COVER FEATURE


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ET Comes of Age

Peter Asbeck and Zoya Popovic

Envelope tracking (ET) is by now a well-established technique that improves the efficiency of microwave power amplifiers (PAs) compared to what can be obtained with conventional class-AB or class-B operation for amplifying signals with a time-varying envelope, such as most of those used in present wireless communication systems. ET is poised to be deployed extensively in coming generations of amplifiers for cellular handsets because it can reduce power dissipation for signals using the long-term evolution (LTE) standard required for fourth-generation (4G) wireless systems, which feature high peak-to-average power ratios (PAPRs). The ET technique continues to be actively developed for higher carrier frequencies and broader bandwidths. This article reviews the concepts and history of ET, discusses several applications currently on the drawing board, presents challenges for future development, and highlights some directions for improving the technique.

Overview of the Technique

In the ET technique, the power supply voltage provided to a radio-frequency (RF) PA is actively varied in accordance with the time-varying envelope of the signal so that the RF PA is kept nearly always in compression, where its efficiency is high. The structure

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of a representative ET amplifier is shown in Figure 1. For class-A, class-AB, and class-B amplifiers, efficiency decreases when the amplifier is operated in a backoff condition—that is, when the output power is less than its maximum value at a given power supply voltage , as shown in Figure 2 for a representative class-B amplifier.

If the power supply voltage is reduced from its starting value V_{dd1}, the maximum possible output power will decrease; at the same time, however, the efficiency at reduced power levels will increase. This effect is also depicted in Figure 2, which shows the efficiency versus output power expected when the power supply voltage is reduced by $\sqrt{2}$ from V_{dd1} to V_{dd2}. The peak output power drops by a factor of two (because power approximately follows V_{dd}^2), but efficiency at the reduced power levels goes up.

In the ET technique, the power supply is changed dynamically so that at a given output power level, the efficiency can have the highest possible value, as shown by the dotted line in Figure 2. A useful way to picture this efficiency improvement is to consider the envelope of the output voltage (at the drain or collector) of the PA transistor as a function of time. Figure 3 shows a representative scenario in which a signal with a time-varying envelope is amplified. If the power supply voltage is constant (as in conventional amplifiers), the difference in voltage between the power supply and the envelope is a voltage overhead that, when multiplied by the corresponding current, leads to excess power dissipation within the output transistor.

In the ET technique, the overhead voltage is kept to a minimum so as to avoid this extra power dissipation. The degree of efficiency improvement achievable with ET is substantial: the overall efficiency, in principle, can be as high as that of the RF PA at the border of saturation (for example, 78.5% for an ideal class-B amplifier). The overall system efficiency, however, includes losses in both the RF PA and the dynamic power supply. This last component, termed here the *envelope amplifier*, is challenging to implement with the high levels of efficiency, accuracy, and slew rate required for broadband signal amplification.

A Brief History of ET

The origins of the ET technique date back to 1952, when a closely related technique, envelope elimination and restoration (EER), was introduced by Leonard R. Kahn to amplify single sideband signals using vacuum tube electronics [1]. An eminently readable account of his work is available in a recent *IEEE Microwave Magazine* article by Robert Caverly, Frederick Raab, and Joseph Staudinger [2].

In Kahn's EER technique, the dynamic power supply voltage had the role of imposing the amplitude modulation of the signal; the raw RF amplifier was kept in full saturation by feeding it a phase-only modulated signal with constant amplitude. The EER technique offers the promise of exceptional efficiency; however, it also leads to very strong requirements for the envelope amplifier's accuracy and experiences challenges in maintaining fidelity when the power supply voltage drops to near zero.

A generalization of the EER amplifier is the polar transmitter, in which separate input signals are used for the RF phase and for the RF envelope. Frequently, feedback loops are used to maintain the requisite signal accuracy. This technique is continuing to receive attention, both because of its potential efficiency improvements and because it facilitates operation over multiple carrier frequencies [3]. In contrast, in the ET technique, the underlying RF PA is nearly linear and is fed with a signal that is both amplitude- and phase-modulated. With ET, to accurately control the output power when the modulation signal approaches zero, for example, the RF input to the PA also goes to zero (instead of relying on the power supply voltage alone to control the output).

Steps toward the ET technique were taken in the tube days by Hilmer Swanson [4]. Extensive studies

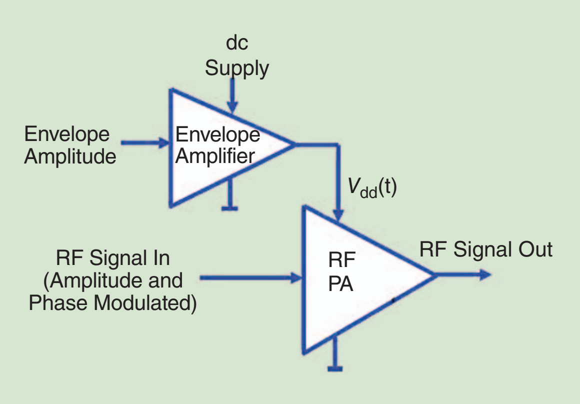

Figure 1. *A schematic diagram of an ET PA.*

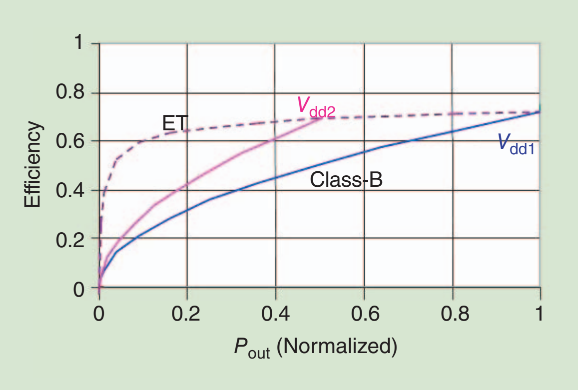

Figure 2. *Efficiency versus output power of a representative class-B PA operating with different supply voltages (here $V_{dd2} = V_{dd1}/\sqrt{2}$). For reduced output power (backoff), efficiency increases with lower power supply voltage V_{dd2}. The dotted line shows the efficiency achieved with the ET technique.*

