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Improved EER Transmitters for WLAN

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Abstract — **The envelope elimination and restoration (EER) transmitter architecture is capable of providing high power efficiency without compromising linearity. This paper shows that for a wireless local area network (WLAN) application, the envelope reconstruction process modulates the supply voltage of the switching amplifier over a large dynamic range. This introduces sufficient nonlinearity to violate emission specifications. Fortunately, the EER architecture can be improved by applying envelope and phase feedback. The phase feedback architecture satisfies the emission specifications of IEEE 802.11a, while envelope feedback provides modest adjacent channel power ratio (ACPR) improvement. The impact of clipping on the ACPR and error vector magnitude (EVM) is also investigated. It is shown that for a WLAN application, a clipping of only 1dB can be tolerated before the output signal is degraded significantly.**

Index Terms — **Nonlinear distortion, power amplifiers, transmitters, wireless LAN.**

I. Introduction

In a wireless communication channel, transmission of RF signals should be achieved without increasing ACPR and adding distortion. Currently available amplifier technologies are unable to amplify high peak-to-mean ratio (PMR) signals (such as produced by the IEEE 802.11 suite of standards) with sufficient linearity and efficiency. Amplifier back-off may ensure that the peaks of the envelope remain within the amplifier's linear range of operation. This results in poor power added efficiency (PAE), and since the power consumption in a mobile equipment is dominated by the power amplifier (PA), it reduces battery life significantly.

II. Envelope Elimination and Restoration

The EER transmitter architecture [1]-[3] is particularly attractive as it can utilise power efficient amplifiers, while also providing high linearity. A block diagram of an EER transmitter is shown in Figure 1. A modulated RF signal is split into its polar components, envelope (*E(t)*) and phase (*ϕ(t)*), by an envelope detector and a limiter respectively. The limiter output (*ϕ(t)*) is a constant envelope signal that can be amplified by a power efficient but highly nonlinear switching PA. In theory, a well-saturated amplifier can be approximated by an RF voltage generator whose output amplitude is proportional to the dc-supply voltage ($P_{out} \propto V_{dd}^2$). The envelope information (*E(t)*) is restored at the output by modulating the supply voltage (V_{dd}) of the PA, where the modulating signal is derived from the envelope detector. Thus, EER shifts the linearity issue away from the PA, but places demands on how accurate the envelope and phase information can be recombined. The delay matching requirement is related to the bandwidth of the signal (B_{RF}), with wideband signals requiring more accurate delay matching. Raab has shown [2]-[3] that the intermodulation distortion (IMD) introduced by the delay mismatch (Δt) can be approximated by $IMD \approx 2\pi B_{RF}^2 \Delta t^2$. In order to achieve a 40dBc IMD level, a value of $\Delta t \leq 0.04/B_{RF}$ is required, e.g. in a system with B_{RF}=20MHz, a time alignment of better than 2nsec is required. Selection of the envelope filter bandwidth (B_E) is a compromise between passing the broadband envelope signal and rejecting the spurious components that are generated in the pulse-width/sigma-delta (PW/ΣΔ) modulator. To achieve 40dBc IMD, a value of $B_E \geq 3B_{RF}$ is required, i.e. more than 60MHz for contemporary WLAN's. A PW/ΣΔ modulation over-sampling rate of $10B_{RF}$ is enough for replicating the envelope with sufficient accuracy.

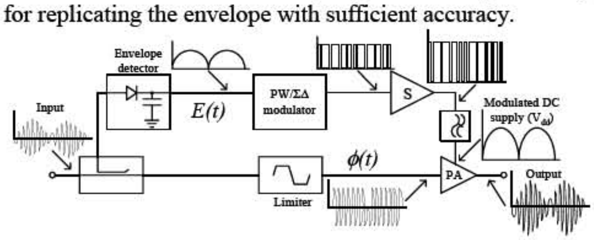

Figure 1: An EER transmitter.

A. *Supply Voltage Modulation of Class-E PA*

Switching amplifiers (class-E/F/S/D) achieve significantly higher PAE than other classes of amplifier. In these amplifiers, the transistor operates as a switch and the output load network shapes the output waveform to prevent simultaneous high voltage and current, which minimises power dissipation in the transistor. A class-E amplifier was designed at 5.2GHz by using a GaAs MESFET (MWT-7) and simulations carried out to demonstrate the effects of V_{dd}

modulation for envelope reconstruction. The mathematical equations used in the design are presented in [4]-[5].

The linearity of the amplifier was investigated by sweeping the drain voltage from 0 to 5.5V. The output voltage vs. V_{dd} (V_{dd}/AM) relationship[1] is shown in Figure 2. The output signal level changes according to V_{dd}, therefore the envelope can be restored. However, Figure 2 also reveals that this relationship is nonlinear. Nonlinearity arises not only at high envelope levels but also in the small-signal region, and thus clipping occurs in both operating regions. Also, an RF feed-through can be seen at V_{dd}=0, which may result in additional distortion at low envelope levels.

