Abstract—The distortion from amplitude and phase imbalance in outphasing amplifiers is discussed. The relation between dynamic range (DR) and suppression of distortion is shown to approximately follow a simple linear relationship depending on the DR. Approximate relations between adjacent channel leakage power ratio (ACLR) for different kinds of commonly used communication signals and two-tone intermodulation distortion are given. Relations between loss in output power and reduction of DR as functions of duty cycle in switching-based outphasing amplifiers are also given. An approximate method to evaluate the possible performance of digital pre-distortion (DPD) is also given by considering a DPD capable of correcting all distortions except amplitude imbalance. The predicted performance is compared to the performance obtained using a DPD-model found in the literature. The results show that the method is in good agreement, demonstrating that the proposed method can be used for design and evaluation of predistorted outphasing amplifiers.

Index Terms—Power amplifier, nonlinear distortion, predistortion, CMOS.

I. INTRODUCTION

Modern wireless communication systems typically employ non-constant amplitude modulation schemes and wide bandwidths. These modulation schemes are used to meet requirements on spectral efficiency and the demand for high data rates. However, to meet the requirements on spectral purity and modulation quality, linear power amplifiers (PAs) are required [1]. A type of PA that has started to attract interest is the outphasing, or linear amplification using nonlinear components (LINC), PA [2], [3]. Ideally, the output of an outphasing PA is a linearly amplified version of the input signal. However, practical devices always experience non-ideal properties. These include limited dynamic range (DR) due to amplitude phase mismatch [3], [4], phase offset between the branches [3], [4], timing offsets between the branches [3], [4], load-pulling due to non-isolating combiners [5], [6], and linear frequency dependency in the matching networks re-introducing amplitude modulation [7]. These factors all contribute to the creation of spectral regrowth and reduce the modulation quality.

Traditionally, two-tone tests have been used to evaluate the linearity in linear and semi-linear PAs. Relationships between third order intermodulation (IM3) and adjacent channel power ratio (ACPR) have been established [8] for such PAs. For outphasing amplifiers such bounds are not equally well established. However, in outphasing PAs the situation is different compared to that in traditional PAs, as the outphasing signals fed to the amplifier stages have constant envelope and as there is no linear relation between the outphasing signals and the original amplitude- and phase-modulated signal.

Analysis of the distortions due to imperfections in amplitude and phase has been presented in [3], [4] but was limited to a few different signal types. This paper reviews part of the theory of distortions in outphasing PAs and gives the amount of out-of-band distortion for commonly used signal types. A method to evaluate the possible performance of DPD in outphasing amplifiers is also proposed and tested. The results are compared to those obtained by using a DPD-algorithm found in the literature.

The paper is organized as follows. Section II introduces the outphasing PA concept, looks at the distortions from imperfect signal combining and the influence of duty cycle mismatches when using switched PAs. The effects of the imperfections on spectral regrowth is derived in Section III. Conclusions are drawn in Section IV.

II. OUTPHASING AMPLIFIERS

A. Operating Principle

The outphasing amplifier is based on splitting an amplitude-modulated signal \( s(t) \) into two signals of constant envelope amplitude, \( s_1(t) \) and \( s_2(t) \). These two signals are then separately amplified by highly efficient amplifiers [2]. The two amplified signals are finally combined to restore the amplitude modulation. These three operations are handled by
three different parts in the outphasing amplifier architecture: the SCS, the amplifiers and the combiner, illustrated in Fig. 1. The outphasing signals \( s_1(t) \) and \( s_2(t) \) are given by [3]
\[
s_i(t) = s(t) \pm e(t)
\]
for \( i \in \{1, 2\} \), where
\[
e(t) = j s(t) \sqrt{\frac{R^2}{|s(t)|^2} - 1}
\]
and \( R \) is the maximum amplitude input signal amplitude. It is common to put \( R = s_{\text{max}} \), i.e., the maximum amplitude of the signal \( s(t) \).

The signal \( e(t) \) typically has significantly wider bandwidth than the original signal \( s(t) \) [3]. In the combiner stage the \( e \) contained in the signals \( s_1(t) \) and \( s_2(t) \) cancel if the outphasing amplifier is ideal. However, practical amplifiers suffer from non-ideal behavior, see [2]–[7], [9], [10].

