

An Adaptive Precoder for Out-of-band Power Reduction in OFDM-Based Cognitive Radio System

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Abstract

Out-of-band (OOB) power emission is a conventional issue in orthogonal frequency division multiplexing (OFDM) system. The spectral leakage results in interference to licensed users (LU) in OFDM-based cognitive radio (CR) system. In this article, an adaptive precoding scheme based on the adaptive orthogonal projection matrix is proposed for OOB power suppression. Low complexity is the main feature of this preceding scheme. Simulation and analysis show that this method reduces the out-of-band power significantly by forcing the power spectrum density (PSD) of several frequency points in OOB to be zero. An advanced precoding scheme proposed later achieves a tradeoff between performance of OOB power suppression and bit error rate (BER) in the receiver. With those schemes, an adaptive precoder is proposed, which has three ways to adaptively adjust precoding matrix to achieve a balance among the complexity of system, the performance of out-of-band power reduction and BER in the receiver.

Keywords: Adaptive, Precoding, Out-of-band, OFDM

1. Introduction

Cognitive radio (CR) [1-2] is a scheme to improve the throughput of wireless communication. From many transmission schemes, the spectrum pooling [3] technology has been introduced and extensively studied as an effective scheme to achieve higher spectral efficiency [4] have been introduced recently and attracted considerable attention, Due to the flexible operability over discontinuous bands, orthogonal frequency division multiplexing (OFDM) technique is considered as a candidate transmission technology for CR system in [5]. However, the out-of-band (OOB) power emission of OFDM signals remains as a major issue, which results in interference to licensed users (LU).

Several approaches to reduce this source of interference have been proposed. Cancellation carriers [6-7] is a promising technique which inserts carriers with optimized amplitudes and phases on the reserved positions in order to cancel the sidelobes of the transmitted signal. The power efficiency decreases for the cancellation carriers do not carry data. Subcarrier weighting [8] is based on weighting the individual subcarriers in a way that their sidelobes cancel each other. But the bit error rate (BER) increase in receiver, and when the number of subcarriers is large, it is difficult to implement in real-time scenario. With the multiple choice sequences [9] method, the transmitted symbol is mapped into multiple equivalent transmit sequences. When the

size of sequences set grows, the throughput of the system is reduced. Constellation adjustment [10] is characterized by the adjustment of the constellation points. The basic idea behind this method is based on the fact that different data symbols have different sidelobe power levels. But difficult implement when the order of quadrature amplitude modulation (QAM) is high. Adaptive symbol transition [11] usually provides weak sidelobes suppression in frequency ranges closely neighboring the secondary user (SU) occupied band. The precoding method is widely used in OFDM system to enhance the performance of transmission reliability over wireless environment. Also there are many methods based on precoding are proposed for OOB power suppression. In [12], the precoder is data independent and is uniquely determined by the order of the signals continuity. However, it has a high symbol error rate (SER) when there is a low number of a data channel. In [13-14], the spectrum efficient decrease for adding reserved subcarriers. The precoding design in [15] can suppress the sidelobe significantly based on the generalized eigenvalue problem. The power leakage suppression in [16] is first treated as a matrix Frobenius norm minimization problem, and the optimal orthogonal precoding matrix design for the power leakage suppression is proposed based on singular value decomposition (SVD). Scheme [15-16] maintain the receiver performance, but increase the complexity significantly when the number of subcarriers is large, for the computation complexity is proportional to the square of the number of carriers. The precoding method suggested in [17] provides significant sidelobes suppression in case of a SU using non-contiguous subcarriers OFDM, and acceptable BER performance in fading channels. The code is not systematic, and the reception requires computationally complex decoding. In [18], two practical approaches are employed in non-contiguous OFDM (NC-OFDM). it achieves the required OOB suppression by insertion of cancellation carriers and windowing.