When the amplifier's drive voltage deviates from its optimum value (5V), V_{dd}/PM changes linearly by 5°/V down to 1.5V. Within the range of 0-1.5V, the V_{dd}/PM characteristic is highly nonlinear and the phase-shift can be as large as 60°. These characteristics demonstrate that low envelope levels are harder to reconstruct than envelope peaks.

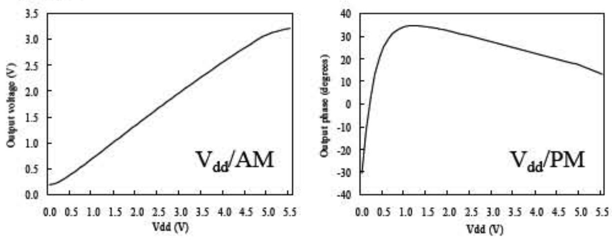

Figure 2: V_{dd}/AM and V_{dd}/PM characteristics.

B. *Ideal EER Transmitter*

Simulations were performed in ADS-Ptolemy using an IEEE 802.11a waveform (54Mbit/s, 52 carriers, B_{RF}=20MHz). The EER architecture shown in Figure 1 was simulated. A first order ΣΔ modulator with 1-bit ADC was constructed, where a 10-fold over-sampling ratio was chosen (200MHz). The input to the ΣΔ modulator was the IEEE 802.11a signal envelope and the output was amplified by the class-S amplifier so that the maximum peak was 5V. The signal path used to process the envelope includes an output low-pass filter (LPF) to convert the binary envelope to an analogue signal. The 3dB roll-off frequency (B_E) of the LPF was 80MHz. The delay matching between the amplitude and phase modulated signal paths was satisfied after some optimization.

The envelope reconstruction was achieved not by modulating the V_{dd} of the PA, but by using an ideal voltage multiplier after the PA. The purpose of this simulation was to investigate if the EER transmitter architecture is capable of satisfying the emission specifications of IEEE 802.11a, when the perfect V_{dd} modulation is assumed. The output spectra from this ideal EER transmitter (Figure 3), shows that the emission specification is met.

[1] Here, the measured amplitude and phase distortion is due to V_{dd} modulation and hence referred to as V_{dd}/AM and V_{dd}/PM respectively.

C. *Non-ideal EER Transmitter*

Subsequently, the same EER transmitter was simulated, but with the V_{dd} of the PA modulated to reconstruct the envelope. The output spectrum, which violates the regulatory spectral mask is shown in Figure 3. This demonstrates that V_{dd}/AM and V_{dd}/PM imperfections are sufficient to cause violation of the spectral mask if the signal has a high PMR. If other system imperfections are included then performance would be degraded further.

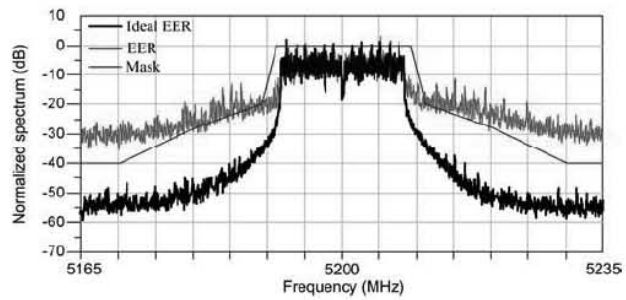

Figure 3: Output spectra of ideal and non-ideal EER.

III. Improved EER Architectures

Residual nonlinearity of the amplifier with V_{dd} modulation can be corrected in several ways:

- Use envelope feedback to correct for V_{dd}/AM.
- Use phase feedback to correct for V_{dd}/AM.
- A PA can be designed that can tolerate V_{dd} modulation.
- The V_{dd} modulation PMR can be reduced by clipping.

EER architectures with envelope [1] and phase [6] feedback loops have been implemented for narrowband applications but have never been investigated for WLAN. One solution is to design an amplifier that can tolerate V_{dd} modulation by introducing little V_{dd}/AM and V_{dd}/PM. This requires an in-depth investigation into novel switching amplifier designs. A lower and/or higher threshold could be set for V_{dd} modulation [7]. This contradicts the original concept of EER since it will result in partial reconstruction of the envelope, but it may help to reduce the V_{dd} modulation dynamic range. Determination of how much clipping can be tolerated in a WLAN application is important. This paper investigates the use of envelope and phase feedback to EER. In addition, the impact of clipping on ACPR and EVM is also investigated to explore the resulting robustness of a WLAN implementation.

