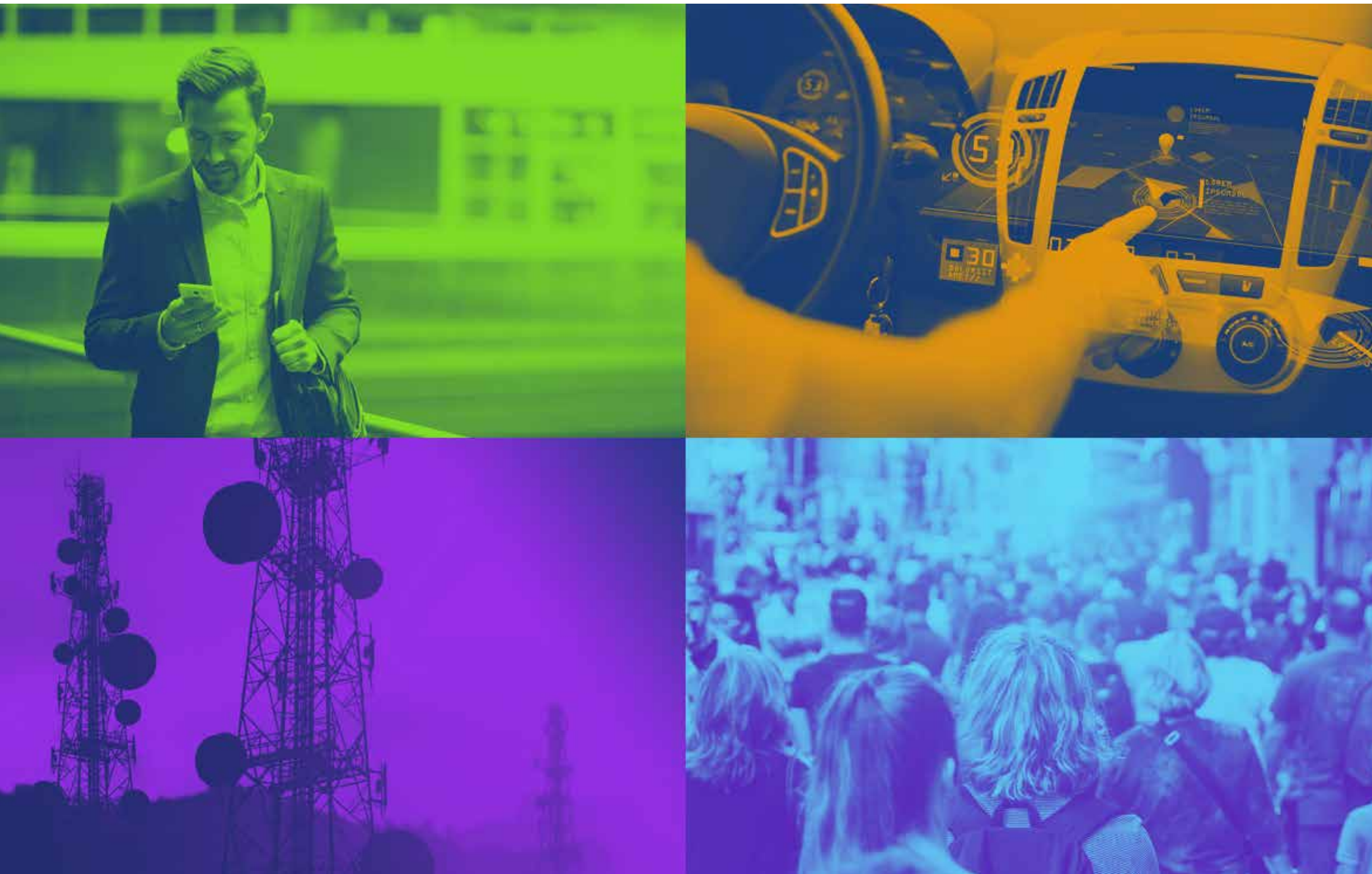

Table of Contents

3 **Introduction**

Pat Hindle
Microwave Journal, Editor

4 **The Challenges of 5G Network Densification**

Luke Getto
Microlab

7 **Microwave Will Drive the Development of 5G**

Tamas Madarasz
Nokia, Espoo, Finland

11 **RF Front-end Technology and Tradeoffs for 5G mmWave Fixed Wireless Access**

Bror Peterson
Qorvo, Greensboro, NC

17 **Optimizing the Perennial Doherty Power Amplifier**

Gareth Lloyd
Rohde & Schwarz, Munich, Germany

Introduction

Design Ideas and Tradeoffs for 5G Infrastructure

As 5G rolls out, there are many infrastructure challenges to design the critical hardware that is needed to enable 5G to deliver on its promise. From fixed wireless access to small cells, many design challenges will need to be overcome to achieve the performance requirements for 5G NR. This eBook addresses some of the challenges with design solutions that were published in *Microwave Journal.*

In the first article, Microlab looks at the challenges and solutions for network densification as small cells will need to be deployed in massive numbers to achieve 5G NR goals. The second article is written by Nokia about how microwave solutions are required to drive 5G deployment. It covers various scenarios and how microwave solutions can address each. 5G Fixed Wireless Access technology is already being deployed using mmWave frequencies, but there are many design challenges such as power, scan angle, thermal heating and efficiency. Qorvo discusses the various technology tradeoffs for designing FWA arrays including beamforming techniques, front-end components and semiconductor materials. Lastly, Rohde & Schwarz looks at optimization techniques for Doherty power amplifier design as these are a prime choice for basestation applications.

This eBook aims to educate design engineers on some of the important challenges for 5G infrastructure and some solutions to address them. Various tradeoffs are reviewed so that designers can optimize appropriately as they create new products. The eBook is available at no cost thanks to our sponsors RFMW and Qorvo. We hope that this spurs some key insights into your next design.

Pat Hindle, Microwave Journal *Editor*

The Challenges of 5G Network Densification

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Network densification will be an integral part of deploying 5G architecture that promises vastly increased data rates, from megabits per second (Mbps) to gigabits per second (Gbps), and ultra-reliable lower latency, from tens of milliseconds to milliseconds. The 4G radio access network (RAN) is roughly 10× denser than the 3G network, and that densification is predicted to continue through 2022 before new 5G equipment takes over the growth trend. Macro cell towers carried the bulk of 4G mobile traffic, with small cells deployed where the capacity is needed most—close to the consumer. It is predicted that 5G networks will need to be 10× denser than 4G networks, a 100× increase over 3G. 5G densification will be accomplished in space, time and frequency.

Mobile network operators (MNO) have invested billions of dollars to buy different frequency bands within the same geographical areas, and they want to maximize their investments by using carrier aggregation to increase capacity. This necessitates using three, four or five different licensed bands at the same time, and they may use MIMO technology for additional capacity. All these requirements multiply the amount of RF hardware at a site. Excellent RF performance, with low loss, low passive intermodulation (PIM) and high inter-band isolation must be maintained, as the demands of 4G LTE-Advanced already require it. There is a cost associated with meeting all of these requirements. These sometimes conflicting factors are difficult to design into the components; nonetheless, new products have been able to solve the challenges and constraints of today's deployments. Solutions for tomorrow's rollouts will take advantage of these new techniques to satisfy the demands of more bands and configurations.

Outdoor small cells come in many different shapes, sizes and configurations. In this article, a small cell is defined as a single geographic site and can be made up of radios, antennas and other equipment. They can differ from city to city, even street corner to street corner, depending on the requirements of the site, municipal jurisdiction, MNO or subscriber population and mobility in the area. They can support multiple frequency bands, multiple sectors and multiple operators within a common structure. Each of these requirements brings unique challenges to the design and deployment of small cells at the scale required for 4G expansion and future 5G networks.

The challenge of location means that small cells must be put in the available space, both horizontally and vertically, which may not be ideal. Small cells can be located on dedicated poles, roof tops, inside street furniture

Fig. 1 Lamp post small cell (Source: Crown Castle).

and on existing utility poles (see ***Figure 1***). In New York City, for example, two of the poles at an intersection are reserved for public safety and traffic control, which limits the physical space available for small cells. What is possible really depends on the restrictions within each municipality. Additionally, neighborhood residents will not accept an eyesore to get better service, so pleasing concealment is vital. Compact and adaptable components are critical to successfully deploying outdoor small cells.

In a neutral host small cell, a third party finances the small cell and rents access to the MNOs. A neutral host small cell can have two or more different network operators, each using multiple frequency bands. With each MNO using multi-band carrier aggregation, it is not uncommon to see 12 or more frequency bands within a single small cell. In this crowded RF environment, signal performance is critical, typically requiring the use of a multi-band combiner with minimal insertion loss and maximum inter-band isolation.

The small cell components must be physically small and offer the necessary RF performance. If the small cell equipment is too large, mounting the cell at the required location may not be possible. Every cubic inch of space within the enclosure is a premium, making component size and dimensions a critical design factor. If the small cell's physical size is small, more options will be available for locating the cell. This presents more options for network engineers, as they design the network architecture; however, it presents a larger challenge to the equipment vendors. Network equipment vendors must continually innovate and optimize designs to fit within the physical constraints and achieve the desired RF performance for the small cell marketplace.

Yet another consideration for small cell equipment is hardiness against the elements. The products must work across a large temperature range, from sub-zero temperatures away from the equator to scorching summers closer to it. They must be designed with dust ingress protection (IP) for desert climates and prevent corrosion in humid, salty coastal areas. The temperature specifications, IP or National Electrical Manufacturers Association ratings and salt/fog compliance are important factors to select the right equipment.

For in-building coverage, distributed RAN (D-RAN) is a cost-effective way to meet wireless coverage and capacity needs in venues like stadiums, hospitals, office buildings and hotels. If small cells were deployed everywhere coverage is required, the cost would be very high and the system would be well over the capacity needed. D-RAN uses a small network of passive components with low power radios as the signal source. D-RAN is generally both a neutral host and multi-band. In the D-RAN architecture, a point of interface (POI) has several ports for combining, with multiple outputs for distribution. The POI allows for efficient combining and is a cost-effective solution for in-building designs, as the coverage and capacity can be optimized simultaneously.

D-RAN has some of the same design constraints as outdoor small cells. Small size of the components is critical to the ability to deploy the equipment where it needs to be placed, not just in a convenient location. But RF performance is still critical—if the network does not have the necessary RF performance, it is not able to do its fundamental job of wireless connectivity.

As the industry begins its foray into the 5G era, small cells need to be future proof. In only the last three years, just for 4G, the large U.S. MNOs have each increased spectrum usage by 100 MHz or more. Typical commercial bands now extend from 600 to 3800 MHz. Additionally, the RAN has begun to include unlicensed spectrum features for LTE-LAA, up to 5925 MHz. Over the next decade, the increase in spectrum usage will be in the thousands of MHz. Ultra-wideband RF components that span several GHz of bandwidth, to cover the licensed and unlicensed sub-6 GHz range, provide the flexibility to adapt to existing and potential spectrum for future use. 5G will require even more spectrum below 6 GHz.

