Prediction and PAPR Reduction in Precoded MIMO-OFDM

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***Abstract*- Emerging multimedia applications require high data rates and reliability which can be met by MIMO-OFDM. Precoding at the transmitter can lead to increased link reliability and this requires channel state information (CSI) at the transmitter. CSI can be obtained through channel prediction. A high peak-to-average power ratio (PAPR) of the transmitted signal on each antenna proves to be a major drawback of MIMO-OFDM. If PAPR is not reduced, it will restrict MIMO-OFDM systems for practical applications. This paper studies the effect of two PAPR reduction techniques, namely clipping and peak insertion (PI) in precoded MIMO-OFDM. Channel prediction is done exploiting the temporal correlation existing among MIMO-OFDM signals. The performance of PAPR reduction techniques and channel prediction is studied through simulations and the PI method is found to provide greater PAPR reduction than clipping method.**

Keywords - MIMO-OFDM; Channel Prediction; SISO Predictor; Precoding; PAPR; Clipping; Peak Insertion

I. INTRODUCTION

Moving from the third generation (3G) communication systems, the present era is of fourth generation (4G) mobile communications. Based on the developing trends of mobile communication, 4G will have broader bandwidth, higher data rate, and smoother and quicker handoff and will focus on ensuring seamless service across a bunch of wireless systems and networks [1]. The bandwidth resource available in 4G is still scarce and there is a need for improvement in spectrum efficiency. The integration of multiple input multiple output (MIMO) and orthogonal frequency division multiplexing (OFDM) appears to be a potential solution in this regard due to its high spectral efficiency, robustness to frequency selective fading, increased diversity gain, and enhanced system capacity [2], [3].

In MIMO-OFDM, the transmission with CSI can provide higher link capacity. Precoding at the transmitter is known to simplify the receiver section. For this, CSI is usually attained through feedback from the receiver. In practical MIMO systems, feedback delay is inevitable due to delays in estimation, processing and feedback. Due to this inherent time delays, the CSI obtained from the receiver may get outdated by the time it is used at the transmitter. This results in significant performance loss, especially in high mobility environments. Erroneous CSI often results in wasted power, high bit error rates and non-optimal throughput. Prediction of the CSI into the future is thus an effective technique for mitigating the performance degradation due to feedback delays [4], [5], [6].

A major disadvantage of MIMO-OFDM lies in the prohibitively large peak-to-average power ratio (PAPR) of the transmitted signal on each antenna [7]. The output in MIMO- OFDM systems is the superposition of several subcarriers. Whenever, the phases and frequencies of these carriers match coherently, instantaneous power outputs may increase greatly and become higher than the mean power of the system resulting in a high PAPR. This demands nonlinear system devices such as high power amplifiers (HPA), ADCs, DACs and speech synthesizers with a large dynamic range, which are extensively expensive. This also causes high consumption of power at the base station leading to very low efficiency-cost. To avoid this, a transmitter side algorithm is required to reduce PAPR. Several works have been done on PAPR reduction in SISO-OFDM [8], [9], [10]. These PAPR reduction techniques can be applied separately to each transmit antenna in MIMO-OFDM, thereby achieving overall PAPR reduction.

In this paper, we formulate a MIMO-OFDM system model for channel prediction [11], [12]. The framework for channel prediction in MIMO-OFDM was taken from [6]. A 2×2 MIMO-OFDM system has been simulated and the channel coefficients has been predicted, exploiting the temporal correlation existing among the MIMO-OFDM signals. Transmitter precoding is done using this predicted coefficients. Two techniques, namely clipping and peak insertion, are used for PAPR reduction in this precoded MIMO-OFDM. Clipping method has been discussed in previous works for SISO systems [8], [9]. Peak insertion method has been extended from [10] for MIMO-OFDM. The channel prediction performance has been depicted using normalized mean square error (NMSE) plot. The PAPR reduction is evaluated using complementary cumulative distribution function (CCDF) plots, and the bit error rate (BER) plots for various cases of MIMO-OFDM have been simulated.