A. *Envelope Feedback*

Envelope feedback was applied to EER as shown in Figure 4. The two envelope detectors operate at the same power level to ensure accurate comparison of the amplifier's input and output. This comparison produces an error signal that quantifies the difference between the input and output envelopes of the PA. Errors in the envelope are produced mainly by V_{dd}/AM conversion, and in practice, by the envelope detectors as well. Here, ideal envelope detectors are used and therefore the feedback loop only corrects for V_{dd}/AM distortion. The two envelope detectors were matched in magnitude by optimizing the output coupling factor where 25dB coupling was found to be suitable. Since envelope information of a signal is independent of the RF carrier frequency, this architecture is also suitable for an EER transmitter with a frequency translation stage before the PA. The output spectra from the envelope feedback system and the traditional (open-loop) EER are compared in Figure 5. The results show that some ACPR suppression is obtained but the emission mask cannot be satisfied.

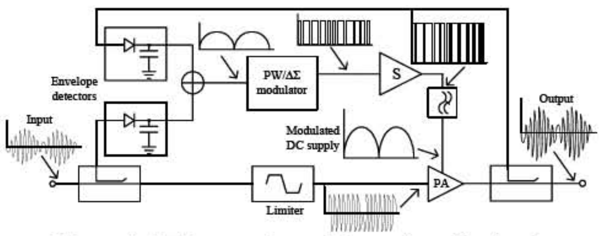

Figure 4: EER transmitter with envelope feedback.

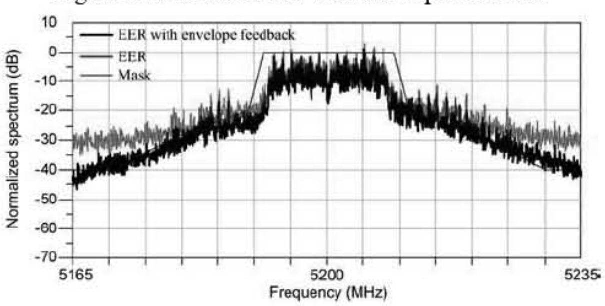

Figure 5: Output spectra when using envelope feedback and open-loop EER.

In practice, the architecture would need to be more complex than shown in Figure 4. A control mechanism may be needed to maintain the magnitude balance between the two envelope detectors, as the amplifier gain is likely to drift with temperature and due to aging. Matching the characteristics of the two envelope detectors is also important as they may introduce different amplitude errors that cannot be corrected. The bandwidth requirement of the feedback loop is dictated by the bandwidth of the signal's envelope. In this application, the feedback loop should operate over more than 60MHz with constant phase characteristics.

B. *Phase Feedback*

Phase feedback was employed in an EER transmitter as shown in Figure 6. The output of the amplifier was coupled and then limited by the limiter on the feedback loop. An RF mixer was used as the phase detector. The input signals of the mixer were at the same RF frequency and the produced error signal was the phase difference between these signals. The error signal was low pass filtered and applied to the voltage controlled phase shifter (VCPS). The ACPR improvement is considerable and the regulatory emission mask can now be satisfied (see Figure 7).

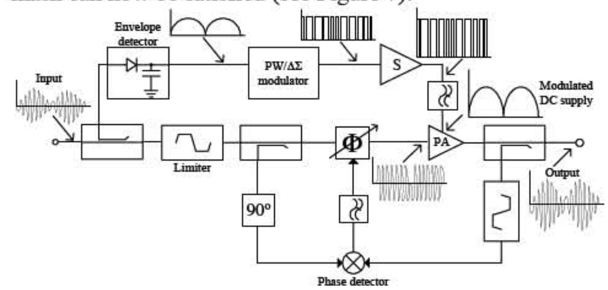

Figure 6: EER transmitter with phase feedback.

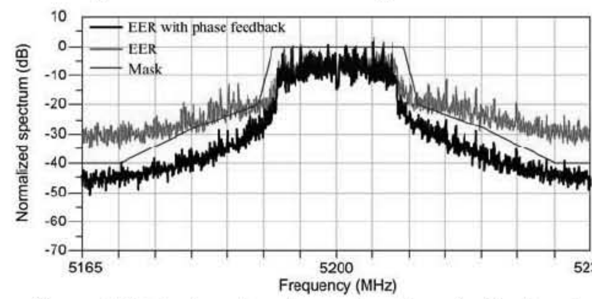

Figure 7: Output spectra when using phase feedback and open-loop EER.

In practice, the two limiters and the phase detecting RF mixer should not introduce phase distortion. The VCPS should provide a linear phase shift with the applied dc control voltage, and the sensitivity (degree/volt) should be sufficient to compensate for the V_{dd}/PM distortion. The VCPS employs semiconductor devices such as varactor diodes. When the dc bias voltage of a varactor diode is modulated, the series resistance changes as well as the capacitance. Consequently, the VCPS should be carefully designed to minimize this effect, which would otherwise result in undesirable AM modulation. The sensitivity of the phase detector is also critical. If this is too low then the detected error signal may need to be amplified to supply the VCPS. This additional amplifier would need to be efficient and highly linear.

