A High-Efficiency Linear Polar Transmitter for EDGE

Néstor D. López, Xufeng Jiang, Dragan Maksimović and Zoya Popović

Department of Electrical and Computer Engineering
University of Colorado, Boulder, Colorado 80309, USA

***Abstract*— This paper discusses a linear polar transmitter for EDGE signals with a total DC-to-RF efficiency of 56%. The transmitter is digitally-controlled, allowing for adjustments of delay, phase and amplitude. The amplifier is a 880-MHz class-E high-efficiency circuit with +20 dBm output power and a PAE of 70%. Two different supply modulators are compared: a 18% efficient linear envelope tracker and a 79% efficient switched-mode envelope tracker. The transmitter meets the EDGE spectral mask for both cases, showing that a high-efficiency amplifier can be linearized with a maintained high overall efficiency.**

***Index Terms*— Polar transmitter, polar modulation, class-E amplifier, envelope tracking.**

I. Introduction

Radio-frequency power amplifiers (RFPAs) dominate the power budget of RF transmitters. Therefore, improving RFPA efficiency by driving the device into saturation can significantly improve the overall transmitter power efficiency. On the other hand, modulated signals for improved spectral efficiency require linear power amplifiers, which are typically operated in backed-off class A or AB mode with efficiencies below 30%.

Supply modulating techniques such as polar modulation [1]-[5] and EER [6]-[8] can linearize non-linear but efficient amplifiers by exploiting the RFPA output power dependence on the supply voltage. Figure 1 shows a diagram of a polar transmitter implemented with an FPGA. The FPGA has three outputs; the amplitude of the complex signal, A and normalized $\overline{I}$ and $\overline{Q}$. Digital-to-analog converters are used at each of the outputs. A is the reference signal to the envelope tracker, while normalized $\overline{I}$ and $\overline{Q}$ are the inputs to an *IQ* modulator. The *IQ* modulator output is a constant-envelope phase-modulated RF signal. Time synchronization between amplitude and phase modulated paths is crucial since both values determine each symbol.

The envelope tracker supplies power to the RFPA. This means that the overall power efficiency not only depends on the RFPA, but also on the efficiency of the envelope tracker. One way to design ultra high-efficiency envelope trackers is with switch mode power supplies (SMPSs). SMPSs can achieve high efficiencies, are small, light, economic and have the capability to step-up or step-down voltages. However, for these converters losses increase with switching frequency and it is a challenge

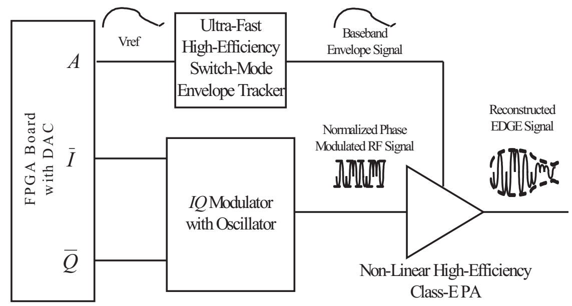


Fig. 1. Block diagram of a polar transmitter. The FPGA has three outputs; the amplitude of the complex signal, A and normalized $\overline{I}$ and $\overline{Q}$. Digital-to-analog converters are used at each output. A is the reference signal to the envelope tracker, while normalized $\overline{I}$ and $\overline{Q}$ are the input to an *IQ* modulator; the output is a constant amplitude phase modulated RF signal. Time alignment between amplitude and modulated phase path is crucial since both values determine each symbol.

to design fast high-efficiency SMPSs and the envelope tracker bandwidth needs to be several times larger than the signal bandwidth. In this work, an ultra fast DC-DC buck converter is used as the envelope tracker.

The remainder of the paper presents details of the envelope tracker, the high efficiency power amplifier and the overall polar transmitter performance. This paper builds on earlier results presented in [9], were a Class-E PA with inefficient linear amplifier envelope tracker is described.

