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The effect of nonlinear distortion on the performance of MIMO systems

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ABSTRACT

Nonlinear amplification in wireless systems results in in-band distortion which degrades system performance. The effect of nonlinear distortion is more severe in multiple-input multiple-output (MIMO) systems because signal encoding at the transmitter (such as transmitter precoding in singular value decomposition (SVD)-based MIMO) results in signals with higher peak-to-average ratio (PAPR) than single-input single-output (SISO) systems. In this paper, the effect of nonlinear amplification on the performance of a MIMO system is analyzed. The performance analysis is based on relating in-band distortion to system BER of a M-QAM modulated signals transmitted over a MIMO Rayleigh fading channel. It is shown that transmitter precoding results in increased in-band distortion and hence, increased system BER over the case when no precoding is used. The results presented in this paper can be used to derive limit of nonlinearity which allow energy efficient MIMO systems.

1. Introduction

Multiple-input multiple-output (MIMO) systems (along with other technologies) have been employed in fourth generation (4G) wireless systems due to their capability of enhancing system capacity and overcoming fading channel effects. However, a number of issues face the design of MIMO systems that achieve the intended enhancement of system capacity and/or system performance. One of these issues is the effect of nonlinearity of High Power Amplifiers (HPA) at the transmitter on system performance where nonlinear distortion tends to degrade the system signal-to-noise ratio (SNR) and hence, system BER at the receiver side [1].

The key to understanding the effect of nonlinear amplification on system performance is to identify the component of the nonlinear output which is responsible for degradation of system SNR. Based on the orthogonalization of the nonlinear model presented in [2–5], the nonlinear output can be partitioned into a useful signal component and uncorrelated distortion component which is responsible of degrading the system performance. The uncorrelated distortion consists of two main components: the first is in-band distortion and the second is out-of-band distortion. While out of band distortion causes Adjacent Channel Interference (ACI), in-band distortion is responsible for the degradation of channel SNR and hence system BER.

The amount of uncorrelated distortion power depends on the envelope variations of the transmitted signal and its peak-to-average power ratio (PAPR). Therefore, different signal modulation schemes introduce different amounts of nonlinear distortion and hence, system BER is affected differently. In MIMO systems, signal precoding results in higher PAPR and hence, nonlinear distortion results in severe degradation of system SNR and BER.

The effect of nonlinear amplification on the performance of MIMO system has been studied in the literature where the objective was to develop performance metrics relating nonlinear amplifier characteristics to system performance such as system BER, spectral broadening and out-of-band emission, etc. [6–13]. These studies aimed to design modulation schemes, transmit precoding schemes, power allocation schemes, and detection techniques for MIMO systems in the presence of nonlinear amplification. In [14], the effect of nonlinear distortion and channel estimation errors on the performance of ZF receivers was studied where an upper bound on the bit error rate (BER) for M-QAM were derived. In [15], the impact of nonlinearities of the transmitter and receiver in multiple antenna OFDM systems was analyzed and probability of error in the presence of nonlinear distortion and Rayleigh fading was derived analytically. It was shown that transmit and receive nonlinearities have different effects on system performance. In [16], the authors investigated the effects of transmit nonlinearity generated by multi-carrier amplifiers in multi-input-single-output (MISO) cellular systems where it was shown that intermodulation distortion can be reduced by proper frequency allocation.

In previous work of the author [2–5], nonlinear distortion of HPA in SISO wireless systems was modeled using the orthogonalization of the nonlinear characteristics which enabled in-band distortion

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to be accurately quantified. In this paper, we use the orthogonalized model of nonlinearity to accurately model the effects of nonlinearity on the performance of MIMO systems. In particular, the performance degradations of M-QAM modulated signals due to nonlinear amplification in different MIMO setups is analyzed. Two MIMO systems are considered: a MIMO system based on Singular Value Decomposition (SVD) which incorporates transmitter precoding; and a MIMO system based on a Zero-Forcing (ZF) receiver where no transmitter precoding is used. The results presented in this paper can be used in the design of coding and predistortion schemes which aim to eliminate nonlinear distortion and for finding optimum operating points of non-linear amplifiers in MIMO channels.

2. Nonlinear distortion in wireless systems

High Power Amplifiers are usually operated in their nonlinear mode in order to achieve high power efficiency. Nonlinear amplification results in signal distortion which degrades system performance. In order to quantify this distortion, a nonlinear model is used to model the input-output relation of the HPA. Nonlinear models are classified into two main groups: memoryless models and models that consider memory effects [5]. In this paper, we consider a memoryless model due to its simplicity.

A memoryless nonlinear amplifier can be modeled using a power series model of the form [2]:

$$y(t)=\sum_{n=1}^{N} a_n x^n(t). \tag{1}$$

where a_n are complex coefficients, $x(t)$ and $y(t)$ are the complex envelopes of the input and output of the HPA respectively.

