High efficiency power amplifiers

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The never-ending quest for greater capacity and higher data rates in radio access networks puts increasing demands on the nominal output power from radio base stations. These demands must be met within the existing RBS footprint where cooling capacity and size are limited. At the same time, operators want to cut their radio network operating expenses (OPEX), of which energy consumption is a significant factor.

Linear radio frequency (RF) power amplifiers (PA) play a major role in terms of base station energy consumption and heat dissipation. More efficient base station power amplifiers are thus a crucial factor in the context of mobile system evolution. Reducing the energy consumed by radio base stations will also reduce the environmental impact of the radio access network.

The authors describe the critical aspects and limitations of highly efficient PA technology and indicate where new technology is needed to reach the industry's ambitious goals for greater efficiency.

Background

Linear RF power amplifiers consume large amounts of energy, dissipate heat, and take up space in base stations. Significantly more efficient PA technology will be instrumental to the evolution of mobile systems. The main requirements for future power amplifier technology are

- high linearity, to satisfy higher-order modulation schemes;
- greater average output power levels;
- broader operating bandwidths (more than twice today's typical 20MHz);
- reduced OPEX by decreasing RBS energy consumption; and
- reduced environmental impact by decreasing radio network energy consumption.

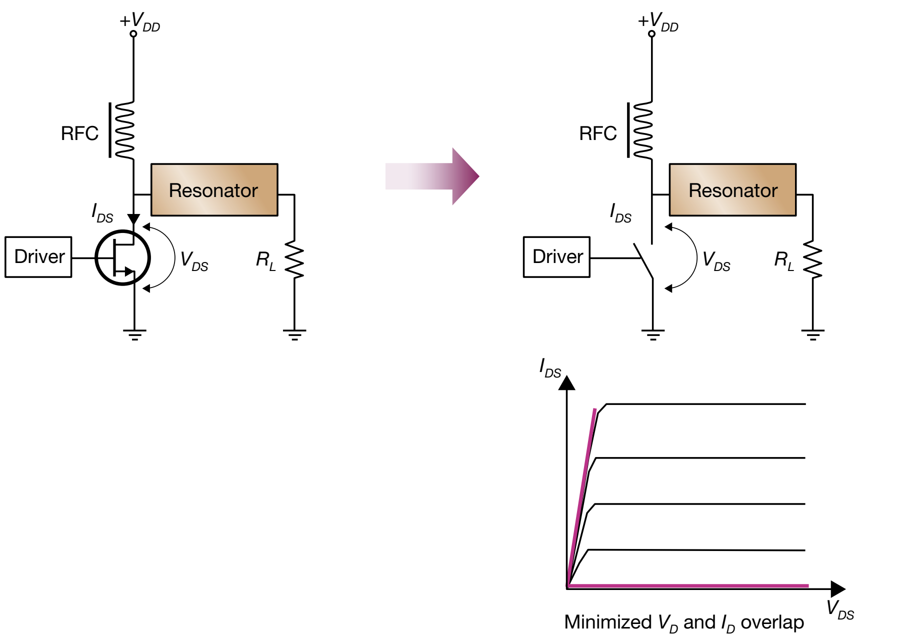
New technologies with greater PA drain efficiency were introduced in the past 12 months, significantly increasing radio unit (RU) power efficiency. Notwithstanding, new technologies with even greater drain efficiencies are needed to meet the challenges of the next three to five years. (Drain efficiency is the ratio of delivered output power divided by applied DC power in the PA.)[1]

The main objective of PA research is to increase efficiency while maintaining linearity and broadening the operating bandwidth. Present-day power amplifiers with Doherty efficiency-enhancement technology will continue to evolve in coming years, but to increase efficiency significantly, other technologies must also be considered. Switch-mode PA technology has been identified as a way of achieving high PA efficiency. This technology is being used successfully with pulse width modulation (PWM) for audio and digital subscriber line (DSL) driver applications. In this role, switch-mode PAs are 80% to 90% efficient but their application is limited to operating frequencies of around a few megahertz. The challenge is thus to apply the technology to operating frequencies for mobile systems in the 1 - 4GHz range.

Because straightforward frequency scaling is not feasible due to the physical properties of the components, suitable methods must be found to mitigate the fundamental limitations of high-frequency operation. The major areas of research in this area are

- switch-mode PA concepts with potentially high drain efficiency (greater than 60%);
- architectures that retain efficiency over a large, dynamic range of output power (typically 20dB) while meeting linearity requirements; and
- RF power transistor technology with performance that is suitable for switch-mode applications in the 1 - 4GHz frequency range.

