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Analysis and Characterization of Mismatches in Outphasing Transmitter

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Abstract—The effect of imbalances in the quadrature modulators and the two RF paths of an outphasing transmitter are studied in this paper. A matlab model describing all the mismatches is used to investigate the effects on error vector magnitude (EVM) and adjacent channel interference. A test vector based method is used to measure and therefore compensate mismatch. This is applied in a 60 GHz outphasing transmitter in 40nm CMOS and measured mismatch is minimized further by using the compensation scheme. This resulted in improvement in output power and efficiency.

I. INTRODUCTION

Wireless communication has seen tremendous increase for high data rate over the last decade. To keep up with this huge demand, especially at Gbps data rates over short distances, mm-wave frequency communication is the way forward [1]. The 60 GHz band offers unlicensed 7 GHz bandwidth which can support this demand [2], [3]. The spectral efficiency is important and hence complex modulated signals with high peak-to-average-ratio (PAPR) is used. This forces the power amplifier (PA) to operate at back-off where efficiency is poor to ensure linearity. Thus there exists intrinsic trade-offs between the PA linearity and efficiency.

Such trade-offs can be delinked with the outphasing technique [4] in which the PA efficiency is maintained along with excellent linearity. The basic concept involves transforming the phase- and amplitude-modulated signal to two phase-only modulated signals, which are then individually amplified using two high efficiency non-linear PAs. Finally the original signal is reconstructed by combining the two amplified signals.

This paper first focuses on the effects of mismatch on the outphasing operation. Although using this technique linearity and efficiency can be maximized simultaneously, it requires both the paths to be matched well. Outphasing benefits from translation of amplitude variation to phase variations. The same benefit becomes detrimental in the presence of mismatch as it causes degradation of linearity and adjacent channel interference. Therefore matching is of utmost importance for outphasing transmitters. In practice, the two paths experience gain and phase imbalance. There have been various detection and compensation techniques for low GHz systems with narrow bandwidth signal which are validated by measurements [5]. In [6], a calibration based method is used which makes use of a correction loop, [7] relies on a model-based pre-distortion technique. In [8] the gain imbalance is minimized by tuning

Fig. 1. Outphasing principle

the supply voltages. In this work, a method similar to [9] is used to detect the mismatch.

The paper is organised as follows. The outphasing principle is explained briefly in section II. As mismatch is crucial for outphasing, it is dealt in section III. In section IV, an 60 GHz outphasing transmitter measurement along with mismatch compensation are described followed by conclusions in section V.

II. OUTPHASING PRINCIPLE

The complex modulated signal (e.g., 16QAM) $S(t) = A(t) \cdot \cos(\omega_c t + \theta(t))$ generally has amplitude and phase modulation. Due to the amplitude modulation the signal has a variable envelope. As shown in Fig. 1 the principle of outphasing is to translate this variable envelope signal $S(t)$ into two constant-envelope phase-only modulated signals, $S_1(t)$ and $S_2(t)$ as follows.

$$S_1(t) = \frac{A_M}{2} \cdot \cos(\omega_c t + \theta(t) + \varphi(t)) \quad (1)$$

$$S_2(t) = \frac{A_M}{2} \cdot \cos(\omega_c t + \theta(t) - \varphi(t)) \quad (2)$$

where ω_c is the carrier frequency, A_M is the peak value of $A(t)$, $\theta(t)$ indicates the modulated phase and the outphasing angle $\varphi(t)$ is given by

$$\varphi(t) = \cos^{-1} \left[\frac{A(t)}{A_M} \right] \quad (3)$$

Fig. 2. Architecture of outphasing transmitter with mismatch sources

The value of the outphasing angle $\phi(t)$ depends on the instantaneous amplitude $A(t)$. By summing the two outphased signals, the original amplitude modulation is restored and the original signal $S(t)$ is regenerated. To facilitate integration, the individual constant-envelope outphased signals $S_1(t)$ and $S_2(t)$ are usually generated by an quadrature upconverter as shown Fig. 2 using the signals from SCS and given by (4) and (5).

$$S_1(t) = S_{1I}(t) \cdot \cos(\omega_c t) - S_{1Q}(t) \cdot \sin(\omega_c t) \quad (4)$$

$$S_2(t) = S_{2I}(t) \cdot \cos(\omega_c t) - S_{2Q}(t) \cdot \sin(\omega_c t) \quad (5)$$

III. MISMATCH SOURCES

The architecture of an outphasing transmitter is shown in Fig. 2. It can suffer from two major types of imbalances, (a) imbalances between the quadrature modulators in each path and (b) imbalance between the two paths itself. The impact of these will be discussed further below.

