

Baseband Compensation Techniques for Bandpass Nonlinearities

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Abstract—In this paper we present and compare several methods of compensating the nonlinearity of the RF front-end of a wireless system. Two baseband compensation techniques, namely predistortion and post-distortion (equalization) of the baseband signal are discussed and the problems associated with each one is addressed. Furthermore a combination of a predistorter and a nonlinear equalizer and also predistortion of oversampled baseband signal are analyzed. It will be shown that under realistic conditions with a frequently saturated amplifier and ISI channel, the latter two methods are able to compensate the nonlinearity up to a good extent, while the first two methods can only operate under certain assumptions for channel conditions and nonlinearity type.

I. INTRODUCTION

Broadband wireless systems require bandwidth efficient modulation schemes such as high constellation QAM. The main drawback of such modulations is the large envelope fluctuations, making the system sensitive to nonlinearity of the high power amplifier. The nonlinearity causes signal compression and as a result introduces distortion and intermodulation. To reduce the signal compression, the operating point of the amplifier can be set far from the compression point which in turn causes low power efficiency. Hence it is necessary to have some means of compensation for the nonlinearity of the RF front-end.

Several compensation techniques have been proposed to reduce the nonlinear distortion. Data predistortion techniques are among the methods which have gained more attentions due to the simplicity of digital implementations [1], [2], [3], [4].

The nonlinearity of the high power amplifier of the transmitter can also be compensated at the receiver [2]. A nonlinear equalizer is required at the receiver to compensate the transmitter nonlinearity, while it can also be used for channel ISI reduction. Such an equalizer can be adaptive if the nonlinearity is unknown or varying with time.

A combination of the predistorter and nonlinear equalizer can also be used to get a better linearization.

An improvement to the compensation methods can be made by oversampling the baseband signal before the D/A. Oversampling of the symbols at the transmitter enables us to pre-filter the signal. This can be viewed as moving part of the filtering to the digital domain.

In this paper we make a thorough study of methods for compensating nonlinearities including data predistortion at the transmitter, nonlinear equalization at the receiver, a combination of a data predistortion and nonlinear equalization, and a predistorter with oversampling of the baseband signal. Furthermore we compare different methods based on their perfor-

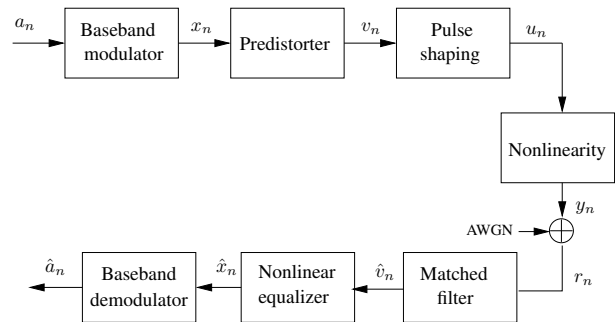


Fig. 1. Block diagram of baseband equivalent of system including the predistorter and nonlinear equalizer.

mance and the complexity.

The organization of the paper is as follows. In section II the model of system under consideration is briefly described. In section III different methods of compensation is theoretically discussed. The performance of the proposed system is evaluated in section IV. Finally section V summarizes the results and draws the conclusions.

II. SYSTEM MODEL

Fig. 1 illustrates the block diagram for the baseband equivalent of the system under consideration. The baseband modulator generates a sequence of complex baseband symbols. The baseband modulation considered in this paper is 16QAM. In a typical transmitter, the baseband modulator is followed by a D/A. After the D/A conversion a pulse shaping filter is used to generate the baseband analog signal. A root-raised cosine pulse shaping filter can be used in order to avoid ISI. The baseband analog signal then modulates a carrier which is the input to the transmit high power amplifier. The nonlinearity block in the system of Fig. 1 represents the baseband equivalent of the high power amplifier. In this paper we use the measurements on a solid-state high power amplifier which is designed for the RF front-end of a 60 GHz transmitter. Fig.2 shows the amplitude conversion (AM/AM) and phase conversion (AM/PM) of the amplifier.

The data predistorter and nonlinear equalizer blocks in Fig. 1 are the additional parts that are discussed in the next section.

