Successive Cancellation of Power Amplifier Distortion for Multiuser Detection

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***Abstract*—This paper presents an iterative interference suppression technique to cancel power amplifier (PA) distortion at the receiver. The focus is mainly on single carrier frequency division multiple access systems, and on removing the distortion created by adjacent users' power amplifier. It is assumed that the receiver has perfect knowledge of all the users' transmitter power amplifier nonlinearities.**

By relaxing the requirement on PA linearity at the mobile terminals, the PA power efficiency can be improved. The simulations show that by utilizing the successive interference cancelation technique, the require signal to noise ratio required to achieve 10^{-3} symbol error rate is decreased by 3 – 4 dB. By using a clipped communication signal instead of backing off the power in the transmitter PA, we are able to improve the power added efficiency by 8 percentage points.

I. Introduction

A common characteristic of modern communication modulation signals is the high dynamic range associated with the peak to average power ratio (PAPR). A major drawback of this high dynamic range is, that due to the requirement on the linearity of RF power amplifiers, significant backoff of power is needed, which reduces the power efficiency of these devices. As the importance of energy preservation in both base stations and mobile handsets increases, advanced algorithms are required to maintain the necessary linearity while conserving as much energy as possible.

The requirement on PA efficiency - which helps determine the battery life for mobile communication systems [1] - and the limited processing power on handset devices has resulted in the suggested use of single-carrier frequency-division multiple access (SC-FDMA) instead of orthogonal frequency-division multiple access (OFDMA) in uplink communications. Compared to OFDMA, SC-FDMA has a lower PAPR, which somewhat relaxes the demand on the linearization of the PA at the mobile handset [2]. However, it seems that in order to maintain the quality of the communication signal and have high power efficiency at the transmitter, distortion reduction techniques are still required.

Distortion reduction techniques can be classified in two main groups depending on the physical location where they are applied; pre-distortion and post-compensation. Predistortion is a transmitter-side technique that attempts to compensate the nonlinearity of the PA by modifying the input signal. Utilizing this technique it is possible to linearize the PA which results in both lower inband and out-of-band distortion. A summary of these techniques can be found in [3], and they are generally focused on PA behavioral modeling and inverse modeling [4]. The linearity of a PA is a requirement in order to prevent interference between adjacent users in multicarrier systems.

Commonly in uplink communications, however, the processing power available on the mobile terminals is limited, which greatly reduces the ability to predistort the signal. Also, in higher order multicarrier systems, due to requirements on high power efficiency in the PAs, some nonlinear distortion seems inevitable. Therefore, post-compensation techniques have also been developed to compensate the nonlinearity of the PA at the receiver.

Some well-known methods for post-compensation of PA nonlinearities are nonlinear equalization [5], Bayesian inference for signal recovery [6], and estimation and cancelation of nonlinear distortion [7], [8]. An advantage of these techniques is that the requirements on bandwidth and power remain unchanged, and they only add to the complexity of the system at the receiver, where computational power is abundant. In [8], maximum likelihood detection of nonlinearly distorted OFDM symbols is presented. An iterative algorithm is proposed for wired channels. This technique was implemented for wireless channels in [9], [10] for space division multiple access (SDMA) OFDM systems, for OFDM relay assisted systems in [11], and for direct sequence CDMA systems in [12].

In the reports discussed above, the focus has been on improving the signal quality by removing the inband distortion caused by the transmitter PA. In this paper, we continue this approach by focusing on cancellation of nonlinear PA distortion in the uplink communication of *adjacent users* in SC-FDMA systems as well as inband distortion. The focus on SC-FDMA is because of the use of this modulation format in uplink communications and because interference from adjacent users can normally be attributed to adjacent frequency bands only. The application of this work can result in relaxing the requirements on out-of-band emission in communication systems. Hence, it can be used to improve the transmitter's PA efficiency by allowing the use of more nonlinear PAs – which

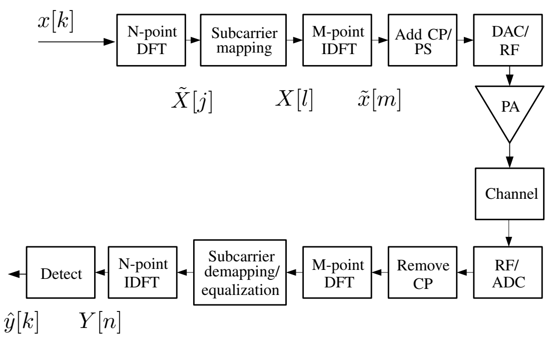

Fig. 1. Transmitter and receiver structure of an SC-FDMA system.