In this paper, an adaptive precoder based on the adaptive orthogonal projection matrix is proposed to suppress OOB power in OFDM-based cognitive radio system. According to the external radio environment, there are three ways to adaptively adjust precoding matrix to achieve a balance among the complexity of system, the performance of OOB power reduction and the BER in the receiver. The rest of the paper is organized as follows. In Section 3, the analysis of the basic orthogonal projection matrix scheme is shown. An advanced precoding scheme is proposed in Section 4. In Section 5, some simulations and the performance analysis of the basic scheme is shown.. And an adaptive precoder is proposed for CR system. Finally, several conclusions are presented in Section 6.

2. System Model

In a CR system employing OFDM as the main modulation scheme, it is assumed that the system is aware of the radio scenario and the channel state information (CSI). After the spectrum sensing step, it is a critical challenge to mitigate the interference between LUs and SUs.

In Figure 1, the typical process of precoding is simply arranged before IFFT block in the transmitter of DFT-based OFDM system. An OFDM system with a total number of subcarriers, is considered. The input data bits are mapped into complex data $d_i (i = 0, 1, \dots, N-1)$, by applying phase-shift keying (PSK) or QAM. The generated symbols are mapped to a data symbol vector $\mathbf{d} = [d_0, d_1, \dots, d_{N-1}]^T$, where $[\cdot]^T$ denotes vector transposition. Then through precoding process, the original symbol vector

remapped to vector $\mathbf{s} = [s_0, s_1, \dots, s_{M-1}]^T$, where $\mathbf{s} = \mathbf{P}\mathbf{d}$, $N < M$, and \mathbf{P} is a precoding matrix.

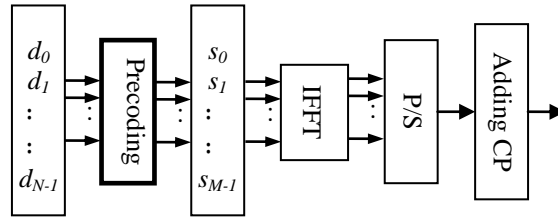


Figure 1. Scheme of Precoding in DFT-based OFDM Transmitter

Dynamic spectrum access (DSA) is derived to achieve high spectral efficiency in CR system, while keeping the interference to LUs in an acceptable level. In order to achieve this goal, OOB power reduction is considered as a necessary step. According to the result of spectrum decision, the modulation constraint of occupied spectrum is generated for adjusting the parameters of the precoder in transmitter.

In a general CR system based on OFDM, it divides the total M subcarriers into a few subbands. Each subband includes a block of continuous subcarriers with different number, while some subbands are not used for data transmission. But the spectrum leakage of information carriers can lead interference to those subbands considered as being occupied by LUs.

In a general OFDM system, the time-domain signal can be defined by a rectangular function (baseband-equivalent)

$$s(t) = \begin{cases} 1, & 0 \leq t \leq T \\ 0, & \text{elsewhere} \end{cases} \quad (1)$$

T is the symbol duration. Its Fourier transform is given by

$$S(\omega) = e^{-j\omega T/2} \frac{\sin(\omega T / 2)}{\omega / 2} \quad (2)$$

Considering $\Delta f = 1 / T$ and $\Omega = 2\pi f$. Let $\omega = f / \Delta f$ be normalized frequency. The frequency-domain representation of m -th subcarrier is written as

$$S_m(\omega) = \begin{cases} e^{-j\omega T/2} \frac{\sin((\omega - m)T / 2)}{(\omega - m) / 2} & (\omega \neq m) \\ e^{-j\omega T/2} & (\omega = m) \end{cases} \quad (3)$$

So when $\omega \neq m$

$$|S_m(\omega)| = \left| e^{-j\omega T/2} \frac{\sin((\omega - m)T / 2)}{(\omega - m) / 2} \right| \leq \left| \frac{2}{(\omega - m)} \right| \quad (4)$$

From (4), the magnitude envelope of $s_m(\omega)$ can be approximately rewritten as

$$\bar{S}_m(\omega) = \frac{1}{(\omega - m)} \quad (5)$$

The representation for the frequency response envelope of the superposition of M subcarriers also approximately rewritten as

$$c_m(\omega) = \sum_{m=0}^{M-1} \bar{S}_m(\omega) = \sum_{m=0}^{M-1} \frac{1}{(\omega - \omega_m)} \quad (6)$$

Note that, $(\omega - m)$ is negative or positive can not affect the computation of power spectrum later parts as analyzed in later part. The representation for the frequency response matrix of ω rewritten as

$$\mathbf{C} = \left(\begin{array}{ccc} \frac{1}{\omega - \omega_{m_0}} & \dots & \frac{1}{\omega - \omega_{m_{(M-1)}}} \end{array} \right) \quad (7)$$

Where ω_{m_i} is the frequency point of i -th subcarrier.