This paper is organized as follows. Section II briefly explains the MIMO-OFDM system model and the channel model used in simulations. The channel prediction scenario and the precoding method are described in section III. The PAPR reduction techniques are included in section IV. Section V discusses the simulation procedure and the results. Finally, conclusions are drawn in section VI.

II. SYSTEM MODEL

Consider a MIMO-OFDM system with M transmit antennas and N receive antennas. The input bit stream is first multiplexed in space and time into M parallel streams, by the MIMO encoder, before being modulated by OFDM modulators. The reverse operation is done at the receiver side by the OFDM demodulators and MIMO decoder.

The received signal at the v^{th} receive antenna is given by

$$r_v(n) = \sum_{u=1}^{M} \sum_{l=0}^{L_m-1} h_{u,v,l} x_u(n-l) + w_v(n) \quad (1)$$

where $x_u(n)$ is the signal transmitted by the u^{th} transmit antenna, L_m is the maximum length of CIR, and $w_v(n)$ is the complex additive Gaussian noise at v^{th} receive antenna with mean zero and variance σ^2.

The received signal vector in the frequency domain is given by

$$\tilde{\mathbf{r}} = \begin{bmatrix} \mathbf{\Lambda}_{1,1} & \vdots & \mathbf{\Lambda}_{2,1} & \vdots & \cdots & \mathbf{\Lambda}_{M,1} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \mathbf{\Lambda}_{1,2} & \vdots & \mathbf{\Lambda}_{2,2} & \vdots & \cdots & \mathbf{\Lambda}_{M,2} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \mathbf{\Lambda}_{1,N} & \vdots & \mathbf{\Lambda}_{2,N} & \vdots & \cdots & \mathbf{\Lambda}_{M,N} \end{bmatrix} \begin{bmatrix} \tilde{\mathbf{x}}_1 \\ \cdots\cdots \\ \tilde{\mathbf{x}}_2 \\ \cdots\cdots \\ \vdots \\ \vdots \\ \cdots\cdots \\ \tilde{\mathbf{x}}_M \end{bmatrix} + \tilde{\mathbf{w}}. \quad (2)$$

where $\mathbf{\Lambda}_{u,v}$ is the diagonal matrix with frequency domain channel coefficients between u^{th} transmit and v^{th}receive antenna, $\tilde{\mathbf{x}}_u$ is the frequency domain transmitted signal vector from u^{th} transmit antenna, and $\tilde{\mathbf{w}}$is the AWGN vector at the receiver.

The impulse response of the wireless channel can be represented as

$$h_{v,u}(t,\tau) = \sum_{l=0}^{L_{v,u}-1} h_{v,u}(t,l)\delta\left(\tau - \tau_{v,u}(l)\right), \quad (3)$$

where $L_{v,u}$ is the number of multiple radio paths of the (u,v)-th antenna pair, δ(.) is the Kronecker delta function, $\tau_{v,u}(l)$ and $h_{v,u}$(t,l) are the delay and complex value CIR at time t of the l-th path from the (u,v)-th antenna pair respectively. The time domain CIR with symbol time T_s can be represented in a discrete manner as

$$h_{n,m}(i,l) = h_{n,m}(iT_s, l) \quad (4)$$

Assume a random Rayleigh fading channel model satisfying the wide-sense stationary uncorrelated scattering (WSSUS) as

$$E\{h_{n,m}(i+\Delta i, l) h_{n,m}(i,l')\} = r_t(\Delta i)\delta(l-l') \quad (5)$$

where $r_t(\Delta i)$ is the channel's time-delay correlation function. Due to WSSUS property, $h_{n,m}(i+\Delta i, l')$ and $h_{n,m}(i,l)$ are uncorrelated for $l \neq l'$.

III. CHANNEL PREDICTION AND PRECODING

A. Prediction Framework

The system model for the channel prediction [6] is shown in Fig.1. Since the time domain prediction approach outperforms frequency domain approach, it is used in this paper. The time-domain channel coefficients of every channel pair (*m,n*) are obtained using channel estimation techniques.