Flexibility to adapt to these changing spectrum requirements helps reduce the total cost for the MNOs to continuously upgrade their networks. Small cells are expensive to deploy and upgrade, especially if upgrades must be approved by the municipality. Deploying future proof technology can dramatically reduce the cost and time to deploy. D-RAN solutions must also be flexible to adapt for various use cases in stadiums, offices, warehouses and other locations. The more flexible the solution, the more likely it is to actually get deployed. Flexibility also extends to configuration, i.e., two sector, multiple bands, etc. Small cells and D-RAN will not just be single sector, single band deployments; the lim-

Fig. 2 Components designed for small cells must be small and withstand outdoor environments with varying temperature and moisture.

ited locations are too valuable for that. Compact, high quality, flexible products that do not sacrifice RF performance are indispensable.

Microlab has been focusing its R&D on small cell components, developing rugged, ultra-wideband and compact components. Each of the product categories offers frequency coverage options from 350 to 5925 MHz for TETRA, commercial wireless, CBRS, LTE-LAA and future 5G bands. These products have multiple mounting configurations that allow system integrators the flexibility to adapt to each site's unique requirements. Many of Microlab's products are designed to cover −40°C to +75°C, and the salt/fog series (see ***Figure 2***) complies with Telcordia GR-3108-CORE paragraph 6.2, Salt Fog Exposure, as Class 4 products for 30 days, defined by ASTM-B117. These products are hard anodized, resulting in an even harder and more durable coating. They come with an IP68 rating, which means they are protected against the effects of immersion in water under pressure for prolonged periods.

For small cell and D-RAN deployments, Microlab's MCC Series™ is a modular POI solution (see ***Figure 3***). Designed to fit any operator or neutral host provider, the series offers a modular solution that can accommodate any wireless communications band up to 6 GHz and can be adapted for any site with any band or carrier configuration. This one-size-fits-all platform was designed as a future proof solution, enabling easy upgrades and reconfigurations as capacity and bandwidth requirements evolve. The custom, bolt-on design supports fast and easy installation, with guaranteed end-to-end performance of the passive components.

Fig. 3 Neutral host small cell and D-RAN systems support several operators and must handle multiple carriers operating on different frequency bands.

For 5G networks, RF performance is even more critical, since 5G essentially maximizes the spectral efficiency (bps/Hz) of the LTE waveform to deliver ultra-reliable and low-latency communication and greater mobile broadband bandwidth. To provide these capabilities, the RAN ecosystem must perform.

5G will not be able to meet its performance goals without cell densification. Actually, hyper-densification is required to deliver the promise of 5G. So the industry must be able to deploy high quality small cells, for use indoors and outdoors, in a cost-effective and adaptable manner.■

Microwave Will Drive the Development of 5G

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Mobile data traffic is growing rapidly, with current estimates suggesting a 40× increase between 2014 and 2020. Networks will also connect some 50 billion devices to the IoT by 2025—with a proliferation of smart objects from fridges to industrial controllers. Many communication service providers (CSP) are, therefore, rethinking their existing transport network architectures as they transition to 5G.

The shift to 5G is unlike the changes experienced with previous generations of mobile communication technology, because 5G is more than just an innovative radio technology using new spectrum. Beyond the extremely challenging capacity considerations already mentioned, 5G introduces a new approach to network architecture, enabling new business models for an industry looking toward the next trillion dollars of growth. This clearly will not come by just selling more smartphones or providing simple connectivity in developing markets; rather, it builds on new concepts such as densification, decomposition of network functions (e.g., the separation of user and control planes), programmable transport, network slicing and end-to-end automation and orchestration to enable new services and business models.[1] A complex interworking of different network domains, technologies, components and services is needed.

As 5G deploys, mobile transport networks must evolve to meet this complex range of new demands, forcing CSPs to respond with backhaul transformation projects to meet the needs of 5G radio access network (RAN) service provisioning. Casual observers might think the future of transport networks is all about fiber optics. It is true that the fiber presence in transport networks is increasing, as CSPs exploit the technology's advantages. Yet fiber is not always available and may be too expensive. When a fiber point of presence is a few hundred meters away from the radio access point, for instance, total cost of ownership (TCO) favors microwave connectivity. Microwave is already used in more than 50 percent of current cell sites, and any cost-effective evolution to 5G will continue to use existing 4G/LTE network assets, particularly since microwave technology is capable of supporting 5G's challenging capacity and latency requirements.

As noted, 5G will enable many new services, including enhanced mobile broadband, augmented reality (AR) and mission-critical communications, creating an unprecedented traffic mix requiring dramatically improved performance. For example, throughput must rise 10× (10 to 25 Gbps for the F1 link and cell site backhaul interfaces), and latency must come down to 1 ms end-to-end. To meet the increasing 5G capacity requirement, new microwave solutions that optimize spectrum use and dramatically increase capacity are already available, with more to follow. When it comes to addressing latency, physics favors microwave. Propagation medium latency depends on the density of the medium, so the latency of a wireless connection is fundamentally lower than that of a fiber cable of the same length. Equipment latencies must also be considered. Mission-critical applications require high resiliency. Wireless is generally more reliable than fiber during major events such as earthquakes, fire or simple road maintenance. In these cases, the recovery time is much faster with a microwave connection. For all these reasons, microwave transport will be a key enabler for 5G, playing an important role as CSPs ramp up their 5G rollouts.

A NEW ARCHITECTURE

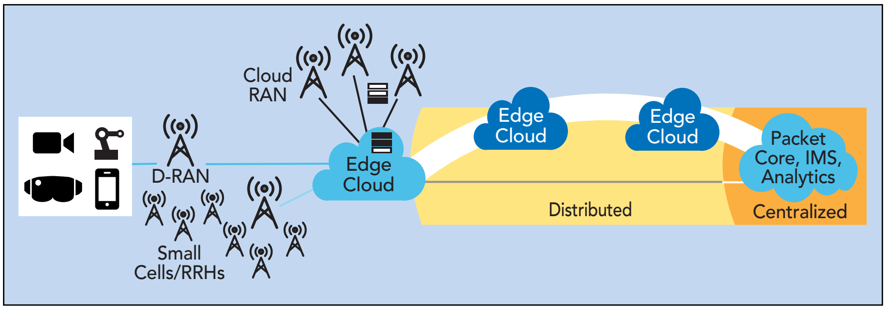
5G is more than just an innovative radio technology. It introduces a new approach to network architecture to deliver the dramatic improvements in performance that 5G users will expect. For example, CSPs traditionally treat the core, transport and RAN independently and tend to integrate the different infrastructure parts only after deployment. In 5G scenarios, however, post-deployment integration costs, time to market and the risk of degraded service quality will increase dramatically using this approach. Without cross-domain design and pre-deployment integration, CSPs risk missing out on new 5G business opportunities. Business-critical applications depending on ultra-reliable low latency communication (URLLC) and extreme network reliability can only be delivered with the seamless, error-free interaction of radio, transport, core, data center and management systems.

Network slicing (see ***Figure 1***) is one of the key enablers of next-generation services and business models. With network slicing, network resources—both virtual network functions and the transport network—are shared by different services. The network is virtually sliced into several, independent logical resources that simultaneously accommodate multiple application fulfillment requests. This is different than the conventional setup for sharing network resources, where a host provides hardware and software resources to one or more guests. Instead, it relies on the concept of software-defined networks (SDN). An SDN-capable microwave network makes its resources available through a virtualized transport service, with the SDN controller acting as a hypervisor to allocate the resources. For example, ultra-low latency applications can be served by a network slice allocating the service to an E-Band (i.e., 80 GHz) channel using carrier aggregation. Other services not requiring low latency can be allocated by a load balancing algorithm in the SDN controller to efficiently use carrier aggregation bandwidth.

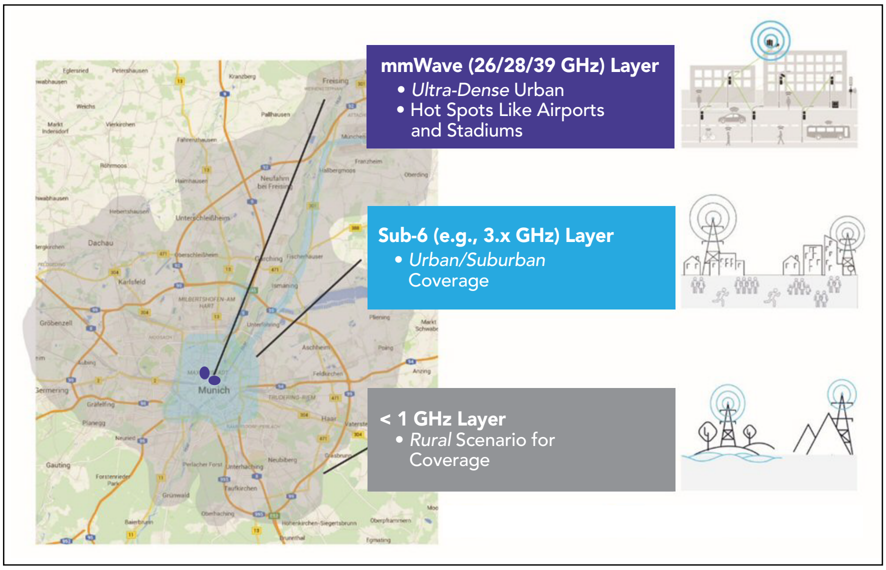
Network slicing requires substantial service automation and optimization. Such a dynamic environment cannot be managed by humans, due to network complexity and the required life-cycle speed of each service. Instead, it demands an end-to-end approach to service fulfillment, which means that newly converged networks must make the transition to IP to support it. The transport network, whatever the mix of microwave and fiber, must adapt in step with the distributed IP core and RAN functions provided by the base stations, to meet the service levels required for each network slice. Complex traffic engineering and the flexibility to deliver shorter service activation cycles—from days or hours to minutes—combine to make a step change in the level of network automation the only sensible option.

It all adds up to far greater complexity. For instance, virtual RAN functions will be distributed over multiple platforms and integrated via new interconnectivity interfaces. Some functions will shift into the cloud and be centralized to optimize cost and performance, while others will move closer to the end user, to better comply with stringent low latency requirements. Such flexible and complex networks will require unprecedented levels of automation, to allow granular end-to-end traffic engineering and satisfy the different service level agreements assigned to each service or network slice. Each slice will effectively be an automated and programmable transport pipe, which can adapt dynamically to meet changing needs.

