ET101 An Introduction to Envelope Tracking for RF Amplifiers

Document Type: **White Paper**

Revision: **1.0**, Published: **29 November 2011**

Author: **Steven Baker**

Access Control: **Unrestricted** ☑

Associate Members ☐

Full Members ☐

Board Members ☐

ET101 An Introduction To Envelope Tracking RF Amplifiers (1.0).docx

This paper introduces the principles of 'envelope tracking', a technique that can significantly increase the efficiency of RF transmitters, and its growing relevance as the cellular industry delivers high-speed, 4G networks.

Twin Challenges

Faster wireless connections are demanded by consumers and increased spectral efficiency is demanded by network operators. This is achieved by squeezing more information into a given radio channel through the use of more complex modulation schemes. The ratio of peak transmitted power to average transmitted power ('PAPR') is generally higher for more complex modulation schemes and this has a detrimental impact on RF transmitter efficiency.

A power amplifier (PA) is at its most efficient when running at maximum output power and it becomes increasingly inefficient at lower powers. An amplifier must be configured to handle peak output power. As PAPR increases, average power is reduced relative to peak power and so the transmitter's average efficiency is reduced.

This effect is clearly illustrated in Table 1, which shows that typical PA efficiency has dropped from 65% for GSM, a constant envelope modulation scheme to just 30% for LTE systems.

Standard	Launch date	Spectral Efficiency bits/sec/Hz	PAPR dB	PA Efficiency typ. %
GSM	2003	0.17	0	65
W-CDMA	2003	0.1	3.4	45
HSUPA	2008	1.5	6.5	35
WiFi	2003	0.9	9.0	25
LTE	2010	4.0	8.0	30

Table 1 Fixed Drain Power Amplifier Efficiency for a Range of Modulation Schemes

A second challenge arises in the form of band fragmentation. A host of frequency bands has been allocated for LTE services by different spectrum authorities around the world. Uplink FDD frequencies range from 698 MHz to 3.5 GHz. While country-by-country such allocations might make sense, they present a real difficulty to mobile network operators (MNOs) with world-wide operations and high-value 'roaming' customers.

Today's W-CDMA handset might have to support operation across five bands and may require three separate PAs, one for 800—900 MHz, one for 1800—1900 MHz and one for 2100 MHz operation. Future devices will have to support many more bands across a greater range of frequencies. To make support of so many bands practical, to keep component counts manageable and to minimise front-end switching losses, broadband PAs, capable of operating over a greater frequency range, will be required.

However, configuring a PA to operate over a greater frequency range tends to reduce its efficiency.

Therefore these two issues, increasing PAPR and the need for broadband PA operation, combine to produce a single effect, namely the significant reduction of PA efficiency in LTE systems.

Workstations and digital signal processors continue to obey 'Moore's Law' and deliver the processing power needed to design, model and implement increasingly complex modulation schemes that get us closer to Shannon's limit. But in the meantime RF transmitter efficiency remains a performance frontier.

Techniques to Increase RF Transmitter Efficiency

Operating a PA in compression will maximise its efficiency. This works well for constant envelope modulation schemes, such as GSM's GMSK, which contain no amplitude modulation (AM) component. But for signals that contain an AM component, 'AM to AM' distortion products ('clipping') will be seen in the output if signal peaks cause the PA to operate in compression. For modulation schemes that include an AM component (often referred to as 'linear modulation') it is common to 'back off' the PA (i.e. operate below maximum output levels) to prevent it going in to compression.

Digital pre-distortion (DPD) is a technique that can reduce AM-AM distortion. An 'inverse distortion' is applied to the baseband signals before they are fed into the RF transmit path. After being compressed in the PA stage, these pre-distorted signals result in a correct signal being produced at the output. This enables an amplifier to be used even in its compressed region and so squeezes more efficiency from a standard PA. The technique works well in infrastructure applications but requires significant processing power and is not, therefore, especially effective in lower-powered handset and modem applications.