II. Envelope Tracker

In this work, the envelope tracker is implemented with a synchronous buck SMPS and the envelope variations are achieved with pulse width modulation. Deadtime control of the synchronous switches in SMPS is essential to enhance the tracker efficiency and it is implemented with a digital counter-based adaptive scheme. Control is also required to produce a well regulated output voltage in the presence of variations in the input voltage, the load and/or element tolerances. The feedback loop around the power stage also achieves disturbance rejection and sensitivity reduction. The feedback loop also improves the tracking performance when compared to open loop operation. To minimize switching harmonics, the envelope tracker is followed by a 4th order low pass Bessel filter with cutoff frequency of 1.3 MHz that limits the 2nd switching harmonic below -65 dBc. The filter provides a constant group delay of 259 ns.

Two factors were considered when choosing the switching frequency: signal bandwidth and switcher efficiency. The bandwidth of EDGE signals is 200 kHz. However, for EDGE, the spectral requirements increase when the signal is converted to polar form. The switching frequency was chosen to be 16 times higher than the EDGE standard transmission rate of 270.833 kHz. This corresponds to a switching frequency of 4.33 MHz. The tracker supply voltage is 3.6V, which corresponds to the nominal voltage of a single-cell Li-Ion battery. The maximum output voltage of the tracker is 3.3V. The switcher measured efficiency is 79% [11]. For additional information about the switch-mode envelope tracker, the reader is referred to [12].

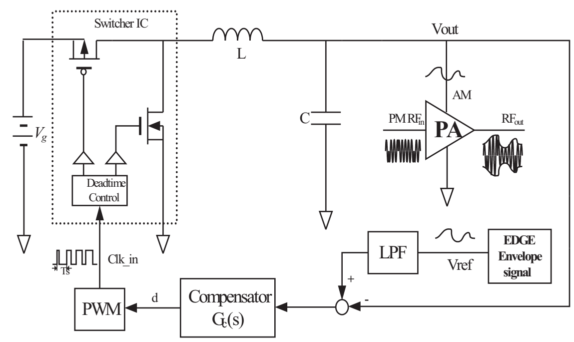


Fig. 2. Schematic of the closed-loop envelope tracker. The tracker is implemented with a synchronous buck switch-mode power supply. Envelope variations are achieved with pulse width modulation and deadtime control is used to enhance the tracker efficiency.

The performance of the transmitter with the switching supply from Figure 2 is compared to that with a linear amplifier envelope tracker such as the one presented in [9]. Although the power efficiency of a linear amplifier is not attractive, it can provide higher bandwidths and better dynamics than other analogous tracking systems. The linear amplifier is followed by a 4th order low pass Bessel filter with a cutoff frequency of 2.5 MHz and constant group delay of 140 ns.

III. Class-E Amplifier

The implemented high-efficiency RFPA is shown in Figure 3. The ideal class-E circuit is designed so that the transistor operates as a switch, which is in reality approximated by choosing a device with a low output capacitance and a cutoff frequency higher than the operating frequency. Class-E amplifiers with efficiencies above 90% have been demonstrated in the low MHz range, and above 65% at 10 GHz [14]-[16].

The transistor chosen for the PA from Figure 3 is a TriQuint TGF-4240 2.4-mm HFET with an output capacitance of approximately 1 pF. This device is intended for operation up to 12 GHz with a maximal output power of 1 W with 10 dB gain at 8 V drain bias. In the EDGE polar transmitter, the transistor supply is a 3.6-V ion battery with a maximal drain bias of 3.3 V limited by the buck converter.

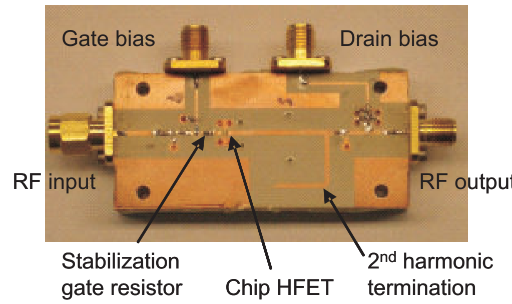


Fig. 3. Photograph of the hybrid 880-MHz class-E power amplifier with integrated bias lines and DC blocking capacitors which also serve for impedance matching. A 10-Ω chip resistor in series with the gate terminal ensures stability of the PA.

