# Optimized Envelope Shaping for Hybrid EER Transmitter of Mobile WiMAX—Optimized ET Operation

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***Abstract*—The envelope signal of a Hybrid Envelope Elimination and Restoration (H-EER) technique is optimally reshaped to improve linearity and efficiency, resulting in an Envelope Tracking (ET) architecture. The bias $V_{ds}$ of the ET is adjusted to be a higher value than that of the conventional H-EER technique to enhance the output power and power-added efficiency (PAE). Furthermore, the bias is shifted above the knee region of the PA to reduce the AM/AM and AM/PM distortions at the low bias region. For the verification, the Mobile WiMAX signal with 8.2 dB peak-to-average power ratio and 5-MHz signal bandwidth is used. In the interlock experiment, the PAE of the transmitter is 40% at an output power of 42.04 dBm. By using the digital predistortion technique, the Relative Constellation Error has satisfied the specification of $-33.6$ dB. These results clearly show that the H-EER transmitter with ET shaping is the most suitable architecture for the highly linear and efficient Base Transceiver Station transmitter.**

***Index Terms*—Envelope tracking (ET), hybrid envelope elimination and restoration (H-EER), power amplifier (PA), relative constellation error (RCE), RF transmitter, world interoperability for microwave access (WiMAX).**

## I. Introduction

HIGH efficiency with high linearity is the most important design parameters for wireless communication transmitters. Currently, the most widely researched architecture of the next generation Base Transceiver Station transmitter is EER/polar transmitter. Theoretically, the transmitter has high efficiency with high linearity, but it has a serious distortion problem due to the drain bias dependent PA's nonlinear behavior ($V_{ds} - AM, V_{ds} - PM$). However, the distortion can be sufficiently linearized using the digital predistortion (DPD) technique, satisfying the specification of the base station system [1].

The traditional EER/Polar transmitter uses the phase information signal with a constant amplitude to accommodate the PA's switching or saturated mode operation over the whole input region. The phase signal with the constant amplitude has a very wide bandwidth, about ten times the original signal bandwidth. However, a low input power is enough to saturate the PA at the low power operation region. Moreover, the low input at the low power region reduces the input drive and enhances the PAE. And the distortion can be smaller for the proper amount of input to saturate the PA. Naturally, to overcome those problems of conventional EER/Polar transmitter, the modulation signal is directly injected as an input signal of the PA, resulting in the hybrid EER(H-EER). The H-EER is well suited for the envelope tracking(ET) technique [2], which is shown in Fig. 1. For the optimized ET operation, the envelope signal is shaped for the improved PAE and linearity and the performance is verified using IEEE 802.16e Mobile WiMAX signal with 8.2 dB peak-to-average power ratio (PAPR).

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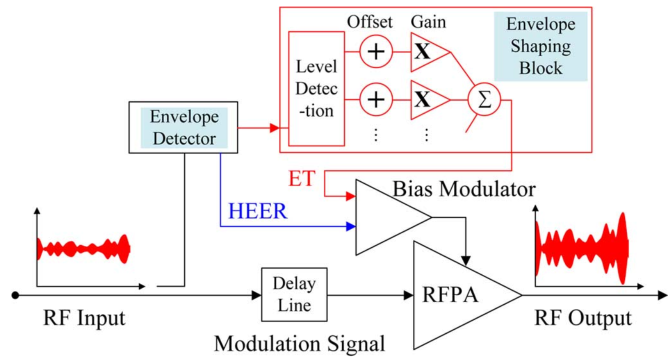


Fig. 1. Architecture of the H-EER transmitter with ET shaping.

## II. Implementation

### A. Envelope Shaping Method

Fig. 2 shows the shaping functions of drain bias modulation signals for the conventional H-EER and optimized ET transmitters. For the normalized input voltage, the magnitude of envelope signal for the H-EER transmitter is increased linearly with a constant slope [3]. On the other hand, the signal for the ET transmitter has two different slopes with an offset voltage. The offset voltage at a low $V_{in}$ region is adjusted to be larger than the power device's knee voltage. Through the operation above the knee region, the PA can avoid the nonlinear behaviors such as gain compression(AM/AM) and serious phase distortion(AM/PM) in that region [4]. Furthermore, the PA for the ET transmitter operates at a higher $V_{ds}$ in all of the input power range than that for the

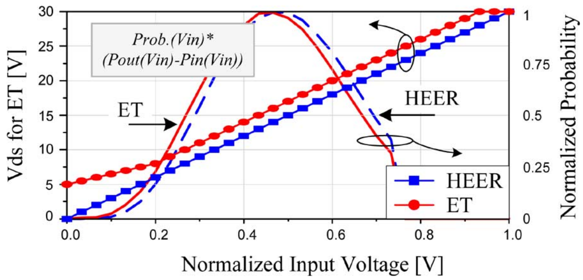


Fig. 2. Shaping functions of the drain bias modulation signals and power-added PDFs of the conventional H-EER and ET transmitters versus normalized $V_{in}$.

