Asymmetric Multilevel Outphasing Architecture for Multi-standard Transmitters

SungWon Chung, Philip A. Godoy, Taylor W. Barton, Everest W. Huang[†], David J. Perreault, and Joel L. Dawson

Microsystems Technology Laboratories, Massachusetts Institute of Technology, Cambridge, MA 02139

[†] Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02420

Abstract— We describe a new outphasing transmitter architecture in which the supply voltage for each PA can switch among multiple levels. It is based on a new asymmetric multilevel outphasing (AMO) modulation technique which increases overall efficiency over a much wider output power range than the standard LINC system while maintaining high linearity. For demonstration, the overall transmitter is simulated in a 65nm CMOS process with HSUPA and WLAN signals. The simulation results show an efficiency improvement from 17.7% to 40.7% for HSUPA at 25.3dBm output power and from 11.3% to 35.5% for WLAN 802.11g at 22.8dBm while still meeting system linearity requirements.

Index Terms— outphasing, LINC, wideband phase modulator, digital predistortion.

I. INTRODUCTION

The primary challenge in RF transmitter design is centered around a design tradeoff between the linearity of the power amplifier (PA) and its efficiency. This tradeoff relates directly to the usefulness of the resulting device: high linearity results in a higher possible data rate and therefore compatibility with complex standards such as WLAN/WiMAX, and high efficiency allows for either longer use or smaller battery size (e.g., in cell phone applications). The general perception that the tradeoff between linearity and efficiency is fundamental tends to produce designs that compromise between the two ideals. The resulting systems may be either linear or efficient, or are designed specifically for a single communications standard and therefore have limited flexibility of use. Meanwhile, consumer demand for both greater transmission rates and smaller devices continues to drive the need for an architecture that is capable of both linearity and efficiency.

We propose the Asymmetric Multilevel Outphasing (AMO) transmitter architecture, described in this paper, as a solution to this linearity-efficiency tradeoff problem. This architecture, shown in Fig. 1, results in significant efficiency improvement over previous methods. Our approach is based on several innovations, including using asymmetric power supplies in a LINC (linear amplification using nonlinear components)-like configuration and an all-digital AMO modulator. Using these techniques, we
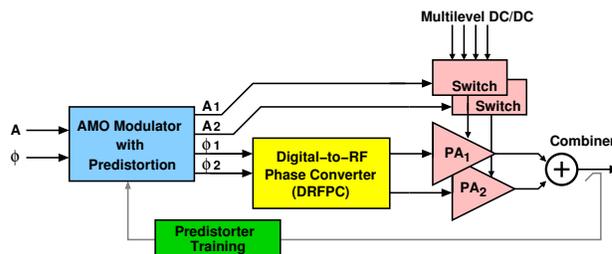
Fig. 1. Asymmetric multilevel outphasing (AMO) architecture.

expect significant improvement over conventional techniques, with a resulting system that is compatible with a wide range of communications standards.

In this paper we first present a summary of conventional approaches to power transmission in Section II. In Section III we introduce the AMO modulation technique, and in Section IV we describe the AMO transmitter architecture. Promising system-level simulation results are presented and discussed in Section V, with conclusions following in Section VI.

II. CONVENTIONAL APPROACHES

Communication standards that support high data rates such as WLAN/WiMAX employ variable-envelope modulation, and so linear amplification is required. One approach is to use an inefficient but highly linear PA. However, there are two main types of transmitter architectures that enable the use of more efficient but nonlinear switching-mode PAs: (1) polar, and (2) outphasing, or LINC.

The fundamental idea of polar architectures, shown in Fig. 2(a), is to divide the signal to be amplified into amplitude and phase components. The phase component is used as the input to a nonlinear, high-efficiency switching PA, while the amplitude component drives the power supply of the PA to create a varying-envelope signal. While this improves the PA efficiency, it also requires the use of an efficient power converter. Because power converter efficiency degrades dramatically as bandwidth increases, it is very difficult to achieve high efficiency for high data-rate communication standards. This is exacerbated by the 5-10x bandwidth expansion that occurs during the conversion from Cartesian to polar coordinates [1]. Thus this method is only practical for low-bandwidth systems.