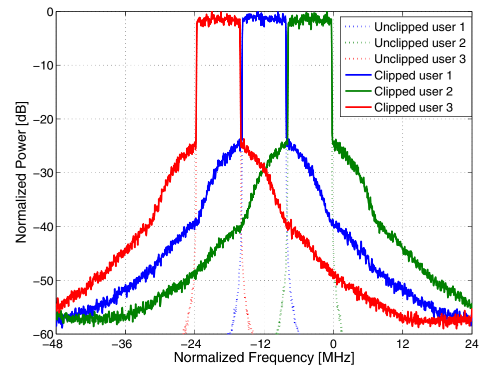

Fig. 2. Spectrum response of 3 users in the SC-FDMA system. Dashed lines are when linear PAs are used and solid lines are when clipping is done on the communication signal

have higher efficiency – in the communication system.

The paper is organized as follows: in Section II the experiment setup is described and PA models are given. In Section III the successive cancellation algorithm is explained and presented, and in Section IV the simulation procedure and results are discussed. The paper is summarized and conclusions are drawn in Section V.

II. Background on the SC-FDMA communication signal

The general transmitter and receiver structure for SC-FDMA is shown in Fig. 1. A detailed description of SC-FMDA is given in [13]. In [14] the performance of SC-FDMA and OFDMA are compared and the statistics for SC-FDMA are analyzed. As in the case of OFDMA, the PAPR of the transmitted user signal is strictly dependent on the number of subcarriers, but for all configurations the PAPR gain by using SC-FDMA instead of OFDMA is approximately 2.2 dB [14].

At the input to the transmitter, baseband modulation transforms the binary input into a multilevel sequence of complex numbers $x[k]$, in either BPSK, QPSK, 16-QAM, or 64-QAM. For this work, we consider a 16-QAM signal as the input sequence. SC-FDMA can be either localized or distributed. In localized all the resource blocks are allocated to the user in a contiguous manner, while in distributed these blocks are randomly distributed over the entire bandwidth [14]. The PAPR of the SC-FDMA signal used in this work is 7.8 dB. An important assumption that is made for simplification in this work is that the users are synchronized.

III. Power amplifier distortion on the communication signal

Under small signal conditions, power amplifiers operate as linear devices. As the drive level increases, power amplifiers become more nonlinear and distorting [15]. In wideband operation, power amplifiers tend to distort the communication signal in two ways; by nonlinear amplification and by exhibiting memory effects. In this work for simplicity, we will only consider the distortion effects of nonlinear amplification.

The simplest memoryless nonlinear model for power amplifiers is the soft limiter. In this model, it is assumed, with some predistortion at the transmitter, that the nonlinear input-output relation of a PA can be estimated as:

$$g(x) = \begin{cases} x & \text{if } |x| \leq A_{\max}, \\ A_{\max}\frac{x}{|x|} & |x| \geq A_{\max}, \end{cases} \quad (1)$$

where $A_{\max}$ is the only parameter in the model and represents the saturation level of the power amplifier. This is equivalent of clipping the samples with amplitude higher than $A_{\max}$ in the communication signal. In this simple PA model, the AM/AM component is considered to be linear to the saturation level $A_{\max}$, and the AM/PM component is zero. While this model may not be realistic for practical devices, with a suitable predistorter the performance will approach this behavior. In this work, it is assumed that the receiver has perfect knowledge regarding all users power amplifier models, i.e. all the users $A_{\max}$.

Clipping causes the constellation diagram of the received signal to become noisy. The clipping however, reduces the PAPR. The PAPR of the clipped signal used in this work is 2.3 dB, compared to the original 7.8 dB for the SC-FDMA unclipped signal.

In Fig. 2, the effect of clipping the communication signal in the frequency domain is shown. For comparison the case for linear power amplifiers is also given. It can be observed that the clipping effect of the PA not only distorts its own signal, but also the adjacent users' signal.

From this figures, the adverse effect of clipping the communication signal can be seen. In terms of PA efficiency however, allowing the PA to clip the communication signal results in higher average efficiency. Power amplifiers are normally designed for high peak efficiency, and when they are in back-off operation the efficiency drops dramatically [16]. In this work, to show this behavior, measurements were done on a class-E Laterally Diffused Metal Oxide Semiconductor (LDMOS) power amplifier [17].

