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Power Amplifier Basics for Advanced Communications

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5G wireless network technology is the true "next generation" of wireless communications, capable of performance levels far beyond the limits of fourth-generation (4G) long-term evolution (LTE) Evolution (LTE) wireless networks. Today's global system-level planners agree on the need for more bandwidth to increase data capacity, and much of that additional bandwidth is expected to come from the mmWave frequency range, such as 60GHz for high-data-rate, short-haul wireless links. The use of mmWave signals has proven quite successful in 77GHz automotive radars as part of collision-avoidance safety systems, and the large bandwidths available within the mmWave frequency range (30 to 300GHz) hold the promise of increased network capacity compared to 4G/ LTE, which is quickly reaching its limits. However, building 5G networks that leverage mmWave bandwidths requires mmWave signals at sufficient signal strength, which will depend on the availability of practical mmWave power amplifiers (PAs).

Designing a mmWave PA is not trivial. Signals at those frequencies are so-named because their wavelengths are only 1 to 10mm long or 1mm to 10mm long. Given the physical connection between frequency, wavelength, and various circuit features needed to support operation at those high frequencies, such as resonators and transmission line structures, design challenges arise from the extreme miniaturization of mmWave circuits and the need to conserve signal power as much as possible by minimizing forward and reflected signal losses.

The Promise of 5G and Beyond

Expectations are great for 5G networks and beyond. Earlier-generation wireless/cellular networks were based on supporting voice communications, although that started to change with 2G and 3G systems. The nature of modern communications has changed, becoming very data-centric—largely due to the influence of the internet—with network performance defined in terms of data transfer speeds and data capacity. (Figure 1)

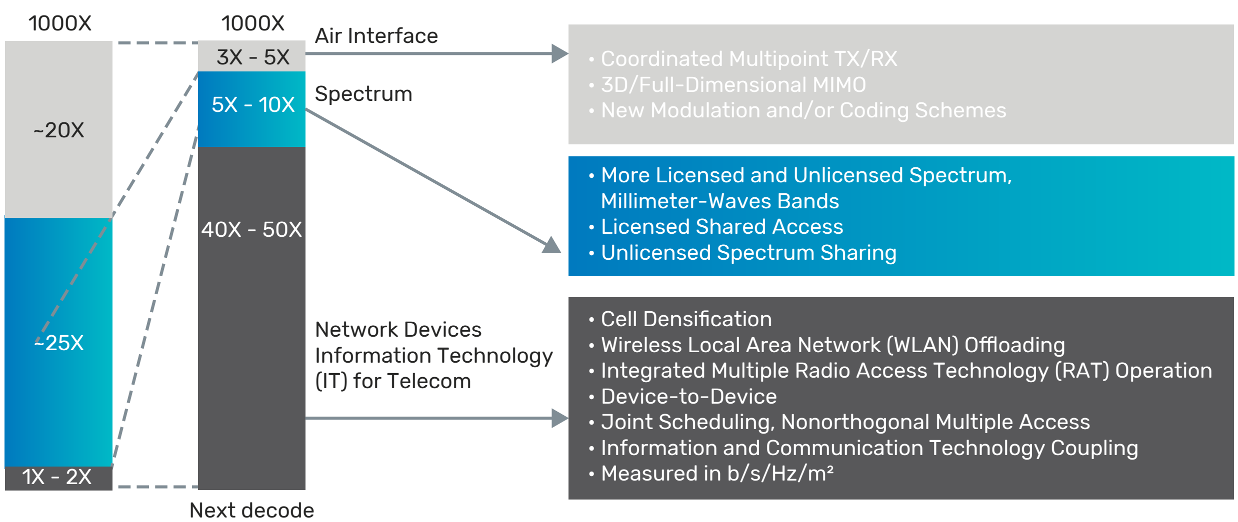

Figure 1: The need for bandwidth to transfer large amounts of data through wireless channels makes using mmWave frequencies in 5G wireless networks inevitable (Image courtesy of National Instruments)

The increasing use of internet of things (IoT) devices requires wireless networks with much higher data capacity and devices with low power consumption. Many of these devices are "always on" and "always connected" to the internet via wireless network bandwidth, unlike a smartphone, which may sit idle for long periods with no consumption of network capacity. However, many IoT devices, such as for medical and healthcare monitoring, will need to remain connected, and that expected network capacity must be available in 5G systems. Projections vary on the number of IoT devices requiring wireless network access in the next few years. However, numbers as high as several trillion devices suggest huge bandwidth/data-capacity requirements based on IoT devices, without even considering a growing number of smartphones on the same networks.