Figure 1
Simplified view of switch-mode PA operation.



Switch-mode PA technology

The main idea behind switch-mode PA technology is to operate the transistor in saturation, so that either voltage or current, depending on amplifier class, is switched on and off. Figure 1 shows a simplified block diagram of a switch-mode power amplifier. For our discussion of fundamental properties, the transistor can be replaced by a switch. When the switch is open, only voltage is present over the transistor. When closed, current flows through it. Since there is no overlap in time between voltage and current, power is not dissipated and one obtains 100% theoretical efficiency. In reality, a transistor is not a perfect switch (see trajectories, Figure 1) and overlap does, in fact, limit efficiency.

For comparison, Figure 2 illustrates a

Class-AB power amplifier. Here, the transistor is biased to an operating point and follows the indicated load line, giving rise to power dissipation and loss.

In the switch-mode power amplifier, an output resonator helps shape the waveform by blocking harmonic components of the voltage and current – that is, it keeps these components from reaching the load. Consequently, only fundamental current is passed to the load and only fundamental voltage is generated over the resonator. A flywheel effect is created generating sinusoidal voltage and current in the load. The two necessary conditions for generating a single tone with 100% efficiency in the load are

- zero overlap between voltage over the transistor channel and current through the channel; and
- blocking of harmonic currents to the load.

Figure 3 compares the simulated efficiency of almost ideal Class-AB and switch-mode Class-D amplifiers. In the Class-AB amplifier, there is significant overlap in time of voltage and current, which degrades efficiency. In real amplifiers, switching and component losses can significantly degrade efficiency. Therefore, a critical task when designing switch-mode power amplifiers is to minimize these losses. Examples of losses are

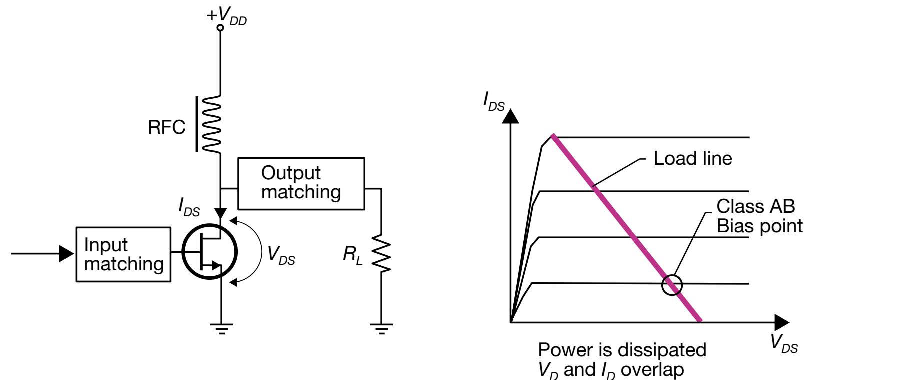


Figure 2
Class-AB power amplifier operation.

