Highly Linear Envelope Tracking Power Amplifier with Simple Correction Circuit

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***Abstract*— In this paper, we propose an envelope tracking (ET) power amplifier (PA) with a simple correction circuit (SCC) for linear operation. The supply dependent AM-AM and AM-PM distortion of an ET PA is linearized by the SCC which is fabricated on chip. The PA and supply modulator are fabricated using I/O device of CMOS 40nm process. For the 9.35-dB peak-to-average-power ratio, 256-QAM IEEE 802.11ah signal, the ET PA delivers a power-added efficiency of 24%, an average output power of 19.4 dBm and an error vector magnitude of -30 dB.**

***Index Terms*— Envelope tracking (ET), power amplifier (PA), simple correction circuit (SCC), broadband, 802.11ah.**

I. Introduction

The 802.11ah standard has been developed to realize the concept of internet of things (IoT), connecting all device to the internet, from the body sensor network to machine to machine network. The coverage area is increased using the sub-GHz carrier with enhanced wave propagation and penetration characteristics. Also, by using the complex modulation technique, the standard has a good spectral efficiency.

However, the power amplifier (PA) should be operated at the back-off power region with poor efficiency because peak-to-average-power ratio (PAPR) of the signal is increased by the complexity of the modulation. The envelope tracking (ET) is a powerful technique to enhance the back-off efficiency of the PA [1] – [6]. Therefore, the ET technique should be utilized to realize the efficient system.

In this paper, we propose a linear ET PA with simple correction circuit (SCC) for the IEEE 802.11ah standard as shown in Fig. 1. The AM-AM and AM-PM responses of the PA are dependent on the supply voltage, and, we adopt the SCC to minimize these nonlinearity. In section II, the ET PA with SCC will be introduced. In section III, implementation and measurement results will be shown.

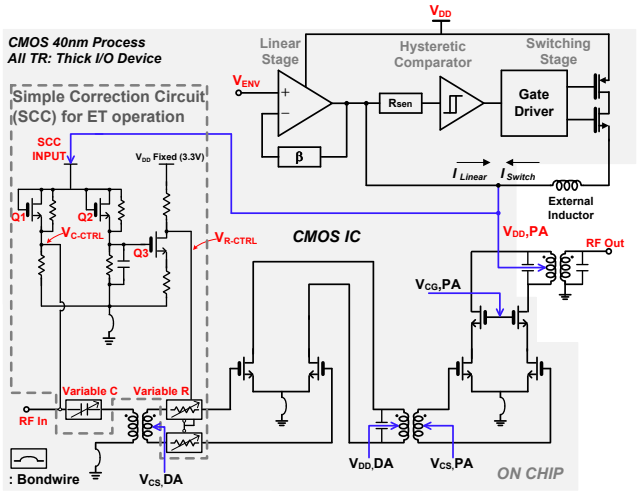

Fig. 1. Schematic of the CMOS envelope tracking power amplifier with the simple correction circuit.

II. Simple Correction Circuit for ET Operation

The fundamental of ET operation is supply voltage modulation. The AM-AM and AM-PM responses of the ET PA are distorted by the supply dependent device parameters, such as transconductance, input and output capacitor [1] – [6]. Fig. 2 show the simulated expected gain and phase responses under the ET operation using the PA we have implemented. As shown in Fig. 2(a), the gain is decreased as supply voltage is decreased. Therefore, the AM-AM trajectory (black-solid line) has gain expansion characteristic. The AM-PM trajectory has also the same characteristic due to the supply voltage dependent nonlinear input and output capacitors of the device (Fig. 2(b)).

To linearize the distortions, a SCC is proposed (Fig. 1). An input signal of the SCC is modulated envelope voltage of the PA whose swing range is 1.0 V to 3.5 V

for the maximum output power level. The SCC consists of two parts. One is the AM-AM control circuit and the other is the AM-PM control circuit. The AM-AM control circuit is composed of a variable resistor which is used as a ballast resistor and its control voltage generator (Q2, Q3). The resistance of variable resistor is inversely proportional to control voltage of V_{R-CTRL} (Fig. 3(a)). For the conventional ET PA, the V_{R-CTRL} is a fixed value for the minimum ballast resistance. For the ET PA with SCC, the V_{R-CTRL} is modulated according to the supply voltage. As shown in Fig. 3(a), for a high supply voltage, the V_{R-CTRL} is decreased with enlarged ballast resistance, decreasing the gain of the PA. Therefore, the expected AM-AM trajectory of the ET PA with the SCC (Fig. 2(a), red-solid line) is linearized by the AM-AM control circuit of the SCC. The gain deviation is decreased from 2.5 dB to 1.2 dB.