The inevitability of 5G wireless networks is because 4G networks are limited in data capacity and speed. Compared to 3G wireless networks, 4G networks achieved performance improvements by enhanced spectrum efficiency, typically using advanced modulation and coding techniques. Antenna techniques such as multiple-input/multiple-output (MIMO) schemes also helped increase spectrum efficiency in 4G systems and the use of novel radio technologies, such as OFDM, to make better use of the available spectrum. These improvements have made possible relatively fast data transfer rates in 4G/LTE systems—as fast as 1Gb/s for stationary devices and about 100 Mb/s for moving mobile devices communicating through the network.

However, the sheer number of IoT devices and the growing demands for fast data transfers and streaming video requires that 5G systems operate at 10 times the speed of 4G/LTE networks or at 10Gb/s.

The capacity of a wireless network is affected by several factors, including the available bandwidth, the number of communications channels, the number of cells, and the signal-to-noise level of the system. By adding bandwidth in the form of mmWave frequencies, 5G wireless networks can gain capacity, but system planners hope to do so without a significant increase in energy consumption, a requirement that will impact the design of PAs for 5G networks, whether at mmWave or lower frequencies (Figure 2).

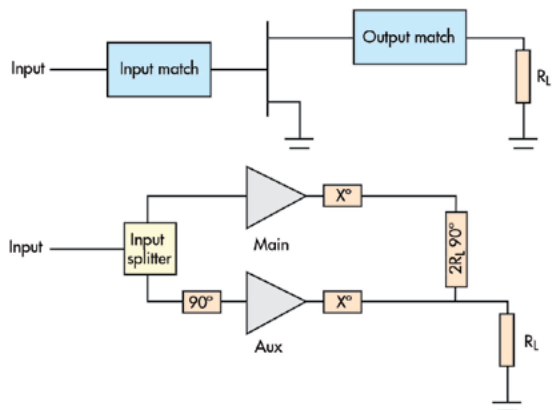

Figure 2: These block diagrams compare a single-ended (one-transistor) Class AB amplifier to a two-way Doherty amplifier

PA Basics

Generally, a PA can be characterized by several performance parameters, including gain, gain flatness, output power, linearity, efficiency, input and output Voltage Standing Wave Ratio (VSWR), and noise figure (NF). The usable frequency range of a given PA is determined by an amplifier's capabilities to deliver acceptable return loss (RL) levels of performance for the greatest number of performance parameters over a given frequency range. Gain, for example, tends to be highest at an amplifier's lowest frequencies and lowest at its highest frequencies, with the variations in gain across frequency RL summarized by an amplifier's gain-flatness specification. For example, a value of ±1dB denotes no more than 2dB variation in gain across the frequency range.

Output power is a function of the input signal power, the gain, and the acceptable amount of gain compression at the output. For most RF through mmWave amplifiers, output power capability is measured and listed at the 1dB compression point, often abbreviated as P1dB. More output power may be possible by increasing the level of the input signal power at the cost of linearity, such as when the amplifier is represented by the signal distortion that occurs when the amplifier is driven to output power at 3dV compression. An amplifier with the highest linearity would be one in which the output signals are most proportional to the input signals in terms of waveform shape, differing in amplitude level as a function of gain. With the digital modulation schemes proposed in 4G and 5G networks, the peak-to-average power ratio (PAPR) is considerably higher than in earlier wireless communications standards. A higher PAPR results in an amplifier operating well into its compression region unless it operates considerably below its compression point (this is achieved using a larger-periphery active device). As a result, amplifiers may be characterized, and model details specified at higher compression points or determining impedance-matching requirements or design activity is focused on optimizing matching networks for output-power backoff operation.

High linearity for most PAs is achieved by operating with lower-than-maximum input power signal levels so that the active devices operate without gain compression. On the other hand, most amplifiers are at peak efficiency when operated with input power levels that cause compression, at a point where an amplifier is considered at saturation and its highest output-power level because an increase in output power no longer follows an increase in input power.

Linearity is a key parameter for 5G PA designers to maintain high signal integrity (SI) and low signal distortion for the complex modulated signal waveforms used to achieve high-data-rate communications. Amplifier linearity traditionally comes at the cost of power consumption, such as in a Class A or Class AB linear amplifier where active devices are always supplied with input power levels to avoid nonlinear operation.

