Multifunctional RF Transmitters for Next Generation Wireless Transceivers

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Abstract:

Future generations of wireless communications are expected to place increasing burdens on the efficiency and linearity of power amplifiers, due to the use of more complex waveforms and OFDM. This has implications for the design of transmitters in portable/mobile devices as well as base stations and access points. This paper will summarize the digital techniques that can be employed to improve the performance of wireless power amplifiers.

1. Introduction

Third generation wireless services are gradually being deployed on a worldwide basis, along with even wider bandwidth standards like WiMax and 802.11a/g. These new services - and the 4G systems that will follow - require wider RF bandwidths and even more exotic modulation schemes. In addition, with 3G systems co-existing with 2G systems for many years to come, multi-mode/multi-band mobile terminals will be required. This evolution of wireless technology places an even greater burden on power amplifier technology. In particular, the evolution towards OFDM as a ubiquitous modulation standard places extreme burdens on the power amplifier.

The typical power amplifier in a mobile terminal utilizes a mix of technologies and design disciplines, unlike the relentlessly CMOS-focused digital baseband and RF transceiver functions. As a result, the power amplifier area is still fertile ground for innovation at the technology, circuit and system level.

Due to form factor considerations, cell phone power consumption is limited to roughly 3W, and the ubiquitous PCMCIA card has similar power restrictions. These limits are not expected to ease dramatically in the foreseeable future and since a cell phone transmits roughly 30 dBm, *any* inefficiency in the power amplifier is one of the major limitations on talk time. Although microwave power amplifiers can be designed with efficiencies approaching 100%, typical power amplifiers operate at efficiencies significantly below this due to the complicated signal characteristics.

As shown in Table I, there are several ways to characterize the signal being transmitted by the power amplifier. The Peak-to-Average Ratio (PAR) compares the peak modulated output power to its short-term average; as the industry move to more spectrally efficient modulation formats this ratio is growing, creating additional challenges. Power amplifier efficiencies typically peak at the maximum saturated output power, but decline precipitously as the power is reduced.

A high Peak-to-Minimum Ratio (PMR) waveform presents a challenge for efficiency, but it can also make certain linearization techniques difficult to implement. In these cases, the output power reaches near zero for a brief period. The Power Control Dynamic Range (PCDR) is a measure of the maximum variation in the *average* output power over long period of time. This variation is especially large in CDMA-based systems. A high PCDR presents problems for maximizing power amplifier efficiency, since the long term *average* output power is typically well below that where the *peak* efficiency occurs. In most CDMA mobile systems, the average output power is log-normally distributed, with a mean of roughly 0 dBm and a peak of approximately 30 dBm.

Table I: Comparison of the modulation characteristics and bandwidths of typical mobile wireless transmitters.

System	PAR (dB)	PMR (dB)	PCDR (dB)	Bandwidth (MHz)	Access Type
GSM	0	0	30	0.2	TDMA
GPRS	0	0	30	0.2	TDMA
EDGE	3.2	17	30	0.2	TDMA
CDMA ONE	5.5-12	•	73	1.25	CDMA
UMTS	3.5-7	•	80	5	CDMA
CDMA 2000	4-9	•	80	1.25	CDMA
802.11 a/g	**8-10**	•	**25**	**20**	TDMA
WiMax	8-10	•	50	20	OFDMA

2. Polar Modulation for Multi-Mode Transceivers

The use of "polar modulation" approaches for handset power amplifiers has become more popular recently, thanks to its compatibility with GSM/GPRS/EDGE standards and its promise for improved efficiency. Polar techniques modulate the baseband data in the magnitude/angle domain rather than the in-phase/quadrature domain. The former approach is better suited to upgrades of phase modulated systems like EDGE. There are also some potential efficiency improvements if the power amplifier can be magnitude modulated directly.