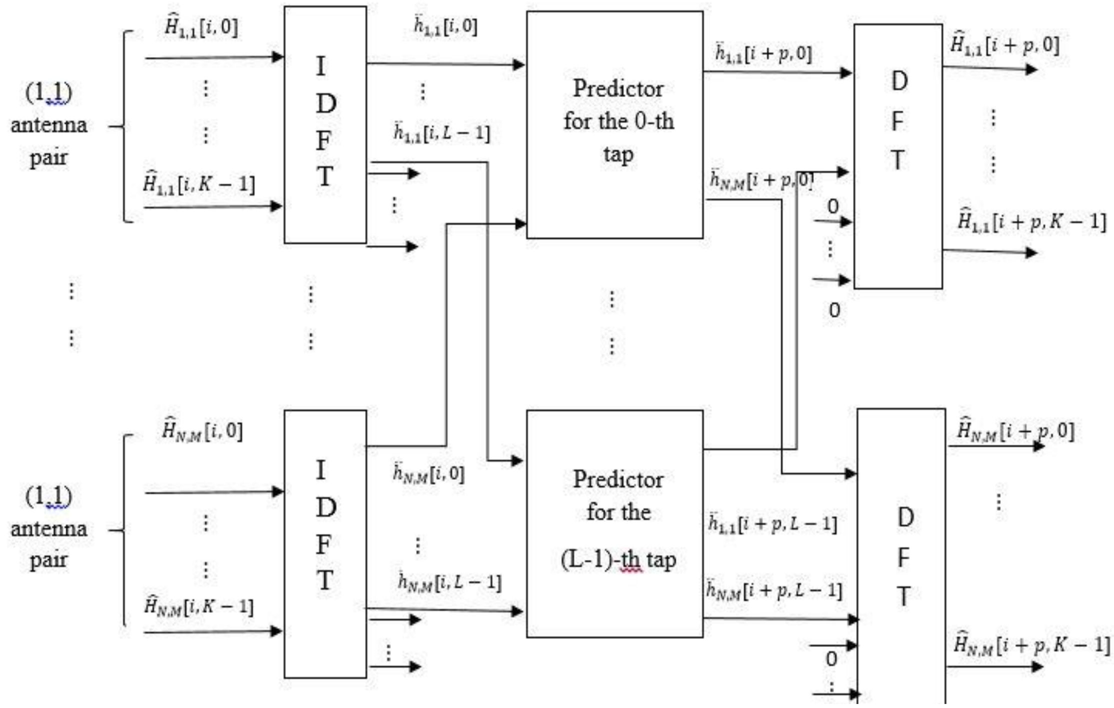

Fig. 1 System model of MIMO-OFDM channel prediction

$$\hat{h}_{n,m}(i,l) = \begin{cases} h_{n,m}(i,l) + z_{n,m}(i,l), l = 0, \dots, L-1 \\ z_{n,m}(i,l), l = L, \dots, K-1 \end{cases} \quad (6)$$

where $z_{n,m}(i,l)$ is a zero mean AWGN with variance

$$\beta^2 = \frac{\sigma_z'^2}{K} \quad (7)$$

and $\sigma_z'^2$ is the variance of the estimation error.

The channel estimation is followed by a MIMO predictor which is designed to predict the time domain channel impulse response $h_{n.m}(i+p,l)$ for each delay l=0,…,L-1, where L-1 denotes the channel's maximum delay and p the prediction length. Finally, the time-domain impulse response sample $\hat{h}_{n,m}^{pre}(i+p,l)$ is transformed to the frequency domain channel coefficient $\widehat{H}_{n,m}^{pre}(i+p,l)$.