Densification at the physical edge of the network means more sites to be connected, with significant implications for transport. For instance, in a typical deployment, a macro cell may be a pooling site for small cells



▲ **Fig. 1 Transport network slicing creates pipes to meet many different performance needs.**

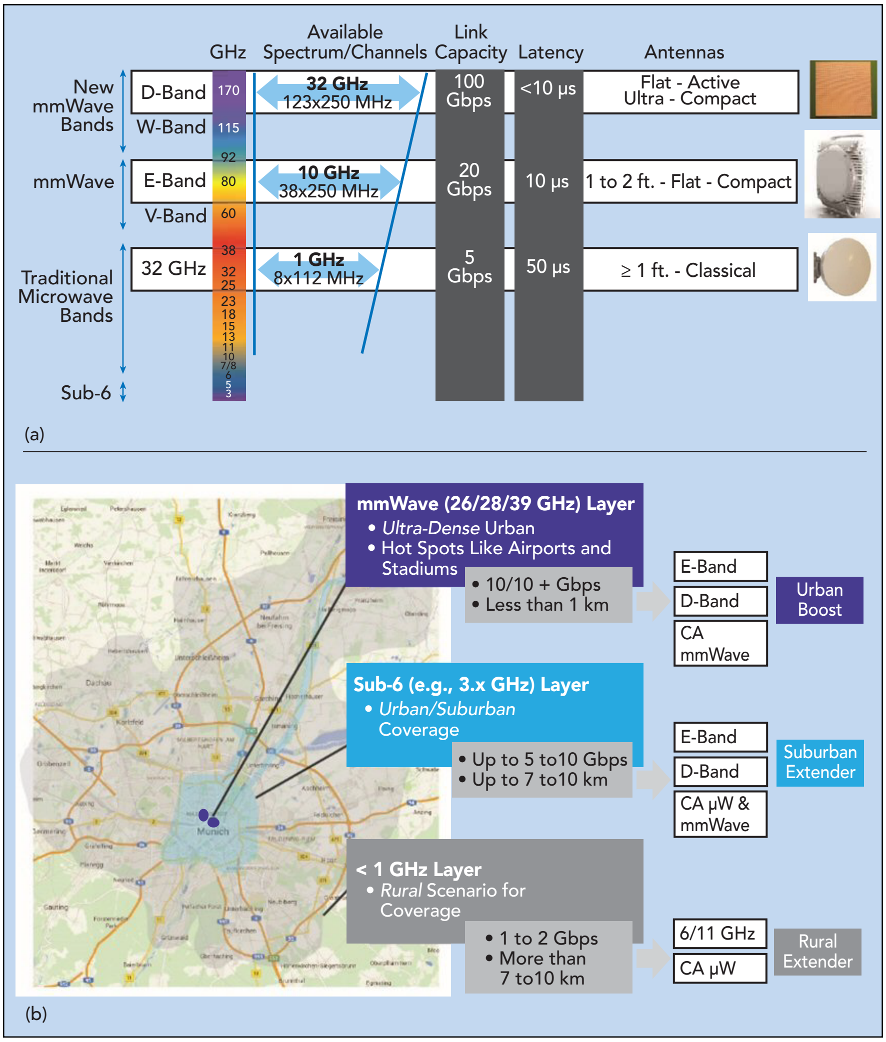


▲ **Fig. 2 Microwave must meet the diverse transport needs, from dense urban hot spots to rural areas.**

in its coverage area. High user density (> 150,000 subscribers/km²) implies increased connectivity between base station sites with different connectivity technologies, so densification needs a shift in topology toward a meshed or partially meshed structure.

MICROWAVE SOLUTIONS FOR ALL SCENARIOS

From high traffic hotspots to rural coverage, there are strong arguments to support microwave solutions for every 5G network scenario (see ***Figure 2***). For example, in ultra-dense urban areas, such as crowded squares, airports and stadiums, 5G networks will be deployed using a mmWave radio access layer (e.g., 26, 28 or 39 GHz), as shown in ***Figure 3***. Very high capacity backhaul is needed (≥ 10 Gbps) with transport link lengths less than 1 km. Low visual impact is another consideration for deployments in dense urban environments, and microwave solutions with very small form factors will be integrated with RAN equipment. In the suburbs, where typical link distances range from 7 to 10 km, the access layer will be based on sub-6 GHz frequencies, with connectivity requirements not quite as extreme, yet still demanding capacity of 5 to 10 Gbps. This contrasts with rural settings, where the geographical coverage is larger, and the access network uses frequencies below 1 GHz. Here, the transport network must backhaul up to 2 Gbps, and link lengths will commonly exceed 10 km.



▲ **Fig. 3 Microwave and mmWave transport networks (a) can meet 5G's data capacity and coverage needs (b).**

In addition to solutions for the full range of scenarios, CSPs must also address their end-to-end service capabilities, including access and management considerations in addition to transport. A microwave portfolio must be fully integrated into an end-to-end vision of the network and service fulfillment.

To meet the 5G requirement for more capacity, new microwave solutions for optimizing the use of spectrum are already available. Carrier aggregation using multiple bands on the same link, more powerful and efficient power amplifiers that use wider channels and the availability of mmWave spectrum meet key requirements for future network solutions. For example, in today's frequency bands used for RAN backhaul (6 to 42 GHz), several suppliers already offer transceivers capable of 2.5 Gbps in a single box, thanks to 4096-QAM modulation in 2 × 112 MHz frequency channels. Beyond this, current E-Band solutions stand ready to satisfy the initial wave of 5G introductions that require up to 10 Gbps transport capacity and 20 µs latency for urban environments. Combining E-Band with a traditional microwave frequency band between 6 and 42 GHz, it is possible to achieve longer distances while preserving high availability for the most valuable traffic. With efficient carrier aggregation, between 10 and 20 Gbps bi-directional capacity is achievable.

Looking further ahead, the telecommunications industry is considering the frequency bands above 100 GHz for the transport segment of future 5G networks. Recent activities reflect the highest interest at W-Band (92 to 114.25 GHz) and D-Band (130 to 174.8 GHz). While W-Band is viewed as a likely extension of E-Band, because the two share similar propagation behaviors, the peculiarities of D-Band enable innovative approaches to equipment design. Also, the very small form factor aids the integration of the radio and antenna—just a few centimeters square. Between transport and access products, this enables new network topologies such as point-to-multipoint and mesh connectivity combined with beam steering.

5G network transformation will affect the microwave solutions already deployed for 3G and the early stages of 4G probably more than any other transport technology. The substantial installed microwave base will inevitably be replaced by new microwave solutions—in some instances fiber—designed for 5G. The goal for CSPs is to optimize budgets during backhaul network upgrades to minimize the TCO of their evolving assets. The latest microwave designs are highly compact, often with integrated antennas and other components, enabling them to be used for a wide range of use cases. New microwave outdoor units also support multi-frequency systems and carrier aggregation, helping lower TCO.

SOLUTIONS TODAY AND TOMORROW

To have maximum flexibility when choosing the best way forward, companies must seek out appropriate solutions and tools to optimize budgets during backhaul network upgrades, considering both CAPEX and OPEX. The optimal solution combines an end-to-end portfolio including cross-domain cloud-native utilities and enabling rapid deployment of virtualized functions across a distributed cloud infrastructure. This will simplify service scaling, shorten time to market and deliver cost efficiencies across the radio, core and transport networks.

Companies seeking to digitally transform require a solution that answers the challenges of 5G transport by converging fronthaul, midhaul and backhaul to serve a variety of use cases within the same network. Every CSP will follow a unique path to 5G, but each one will tackle the evolving transport network. Right now, the transport layer must handle many technologies, both legacy and evolving, and will soon need to flex to meet more extreme demands (see ***Figure 4***). CSPs need to adopt an end-to-end approach to transport, and microwave technology will play a role as a key enabler of the new approach. It will help CSPs leverage existing investments while continuing to build the new capabilities needed for 5G.■

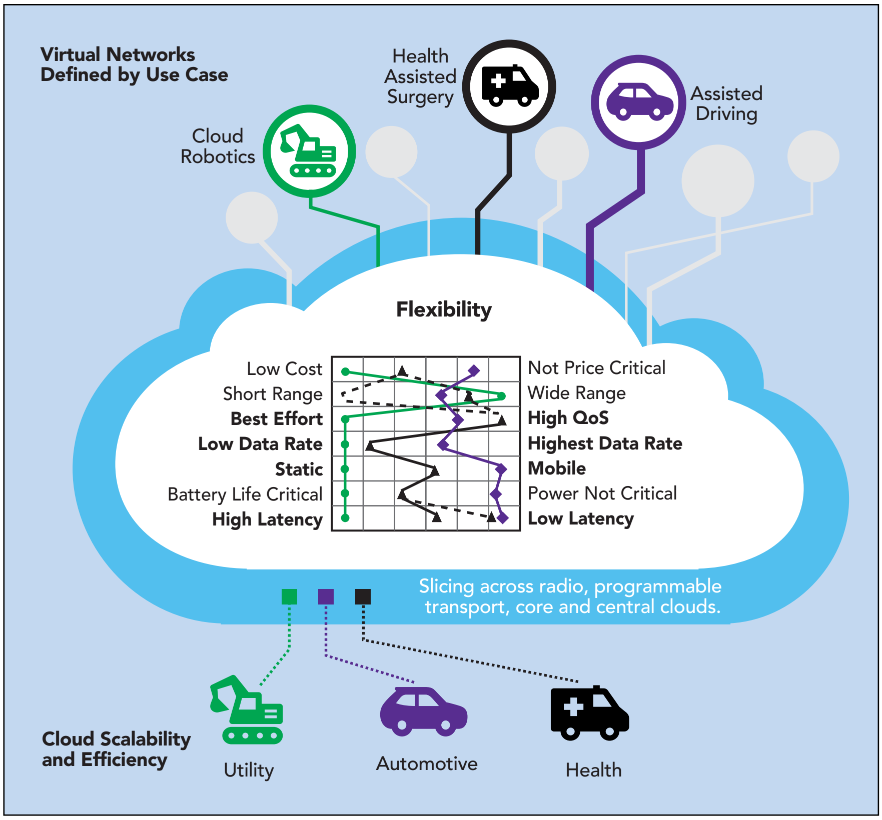


Fig. 4 Using network slicing across the radio, transport, core and central clouds, 5G has the flexibility to support diverse use cases with a common underlying infrastructure.

Reference

1. "The Evolution of Microwave Transport—Enabling 5G and Beyond," *Nokia*, 2019, pp. 1–24, https://nokia.ly/2NrxmWK.

RF Front-end Technology and Tradeoffs for 5G mmWave Fixed Wireless Access

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Presented at EDI CON USA 2018.

Fixed Wireless Access (FWA) has entered as one of the first enhanced mobile broadband (eMBB) use-cases. Many carriers are performing FWA deployment in targeted locations throughout their networks. In this technical paper, we analyze the architecture, semiconductor technology, and RF front-end (RFFE) design needed to deliver mmWave FWA services. Discussing topics such as;

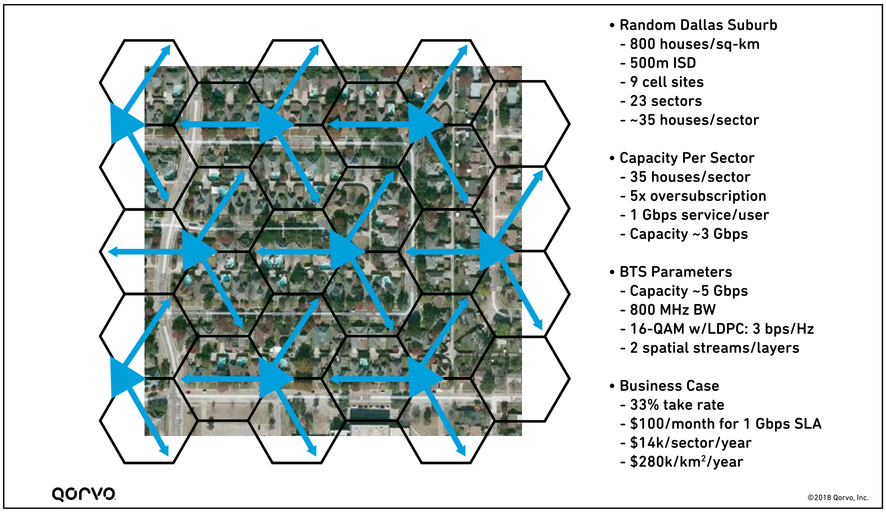
- Scan-angle requirements
- Tradeoffs of Hybrid-beamforming versus All-Digital Beamforming for the Base Transceiver Station (BTS)
- Analyze BTS semiconductor technology and RF front-end components
- Gallium-Nitride on Silicon Carbide (GaN-on-SiC) front-end modules (FEMs) designed specifically for the 5G FWA

MMWAVE SPECTRUM & DEPLOYMENT

Operators have already taken steps to meet their first FWA challenge: obtaining spectrum. Most deployments are expected to use mmWave frequencies, where large swaths of contiguous unpaired bandwidth are available at very low cost. Based on the initial trials and the geographical bandwidth it is clear the 26.5-29.5 GHz and 37-40 GHz bands will be the first used and 24.25-27.5 GHz will closely follow.