Polar modulation can operate in either open-loop (Fig. 1(a)) or closed-loop mode (so-called *polar loop* modulation (Fig. 1(b))). Open-loop operation suffers from the inevitable errors associated with open loop operation of any analog system, and polar-loop techniques exhibit limited bandwidth. These dilemmas can be partially addressed through digital compensation approaches.

For example, the M/A Com DtX Transmitter architecture uses digital predistortion to compensate for the nonlinear AM-AM response of the digitally controlled switching-mode power amplifier in the AM path, and a digital pre-emphasis filter to compensate for the frequency response of the frequency synthesizer in the phase modulator [1].

Polar modulation schemes can also be used for efficiency enhancement if the amplitude modulator is an efficient switching amplifier. This is known as Envelope Elimination and Restoration (EER) (if the amplifier is operated in the nonlinear switching mode) or Envelope Tracking (ET) if the amplifier is operated in the linear mode with both amplitude and phase inputs, as shown in Fig. 1(c).

In all these amplifiers, the alignment between the magnitude and phase paths is critical to achieving the lowest possible EVM. An adaptive real-time time-alignment technique is needed because of inevitable environmental variations. For example, a time alignment of better than two nanoseconds is required to make the EVM lower than 3% for an OFDM 802.11a/g signal [2]. In this case, the signal bandwidth is approximately 20 MHz, and with a data converter sample rate of approximately 100MHz, linear interpolation is required to achieve the necessary sub-sample delay accuracy.

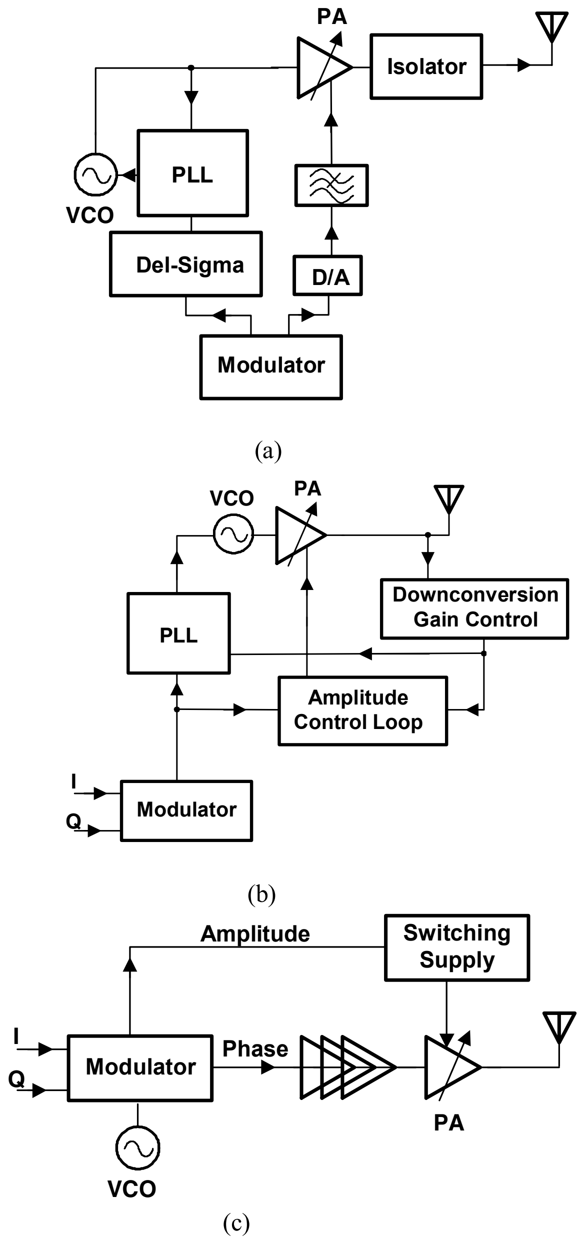

Fig. 1 (a) Polar modulation, (b) polar loop modulation, (c) envelope elimination and restoration (EER) or envelope tracking (ET) when the output of the modulator contain both amplitude and phase information, and the PA is operated in the linear mode.