B. *SISO Predictor*

A prediction algorithm that only considers the temporal correlation in MIMO-OFDM, called the SISO predictor is used in this paper. Let p be the prediction length and Q be the number of current and previous estimated coefficients of the channel taken into consideration for every tap of the channel. $\hat{h}_{n,m}^{pre}(i+p,l)$ is predicted using the data set $\mathbf{h}_{n,m}(i,l)$ with a Q-order MMSE filter w_S as

$$\hat{h}_{n,m}^{pre}(i+p,l) = w_s^H \hat{\boldsymbol{h}}_{n,m}(i,l), \quad (8)$$

where

$$\hat{\boldsymbol{h}}_{n,m}(i,l) = [\hat{h}_{n,m}(i,l), \hat{h}_{n,m}(i-1,l), \dots, \hat{h}_{n,m}(i-Q+1,l)]^T, (9)$$

and

$$w_s(\boldsymbol{R}_s + \beta^2 \boldsymbol{I})^{-1} \boldsymbol{r}_s, \quad (10)$$

Here, $\mathbf{R}_s$ is the Hermitian-symmetric and Toeplitz $Q \times Q$ temporal autocorrelation matrix with entries

$$[R_s]_{i,j} = r_t((i-j)T_s)$$

$$\boldsymbol{r}_s = [r_t(pT_s), \dots, r_t((p+Q-1)T_s)]^T.$$

where $r_t(\Delta t)$ is defined in (5).

C. *Precoding*

Precoding takes advantage of the frequency selectivity of the multipath fading channel [12]. It is a method equivalent to frequency equalization, except that it is done at the transmitter instead of receiver. In frequency equalization, there are chances that the noise power gets magnified at the receiver, if the channel response has null points. This problem is avoided in precoding where the signal is multiplied by inverse of the channel response, so that noise power is not magnified. If **H** is the channel matrix obtained through channel prediction, and **X** is the signal after OFDM modulation, precoding is done as

$$\boldsymbol{P} = \frac{\boldsymbol{X}}{\boldsymbol{H}} \quad (11)$$

where **P** is the precoded signal to be transmitted.

IV. PAPR REDUCTION TECHNIQUES

For a M × N MIMO-OFDM, the PAPR of the i^{th}symbol on the n^{th}transmit antenna can be defined as

$$PAPR_{i,n_t}\left(x_{i,n_t}\right) = \frac{\max[|x_{i,n_t}|^2]}{\mathrm{E}[|x_{i,n_t}|^2]}.$$

where x_{i,n_t} is the time domain OFDM signal from n_t transmit antenna. In MIMO-OFDM, high PAPR exists on each of the transmitted signals from different antennas at the base station. Hence the overall PAPR is defined in case of MIMO-OFDM which is the maximum of PAPRs among all transmit antennas.

$$PAPR_{i(overall)} = \max_{i<m<M} PAPR_{i,m} \qquad (13)$$

where $PAPR_{i,n_t}$ is defined in (12). CCDF of PAPR in MIMO-OFDM is defined as

$$CCDF = P(PAPR_{overall} > PAPR_0) \qquad (14)$$

where $PAPR_0$ is the threshold value.

A. *Clipping Method*

One of the simplest and easiest approaches for PAPR reduction is clipping which can snip the signal at the transmitter so as to eliminate the appearance of high peaks above a certain level. The pseudo-maximum amplitude above which the signal is clipped in this approach is referred to as the clipping level and is denoted by A. Let $x[n]$ denote the pass band signal and $x_c[n]$ denote the clipped version of $x[n]$. Then $x_c[n]$ can be expressed as

$$x_c[n] = \begin{cases} -A, & x[n] \le -A \\ x[n], & |x[n]| < A \\ A, & x[n] \ge -A \end{cases} \qquad (15)$$

where A is the pre-specified clipping level.

B. *Peak Insertion Method*

The PI technique takes its form from the duality property of the DFT and from the fact that the PAPR of a signal in one domain (time or frequency) is reversely proportional to the PAPR of the same signal in the other domain. PI technique involves insertion of a single relatively high peak into the OFDM symbol (from each transmit antenna) in the frequency domain to increase its PAPR, so that the PAPR is reduced in the time domain.