Base stations and mobile devices do not always transmit at their maximum power levels. Messages are exchanged between base stations and terminals to set the desired transmit power level for a given transmission 'slot' or 'frame'. With this knowledge, a technique known as DC tracking or average power tracking can be used to adjust the PA's supply rail from one timeslot to the next, enabling the PA to handle peak levels in a particular slot while reducing heat dissipation in those slots for which maximum transmit power is not required. This offers some efficiency enhancement but does not deal with the increasing PAPR problem and has no impact on the broadband challenge.

Doherty amplifiers offer a more sophisticated solution to the efficiency challenge by combining the output of two PAs. At lower transmit power levels one PA is switched off and the other operates linearly but inefficiently. At higher output power levels one PA operates linearly to handle the (relatively infrequent) signal peaks while the other operates in saturation to deliver the majority of the output power with higher efficiency. This scheme is widely used in base stations. It increases overall transmitter efficiency but introduces complex RF combiner circuitry which tends to limit practical amplifier bandwidth.

This leads us to envelope tracking, a scheme first conceived in the 1930s and used in AM radio broadcast systems but which has only relatively recently been reduced to commercial practice for contemporary cellular systems.

Envelope Tracking—Overview

In a conventional fixed-supply PA, energy is wasted whenever the device is transmitting below maximum output power. If the output signal is of constant amplitude it would be possible to adjust the fixed supply to be just sufficient to power the PA while minimising energy wastage and, indeed, this is the very approach that enables GSM PAs, operating on constant envelope signals, to achieve efficiencies of the order 65%.

But, in the world of 3G and LTE, variable envelope signals are a given and so a different approach is taken: the supply voltage is dynamically adjusted to track the requirements of the RF power envelope. This is done by monitoring the I,Q signals, performing a magnitude calculation and driving a power supply modulator accordingly.

'Average power tracking' or 'DC tracking' schemes, follow the relatively slow, protocol-commanded, average power level changes in output signal. In contrast, envelope tracking entails the instantaneous tracking of the RF envelope and continuous updating of the power supply voltage at I,Q sub-sample rates.

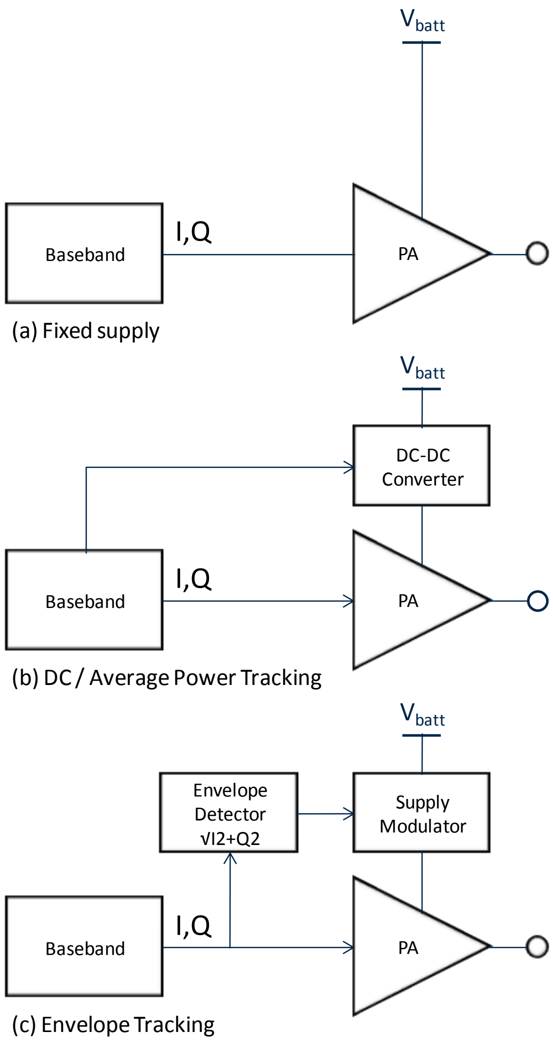

Figure 1 PA Power Supply Architecture Overview

Simplified power supply architectures for each of fixed supply, DC tracking and envelope tracking are presented in Figure 1 and the corresponding supply voltages are illustrated in Figure 2.