Outphasing [2], and specifically the LINC architecture, introduced by Cox in [3], is shown in Fig. 2(b). It is based
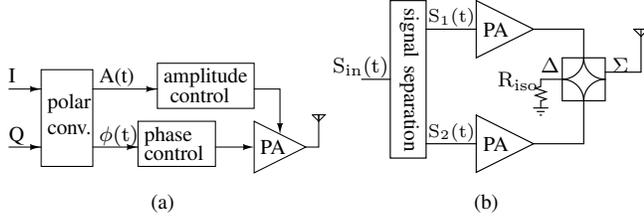
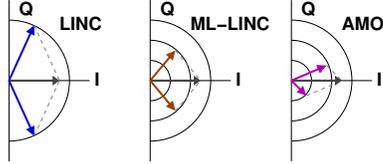Fig. 2. Conventional multi-standard transmitters: (a) Polar (b) LINC.

Fig. 3. Signal component vector diagram for LINC, ML-LINC, and AMO. The smallest outphasing angle is achieved with AMO.

on the idea that an arbitrary input signal can be divided into two constant-amplitude, phase-modulated signals that can each be non-linearly amplified and then passively recombined as a vector sum to produce an output signal that is a linearly amplified version of the input. The LINC strategy eliminates the high-bandwidth power converter of the basic polar architecture, using outphasing to realize amplitude variation. However, the efficiency of the power combining is high only over a small range of output powers. To avoid signal distortion and preserve switching amplifier efficiency, an isolating combiner such as a Wilkinson combiner must be used. Isolating combiners achieve 100% efficiency only at maximum output power. When the inputs are outphased to vary the amplitude, power is wasted as heat in the isolation resistor [4]. The overall efficiency is therefore inversely proportional to the peak-to-average power ratio (PAPR), limiting the benefits of this technique in high data-rate communication standards such as WiMAX, in which the PAPR is high.

III. PROPOSED APPROACH

A. AMO Modulation

Fundamentally, AMO modulation decomposes a complex vector, which represents a baseband constellation point, into two vectors such that the sum of the two vectors constructs the original complex vector with the *minimum* outphasing angle, as illustrated in Fig. 3. The two vectors are the baseband representation of the two PA outputs. As compared to the multilevel LINC (ML-LINC) technique [5], by making independent changes in the supply voltage for each of the two PAs, the AMO technique results in smaller outphasing angles so that higher efficiency can be achieved even in relatively high-PAPR standards.

Mathematically, AMO modulation can be defined with a polar representation of a baseband signal,

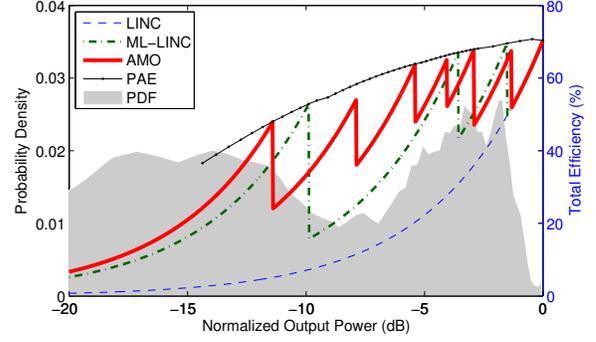$$C(t) = r_i(t) + jr_q(t) = A(t) e^{j\theta(t)}. \quad (1)$$

Fig. 4. Amplitude distribution of HSUPA signal and corresponding efficiency for standard LINC, ML-LINC, and AMO.
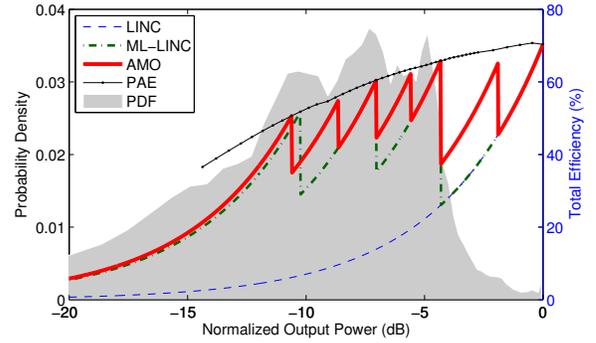

Fig. 5. Amplitude distribution of WLAN signal and corresponding efficiency for standard LINC, ML-LINC, and AMO.

