Understand and characterize envelope-tracking power amplifiers

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The process of designing traditional fixed-supply power amplifiers has been well-established for many years. Well-defined metrics for performance assessment exist, and the amplifier designer’s job is to design a power amp with the best set of performance metrics. This task is far from simple, but designers at least understand the well-established assessment criteria. For envelope-tracking power amplifiers, the situation is more complex and requires the use of more sophisticated characterization techniques.

The objective of envelope tracking is to improve the efficiency of power amps carrying high peak-to-average-power-ratio signals. The drive to achieve high data throughput within limited spectrum resources requires the use of linear modulation with high peak to average power. Unfortunately, traditional fixed-supply power amplifiers operating under these conditions have low efficiency. You can improve the efficiency of an envelope-tracking power amplifier by varying the amplifier’s supply voltage in synchronism with the envelope of the RF signal.

The power amplifier’s fundamental output characteristics—power, efficiency, gain, and phase—now depend on two control inputs, RF input power and supply voltage, and can be represented as 3-D surfaces.

A typical envelope-tracking system dynamically adjusts the supply voltage to track the RF envelope at high instantaneous power. In this case, the power amplifier operates with high efficiency in compression. The instantaneous supply voltage primarily determines the amplifier’s output characteristics. Conversely, when the instantaneous RF power is low, the supply voltage remains substantially constant, and the instantaneous input power in the linear region primarily determines
the power amplifier’s output characteristics. A transition region in which both supply voltage and input power influence the output characteristics exists between these two extremes (Figure 1).

Envelope-tracking linearity You can construct a simple quasistatic—that is, memoryless—behavioral model of a power amplifier if you know its AM (amplitude-modulation)/AM and AM/PM (phase-modulation) characteristics. The mapping between the instantaneous RF envelope and the applied supply voltage profoundly influences these characteristics, along with other key power-amp metrics, such as power and efficiency. In an envelope-tracking system, the contents of a shaping table in the envelope path determine this mapping (Figure 2).

To achieve “ISOgain” shaping, the mapping between RF envelope and supply voltage is chosen to achieve a particular constant power-amplifier gain (Figure 3). With this mapping, the envelope-tracking amplifier system achieves low AM/AM distortion despite operating in compression over much of the envelope cycle (Figure 4). The figure also shows the equivalent trajectory for fixed-supply operation; from this trajectory, it is apparent that you can use envelope tracking to linearize a power amplifier, reducing adjacent-channel power ratio and error-vector magnitude.

The system trade-off of using the shaping table to linearize the power amplifier is a small loss of efficiency for a substantial improvement in linearity (compare figures 1 and 5 and figures 4 and 6). The choice of shaping function also has a strong influence on the bandwidth requirement of the envelope path. A smooth transition between the linear and the compressed regions results in a lower bandwidth requirement for the envelope amplifier for a 1 to 2% loss in system efficiency.
When designing a fixed-supply linear power amplifier, you must pay a great deal of attention to achieving adequate linearity characteristics at maximum output power. Many factors, including fundamental technology characteristics, biasing, and RF matching, influence the linearity, and it is up to the designer to achieve the best trade-off between efficiency and linearity. For an envelope-tracking power amplifier, however, the linearity in the compressed region is no longer a self-contained power-amplifier parameter. The amplifier still must be linear in the low-power, low-voltage region. At higher powers, however, there is no AM-linearity constraint, and developers can design the power amplifier for optimum envelope-tracking efficiency without regard to AM linearity. Unlike with AM distortion, the envelope shaping table does not directly control phase distortion. However, many power amplifiers show reduced PM distortion when operating in envelope-tracking mode.

As a result of this self-linearization, you can push harder into compression at signal peaks with an envelope-tracking system than with a fixed-supply amplifier, allowing increased output power for given linearity. Figure 7 shows measured adjacent-channel leakage ratio and error-vector-magnitude performance for a power amplifier operating in fixed-supply and envelope-tracking modes. In this example, the amplifier’s output power for −40-dBc adjacent-channel leakage ratio is 2 dB higher in envelope-tracking than in fixed-supply mode.
Characterization techniques

You cannot measure the stand-alone performance of envelope-tracking power amps without first defining the shaping table. This definition requires measurement of the power amplifier’s fundamental characteristics—output power, efficiency, gain, and phase—over the full range of supply voltage and input power. In principle, you could perform this characterization using a continuous-wave network analyzer and a variable dc supply, but results are typically poor due to thermal effects, ranging errors, and drift in phase measurements. It is also too slow to allow the use of load-pull techniques. An alternative approach is to use a pulse characterization using standard automatic-test equipment. This approach avoids the need for a high-bandwidth, low-impedance supply and is sufficiently fast for load pull to be viable. The approach makes it difficult to make accurate phase measurements, however. A third approach is to use real waveforms and to vary the shaping table to allow the measurement of all combinations of input power and supply voltage. This approach requires a supply modulator but is fast, allows you to gather accurate phase information, and can also characterize memory effects (Figure 8).
You can use a basic envelope-tracking power-amp characterization to create a quasistatic data model of the power amplifier. This model can have output power, phase, and efficiency as outputs and input power and supply voltage as inputs. Once the shaping table is defined, you can use the model to predict the amplifier’s performance parameters, such as adjacent-channel power ratio, error-vector magnitude, and efficiency for standard test waveforms.