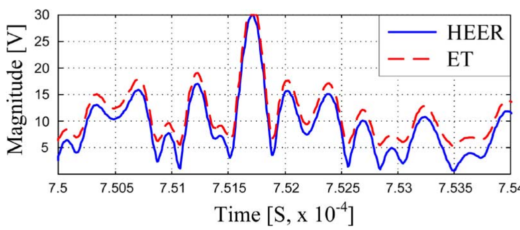


Fig. 3. Waveforms of drain bias modulation signals for the H-EER and ET transmitters.

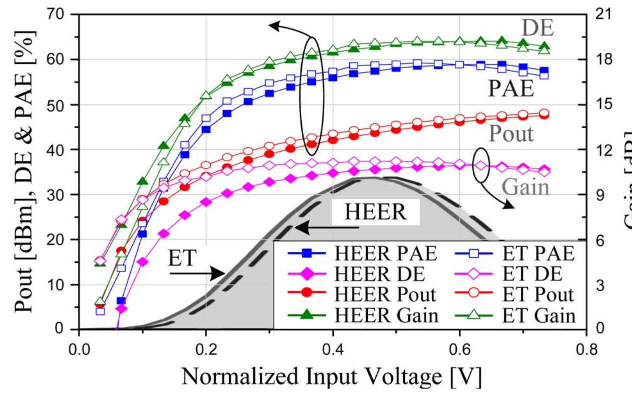


Fig. 4. Measured CW performance of 100-W GaN HEMT PA versus normalized $V_{in}$ under the H-EER and ET operations.

H-EER transmitter. Accordingly, the PA delivers a higher output power over the whole input range, increasing the power gain. For high efficiency, both PAs for the H-EER and ET transmitters have been operated at a saturated state along the drain bias modulation signal, and the PA for the ET operation has an improved drain efficiency(DE) compared to the H-EER transmitter due to the reduced knee effect and nonlinear capacitance mismatch $(C_{ds})$ [3]. Consequently, the enhanced overall PAE performance can be achieved by the ET operation. The slope and offset voltage of the drain bias modulation signal for the ET operation is adjusted for the minimum spurious emission and high PAE performance at an improved output power compared with the conventional H-EER transmitter. The waveforms of two signals in the time domain are presented in Fig. 3.

### *B. Measured Results of PA and Bias Modulator*

The average PAE performance of each transmitter can be calculated as follows [5]:

$$PAE = \frac{\int prob.(V_{in}) * [Pout(V_{in}) - Pin(V_{in})] dV_{in}}{\int prob.(V_{in}) * Pdc(V_{in}) dV_{in}}.$$

The $prob.(V_{in})$ is the probability of occurrences at $V_{in}$ for the input modulation signal based on a Rayleigh distribution. In this equation, the overall PAE is determined by the ratio of the multiplications of the Rayleigh distribution and the power generation terms $(Pout - Pin)$ over the distribution and the dc power input through the bias modulator. The numerator of the above function is the power-added probability density function(PDF) of the H-EER and ET transmitters, which is depicted in Fig. 2 [3], [6]. The distribution indicates the important power generation region for the H-EER or ET operation, and the average PAE is also determined by the operation at the region. In Fig. 4, the DE, PAE, Pout and Gain are described for two modes of operation using a continuous wave(CW) measurement at 2.655 GHz.

It is hard to implement a switch or saturated mode PA, for example, the class D, E, F, or $F^{-1}$, for a high power application due to the large output capacitance $(C_{ds})$. In this work, the PA has been designed using a class AB mode with the 2nd harmonic optimization. The PA has been implemented using a Nitronex's 100 W peak envelope power(PEP) GaN HEMT device, and tuned to achieve a high PAE performance at the high PDF region. At the high PDF region, the PA under the ET operation clearly shows higher PAE than that under the H-EER operation. In Fig. 2, if the important region for the overall PAE performance is defined as the region with a normalized probability above 0.5, the dominant output voltage regions of the bias modulator for the H-EER and ET transmitters are 9–21 V and 10–22 V, respectively.

The bias modulator has been implemented using a hybrid switching amplifier(HSA) [2]. The HSA has a high efficiency at a high output voltage because the dc–dc converter, a high efficiency current source, more efficiently supplies most of the output current to the load for the high output voltage signal with a low PAPR. Therefore, the bias modulator for the ET envelope signal has higher average efficiency than that for the H-EER case. In Table I, the measured efficiency performances of the bias modulator for the H-EER and ET drain bias modulation signals are summarized. The load impedances for the two cases, $V_{ds}/I_{ds}$, are calculated and depicted in Fig. 5, showing almost the same resistances of 5 $\Omega$. The experimental results also show that the HSA for the ET transmitter operates more efficiently for the drain bias modulation signal with a reduced PAPR than that for the H-EER transmitter. The output spectrum of the HSA is presented in Fig. 6, showing enough bandwidth up to 7 MHz for the linear drain bias modulation.

## III. Interlock Experiment

For the interlock experiment, Agilent's E4438C and 8267D have been used as master and slave units, respectively, for the baseband and RF signal generators [3]. The measured results are summarized in Table II. The ET transmitter has achieved 40.9% PAE performance at an average output power of 42.8 dBm with $-25.5$ dB of Relative Constellation Error (RCE) performance.