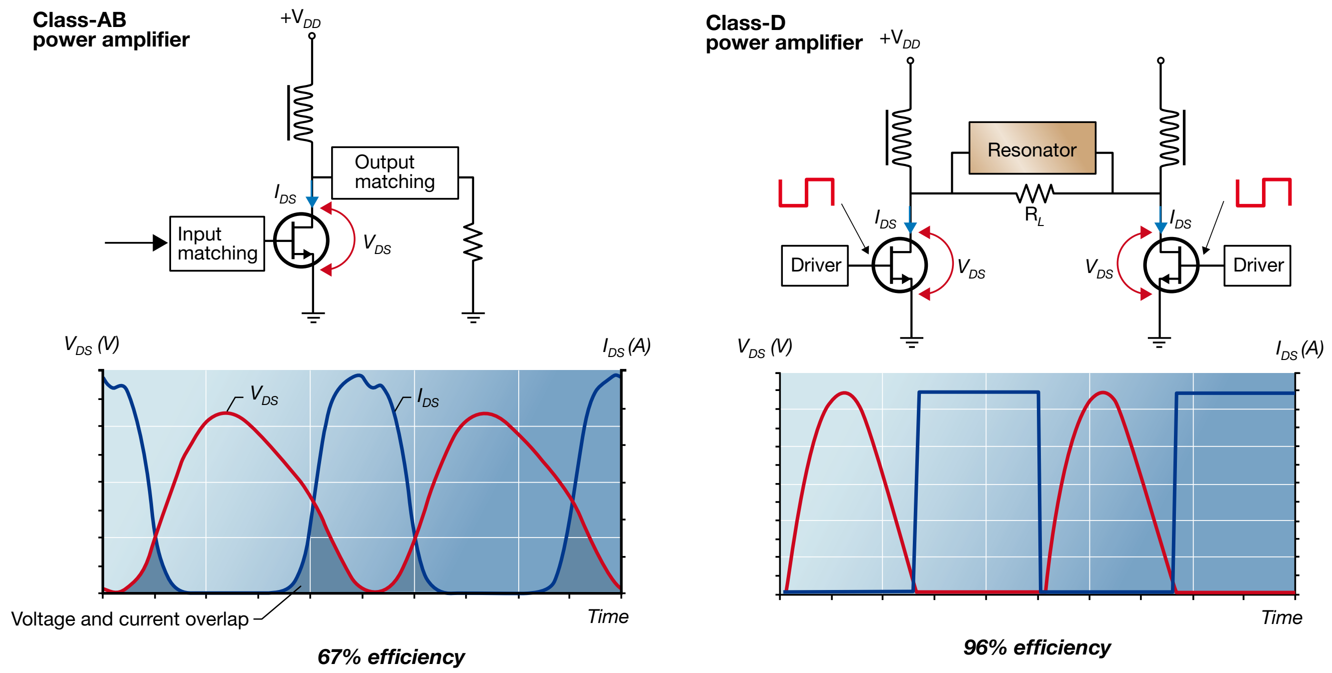
- parasitic capacitors, such as C_{ds} (drain to source capacitance). Parasitic capacitors cause loss when voltage is switched;
- R-ON (the drain-to-source resistance when the transistor is conducting);
- non-zero transition time. The square waveform requires a fast transistor (high f_t). If the switching frequency is close to f_t then loss occurs due to overlap between voltage and current in the transistor; and
- PA implementation losses, including driver power consumption, output circulator, and filtering.

Taking all these loss mechanisms into account for PAs designed to operate in the gigahertz range, one can anticipate PA efficiencies of around 60% to 70% at best.

Switch-mode PA architectures

Numerous switch-mode PA classes of operation have been invented over the years. The main differences between these classes are topologies,

Figure 3
Left: Current and voltage waveforms in Class-AB power amplifiers. Right: Current and voltage waveforms in Class-D power amplifiers.