The goal of OOB power reduction is to reduce the power in the subbands without data transmission.

3. Orthogonal Precoding Scheme

The orthogonal projection method is to force the Power Spectrum Density (PSD) of several frequency points in OOB to be zero. The number of suppression frequency points is n . The number of total information carrier is M . To keep the analyses of this method generally, the subcarrier is continuous, and the carrier index is from m_0 to $m_{(M-1)}$. The subcarriers also can be discontinuous as shown in later simulation.

The precoding process is expressed in matrix form

$$\mathbf{s} = \mathbf{P}\mathbf{d} \quad (8)$$

Where \mathbf{d} is original source data signal vector, \mathbf{s} is precoded signal vector, \mathbf{P} is a precoding matrix. The OOB frequency points $\{\omega_0, \omega_1, \dots, \omega_j, \dots, \omega_{n-1}, (\omega_j < \omega_{m_0} \text{ or } \omega_j > \omega_{m_{(M-1)}})\}$ are chosen to achieve

$$\mathbf{C}\mathbf{P}\mathbf{d} = \mathbf{0}, \quad \text{for any source data vector } \mathbf{d} \quad (9)$$

Where \mathbf{C} is a frequency response coefficient matrix, $\mathbf{C}_{i,j} = c_i(\omega_j)$, i indicates the information carrier frequency point ω_{m_i} , and j indicates OOB frequency point ω_j as Fig. 2 shown.

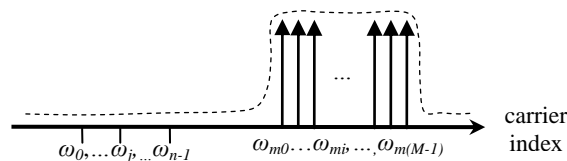


Figure 2. OOB Power Suppression Scheme Frequency Point Distribution

The frequency response coefficient matrix is invariable, so the problem is equivalent to finding a precoding matrix \mathbf{P} to meet (8). From (6), the suppression frequency response coefficient matrix is given

$$\mathbf{C} = \begin{pmatrix} \frac{1}{\omega_0 - \omega_{m_0}} & \frac{1}{\omega_0 - \omega_{m_0}} & \dots & \frac{1}{\omega_0 - \omega_{m_{M-1}}} \\ \frac{1}{\omega_1 - \omega_{m_0}} & \frac{1}{\omega_1 - \omega_{m_0}} & \dots & \frac{1}{\omega_1 - \omega_{m_{M-1}}} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{\omega_{n-1} - \omega_{m_0}} & \frac{1}{\omega_{n-1} - \omega_{m_0}} & \dots & \frac{1}{\omega_{n-1} - \omega_{m_{M-1}}} \end{pmatrix} \quad (10)$$

3.1. Precoding Scheme

The solution of (8) is equivalent to map source data vector to the nullspace of \mathbf{C} , as shown in Figure 3. There many linear mapping methods can reach (8). In [19], the orthogonal projection can achieve

$$\min \|\mathbf{P}\mathbf{d} - \mathbf{d}\| \quad (11)$$

This scheme indicates precoded data vector $\mathbf{P}\mathbf{d}$ is closest to source data vector \mathbf{d} , which can decrease deterioration of performance in the receiver as later shown. Considering \mathbf{C} is a column full rank matrix, the projector \mathbf{P} onto \mathbf{C}^\perp along \mathbf{C} is considered as orthogonal projector onto \mathbf{C}^\perp .

$$\mathbf{P} = \mathbf{I} - \mathbf{C}(\mathbf{C}^H \mathbf{C})^{-1} \mathbf{C}^H \quad (12)$$

The geometry space presentation of precoding is demonstrated as Figure 3.