FWA describes a wireless connection between a centralized sectorized BTS and numerous fixed/nomadic users. Systems are being designed to leverage existing tower sites and support a low-cost self-installed CPE build-out. Both are critical to keeping initial deployment investment low, while the business case for FWA is validated.

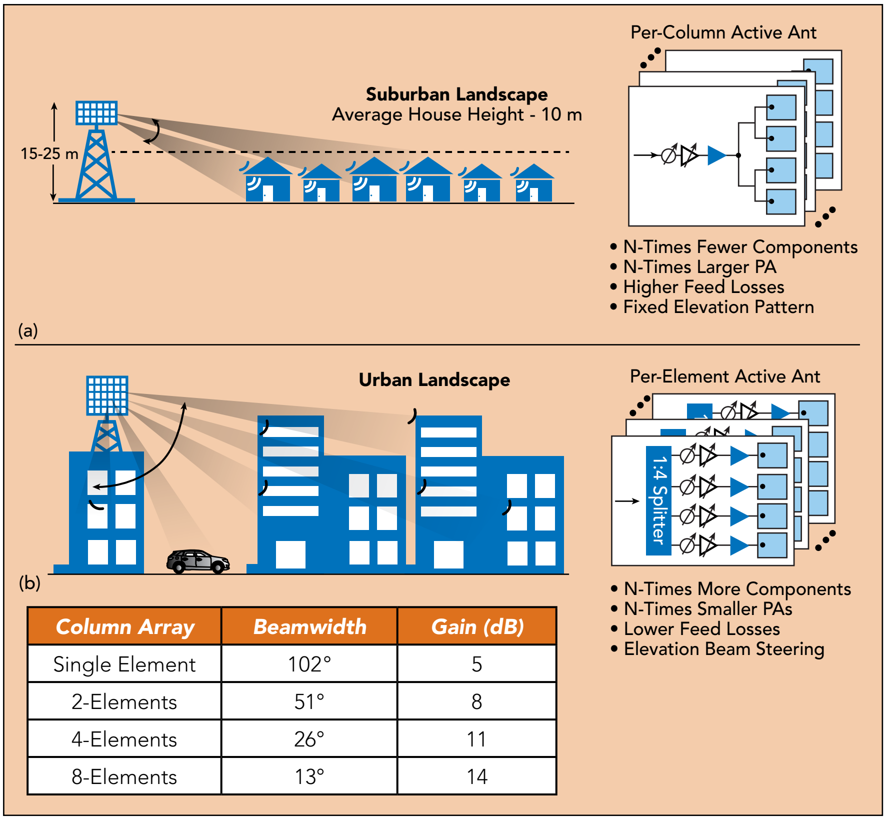
Large coverage is essential to the success of the FWA business case. To illustrate this, let's consider a suburban deployment with 800 homes/km^2, as shown in ***Figure 1.*** For BTS inter-site distance (ISD) of 500 m, we need at least 20-sectors each covering 35-houses from 9 cell-sites. Assuming 33% of customers sign up for 1 Gbps service and a typical 5x network oversubscription ratio, an average aggregate BTS capacity of 3Gbps/sector is needed. This capacity is achieved in 800 MHz, assuming an average spectrum efficiency of 3 bps/Hz and 2-lay-



▲ **Fig. 1 Fixed Wireless Access in a Suburban Macro Environment.**

ers of spatial multiplexing. If customers are paying $100/month, the annual revenue is $280,000/km^2/yr. Of course, without accounting for recurring costs it's 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 operates up to regulatory limits to maximize coverage and profitability.

In the U.S., the Federal Communications Commission (FCC) has defined very high effective isotropic radiated base station power (EIRP) limits[1] at 75 dBm per 100 MHz for the 28 and 39 GHz bands. The challenge becomes building systems that meet these targets within the cost, size, weight, and power budgets expected by carriers.



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

Fig. 2 Array Complexity Depends on the Scanning Range Needed for the Deployment Scenario.

FWA LINK BUDGET

The standards community has been busy defining the performance requirements and evaluating several 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.

Closing the link budget depends on many variables including transmit EIRP, receive antenna gain, receiver noise figure (NF), and minimum edge-of-coverage throughput. In the following, we explore several architecture trades that are key to technology selection and design of RFFE components.

SCAN-ANGLE REQUIREMENTS

The number of active channels in the array depends on many things. Let's start by first understanding the scanning (azimuth and elevation) requirements and whether two-dimensional beamforming is required for typical FWA deployment or if a lower complexity one-dimensional (AZ only) beamforming array is sufficient. We will see that this decision impacts the power amplifier (PA).

We show two FWA deployment scenarios in ***Figure 2.*** In the suburban deployment, the tower heights ranging from 15 to 25 m and the cell-radius is 500 to 1000 m with an average house height of 10 m. Just as in traditional macro cellular systems, where the typically vertical beamwidth is 5-8 degrees, there is no need for fully adaptive elevation scanning.

This allows the elevation beam-pattern to be focused down by corporately feeding several passive antenna elements, as shown in Figure 2(a). 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 a more uniform coverage for both near and far uses.

The nominal half-power beam-width can be approximated as 102°/NANT and the array gain by 10log10(NANT) + 5 dBi. As we passively combine antennas the elevation beam pattern is focused, and fixed antenna gain increases, as shown in the Table of Figure 2. For the suburban FWA use-case, a 26° to 13° beamwidth is sufficient and the passively combined column array can be 4 to 8-elements, respectively. In the urban scenario, the elevation scanning requirements are greater and systems will be limited to 1 or 2 passive elements. Figure 2 far right (a) and (b) illustrates the two approaches. Both 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 four times as many PA, phase shifter, and variable gain components. Whereas, the column-fed PA will need to be four times larger, which can easily change the semiconductor technology selection.

It's 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.

ALL-DIGITAL AND HYBRID ARRAY DESIGN

It is natural for BTS vendors to first explore extending current sub-6 GHz all-digital beamforming AAS platforms to mmWave. This preserves the basic architecture and the advanced signal processing/algorithms needed to realize 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 new hybrid-beamformed architectures[2], which allows flexibility between the number of baseband channels to the number of active RF channels. This approach may provide a better balance of analog beamforming gain and baseband processing. In the following sections, we analyze the two architectures and discuss the RFFE approaches needed for each.

All-Digital approach

The most obvious choice in mmWave base station applications is to upgrade the current platform. Three key elements would be required to do this, namely: efficient wide-band analog-to-digital/digital-to-analog converters (ADCs/DACs), highly integrated direct-conversion transceivers, and high-efficiency high-power amplifiers.

Analysis can show that even with todays off-the-shelf components and using a traditional high-power 9 W Psat linear GaN amplifiers (e.g. QPA2595) an all-digitally beamformed dual-polarized BTS can be designed to achieve 60 dBm EIRP/polarization with only 16 channels at a dissipated power of 320 Watts. Unfortunately, for all outdoor passive-cooled, tower-top electronics, it's challenging to thermally manage more than 300 W from the RF subsystem. Fortunately, there are new technologies being introduced that will make this architecture a reality:

- Next-generation 14 nm digital-to-analog and analog-to-digital converters that save power
- Advances in mmWave CMOS direct-conversion transceivers
- Increased levels of small-signal integration
- Last but not least, new PA technology advances

As an example, Qorvo has been developing a 9 W Psat Doherty GaN PA at 28 GHz that provides over 20% PAE at 8 dB backoff. When compared to an equivalent traditional amplifier this is a 10% improvement and without any other changes to the above off-the-shelf design brings the dissipated power below 200 W. In combination with new ADC/DACs and highly integrated mmWave transceivers, the idea of extending a 16T16R Sub6GHz BTS platform to mmWave frequencies is nearer than most people think.

Hybrid approach

An alternative architecture being explored is hybrid beamforming ***(Figure 3),*** where the spatial multiplexing

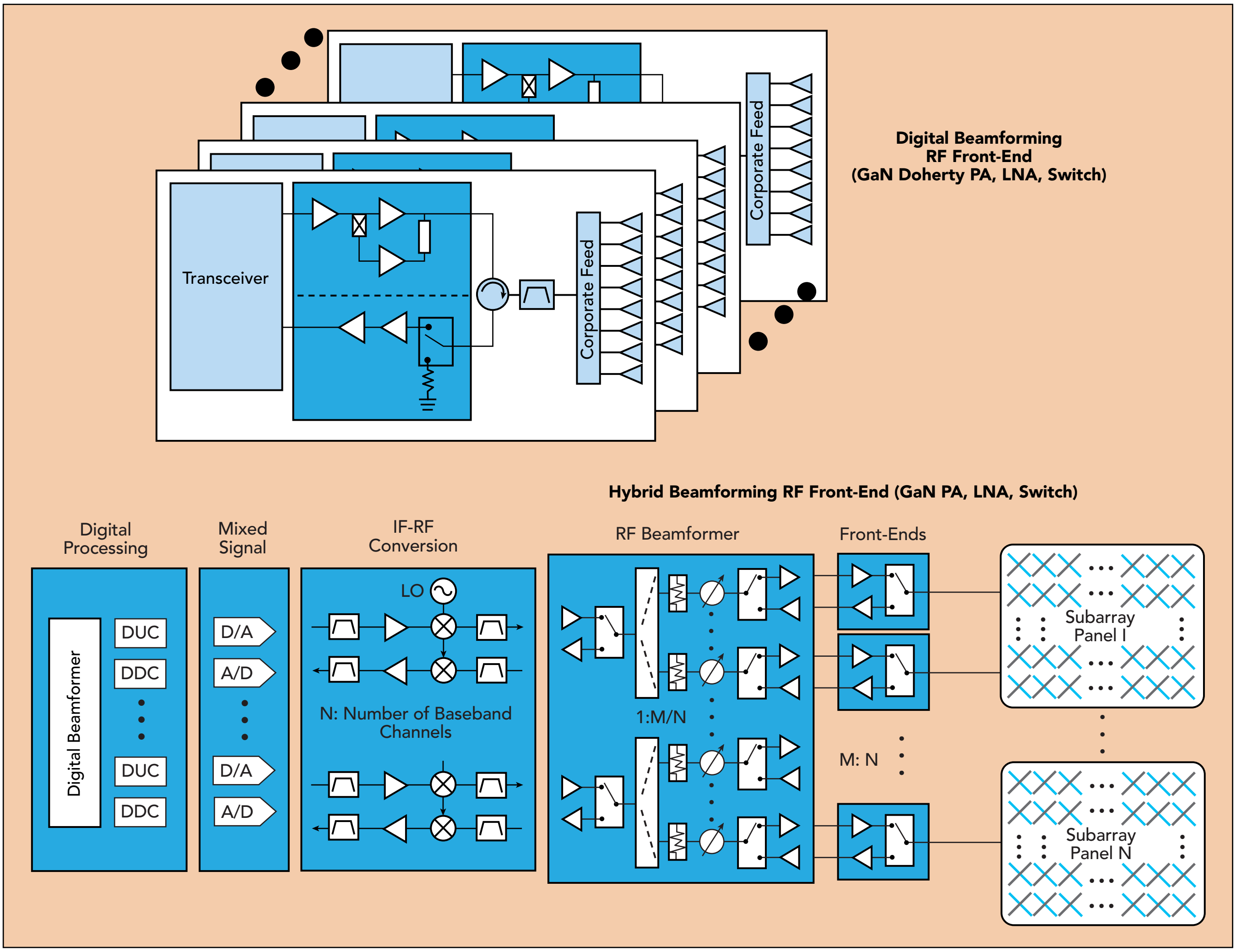


Fig. 3 Digital and Hybrid RF Front-End Approaches.