It should be noted that envelope tracking is not a form of polar modulation, in which all AM information in the transmitted signal is introduced via the PA supply. In fact, as shown in Figure 3, the envelope tracking supply never falls below ~1.5 V. It seems a wise precaution to maintain a PA supply voltage that is at least a couple of diode drops above ground. Moreover, tracking right down to zero volts would produce an envelope signal of colossal bandwidth.

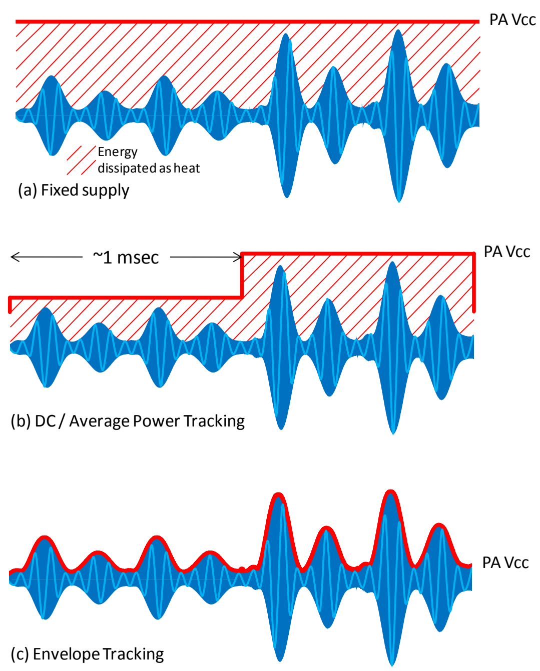

Figure 2 Comparison of Supply Voltages for Different Configurations Supply Configurations

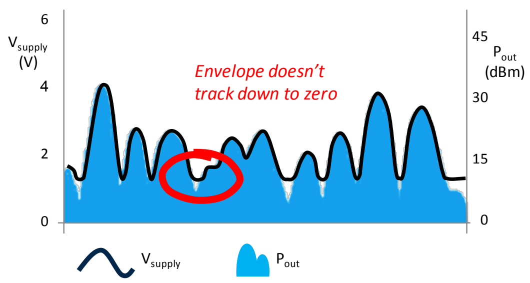

Figure 3 Envelope Signal

We noted earlier that operating a PA in compression increases its efficiency. One of the key objectives in envelope tracking transmitter design, therefore, is not merely to maintain 'a' lower supply voltage to the PA but to deliver 'the' lower, and constantly changing, supply voltage that causes the PA to operate in compression across a wider range of output powers than can be achieved with either a fixed or DC tracking supply.

Efficiency, in an Instant

Figure 4 plots instantaneous device efficiency against output power across a range of supply voltages for a conventional handset PA. For a fixed supply PA, efficiency for a given output power can simply be read from the 5.0 V curve. However, in an envelope tracking configuration the supply voltage will be varied as a function of output power to ensure that the device is always operating at the maximum possible efficiency. As a consequence, the envelope tracking efficiency locus always delivers better performance than the fixed supply efficiency locus.

Thus, by way of comparison, a fixed supply PA implemented with this device would deliver ~20% efficiency when outputting 25 dBm while the corresponding envelope tracking PA implemented using the same device would deliver ~50% efficiency using a 2.0 V supply.

