Enhancing the inefficiency of an RF power amp: The envelope tracking (ET) system

Steve Taranovich - October 09, 2013

Wideband power amplifiers (PAs) are notoriously inefficient, especially due to the high peak-to-average power ratio (PAPR) in wireless telecom and other base station transmitters. The PA necessitates the usage of far larger power supplies than the average power would demand.

Fortunately, there have been numerous efforts to solve these problems with digital pre-distortion (DPD), crest factor reduction (CFR) and more recently, envelope tracking.

Envelope tracking as a solution

One technique to increase the efficiency of the PA is to modulate the drain bias voltage of the RF transistor by tracking the input envelope power. This is called envelope tracking.

The PA is biased in class B, and the dc current is gets adjusted to the power level. The resulting PA has high efficiency for all power levels, very close to the maximum efficiency of the PA at high power.

An older envelope elimination and restoration (EER) technique was proposed in the early 1950s for this purpose by Kahn in reference [3], but it has several problems, and ET is more popular nowadays.

Figure 1 shows a basic block diagram for the ET inside the PA.
Let’s take a look at the techniques and waveforms of a conventional PA, an envelope tracking PA and an EER PA.

Block diagrams of conventional linear PA, envelope tracking PA, and EER (Image courtesy of reference [4])

Using a digitally-assisted envelope amplifier as an ET solution

Using a DSP control along with analog hysteretic feedback can be implemented by coordinating two high efficiency buck switching regulators to provide wideband envelope power for the RF stage. A GaAs high voltage PA is used in the design.

Previous designs have typically used a linear regulator along with a switching buck regulator where the switcher gives an output following the desired envelope and the linear regulator assures high output accuracy at the expense of lower efficiency.

In the newer design, the hysteretic controller attenuates and spreads out the switching noise frequency from the buck. A loop filter inside the linear regulator further attenuates the residual noise. The newer architecture is shown in Figure 2.
Figure 2: The block diagram of the newer envelope amplifier architecture (Image courtesy reference [1])

Figure 2 shows the DSP generating a high frequency control signal for the switcher by using something like pulse width modulation (PWM), delta sigma modulation or even pulse density modulation (PDM). The algorithm approaches an ideal hysteretic control loop.

The experimental results outlined in reference [1] showed a significant efficiency improvement in the PA performance.

**An ET solution implementing high speed eGaN FETs in a multi-phase buck converter**

An ET solution implementing high speed eGaN FETs in a multi-phase buck converter

A better ET solution which uses a new FET technology that enables power transistor devices that have switching transition speeds in the sub nano-second range, making them capable of hard switching applications above 10 MHz.

In the following video Efficient Power Conversion (EPC) demonstrates what power and efficiency levels are readily realizable using eGaN FETs in a buck converter for high power envelope tracking applications (See also the white paper by EPC on this issue). The need for improving the RF Power Amplifier (PA) system efficiency used in envelope tracking has become an intense topic of research and development due to the ever increasing need for improved cell phone battery life, better base station energy efficiency, and more output power from very costly RF transmitters.

eGaN FETs in a buck converter for high power ET in a PA (Video courtesy of EPC)
Two-stage ET for the PA

Usually the main amplifier will have reduced gain in an ET application. Reference [2] introduces the technique of applying ET to both the drive and main PA which will improve efficiency of the drive amp (operating at lower frequency)

It seems that there is an improved efficiency of 2.1% of the total system and an 8% improvement in the drive amp by itself. An added benefit of this technique also improves the linearity error which typically occurs with ET. This is achieved by a new sequential digital predistortion (DPD) architecture. This DPD addition will allow the stringent LTE system linearity spec to be met.

Sequential DPD structure

![Sequential DPD structure](Image)

Figure 3: The block diagram of the sequential DPD structure for the two-stage ET (Image courtesy of reference [3])

In the sequential DPD, the drive PA is linearized using the first DPD loop. Then, the linearized output from the drive PA is injected into the main PA. The distortion generated by the main PA non-linearity is linearized using the second DPD loop. This gives a total efficiency of 43% which is 2.1% better than ET being applied only to the main PA.