of amplifiers with varying power supply voltage were done by Raab and others [5], [6]. The ET technique in close to its present form was described by A.A.M. Saleh and D.C. Cox [7] and B.D. Geller, F.T. Assal, R.K. Gupta, and P.K. Cline [8], among others.

Interest in ET for widespread applications received a large boost with the advent of cellular communications. The most power-hungry part of the early systems—before the elaborate displays in today's smartphones came into widespread use—was the RF PA. Hand-held units are constrained by battery energy, and thus the efficiency of the PA is a key concern. Early modulation techniques adopted in the AMPS (i.e., Advanced Mobile Phone System) and GSM (i.e., Global System for Mobile) wireless standards used constant envelope signals, so PAs were operated in their most efficient mode. But code-division multiple-access (CDMA), wideband CDMA (WCDMA), and LTE standards used in 4G wireless communications have changed the picture.

The PAPR of signals has grown steadily as attempts are made to pack more and more bits of information into the available and expensive bandwidth. Some of the early work for cellphone PAs showed how ET could dramatically boost efficiency by countering the backoff effects of both modulation PAPR and average power variations [9], [10]. The prospects for ET in handsets became brighter when it was shown that the envelope amplifier could be integrated into a single complementary–metal-oxide-semiconductor (CMOS) integrated circuit (with an off-chip inductor) [11]. More recently, with the introduction of LTE, PAPR values have shot up, in some instances to over 10 dB. ET is now viewed as a preferred method for maintaining PA efficiency—so that the battery does not drain too fast and the phone does not get too hot to hold!

Base stations have signals that combine together those of multiple mobile users, and the resulting (downlink) signals historically have had higher PAPR values than those for the uplink. The efficiency gains from ET compared to class-AB operation are also of major importance for the overall base-station power budget and have led to substantial research for ET in high-power systems (10–40 W average power) at 1–2 GHz.

ET Today

To handle the high PAPR values associated with the downlink signals, virtually every base station uses an advanced architecture for backoff efficiency improvement: the Doherty architecture, outphasing, or ET. All of these, interestingly, involve using more than one basic PA to get the job done, as shown in Figure 4.

For the first two cases, the extra PA is at the carrier frequency; for ET, the extra PA operates over the signal envelope bandwidth only. For simplicity and high performance, as well as to minimize changes from the earlier typical class-AB amplifiers, most base stations today use the Doherty transmitter architecture. ET base-station amplifiers are still in the research phase, although they can offer superior performance in several contexts. They have shown outstanding efficiencies: up to 66% power-added efficiency (PAE) for signals with 6.6-dB PAPR, signal bandwidths of 5 MHz, and average output power of 20 W [12]. These are comparable to—and perhaps a little better than—what has been achieved with Doherty transmitters.

For these heroic efficiency results, the basic RF PA operates at above 80% efficiency (as shown in Figure 5) using gallium nitride (GaN) transistors in nearly switching-mode operation, and the envelope amplifier is also at about 80% using a hybrid switching-mode analog design (described later in the article). But the efficiency of ET transmitters currently in development tends to drop off with wider bandwidths, and the margin over Doherty PAs gets eroded. As discussed later, however, the choice of one architecture versus the other will be different if the same PA is required to work with a wide range of carrier frequencies. The Doherty combiner has relatively narrow tuning (recent work has shown Doherty amplifiers with 30–50% fractional bandwidths [13], [14]), but ET holds the promise for covering the entire 0.7–2.7-GHz range for the wide variety of LTE bands. Also, ET outperforms other architectures

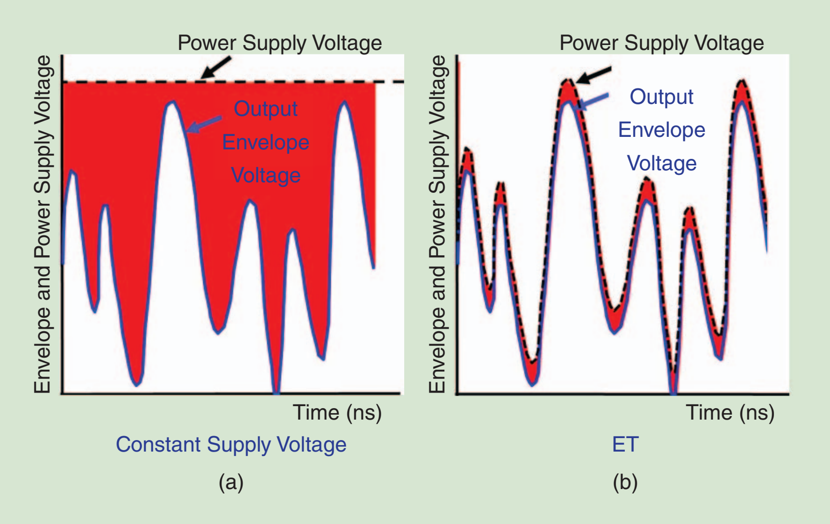

Figure 3. *Illustrations showing the reduced voltage overhead (indicated in red) for an ET PA: (a) a PA operating with a constant supply voltage compared with (b) an ET PA where supply voltage varies with the signal envelope. The power dissipation in the output transistor is proportional to the voltage overhead multiplied by the corresponding current waveform.*