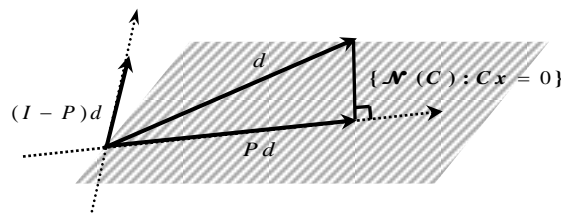


Figure 3. OOB Power Suppression Scheme

As known in matrix computing, multiplication costs plenty of hardware resource when the number of row and column is large. So the complexity also cannot be tolerated in OFDM system applying direct matrix multiplication precoding algorithm. Especially the number of carriers is large, and it is implemented in delay sensitive system. So the complexity of the precoding based on matrix multiplication algorithm is considered seriously in practical system.

The characteristic of the orthogonal projection scheme is low complexity. For its inherent feature, the complexity decreases significantly by changing the order of the computing process. In the transmitter, the source signal data is $\mathbf{a} = [d_0, d_1 \dots d_{N-1}]^T$. The process of precoding represents as

$$\begin{aligned}
 \mathbf{s} &= \mathbf{P} \mathbf{d} \\
 &= (\mathbf{I} - \mathbf{C}(\mathbf{C}^H \mathbf{C})^{-1} \mathbf{C}^H) \mathbf{d} \\
 &= \mathbf{d} - \mathbf{C}((\mathbf{C}^H \mathbf{C})^{-1} \mathbf{C}^H) \mathbf{d} \\
 &= \mathbf{d} - \mathbf{C}(\mathbf{Q} \mathbf{d})
 \end{aligned} \tag{13}$$

Where $\mathbf{Q} = (\mathbf{C}^H \mathbf{C})^{-1} \mathbf{C}^H$, n is the number of suppress frequency points, \mathbf{Q} is $n \times M$ matrix, \mathbf{C} is $M \times n$ matrix, and \mathbf{s} is precoded data. The elements of the matrix \mathbf{Q} can be stored at the transmitter.

Table 1. Complexity in Transmitter

Precoding	Multiplication	Addition
\mathbf{Qd}	$n \times M$	$n \times (M-1)$
$\mathbf{C}^H(\mathbf{Qd})$	$n \times M$	$n \times (M-1)$
$\mathbf{s} = \mathbf{d} - \mathbf{C}^H(\mathbf{Qd})$	0	$M-1$
Total	$2n \times M$	$(2n+1) \times (M-1)$

In the receiver, the data directly recover from information carriers. The received data are considered as the estimate of source data. There is no deprecoding process.

3.2. Advanced Precoding Scheme

As the analysis in the former part, the performance in receiver decreases after precoding. The BER can be adjusted by changing the vector distance between $\mathbf{P} \mathbf{d}$ and source data \mathbf{d} , and the number of suppression frequency point n changes the precoding complexity. To improve the performance in the receiver, one way is to change n . In this part, another method based on the approximate orthogonal projection matrix is demonstrated.

The orthogonal projection precoding matrix \mathbf{P} in (12) can be rewritten as

$$\mathbf{P}_\alpha = \mathbf{I} - \alpha \times \mathbf{C}(\mathbf{C}^H \mathbf{C})^{-1} \mathbf{C}^H \quad \alpha \in [0,1] \tag{14}$$

Where \mathbf{P}_α is an approximate orthogonal projection matrix.

This method is based on matrix approximate orthogonal projection. The precoding index α changes the distance between precoded data vector and source signal data vector, and affects BER in receiver directly.

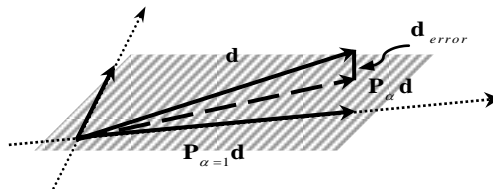


Figure 4. Scheme of Precoding Matrix with Different Precoding Index

The length of d_{error} denotes the level of error between original signal and precoded signal as shown in Figure 4. α is larger in precoding method, the BER in receiver is increase at the same time.

