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978-1-107-05917-7 - Dynamic Power Supply Transmitters: Envelope Tracking, Direct Polar, and Hybrid Combinations
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Excerpt
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Part I

Motivations, definitions, and principles

1 Motivations

Energy efficiency in radio frequency (RF) transmitters – this is the entire reason there is any interest at all in transmitter designs that incorporate dynamic power supplies. So what does this mean?

Whenever an amplifier provides a signal into a load resistance R_L, Ohm's Law says that the corresponding root-mean-square (rms) current that the signal has is related to the rms output power (P_{OUT}) according to

$$I_{Signal} = \sqrt{\frac{2P_{OUT}}{R_L}}. \tag{1.1}$$

The current from (1.1) must flow through the load no matter what the amplifier structure is. So whatever the supply voltage is, this current must flow from it as shown in Figure 1-1.

Power is dissipated (lost) when this current flows through any resistance, which includes the amplifier's transistor. This dissipated power is the product of the current in the load times the voltage difference between the supply voltage to the amplifier and the output signal voltage. When the voltage supplied to the amplifier is a constant value, which is by far the most common design practice, the situation in Figure 1-2(a) results. Power dissipation in the amplifier is at its maximum when the output signal voltage is half of the supply voltage. When the output signal voltage is higher, even though the current value is larger, the voltage drop is less and the power dissipation is lower. Similarly, when the output signal voltage is small, even though the voltage drop is now large, the current in the load is smaller and again the power dissipation is lower.

To keep this internal power loss in the amplifier small, the voltage drop must remain small at all times, because the signal current cannot change for the same output power. Various techniques to achieve this goal are shown in the progression of the charts in Figure 1-2. When the signal peak voltage is known not to go all the way to the available supply voltage, the actual supply voltage to the amplifier can be reduced as shown in Figure 1-2(b). This is called the average power tracking (APT) technique. The voltage drop inside the amplifier is reduced further when the supply voltage to the PA (the dashed line) now varies along with the output signal envelope. This situation was shown in Figure 1-2(c). How closely the dynamic power supply (DPS) follows the signal envelope, the *voltage offset*, has a *huge* impact on the operating properties of the amplifier and the transmitter it is in. Details set by the specific application this transmitter supports dictate design limits on this voltage offset based on the required properties

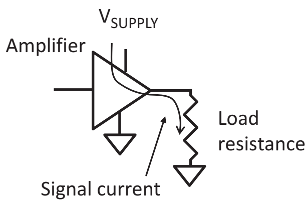

Figure 1-1 Any transmitter must generate a signal current in the load resistance. This current must flow from the amplifier power supply, no matter how it gets modified through the amplifier by the amplifier DC to RF conversion process.

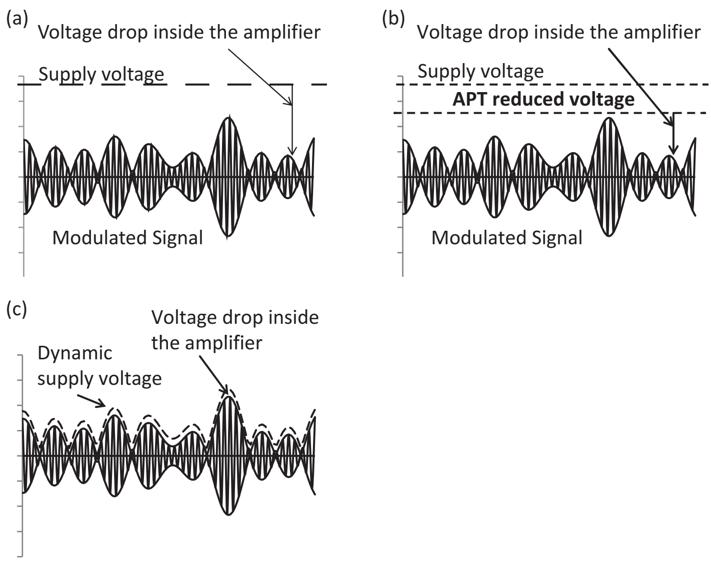

Figure 1-2 Power loss in an amplifier depends on the voltage drop inside the amplifier: (a) voltage drop across the PA transistor with a fixed supply; (b) voltage drop inside the amplifier with a reduced supply voltage from APT operation; (c) voltage drop across the PA transistor with a dynamic supply that follows the signal envelope.

the transmitter must have. In general, this voltage offset must be very carefully controlled.