3. Digital Predistortion for Linearity Enhancement

The field of adaptive digital predistortion has a long history [3], and has found increasing acceptance in the base station field, replacing analog feed-forward techniques in recent years. With the increasing sophistication of DSP techniques, as well as lower power high-speed DACs, adaptive digital pre-distortion has recently become possible for mobile terminals as well [4]. As shown in Fig. 2, the digital baseband signal is scaled by the inverse of the PA nonlinearity; and when fed to the nonlinear PA, the output is "ideally" perfectly linear.

There are several limitations to adaptive digital predistortion: significant bandwidth expansion, a relatively high digital processing overhead, and a susceptibility to memory effects (long time constant variations in the PA gain and phase responses that are difficult to incorporate into the predistorter transfer function). In addition, the predistortion coefficients require constant updating, due to aging, temperature and power supply variation effects over long periods of time.

In an era of 90nm and below CMOS, the first two limitations are becoming less significant, and there have been a number of recent attempts to compensate for memory effects. Adaptive digital predistortion works best for standards requiring a high PAR (from Table I) and moderate-low PCDR, such as base stations, wireless LAN cards, and EDGE. It also works best in conjunction with efficiency enhancements schemes such as the Doherty amplifier [5] or Envelope Tracking/EER [6], since it does little to enhance the overall efficiency of the basic amplifier, but it can have an enormous effect on linearity.

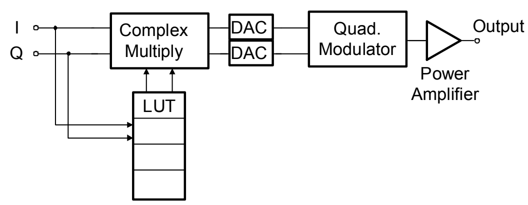

Fig. 2: Simplified schematic of digital predistortion employing table look-up.

Typically, the baseband AM-AM and AM-PM behavior of the PA can be modeled by a complex polynomial of the form

$$y_n = x_n \sum_{k=1}^{m} a_k \left| x_n \right|^{k-1} \qquad (1)$$

where y is the instantaneous complex baseband output, x is the instantaneous complex baseband input to the power amplifier, and the a coefficients are the complex gain of the amplifier. Once these coefficients are known, the nonlinearity can be inverted in the digital baseband through a complex series reversion and the nonlinearity eliminated.

One limitation of digital predistortion is the bandwidth expansion that results from the predistortion. This puts greater burden on the sampling rate of the DAC, as well as the bandwidth of the subsequent RF stages. The magnitude of the bandwidth expansion depends on the desired linearity improvement; if IM3 is the main source of the undesirable distortion, then a bandwidth expansion by a factor of three is required.

Long time constant memory effects can have a significant impact on the improvement achievable with adaptive digital predistortion. Memory effects (due to thermal effects, surface traps, or dc bias effects) introduce a time dependence into the a coefficients.

The memory effects can be modelled with a revision to (1) of the form

$$y_n = \sum_{m=0}^{M} x_{n-m} \sum_{k=1}^{K} a_{k,m} \left| x_{n-m} \right|^{k-1} \qquad (2)$$

where the memory effects of the amplifier are included in the model back to time MT, where T is the sample rate of the system.

Again, once the $a_{k,m}$ are known, the function can be inverted in the digital domain and the desired linear response obtained. In this case, it is difficult to find an analytical solution for the inverse polynomial function once the coefficients are known, and iterative procedures are required [7]. We expect digital predistortion techniques to have a significant impact on mobile power amplifiers in the coming years.

4. Digital Modulation of Switching-Mode Power Amplifiers

Switching-Mode power amplifiers, like Class-E or Class-S, can approach 100% power-added efficiency under certain conditions. But due to their essentially binary mode of operation – they are either "on" or "off" - it is not possible to impress amplitude information onto the resulting signal.