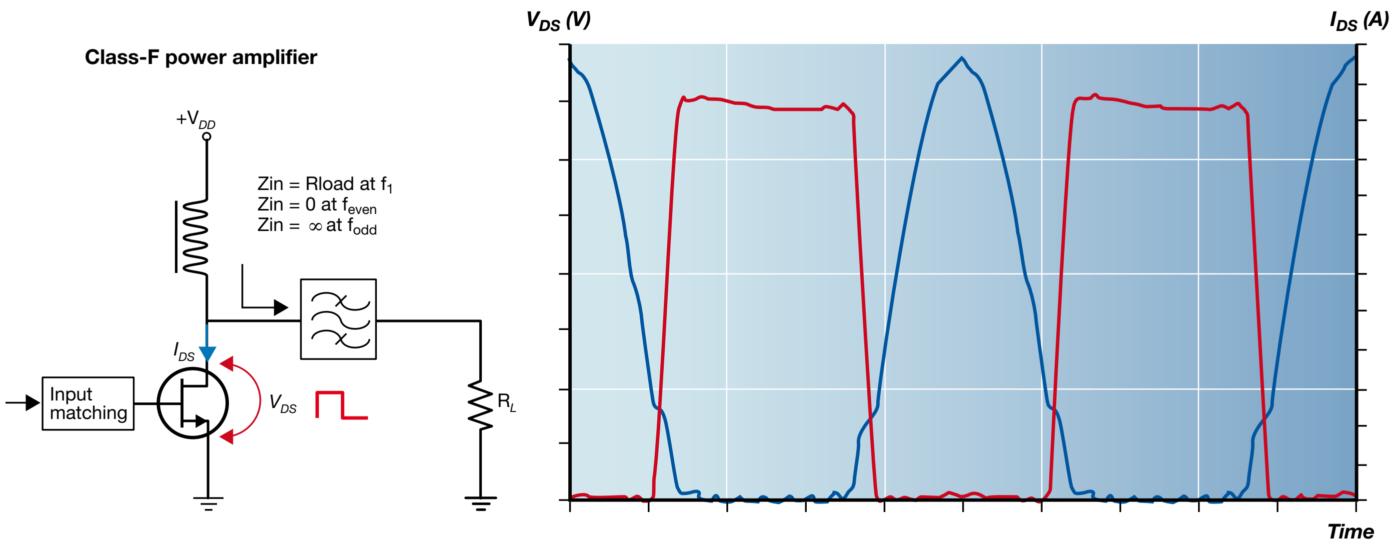
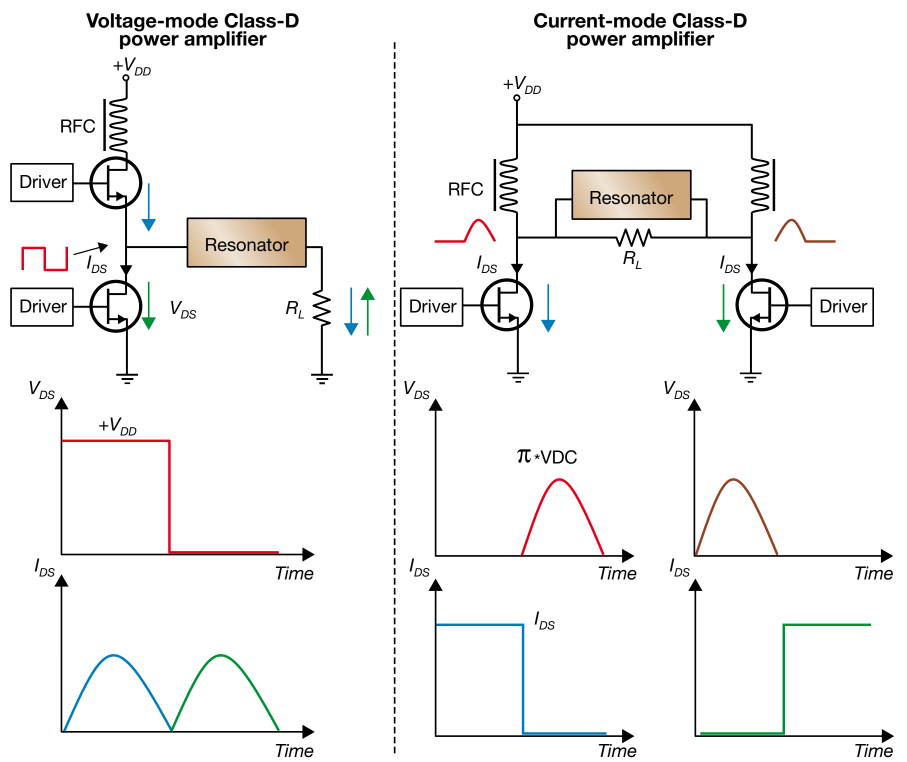


Figure 4
Left: Class-F power amplifier. Right: Class-F waveforms.

Figure 5
Voltage- and current-mode Class-D power amplifiers and their waveforms.



waveform shaping, and method of analysis.

Below follows a brief description of some common switch-mode classes of operation.

Class-F

Class-F power amplifiers use multiple resonators to control the harmonic contents of the drain voltage and current. In an ideal Class-F power amplifier, the drain voltage is square wave; current waveforms are half-sinusoidal (Figure 4).

The main obstacle to the Class-F design is the realization of harmonic terminations at high frequencies. Practical designs are typically limited to terminating the third harmonic, which limits the maximum theoretical efficiency to 75%. For a 2.2GHz design, this means the terminations must operate at 6.6GHz.

Class-D

There are two main realizations of Class-D power amplifiers:

- voltage-mode Class-D with serial resonator circuit; and
- current-mode Class-D using a parallel resonator circuit.

Each type has a topology with two transistors.

Figure 5 (left) shows a classic voltage-mode Class-D power amplifier where voltage is switched and the output resonator forces the current to be sinusoidal. Voltage-mode Class-D power amplifiers and PWM technology make a highly efficient combination for audio applications. But because transistor output capacitances quickly become a dominant loss factor at higher frequencies, it is difficult to achieve the same good efficiency in the gigahertz frequency range.