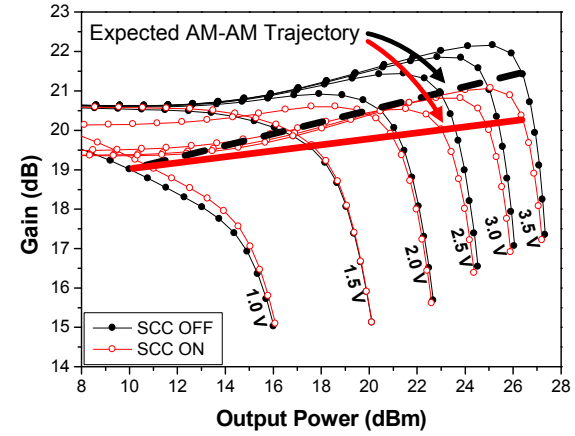

Fig. 2. Simulated AM-AM and AM-PM responses of the PA according to the supply voltage.

The AM-PM control circuit is composed of a variable capacitor and its control voltage generator (Q1). The capacitance of the variable capacitor is proportional to control voltage of V_{C-CTRL} (Fig. 3(b)). For the conventional ET PA, the V_{C-CTRL} is fixed value as the input impedance is matched to 50 Ω. For the ET PA with SCC, the V_{C-CTRL} is modulated according to the supply voltage. As shown in Fig. 3(b), for a high supply voltage, the V_{C-CTRL} is increased to enlarge the capacitance. Therefore, the phase response of the PA with SCC at a high supply voltage is decreased. The expected AM-PM trajectory of the ET PA with the SCC (Fig. 2(b), red-solid line) is linearized by the AM-PM control circuit. The phase deviation of the trajectory is decreased from 17° to 10°.

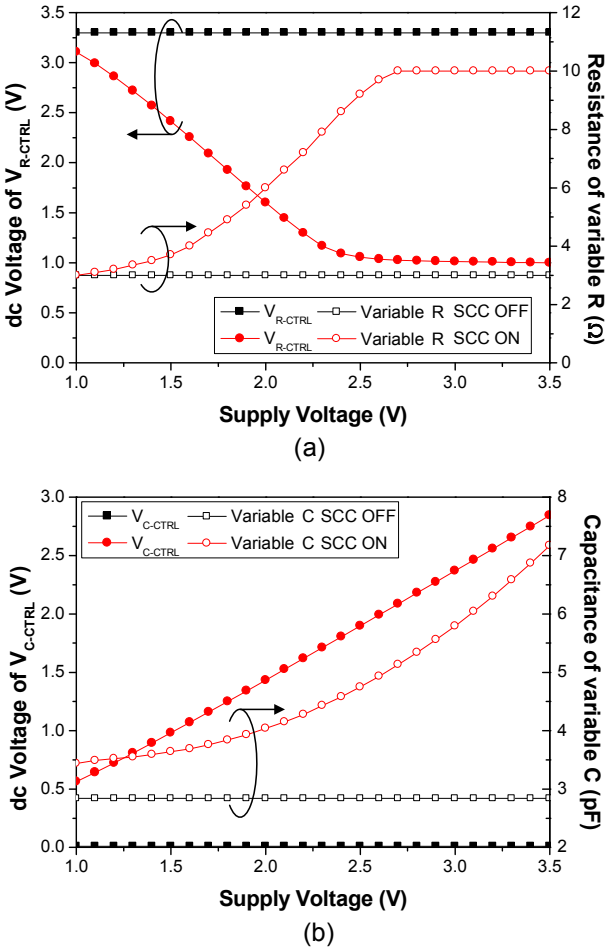

Fig. 3. Reshapaed dc voltages, resistance and capacitance by the SCC according to supply voltage. (a) Gain control and (b) phase control.

III. Implementation and Experimental Results

The ET PA with the SCC is fabricated using a 40-nm CMOS technology. Thick-oxide 0.3-μm device is selected for all transistors to overcome the low breakdown voltage.