In Fig. 3 the power added efficiency (PAE) is shown versus

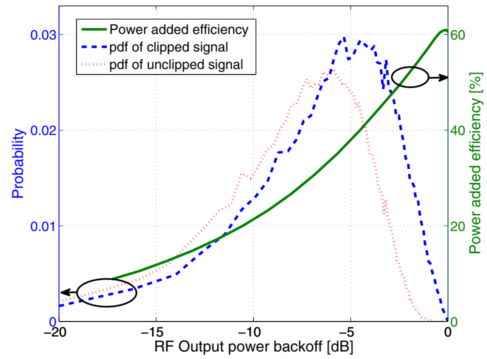

Fig. 3. The power added efficiency vs the probability density of the clipped and unclipped communication signal.

backoff power for this PA. The PAE is defined as [16]

$$\text{PAE} = 100 \times \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{DC}}}, \tag{2}$$

where P_{out}, P_{in} and P_{DC} are the RF output power, RF input power and DC power supplied to the PA respectively. It can be noticed that while the PA has acceptable peak efficiency performance, the efficiency decreases at backoff. Averaging the clipped and unclipped communication signals over this efficiency, the average PAE can be obtained. For the unclipped signal, the average PAE is 34% while for the clipped signal this value is 42%. Although by using the clipped signal the communication signal becomes distorted, the PA efficiency improves by 8 percentage units; a relative improvement of 25%.

IV. Distortion cancelation algorithm

In order to maintain the orthogonality of users in the presence of PA nonlinearity in a SC-FDMA system, different approaches have been taken. In some approaches, a guardband has been inserted between users which results in a decrease of frequency utilization. Another approach is to filter the output of the PA, which results in a loss in power efficiency. Backoff has also been used to maintain the orthogonality, which also results in a lower power efficiency as shown in Section II.

Successive interference cancellation algorithm has been used to compensate self-distortive effects of the PA in [8], [10], [11] and [12]. In this work, the algorithm is extended to compensate adjacent user distortion as well. This well-known technique can help alleviate the hardware deficiency in the PA. By using this algorithm, we allow the PAs to behave nonlinearly and hence with high power efficiency, and cancel the known distortive effects at the receiver. The general structure of the distortion cancelation method for 2 users is shown in Fig. 4.

In this figure, the "Detect $y_i[k]$" block maps the received signal Y_{received} to user i's sequence, and the "Estimate $d(y_i[k], y_j)$" block estimates the distortion created by user i on user j by recontracting the output signal (with the nonlinear distortion created by the PA) at user i's terminal.

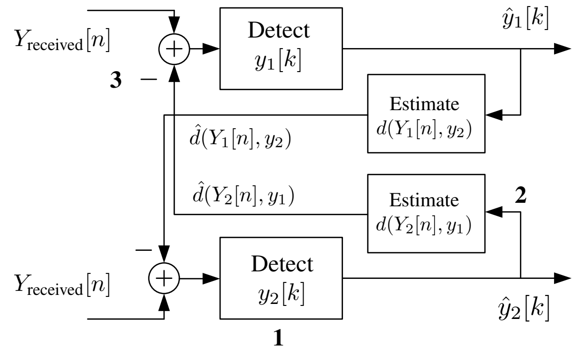

Fig. 4. Block diagram of the successive nonlinear cancelation method. The algorithm steps are numbered, so the first step is to detect $y_2[k]$ and so on. The same procedure is then done on for user 1.

TABLE I
Successive Distortion Cancellation Algorithm.

1. Detect QAM signal for user 2
Down-sample and filter $Y^0_{\text{received}}[n]$.
$\tilde{y}^0_2[k] = \sum_i h(i) y_{\text{received}}(i-k)$.
$\hat{y}^0_2[k] = \min_{a_i} \|\tilde{y}^0_2[k] - a_i\|$.

2. Estimate distortion created by user 2 on user 1's signal
a. Modulate $\hat{y}^0_2[k]$,
b. Up-sample to $\hat{Y}^0_2[n]$,
c. Shift in frequency
$\check{Y}^0_2[n] = \hat{Y}^0_2[n] e^{-i2\pi n f_0}$,
d. Clip with known information of user 2's PA model.
$\hat{d}^0\left(Y_2[n], y_1\right) = g_2(\check{Y}^0_2[n])$.

3. Subtract the distortion from the total received signal
$Y^1_{\text{received}}[n] = Y^1_{\text{received}}[n] - \hat{d}^0\left(Y_2[n], y_1\right)$.

4. Go to step 1 and switch places of users

For simplicity we assume that there are two adjacent users, but the technique can be easily extended for more users. In order to make a joint decision on the symbols of both users, an iterative approach is taken. The algorithm implemented is shown in Table I. The superscripts represent the iteration number, while the subscripts represent the users.