As shown in Fig. 3(a), digital modulation of switching-mode amplifiers attempt to modulate the envelope through noise-shaping techniques, most typically with a delta-sigma modulator [8]. One of the advantages of this architecture is that it has a one-bit output stream, so that the DAC requirements are alleviated. In addition, the RF filtering can be done before the power amplifier, so that a conventional PA can be used if desired. This approach represents a great opportunity for a radical improvement in power amplifier efficiency, and is analogous to pulse-width modulated audio amplifiers; but there are a number of practical challenges.

For RF signals centered at several GHz, the over-sampling of the carrier will require enormous digital clock rates, and resulting high power dissipation. In [9] (Fig. 3(b)), a bandpass delta-sigma modulator was employed, reducing the switching frequency requirements by roughly a factor of four, but this is still quite high.

Another approach, which will require considerably less dc power, shown in Fig. 3(c), is to quantize the I/Q envelope data to three levels at baseband using a low-frequency delta-sigma modulator, and then upconvert the resulting signal using standard RF vector modulation [10]. The combined signal maintains its constant amplitude – which is required for switching-mode operation -

by simply applying a "1010" mask to the *I* channel and a "0101" mask to the *Q* channel prior to combining.

All of these digital modulation of switching-mode amplifier approaches suffer from two fundamental problems. The first is that the high level of quantization noise extends into other frequency bands, even as it is suppressed in the desired band. In low-frequency data converter and frequency synthesizer applications, this noise is filtered out of the band of interest in a straightforward manner. But the stringent out-of-band and receive band spurious emission requirements of most cellular systems, combined with the poor isolation inevitable at high frequencies, make this filtering almost impossible to achieve at RF.

Second, although the power efficiency of the switching-mode amplifier itself might be very high, the dc power consumption of the delta-sigma modulator and driver stages represents a significant overhead. As Professor Tom Lee succinctly put it: "the switch (and its-drive circuitry) has to be *n* times faster than in a non-PWM amplifier, where *n* is the desired dynamic range" [11]. For high dynamic range signals, the switching speed requirements are prohibitive for the near-term future.

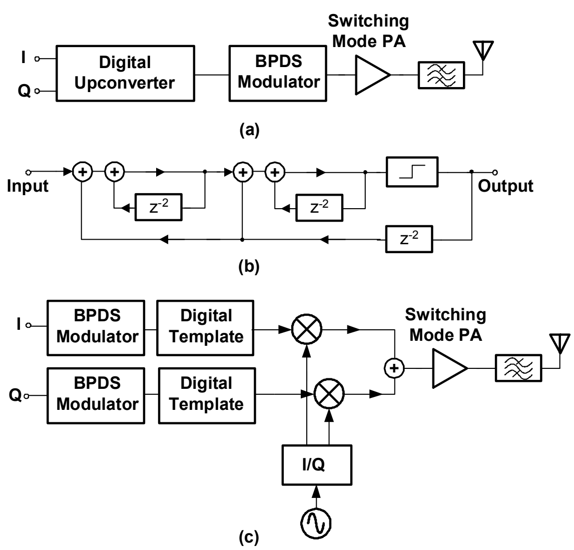

Fig. 3: (a) Switching-mode RF power amplifiers modulated with bandpass delta sigma modulators. (b) Implementation of bandpass delta-sigma modulator [9], (c) lower-speed baseband delta-sigma modulation of switching-mode amplifiers [10].

5. Conclusions

The use of digital techniques to correct the imperfections and limitations of RF power amplifiers represents the "next stage" of development for high-frequency wireless devices, especially since transistor technology is nearly "maxed-out" in performance. In the near term, digital pre-distortion will move from the realm of the base station and into the handset environment. In the longer term, completely digital approaches for modulation will dominate for the highest possible efficiency.

6. Acknowledgements

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