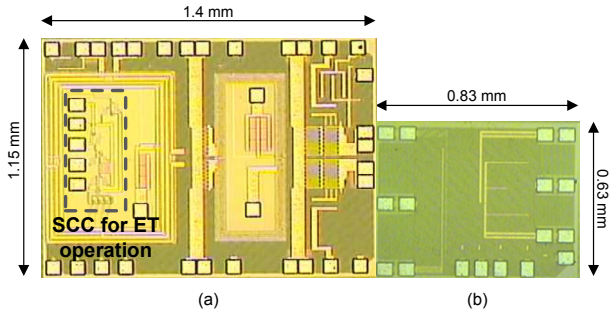

Fig. 4. Fabricated chip photographs of (a) the PA and (b) supply modulator.

To compensate source degeneration of the CMOS process, the differential structure is selected for both the drive and power stages. The total gate width of the drive stage and power stage are 1,680 μm and 5,040 μm, respectively. As shown in Fig. 1, the SCC, input and interstage baluns are integrated on the PA die. The output transformer is fabricated by a 4-layer FR-4 printed circuit board (PCB) and its insertion loss is 0.4 dB, including all matching components. The two chips of PA and supply modulator are mounted on an FR4 PCB to demonstrate the ET operation. The chip sizes of the PA and supply modulator are 1.4 mm $\times$ 1.15 mm and 0.83 mm $\times$ 0.63 mm, respectively (Fig. 4). The supply modulator is biased at 4.0V and the efficiency is 82% at the peak power level. The envelope shaping function described in [1] is adopt for linear ET operation.

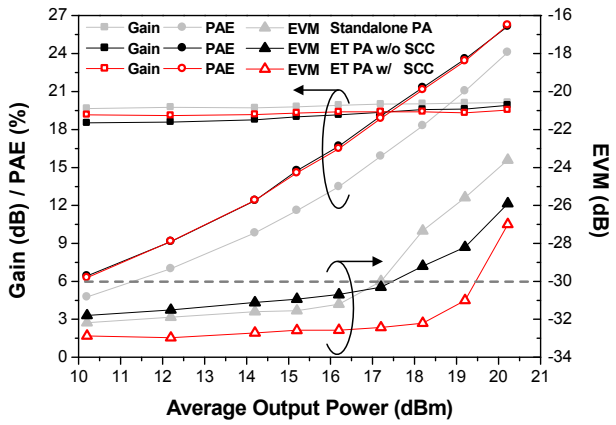

Fig. 5. Measured PAE, gain and EVM of the standalone PA, conventional ET PA and proposed ET PA with the IEEE 802.11ah signal.

Fig. 5 shows measured performances of the ET PA with the SCC, ET PA without the SCC and a standalone PA whose supply voltage is fixed at 3.5 V. The PA is measured using a 256-QAM, 2-MHz bandwidth and 9.35-dB PAPR 802.11ah signal at 920-MHz center frequency. The ET PA with the SCC delivers significantly higher linearity, about 2 dB improvement as shown in Fig. 5. The power-added efficiency (PAE) and error vector magnitude (EVM) are 24% and -30 dB, respectively at an average output power of 19.4 dBm. Comparing the ET PA with the SCC and the standalone PA, the linear output power and PAE are improved by 2.2 dB and 8%, respectively. Fig. 6 show the measured EVM of the conventional and proposed ET PA at the same average output power of 19 dBm. The output spectrum of the proposed ET PA (Fig. 7) meets the 802.11ah specification with a good margin.