By adopting a dynamic supply voltage, there are two new problems that need to be solved. One is how to get the waveform needed for the tracking supply, which in modern times is most often directly calculated by the digital signal processor that is calculating the signal itself. Once this waveform exists, it must be properly aligned in time with the signal when they both come together at the final power amplifier. This is discussed in Section 5.5.

This amplifier power dissipation problem is nothing new. Just a few years after vacuum tubes were invented (about one century ago), it was very obvious that as output power was increased, the amplifiers got extremely hot. It was realized before 1920 that if the amplifier could be made to work with a varying supply voltage, then much of this heat would not occur. This problem was solved in a few years to a "good enough" level [1-1], and the resulting transmitter design stayed in wide use for more than 60 years.

It is very important to separate the concepts of instantaneous voltage drop in the amplifier from the peak value of the power supply available to the amplifier. Ohm's Law says that while keeping the instantaneous voltage drop small to gain high efficiency, it is equally important to operate any real amplifier from the highest practical voltage available to further improve its efficiency. Radio transmitters are power-based signal processors, and as for the electric utility, transmission efficiency is greatest when starting from a high voltage. This characteristic is opposite to the energy-based signal processing performed by digital circuitry (particularly complementary metal oxide semiconductor – CMOS) where energy efficiency is improved at lower voltages. These two circuit types optimize at opposite ends of the voltage scale.

1.1 Linearity and linearization

In more modern times, wireless signals are used to communicate a lot of information. These signals are increasingly intolerant of distortion in the transmitter circuitry (and anywhere else, for that matter). This increases the demands on linear performance of the amplifier circuitry. Nothing comes for free – improve the circuit linearity and the power dissipation also increases. And any attempt to reduce the single transistor power dissipation for the same output signal power necessarily results in reduced linearity from the circuit. This has to happen, according to the laws of physics. This sets up a well-known trade-off, between having good energy efficiency or having good circuit linearity. Choose one.

Customers usually do not care about the laws of physics. They want good linearity and high energy efficiency. To meet this demand, we in the product engineering community need to more carefully understand the actual need, which is output signal accuracy. Circuit linearity is not necessary to obtain output signal accuracy, but it is harder to achieve if circuit linearity is not available. The term used for obtaining output signal accuracy, without depending solely on circuit linearity, is called *linearization*.

Fortunately, it is possible to achieve very accurate output signal properties in the complete absence of circuit linearity. This does appear to solve the linearity/efficiency trade-off, but as always there is a cost that may or may not be acceptable. Mainly the costs here are (1) much higher complexity in the necessary implementation along with (2) an inherent incompatibility with several of the high data rate signals used in present communication systems.

Linearity in circuit performance is not necessarily easy to achieve either. Particularly in the CMOS geometries below 100 nanometers, the individual transistors become progressively faster and progressively less linear. Architectures that use this dynamic supply voltage for improved energy efficiency and that also can use the varying supply to improve output signal accuracy become attractive. The amplifier operating mode must change to have the DPS shift from being a source of output signal distortion to being a linearizer.

1.2 Reliability improvement

When power dissipation goes down, temperature goes down. When operating temperature goes down, it is well known that circuit reliability goes up exponentially. Therefore, the most important parameter that predicts long-term reliability of a component is its operating temperature, and the parameter driving the operating temperature is the component power dissipation. Anything that can be done to reduce component power dissipation will improve its reliability. Incorporating a DPS into the transmitter power amplifier (PA) directly reduces power dissipation in the PA.

1.3 High peak-to-average power signal types

Standardization committees have adopted signals in recent decades that have increasingly high peak-to-average power ratio (PAPR) properties, as shown in Figure 1-3 for uplink (mobile to infrastructure) signals [1-2]. The bandwidth efficiency of these signals does not track well with the PAPR; indeed, there are several signals where the bandwidth efficiency decreases while the PAPR increases. This is particularly true for the 3G signal used in the universal mobile telephone service (UMTS), where the spread spectrum chip code needed for code division multiple access (CDMA) operation expands the signal bandwidth with no change in the information data rate. It is widely assumed that in order to achieve high values of bandwidth efficiency, the signal necessarily must have a high PAPR value. This correlation is actually very weak, as the data in Figure 1-3 show.