However, in a 5G wireless network, the mmWave and lower-frequency amplifiers must also operate with high efficiency so that the energy consumption of a base station or microcell is minimized. Similarly, for microwave and mmWave amplifiers integrated into smartphones and other mobile/portable wireless devices powered by batteries, high linearity must be achieved without sacrificing high power-added efficiency (PAE)—two amplifier parameters traditionally viewed as tradeoffs.

Various amplifier design techniques are available to improve linearity or efficiency. For enhanced efficiency, Doherty amplifier configurations have been used, in which the amplifier essentially consists of two separate amplifiers operating under different bias conditions (Figure 3). Input signals are split between the two amplifiers and combined at the outputs of the amplifiers to achieve the best use of bias energy based on waveform shape and level. Envelope-tracking (ET) power-supply techniques are also used to boost PA efficiency, in which the power supplied to the PA follows the shape of the waveform to be amplified, with DC power increasing or decreasing as needed to maintain output power at a certain level.

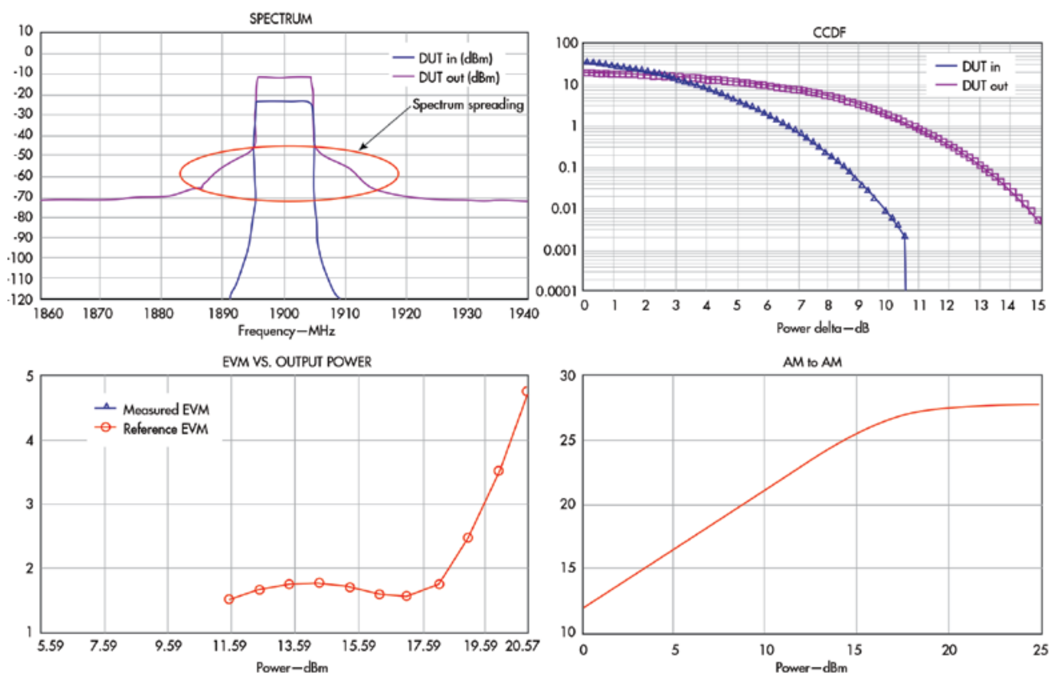

Figure 3: Many current mmWave PA designs incorporate waveguide interconnections to minimize input and output interface losses (Photo courtesy of Millitech Corp.)

Digital predistortion (DPD) techniques often provide high PA linearity while achieving reasonable efficiency. Since an amplifier is most efficient when operating near saturation, DPD techniques help shape the modulated waveforms to be amplified so that an amplifier can operate with high efficiency but without causing distortion or nonlinearity.

Sorting Through Semiconductors

Amplifiers for 5G and other mmWave applications employ several different semiconductor technologies, including transistors fabricated on silicon-germanium (SiGe), gallium-arsenide (GaAs), indium phosphide (InP), gallium-nitride (GaN), and devices on substrates of different materials, such as GaN on silicon (GaN-on-Si) and GaN on silicon carbide (GaN-on-SiC), which has excellent thermal properties for the effective dissipation of heat.