### B. Imperfections and Distortions

In the following only the amplitude and phase imbalances are studied. The effect of frequency dependency in the matching networks was studied in [7] and the nonlinear interaction between the amplifiers in [5], [6]. Timing mismatch can be approximated as phase mismatch if the timing mismatch is “small” relative to the frequency content of the baseband signal.

Assume that the nominal output amplitude of the amplifiers \( A_1 \) and \( A_2 \) in Fig. 1 is \( g_1 = g_0 \) and \( g_2 = g_0(1 + \Delta_G) \), respectively. \( \Delta_G \) is the relative amplitude mismatch. Also assume that there is a phase mismatch of \( \Delta \). Then the output signal is given by
\[
y(t) = g_0 s(t)(2 - \Delta) + g_0 e(t) \Delta
\]
where \( \Delta = 1 - e^{j \Delta \phi} - \Delta_G e^{j \Delta \phi} \), with \( \Delta = 0 \) without amplitude and phase mismatch.

In [3] it was noted that the adjacent channel interference could be computed from (3) under some conditions that will be given shortly. Using (3) the power of the distortion in the frequency region \( C \), relative to the power in the frequency region \( R \), can be expressed as
\[
\frac{\int_C |E(f)|^2 df}{\int_R |S(f)|^2 df} = \frac{\int_C |E(f)|^2 df}{\int_R |S(f)|^2 df} \Delta^2
\]
given that the input signal \( s(t) \) has negligible power in the out-of-band region and that the power out-of-band is caused by \( e(t) \). \( S(f) \) and \( E(f) \) are the Fourier transforms of \( s(t) \) and \( e(t) \), respectively. \( C \) and \( R \) are the integration bandwidths for the frequency appropriate regions, e.g., for adjacent channel leakage power ratio (ACLR) \( C \) corresponds to the adjacent channel and \( R \) the channel used for the reference. \( D_S \) is the suppression of \( e(t) \) relative to \( s(t) \), assuming that \( \Delta E(f) \) is sufficiently small in comparison to \( (2 - \Delta)S(f) \).

Define dynamic range by [9]
\[
\text{DR} = 20 \log_{10} \left| \frac{g_1 + g_2}{g_1 - g_2} \right|
\]
i.e., the DR is the ratio of the largest-to-smallest output signal that can the amplifier can generate.

\( D_S \) is then a function of DR and phase mismatch, as illustrated in Fig. 2. The ACLR, or other measure of spectral regrowth, can be approximately computed using \( P_c \) and \( D_S \). \( P_c \) is computed for commonly used telecommunication signals in the next sections.

### C. DR and Duty Cycle in Switching Amplifiers

For switching amplifiers the amplitude imbalance can be related to the duty cycle of the driving signal of the switching transistors or asymmetries in the load impedances. Here, the effect of different duty cycles are investigated. Consider a rectangular wave-train with duty cycle \( d_i \), for \( i \in \{1, 2\} \) for the two paths. The Fourier-coefficients are given by [11]
\[
a_{i,n} = \frac{2A_i}{n\pi} \sin(n\pi d_i)
\]
where \( n \) is the harmonic number and \( A_i \) are the amplitudes. Assume that \( A_1 = A_2 = A \) and add the fundamental components \((n=1)\) for paths 1 and 2 to get the maximum output amplitude
\[
A_{\text{max, out}} = \frac{4A}{\pi} \sin \left( \frac{\pi(d_1 + d_2)}{2} \right) \cos \left( \frac{\pi(d_1 - d_2)}{2} \right).
\]

For 50% duty cycles on both amplifiers the output power is the maximum \( 4A/\pi \) but is reduced when \( d_1 \neq d_2 \).

Also the DR is affected by varying the duty cycle. Consider first the minimum amplitude given by
\[
A_{\text{min, out}} = \frac{4A}{\pi} \cos \left( \frac{\pi(d_1 + d_2)}{2} \right) \sin \left( \frac{\pi(d_1 - d_2)}{2} \right).
\]
Fig. 3. Contour plot showing the relative loss in output power and DR as functions of duty cycles $d_1$ and $d_2$ for the two branches of switching amplifiers. DR is shown in dotted grey lines and relative loss of output power in solid blue circles, both in dB.