if the output power must change over a large range—for example, if the base station's average power varies by 10 dB from daytime to nighttime, the power variation is outside the range over which a Doherty can comfortably operate, but it could be accommodated with an ET amplifier.

In the world of handsets, the variation of average output power from morning to evening—or even from minute to minute as the radio signal gets shadowed—has long been recognized as an important factor in overall efficiency. Consequently, most cell phones today use a simplified form of ET, called *average power tracking*, or APT. The power supply voltage is changed on a minute-to-minute, or even second-to-second, basis using a dc-dc converter chip in the cell phone. The emerging situation, however, is for a change to full ET: the dynamic power supply voltage will be varied at the full bandwidth of the envelope signal. It is now being introduced

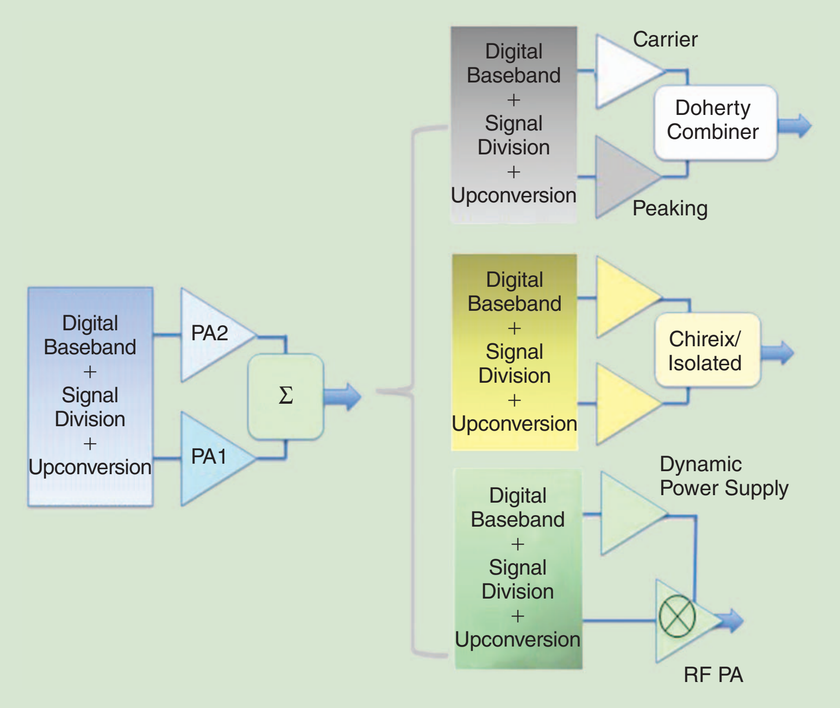

Figure 4. *High-level block diagrams of transmitter architectures that improve efficiency for high PAPR signals. PA1 and PA2 are at the same carrier frequency in both the Doherty and outphasing approaches. Although both operate by load modulation, the output combiners are different, and the two PAs are the same only in the outphasing case. In supply modulation (ET), the second PA operates at multiple times the signal envelope bandwidth, and the output combining occurs in the RF PA.*