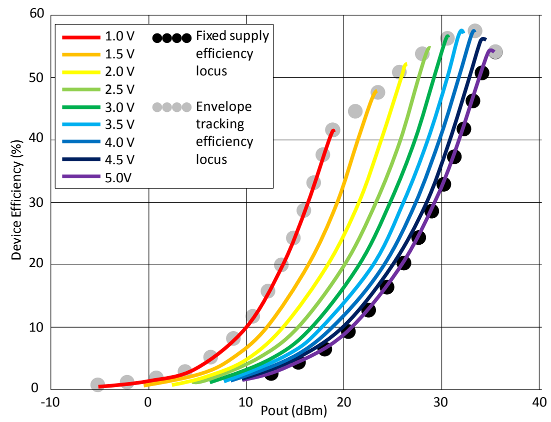

Figure 4 Instantaneous Efficiency For A Range Of Supply Voltages

A Closer Look

The digital I,Q data path, fed through a pair of DACs, filtered and quadrature-mixed to RF before being fed through RF driver and PA stages, as illustrated in Figure 5, is common to both conventional and envelope tracking transmitters and will be referred to hereafter as the 'signal path'. However, the envelope tracking transmitter also includes an 'envelope path'. Instantaneous power levels are calculated on each I,Q sub-sample pair, using $\sqrt{I^2 + Q^2}\ x\ RF\ Driver\ Gain$. The shaping table determines the correct PA supply voltage for a given instantaneous power. The shaping table transfer function is key to transmitter performance and is explained in more detail below. A DAC and filter provide the nominal envelope waveform to the power supply modulator which, in turn, translates the envelope waveform into a high-current, dynamic voltage supply for the PA.

Conventionally, significant supply decoupling would be applied to the PA to maximise rejection of supply noise. In an envelope tracking configuration there is no such decoupling owing to the high bandwidth of the envelope signal.

It is important that the envelope and signal paths are closely aligned in both timing and magnitude at points (A) and (B) respectively (see Figure 5) to preserve the integrity of the transmitted RF signal. For this reason delay, gain and offset adjustments must be allowed for in the envelope path.