In a current-mode Class-D power amplifier, current is switched. The short-circuit harmonic termination of the output resonator forces the voltage to be sinusoidal. The amplifier has an interesting balanced topology: both its transistors are grounded, and their output capacitances can be used in the output filter. The half-wave rectified sinusoidal waveform is created by the flywheel effect of the output network and the balanced configuration. In a balanced configuration, one needs only short-circuit the output at odd harmonics. Therefore this amplifier shows promise as a highly efficient performer at high power in the gigahertz range. A main drawback is high peak voltage, which calls for transistors with high breakdown voltage.

Class-E

The Class-E power amplifier, which is an interesting compromise between a linear Class-AB power amplifier and a switched power amplifier, has zero overlap between voltage and current over and through the transistor, giving 100% theoretical efficiency and potentially robust performance (Figure 6).[2]

The output network of a Class-E power amplifier starts with a shunt capacitor that absorbs the output capacitance of the transistor. Current passes through the capacitor when the transistor channel is closed. Compare I_s and I_c with I (Figure 6). The inductance and capacitance (LC) resonator ensures that only the fundamental frequency current can flow in the output network to load, giving a single tone in the load. The flywheel effect of the LC network drives the current through either the switch or the capacitor.

The waveforms of the Class-E power amplifiers are analog in shape without the ideal pulse-shaped form presented by other modes of operation. The Class-E mode can thus be supported by a transistor with slower switching characteristics and is better suited to high-frequency operation. As with Class-D mode, high peak voltage is a drawback.

Switch-mode PA performance

Research on switched PAs has produced promising results: Class-D, Class-E and Class-F power amplifiers have reached high peak drain efficiencies in the gigahertz range at high power levels. In particular, note the results of Class-D and Class-E power amplifiers using gallium nitride (GaN) transistors (Table 1).

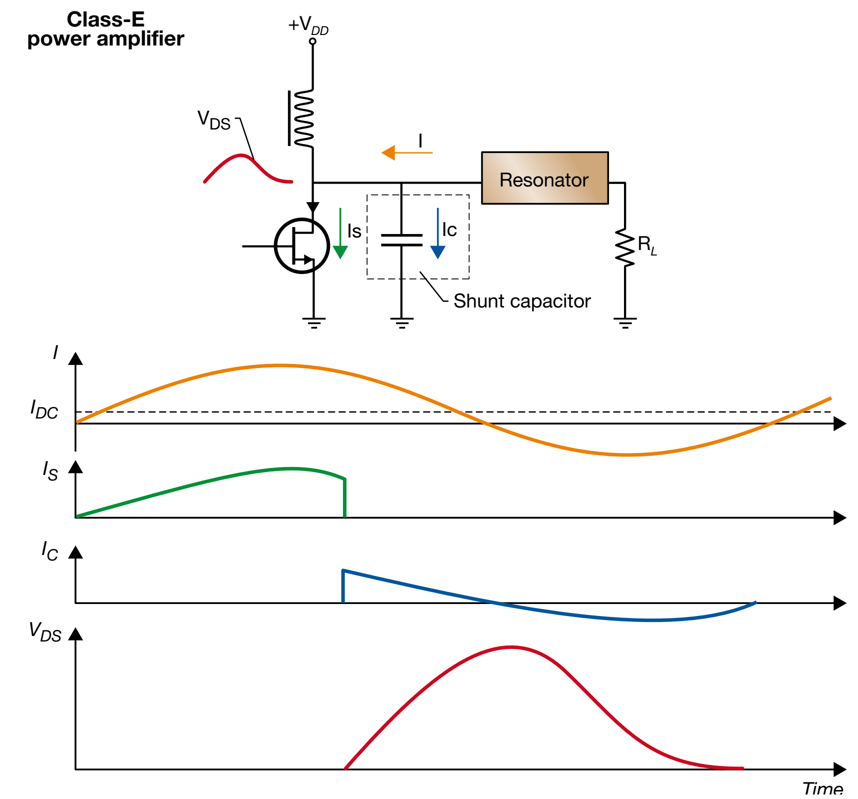


Figure 6
Class-E power amplifier and waveforms.