A. Outphasing Matlab model

To evaluate the behaviour of an outphasing transmitter, an MATLAB[®] model is constructed which has the possibility to individually induce the various types of mismatch. An ideal receiver model with perfect carrier and timing recovery is assumed. The baseband dataset consisted of 8192 symbols of 16-QAM. They were pulse-shaped with raised cosine filter with roll-off factor of 0.35. Using this model, the effects of the mismatch on various performance metrics such as EVM and spectrum can be obtained.

B. Quadrature mismatch

In the architecture shown in Fig. 2, there are two quadrature modulators highlighted in gray box. The imbalances of the baseband and LO signal can all be lumped together into one set of amplitude and phase mismatches as ΔA and $\Delta\psi$ respectively. At this point it is assumed that both the quadrature modulators suffer from same mismatch to ease the analysis. Including the imbalances, (4) and (5) becomes,

Fig. 3. Degradation of EVM with quadrature phase mismatch for IQ and OP mode

$$\begin{aligned} S_i(t) &= S_{iI}(t) \cdot \Delta A \cdot \cos(\omega_c t + \Delta\psi) + S_{iQ}(t) \cdot \sin(\omega_c t) \\ &= [\Delta A \cdot S_{iI}(t) \cdot \cos(\Delta\psi)] \cos(\omega_c t) \\ &\quad + [S_{iQ}(t) - \Delta A \cdot S_{iI}(t) \cdot \sin(\Delta\psi)] \sin(\omega_c t) \end{aligned} \quad (6)$$

where $i = 1$ or 2 for the two paths. Amplitude or phase mismatch generates non-constant amplitude $S_1(t)$ or $S_2(t)$ which is undesired and leads to incorrect reconstruction of the output signal $S(t)$.

The above architecture (Fig.2) can also be used in conventional IQ mode by changing the baseband inputs $S_{1I}(t), S_{2I}(t)$ to $I(t)$ and $S_{1Q}(t), S_{2Q}(t)$ to $Q(t)$. Fig. 3 compares the EVM degradation of outphasing (OP) and conventional IQ mode as a function of quadrature phase mismatch (quadrature amplitude mismatch ΔA is assumed to be 0 dB and no RF path mismatch is assumed for simplicity). It is observed that OP mode degrades faster than conventional IQ. This is due to the nonlinear mapping of amplitude as in (3) where the $S_1(t)$ and $S_2(t)$ vectors are away from each other which enhances the mismatch effect. The impact is smaller in case of IQ mode as both the vectors $S_1(t)$ and $S_2(t)$ are equal and linearly mapped. Hence quadrature matching becomes more important for outphasing transmitters.

Fig. 4. Degradation of spectrum with phase mismatch between the two paths

C. Outphasing path mismatch

Another source of mismatch is the imbalance between two RF outphasing signals. It can occur either due to mismatch between the active devices of the PA stage or the passive components in the matching network. As shown in Fig. 2 the combined path imbalances can be captured with an effective amplitude and phase mismatch in one of the PAs, ΔG and $\Delta\varphi$ respectively as expressed by (7). This implies that one of the vectors has an error and the summation will lead to improper reconstruction. Fig. 4 shows the effect of phase mismatch on the output spectrum. As it is observed, phase mismatch causes the spectrum to spread which introduces adjacent channel interference potentially violating the spectral mask. It also causes in-band distortion as depicted by the degradation of EVM in Fig. 5. The outphasing Matlab model described in section III-A is used to perform these analysis.

$$S(t) = A_M \cdot \Delta G \cdot \cos(\omega_c t + \theta(t) + \varphi(t) + \Delta\varphi) + A_M \cdot \cos(\omega_c t + \theta(t) - \varphi(t)) \quad (7)$$

The reason behind the spectral spreading is obtained by simplifying (7) which yields four terms by trigonometric manipulation as in (8).

$$S(t) = A_M \cos(\varphi(t)) [1 + \Delta G \cos(\Delta\varphi)] \cos(\omega_c t + \theta(t)) - \Delta G A_M \cos(\varphi(t)) \sin(\Delta\varphi) \sin(\omega_c t + \theta(t)) + A_M \sin(\varphi(t)) [1 - \Delta G \cos(\Delta\varphi)] \sin(\omega_c t + \theta(t)) - \Delta G A_M \sin(\varphi(t)) \sin(\Delta\varphi) \cos(\omega_c t + \theta(t)) \quad (8)$$