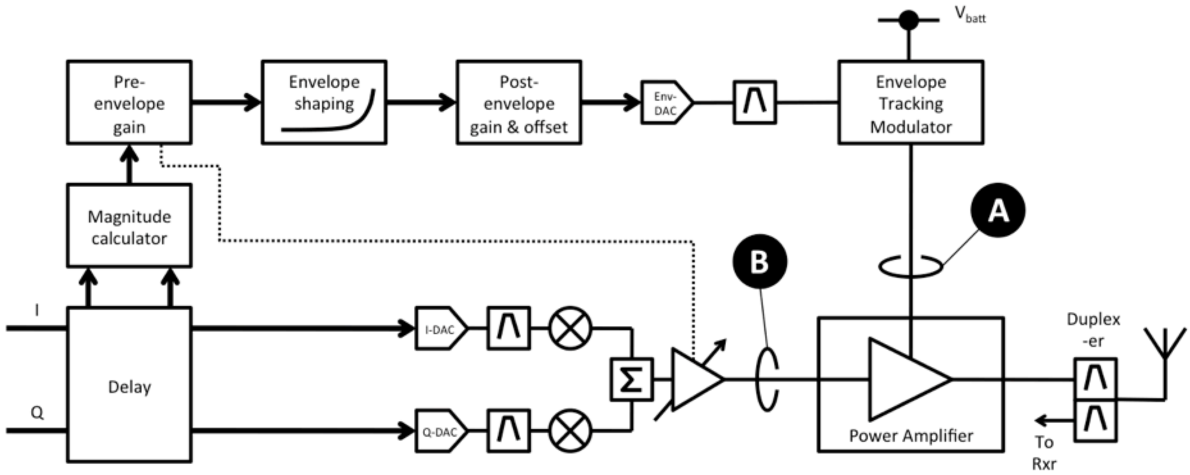

Figure 5 Envelope Tracking Transmitter Block Diagram

Envelope Shaping

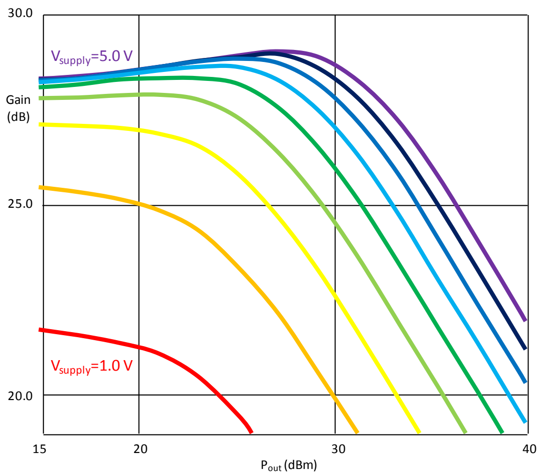

Figure 6 Handset PA Gain vs. Pout

The PA supply rail is now a controlled parameter and we intend to vary the PA supply dynamically to optimise efficiency. Therefore it is necessary to characterise the PA over a range of supply voltages. Such a characterisation, for a commercial cellular handset PA, is shown in Figure 6. With a nominal gain of ~28 dB at V_{supply} of 5 V, the PA shows ~1 dB of gain expansion before rolling off into compression above P_{out} of ~30 dBm. When operated at V_{supply} of 2.5 V the PA has a nominal gain of ~27.5 dB, does not offer gain expansion but rolls off into compression above P_{out} of ~23 dBm.

Operating the PA with a high degree of compression will maximise efficiency. Such a scheme is illustrated in Figure 7 in which the supply voltage for a given Pout is selected to ensure that the PA is operating in compression across as much of the output power range as possible. The graph shows that gain of ~26 dB and compression of 2 dB is achieved with a 5 V supply while gain of ~23 dB and compression of ~1.5 dB is achieved with a 1.5 V supply.

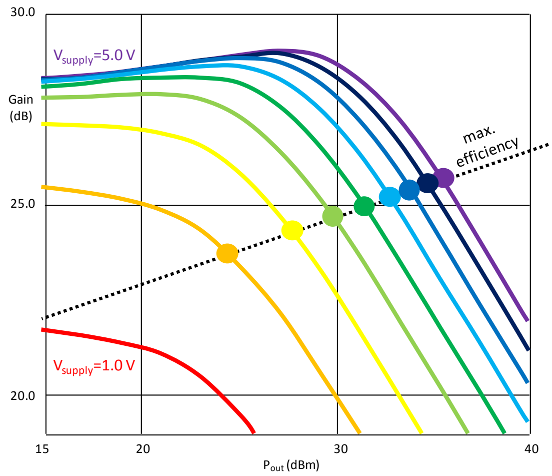

Figure 7 Shaping Function for Maximum Efficiency

Replotting this data as V_{supply} against P_{out} we see the form of the shaping lookup table for this high-efficiency strategy. From Figure 8 we can see that if a given I,Q sub-sample pair and RF drive setting require a 30 dBm output then a 2.5 V supply will be required.

It is also observed that, for lower values of P_{out}, V_{supply} plateaus at ~1.5 V. At these lowest power levels the PA will be operating linearly.

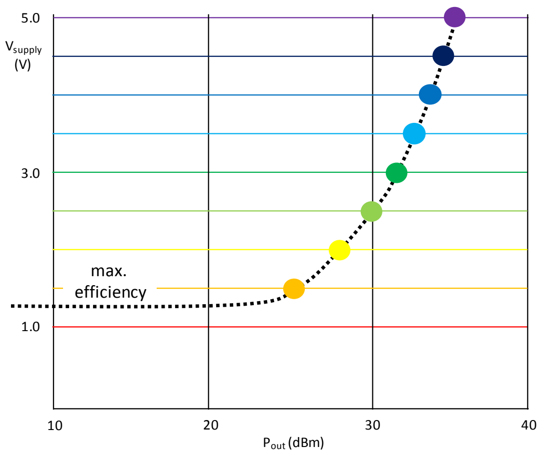

Figure 8 Maximum Efficiency Shaping Table

The efficiency of this scheme is delivered, in part, at the expense of reduced absolute gain. A PA capable of delivering ~28 dB of gain when operated with a fixed 5 V supply is only providing a maximum gain of ~26 dB when operated in this envelope tracking configuration. A gain reduction in the PA stage will require increased signal levels in the driver stage.

There is one further wrinkle with this scheme: it will result in significant AM-AM distortion in the output because the gain of the PA stage varies, albeit linearly, with output power. (Indeed, as plotted in Figure 7, this configuration offers controlled gain expansion as P_{out} increases.) In fact this is not an insurmountable problem in infrastructure applications where DPD can be applied to correct for AM-AM effects. However, in lower-power handset applications the energy-cost of implementing DPD would outweigh the transmitter efficiency gains that would otherwise accrue.