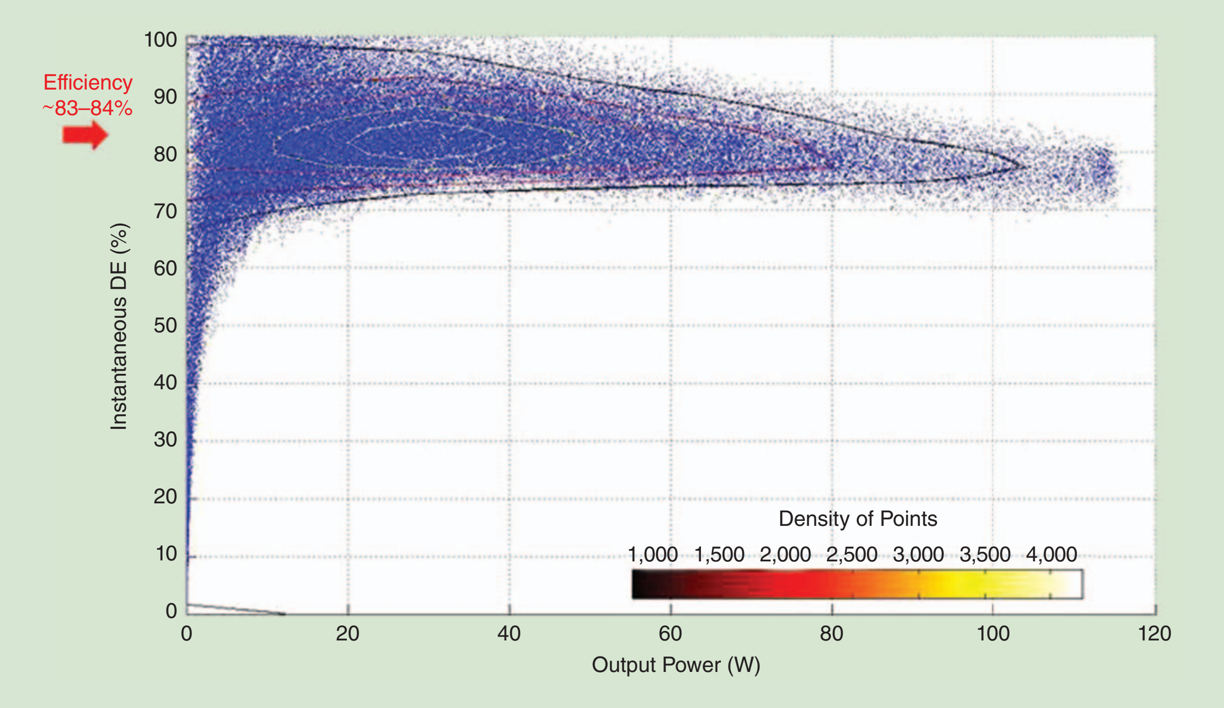

Figure 5. *Measured values of the drain efficiency (DE) of an RF PA operating in ET mode. As the output power dynamically varies during the modulation, the drain voltage and current are measured and then used to compute these values. The spread in the data reflects memory effects in the system. Contours show the probability distributions of the measured efficiencies.*

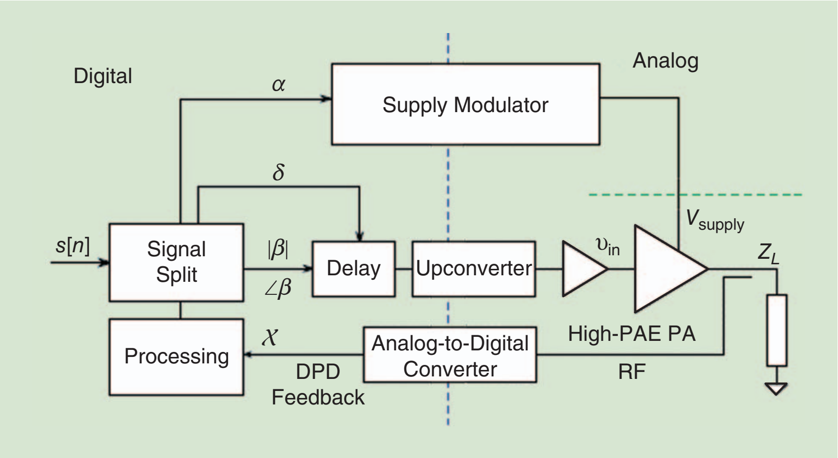

Figure 6. *A general block diagram of a supply-modulated transmitter. The baseband signal is converted from I/Q to partial polar form, where most of the envelope bandwidth and amplitude variation is used to determine control signals for the supply modulator.*

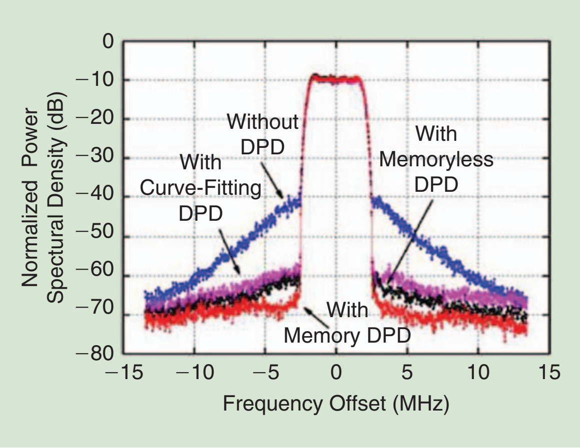

Figure 7. *The output spectra of a representative base-station ET amplifier with a 4-MHz bandwidth WCDMA signal, showing the effects of DPD using various algorithms.*

into high-end handsets and smartphones, driven by the higher PAPR's of LTE signals. Integrated envelope amplifier circuits are now available commercially from a number of suppliers.

ET PA systems are, in general, somewhat more complicated than the simple RF PAs they replace. For both, there is an RF signal with amplitude and phase modulation that must be delivered to the RF PA. In addition, for ET an appropriate dynamic supply voltage signal must be delivered to the envelope amplifier. This signal can be generated from the RF signal envelope itself, but it is easier to leverage modern transmitter architectures and generate the dynamic supply signal in digital baseband. Recently, a standard for communicating envelope signals within transceiver systems has been adopted so as to facilitate the development of interchangeable system components—the eTraK standard within the Mobile Industry Processor Interface Alliance specification framework. Specifications are provided for the transfer of digital control information and analog signals including dynamic supply waveforms (via a unidirectional analog differential interface).

The dynamic supply waveform and the RF signals must arrive at the RF PA properly time-aligned with one another (to within about 2% of the inverse signal bandwidth, or 4 nsec for a 5-MHz signal); if not, both output fidelity and efficiency suffer. Although there is not much drift in the signal timing over temperature and output power levels, today's systems incorporate feedback control systems to adjust the timing. The control can be exercised with a closed-loop monitoring system, which feeds back a replica of the PA output, downconverts and digitizes it, and compares the result with the desired signal. Any differences are reduced by predistorting the signal in the baseband signal processor.