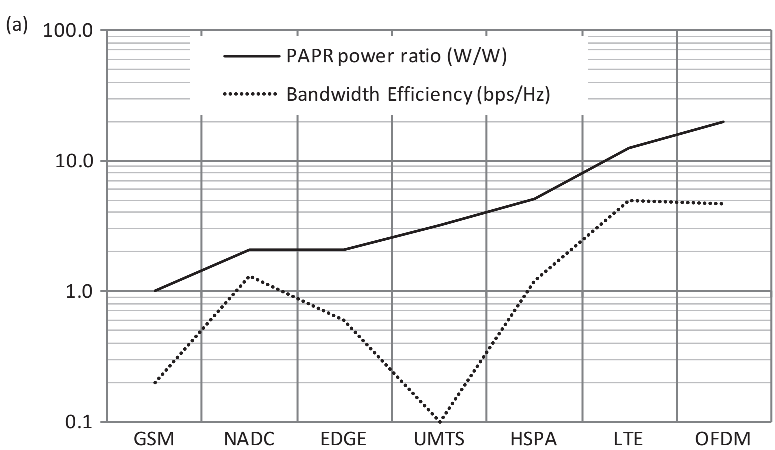

Figure 1-3 PAPR (solid line) and bandwidth efficiency (dotted line) for a progression of uplink signal modulation types in wide use: (a) logarithmic scale; (b) linear scale.

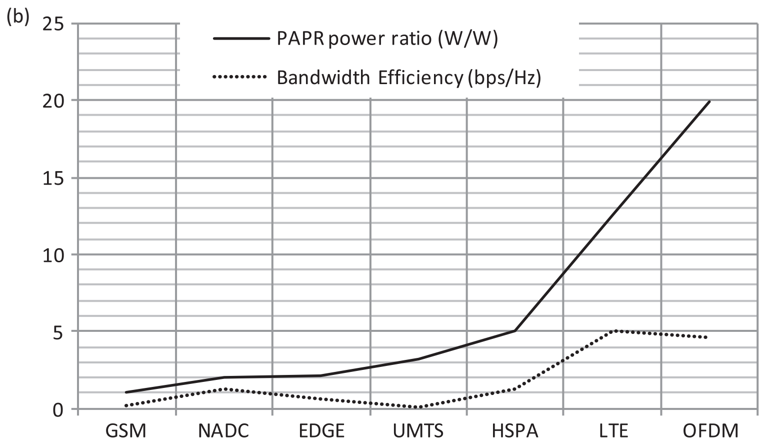

Figure 1-3 (cont.)

1.4 Energy efficiency

Adding a DPS into any transmitter costs money, so compelling economic reasons and performance gains received from doing so must exist to justify spending this money. The compelling motivation follows from the adoption of communication signals that have high peak-to-average power ratios. Any power amplifier is a peak power limited device, meaning that the PA must be capable of generating the signal peak power. For amplifier linearity, the upper limit of voltage clipping must exceed the peak envelope voltage. Therefore, as the PAPR of the signal modulation being used increases, the average power available from the amplifier decreases proportionally.

This situation is illustrated in Figure 1-4. A perfectly linear amplifier would have its transfer function follow the straight dashed line. But any real amplifier has a finite limit to its maximum output voltage, and this amplifier response curve is normalized to this peak voltage value. The voltage clipping boundary is set where the output voltage no longer increases. The amplifier output efficiency available from a good transistor is also shown by the dotted curve. This output efficiency peaks slightly above the amplifier input signal voltage that reaches the voltage clipping boundary, which corresponds to the square wave shape needed for maximum energy efficiency.

Envelope variations from signal modulation define what the signal PAPR is. And these envelope variations also define what the amplifier linearity requirements must be. Taking four of the signal examples from Figure 1-3 and converting the power values used in the PAPR evaluation to envelope voltage ratios allows the energy efficiency impact of the signal envelope variation to be evaluated in Figure 1-4. The GMSK (Gaussian minimum-shift keying) modulation used for GSM has no envelope variation, and so it can be operated at the amplifier peak efficiency point − here at 61%. The basic UMTS modulation is a special form of quadrature amplitude modulation (QAM), with a PAPR of 3.5 dB. Setting the envelope peak at the amplifier voltage clipping boundary, the signal average moves down to where the amplifier output