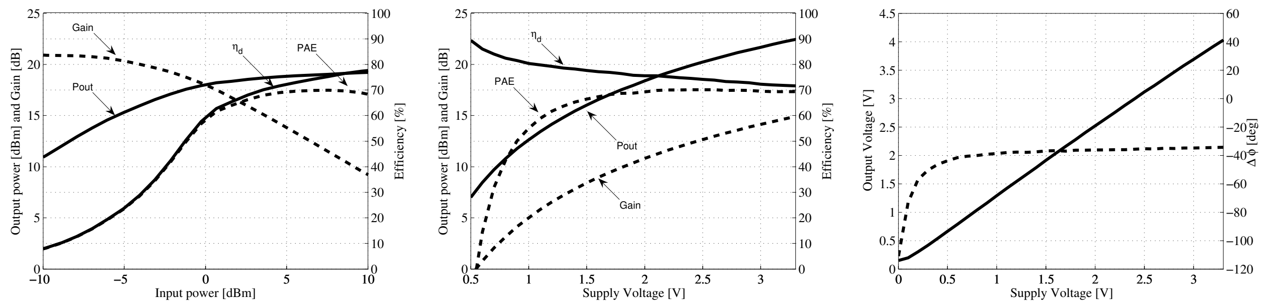
The PA is implemented as a hybrid circuit that combines transmission lines and lumped elements. Transmission lines are used to present a high impedance to the transistor second harmonic in the form of an open stub. The fundamental frequency input and output matching networks are implemented with lumped inductors and capacitors. The PA output impedance for Class-E operation is $(42+j48)\,\Omega$ at 880 MHz. A $10-\Omega$ series resistor is included in the gate input line to eliminate low-frequency instabilities.

Careful attention needs to be given to bias line design to avoid distortion and linear memory effects [18]. The bias line low-pass performance has to be designed to allow for supply modulation at the signal envelope bandwidth. The measured performance of the PA is shown in Figure 4: at 880 MHz, the PA gives +19 dBm output power at 3 V supply voltage with 70% power added efficiency and 11.5 dB gain.

Class E operation is particularly well suited for polar modulation since it can be shown from ideal class-E equations that the output RF voltage across a fixed resistive load (R_L) is linearly proportional to the supply voltage (V_{SS}) [16]-[17]:

$$V_{\text{out}} = \pm\left(26 \cdot f_s \cdot C_{\text{out}}\sqrt{R_E \cdot R_L}\right) \cdot V_{SS} \qquad (1)$$

where R_E is the real part of the optimal impedance presented to the device for class-E switched mode operation, f_s is the operating frequency which is also the switching frequency, and C_{out} is the output capacitance of the active device. From the above equation, the AM-AM characteristic is expected to be perfectly linear. However,



(a) (b) (c)

Fig. 4. Measurements for EDGE 880-MHz class-E PA with $V_{GS} = -1.7$ V. (a) Power sweep for V_{SS} = 2.16 V, the maximal PAE is 70% with a drain efficiency of 75%, gain of 11.5 dB and output power of +19 dBm for input power of +7.6 dBm. (b) Measured output power, gain, drain efficiency and PAE for supply sweep with input power of +7.6 dBm. (c) Measured AM-to-AM (solid line) and AM-to-PM conversion (dashed line).

since the device is heavily saturated, the transistor internal capacitances allow feedthrough under low supply voltages as shown in Figure 4c (solid line). The dashed line in the figure shows measured the PA AM-to-PM characteristic and it can be seen that there is significant relative phase difference at low supply voltages. These regions cause distortion. Fortunately, they are avoided in the EDGE modulation scheme since the envelope of the signal is kept above a certain value. For additional information on the Class-E amplifier the reader is refereed to [9].

IV. Polar Transmitter Performance

The diagram shown in Figure 1 is implemented with a Xilinx Virtex II FPGA and commercial oscillator, IQ modulator and DACs. The oscillator is an Analog Devices ADF4360-7 and the IQ modulator is Texas Instruments TRF3701. For testing purposes an EDGE signal segment consisting of 256 pseudo random symbols is stored as a look up table in the FPGA and streamed out repeatedly. Given the standard EDGE transmission rate of 270.833 kHz and an oversample ratio of 8, the signals are streamed out of the FPGA at the rate of 2.17 MHz.