You can use the same hardware for both the power-amplifier device-level characterization and the direct verification of power-amp system performance using a defined shaping table (Figure 9). For higher-bandwidth waveforms, the amplifier’s memory effects can be a significant source of nonlinearity. The power amplifier’s output parameters, including AM, PM, and efficiency, now depend on time—that is, the signal history—along with instantaneous input power and supply voltage. Memory effects show up in the amplifier’s characterization as a broadening of the AM/AM and AM/PM characteristics and can result from electrical time constants in input or output bias circuits, thermal time constants associated with local die heating, or technology-specific charge-storage effects.
Increasing efficiency

The statistics of typical high peak-to-average-power-ratio signals are such that an envelope-tracking power amplifier typically spends most of its time operating with relatively low supply voltage, with only occasional high-voltage excursions on high-power peaks. It makes sense, therefore, to optimize the amplifier’s matching to achieve the best efficiency with the target peak-to-average-power-ratio signals rather than simply designing for best efficiency at peak power and maximum supply voltage, as would be the case for a fixed-supply power amplifier. Designers can alter the amplifier’s matching to increase efficiency around the peak of the signal’s probability-density function, even if this necessitates a slight compromise in the peak power efficiency, as the following equation shows (Figure 10):

$$\text{EFFICIENCY} = \frac{\int_{0}^{V_{\text{MAX}}} \text{PROBABILITY} \times \text{POWER} \, dV}{\int_{0}^{V_{\text{MAX}}} \text{PROBABILITY} \times \text{POWER} \, dV}$$

Figure 10: Designers can alter the amplifier’s matching to increase efficiency around the peak of the signal’s probability-density function, even if this necessitates a slight compromise in the peak power efficiency.
To fully optimize the efficiency of an envelope-tracking power amplifier, you can extend the device’s characterization to include sweeping the load impedance—using fundamental or harmonic load pull—along with the input power and the supply voltage. This characterization produces a large set of data, and tools, such as Matlab, can be used to automate the analysis of this data to predict the average efficiency when operating with a specific set of envelope-tracking parameters. Using this characterization method, you can predict how an amplifier’s average efficiency varies with shaping function, output-voltage swing, backoff from maximum power, and waveform statistics when operating in envelope-tracking mode (Figure 11).

![Figure 11](image) You can predict how an amplifier’s average efficiency varies with shaping function, output-voltage swing, backoff from maximum power, and waveform statistics when operating in envelope-tracking mode (a); also shown is peak output power (b).

**Parameter variation sensitivity**

You might expect the performance of envelope-tracking power amplifiers over temperature to be worse than that of their fixed-supply counterparts. The reverse situation is true, however. An envelope-tracking power amplifier’s performance is more sensitive than that of a fixed-supply amp to changes in the supply-voltage characteristics than to changes in gain of the RF chain driving the power amplifier. Because you can better control the characteristics of the supply voltage over temperature than the variation of the RF gain, little variation in linearity occurs for extreme temperature variations (Figure 12).

![Figure 12](image) Because you can better control the characteristics of the supply voltage over temperature than the variation of the RF gain, little variation in linearity occurs for extreme temperature variations.
In a handset environment, the power amp receives an uncontrolled load impedance due to reflections from nearby objects, which can result in the amplifier’s having to work into load mismatches with a VSWR (voltage-standing-wave ratio) as high as 3-to-1. The envelope-tracking power amplifier’s self-linearization principle also applies under high-VSWR conditions, and this operation can result in significantly better adjacent-channel power ratio and error-vector-magnitude performance than that of an amplifier operating in fixed-supply mode (Figure 13).

The system-efficiency benefit of operating a power amplifier in envelope-tracking mode is well-known. However, it also offers other useful system benefits, such as increased output power, improved operation into mismatched loads, and insensitivity to temperature variations. In contrast to fixed-supply power amplifiers, the performance of an envelope-tracking power amplifier requires the gathering of substantially more data to predict system performance and the use of a test environment that allows sweeping of the supply voltage and the input power. A key aspect is the definition of the shaping table, which defines the relationship between supply voltage and RF power. Once you define the shaping function, you can directly measure efficiency and linearity using an appropriate system-characterization bench.

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**Author’s biography**
Gerard Wimpenny is the chief technology officer of Nujira Ltd and a member of the OpenET Alliance. He has more than 20 years of RF and signal-processing experience and has been responsible for strategic R&D, design-process definition, and top-level technical support for business-development activities. Wimpenny has been instrumental in delivering numerous wireless products to semiconductor vendors and infrastructure and handset manufacturers. He has a master’s degree from Cambridge University (Cambridge, UK).