In order to have linear PA output, $C(t)$ is predistorted into

$$P(t) = A_p(t) e^{j\theta_p(t)} \quad (2)$$

by a polar lookup table (LUT). $P(t)$ is decomposed into two parts as

$$P(t) = W\left(V_1(t) e^{j\phi_1(t)}, V_2(t) e^{j\phi_2(t)}\right) \quad (3)$$

where W represents Wilkinson power combining and

$$\phi_1(t) = \theta_p(t) + \cos^{-1} \frac{\left(V_1(t)^2 + 4A_p(t)^2 - V_2(t)^2\right)}{4V_1(t)A_p(t)},$$

$$\phi_2(t) = \theta_p(t) - \cos^{-1} \frac{\left(V_2(t)^2 + 4A_p(t)^2 - V_1(t)^2\right)}{4V_2(t)A_p(t)}.$$

B. Multi-standard Efficiency Optimization

As we use AMO to minimize loss in the Wilkinson combiner, we have to determine the optimal value of each level r_k (these are the maximum output amplitudes for each of the different supply voltage levels when both PAs are driven by the same supply). The Wilkinson combiner efficiency at a given output amplitude A and driven by two PAs with different supply voltages is given by

$$\eta_c(A, r_k, r_j) = \left(\frac{A}{\left(\frac{r_k+r_j}{2}\right)}\right)^2 \left(\frac{2\left(\frac{r_k+r_j}{2}\right)^2}{r_k^2 + r_j^2}\right) \quad (4)$$
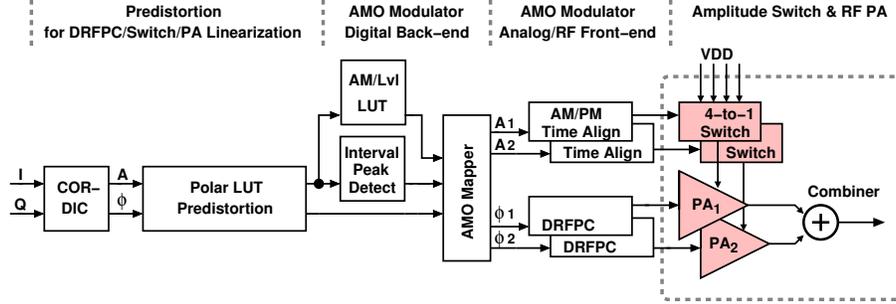
Fig. 6.   AMO transmitter block diagram.

Note that this simplifies to the standard Wilkinson efficiency when $r_k = r_j$. The total average efficiency can be computed if the amplitude PDF $p(A)$ of the signal is known (see Fig. 4 and Fig. 5 for the PDFs of HSUPA and WLAN signals, respectively). This is done by dividing the PDF into several regions separated by the r_k (and their combinations), integrating the PDF curve to find the efficiency in each region, and summing the result. For N different supply voltages, there are $\binom{N}{2}$ combinations of supply voltages for the two PAs. However, the combiner efficiency decreases as the difference between two levels increases. Also, the efficiency improvement is small when the difference between the two levels is large. Therefore, in our system we restrict the combinations to be adjacent supply levels (i.e., r_k and r_{k+1}). With this restriction, the total average efficiency can be computed as

$$\eta_{tot} = \int_0^{r_1} p(A)\,\eta_c(A, r_1, r_1)\,\eta_{PA}(r_1, r_1)\,dA$$

$$+ \sum_{k=1}^{N-1} \Big[\int_{r_k}^{\frac{r_k + r_{k+1}}{2}} p(A)\,\eta_c(A, r_k, r_{k+1})\,\eta_{PA}(r_k, r_{k+1})\,dA$$

$$+ \int_{\frac{r_k + r_{k+1}}{2}}^{r_{k+1}} p(A)\,\eta_c(A, r_{k+1}, r_{k+1})\,\eta_{PA}(r_{k+1}, r_{k+1})\,dA \Big]$$

where $\eta_{PA}(r_k, r_j)$ is the total PA efficiency at the two supply voltages r_k and r_j. Using this equation, the optimum set of supply voltage levels for a given amplitude PDF can be found by exhaustive search.