Envelope tracking PA in handsets

Multimode (MM) and multiband (MB) PAs give handsets the ability to make and receive calls the world over. Here designers typically gravitate towards a CMOS solution because of the battery life issues in a handset. Now research is working to have the linear PA on a monolithic CMOS die with the supply modulator architecture. There are certainly challenges with performance, but I do believe this will ultimately be a solution soon for handsets.

Enhancing efficiency in the back-off power region in handsets

Scintera outlines the two most commonly used and basic linearization techniques: pre-distortion and back-off operation (See reference [5]):
When a PA receives a multi-tone signal at its input, it will amplify the desired signal and also generate unwanted intermodulation (IM) terms (Figure 4a). This non-linear distortion increases as the PA approaches its saturation point and will vary in nature based on operating conditions and from PA to PA.

To get the desired linearity at the PA output (without pre-distortion), the PA must be operated with significant back-off from its saturation point ($P_{\text{SAT}(3\text{dB})}$ in Figure 5a).

Operation in back-off is defined as the case when the PA’s maximum output power level must be reduced so that the entire signal is within the linear region of the PA transfer curve. However, the PA’s efficiency (PA’s ability to convert DC supply power into RF energy) decreases as the PA’s operating point is lowered further away from its saturation point (Figure 4b).
Efficiencies of 8% or less for a Class AB PAs are not unusual to accommodate the signal’s peak-to-average ratio (PAR) and the additional back-off required to meet system linearity requirements.

Considering that the most popular linearization method by far for Class A/AB PAs transmitting 20W average power and below is operation in back-off, for these applications active linearization can provide very attractive benefits. Active linearization techniques, including digital pre-distortion (DPD) or RF pre-distortion (RFPD), allow the transmitter to operate close or even slightly above its $P_{\text{SAT}}$-PAR operating point (Figure 5b).

To enhance efficiency in the back-off power region, the use of a PA with a tunable load is the approach of choice in handset applications. Using a boosted supply modulator can further improve the efficiency in all power ranges. (Reference [4])
Figure 6 shows the conceptual curve of the PAE for a dual power-mode ET PA.

Figure 6: The Power-added Efficiency (PAE) curves of the dual mode with ET PA (Image courtesy of reference [4])

In reference [6], it was shown that a dual-mode PA can be operated as an MB PA and can realize good performance at high frequencies of 1.7–2.0 GHz; the performance graph is shown in Figure 7.
Figure 7: Measured performance of the dual-power-mode ET PA with 16-QAM 7.5-dB PAPR LTE signal across the average output power. (Image courtesy of reference [4])

A new RF Envelope Tracking power supply

TI recently announced what they claim is the industry's most efficient and robust RF envelope tracking power supply solution, supporting all 3G and LTE bands. The LM3290 step-down converter and integrated DC boost and companion LM3291 linear amplifier enable the use of envelope tracking techniques in RF transmitters to reduce the power amplifier temperature by 20 degrees C and reduce overall power consumption by 25 percent.

TI shows how to improve cellular handset transmit efficiency by using ET and Average Power Tracking (APT).
PA efficiency can be improved with APT and ET at high-Peak to Average Ratio (PAR) and high-power (Image courtesy of Texas Instruments)

Even at low-PAR and high power, the PA will be more efficient with APT and ET.

At low power and low/high-PAR, APT is most effective and will increase PA efficiency, but ET will not be effective due to PA minimum supply voltage requirements.

ET will improve heat and battery current where it is most needed, i.e. at high power and high PAR. APT performance is critical for low power and low PAR, so integrating ET and APT will give the best performance in the radio power transmitter PA.

It has been shown that ET reduces PA temperature by 20°C and raises system efficiency by +10% while saving 138 mA of current in the handset PA at high power LTE operation. While operating at low power LTE, APT saves 26 mA of current and reduces current drain by 72%.
TI has one of the commercially available ET+APT solutions, the LM3290 (with integrated DC-DC boost converter for ET operation and a buck for APT and ET operation) and LM3291 (High speed linear amplifier) ET power supply solutions to create an RF envelope supply modulator.

**Conclusion**

So we see that Envelope Tracking can be applied to handsets operating at low battery power as well as telecom base stations or broadcast transmission systems operating at 10 kW and even higher. There are many different techniques and component solutions with which to implement ET and I am very sure we will see newly conceived ideas and technologies to improve upon the limitations we still have even today with this technology.

**References**

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