A representative transmitter system is shown in Figure 6. The signal correction technique—referred to as *adaptive digital predistortion* (DPD)—is already used almost universally in base-station PAs, whether or not they use the ET technique. The power cost of the auxiliary receiver for signal feedback is negligible compared to the gains in efficiency for the whole system. DPD algorithms for computing the predistorted inputs have different constraints than for conventional DPD, and efficient schemes for ET DPD have been demonstrated, achieving −50-dBc adjacent-channel power ratio (ACPR) or better, as needed for many base-station applications [15]; Figure 7 illustrates some typical results.

Within handsets, however, the use of DPD is a topic of debate. ET systems can be manufactured that do not use DPD and that, in fact, configure the dynamic supply voltage waveform to keep the overall amplifier operating with good linearity (even if this might come at the cost of some efficiency). On the other hand, the cost of DPD is continuously dropping as a result of Moore's law advances, so the extra burden on the system power budget from DPD is becoming less significant.

The Key Component of an ET Transmitter: The Envelope Amplifier

As noted earlier, overall ET amplifier efficiency is the product of efficiency factors for the RF PA and for the dynamic voltage supply (the envelope amplifier). It is critical to increase the efficiency of the envelope amplifier as much as possible; current practice achieves between 65% and 85%, depending on the power level and bandwidth. The job is complicated by the fact that the required envelope bandwidth is broad, covering from dc to over three times the signal bandwidth.

For example, Figure 8 shows the power spectrum for the envelope of a representative 4-MHz WCDMA signal, the baseband I/Q bandwidth of which is illustrated in Figure 7. The envelope power has a strong delta function at dc, and then an overall spectral width of more than 10 MHz. For 20-MHz LTE signals, the associated envelope bandwidth is as high as 60–75 MHz. The peak output power required of the envelope amplifier is on the order of 1.5 times the peak power of the RF PA (to account for inefficiencies) and so is on the order of 300 W for base stations and 3 W for handsets.

The signal to be delivered by the envelope amplifier is very similar to the RF envelope signal but is modified from it somewhat in the interest of amplifier accuracy. In particular, if the dynamic supply voltage drops to below the "knee voltage" of the RF PA output transistor, the RF PA gain will plummet. To avoid this, the dynamic supply voltage waveform is always kept above a certain minimum voltage (10–20% of the maximum voltage) and is calculated by a process called *decresting* of the envelope. Other waveform variations are often included in the interest of optimizing system linearity, by introducing a "shaping function" to determine the most appropriate dynamic supply waveform [16]–[18].

For producing the dynamic supply voltage, a possible approach is to use a purely analog technique: for example, a source-follower transistor driven by a (low-power) envelope signal—essentially, a low-dropout regulator. The circuit accuracy will be good—except efficiency will be much lower than targeted values. An alternative approach is to use a switching dc-dc converter (generally, a buck converter) to change the fixed-supply voltage to a value that is most appropriate for the instantaneous envelope [19]. If the buck converter's output is pulse-width modulated, it requires a very high switching frequency—of an order ten times the signal bandwidth or more—and the efficiency of the buck converter suffers due to CV^2f losses in switching. The use of multiple switching circuits with interleaved outputs is a partial answer to this problem [20].

Alternative approaches have been widely explored that combine both analog and digital (switching-mode) sections, with the digital parts corresponding to the dc and low-frequency components of the signal produced at very high efficiency, and the analog parts corresponding to the higher-frequency parts of the spectrum produced at lower efficiency [21]–[24]. A comprehensive review of these circuit developments in recent years is provided in [22].

The analog portions can also be arranged to improve signal accuracy—for example, by using a feedback network to suppress deviations from the desired dynamic supply waveform. This allows the analog stage to "eat up" the errors and quantization noise produced by the digital switching-stage. A representative configuration for the hybrid envelope amplifier is shown in Figure 9. Such amplifiers have been produced in hybrid form with output power of up to 300 W as required for base stations (using silicon-based components), as well as in integrated-circuit form at power levels appropriate for handsets and micro base stations.

Another approach to the problem of delivering variable power supply voltage is to deliver a multiplicity of discrete power supply voltages, switched into the network in accordance with the instantaneous demands. The multiple supplies allow the overhead voltages to be minimized for the different stages; the challenge is to minimize the effect of the supply voltage step on the output voltage when the transitions occur, which can be accomplished with intervening analog circuitry or by elaborate digital adjustment of the RF amplifier gain.

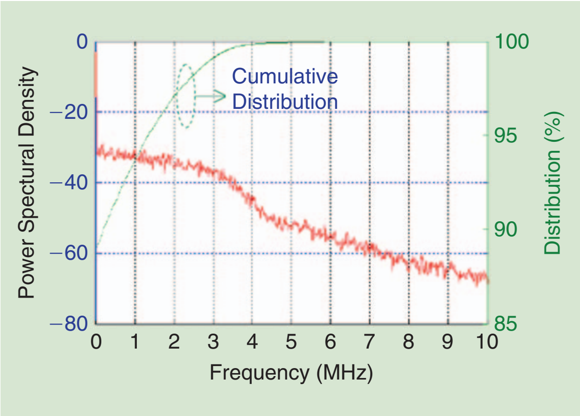

Figure 8. *The power spectrum of the envelope waveform for a 4-MHz WCDMA signal, showing the broad bandwidth. Also illustrated is the cumulative distribution function versus frequency.*