Modulated signals with high PAPR

The results in Table 1 show that it is possible to obtain high peak drain efficiencies even at microwave frequencies. The remaining challenge is to maintain high efficiency for signals with high peak-to-average power ratio (PAPR). To benefit from increased peak efficiency for amplitude-modulated signals with high PAPR (typically 6 to 9dB for WCDMA and OFDM signals), the amplifier must work in saturation even when signal amplitude is backed off. Moreover, given that switch-mode amplifiers are inherently non-linear, the transmitter architecture must also provide a means of linearizing the amplifier. Several PA modulation technologies have the potential to work with high PAPR signals[8]:

- drain modulation (the drain voltage follows the signal envelope, keeping the power amplifier operating at maximum efficiency);

TABLE 1, PERFORMANCE OF SWITCH-MODE PAs.

Class	F(GHz)	Peak drain efficiency (%)	P_{out}(W)	Gain	Transistor technology	Reference
F-1	1	77.8	12.4	12.9	LDMOS	3
E	1	73	7.9	10	LDMOS	4
E	2	85(PAE)	10	12	GaN	5
CMCD	1	71	20.3	15.1	LDMOS	6
CMCD	1	78	51.1	10.6	GaN	7

TERMS AND ABBREVIATIONS

AlGaN	Aluminum GaN
CMCD	Current-mode Class-D
CMOS	Complementary metal oxide semiconductor
DC	Direct current
DSL	Digital subscriber line
F_{max}	Frequency at which transistor unilateral power gain has rolled of to 0 dB
F_t	Frequency at which the magnitude of the transistor short-circuit current gain, h21, has rolled off to 0 dB
GaN	Gallium nitride
HEMT	High electron mobility
LC	Lumped component
LDMOS	Lateral double-diffused metal-oxide semiconductor
OFDM	Orthogonal frequency-division multiplexing
OPEX	Operating expenditure
PA	Power amplifier
PAE	Power-added efficiency
PAPR	Peak-to-average power ratio
PWM	Pulsewidth modulation
RBS	Radio base station
RF	Radio frequency
RFC	RF choke
RL	Load resistance
RU	Radio unit
Si	Silicon
V_{dd}	Drain voltage
V_{ds}	Drain to source voltage
WCDMA	Wideband CDMA

- load modulation (the load impedance is adapted to the signal envelope to keep the amplifier operating at peak efficiency); and
- RF pulse width modulation (this technique is mainly used at low frequencies but has the potential to work over a broad bandwidth with high efficiency).

More complex modulation and linearization schemes that require advanced signal processing might actually remove efficiency gains. Further research is needed to find the best compromise between efficiency, linearity, and bandwidth throughout the entire transmitter chain.

RF power transistor technology

Silicon LDMOS

LDMOS transistors have been the dominating technology for high-power RF amplifiers for almost ten years and it is difficult to see any other technology competing in Class-AB applications at frequencies below 3GHz. However, for higher frequencies and emerging switch-mode architectures, fundamental limitations, such as comparatively low f_t/f_{max} and high, lossy parasitic output capacitance, call for alternative technologies.

Gallium nitride

A comparison of intrinsic material properties shows that HEMTs (high electron mobility transistors) which utilize AlGaN/GaN heterostructures clearly stand out as the most promising of emerging technologies.

The energy gap of GaN is three times that of silicon (Si), resulting in reduced performance degradation at high temperatures. Similarly, breakdown at a six-fold electric field and two-and-a-half-fold carrier saturation velocity enable much greater power densities, resulting in the same output power capability at a much higher impedance level.

To reap the full benefit, devices must be optimized for a particular application. Therefore, the performance of GaN transistors in future switch-mode architectures might depend on what manufacturers see as the main application for these devices.

Compared with silicon LDMOS, GaN technology is still immature, hampered by basic manufacturability and reliability issues, and is far from being competitive in terms of cost.

Conclusion

The next generation of power amplifiers for mobile systems requires extensive research and component development to meet demanding requirements for efficiency, linearity output power, and bandwidth. Needed are advanced PA architectures, used in combination with complex signal processing and RF power transistors with very low parasitics.

Switch-mode PA architectures are promising candidates, provided RF power transistors with low parasitics and high breakdown voltage can be developed.

GaN transistors show potential for use in switch-mode applications but are still a long way from being a reliable and cost-effective component for commercial applications.

Silicon LDMOS technology and accompanying efficiency-enhancement technologies will continue to improve, mainly through the reduction of parasitic capacitors and further development of PA architectures, possibly to a point where the benefits of complex switch-mode architectures can be called into question. Either way, researchers anticipate significant increases in PA efficiency in coming years.

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