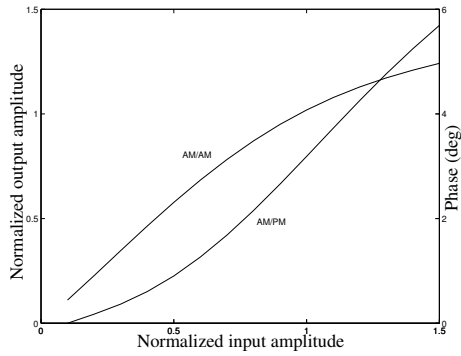


Fig. 2. AM/AM and AM/PM conversions of the high power amplifier

III. COMPENSATION METHODS

In this section signal distortion at the receiver is considered as the cost function in an optimization problem, and we try to make the distortion as small as possible with different methods.

Four different structures are analyzed and their ability to minimize the nonlinear distortion is discussed. It will be shown that two of the solutions can only remove a small part of the distortion, while the last two ones can give better results.

In the following subsections we consider the above mentioned methods and point at the advantages and disadvantages of each method

A. Data predistorter

In this section we consider the system of Fig. 1 with a predistorter at the transmitter and without any nonlinear equalization at the receiver. The predistorter is a polynomial one with parameters optimized adaptively through a minimum mean square method.

The idea is to design the predistorter such that the combination of predistorter-filter-nonlinearity performs exactly like the pulse shaping filter followed by a constant gain [5]. This is important from the view point of minimizing the ISI at the receiver. Therefore a proper design of predistorter must include the pulse shaping filter, and the formulation of problem is the minimization of

$$J = E[|y_n - \hat{u}_n|^2], \quad (1)$$

where \hat{u}_n is the output of the pulse shaping filter with ideal baseband input data and no predistortion as illustrated in Fig. 3.

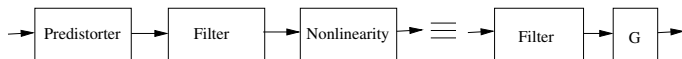


Fig. 3. The concept of data predistortion to compensate the nonlinearity of the transmitter front-end.

As an example we design an adaptive predistorter for the solid state high power amplifier discussed earlier in this section. The predistorter is a polynomial one with an input-output characteristic of the form

$$(\gamma_1 r + \gamma_2 r^2 + \dots + \gamma_L r^L) \exp(\psi_0 + \psi_1 r + \psi_2 r^2 + \dots + \psi_L r^L), \quad (2)$$

where r is the magnitude of the input signal, γ_i 's are the coefficients of the amplitude predistorter and ψ_i 's are the coefficients of the phase predistorter. The expression (2) can be written in vector form as

$$\mathbf{\Gamma} \mathbf{R}_\gamma \cdot \exp(\mathbf{\Psi} \mathbf{R}_\psi) \quad (3)$$

where $\mathbf{R}_\gamma = [r, r^2, \dots, r^L]$ and $\mathbf{R}_\psi = [1, r^1, \dots, r^L]$. To minimize the J in (1) we have to find the vector of predistorter coefficients $\mathbf{\Gamma}$ such that the following expression is minimized [6]

$$E[\mathbf{\Gamma} \mathbf{R}_\gamma - Gr] \quad (4)$$

and the coefficients $\mathbf{\Psi}$ should minimize

$$E[\mathbf{\Psi} \mathbf{R}_\psi - \phi(r)] \quad (5)$$

where $\phi(r)$ is the AM/PM conversion of the amplifier.

Using a gradient method the solutions to the above optimization problems can be found by iterating the following expressions

$$\begin{aligned} \mathbf{\Gamma}_{k+1} &= \mathbf{\Gamma}_k - \epsilon_\gamma \nabla J_k(\mathbf{\Gamma}), \\ \mathbf{\Psi}_{k+1} &= \mathbf{\Psi}_k - \epsilon_\psi \nabla J_k(\mathbf{\Psi}). \end{aligned} \quad (6)$$

The parameters ϵ_γ and ϵ_ψ are the step sizes and ∇ is the gradient operator.

Fig. 4 shows the convergence behavior of the coefficients of the polynomial predistorter, γ_i and ψ_i .

In section IV the performance of this method is evaluated and compared to the other methods.