Note that this model can be used to quantify the out-of-band distortion by deriving the signal spectrum of the total nonlinear output. Quantifying in band distortion, however, requires partitioning the nonlinear the output into correlated (useful) and uncorrelated (distortion) components where in-band distortion is quantified as the power in the in-band component of the uncorrelated output.

In order to estimate the effective distortion component of the nonlinear output, the nonlinear model in 1 can be converted into a model with orthogonal components of the form [2]

$$y(t)=\sum_{n=1}^{N} c_n u_n(t) \tag{2}$$

where $u_n(t)$ represent the nth order orthogonalized nonlinear components and c_n are a new set of envelop coefficients which represent the orthogonalized model. The orthogonal set u_n can be obtained using Gram-Schmidt orthogonalization procedure as [2]

$$u_n(t)=x_n(t)-\sum_{m=1}^{n-1} \alpha_{nm} u_m(t) \tag{3}$$

where

$$c_n=\sum_{m=n}^{N} a_m \alpha_{mn} \tag{4}$$

and α_{mn} is the correlation coefficients between the x_n and u_m and can be found as [2]

$$\alpha_{nm}=\frac{E[x_n(t)u_m^*(t)]}{E[u_m(t)u_m^*(t)]} \tag{5}$$

where $x_n(t) = x^n(t)$. Note that the new set of coefficients depends on the original envelop coefficients and the input signal power level represented by the correlation coefficient α_{mn}.

As a result, the nonlinear output can be expressed as

$$y(t)=y_c(t)+y_d(t). \tag{6}$$

where using (2)

$$y_c(t)=c_1u_1(t)=c_1x(t) \tag{7}$$

is the useful component correlated with the input signal, and

$$y_d(t)=\sum_{n=2}^{N} c_n u_n(t) \tag{8}$$

is the uncorrelated distortion component.

Note that from (3), $u_1(t) = x(t)$ represents the useful signal of the nonlinear output. The effects of nonlinearity in this term are included in the coefficient c_1 which results in gain compression. Nonlinear distortion effects are consolidated in the uncorrelated term $y_d(t)$ which represent all the output terms uncorrelated with the input signal $x(t)$. Hence, the distortion component $y_d(t)$ can now be dealt with as an additive noise component and hence, the effective SNR within the signal bandwidth and system BER can be calculated.

3. MIMO system model

The input/output relationship of an $M_t \times M_r$ MIMO system can be written as [17]

$$\mathbf{r}=\mathrm{Hy}+\mathrm{n} \tag{9}$$

where the vector $\mathbf{y}=[\,y_1 \quad y_2 \quad \ldots \quad y_{M_t}\,]^T$ represents transmitted signal after power amplification, the vector $\mathbf{r}=[\,r_1 \quad r_2 \quad \ldots \quad r_{M_r}\,]^T$ represents the received signal vector, the matrix $\mathbf{H}$ represents the $M_r \times M_t$ channel matrix and $\mathbf{n}$ is a complex zero-mean Gaussian noise vector such that $E[\mathbf{nn}^H]=\sigma^2\mathbf{I}_{M_r}$. Note that the time variables have been dropped for shortening the notation. The MIMO channel is considered as an uncorrelated Rayleigh flat fading channel and hence, the channel matrix $\mathbf{H}$ has zero mean unit variance i.i.d complex Gaussian entries [8].

Fig. 1 shows a MIMO transmitter model where source data is split into multiple data streams which are then modulated, precoded, pulse-shaped, power amplified and then applied to multiple antennas. Up-conversion to the carrier frequency is dropped from this model given that the analysis is done at the complex envelope level where an envelop model of the nonlinear PA is used. Therefore, let the $\mathbf{s}_i$ be the modulated data symbol at branch i, and s be the data symbols stacked, then the vector $\mathbf{s}$ is the linear combination of data symbols stacked in a vector $\mathbf{s}=[\,\mathbf{s}_1 \quad \mathbf{s}_2 \quad \ldots \quad \mathbf{s}_{M_t}\,]^T$, obtained by splitting an input bit stream and mapping each resulting sub-stream to a finite signal constellation. In general, data symbols of different sub-streams belong to a given complex constellations, such that $s_i \in A_l$, where A_l denotes the symbol alphabet for the l-th sub-stream, $l = 1, 2, \ldots, M_t$. The modulated symbols are precoded using a precoding matrix $\mathbf{B}_t$ and hence, the precoded vector $\mathbf{s}^p$ writes as

$$\mathbf{s}^p=\mathrm{B_t s} \tag{10}$$

where $\mathbf{B}_t$ represents the $M_t \times M_t$ precoding matrix [8].

According to Fig. 1, modulated symbols $\mathbf{s}^p$ of each branch are applied to a pulse-shaping filter with impulse response $g(t)$.