It is important to remember that the power amplifier affects the RF communication signal, and not the baseband signal. In order to remove its effects, we assume that the received signal $Y_{\text{received}}[n]$ is an oversampled baseband version of the RF signal at the receiver. It has been down-converted in frequency to baseband, but it is still oversampled to represent an RF signal.

In the first step, the total received signal $Y_{\text{received}}[n]$, is filtered to user 2's frequency range. User 2's signal is detected using the minimum Euclidean distance using a warped constellation by applying the PA nonlinearity to the normal 16-QAM constellation points. With this warped constellation, in practise, we have accounted for the inband distortion created by the PA, and $\hat{y}^0_2[k]$ is found,

$$\hat{y}^0_2[k] = \min_{a_i} \|\tilde{y}^0_2[k] - a_i\|, \tag{3}$$

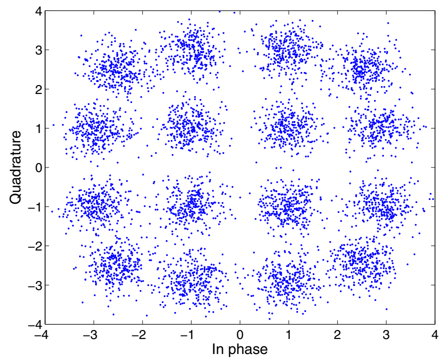

Fig. 5. Constellation diagram at the receiver for user 1, iteration 0, when both users have nonlinear PAs.

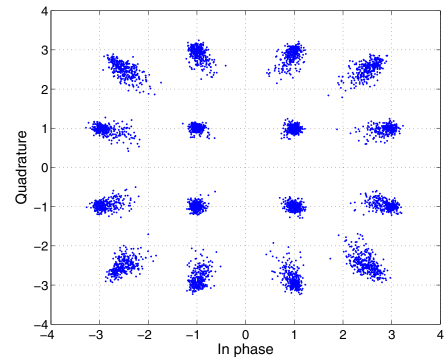

Fig. 6. Constellation diagram at the receiver for user 1 after the first iteration.

where a_i are the warped constellation points.

In the second step, the receiver reconstructs user 2's transmitter by constructing the FDMA modulator, up-converting the signal and applying the PA nonlinearity. The signal will also be shifted in frequency to the appropriate frequency band.

In the third step, the distortion is subtracted from the total received signal,

$$Y^1_{\text{received}}[n] = Y^1_{\text{received}}[n] - \hat{d}^0\left(Y_2[n], y_1\right). \tag{4}$$

Finally in the fourth step, the users place are interchanged and the algorithm is run for the next user. Once all steps are run for both users, the first iteration is over. The process will be iterated until the changes in the detections are very small. In this work, during the detection process, we have used hard decoding to detect the symbols, which has resulted in a fast convergence of the algorithm; in most cases, only a single iteration is needed.

A final note regarding the PA nonlinear distortion is that the effect of a users PA nonlinearity mainly only affects the direct adjacent users and to a lesser extent users that are 2 channels away, so applying the technique in multiple access schemes will not result in exponential growth in complexity.

V. Simulations

In this section, the simulation results of a 16-QAM signal with FDMA for 2 adjacent users is provided. Analysis of the effect of PA nonlinearity on system capacity is available in [10]. It was shown that the asymptotic channel capacity is bounded due to the nonlinear distortion of the PA. Channel state information is assumed to be known at the receiver to be able to only analyze the effect of PA nonlinearity.

The constellation diagram at the receiver for user 1 in a AWGN channel with Signal to Noise Ratio (SNR) of 25 dB and with nonlinear distortion for user 2 is shown in Fig. 5. This is the received signal constellation for user 1, iteration 0 and at step 1 for the aforementioned algorithm.

The algorithm is applied to this sequence, and the nonlinear distortion from user 2's signal is removed. The resulting constellation diagram for user 1 is shown in Fig. 6. It can be observed that compared to Fig. 5, the distortion is decreased and the constellation points are less noisy.

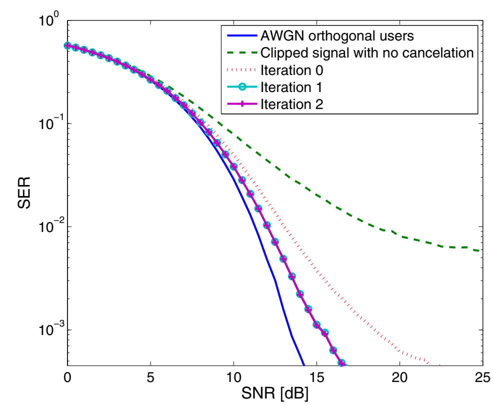

Fig. 7. Symbol error rate vs signal to noise ratio for different scenarios. The PA nonlinearity is assumed to be known in the algorithm.