Figure 8 shows that the phase feedback architecture is 4% more efficient (PAE) than the equivalent open-loop system when a loss-less VCPS is used. The PAE of the envelope feedback system declines faster than the other architectures, which demonstrates its sensitivity to changing signal levels. The PAE characteristic of the phase feedback architecture is similar to open-loop EER, thus it is insensitive to magnitude matching between the two compared signals. This reduces the complexity of the transmitter in a practical application.

The design of a switching mode power supply (SMPS) that can handle the broadband envelope of WLAN signals is a bottleneck for every EER architecture. A practical class-S amplifier with a ΣΔ modulated input signal has been demonstrated at 10MHz [8]. Although this is currently too low for a WLAN application, it is envisioned that DSP techniques can be used to achieve high frequency ΣΔ modulation. The bandwidth of the class-S amplifier can be extended by combining it in parallel with a class-B amplifier [9]. This would compromise the PAE but would increase the bandwidth.

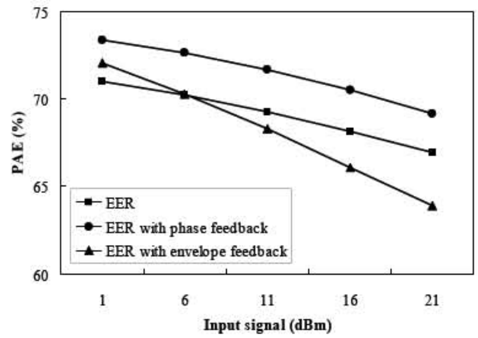

Figure 8: Comparison of the PAE when using the improved and traditional EER architectures.

C. Impact of Clipping on ACPR and EVM

Clipping may be implemented to reduce the PMR of a WLAN waveform. The impact of clipping on ACPR has been simulated by using the same IEEE 802.11a signal as used previously. The modulated signal was clipped in 0.5dB steps by the limiting amplifier. Increases in the output ACPR were calculated by integrating the power in the adjacent channels on the low (L) and high (H) sidebands of the spectrum. The relationship between ACPR and the severity of clipping is plotted in Figure 9. The IEEE 802.11a waveform can tolerate 1dB clipping without adding significant ACPR to the output spectra, whereas 1.5dB clipping adds more than 20dB ACPR.

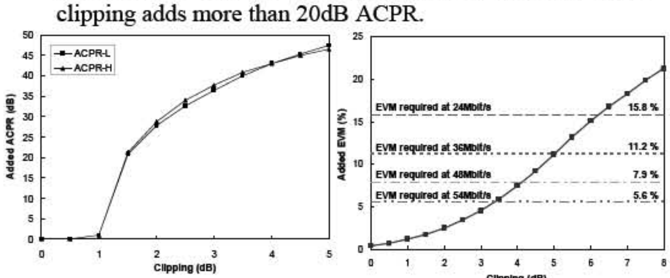

Figure 9: Impact of clipping on ACPR and EVM.

The impact of clipping on EVM was simulated using the IEEE 802.11a EVM measurement tool in ADS-Ptolemy. The waveform was clipped in 0.5dB steps and the EVM of the received signal was calculated. Figure 9 shows that 1.5dB clipping increases the EVM by 1.7%. The EVM requirement for IEEE 802.11a is more severe for high rate transmission than for lower rate modes. This analysis only quantifies the component of EVM added to the received signal due to clipping. If other imperfections are considered (e.g. PA nonlinearity, phase-noise, I/Q impairments, etc.) then it would be extremely difficult to satisfy the EVM requirement of IEEE 802.11a especially for high data rate transmission.

IV. Conclusion

The EER transmitter architecture has been investigated for WLAN applications. In addition to well known delay matching, envelope bandwidth and over-sampling requirements of EER, simulations show that high dynamic range V_{dd} modulation of a class-E amplifier introduces sufficient V_{dd}/AM and V_{dd}/PM to violate the emission specifications of a contemporary WLAN standard. The EER architecture has been improved by employing envelope and phase feedback. Envelope feedback is shown to improve ACPR performance, but the emission specifications cannot be satisfied. In contrast, with a phase feedback architecture the emission specifications of IEEE 802.11a can be met. Furthermore, the phase feedback architecture is insensitive to the amplitude matching between the two compared signals. This feature reduces the complexity of the transmitter. If clipping is implemented, then it is important to note that a clipping of only 1dB can be tolerated before the output of an IEEE 802.11a signal is degraded significantly.

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