Let $X(k)$ be the original OFDM symbol. Then the resulting signal $Y(k)$ after PI is given by

$$Y(k) = X(k) + \alpha\delta(k - k_\alpha), 0 \le k \le N - 1$$
(16)

where α is a positive real number representing the strength of the inserted peak, k_α is the position of the inserted peak and $0 \le k_\alpha \le N-1$, and N is the number of subcarriers. After PI and oversampling, the peak of $Y(k)$) will become $|\alpha + X(k_\alpha)|$. $Y(k)$ is then transformed to the time domain by IDFT. The resulting signal will have a low PAPR with respect to the same signal obtained without PI.

V. SIMULATION RESULTS

A 2×2 MIMO-OFDM system is simulated using Matlab, to study the effect of PAPR reduction and channel prediction in the precoded MIMO-OFDM systems. Prior to this, the same simulations have been done in SISO-OFDM too. Different parameters used in the system simulation are given in Table I. The simulated 2 × 2 MIMO-OFDM has 64 subcarriers for each transmitter.

Simulation is done under the assumption that proper synchronization is maintained between the transmitter and the receiver. The length of the cyclic prefix is chosen to be greater than the maximum delay spread in order to avoid inter symbol interference. Simulations are carried out for different signal-to-noise ratios (SNR). Perfect channel

Table 1 SIMULATION PARAMETERS FOR MIMO-OFDM

Parameters	Specifications
No. of transmitted bits	128
FFT size	64
No. of subcarriers per antenna	64
No. of antennas	M=N=2
Symbol constellation	QPSK
Channel model	Rayleigh fading/AWGN
No. of simulation runs per SNR	1000

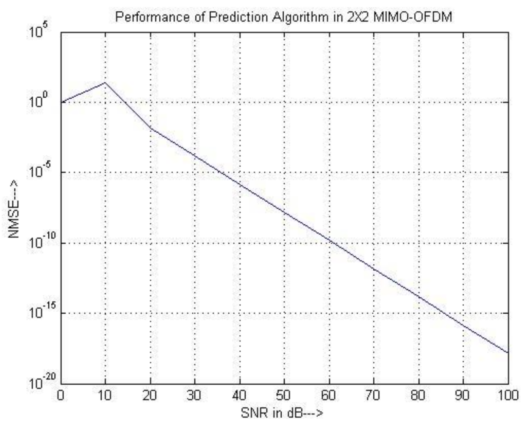

Fig. 2. NMSE plot for prediction in MIMO-OFDM

estimation was considered for channel prediction.

The noise variance and the correlation matrix are assumed to be known in all simulations. The channel prediction accuracy is measured in terms of the NMSE, which is defined as

$$NMSE = 10\log\left\{\frac{E\{||h_{n,m}(i+p,l)-\hat{h}^{pre}_{n,m}(i+p,l)||^2\}}{E\{||h_{n,m}(i+p,l)||^2\}}\right\}. \quad (17)$$

The channel prediction exploiting temporal correlation is done in 2×2 MIMO-OFDM system. The NMSE vs SNR plot for channel predictor is given in Fig. 2. The NMSE is found to decrease linearly with increase in SNR and the prediction algorithm has negligible NMSE for higher SNRs.

The two PAPR reduction techniques carried out in this paper are clipping and PI method. Clipping is done with a clipping level of 0.7 and the PI technique uses an impulse of strength 0.3. Both these methods are simulated in SISO-OFDM as well as MIMO-OFDM precoded systems.