Subsequently, the algorithm is now applied to find user 2's sequence. The estimate of user 1's sequence is fed the the reconstructed transmitter and its PA nonlinearity is applied. User 1's distortion on user 2's signal is then found and user 2's signal is detected again, which will be improved. The iterations are continued until the change in decisions are minute. With the hard decisions in this work, the algorithm converges after the first iteration for each user, but by allowing soft decisions to be made the performance could be further improved with more iterations.

Fig. 7 shows the Symbol Error Rate (SER) vs SNR for this system. For comparison, the perfect AWGN channel with orthogonal users is shown, and the case when the nonlinearity is not known at the receiver is also given.

When no compensation is done on the receiver, multiuser interference results in the SER saturating at around 5×10^{-3}. The dotted red line shows iteration zero in the algorithm. This is equivalent of only removing the inband distortion created by the PA, and no inter user distortion cancellation. We can see that compared to the case of no cancellation algorithm, the performance is greatly improved, but still far from the

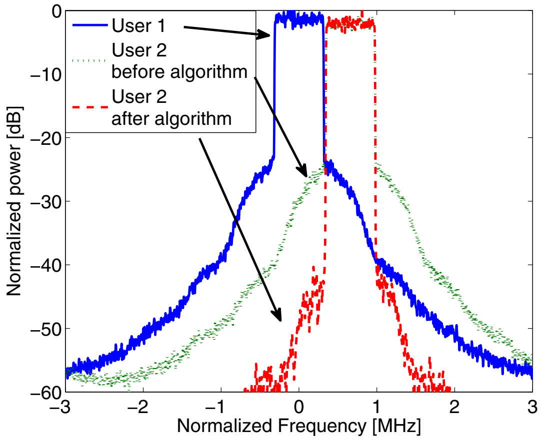

Fig. 8. The spectrum of the communication signals before and after applying the algorithm. The green dotted line is the spectrum for the adjacent user, and the red dashed line is the signal spectrum after applying the algorithm to remove distortion. The inband signal before and after applying the algorithm for user 2 overlap.

orthogonal users case.

By utilizing the successive distortion cancelation technique and canceling inter-user interference, at SER of 10^{-3} the improvement in SNR is about 3 – 4 dB compared to the case when PA knowledge is used to only cancel inband distortion. It can also be observed that the improvement in the second iteration is minute, and the algorithm converges in the first iteration. Further, the fast convergence of the algorithm only adds a small processing delay to the system.

Finally, the out-of-band spectrum of the signal using this technique can be compared with the original distorted signal. A common measure of out-of-band distortion is the Adjacent Channel Power Ratio (ACPR) [4]. The ACPR value for user 2's original signal is -28.3 dB. The value for the the signal after applying the distortion reduction algorithm is -46 dB. This represents a huge improvement in channel power leakage. This can also be observed from Fig. 8, where the spectrum of the signals are shown.

It can be observed that the adjacent user's signal has much less power leaked into the main users bandwidth compared to the original case. Since this is done at the receiver, and distortion was allowed at the transmitter, the possibility to remove the PA distortion without negatively affecting the power efficiency was shown.

The PA model was assumed to be similar for all transmitters and known at the receiver, but more studies could be done on how robust the algorithm is to more practical situations where users have different PAs and the power received differs between users. Further, the work can be continued by analyzing the assumption of synchronous users, and by using a more realistic PA model. It can also be improved by taking "soft decisions" instead of "hard decisions" in the present algorithm, to obtain better performance.

VI. Conclusions

In this paper, a successive distortion cancelation technique is presented to cancel the nonlinear distortion created by power amplifiers. By removing the PA distortion caused by clipping at the receiver instead of backing off in the power at the transmitter or inserting a guardband, power amplifier power efficiency can be improved while maintaining spectral efficiency. This work can result in relaxing the requirements on out-of-band emissions from levels in current standards.

The simulations showed that at a symbol error rate of 10^{-3}, with the proposed technique an improvement of 3 – 4 dB in SNR is achieved compared to only removing distortion from the inband signal. By using the clipped signal with lower PAPR, the power added efficiency of the power amplifier is increased by 8 percentage units.

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