The synchronization of envelope and phase signals is crucial for obtaining linearity, as discussed in [17]. In addition, the DACs introduce a DC offset in the I and Q channels, and compensation is required. Since the envelope tracker is followed by a 4$^{\text{th}}$ order Bessel low pass filter it was sufficient to compensate digitally by the filter group delay τ in the phase signal path. The implementation from Figure 1 allows all the required adjustments to be performed digitally.

Figure 5 shows the measured output spectrum of the polar transmitter, with the switcher (blue) and the linear amplifier (red) as the envelope tracker. As expected the linear amplifier shows less spectral regrowth (larger bandwidth), but the 79% efficient switcher also meets the EDGE spectral mask.

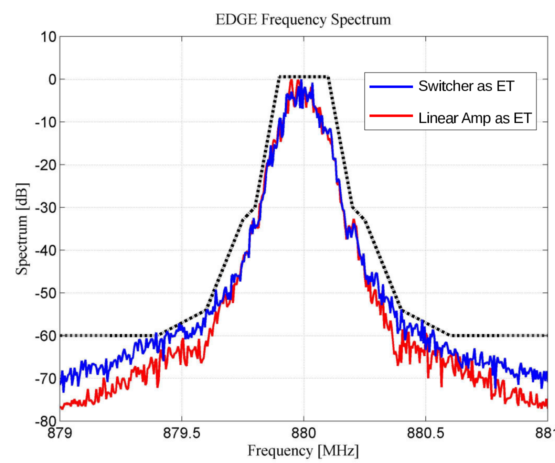


Fig. 5. Measured output spectrum of the polar transmitter when the envelope tracker is the linear amplifier (red) and fast switching buck converter (blue). The dashed line indicates the EDGE spectral mask requirement.

The RFPA efficiency averaged over varied supply voltage for the EDGE sequence is 71%, while the switch-mode envelope tracker is 79% efficient, resulting in an overall efficiency of 56% with an average RF output power of +20 dBm. The RFPA is able to deliver more than +30 dBm of output power at 8 V drain voltage, however it is desired to use a 3.6 V Li-Ion power battery as the power source. This power source in combination with a buck converter limits the maximum PA supply voltage to 3.3 V thus constraining the output power capabilities of the PA.

V. Discussion of Results

In conclusion, it is possible to linearize a high-efficiency switched mode RFPA using a polar architecture, while maintaining high overall efficiency. This paper demonstrate a 56% efficient polar transmitter for EDGE. The envelope tracker is a 79% efficient switch-mode buck converter and the RFPA is a 71% non-linear Class-E power amplifier. The transmitter meets the EDGE mask for the high-efficiency and a less efficient linear envelope tracker. The transmitter is digitally controlled which allows for various delay, phase and amplitude adjustments.

As a future step, it is desired to set up a system that downconvert and collects the output signal. This will allow us to perform EVM measurements and adaptive predistortion. We are also interested in increasing the RF output power of the transmitter. A larger periphery device will deliver more power for the same supply voltage and load-pull techniques will be used to optimize the tradeoff between power and efficiency. Higher RF power levels can also be accomplished under higher supply voltages. A buck-boost topology for the envelope tracker will allow voltage swings above and below the one provided by the 3.6 V Li-Ion battery. Another option is to increase the supply voltage with a a slow and extremely efficient boost converter. Amplitude variations can then be accomplished by a fast buck converter similar to the one presented here. In Class-E amplifiers, the voltage across the device can be higher than 3.2 times the supply voltage. Wide-bandgap transistors, such as GaN, can operate at higher voltages and withstand the stress associated with Class-E.

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References

[1] S. Mann, M. Beach, P. Warr and J. McGeehan, "Increasing the talk-time of mobile radios with efficient linear transmitter architectures," *Electronics & Communication Engineering Journal*, pp. 65-76, April 2001.

[2] M.R. Elliott, T. Montalvo, B. Jeffries, F. Murden, J. Strange, A. Hill, S. Nandipaku, and J. Harrebek, "A Polar Modulator Transmitter for GSM/EDGE," *IEEE Journal of Solid-State Circuits*, vol. 39, No. 12, pp. 2190-2199, December 2004.