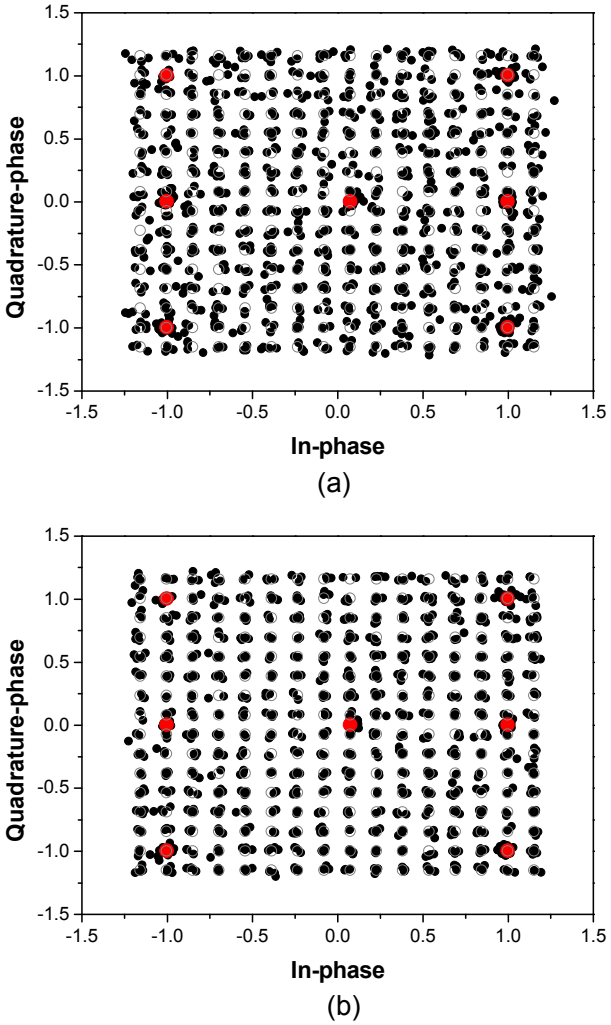

Fig. 6. Constellation diagrams of a 256-QAM signal at an average output power of 19 dBm. (a) Conventional ET PA, EVM = -28 dB. (b) Proposed ET PA, EVM = -30.5 dB.

Frequency usage plan for the 802.11ah are different in nations, therefore, the multiband operation characteristic of the PA is essential for 802.11ah standard. Fig. 8 shows

TABLE I
PERFORMANCE COMPARISION OF RECENTLY PUBLISHED WLAN PA

Performance	[7]	[8]	This work
Frequency (GHz)	2.4	2.4	0.92
Pout (dBm)	16	18.2	19.4
PAE (%)	17	21.3	24
EVM (dB)	-28	-28	-30
Signal (QAM)	64	64	256
Technique	Doherty DPD	MGTR	ET with SCC

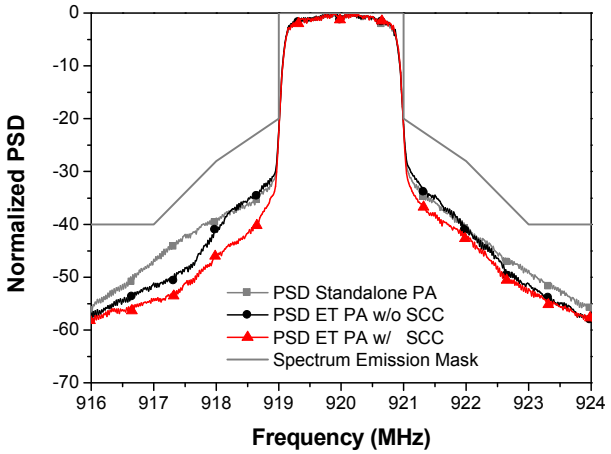

Fig. 7. Output spectra of the PAs for an IEEE 802.11ah, 2-MHz BW, 9.35-dB PAPR and 256-QAM signal at average output power of 19 dBm.

the measured output power, PAE and EVM across the 780 – 960 MHz frequency. Measurement results show that the SCC operates properly across the broad band. Table I show the recently published WLAN PAs. Among them, the proposed ET PA shows good performance. To the best of the authors' knowledge, this work proposes the first ET PA for the 802.11ah standard.

IV. CONCLUSION

An ET PA with the SCC is developed for linear operation. Supply dependent AM-AM and AM-PM distortions are linearized by the SCC. For 802.11ah signal, the ET PA delivers a PAE of 24% and EVM of -30 dB at an average output power of 19.4 dBm.

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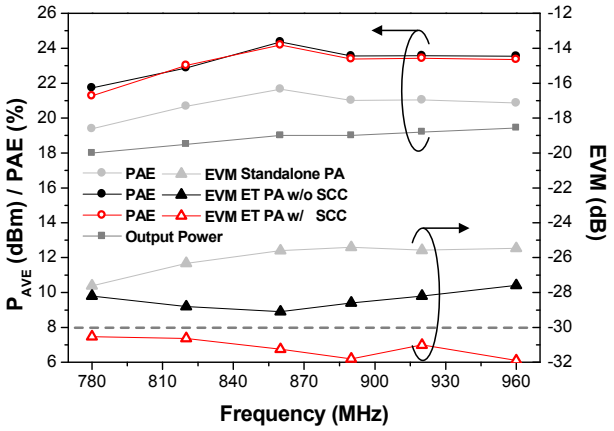

Fig. 8. Measured PAE, output power and EVM of the standalone PA, conventional ET PA and proposed ET PA according to frequecy. PAE and EVM are compared at the same average output power in this figure.

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