This leads to another strategy: instead of configuring the transmitter for maximum efficiency it can be configured for maximum linearity, as illustrated in Figure 9. Here a constant gain of 25 dB is chosen and this is translated into the lookup table shown in Figure 10. By using this data set in the shaping table the PA can be linearized and AM-AM distortion can be all but eliminated. It is also evident that the lookup table curve is less severe in this constant gain scheme which, in turn, translates into a reduced envelope-signal bandwidth.

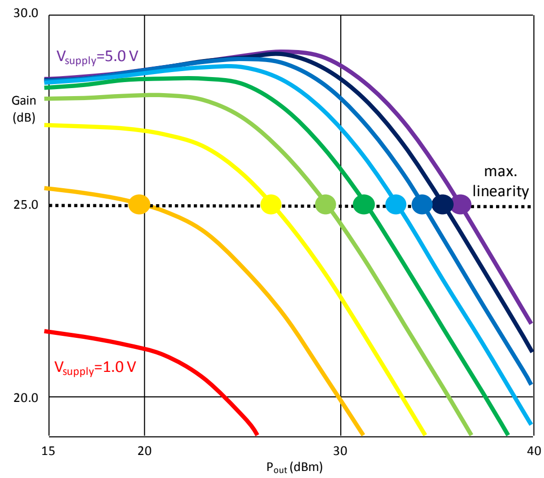

Figure 9 Shaping Function for Maximum Linearity

While this 'isogain' scheme does not provide the same degree of compression as the 'maximum efficiency' scheme, it provides a far greater degree of compression than a fixed supply PA could deliver and it delivers the greatest degree of compression at the highest power levels where the absolute energy savings will be greatest.

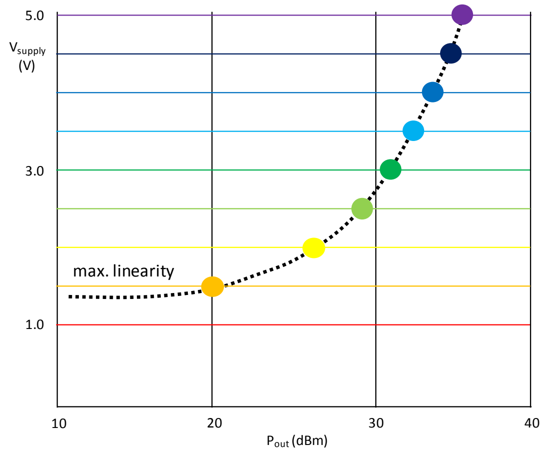

Figure 10 Maximum Linearity Lookup Table

Thus the same PA, by means of a different shaping table strategy, can deliver markedly different performance.

The Challenges

Envelope Bandwidth

Typically the envelope bandwidth needs to be three times greater than the modulation bandwidth to achieve the necessary EVM and spectral performance at the output.

Thus an LTE20 signal requires a 60 MHz envelope which, in turn, demands a minimum sample update rate of 120 Msample/s.

If the envelope bandwidth is insufficient, noise will be seen to rise on either side of the carrier beyond the envelope path bandwidth.

Timing Mismatch

Correct alignment of the RF signal and the requisite supply voltage is critical. Suppose the rising supply voltage arrives 'late' compared to the rising RF output. The supply will then be insufficient for the RF signal going in to the PA and the PA output will be over-compressed. The power supply will then peak some time after the RF signal peaks at which time the PA will be over-supplied, causing it to operate inefficiently in its linear region.

Such offsets introduce close-in AM-AM distortion in the output while also raising the far-out noise floor.

To put this in context, an LTE20 signal requires timing alignment of ~1 nSec to meet 3GPP transmit performance specifications.

The Benefits

PA Efficiency

What benefits does envelope tracking deliver in practice? Figure 11 compares the power consumption of a 40 W envelope tracking LTE remote radio head with a fixed supply equivalent.