The first two terms have $A_M \cdot \cos(\varphi(t))$ which is $A(t)$, the amplitude modulation. Whereas the last two terms have $A_M \cdot \sin(\varphi(t))$ which causes the nonlinearity. Mathematically, the operation is that of a $\sin(\cos^{-1}(A(t)/A_M))$ which cannot restore the amplitude modulation. Fig. 6 shows the spectrum of individual terms of (8) which supports the analysis and identifies the cause of spreading to be the $\sin(\varphi(t))$ term. The mismatch factors, ΔG and $\Delta\varphi$ only act as scaling factors in the form of $(1 \pm \Delta G \cos(\Delta\varphi))$ and $\sin(\Delta\varphi)$ which scales the effect of $\sin(\varphi(t))$.

Fig. 5. Degradation of EVM with phase and amplitude mismatch between the two paths

Fig. 6. Normalised spectrum of individual terms. Term 1, $A_m \cdot \cos(\varphi(t))$ and term 3, $A_m \cdot \sin(\varphi(t))$ for 5° path mismatch

IV. CASE STUDY : 60 GHz OUTPHASING TRANSMITTER

The above analysis highlighted the importance of quadrature and path matching for outphasing transmitters. A method similar to [9] is used for mm-wave mismatch detection. As the outphased signals $S_1(t)$ and $S_2(t)$ have constant-amplitude, it enables the use of single-tone as test signals with identical amplitude but different phases to detect the path mismatch. The method makes use of four test vectors comprising of one in-phase, two out-of-phase and one 90° phase difference signals to detect the path mismatch. At the output, only the amplitude of the reconstructed signal $S(t)$ is measured in all the cases and using a closed form expression, the amplitude and phase mismatch are calculated. Based on the detected mismatches, the compensation can then be applied on to $S_{1I}(t)$, $S_{1Q}(t)$ and $S_{2I}(t)$, $S_{2Q}(t)$ so that they compensate for the measured mismatch.

As a case study, a 60 GHz outphasing transmitter is fabricated in 40 nm CMOS [10]. Special precaution is taken in the layout to keep all the high frequency interconnects to be symmetrical. The measurement setup used to measure the mismatch is as shown in Fig. 7. The outphasing signals are generated by two synchronized arbitrary waveform generators (AWGs). The wafer is directly probed using two V-band probes for the LO and the RF_{out} . The transmitted signal-tone measurements to calculate the mismatch is performed by using Rhode & Schwarz Spectrum Analyzer. The initial measured phase error is only 1.5° as shown in Fig. 8. The computed

Fig. 7. Test setup to characterize mismatches in outphasing transmitter

Fig. 8. Measured mismatch at different compensation iterations

TABLE I
EFFECT OF MISMATCH COMPENSATION (MC) WITH DIFFERENT MODULATIONS AT EVM OF -25 dB ON MEASURED P_{AVG} AND η_{AVG}

	QPSK	8PSK	16QAM
P_{AVG} [dBm] (without MC)	14.2	14.0	10.4
P_{AVG} [dBm] (with MC)	14.7	14.5	11.2
η_{AVG} [%] (without MC)	19.5	21.0	10.5
η_{AVG} [%] (with MC)	20.5	22.5	12.5

compensations are applied and the data is re-loaded onto the AWGs to see the improvement. Because of good layout techniques, excellent matching is obtained in first place and it is further improved by applying the compensation method. The method is applied iteratively until no more improvement is possible. After correction, the mismatches converge to a lower bound, probably limited by the errors in the measurement setup. For the EVM measurement, the setup is slightly modified. The transmitted modulated signal is down-converted by a V-band mixer and sampled by an oscilloscope and the EVM is measured with a built-in software. A power meter is used to measure the output power. Table I summarizes the improvements obtained for different modulation schemes. For a fixed EVM of -25 dB, both the output power and efficiency are improved by 0.8 dB and 2 % for 16QAM signal by mismatch compensation at an output power of about 11 dBm.

V. CONCLUSION

In this paper, the analysis of quadrature and RF path mismatches on outphasing transmitters are described. The impact of mismatch on linearity and spectrum broadening are presented. The measurements on the 60 GHz outphasing transmitter confirmed that due to mismatch there is a loss in output power and efficiency for a fixed EVM and can be improved by compensation.

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