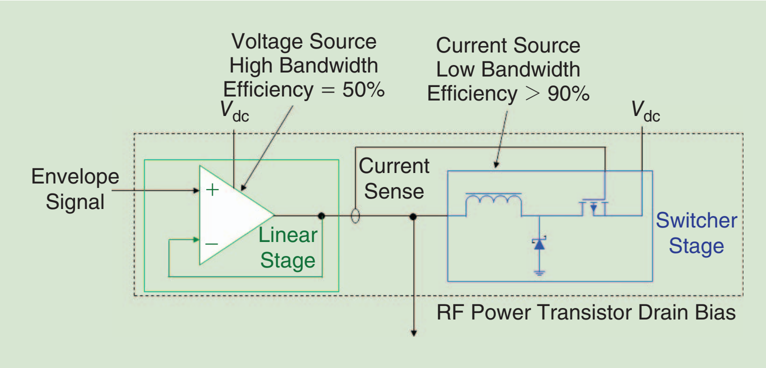

Figure 9. *The typical architecture for an envelope amplifier with a linear-amplifier assisted-switcher stage, using feedback to improve output fidelity and hysteretic control of switching.*

ET is poised to be deployed extensively in coming generations of amplifiers for cellular handsets because it can reduce power dissipation for signals using the LTE standard required for 4G wireless systems, which feature high PAPRs.

One requirement for the envelope amplifier is to create a signal that accurately reproduces the desired dynamic supply waveform without spurious noise or interference (generally, 1–2% accuracy is required). This accuracy requirement derives from the fact that the RF PA is typically operated in strong compression so that its power supply rejection is not high (an exception is for output at very low power levels, where the PA is not compressed).

There is one spectral region that is dramatically more important, however, in most cell-phone applications: the receive (Rx) band of the cell phone itself. Most of today's cell-phone links feature frequency-division duplex (commonly referred to as FDD) operation so that transmitting and receiving can take place simultaneously in different frequency bands separated by 40–180 MHz (according to the particular LTE band). It is important to ensure that the envelope amplifier does not produce noise at a frequency corresponding to the transmit–receive (Tx–Rx) band offset because this noise will show up convolved with the Tx output spectrum and invade the Rx band. Strategies such as baseband filtering of the switching signal have been used to alleviate this problem [25].

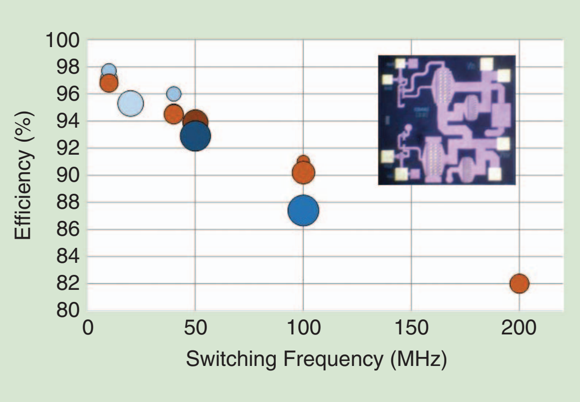

Figure 10. *A plot of the measured efficiency versus switching frequency for the pulse-width-modulated MMIC buck converters implemented in the Qorvo 150-nm GaN-on-SiC process. The size of the dots represents the power level. The inset is a photo of one of the switchers, with a measured efficiency over 90% at 100-MHz switching [32].*

Where ET Is Going

As ET moves into the mainstream for cell-phone systems, awareness is increasing that better efficiencies for other applications can be obtained with ET. Within the world of wireless infrastructure, one of the significant trends is that very many frequency bands must be accommodated (more than 40 for the standards around the world). In macro base stations, these can generally be managed by using multiple, distinct single-band amplifiers coupled together. In micro base stations, however, space and economics might make this approach untenable. Single amplifiers have already been demonstrated to cover a wide frequency range. Unfortunately, it is difficult to improve their efficiency over very wide ranges with Doherty and outphasing techniques, as mentioned earlier. ET offers a potentially better solution for this problem because its implementation is essentially agnostic regarding the carrier frequency of the RF PA (it is only concerned with the signal envelope and its bandwidth).

As commercial wireless communications evolve from 4G to 4.5G and 5G, the signal bandwidths are continually increasing. An initial phase of system deployment involves carrier aggregation, where signals in more than one spectral band are transmitted simultaneously [26]. These bands could be contiguous or separated by 500 MHz or more. When multiple carriers come into play at the same time, even if each one has a constant envelope, the net result can have large PAPR. Some 5G systems are slated to operate in the cm-wave and mm-wave bands (6–30 GHz and 30–100 GHz, respectively). Here, the envisioned signal bandwidths are of the order of 200 MHz–2 GHz. The wide bandwidths pose challenges for ET implementation; it is not straightforward to extend the bandwidth of the envelope amplifiers without affecting their efficiency.

To understand the dimension of the challenges for the envelope amplifiers, it is worthwhile to consider the difference between results to date for handsets and base-station amplifiers. For handsets, signal bandwidths of 20 MHz have been reached in relatively straightforward fashion; it has been a struggle for comparable base-station systems to reach this milestone. Why should this be so? The answer lies, to a considerable extent, in the fact that reaching the high power levels needed by base stations requires that the corresponding transistors have a high breakdown voltage (typically above 80–150 V for commonplace input power supplies of 32–50 V). Tradeoffs in transistor design dictate that the current gain cutoff frequencies (f_Ts) must then be relatively low (for transistors in silicon). For handsets, the transistors are not constrained to support high voltages; 6–8 V is typically enough. Transistors for these applications are faster and can be integrated with low parasitics.