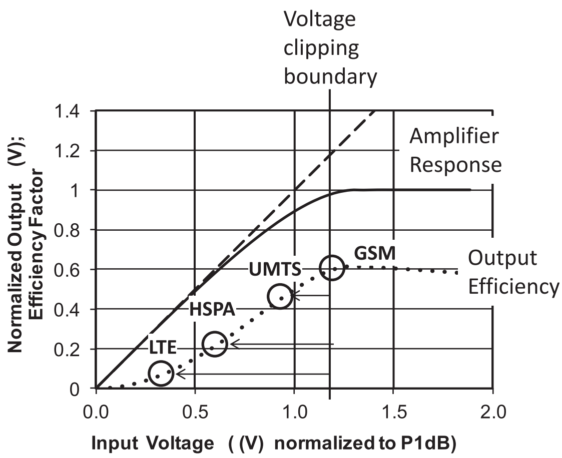

Figure 1-4 Energy efficiency impact on a linear amplifier from signal PAPR for four common signals: higher PAPR necessarily results in lower energy efficiency.

efficiency is still above 40%. The more complicated QAM modulation used for high-speed packet access (HSPA) has a much larger PAPR, and this pushes the amplifier operation down to a maximum operating efficiency just above 20%. Finally, the orthogonal frequency division modulation (OFDM) signal that long-term evolution (LTE) is based on has a PAPR large enough to force the operating efficiency of this PA below 10%. It is important to make clear that these efficiencies are the maximum available efficiencies for these signals. At reduced output powers, the PA efficiency drops further along the efficiency curve from these maximum values.

At 10% efficiency, for every ten electrons drawn from the battery only one is useful for making the desired output signal, and the remaining nine stay behind and generate heat through amplifier power dissipation. This is dreadful performance, which forces transmitter designers to find different architectures from this single linear power amplifier that can still provide an accurate output signal, but also provide efficiency closer to 40%.

History holds that products are acceptable when PA efficiency is at or above 40%. For the amplifier shown in Figure 1-4, this efficiency corresponds to a signal PAPR of 6 dB, which is a power ratio of 4:1 and equivalently a voltage ratio of 2:1. The efficiency drop from a conventional linear amplifier when the signal PAPR is less than 6 dB is historically tolerable, and considered to not justify any change to the simple architecture used for simpler signal modulations. As the signal PAPR increases above 6 dB, or 4 W/W, the efficiency drop is less tolerable and does begin to justify the effort to change the transmitter architecture and to accept the resulting production cost and complexity increases. Dynamic power supply transmitters (DPSTs) are one viable option to meet this new requirement.

When the primary energy source is a battery, or particularly some type of energy harvesting mechanism, the electrons from the electron source are best considered as finite. The wireless communication feature exists to communicate, and it is viable to

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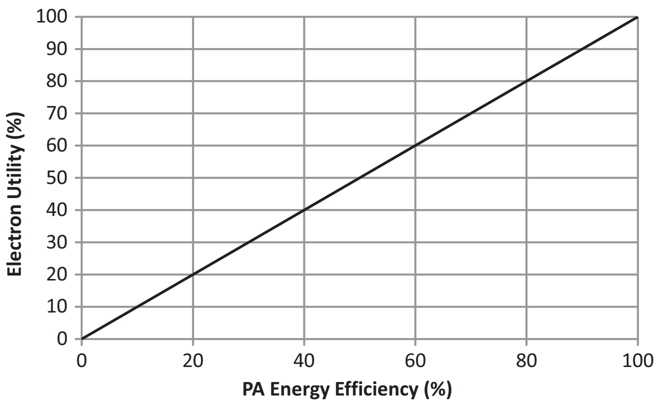

Figure 1-5 Electron utility ratio of a transmitter depends on the PA operating energy efficiency: when the energy source is finite (like a battery), signals and circuits that enable higher electron utility are more viable and valuable.

consider the radio with regard to its effectiveness at using these electrons for the needed communication. Implementation architectures and circuits must consider this electron utility factor – the ratio of electrons drawn from the primary energy source to those that actually result in the needed communication signal – to select the most effective option.

Looking only at the transmitter PA, the electron utility factor is exactly equal to the amplifier efficiency factor, as shown in Figure 1-5. This is obvious, but still useful to describe in this electron utility format because it is electron utility that governs the real design target: battery life.