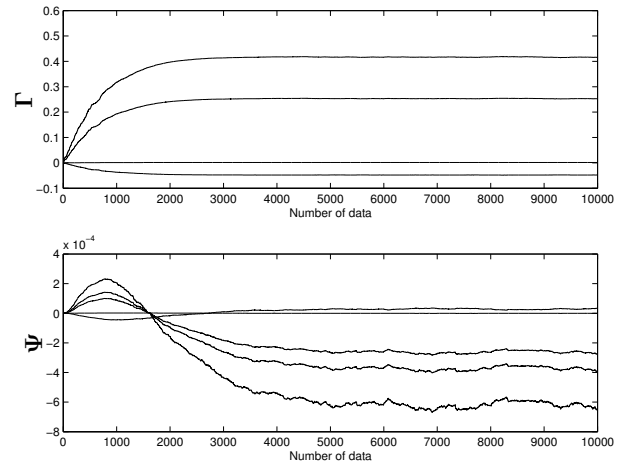


Fig. 4. Coefficients of the amplitude and phase predistorters

B. Nonlinear equalizer

A memoryless data predistorter can not remove the nonlinear distortion made by a filter-nonlinearity which is a nonlinearity with memory. An alternative solution is a linearizer with memory. A Volterra predistorter or equalizer can be used at the transmitter or receiver to mitigate the nonlinear distortion. We assume the same nonlinearity of the last section and design a 3rd order nonlinear equalizer of the form

$$\hat{x}_n = \sum_{k=0}^{K-1} c_k \hat{v}_{n-k} + \sum_{k_1=0}^{K-1} \sum_{k_2=0}^{K-1} \sum_{k_3=0}^{K-1} c_{k_1 k_2 k_3} \hat{v}_{n-k_1} \hat{v}_{n-k_2} \hat{v}_{n-k_3}^* \quad (7)$$

where \hat{v} is the received signal after the matched filter sampled at $t = nT$. The equalizer coefficients c can be found using a Recursive Least Square (RLS) [7] to minimize the following error expression

$$e = E[|\hat{x}_n - x_n|^2], \quad (8)$$

Fig. 5 shows the convergence behavior of the coefficients of the nonlinear equalizer found using the method explained here.

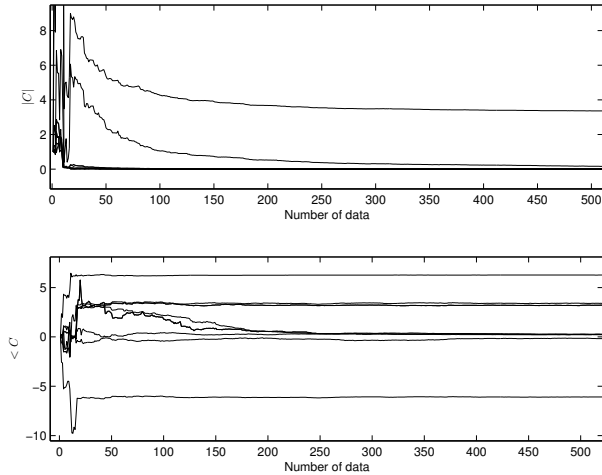


Fig. 5. Magnitude and angle of the nonlinear equalizer's tap

The performance of this method is analyzed in section IV. We will also discuss how a Volterra system works when it is used at the receiver.

C. Combination of predistorter and nonlinear equalizer

In this section we use the polynomial predistorter in combination with a nonlinear equalizer to minimize the error expression

$$e = E[|\hat{x}_n - x_n|^2], \quad (9)$$

Expressions (1) and (9) can be minimized jointly through a recursive method. This is done in section IV and the performance is compared to the other methods discussed earlier.

D. Oversampling the baseband data

Oversampling the baseband signal enables us to do operations such as filtering the signal before the D/A. Therefore compensation for the memory of the system is also possible in baseband. Furthermore oversampling the baseband signal avoids aliasing. Due to the hardware limitations a high oversampling rate is not possible. However in many cases at least some oversampling is affordable. In section IV we present results on this method and the ability of it to mitigate the nonlinear distortion.

IV. PERFORMANCE OF THE PROPOSED METHODS

In this section we discuss the methods of compensation presented in the previous section, in terms of their ability to correct the signal points and mitigate the nonlinear distortion.