4. Adaptive Precoder

Cognitive radio improves spectrum utilization by accessing the unused spectrum opportunistically. To use these spectrums, in case of dynamic resource allocation among CR users, each CR user needs to adapt its transmission parameters to the varying spectrum condition to maintain the Quality of Service (QoS) requirements.

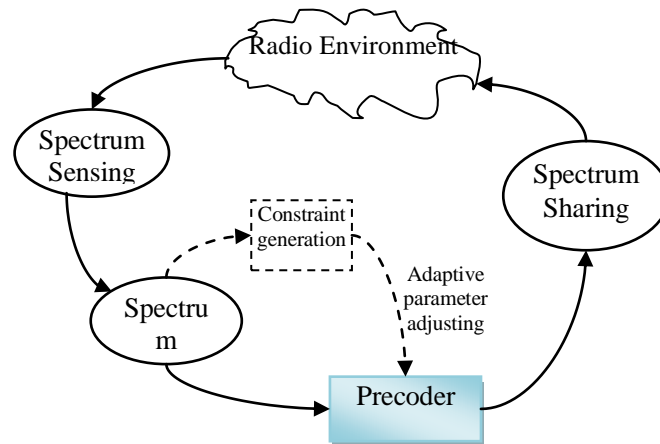


Figure 5. Adaptive Precoder in CR System

For adaptive modulation is an effective method of increasing the link spectral efficiency of communication, applying adaptive modulation to cognitive radio is a natural choice. Similarly as another adaptive scheme according to transmit rate, energy efficient...etc, there is an adaptive OOB power reduction procedure proposed based on the adaptive preceding method for the flexibility shown in prior analysis.

The relationship between the adaptive parameters and the performance of the system is shown in Table.2.

The adaptive precoding scheme is adjusting the precoding matrix \mathbf{P} according to the performance constraint as Figure 5 shown. There are many factors affecting the performance of precoding scheme. It can adaptively adjust parameters according to QoS requirements.

Table 2. Relationship between Parameter and Performance Constraint

Parameter \ Constraint	Complexity	OOB Power Suppression	BER
Number of power suppression frequency point n	√	√	√
Position of power suppression frequency point ω_j	—	√	—
Precoding index α	—	√	√

5. Performance of Precoding Scheme

In this section, analysis and simulations are run to show the performance of the precoding scheme. To demonstrate the OOB power suppression effect, the PSD of the signal is calculated in later simulation. The number of total information carriers is 60. There is no channel coding.

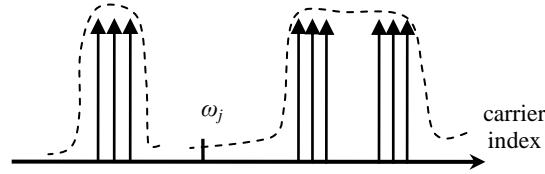


Figure 6. NC-OFDM System

In a CR system, employing OFDM-based spectrum pooling technology, discontinues carriers is considered as Figure 6 shown. OOB frequency point ω_j is between two valid transmit subbands.

5.1. The Position of Power Suppression Frequency Point

The position of suppression point can change the element of precoding matrix in (6). The length $(\omega_m - \omega_j)$ between suppression point and information carriers affects the feature of OOB power suppression.