The fundamental relationships among breakdown voltage, on-resistance, and input capacitance that determine the efficiency for switching-mode devices (such as those used in envelope amplifiers) have been captured by Jayant Baliga in his second figure of merit [27], according to which efficiency is governed by

$$f_\beta = \frac{1}{R_{\rm on} C_{\rm in}},$$

where $R_{\rm on}$ is the on-resistance of the switching device and $C_{\rm in}$ is its input capacitance. The figure of merit, in turn, is determined principally by characteristics of the material used for transistor implementation:

$$f_\beta = \frac{\mu E_c^2 V_g^{1/2}}{2 V_b^{3/2}},$$

where μ is the material mobility, E_c is the breakdown electric field of the material, V_g is the gate input voltage swing, and V_b is the breakdown voltage. Accordingly, because the breakdown voltage must go up in moving from handset to base-station scenarios, the figure of merit and the efficiency are forced to go down at a given switching rate. This straightforward analysis suggests a way to overcome the dilemma: use a material with higher figure of merit.

ET will continue to be at the forefront of the research efforts to provide PAs needed in the future.

GaN fits the bill (μ is higher by ×1.2–4 than silicon, depending on the embodiment; E_c is higher by ×10). Accordingly, recent research has focused on GaN as a material to improve efficiency at high power levels for ET, and some impressive results have been obtained [28]–[30]. A complication, however, is the fact that only n-channel field-effect transistors are available in GaN, so that some of the circuit ingenuity embodied in CMOS integrated circuits cannot be directly copied in the case of GaN. The most straightforward efforts use envelope amplifiers based only on buck converters with pulse-width modulation at very high sampling rates.

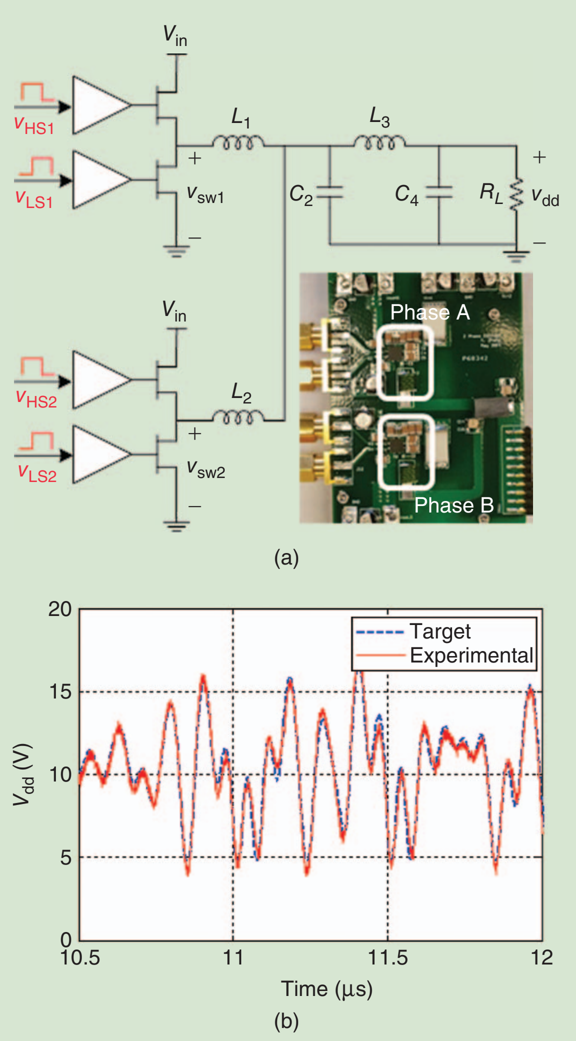

Figure 11. *(a) The schematic and photograph of a packaged two-phase buck switcher. The switcher tracks a 20-MHz LTE signal with better than 3% RMS error, as shown by the measurement in (b).*

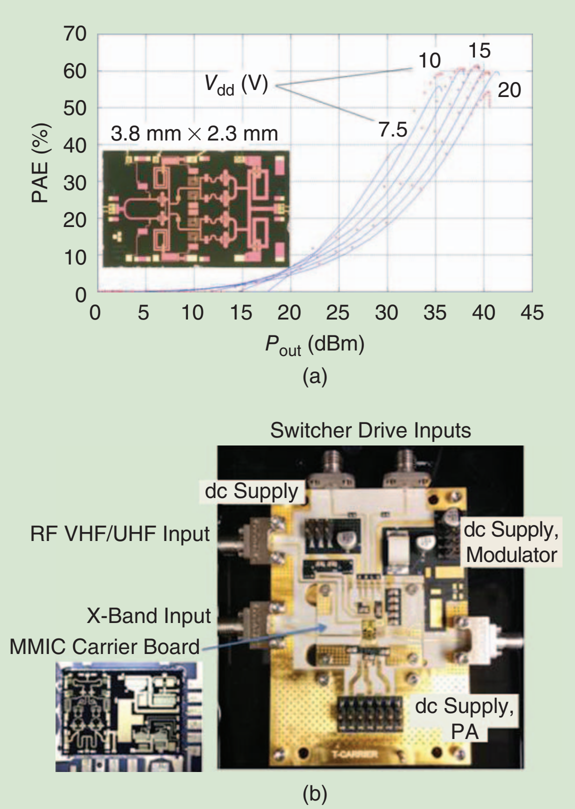

Figure 12. *(a) A 10-W GaN MMIC PA's measured and simulated efficiency for static supply modulation. (b) An integrated MMIC 100-MHz buck converter with a 10-GHz PA in a 3.8-mm x 5-mm die packaged with all supply voltages and an external filter between the switcher and PA. A UHF cascode PA is also integrated to enable increased envelope bandwidth tracking [34].*

The origins of the ET technique date back to 1952, when a closely related technique, envelope elimination and restoration (EER), was introduced by Leonard R. Kahn to amplify single sideband signals using vacuum tube electronics.