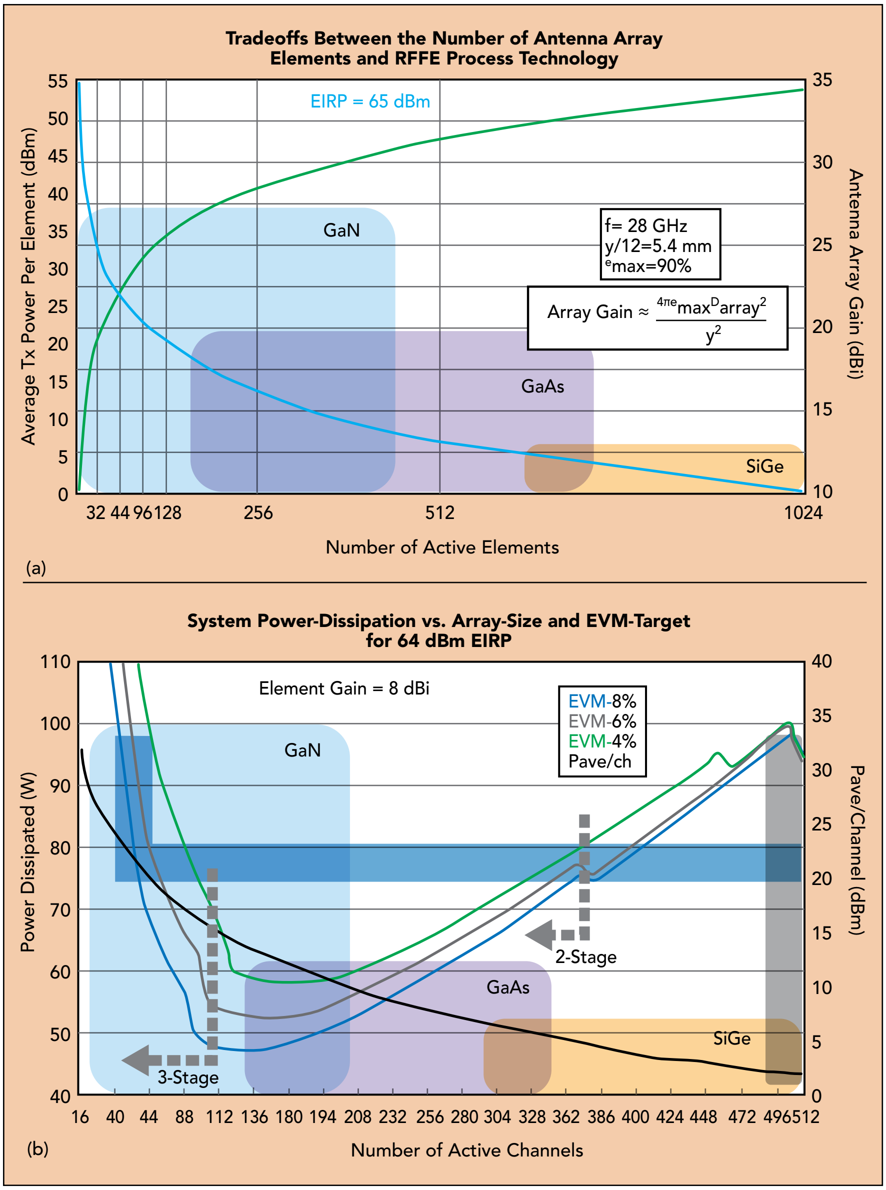


Fig. 4 Technology System Trade-Offs.

and beamform precoding functions can be separated into digital baseband processing and analog RF processing, respectively. This provides a new design knob that allows the number of baseband chains to scale independently from the number of active antenna elements in the array. Unlike the all-digital architecture, where there is typically a 1:1 relationship with the number of active RF chains, the hybrid architecture allows a 1:N relationship.

As shown in Figure 3, the RF beamformer subsystem fans out the upconverted baseband stream into N branches, which are then adjusted for amplitude and phase, and fed to a multi-element panel antenna. By setting the correct phase and amplitude coefficients the radiated signals coherently combine to provide the needed beamforming gain in the direction of the intended user.

Although this approach reduces the number of ADC/DACs required, it sharply increases the number of RF front-ends that are needed and introduces the need for careful analog phase and amplitude control on each RF branch. Fortunately, these small-signal functions can be highly integrated on a single chip using SiGe semiconductor technology. The most typical configuration is to have 4-branches per core-beamformer chip but there are examples demonstrating up to 32-channels.

These core-beamformer chips act as a driver to feed the front-end modules (FEM) which provides the final PA, T/R switch, and LNA functions. If the required power from the FEMs is small enough, it is possible to also use SiGe technology and monolithically integrate into the core-beamformer chip. However, for base station applications where high EIRP is required, analysis shows that an all-SiGe solution will not provide optimum power consumption or cost because 1000's of elements would be required. To optimize the cost and power consumption, it can be shown that using compound semiconductor technology, like GaN and GaAs, for the FEM allows the array size to be far less complex, consume less power, and be lower cost. The following section provides additional insight into this important trade.

FRONT-END SEMICONDUCTOR TECHNOLOGY

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, we show in ***Figure 4(a),*** the average per-channel PA power (PAVE) needed as a function of array size and antenna gain for a uniform rectangular array achieving 65 dBm EIRP.

The graph is overlaid with an indication of power ranges that are best suited for each semiconductor technology. The limits were set based on benchmarks of each technology, trying to avoid exotic power-combining or methods that degrade component reliability or efficiency.

As array size gets large (>512 active-elements) the power-per-element becomes small enough to allow SiGe/SOI, which could then be integrated into the core-beamformer RFIC. In contrast, by using GaN technology for the front-end, the same EIRP can be achieved with 8-to-16 times fewer channels. Now let's examine these two cases further.

GAN VERSUS SIGE FRONT-END MODULES

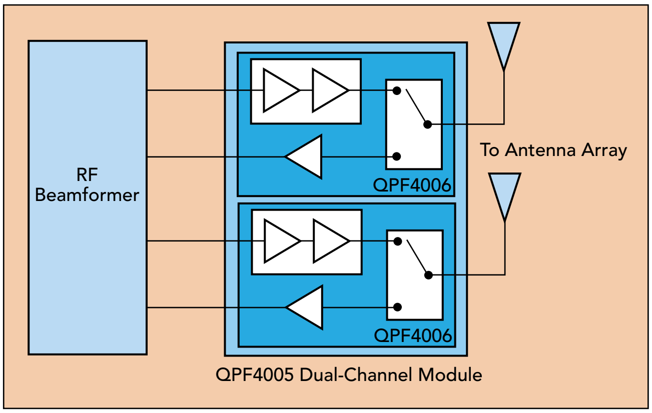
System Power Dissipation

We start by analyzing the total system PDISS of the beamformer plus the front-end versus the number of active-array elements in each subarray-panel, as shown in

TABLE 1

ASSUMPTIONS, TOTAL DIE AREA, AND RELATIVE COST OF ALL-SIGE VS. SIGE BEAMFORMING + GAN FEM ARCHITECTURE

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



▲ **Fig. 5 Qorvo FWA solutions: mmWave GaN front ends.**

Figure 4(b). The PDISS is shown for several error-vector-magnitude (EVM) levels and a requisite 64 dBm EIRP. EVM-level sets the back-off efficiency achieved by the front-end.

In this Figure 4b analysis, we assume that each beamformer branch consumes 190 mW. This is a typical power consumption of core-beamformers currently in the market [3]. The system on the far right (dark gray bar) represents an all-SiGe solution with 512-elements consuming ~100 W with an average power-per-element of 2 dBm. As we move left, the number of elements decreases, the PAVE per-channel increases, and we observe that PDISS is optimized up to a point where beamforming gain starts to roll-off sharply and PDISS needed to maintain the EIRP rapidly increases. The small steps in the dissipation curves represent the points where the front-end transitions from a single-stage, to 2-stage, and finally 3-stage design to provide sufficient gain. As stages are added the efficiency drops slightly and thus we see small jumps in power dissipation.

If we design to optimize system *PDISS* without regard for complexity/cost, an array of about 128-elements with a 2-stage 14 dBm (24 dBm P1dB) PA would make the best choice. However, if we strive to optimize cost/complexity/yield for a given budget of ≤100 W then the optimum selection (shown as the dark blue bar) would be 48-to-64 active channels using a 3- stage GaN PA with an average power of 20-to-23 dBm, depending on the EVM-target.

The trends shown in Figure 4(b) are less a function of PA efficiency and more a function of beamformer inefficiency. In other words, the choice to increase array size 8-fold to allow an all-SiGe solution comes with a penalty given that the input signal gets divided many more ways and requires power-hungry linearly biased devices to gain it back up.

Cost Analysis

The cost of phased-array systems includes the RF components, the PCB material, and the antennas themselves. Using compound-semi front-ends allows an immediate 8x reduction in array size with no increase to PDISS. Even with lower-cost printed antenna technology, this is a large saving in expensive antenna quality substrate material. But what about component cost?

Currently, the die cost per square-millimeter of 150 nm GaN-on-SiC on 4”-wafers is only 4.5-times the cost of 8” 130 nm SiGe. As we shift into high-volume on the 6”-GaN production lines, the cost relative to SiGe, drops to 3X. Using this information, we compare the relative raw die cost of the two systems based on the assumptions defined in ***Table 1 (a) and (b).*** The resulting cost comparison is summarized in ***Table 1(c).***

We observe that using a high-power density compound-semiconductor solution like GaN on 6”-wafers can save up to 35% in raw die cost relative to an all-SiGe architecture. Put simply, even though the cost of silicon technologies is lower per device, the cost of the complete system is significantly higher. The savings in cost increased further when factors such as antenna substrate, packaging cost, testing time, and yield are considered.

A GaN FWA front end provides other benefits:

- **Lower total power dissipation.** GaN provides a lower total power dissipation than SiGe. This is better for tower- mounted system designs.
- **Better reliability.** GaN is more reliable than SiGe, with >10^7 hours MTTF at 200° C junction temperature. SiGe’s junction temperature limit is around 130° C. This has a big impact on the heat-sink design.
- **Reduced size and complexity.** GaN’s high power capabilities reduces array elements and size, which simplifies assembly and reduces overall system size.

Based on these trades, Qorvo has created a family of front-end modules for mmWave. These integrated modules include a multi-stage high-power PA, high linearity T/R switch, and low noise figure LNA, all monolithically integrated using our 150 nm GaN/SiC process.

In addition to the above listed 39 GHz GaN components Qorvo also has similar modules addressing the 28 GHz market.