Silicon laterally diffused metal oxide semiconductor (LDMOS) devices are well established as high-power active devices in 3G and 4G base stations, capable of generating the transmit power levels required. Silicon semiconductor PAs based on silicon-on-insulator (SOI) CMOS devices have also delivered lower power levels when multiple transistors are used in stacked configurations. Output power levels approaching 1W with linear gain have been achieved at frequencies as high as 28GHz, with diminishing power levels at frequencies extending into the higher mmWave range, demonstrating that low-cost silicon substrates may still be a viable semiconductor material candidate for 5G handset applications at mmWave frequencies.

The choice of semiconductor material for a 5G PA will likely be determined by whether the PA will be used in a handset or a base station and the operating frequency range since regulatory organizations around the world have allocated several different frequency bands. Frequencies from 4 to 6GHz and 24 to 86GHz have been considered for different portions of 5G networks, with different PA output-power requirements ranging from as little as 0.2W at higher frequencies to as much as 30W in the lower-frequency range.

A key characteristic for any semiconductor material as a starting point for 5G PAs is relatively high electron mobility so that different device structures will provide higher than unity gain at mmWave frequencies. A variety of different device topologies have been fabricated. All these substrate materials offer higher electron mobility than ever-popular silicon substrate materials, making them attractive substrate materials for mmWave active devices. Many different device topologies have been fabricated on these high-frequency substrate materials, including metal-semiconductor field-effect transistors (MESFETs), heterojunction bipolar transistors (HBTs), and high-electron-mobility transistors (HEMTs), each with its own gain and power characteristics in support of mmWave PAs.

GaN in its various forms has gained favor among PA designers at RF and microwave frequencies, and GaN mmWave devices are starting to become more practical. While semiconductor substrate materials such as SiGe, InP, and GaAs can support transistors with cutoff frequencies (fT) of 300GHz and higher, GaN substrates support active devices with much higher power densities, making it possible to fabricate discrete devices or monolithic microwave integrated circuits (MMICs).

Design Strategies

As noted, designing an effective mmWave PA for 5G applications requires balancing several competing performance parameters, such as linearity and efficiency. Depending upon the capabilities of a particular active device technology, a designer can choose from different amplifier topologies, from single-stage amplifiers to multistage designs. The final set of performance requirements, such as frequency range, gain, output power, linearity, and power-added efficiency (PAE), will dictate the design.

Achieving the optimum performance from the active devices in a PA requires matching the complex source and load impedances of a given device to the 50Ω characteristic impedance of a 5G system. This is typically done using measurements of device S-parameters using a vector network analyzer (VNA) with a suitable frequency range for the device under test (DUT) for small-signal (and input impedance matching) and a source/load-pull tuner capable of presenting a wide range of impedances to a DUT with a fine-tuning resolution for large-signal (nonlinear) output impedance matching. Optimum source impedance will usually enable a PA to deliver low NF performance, while optimum load impedance is required for nonlinear performance, such as for acceptable levels of output power, PAE, and linearity, including adjacent channel power ratio (ACPR) and error-vector magnitude (EVM), as shown in Figure 4. Because a large number of measurements may be required to determine the optimum source and load impedances, the use of an automated load-pull measurement system from companies such as Maury Microwave and Focus Microwaves, as well as test system software programs such as LabVIEW from National Instruments can dramatically reduce the time needed to characterize an active device in preparation for developing PA matching networks.

Amplifier design in the Cadence® AWR Design Environment® platform, specifically AWR® Microwave Office® circuit design software, can either be based on a compact or behavioral model representing the transistor(s). An alternate design approach is to develop matching circuits based on the results of load-pull data (measured or simulated from a compact model). To use the large data sets that may characterize the power transistors used in communications amplifiers, circuit simulation tools such as AWR Microwave Office software support dedicated RF design features that help the engineer plot critical performance metrics via contour mapping and develop impedance-matching networks through self-guided design utilities. The circuit simulation engines (linear and harmonic balance) combine with integrated EM simulation (2.5D and 3D) to enable “what-if” type analyses of a circuit design to predict the effects of different transmission-line lengths and configurations of passive devices, even different impedance-matching networks on the output power and gain possible from a particular device.