There have been significant efforts, however, in GaN-integrated envelope amplifiers, with the results from [31], [32] summarized in Figure 10. Switchers with integrated gate drivers in the Qorvo 150-nm RF GaN-on silicon carbide (SiC) process have demonstrated over 90% peak efficiency, at up to 200-MHz switching frequency and up to 15-W peak power. The example chip shown in the Figure 10 inset is a 100-MHz switcher with integrated gate drivers that tracks a 20-MHz LTE waveform with an efficiency of 92% at 10-W peak output power, measured in a standard quad flat no-leads package.

A different approach for improving the response speed of envelope amplifiers is to use multiple converters in parallel, with time offsets between them. By coordinating the inputs of *N* switchers, the output bandwidth can be increased by a factor of *N*. Examples include the multiphase switchers discussed in [20], [31], and [32] and illustrated in Figure 11, where a two-phase converter can switch more slower (at 50 MHz for each converter) and track an LTE waveform with better than 3% root-mean-square error (RMS) error. In this circuit, two converters like those shown in Figure 10 are integrated in a hybrid manner, where the values of the inductors and the output filter are critical design parameters.

The switcher shown in Figure 10 has also been tested with several PAs [33], including a 10-W GaN monolithic microwave integrated circuit (MMIC) PA with a peak PAE greater than 60% and greater than 23-dB saturated gain, as shown in Figure 10 [27]. The resulting average efficiency for a 20-MHz LTE signal, with an optimized split in digital baseband, increases from 26% to 48%. The main challenge for integration is the interconnect between the envelope modulator and the PA. The envelope modulator is effectively a dynamic broadband bias line, which can present stability issues for the PA. On the other hand, the PA under large signal operation presents a dynamic complex load to the supply modulator [34]. Therefore, an appropriate filter is required between the two components of the ET transmitter. Figure 12 illustrates a single chip that integrates a fast dynamic-supply and RF PA, where a 10-W PA is combined on the same die with a 100-MHz switcher.

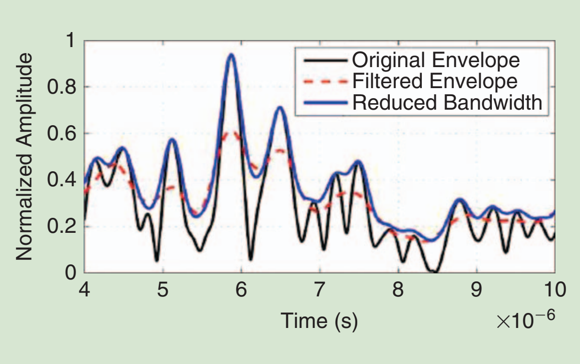

Figure 13. *A representative waveform of the output envelope (black), a potential dynamic voltage waveform with reduced bandwidth (blue), and a lowpass filtered envelope waveform (dashed red). The dashed waveform is inadequate because it causes clipping.*

An additional research thread being pursued relates to the difference between the dynamic power supply voltage and the RF envelope itself. As described earlier, if the dynamic supply voltage closely follows the envelope, then the power dissipation in the transistor is minimized. But suppose the dynamic supply voltage is somewhat slow in responding? It has been argued that with a reduced bandwidth dynamic supply voltage, as shown in Figure 13, one can still appreciably increase the efficiency of the system by lowering the overhead voltage almost everywhere (while missing, perhaps, at the lowest points of the envelope where the current is low anyway). It is necessary to generate dynamic supply voltage waveforms that are always greater than the desired envelope; otherwise, objectionable clipping of the peaks would occur.

A feature of this technique is that the dynamic supply voltage the RF PA sees at a particular envelope voltage depends on past history (rather than just on the instantaneous envelope amplitude) and so its gain may be correspondingly different. The use of the bandwidth (or slew rate) limited supply voltage thus introduces an unwanted memory effect. Research shows, however, that the memory effect can be accurately quantified and taken into account in the predistortion of the amplifier system [35], [36].

To summarize, the ET PA approach has been a dominant theme in the development of RF PAs that can achieve high efficiency for signals with time-varying envelopes. As wireless communications progressively evolve to provide greater data rates, the constraints of the finite RF spectrum dictate that signal modulation formats will continue to have time-varying envelopes with potentially increasing ACPR. At the same time, requirements for high efficiency will continue to be strong in the hope of reducing the energy per bit needed for transmission. ET will continue to be at the forefront of the research efforts to provide PAs needed in the future. The advantages of ET amplifiers will, in fact, become increasingly important as the number of frequency bands used for wireless communications around the world increases. Challenges remain for improving the main PA efficiency, as well as for maintaining the efficiency of the envelope modulator as signal PAPRs and bandwidths continue to increase.

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