SUMMARY

FWA is rapidly approaching commercialization. Due in part 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 and analyzed. These architectures capitalize on the respective strengths and differences of 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.

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Optimizing the Perennial Doherty Power Amplifier

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The Doherty power amplifier (PA), invented almost 100 years ago, is used in an increasing number of radio transmitter applications to improve energy efficiency, with numerous ways to build the PA. This article begins with an overview of linearization and efficiency enhancement and, against that backdrop, highlights the associated challenges and some of the numerous solutions. Finally, there is an alternative design flow, illustrated with a case study providing insight into the design and how to achieve the best performance-cost compromise.

LINEARIZATION TECHNIQUES

The four key technical performance parameters in a transmit (Tx) RF front-end (RFFE) are the efficiency, output power, linearity and bandwidth. The latter three are often dictated by system requirements, such as a communications standard. The former, (energy) efficiency, is the differentiator. All other performance parameters being equal, a higher efficiency for a front-end is preferred.

Devices used in the RFFE have imperfect linearity characteristics, preventing them from being fully utilized merely as drop-in components. The linearity of a Tx RFFE can be improved by implementing a linearization scheme. Typically, this will increase the raw cost of a Tx RFFE, trading that for a combination of efficiency, linearity and output power improvement. Numerous linearization methods have been published, stretching back at least to the feedforward[1] and feedback[2] patents. Arguably, the use of nonlinear predistortion dates similarly to the invention of companding.[3] These schemes may be classified according to their modus operandi (see ***Figure 1*** and ***Table 1***).[4] One way of dividing the linearization pie is to identify whether a scheme predicts or extracts its unwanted

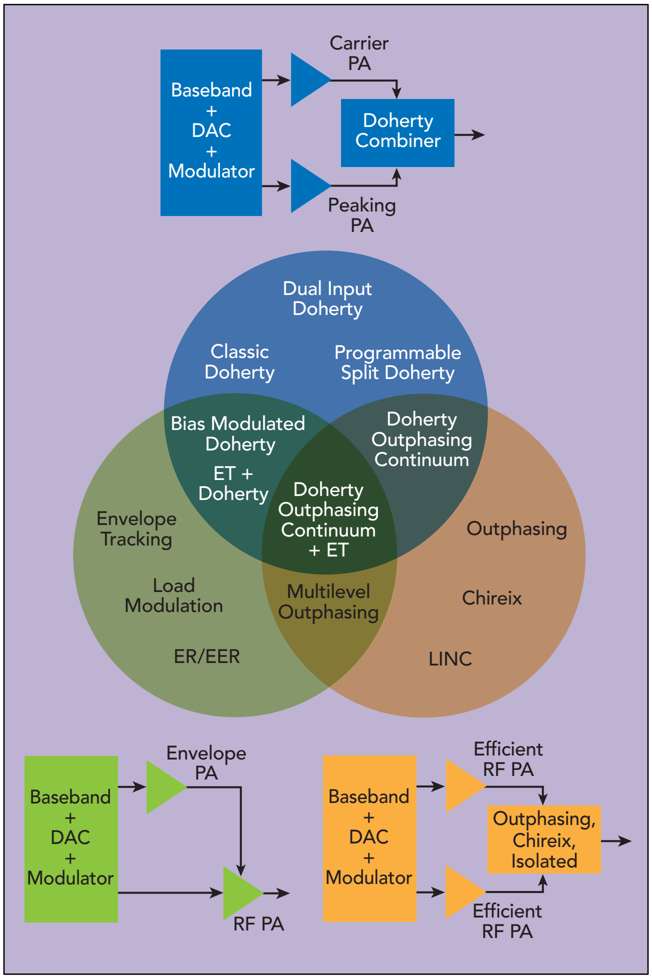


Fig. 1 Amplifier linearization options using post-source, predicted/synthesized composition schemes.

TABLE 1

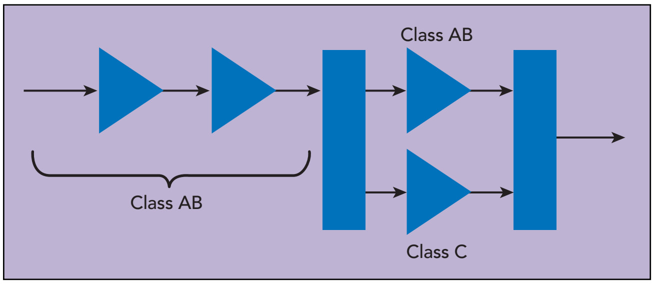
AMPLIFIER LINEARIZATION METHODS

		Impediment Generation	
		Predicted/ Synthesized	Measured/ Extracted
Correction Location	Pre-Source	Digital Predistortion	Cartesian Feedback
		Analog Predistortion	Polar Feedback
	Post-Source	Analog Post-Distortion	Feedforward
		Composition Schemes	Fixed Filtering (e.g., Bandpass)

signal and whether that unwanted correction is applied before or after its creation. Classification is useful to understand the general properties and identify the best approach for the application.

Feedforward is an example of a measured, post-correction scheme; feedback is a measured, pre-correction scheme; and predistortion is a predicted, pre-correction scheme. Predictive schemes rely on the unwanted signal being generated, which can potentially be onerous in wider band and lower power systems for digital predistortion (DPD). On the other hand, predictive schemes do not require that distortion exists and can, potentially, eliminate distortion completely.

Missing from these examples is a whole class of linearization techniques using predictive post-correction. This family of techniques has also been heavily researched and documented over the last 100 years. Outphasing,[5] envelope[6] and Doherty[7] transmitters, along with their hybrids by Choi,[8] Andersson[9] and Chung[10] are examples of such techniques, except they have been primarily marketed for efficiency enhancement rather than as linearization techniques. In their purest forms, envelope and outphasing schemes construct their signals from efficiently generated, nonlinear components, using multiplication and summing of their paths, respectively. A Doherty comprises a reference path, referred to as the "main" or "carrier," and an efficiency path, named the "peaking" or "auxiliary." A more comprehensive mathematical analysis of the Doherty design is beyond the scope of this article and is available in a plurality of texts. For further information, the reader is especially referred to Cripps.[11]



▲ **Fig. 2 Simplest implementation of the Doherty amplifier.**

DOHERTY IMPLEMENTATIONS

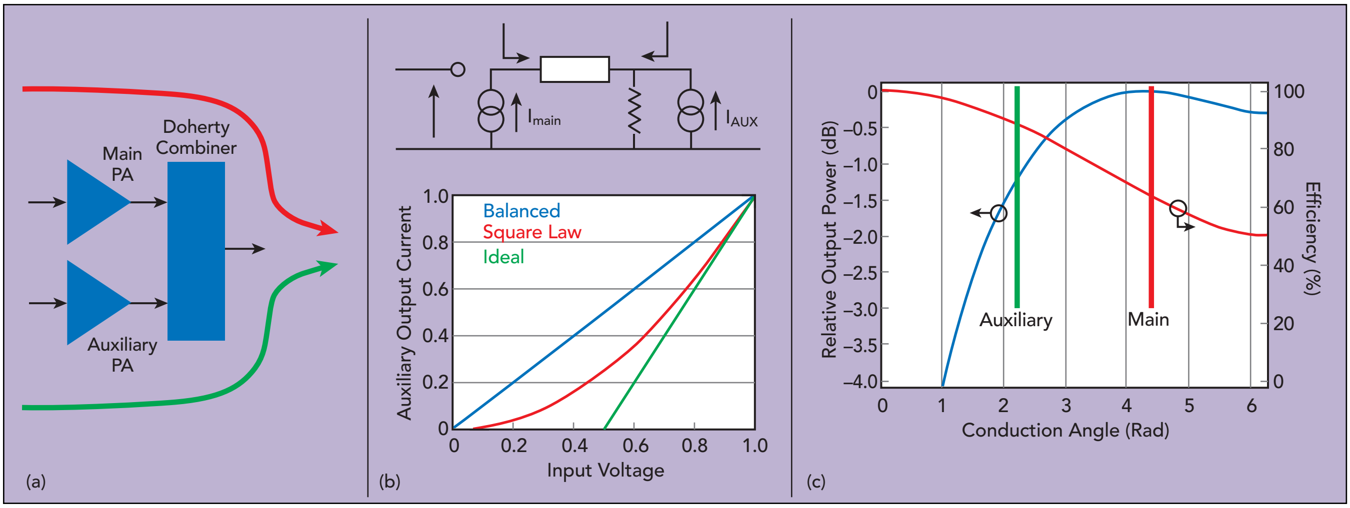
Arguably, the most common and often quickest starting point for a Doherty amplifier design is the "zeroth embodiment" (see ***Figure 2***), comprising a

- Fixed RF input to the final stage power splitter.
- Main and auxiliary amplifiers, differently biased (e.g., using class AB and class C).
- Doherty combiner made from a quarter-wavelength transmission line.

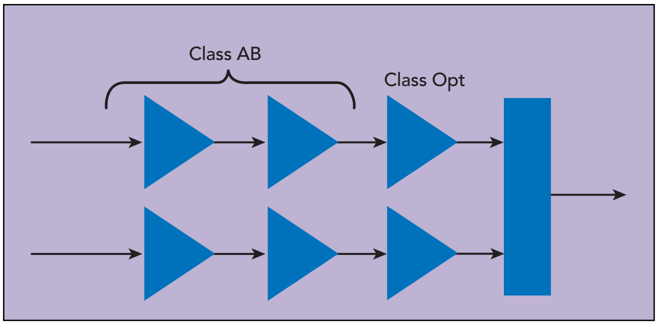
In most applications, this architecture does not provide sufficient power gain—at least not from a single, final stage—and additional gain stages are cascaded ahead of the power splitter. Criticism of this most commonly used implementation include

- No method for compensating gain and phase variations in any domain after the design is frozen.
- Both the efficiency and output power are traded-off because of the bias class. In effect, the class C bias, an open loop analog circuit, is driving this.
- Efficiency enhancement is limited to a single stage. With a multistage cascade, this limits the performance improvement, especially as gain diminishes at higher frequencies.

From another perspective, the Doherty engine is an open loop scheme, with several key functional mechanisms derived from the bias points of the transistors.



▲ **Fig. 3 Doherty amplifier challenges: combiner amplitude and phase matching (a), auxiliary amplifier current response (b) and power-efficiency trade-off (c).**



▲ **Fig. 4 Digital Doherty amplifier, where the main and auxiliary amplifier operating class is digitally controlled.**

Once the other variables are defined (e.g., phase offsets, splitter design, etc.), only one or two handles are provided, upon which multiple critical adjustments rely.

Challenges

One of the ways the Doherty improves efficiency is load modulation. The engine that drives that is the difference in output currents, sourced into the combiner from two or more amplifiers. Since the engine can only approximate the Doherty operation, the challenge for the designer is to enable the engine to approximate it with the best, but still appropriate, cost-performance paradigm. Some of the potential hindrances or impediments to Doherty performance are 1) the amplitude and phase matching of the signals incident to the combining node, especially over frequency (see ***Figure 3a***). Deviation from the ideal degrades efficiency and output power. Potentially, this can be more destructive, as the devices are intentionally not isolated, with the efficiency enhancement relying on their mutual interaction through the combiner. 2) Ideally, the auxiliary path of the Doherty engine exhibits a dog leg or hockey stick characteristic (see ***Figure 3b***). Failure to achieve the ideal is often the primary reason for not realizing the famous efficiency saddle point. As the characteristic tends from the ideal to a linear response, the Doherty amplifier increasingly behaves like its quadrature-balanced relative—albeit with a non-isolated combiner—especially its efficiency performance. 3) The commonly used "differential biasing" of the main and auxiliary operating in class AB and class C, respectively, forces the output power and efficiency of both amplifiers to be degraded (see ***Figure 3c***). As Cripps showed,[11] the continuum of quasi-linear amplifier classes from A to C, which theoretically operate with sinusoidal voltages across their sources, varies their respective maximum output power and efficiency characteristics. At the same time, if biasing is used to create the difference engine, as is the case in the classical Doherty embodiment, there is intrinsically a trade-off between output power and efficiency. Simultaneously, differential biasing increases the Doherty effect, yet decreases the achievable performance.