The information carrier index is $\{\omega_{m_0}, \omega_{m_1}, \dots, \omega_{m_{(M-1)}}\}$. Considering only one suppression frequency point ω_j ($\omega_j < \omega_{m_0}$ or $\omega_j > \omega_{m_{(M-1)}}$), that means forcing the frequency response magnitude of $\mathbf{P}(\omega_j)$ to be zero. From (10), the frequency response coefficient matrix of ω_j can be written as

$$\mathbf{C}_j = \begin{pmatrix} \frac{1}{\omega_{m_j} - \omega_0} & \frac{1}{\omega_{m_j} - \omega_1} & \dots & \frac{1}{\omega_{m_j} - \omega_{(M-1)}} \end{pmatrix} \quad (15)$$

The frequency response coefficient matrix of OOB after precoding

$$\begin{aligned} \mathbf{C}\mathbf{P} &= \mathbf{C}(\mathbf{I} - \mathbf{C}_j(\mathbf{C}_j^H \mathbf{C}_j)^{-1} \mathbf{C}_j^H) \\ &= \mathbf{C} - \mathbf{C}\mathbf{C}_j(\mathbf{C}_j^H \mathbf{C}_j)^{-1} \\ &= \mathbf{C} - \frac{1}{\sum_{m=0}^{M-1} \left(\frac{1}{\omega_m - \omega_j}\right)^2} (\mathbf{C}_j^H \mathbf{C}) \mathbf{C}_j^H \\ &= \mathbf{C} - \frac{\sum_{m=0}^{M-1} (\omega_m - \omega_j)^2}{\sum_{m=0}^{M-1} (\omega_m - \omega)(\omega_m - \omega_j)} \mathbf{C}_j^H \end{aligned} \quad (16)$$

Where the matrix n in (14) is the frequency response coefficient matrix of arbitrary point ω in OOB.

$\mathbf{C}\mathbf{P}=\mathbf{0}$, when $\mathbf{C}=\mathbf{C}_j$, that denotes that the power magnitude of ω_j is zero, matching (8). The power magnitude of $\omega_j(\omega \neq \omega_j)$ in OOB is

$$\mathbf{P}(\omega) = \|\mathbf{C}\mathbf{P}\|$$

$$= \sum_{m=0}^{M-1} \left(\frac{1}{\omega_m - \omega} - \frac{\sum_{m_i=0}^{M-1} (\omega_{m_i} - \omega_j)^2}{(M-1)(\omega_m - \omega_j) \sum_{m_i=0}^{M-1} (\omega_{m_i} - \omega)(\omega_{m_i} - \omega_j)} \right)^2 \quad (17)$$

For the OOB frequency point ω in the same area with ω_j , so $(\omega_m - \omega)$ and $(\omega_m - \omega_j)$ have same sign, $(\omega_{m_i} - \omega)$ and $(\omega_{m_i} - \omega_j)$ have same sign. It denotes that ignoring the sign in (5) has no effect to power magnitude computation. Only taking care about the value of ω_j , a function is established for analyzing the effect of different position of power suppression frequency point.

$$f(x) = \sum_{m=0}^{M-1} \left(\frac{1}{\omega_m - \omega} - \frac{\sum_{m_i=0}^{M-1} (\omega_{m_i} - x)^2}{(M-1)(\omega_m - x) \sum_{m_i=0}^{M-1} (\omega_{m_i} - \omega)(\omega_{m_i} - x)} \right)^2 \quad (18)$$

Form (18), we can briefly have

$$f(x_1) - f(x_2) = \begin{cases} > 0 & x_2 < x_1 < \omega < \omega_m \\ < 0 & \omega < x_2 < x_1 < \omega_m \end{cases} \quad (19)$$

From (19), the position of suppression frequency point ω_j is closer to the information subband ($(\omega_m - \omega_j)$ decrease), the power of OOB is lower when $\omega_m - \omega < \omega_m - \omega_j$, but increase when $\omega_m - \omega > \omega_m - \omega_j$. Different values of ω_j achieve different suppression effect.