Using (7) and (8) in the expression for DR results in

$$DR = 20 \log_{10} \frac{A_{\text{max, out}}}{A_{\text{min, out}}} = 20 \log_{10} \tan \left( \frac{\pi (d_1 + d_2)}{2} \right).$$

(9)

The relative loss in output power $A_{\text{max, out}}/(4A/\pi)$ and the DR in (9) are shown as contour plots in Fig. 3. The plots are symmetrical around the lines $d_1 = d_2$ and $d_1 = -d_2$.

### III. Spectral Regrowth

The two-tone signal was studied in [3], [4]. The results are repeated here for comparison purposes with signals used in modern telecommunication systems. Define an equivalent lowpass two-tone signal with frequency $\omega$.

The Fourier coefficients of the outphasing signal $e(t)$ shows that the IM products are approximately given by

$$\text{IM}_n = 2 \left( \frac{(-1)^n - 1}{\pi} \right) \frac{\pi (d_1 + d_2)}{2} D_s$$

where $n \in \{3, 5, \ldots \}$ and $D_s$ is defined in (4). In particular, $\text{IM}_3 = 2 D_s$.

To obtain approximate values for the out-of-band spectral content of the signal $e(t)$ given $s(t)$ for communication signals we use representative realizations of the given signal types. Simulations of an outphasing amplifier with varying DR are then compared to ACLR and two-tone intermodulation distortion (IMD) obtained theoretically. For all the signals the maximum DR is used by setting $R = s_{\text{max}}$.

In Fig. 4 the ACLR of 5 MHz Long Term Evolution (LTE) downlink, Universal Mobile Telecommunications System (UMTS) downlink, UMTS uplink and IM3 of two-tone signals are shown as functions of DR. The original signals $s(t)$ have different ACLR which explains the variation in ACLR at DR larger than 50 dB. However, in the region 20-50 dB DR, all of the tested signals have the same decrease in ACLR or IMD as function of DR, as predicted by (4). The final ACLR depends on the out-of-band ratio of $e(t)$ to the in-band ratio of $s(t)$, as shown in (4). The values of these ratios for the tested signal types are given in Table I. Note that for IM3 the ratio is given in relation to the amplitude of one of the two tones.

<table>
<thead>
<tr>
<th>Signal</th>
<th>LTE DL</th>
<th>UMTS DL</th>
<th>UMTS UL</th>
<th>Two-tone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio [dB]</td>
<td>-3.2</td>
<td>-7.4</td>
<td>-13.6</td>
<td>-3.0</td>
</tr>
</tbody>
</table>

### 1) DPD in Outphasing Amplifiers

The goal of DPD is often stated as applying a pre-inverse before the PA, such that the output signal is equal to the input signal, except for gain and time-delays. We assume that a DPD capable of correcting all distortions (phase, cross-talk and frequency dependency) except gain-imbalance, i.e., finite DR, is available. This is equivalent to limiting the lowest amplitude to $|g_1 - g_2|$. Such a DPD is the optimum from a sum-square perspective but it does not necessarily result in the lowest ACLR or IMD. However, most DPD-algorithms are constructed to minimize the sum-square error, which thus is equivalent to being limited by DR. The method gives an approximate number on practically
achievable linearity for a given DR.

The authors of [10] proposed a model-based DPD for outphasing amplifiers. The method is here tested on the “PA” in (3). Results for the cases of no DPD, DPD using the model in [10] and the DR-limit are shown in Fig. 5 for the lower IM3. Results are similar for upper IM3. The DR-limit shows approximately the same IM3 as that achieved by the DPD-method of [10] for all tested values of DR. Thus, the obtained results indicate that the DR-limit gives a useful estimate of achievable DPD-performance for amplifiers with finite DR, given that a sufficiently advanced linearizer is available.

IV. CONCLUSIONS

Relations between DR, duty cycle in switching-based outphasing amplifiers, two-tone IM3 and ACLR of modern communication signals are shown for outphasing amplifiers.

The resulting amount of distortion is shown to be an approximately linear function of the amplifier’s DR for DR larger than 20 dB, and the power of the distortion in the outphasing signal $e(t)$. Values for the distortions for some commonly used communication signals are also given. A method to estimate the performance of DPD in outphasing amplifiers with finite DR is also proposed and tested using a DPD-algorithm earlier proposed in the literature. The results from the DR-limit method and the DPD-model agree well, illustrating that the proposed method can be used for design and evaluation of predistorted outphasing amplifiers.

REFERENCES