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Quenching the thirst of RF power amps and extending the life of portable devices

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Battery life or rather runtime is crucial in portable wireless systems such as cell phones, PDAs, laptop computers, and so on because it ultimately defines the device’s mobility. With decreasing form factors and increasing functional densities, energy, which is another way of saying battery life, is in short supply, decreasing the practical nature of these mobile electronic solutions. Within a wireless system, the radio frequency (RF) power amplifier (PA), in fact, consumes most of the energy because it must drive the antenna with sufficient power to transmit signals across space to remote receivers. As a result, the battery life of a wireless system is strongly dependent on its PA and the efficiency of the PA should therefore be as high as possible, but not at the cost of linearity.

To achieve both high efficiency and linearity in RF PAs, two approaches can be undertaken: (1) linearize an efficient, non-linear (switching) PA with feedback control and (2) increase the efficiency of an inherently linear PA. In the former, the bandwidth of the control loop must be significantly higher than the linearizing signal, be it the envelope or the complete RF signal, to process the information fast enough to truly follow the signal. Understanding that technology is already being pushed to its limits and high frequency operation necessarily implies higher switching losses, linearizing a PA inevitably decreases the maximum bandwidth of the PA to well within the limits and not at the limit of a given process technology, which is especially detrimental in high bandwidth, highly linear applications like 802.11 a/b/g applications (see Table 1). Consequently, increasing the efficiency of linear PAs may be a more tenable approach for improving battery life without significantly degrading linearity.

Several wireless technologies have been developed and widely used nowadays, such as global system for mobile (GSM) communication, CDMA IS-95, WCDMA, IEEE 802.11a/b/g, etc. The demand for local wireless applications has grown and 802.11 a/g signals have therefore gained popularity. Unfortunately, higher spectral density and consequently higher linearity are the side-effects of this trend, as seen by the high bandwidth, high peak-to-average power ratios (PAPR), and high propensity for above-average power levels required by 802.11 a/g signals (Table 1). The average efficiency of conventional and state-of-the-art PAs in this environment degrades, as a result, because not only are linearity requirements increased but also signal and envelop bandwidths, all of which incur efficiency trade-off losses.

Table 1. Key RF signal parameters for various state-of-the-art wireless technologies

Wireless Technology	**Typical Carrier Frequency [GHz]**	**Application**	**PAPR [dB]**	**Above-Average Power Levels [dB] with roughly 1% Probability of Occurrence**	**Envelope Bandwidth [MHz]**

802.11a	5	Wireless LAN	8.2	6.6	20
802.11g	2.4	Wireless LAN	8.2	6.6	20
802.11b	2.4	Wireless LAN	1.8	1.3	20
CDMA IS-95	1.95	Mobile phone	5.1	3.7	1.23
WCDMA	1.95	Mobile phone	3.2	2.4	3.84
GSM	0.9/1.8/1.9	Mobile phone	0	0	0

The efficiency of a conventional, fixed-supplied linear PA is highest at the maximum output power and drops quickly as the output power decreases [1-2]. The difference of the supply voltage and the RF signal's peak voltage is a measure of power not delivered to the load (power losses). Unfortunately, the supply voltage must be high enough to supply the worst-case output power, in other words, the highest peak voltage of the RF signal, and when the output power is below that level, power is lost. Consequently, dynamically adjusting the supply voltage as a function of RF power (e.g., envelop of transmitted signal) is an attractive means of increasing PA drain power efficiency.

Before blindly working on designing adjustable supplies, the power probability distribution of the RF signal must be considered because it defines how battery life can best be improved. Figure 1 shows an example of the power output probability distributions for 802.11g signals [1], illustrating the tendency for portable systems to mostly operate in light-to-moderate power-level conditions, not high power modes. The maximum output power may be 25 dBm but the most probable value is approximately 16 dBm, which is where the PA's efficiency is significantly lower, and this is similar for 802.11 a/g, CDMA IS-95, and WCDMA signals [1, 3-4]. Consequently, the efficiency of PAs in light-to-moderate loading conditions is critical for operation life.