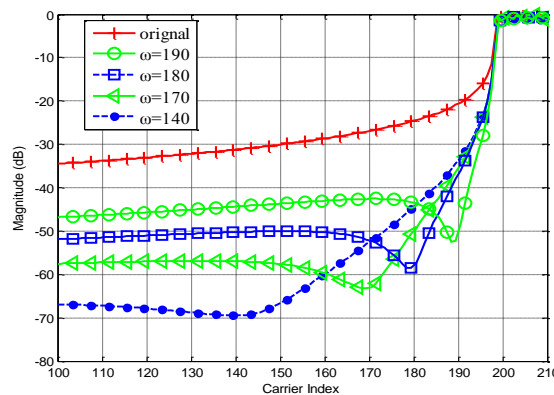


Figure 7. Performance of Different Position of Suppression Frequency Point

In Figure 7, the position of suppression point is $\omega = \{140, 170, 180, 190\}$ respectively. The index of information carriers is from 200 to 259. Different suppression effects can be achieved by changing the value of ω_j in (18). From simulation result, the smaller distance between suppression point and information carriers, quicker power reduction in the area close to the main transmission band, however, larger in the far from information area.

5.2. The Number of Suppression Frequency Points

Considering the number of suppression frequency points in OOB is n , and The frequency points are $\{\omega_0, \omega_1 \dots \omega_j \dots \omega_{n-1}\}$ respectively. The PSD of those frequency points is forced to be zero in the proposed scheme. The value of n affects the performance of OOB power reduction directly.

As shown in Figure 6, the scenario of discontinuous subcarrier is considered. The index of information carriers is from 200 to 229 and 261 to 290. The carrier index with no information data is from 230 to 260. The suppression frequency point is $\omega = \{245\}$ when $n = 1$, $\omega = \{240, 250\}$ when $n = 2$, and $\omega = \{236, 242, 248, 254\}$ when $n = 4$ respectively.

Different suppression effects can be achieved by changing the number of suppression points. The larger value of n can reduce power effectively, however, complexity in transmitter increase as Table.1 shown.

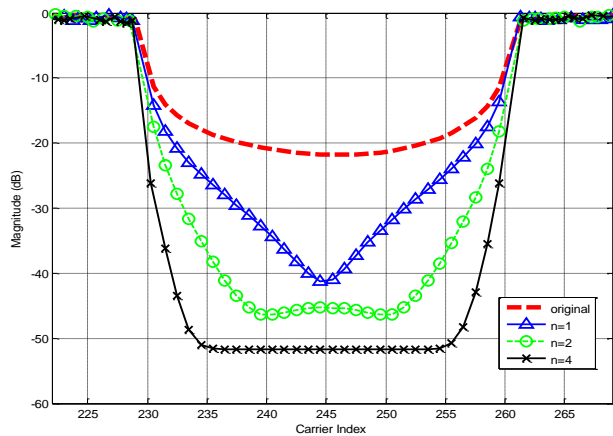


Figure 8. Performance of Different Number of Suppression Frequency Points for OOB Power Reduction

5.3. BER in Receiver

As shown in Figure 3, $\hat{\mathbf{a}}$ is the estimate of \mathbf{a} in the receiver. The distance between $\hat{\mathbf{a}}$ and \mathbf{a} denote the performance of BER in the receiver. Rank of \mathbf{P} is $M - n$. More suppression frequency points indicate Rank (\mathbf{P}) is smaller and larger BER in receiver as demonstrated in Figure 8. The rank of \mathbf{P} directly affects the performance of reception. Where the number of suppression frequency points is n in precoding matrix \mathbf{P}_{C_n} . The length of \mathbf{a}_{error} denotes the level of error between original signal and precoded signal.

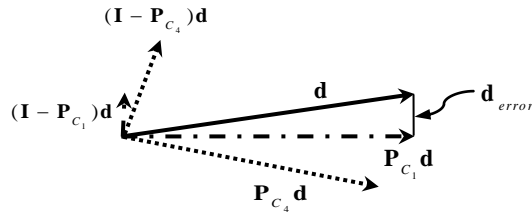


Figure 9. Scheme of Different Precoding Matrix with Different Number of Suppression Frequency Points

As BER shown in Figure 10, QPSK signal is selected over AWGN radio channel. The value of n is $\{1, 2, 4\}$ separately. Larger number of suppression frequency points can achieve better suppression effect as Figure 8 demonstrated. But the BER in the receiver increases at the same time.