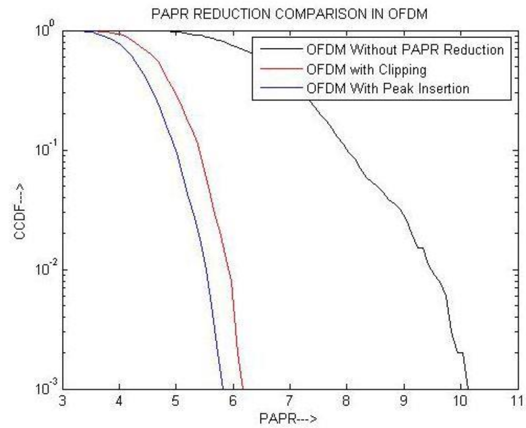

Fig. 3. CCDF plot for PAPR reduction in SISO-OFDM

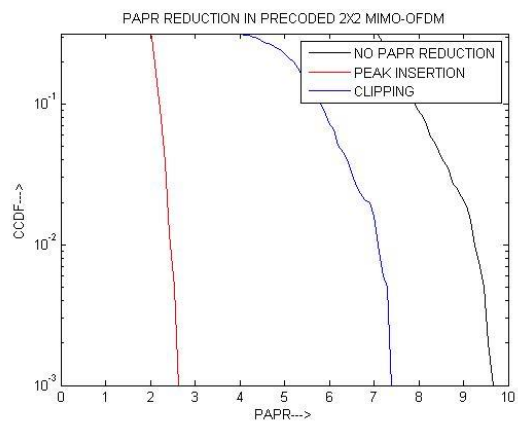

Fig. 4. CCDF plot for PAPR reduction in MIMO-OFDM

The CCDF plot comparing the two techniques in SISO-OFDM is shown in Fig. 3, and that of MIMO-OFDM in Fig. 4. From the plots, it is clear that PI technique results in better PAPR reduction than clipping.

The BER plot for various precoding cases for SISO-OFDM is shown in Fig. 5 and for MIMO-OFDM is shown in Fig. 6. The BER performance is shown to improve with the precoding, compared to unprecoded systems. However, on using PAPR reduction techniques, the BER plot gets further worse, the worst being for PI method. Comparing Fig. 4 and Fig. 6, we can see that as PAPR reduction increases, the BER performance gets worse.

VI. CONCLUSION

This paper has discussed about the performance of wireless channel prediction and PAPR reduction in precoded MIMO-OFDM. A SISO-OFDM as well as a 2X2 MIMO-OFDM are simulated and the channel

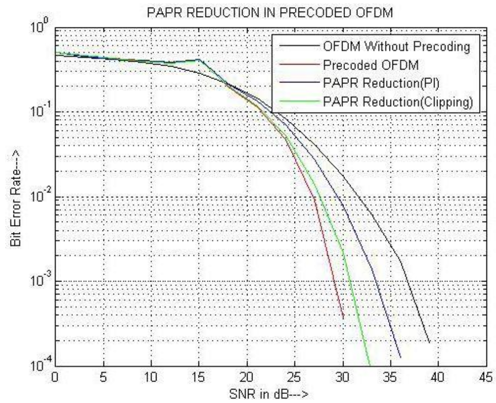

Fig. 5. Performance of PAPR reduction in precoded SISO-OFDM

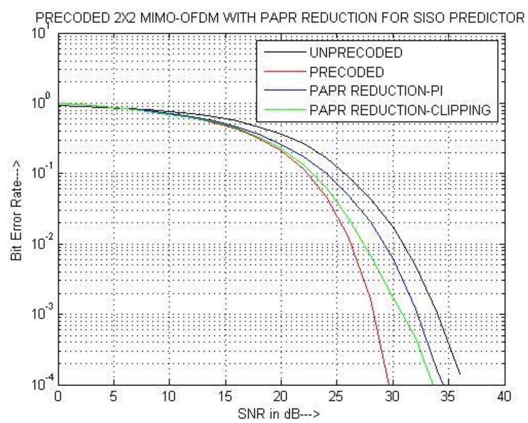

Fig. 6. Performance of PAPR reduction in precoded 2X2 MIMO-OFDM

prediction has been done in both the systems, making use of the temporal correlation existing among various signals. The NMSE decreases linearly with increase in SNR and the prediction performance is found to be nearly accurate at higher SNRs. These predicted coefficients are utilized for transmitter precoding, there by overcoming the defect caused by frequency equalization at the receiver, and resulting in a low complexity receiver.

Two PAPR reduction techniques were compared in the precoded MIMO-OFDM system, namely, the clipping and peak insertion methods. We had extended the PI method for OFDM systems to MIMO-OFDM and it is shown to have better PAPR reduction than clipping. However, regarding BER performance, PI method is proven to be worse than clipping. Hence there should be a trade-off between the PAPR reduction and BER performance. Based on the requirements of the application, a PAPR reduction method should be chosen.

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