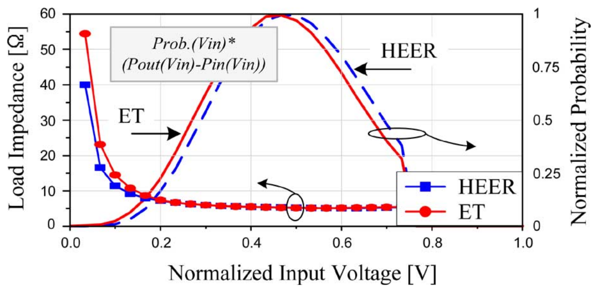


Fig. 5. Load impedances of bias modulator versus normalized $V_{in}$ for the H-EER and ET transmitters.

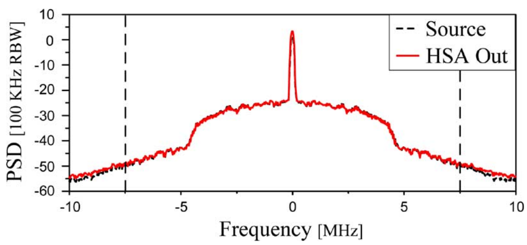


Fig. 6. Measured spectrum of the HSA for IEEE 802.16e Mobile WiMAX envelope signal.

TABLE I
PERFORMANCE COMPARISONOF THE HYBRID SWITCHING AMPLIFIER FOR THE H-EER AND ET'S DRAIN BIAS MODULATION SIGNALS

| - | PAPR | Vpeak | Pdc | Pout | Eff. |
|---|---|---|---|---|---|
| H-EER | 8.2 dB | 30 V | 32.41 W | 23.37 W | 72.1 % |
| ET | 7 dB | 30V | 41.11 W | 30.75 W | 74.8 % |

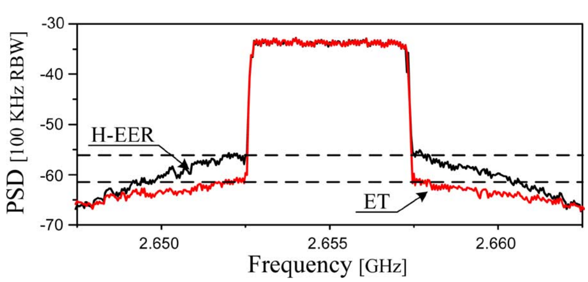


Fig. 7. Measured output spectra of the H-EER and ET transmitter under interlock experiment.

The measured output spectra are shown in Fig. 7. In all aspects, the ET transmitter has shown to be superior to the H-EER transmitter. After linearization using DPD technique, the RCE performance of the ET transmitter satisfied the specification of $-33.6$ dB. The constellation diagrams with and without linearization are presented in Fig. 8. Therefore, it is successfully verified that the proper envelope shaping for the H-EER transmitter is very important and is the most suitable architecture for the highly efficient and linear Base Transceiver Station transmitter.

## IV. CONCLUSION

For the next generation transmitter, the envelope signal of the H-EER is properly shaped to get an improved performance, resulting in the ET transmitter. The IEEE 802.16e Mobile WiMAX signal with 8.2 dB PAPR and 5 MHz signal bandwidth is used for the design. Through the ET operation, the PA has achieved enhanced output power and PAE performance at the high probability region on the power-added PDF, and the spurious emission has been successfully reduced. Furthermore, the bias modulator also has a higher efficiency due to the high output voltage operation and the reduced PAPR of the envelope signal. For the interlock experiment, the ET transmitter has demonstrated 40% PAE performance at an average output power of 42.04 dBm with $-33.6$ dB of RCE performance, after linearization by the DPD. These data clearly indicated that the ET transmitter based on the H-EER is the most attractive architecture for the efficient and linear Base Transceiver Station transmitter.

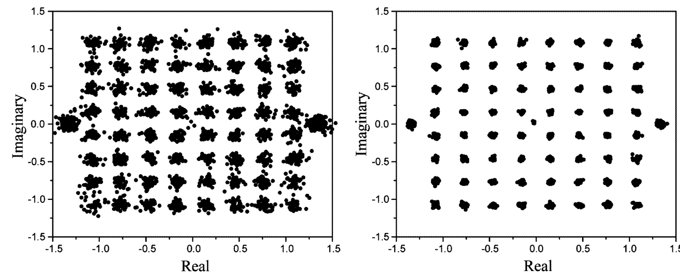


Fig. 8. Measured signal constellation diagrams of the ET transmitter before(left) and after(right) linearization.

TABLE II
SUMMARIZED PERFORMANCES OF THE H-EER AND ET TRANSMITTER FOR IEEE 802.16E MOBILE WIMAX SIGNAL AT 2.655-GHZ

| - | H-EER | ET | ET with DPD |
|---|---|---|---|
| Gain | 10.1 dB | 11 dB | 11.4 dB |
| Pout | 42.3 dBm | 42.8 dBm | 42.04 dBm |
| PAE | 39.5 % | 40.9 % | 40 % |
| RCE | -21.2 dB | -25.5 dB | -33.6 dB |

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