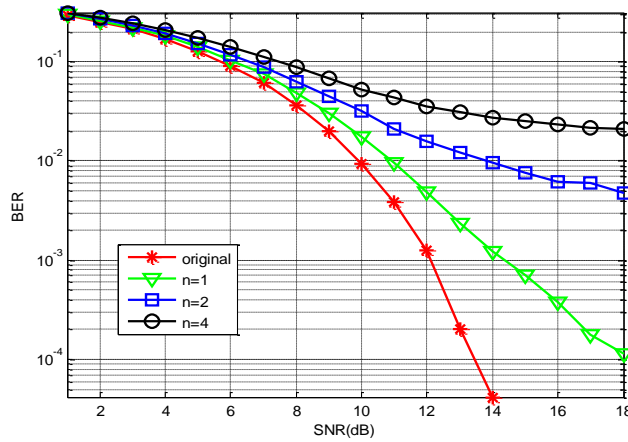


Figure 10. BER with Different Number of Suppression Frequency Points in the Receiver

5.4. Advanced Precoding Scheme

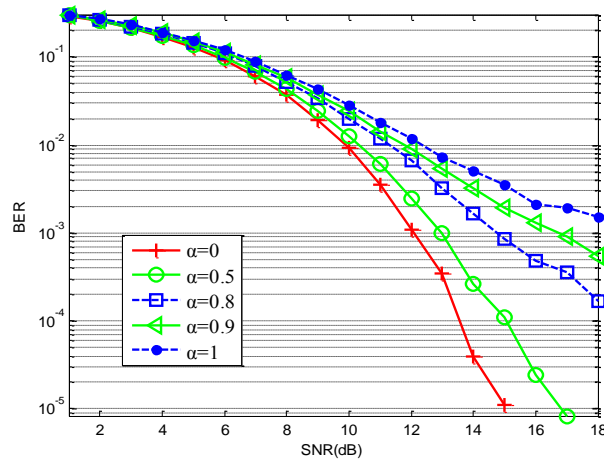


Figure 11. BER with Different Precoding Index in the Receiver

As BER shown in Figure 11, QPSK signal is selected over AWGN radio channel. The advanced precoding index is $\{0, 0.5, 0.8, 0.9, 1\}$ separately. It indicates original OFDM signal when the preceding index α is 0. The orthogonal projection scheme is achieved when α is 1.

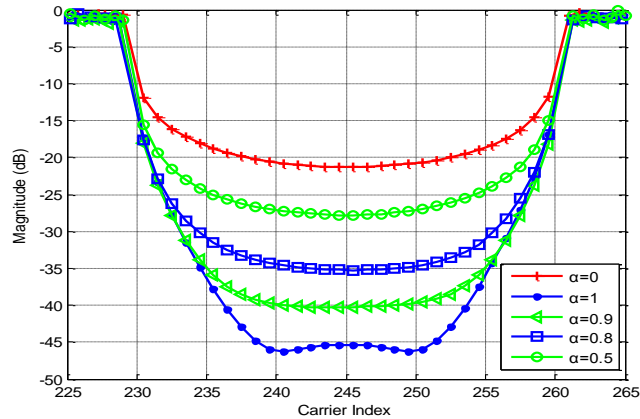


Figure 12. Performance of Different Precoding Index for OOB Power Reduction

The precoding index α affects the BER in the receiver, and the performance of OOB power suppression is changed at the same time in Figure 12. The advanced precoding scheme can balance the performance between OOB power reduction and BER by changing the precoding index α . It has a tradeoff between performance of OOB power suppression and BER in the receiver.

6. Conclusion

An adaptive precoder based on orthogonal projection matrix is designed to suppress OOB power for OFDM-based cognitive radio system by forcing the PSD of several frequency points in OOB to be zero. Simulation and analysis show that this method reduces the out-of-band power significantly. In later part an advanced precoding scheme proposed can have a tradeoff between performance of OOB power suppression and BER in receiver. Changing the number or the position of suppression frequency points and the orthogonal projection precoding index can achieve a balance among the complexity of system, the performance of power reduction and BER in the receiver. This precoder adapts to cognitive radio system, employing non-contiguous subcarriers OFDM technology.

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