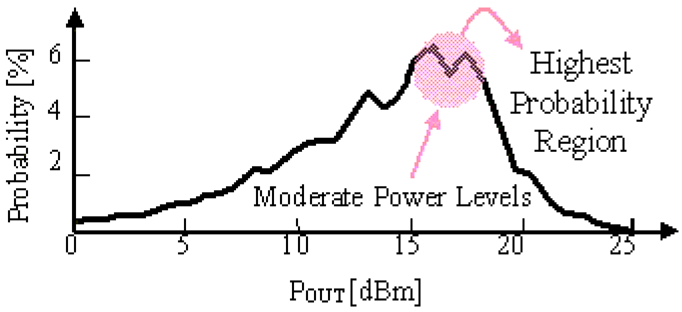

Figure 1. Power output probability distribution for 802.11 g signals [1]

State-of-The-Art in Efficient Linear PAs

There have been several techniques proposed to improve the average efficiency of linear PAs, and most notable are the dual PA (Doherty), envelope following, and power tracking schemes [5-6]. As justified earlier, linearizing switching PAs with negative feedback is discounted in this foregoing discussion because of its inherent bandwidth (speed) limitations. Feedforward schemes are also discounted because the forward-bypass signals must synchronize with the main transmitting RF or phase signal and the delays must therefore match to maintain linearity, which present practical difficulties in high performance applications and is why the envelope elimination and restoration (EER) method [7] is not further discussed in this article.

Dual PA Power-Sharing Approach (Doherty Technique)

In the dual PA scheme, one amplifier sources the low-to-moderate load power levels while the other sources the above-average power range (Figure 2). Only one PA is therefore active and optimally designed (i.e., near its gain-compression point [8]) for the critical light-to-moderate load region, where efficiency is normally lost. At higher power levels, both PAs can continue to operate in their gain-compression regions, thereby maintaining peak power efficiency. Unfortunately, the power divider and combiner required are lossy, especially when integrated on-chip [9], and designing two PAs may not be entirely attractive, in terms of cost.

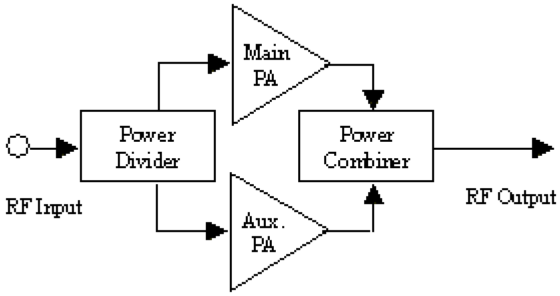

Figure 2. Dual PA power-sharing approach

Envelope Following Supply

Avoiding the dual PA paradigm implies adding intelligence to the supply voltage, and in the case of the envelope follower, forcing the supply to follow the envelope of the transmitted RF signal, as shown in Figure 3. The envelope-following supply is therefore kept slightly above the actual peak of the signal to allow the PA to fully process the RF signal, envelop and phase, which is how linearity is maintained. Since the difference in supply and signal peak voltage is kept low, minimal power losses are incurred by the PA.

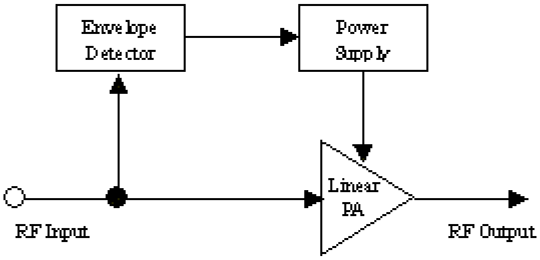

Figure 3. Envelope-following supply scheme

To add the intelligence to the supply is to design a dynamically adaptive supply circuit, which unfortunately also incurs power losses, but hopefully less than the PA drain losses just saved by the envelope-following scheme. Switching power supplies are therefore viable solutions, given their propensity for high efficiency. Their efficiency performance, however, is ultimately limited by their switching frequencies (higher frequencies incur more power losses), which is why RF signals with low envelope bandwidths like CDMA and WCDMA signals benefit the most from this scheme, unlike the higher spectral-density signals like the 802.11 a/b/g signals.