First we consider the system with a predistorter as discussed in section III. The resulting signal constellation at the receiver

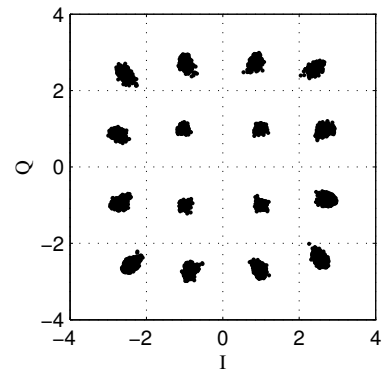


Fig. 6. IQ plot of the original received signal

is shown in Fig. 7. As it can be seen from the figure, although the center of the clouds are corrected, the variance of the cloud is even larger than the uncompensated signal constellation (Fig. 6). The problem mainly resides in the fact that there is a filter in the chain which introduces memory to the system. If there is no filtering between the predistorter and the nonlinearity, and the nonlinearity is perfectly known and invertible, one can perfectly compensate the first zone output of the bandpass nonlinearity using a data predistorter. In practice, however there is always a pulse shaping filter before the nonlinear amplifier. As a consequence a compensation method with memory must be used to counteract the memory of the system as well.

A baseband predistorter gives rise to nonlinear ISI, while it corrects the center of each cluster. A Volterra predistorter or postdistorter can compensate the nonlinear distortion to a better level.

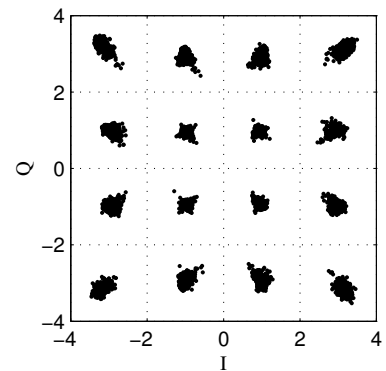


Fig. 7. System with data predistorter

The second method which is considered here is the nonlinear equalizer. As discussed earlier a nonlinear equalizer has the advantage of containing memory which can take care of the nonlinearities with memory. The signal point constellation of the equalized system is also shown in Fig. 8.

A major problem with the nonlinear equalizer is its sensitivity to the channel noise. In addition, the complexity of the nonlinear equalizer increases exponentially with the number of taps. Also since the nonlinear equalizer operates at the re-