Fig. 4 shows the amplitude PDF for a HSUPA signal and the corresponding optimum efficiency curves for standard LINC, ML-LINC, and AMO using 4 different supply levels.[1] The figure shows that ML-LINC increases the efficiency over a much wider power range than the standard LINC system, and AMO increases this range even further by effectively doubling the number of levels. Fig. 5 shows the amplitude PDF and optimum efficiency curves for the WLAN signal.

IV. AMO ARCHITECTURE

Fig. 6 shows the AMO architecture, which consists of 1) predistorter for linearizing the combined nonlinearity

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[1] The PA efficiency curve was obtained from simulation, which will be described in Section V.
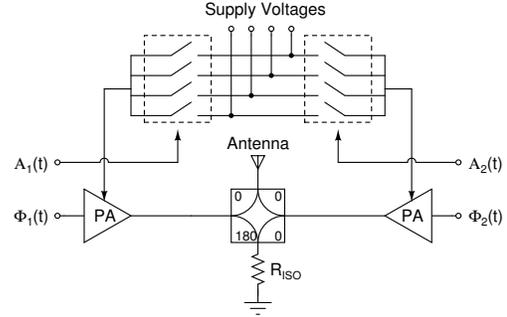

Fig. 7.   Amplitude switching network and PAs.

from DRFPC (digital-to-RF phase converter)/Switch/PA, 2) AMO modulator, and 3) amplitude switch and RF PA.

The AMO modulator first determines the combination of the two PA supply voltages based on a peak amplitude within a time interval. The AMO mapper decomposes the predistorted amplitude and phase into two pairs of amplitude and phase commands. The AMO mapper is implemented with a first order approximation of (3). The time delay mismatch between the amplitude and phase paths is maintained to within less than 1ns by a time aligner between the AMO mapper and the amplitude switch.

The DRFPC, which is based on the direct-digital RF modulator [6], performs phase modulation by embedding the phase component of the AMO mapper output into an RF carrier. The DRFPC consists of an array of current steering switches as in the direct-digital RF modulator. The DRFPC brings a significant transmitter power efficiency boost particularly for low output power levels for two reasons. First, the analog matching requirement in the current steering switches is relaxed because the static phase errors in the DRFPC output, which result from analog mismatch, can be corrected by the predistorter. Second, as compared to traditional IQ modulators, the DRFPC does not need baseband active filters for DAC output shaping.

Fig. 7 shows the schematic of the PA supply modulator, which consists of a fast switching network driven by the AMO modulator. For maximum efficiency, the PAs are switching-mode amplifiers (e.g., class-E, class-F, class-
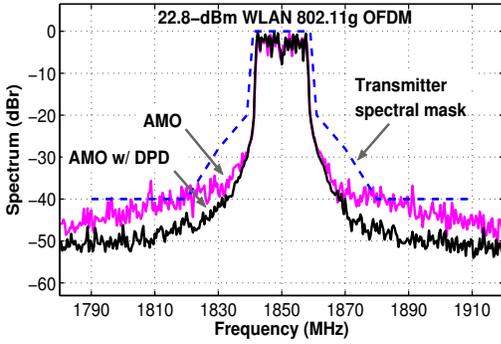
Fig. 8. Simulated spectrum for WLAN 802.11g transmission with 22.8-dBm channel power, 20-MHz channel bandwidth, and 7.0-dB PAPR.
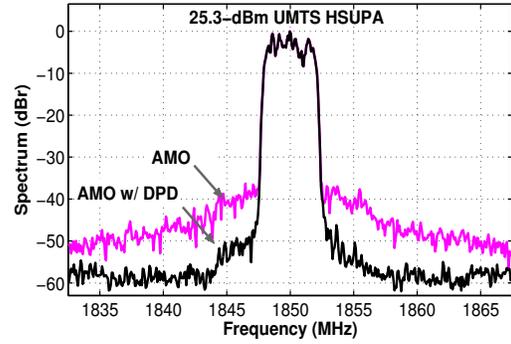

