Signal decomposition technique for enhanced power added efficiency of OFDM transmitters employing MIMO scheme

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Abstract: The authors have proposed the signal decomposition technique as the powerful solution to mitigate the large peak-to-average power ratio (PAPR) to be addressed in OFDM transmitters, and the simple noise elimination techniques working together with the signal decomposition in receivers. It is shown that the proposed signal decomposition technique improves the PAPR by 4 dB and doubles the power added efficiency (PAE) at the complementary cumulative distribution function (CCDF) of 1%. In order to show the feasibility of the proposed techniques when they are applied to MIMO transmissions, BER performances of the proposed techniques are also demonstrated.

Keywords: power added efficiency, OFDM, power amplifier, MIMO

Classification: Wireless Communication Technologies

References


1 Introduction

OFDM is a powerful solution to offer broad band digital communication. It is widely used for cellular mobile communication because the degradation caused by delay spread is negligible, as far as the delay spread of the channel is within guard interval (GI). However, OFDM signals require much wider linear dynamic range to the transmitter power amplifier (PA) than the average output power. In another word, large PAPR of OFDM signals incurs great expense of power consumption of the transmitter, because of low PAE of the PA. There are many previous works to reduce PAPR of OFDM signals like Selected Mapping (SLM) and Partial Transmit Sequence (PTS) [1]. On the other hand, the authors have proposed a signal decomposition technique and independent transmission of the resulting decomposed signals [2]. Our goal is to minimize power consumption of the transmitter so as to make OFDM scheme applicable to the uplink for mobile terminals. Furthermore, noise added on the decomposed on-off-signal signals can be eliminated by taking advantage the knowledge of their constant amplitude [2, 3]. In order to reconstruct the OFDM signals, the decomposed signals are combined coherently after being amplified independently. It is preferable to perform the spatial combining because the combining loss by the power combiner/splitter is as large as 6 dB when the reconstruction is performed within the transmitter. However, coherent spatial combining can be performed at only the place where the phase shift along the transmission paths from the two transmitter antennas is equal. But fortunately, MIMO scheme that enables simultaneous transmission of the independent data streams using the same frequency, can release such a spatial restriction. Taking advantage of 2x2MIMO scheme, we achieve higher PAE of the transmitter PAs instead of obtaining double system throughput.

2 Overview of the proposed OFDM system

2.1 System description

On the transmitter side, the OFDM signal to be transmitted $S(k)$ is decomposed into the constant amplitude on-off-signal $c(k)$ and the residual signal $r(k)$ based on the pre-determined threshold $d$, where $k$ is the sample index in the time domain. Fig. 1 explains the proposed decomposition signal processing. $c(k)$ and $r(k)$ are described as the following equations [2];

$$c(k) = \begin{cases} 0 & ; \quad |S(k)| < d \\ \frac{S(k)}{|S(k)|} \cdot d & ; \quad d \leq |S(k)|, \end{cases}$$  \hspace{1cm} (1)

$$r(k) = \begin{cases} S(k) & ; \quad |S(k)| < d \\ \left(1 - \frac{d}{|S(k)|}\right) \cdot S(k) & ; \quad d \leq |S(k)|. \end{cases}$$  \hspace{1cm} (2)

It is obvious that the peak amplitude of the residual signal $r(k)$ that requires linear amplification is reduced by the threshold value $d$. Furthermore, because of its constant amplitude, $c(k)$ can be amplified by highly efficient nonlinear amplifiers. As a result, the proposed technique is effective for power consumption reduction of the transmitter amplifiers.
In order to enhance the receiver SNR, a noise elimination technique has been proposed for \( c(k) \), taking advantage of the knowledge of its constant amplitude. The noise elimination output \( \hat{c}(k) \) is described as the Eq. (3).

\[
\hat{c}(k) = \begin{cases} 
0 & ; |c'(k)| < d/2 \\
 c'(k) & ; d/2 \leq |c'(k)| 
\end{cases}
\]  

(3)

On the receiver side, the threshold \( d \) could be set according to the amplitude of the preamble signals added at the head of each packet for channel estimation and synchronization. \( d \) would be obtained by measuring and averaging the amplitude of preamble signals for \( c_0(k) \) and \( r_0(k) \), respectively and then multiplying the pre-calculated ratios of the preamble signal amplitude to \( d \).

2.2 Receiver SNR of the proposed signal decomposition technique using MIMO transmission

In this section, the receiver SNR after reconstructing the original OFDM signals is formulated when the proposed signal decomposition technique is applied to a fixed 2x2 MIMO system. Here, we use Zero-Forcing scheme to calculate MIMO weight matrix. For easy explanation, we assume line-of-sight (LOS) conditions, i.e. the channel is not frequency dependent. The weight matrix \( W \) can be described using channel matrix \( H \) as follows

\[
W = (H^H H)^{-1} H^H, 
\]

(4)

where the superscript symbol \( H \) shows Hermitian-transpose. When we notate each elements of \( W \) as \( w_{11} \sim w_{22} \), the signal after the MIMO separation \( c'(k) \), \( r'(k) \), and the resulting reconstructed signal \( y(k) \) are described as the following equations, respectively.

\[
c'(k) = c(k) + w_{11}N_1(k) + w_{12}N_2(k), 
\]

(5)

\[
r'(k) = r(k) + w_{21}N_1(k) + w_{22}N_2(k), 
\]

(6)

\[
y(k) = r'(k) + c'(k) \\
= x(k) + (w_{11} + w_{21})N_1(k) + (w_{12} + w_{22})N_2(k), 
\]