[3] F. Wang, A.H. Yang, D.F. Kimball, L.E. Larson, P.M. Asbeck, "Design of Wide-Bandwidth Envelope-Tracking Power Amplifiers for OFDM Applications," *IEEE Trans. on Microwave Theory and Techn.*, vol. 53, No. 4, pp. 1244-1255, April 2005.

[4] J. Popp, D. Lie, F. Wang, D. Kimball, L. Larson, "A Fully-Integrated Highly-Efficiency RF Class-E SiGe Power Amplifier with an Envelope-Tracking Technique for EDGE Applications," *IEEE Radio and Wireless Symp. Dig.*, 2006, pp. 231-234

[5] D.F. Kimball, J. Jeong, C. Hsia, P. Draxler, S. Lanfranco, W. Nagy, K. Linthicum, L. Larson, and P. Asbeck, "High-Efficiency Envelope-Tracking W-CDMA Base-Station Amplifier Using GaN HFETs," *IEEE Trans. on Microwave Theory and Techn.*, vol. 54, No. 11, pp. 3848-3856, November 2006.

[6] L.R. Kahn, "Single sideband transmission by envelope elimination and restoration," *Proc. IRE*, vol. 40, pp. 803-806, July 1952.

[7] F.H. Raab and D.J. Rupp, "High-efficiency single-sideband HF/VHF transmitter based upon envelope elimintation and restoration," in *Proc. 6th Int. Radio Systems Techniques Conf.*, Jul. 1994, pp. 21-25.

[8] N. Wang, X. Peng, V. Yousefzadeh, D. Maksimovic, S. Pajic, Z. Popovic, "Linearity of X-Band Class-E Power Amplifiers in EER Operation," *IEEE Trans. on Microwave Theory and Techn.*, vol. 53, No. 3, Mar. 2005.

[9] N.D. Lopez, X. Jiang, D. Maksimovic, and Z. Popovic, "Class-E Power Amplifier in a Polar EDGE Transmitter," *IEEE International Microwave Symposium Digest*, pp. 785-788, June 2006.

[10] V. Yousefzadeh, E. Alarcon, and D. Maksimovic, "Band Separation and Efficiency Optimization in Linear-Assisted Switching Power Amplifiers," *37th IEEE Power Electr. Specialists Conf., 2006*, pp. 1-7, June 2006.

[11] X. Jiang, *Envelope-Tracking Power Supplies for RF Power Amplifiers in Portable Applications*, PhD Dissertation, Department of Electrical Engineering, University of Colorado, Boulder, 2007.

[12] X. Jiang, N.D. Lopez, and D. Maksimovic, "A Switched Mode Envelope Tracker for Polar EDGE Transmitter," 37^{th} *IEEE Power Electronics Specialists Conference*, June 2006, pp. 1-7.

[13] T.B. Mader, E.W Bryerton, M. Markovic, M. Forman, M., and Z. Popovic, "Switched-mode high-efficiency microwave power amplifiers in a free-space power-combiner array," *IEEE Trans. on Microwave Theory and Techn.*, Vol. 46, No. 10, Part 1, Oct. 1998, pp. 1391 - 1398.

[14] N.O. Sokal and A.D. Sokal, "Class-E a new class of high-efficiency tuned single-ended switching power amplifiers," *IEEE Journal of Solid-State Circuits*, Vol. SC 10, pp. 168-176, June 1975.

[15] F.H. Raab, "Idealized operation of class-E tuned power amplifier," *IEEE Trans. Circuits Syst.* vol. CAS-24, No. 12, pp. 725-735, Dec. 1977.

[16] S. Pajic, N. Wang, P. Watson, T. Quach, and Z. Popovic, "X-Band Two-Stage High-Efficiency Switched-Mode Power Amplifiers," *IEEE Trans. on Microwave Theory and Techn.*, vol. 53., No. 9., September 2005.

[17] N. Wang, N.D. Lopez, V. Yousefzadeh, J. Hoversten, D. Maksimovic and Z. Popovic, "Linearity of X-band Class-E Power Amplifiers in a Digital Polar Transmitter," *IEEE International Microwave Symposium Digest*, June 2007.

[18] K.A. Remley, D.F. Williams, D.M. Schreurs, J. Wood, "Simplifying and interpreting two-tone measurements," *IEEE Trans. on Microwave Theory and Techn.*, vol. 52., No. 11., September 2004.