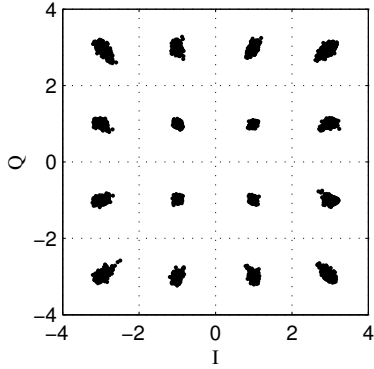


Fig. 8. System with nonlinear equalizer

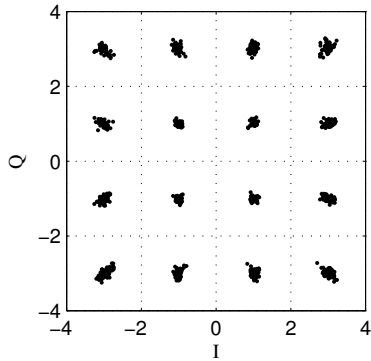


Fig. 9. System with predistorter and nonlinear equalizer

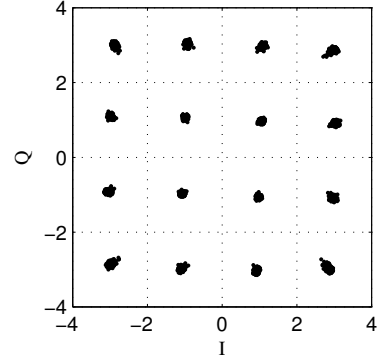


Fig. 10. System with oversampled data and predistorter

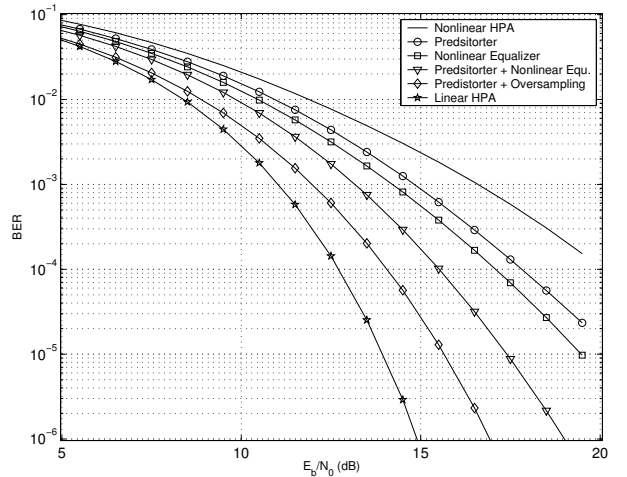


Fig. 11. Bit error rate as a function of SNR for different compensation methods

ceiver side, the out of band power at the transmitter RF is not changed. This makes the nonlinear equalizer less attractive.

The results for the nonlinear equalizer presented here also hold for a similar structure used at the transmitter, because we did not consider channel noise and ISI. As it was shown, the improvement in the signal space correction is not that much with a nonlinear equalizer of reasonable complexity. According to the above discussion, combating the nonlinear distortion of the transmitter, using a predistorter or equalizer of affordable complexity is quite challenging.

As an alternative to the aforementioned methods we used a combination of the predistorter and nonlinear equalizer. It can be shown that a joint optimization of the parameters of the predistorter and nonlinear equalizer leads to less nonlinear ISI. A combination of the predistorter and nonlinear equalizer is used in the system of Fig. 1. Fig. 9 shows the resulting signal constellation at the receiver.

The last method that was discussed in section III was the predistorter with oversampled baseband signal. Oversampling can be seen as moving part of the analog signal processing to the digital domain. An oversampling rate of infinity would therefore mean that the filtering effect can be totally neglected and the predistorter can be placed after the pulse shaping filter. Fig. 10 shows the signal constellation at the receiver when an oversampling of order four is used with a polynomial predistorter. A better compensation is possible if higher oversampling rate can be used.

V. CONCLUSIONS

Four different baseband methods for the compensation of nonlinearity of the RF front-end in a wireless transmitter is discussed and compared to each other. It was shown that to compensate a bandpass nonlinearity a memoryless compensation technique is not good enough. The other three methods perform better because of a memory that was included in the compensation. On the other hand these techniques have higher complexity. The performance comparison shows that a predistorter with a baseband oversampling rate four outperforms all the other methods.

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REFERENCES

- [1] S. Pupolin and L.J. Greenstein, "Performance analysis of digital radio links with nonlinear transmit amplifier," *IEEE Journal on Selected Areas in Communications*, vol. 5, pp.534–536, Apr. 1987.
- [2] G. Karam and H. Sari, "Analysis of predistortion, equalization, and ISI cancellation techniques in digital radio systems with nonlinear transmit amplifier," *IEEE Transactions on Communications*, vol. 37, pp.1245–1253, Dec. 1989.
- [3] G. Lazzarin, S. Pupolin and A. Sarti, "Nonlinearity compensation in digital radio systems," *IEEE Transactions on Communications*, vol. 42, pp.988–999, Feb. 1994.
- [4] D.S. Han and T. Hwang, "An adaptive pre-distorter for the compensation of HPA nonlinearity," *IEEE Transactions on Broadcasting*, vol. 46, pp.152–157, June 2000.
- [5] C. Eun and E.J. Powers, "A predistorter design for a memory-less nonlinearity preceded by a dynamic linear system," *Proceeding of the IEEE Global communications conference*, pp.152–156, Nov. 1995.
- [6] H. Besbes and T. Le-Ngoc, "A fast adaptive predistorter for nonlinearly amplified M-QAM signal," *Proceeding of the IEEE Global communications conference*, vol. 1, pp.108–112, Nov.-Dec. 2000.
- [7] A. Papoulis and S. Unnikrishna, "A fast adaptive predistorter for nonlinearly amplified M-QAM signal," *Probability, Random Variables and Stochastic Processes*, McGraw-Hill, 2001.