VARIANTS AND IMPROVEMENTS

The following variations on the basic concept may be more appropriate for some applications and, with the classical implementation, offer the designer performance and flexibility options.

- Multiple gain stages inside the Doherty splitter and combiner.
- N-way Doherty.
- Intentionally dispersive splitter.
- Programmable splitter.
- Bias modulation.
- Supply modulation, i.e., adding a third efficiency enhancement technique to the two leveraged by Doherty.
- Envelope shaping.
- Digital Doherty.

In addition to the different architectures available to the designer, three points in the product life cycle allow adjustments. During the design phase, the design parameters can be modified, recognizing the parameters will be passed to production as fixed values (e.g., the input splitter design). During production, the parameters may be modified or tuned, typically based on measured data, and then frozen or fixed through programming. One example is the nominal bias voltage used to generate the target bias current in the devices. Once the equipment is deployed in the field, parameters may be updated, either continuously or at specific times, either open or closed loop. Open loop concepts rely on sufficiently predictable behaviors, while closed loop concepts might require built-in measurement and control. One example is circuitry for temperature compensation. These product life cycle options provide a plurality of solutions with no "best" solution. It is just as important for the designer to be aware of the manufacturing and supply capabilities following the design as the design challenges and trade-offs made during the design phase.

At the opposite end of the solution spectrum from the zeroth embodiment is the digital Doherty (see ***Figure 4***). This architecture is characterized by an input split which stretches back into the digital domain, prior to the digital-to-analog conversion. The ability to apply digital signal processing to the signal applied to both amplifier paths potentially gives unsurpassed performance from a set of RF hardware. Compared to the standard Doherty implementation, the digital version can achieve 60 percent greater output power, 20 percent more efficiency and 50 percent more bandwidth without degrading predictive, pre-correction linearity.[12]

MEASUREMENT-AIDED DESIGN FLOW

To optimize any Doherty design, it is advisable to build simulation environments that correlate well with the design, to understand trends and sensitivities. The simulation enables a significant part of the development to be covered quickly. Inputs to the first step might include load-pull data or models for the candidate devices, a theoretical study of the combiner and matching network responses, evaluation boards with measured data or other empirical data. Building on this starting point, the design flow can be supplemented with measurement-aided design (see ***Figure 5***).

For the digital Doherty, the starting point for this approach is a Doherty comprising two input ports, input and output matching networks, active devices, bias networks and the Doherty combiner (see ***Figure 6***). Measuring the prototype Doherty as a dual-input device provides greater insight into the performance limitations, trade-offs and reproducibility expected in a production environment. Critical to the test set-up are two signal paths, whose signals may be varied relative to each other. In addition to applying precise, stable and repeatable amplitude and phase offsets to the signals, it is advantageous to be able to apply nonlinear shaping to at least one of the signal paths.

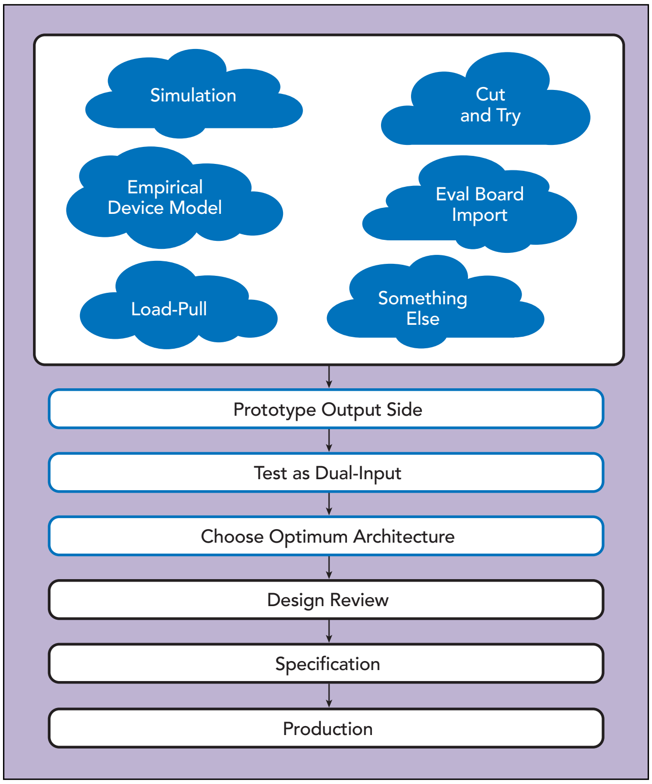


Fig. 5 Measurement-aided design flow for a digital Doherty amplifier.

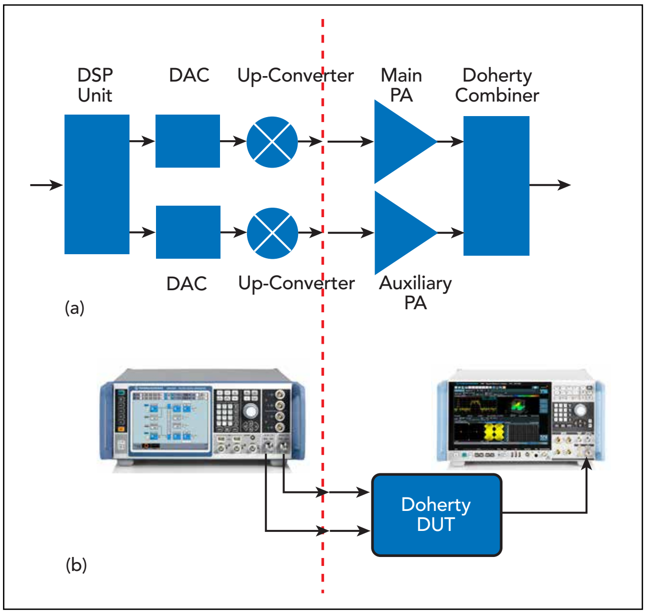


Fig. 6 Simplified block diagram (a) and hardware setup (b) for designing a digital Doherty amplifier.

The measurement algorithm may be rapid or more exhaustive, programmed to seek the optimum values for desired parameters or configured to characterize a wide range of parameters. In a simple case, the designer may want to confirm the best-case quantities and their relative amplitude and phase balance values. More complicated, a detailed sweep to enable a sensitivity analysis or rigorous solution space search may be war-

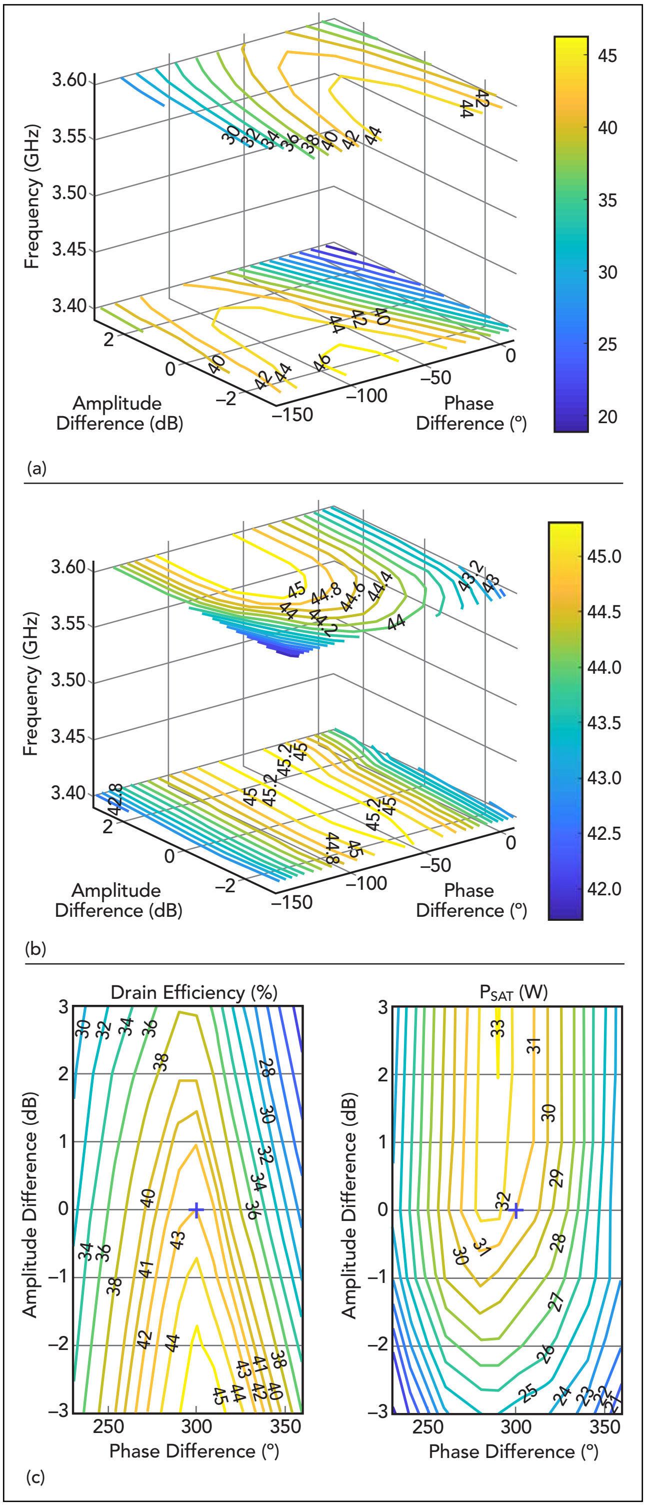
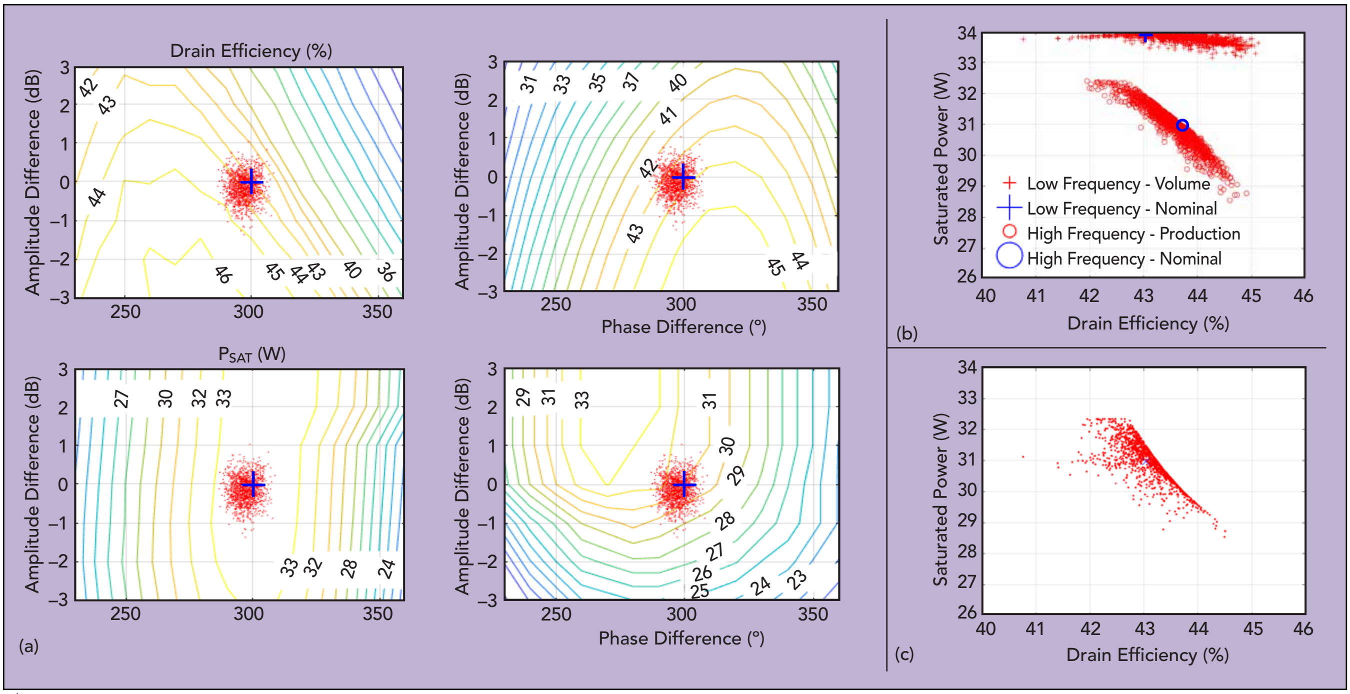