Power Tracking Supply

As envelope bandwidths increase, another dynamic scheme must therefore be implemented, which is how average power tracking finds its niche (Figure 4). The bandwidth required to track the average power of high bandwidth envelopes is significantly lower, given the nature of the averaging function, which is attractive for switching power supply circuits, within the context of power efficiency, of course. Since the supply is now at an average level, the PA incurs the power losses the envelop-following scheme saves for low output power levels, but significant savings are still achieved over the conventional fixed supply scheme.

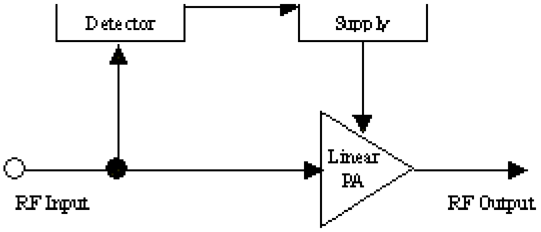

Figure 4. Power tracking supply

In tracking the average power, high peak-to-average power ratio (PAPR) signals are clipped and therefore distorted (i.e., linearity is compromised), which is why this method is most attractive for low PAPR and infrequent above-average power level applications, like CDMA, WCDMA, and 802.11 b, not 802.11 a/g applications. The few and low power signals that clip ultimately translate to acceptable bit-error rates, and in the case of 802.1 a/g signals, bit-error rates would increase significantly.

Table 2 shows a qualitative comparison of the techniques just discussed. Because there are numerous system tradeoffs, no single solution is best suited for all applications. Therefore, assuming the number one concern is a practical portable solution, we picked chip integration, efficiency, linearity of spectrally dense signals, and complexity as the most important parameters to consider and assigned them weighing factors of three, three, two, and one, respectively. We then qualitatively rated the schemes from one for the poorest performance to four, the best rating.

Table 2. Qualitative evaluation of PA efficiency enhancement schemes.

Priority Weight	**Performance Parameter**		**Dual PAs**	**Follow Envelope**	**Track Power**
3	Integration Capability (Rating)		Low(1)	High(3)	Very High(4)
3	Efficiency (Rating)	Main PA	High	Moderate	Low
		Supply or 2nd PA	High	Moderate	High
		Total	High(4)	Moderate(2)	Moderate(2)
2	Output signal quality (Rating)		High(4)	Moderate(3)	Low(2)
1	System Complexity (Rating)		Very High(1)	Moderate(3)	Low(4)
	Scores (Cumulative Rating = ΣRating x Weight)		21	24	26

(x) is the rating, where a high rating (e.g., x = 4) implies better performance

Following the envelope is not the most attractive solution because of its bandwidth requirements and therefore supply efficiency limitations. Tracking average power, on the other hand, seems to be the best solution, scoring high on integration and complexity. In the case of highly probable, high PAR, spectrally-dense signals like 802.11 a/g, the dual PA approach may be the only viable option, in spite of its relative complexity and integration limits. It is noted, at this point, that completely adjusting the biasing conditions of any dynamically adaptive supply scheme (i.e., also adjusting bias current) improves efficiency, be it an envelope or power tracking scheme.

Considering the growing demand for 802.11 a/g signals and the less-than-ideally suited techniques discussed, we are focusing on increasing the ability of the power-tracking scheme to capture PAR events and therefore improve linearity and bit-error rate performance. In short, we are seeking to reduce the slow-moving PA supply voltage to increase PA efficiency and maintain high supply efficiency by adding a nonlinear but continuous circuit to track frequent PAR events – all this while keeping complexity and integration in check. The ultimate gauges, of course, will be the PA linearity performance of spectrally dense signals and battery life.

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