Fig. 10. Simulated spectrum for HSUPA transmission with 25.3-dBm channel power, 5-MHz channel bandwidth, and 5.0-dB PAPR.
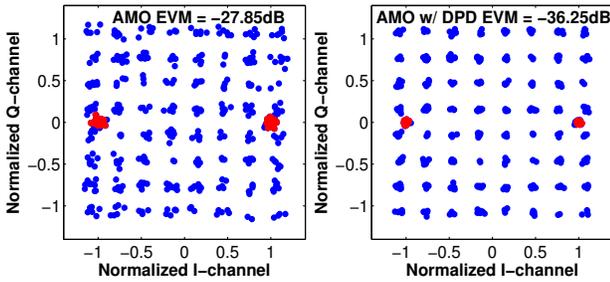

Fig. 9. EVM for the WLAN 802.11g 54Mbps OFDM transmission (BPSK constellations for frame preambles are shown in red).

E/F, etc.).

TABLE I
PERFORMANCE COMPARISON FOR LINC, ML-LINC, AND AMO

Wireless Standard	Architecture	EVM	Linearity Margin	η_{avg}
HSUPA (PAPR 5dB)	LINC	-38.5dB	7.9dB	17.7%
	ML-LINC	-33.6dB	0.1dB	37.7%
	ML-LINC w/ DPD	-42.4dB	7.2dB	37.1%
	AMO	-33.9dB	0.2dB	41.1%
	AMO w/ DPD	-42.3dB	9.0dB	40.7%
WLAN 802.11g (PAPR 7dB)	LINC	-34.7dB	9.0dB	11.3%
	ML-LINC	-26.1dB	-4.7dB	31.9%
	ML-LINC w/ DPD	-35.6dB	4.8dB	30.9%
	AMO	-27.8dB	-2.7dB	37.1%
	AMO w/ DPD	-36.3dB	3.3dB	35.5%

V. SIMULATION RESULTS

To demonstrate the feasibility of the AMO transmitter, the system was simulated using Cadence Spectre and Agilent ADS using 4 different supply voltages. The PAs and switching network were designed in a 65nm CMOS process to model the main sources of power loss. The fully differential PAs were implemented as cascoded class-E amplifiers with inverters for the pre-drivers and adaptive biasing for the cascodes to increase efficiency [7]. Both the PA cascode transistors and the multi-level switching network were implemented with thick oxide devices. All other blocks in the system were implemented using Verilog-A. For WLAN, digital predistortion (DPD) linearizes both the transmit spectrum (Fig. 8) and EVM (Fig. 9) by more than 8 dB. Fig. 10 shows more than 10-dB improvement in the HSUPA transmit spectrum after predistortion is applied. Table I summarizes the EVM, ACLR (adjacent channel leakage ratio) margin for HSUPA, transmit spectral mask margin for WLAN, and average power efficiency of the proposed AMO transmitter in comparison with LINC and ML-LINC. The efficiency considers 1-dB insertion loss from the Wilkinson combiner as well as the power loss from the switch and the PA.

VI. CONCLUSIONS

The AMO transmitter architecture was proposed to not only greatly increase transmitter efficiency but also maintain high linearity by using digital predistortion. The AMO modulation technique was described, along with the optimization procedure for the supply voltages based on the envelope distribution of the modulated signal. Finally, we demonstrate in simulation a four-level AMO transmitter as a design example which improves the overall efficiency from 17.7% to 40.7% for HSUPA and from 11.3% to 35.5% for WLAN 802.11g while still meeting system linearity requirements.

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