Depending on the specific application (mobile or base station), a 5G PA must address a given frequency range, power level, efficiency, and linearity specifications. Standard linear simulations are used to derive many of these amplifier performance metrics, such as gain vs. frequency, return loss, etc. The advanced measurements associated with 4G/5G operations require simulation testbenches that can replicate standard-defined modulated waveforms. AWR Design Environment provides the simulation technology, 5G modulation waveforms (the major proposed techniques including CP-OFDM), and preconfigured testbenches (Figure 4) to simulate performance such as the ACPR, a measure of spectral regrowth due to amplifier nonlinearity or EVM, another linearity measurement that describes the error vector in the I-Q plane between the ideal constellation point and the point recovered by the receiver.

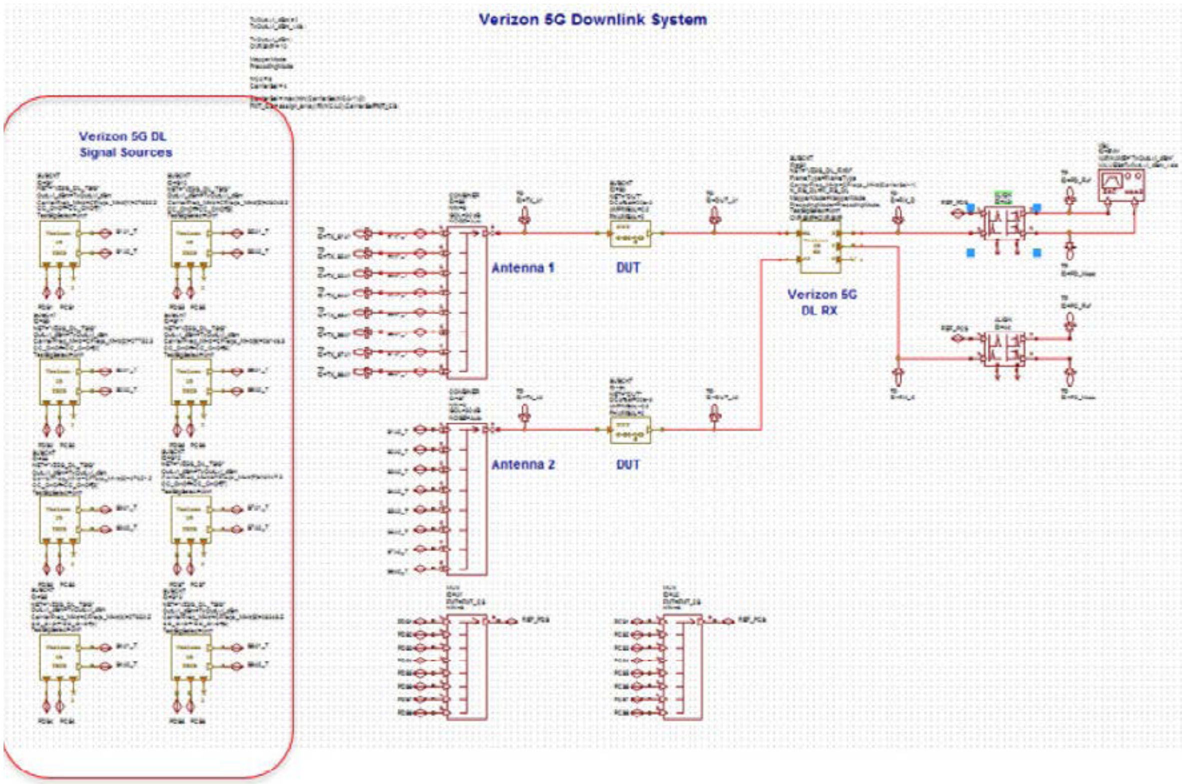

Figure 4: Microwave Office helps simulate critical PA performance parameters such as error vector magnitude (EVM, RMS% and absolute) based on transistor model or measured load-pull data

Conclusion

Although mmWave frequencies represent enormous amounts of bandwidth for 5G networks and other EM-based applications, such as automotive radar/safety systems, the PAs for those applications will most likely be needed and designed for relatively narrow bandwidths. For one thing, channel allocations by organizations such as the FCC refer to relatively narrow frequency bands around a center frequency, such as 24, 28, or 60GHz, so wide bandwidths are not needed for these wireless channels. In addition, the necessary impedance-matching networks for optimum PA performance are much easier to design at narrow bandwidths than at wider bandwidths, especially as the center frequency of the amplifier increases well into the mmWave range.

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