Fig. 7 Dual-input Doherty in linear operation: measured efficiency at 35.5 dBm (a), saturated power (b) and worst-case efficiency and power (c).



▲ **Fig. 8 Gain and phase variation of a population of split digital Doherty amplifiers with a fixed RF input (a), saturated power and efficiency using a look-up concept (b) and cumulative, worst-case production distribution (c).**

ranted. The post-processing of these measurements can be as simple or sophisticated as the user wishes.

CASE STUDY

To demonstrate the design flow and achievable results, a digital Doherty PA for a 3.5 GHz, 5G New Radio (NR) base station was designed using a single stage unmatched GaN power transistor, the Qorvo® TQP0103. A dual-path R&S®SMW200A vector signal generator provided the two input signals to drive the GaN amplifier. For measurement of dependent quantities, the single RF output of the amplifier was connected to an R&S®FSW Signal Analyzer. DC power for the devices was sourced from an R&S®HMP power supply, which measured the DC power consumption. The amplifier was stimulated using differentially linear and nonlinear signals, the former sweeping the input power, amplitude and phase. The nonlinear tests used a variable shaping function, amplitude dependent, at two frequencies. Output power, output peak-to-average power ratio, adjacent channel leakage ratio (ACLR) and current consumption were measured, and the measurement results were analyzed using MATLAB®.[13]

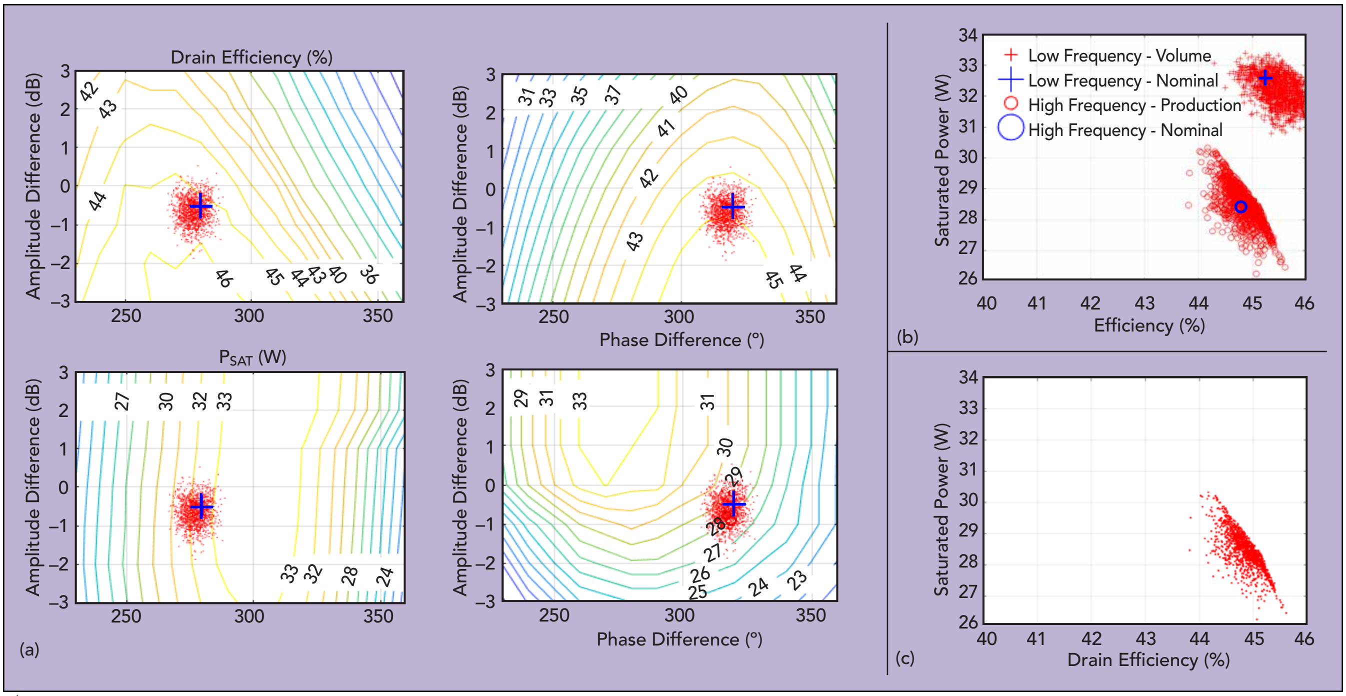
Analyzing the linear measurements, efficiency at a specified power level and saturated power were plotted versus the amplitude and phase differences (see ***Figure 7***), with the worst-case efficiency and output power shown in Figure 7c. In the basic Doherty embodiment, a quasi-constant amplitude/phase split is chosen for the operating frequency. The efficiency and saturated power for these amplitude/phase values can be determined by extracting the worst-case performance at the test frequencies.

Selecting a nominal amplitude/phase split, a perturbation representing the natural variation in production may be added to the evaluation. Using a look-up table, the bulk effect of these part-to-part variations can be observed, as shown in ***Figure 8***. Figure 8a shows the drain efficiency and saturated output power at two frequencies, Figure 8b shows the estimated production spread of saturated output power and drain efficiency versus the nominal values for the same two frequencies. Figure 8c shows the cumulative production spread, aggregating the results from the two frequencies. Paradoxically, in this case, most of the part-to-part variation is in the target variable, efficiency.

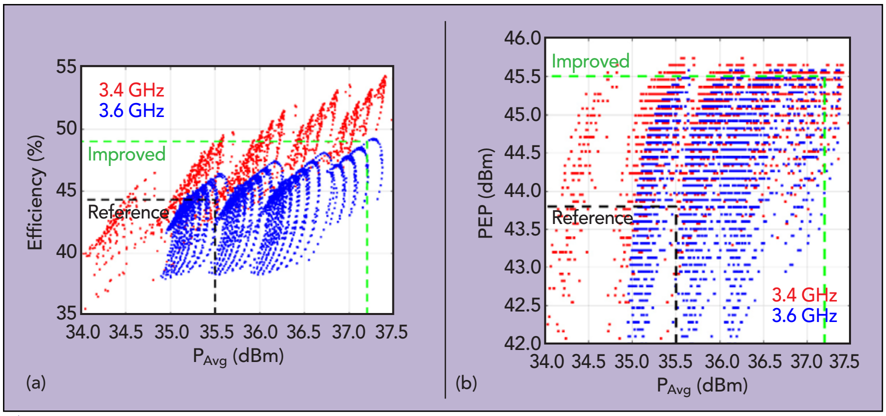
By adopting an alternative approach to the input splitter design, this variation can be reduced. Using a dispersive input splitter design, meaning using different amplitude and phase differences at the two design frequencies, advantageously enables the stacked contour plots shown in Figure 8a to, in effect, slide over one another. Using the same part-to-part variation data with this dispersive splitter design yields a better result (see ***Figure 9***), with a higher mean efficiency and lower standard deviation.

By directly generating signals for the two amplifier inputs in the digital domain, the deficiencies of the Doherty amplifier are significantly reduced. Additionally, the simple part-to-part amplitude/phase variations shown in the linear example may be eliminated. To illustrate this, albeit not exhaustively, the auxiliary path was programmed with a square law shaping function applied to both the amplitude and phase, with the phase "start" and "end" values—the phase with zero and maximum input amplitude—varied randomly. With a common bias for the two amplifiers, only a trade-off between output power and efficiency remains, rather than those and the Doherty difference engine magnitude.

To establish a baseline, driving the commonly biased amplifiers with a linearly differential signal enabled the equivalent "balanced" performance to be ascertained:



▲ **Fig. 9 Digital Doherty amplifier population using a dispersive input split: gain and phase variation (a), saturated power and efficiency (b) and cumulative, worst-case production distribution (c).**



▲ **Fig. 10 Efficiency vs. average output power (a) and PEP vs. average output power (b) for a dual-input Doherty amplifier using with square-law shaping and randomized phase.**

the available saturated output power in this mode was 0.5 dB higher than the differential biased case (12 percent higher power). That represents the "cost" of operating the Doherty engine using differential bias points. The scatter plot of random shaping functions applied to the auxiliary path yields the locus of performance shown in ***Figure 10***, reflecting the distributions of average power versus efficiency and peak envelope power (PEP) versus average power. The saturated output power is 1.7 dB higher than the conventional Doherty amplifier (48 percent higher power), suggesting that 1.2 dB of the improvement (32 percent) is from better amplitude/phase matching of the signal paths.

The 1.7 dB improvement in saturated output means the amplifier may be operated at that increased output power without compromising headroom, and the increase in average power is associated with a 5 point increase in efficiency (from 44 to 49 percent). Alternatively, devices with 48 percent smaller periphery may be used to achieve the original target output power. Taking into account the expected part-to-part variation, this reduction in device periphery might be reduced further.

CONCLUSION

Significant improvements in Doherty performance can be achieved by addressing the input side of the design. The use of either an intentionally dispersive or programmable input split can improve performance, especially considering manufacturing distributions. According to peer reviewed research,[12] the digital Doherty with nonlinear input splitting or shaping can achieve 60 percent more output power, 20 percent more efficiency and 50 percent greater bandwidth without any degradation in predictive linearization. The case study described in this article achieved 47 percent higher output power and 11 percent greater efficiency over a fixed bandwidth.

A measurement-aided methodology for extracting and understanding possible improvements was demonstrated. While efficiency and saturated power served as examples, they do represent the two most important parameters in most Doherty designs. Regardless of which Doherty architecture is used, this design methodology provides more detailed and rigorous insight and improves both time-to-market and the cost-specification paradigm.■

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