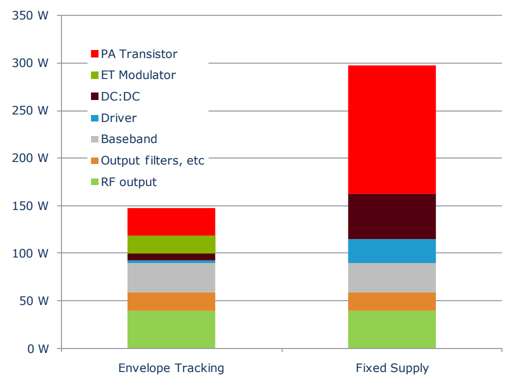

Figure 11 LTE 40W Remote Radio Head Power Consumption

To achieve 40 W output power to the antenna requires a total of ~150 W using envelope tracking. To achieve the same output power using a fixed supply PA would require approximately 300 W. The majority of that additional energy is attributed to heat dissipation in the PA transistors. Allowing for front end losses of 3 dB, 40 W at the antenna requires 60 W at the PA output. A 60 W envelope tracking PA operating at ~65% efficiency will dissipate 32 W. A fixed supply PA operating at just over 30% efficiency will dissipate 130 W.

Other power savings can be found in the driver stage. Typically drivers are designed to be highly linear—on the basis that any error introduced in the driver is unrecoverable—and, therefore, tend to have high power requirements. However, owing to the degree of control that can be exercised over the gain characteristics of the PA stage in an envelope tracking transmitter, is it possible to use a lower power driver stage that runs in compression and to operate the PA stage under controlled gain expansion to achieve a net-linear transmit path.

The benefits of lower power consumption in base station applications quickly cascade. Lower power PAs require smaller heatsinks and smaller cooling plant which in turn reduce cost, size and weight. Moreover, cell site power supply and backup supply requirements are reduced, further lowering both opex and capex for the network operator.

Broadband

In general, as the operating bandwidth of an amplifier is increased it is necessary to reduce the Q of the output matching network and this, in turn, reduces overall efficiency of the amplifier.

And so a fixed-drain amplifier delivering 30% efficiency in a 1.7 GHz band may achieve only 25% efficiency if configured to operate from 1.2 to 2.0 GHz. Such performance would be unacceptable in a smartphone application.

While an envelope tracking amplifier might suffer similar efficiency losses when configured for wideband operation, such losses can be tolerated more easily when the starting efficiency is already greater than 50%.

However, envelope tracking can deliver an additional advantage in wideband applications. Typically an envelope tracking power supply modulator will make use of a boost-buck regulator which can generate an output voltage that is higher than the nominal battery voltage. This higher supply voltage can be applied to the PA when generating peak output, enabling a greater voltage swing to be achieved at the PA output. This, in turn, reduces the transformation ratio between PA output and antenna, so simplifying implementation of the LC matching circuit and reducing matching losses.

The inherent efficiency and superior broadband performance of envelope tracking transmitters are clearly illustrated in Figure 12, which compares envelope tracking and fixed supply efficiency of a handset PA fed with an 8.0 dB PAPR LTE signal.

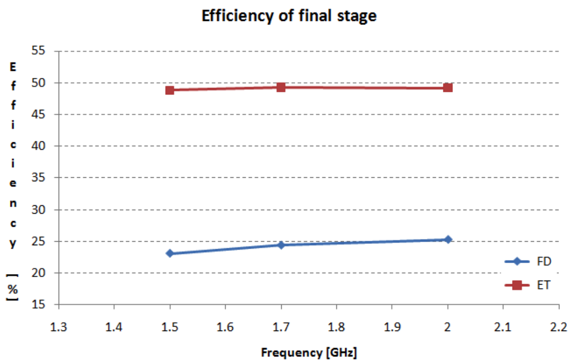

Figure 12 Broadband performance of handset PA

Conclusion

The cellular industry faces twin challenges of increasing PAPR and frequency band proliferation, both of which have an impact on transmitter efficiency. Of all the various efficient transmitter architectures available to RF systems engineers, envelope tracking uniquely addresses these twin challenges, delivering high transmitter efficiency with effective broadband operation.

To find out more visit www.open-et.org.