1.5 Efficiency improvement vs. signal PAPR

From Figure 1-4 it is apparent that output efficiency of an amplifier can improve when used with an envelope-varying signal only when the input drive level is increased, forcing the amplifier into clipping on the signal peaks and therefore no longer supporting the entire range of the envelope variation required of the modulation. By definition, this is a nonlinear operation of the PA. This is another way to view the well-known trade-off between linearity and efficiency in any linear amplifier. Again, we only get to choose one. Fortunately the relationships in Figure 1-4 also illustrate that there is another degree of freedom in the communication system design to improve its efficiency, and that is the selection of signal modulations with lower PAPR values which provide the needed communication properties.

The effectiveness of DPS architectures in providing the needed output efficiencies differ among the available DPS architectures. The simplest DPS architecture is called average power tracking (APT), which actually is a misnomer because what really is happening is peak power tracking. In this DPS architecture, the voltage applied to the PA is set to be slightly above the peak signal envelope voltage as the output power is varied

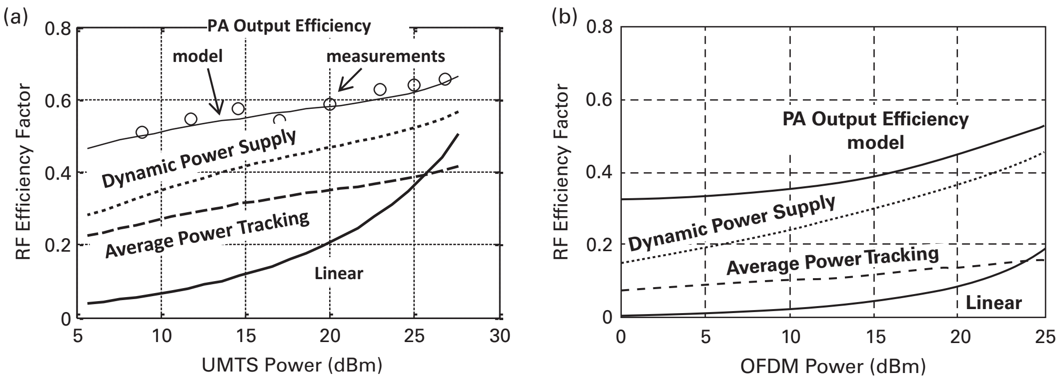

Figure 1-6 PA energy efficiency gains from DPS operation options: (a) UMTS; (b) OFDM.

in an attempt to always operate the PA at its maximum available output efficiency for the signal being used, as shown in Figure 1-4.

At the other extreme of DPS architectures is one that operates the power amplifier in accordance with Figure 1-2(c), but with the voltage drop inside the amplifier set to zero. This provides the highest possible overall energy efficiency the transmitter can have, though at some costs that the application may not want to accept. Setting those costs aside for the moment, the top-level relationships between overall transmitter energy efficiency, PA energy efficiency, and signal PAPR are illustrated in Figure 1-6.

The first step in efficient transmitter design is to make the PA itself maximally efficient. This is done by eliminating all amplifier circuit linearity, with the techniques presented in Chapters 6 and 8. In Figure 1-6, these maximum efficiency results are shown as the top line labeled "PA output efficiency model." Two signal modulation cases are shown in Figure 1-6, a UMTS signal with 3.5 dB PAPR in Figure 1-6(a), and an orthogonal frequency division modulation (OFDM) signal with 10 dB PAPR in Figure 1-6(b). The UMTS design chart also includes direct measurements of the maximum available PA output efficiency at various UMTS output power levels, which validate the model.

It now becomes a task of the adopted architecture to make this efficiency "visible" to the local energy source. The bottom solid line is a measure of the corresponding efficiency of this amplifier when operated as a conventional fixed-supply class A linear amplifier such as that in Figure 1-4. The overall efficiency is low, a well-known problem for linear class A amplifiers. The peak efficiency in this curve corresponds to the open circles in Figure 1-4, as well as the efficiency curve in that figure. The dashed line shows the overall efficiency seen with the average power tracking (APT) technique, which only reduces the power supply voltage to the amplifier to the limit of the highest signal peak as shown in Figure 1-2(b). At the highest output power, APT is actually less efficient than just the linear amplifier itself. This is because the DPS implementing the APT reduced supply voltage has some power dissipation of its own, which is not present when the DPS is not there. The major APT benefit is seen at the lower output power levels where the overall efficiency drops much more slowly, which now corresponds more closely with the efficiency curve available from the PA.