(7)

where \( N_1(k) \) and \( N_2(k) \) denotes the noise signal at each receiver both of whose power equals to \( \sigma_n^2 \). Thus, the noise power \( N \) added on the reconstructed signal \( y(k) \) is written as
\[ N = \| w_{11} + w_{21} \|^2 \cdot \sigma_n^2 + \| w_{12} + w_{22} \|^2 \cdot \sigma_n^2 \]
\[ = A \sigma_n^2, \]  
\[ A = \| w_{11} + w_{21} \|^2 + \| w_{12} + w_{22} \|^2. \] 

Using the coefficient \( A \) and the receiver SNR of the conventional OFDM \( \gamma_0 \), the receiver SNR after reconstruction \( \gamma \) is described as

\[ \gamma = A^{-1} \gamma_0. \] 

Please note that the value of \( A \) will vary according to the channel condition. When the proposed noise elimination techniques are applied, the coefficient \( A \) asymptotes to \( A' \) shown below, by excluding \( w_{11} \) and \( w_{12} \) in Eq. (9).

\[ A' = \| w_{21} \|^2 + \| w_{22} \|^2 \]

3 Performance evaluation

We demonstrate the advantages of the proposed techniques; firstly, PAPR reduction of \( r(k) \) is evaluated, and then BER performances when the decomposed signals are transmitted over a 2x2 MIMO channel are shown in order to confirm the receiver SNR formulated in the previous section. The number of subcarriers is 52 which include 4 pilot subcarriers, and IFFT size \( N \) is 64. QPSK and 16QAM scheme are used for modulation.

3.1 PAPR of \( r(k) \) and the total PAE of PAs

Since \( r(k) \) shall be linearly amplified while highly efficient non-linear amplifiers can be used for \( c(k) \), the PAPR of \( r(k) \) is firstly estimated as a matter of concern. The PAPR depends on the pre-determined threshold \( d \). Fig. 2 shows the CCDF of the PAPR of \( r(k) \) for some threshold values and the conventional OFDM for QPSK scheme. The threshold \( d \) is normalized by \( 4 \sigma \) as the maximum amplitude of \( r(k) \), where \( \sigma \) is the standard deviation of the amplitude of \( r(k) \). The CCDF curve changes suddenly at the PAPR of around 5 dB because of nonlinear signal processing. PAPR decreases with the increase of \( d \) until it reaches an optimal value of 0.42 that gives the minimum PAPR of 5.3 dB. Please note that it is estimated at the CCDF of 1%. Larger \( d \) than the optimal value, on the contrary, worsens the PAPR. Though, we do not show the curve, the CCDF curves for 16QAM scheme are quite similar to those for QPSK. Assuming the I/O and PAE characteristics of the PA in [4] as the typical microwave band amplifiers, we evaluate the PAE of the PA for \( r(k) \) when the average transmit power is set to \((P_{-1db} - \text{PAPR}) \) [dBm]. The proposed signal decomposition achieves the peak PAE as high as 35%. The total PAE of the transmitter PAs can be calculated as 36% that is twice comparing with the conventional OFDM [2]. The value is nearly the same as the PAE of the PA for \( r(k) \) because the duty factor of \( c(k) \) is quite small; we observe that it is only 2.6% at the optimal threshold.

3.2 BER performances

BER performances are evaluated assuming a fixed 2x2 MIMO transmission. It is well known that the rank of the channel matrix should be larger than the number of streams to be transmitted simultaneously by MIMO transmission. In this paper, we
choose the conditions so that the eigen value of the channel matrix could be sufficiently large, in which the 2x2-MIMO reception would be performed properly even in LOS conditions. The antenna separation both in the transmitter and receiver is set to $10\lambda$, where $\lambda$ is the wave length at the radio frequency. The distance between the transmitter and the receiver $L$ and the azimuth of the receiver $\theta$ are set to 50 m, 30 deg, respectively and the radio frequency is 800 MHz. Ideal channel state information (CSI) is assumed to be known at the receiver. Fig. 3 shows the BER performances of the proposed signal decomposition with and without noise elimination. The BER of the proposed signal decomposition without noise elimination is 2.6 dB worse than the conventional OFDM at the BER of $10^{-3}$. With the proposed noise elimination, the performance is improved by 4.6 dB, which is 2 dB better than the conventional OFDM.

The channel matrix $H$ and the weight matrix $W$ are calculated as follows for this example.

$$H = \begin{pmatrix} 0.5093 - j0.8606 & 0.5704 + j0.8214 \\ 0.5058 + j0.8626 & 0.5090 \quad - j0.8608 \end{pmatrix} \quad (12)$$

$$W = \begin{pmatrix} 0.4721 + j0.3016 & 0.4709 \quad - j0.3035 \\ 0.4928 \quad - j0.2665 & 0.4720 \quad + j0.3018 \end{pmatrix} \quad (13)$$

Substituting Eq. (13) for Eq. (9) and Eq. (11), the coefficients $A$ and $A'$ are calculated as 1.82 and 0.63, respectively. Thus the proposed signal decomposition without noise elimination shows worse receiver SNR by 2.6 dB that is equal to $10 \log_{10}(A)$ comparing with the conventional OFDM. By using the noise elimination, gain is expected to be 4.6 dB, that is equal to $10 \log_{10}(A'/A)$, it is 2 dB better than the conventional OFDM. Since $A$ and $A'$ obtained theoretically well support the SNR differences in Fig. 3, it is confirmed that the proposed signal decomposition technique and the noise elimination techniques work properly for MIMO systems.

4 Conclusions

This paper demonstrates that the proposed signal decomposition technique doubles the total PAE of the transmitter PAs comparing with that of the conventional OFDM transmitter. The receiver SNR is formulated and the corresponding BER performances are evaluated for 2x2 MIMO applications to confirm the feasibility of the proposed techniques employing MIMO scheme. In our technique, out-of-band emission would not be a problem by using adequate band pass filter.