Low PAPR Precoding Design with Dynamic Channel Assignment for SCBT System

Juinn-Horng Deng, Sheng-Yang Huang, and Jeng-Kuang Hwang
Communication Research Center and Department of Communications Engineering
Yuan Ze University
135 Yuan-Tung Road, Chung-Li, Taiwan
E-mails: jh.deng@saturn.yzu.edu.tw; s1008602@mail.yzu.edu.tw

***Abstract*—The single carrier block transmission (SCBT) system has become one of most popular modulation system due to its low peak to average power ratio (PAPR). In this paper, the precoding systems at the transmitter side are proposed to retain low PAPR, acquire better performance, and reduce the computation complexity at receiver side. It is designed in accordance with the following procedure. First, the upper-triangular dirty paper coding (UDPC) is proposed to pre-cancel the multiple streams interference and post one-tap time-domain equalizer for SCBT system. Next, to overcome the high PAPR problem for UDPC precoding system, Tomlinson-Harashima precoding (THP) is introduced to maintain low PAPR performance. Finally, because the UDPC-THP system will be degraded by the deep fading channel, the dynamic channel on/off assignment via the water filling algorithm is proposed to enhance bit error rate (BER) performance. Simulation results show that the proposed precoding transceiver can provide excellent BER and low PAPR performances for SCBT system over multipath fading channel.**

Keywords- *single carrier block transmission (SCBT), peak-to-average power ratio (PAPR), dirty paper coding(DPC), Tomlinson-Harashima Precoding (THP), Upper-Triangular dirty paper coding(UDPC).*

I. INTRODUCTION

In the communication area, the technique of digital communications progress so fast, from traditional quadrature phase shift keying (QPSK), time division multiple access (TDMA), to orthogonal frequency division multiplexing (OFDM) system. In order to increase the performance of wireless communication systems, the researchers propose the novel equalizer or signal transmitted method, trying to find the best and effective modulation technique. In recent years, the demands of indoor short-range wireless communications applications for high data rate become great eagerness, e.g., digital home cinema...etc. IEEE 802.15.3c [1] is a high-speed short-range wireless personal area network transmission system standard, which is used for 60 GHz millimeter-wave band environment. Therefore, in order to achieve G bps transmit rate, the requirements of the low peak-to-average power ratio (PAPR) at transmitter, low complexity and excellent BER performances at receiver are very important Besides, after multipath fading channel, the multiple streams interference, i.e., parallel signal transmission interference, will be induced for the high data rate system. In order to achieve the requirements and combat the interference problem, many techniques are proposed to realize it, e.g., OFDM and single carrier block transmission (SCBT). For OFDM system, it involves the problem of high PAPR, it will cause power amplifier working in the non-linear area. Thus, it needs to back off output power which will reduce the efficiency of power amplifier. For SCBT system, it is the one of the popular themes in recent years [2]-[4]. It can provide low PAPR performance, so we try to study the precoding technique to maintain low PAPR, provide the excellent BER performance, and reduce the computation complexity at receiver.

In this research, we change the signal processing mechanisms from the receiver side to the transmitter side in order to make receiver much simpler and acquire better performance. Reference [5]-[6] introduces pre-equalization systems, but it will induce high complexity due to using the inverse matrix at the transmitter. Thus, we study for the dirty paper coding (DPC) [5], [7] to reduce the complexity at the transmitter. Beside, for SCBT system, the DPC technique can provide low-complexity one-tap time-domain equalizer at the receiver. But, after precoding, it will increase PAPR. Next, the UDPC with symmetric modulo operation, i.e., Tomlinson-Harashima precoding (THP) [5], [8] is proposed to reduce the PAPR of transmitted signals. Finally, for further performance enhancement, the dynamic channel assignment technique via the water filling algorithm [9] is proposed to turn off the signal transmitted through the deep fading composite channel. Simulation results confirm that the proposed system can provide better BER and lower PAPR performances.

The paper is organized as follows: In Section II, we introduce the system block diagram consisting of frequency domain equalizer and time domain pre-equalization. In Section III, the UDPC-THP with water filling algorithm is proposed. Simulation results of the proposed system are then investigated in Section IV. And the paper is concluded in Section V.

II. SCBT SYSTEM MODEL

A. Traditional Frequency Domain Equalization System

Figure 1 shows a basic configuration of the SCBT system. First the nth information signal block of size $N\times 1$ can be define as

$$\mathbf{x}(n) = [x_0(n), \cdots, x_{N-1}(n)]^T \tag{1}$$

where the superscript $(\cdot)^T$ stands for the transpose. The transmitted signal block $\hat{\mathbf{x}}(n)$ of size $(N+K)\times 1$ is generated from $\mathbf{x}(n)$ by adding the cyclic prefix (CP) of K symbols length as the guard interval (GI), namely,

$$\hat{\mathbf{x}}(n) = \mathbf{T}_{cp}\mathbf{x}(n) \tag{2}$$

where $\mathbf{T}_{cp}$ donates the CP insertion matrix of size $(N+K)\times N$ defined as

$$\mathbf{T}_{cp} = \begin{bmatrix} \mathbf{O}_{K\times(N-K)} & \mathbf{I}_{K\times K} \\ \mathbf{I}_{N\times N} & \end{bmatrix}_{(N+K)\times N} \tag{3}$$

$\mathbf{O}_{K\times(N-K)}$ is a zero matrix of size $K\times(N-K)$, and $\mathbf{I}_{N\times N}$ is an identity matrix of size $N\times N$. The received signal block $\hat{\mathbf{y}}(n)$ is written as

$$\hat{\mathbf{y}}(n) = \mathbf{H}\hat{\mathbf{x}}(n) + \mathbf{n}'(n) = \mathbf{h} \otimes_c \hat{\mathbf{x}}(n) + \mathbf{n}'(n) \tag{4}$$

where $\mathbf{n}'(n)$ is a channel noise vector of size $(N+K)\times 1$. $\otimes_c$ represents as circular convolution and $\mathbf{h} = \{h_0,\ldots,h_{L\text{-}1}\}$ denotes the channel impulse response which can arrange the toeplitz channel matrices $\mathbf{H}$ of size $(N+K)\times(N+K)$. After discarding the CP portion of the received signal block, the received signal block $\mathbf{y}(n)$ of size $N\times 1$ can be written as

$$\mathbf{y}(n) = \mathbf{R}_{cp}\mathbf{H}\mathbf{T}_{cp}\mathbf{x}(n) + \mathbf{n}(n) \tag{5}$$

where $\mathbf{R}_{cp}$ denotes the CP discarding matrix of size $N\times(N+K)$ defined as

$$\mathbf{R}_{cp} = \begin{bmatrix} \mathbf{O}_{N\times K} & \mathbf{I}_{N\times N} \end{bmatrix}_{N\times(N+K)} \tag{6}$$

and $\mathbf{n}(n) = \mathbf{R}_{cp}\mathbf{n}'(n)$. Next, after CP insertion and discarding CP portion, the channel matrix $\mathbf{H}$ will change into a circulant matrix $\mathbf{H}_c$ of size $N\times N$ can be written as

$$\mathbf{H}_c = \mathbf{R}_{cp}\mathbf{H}\mathbf{T}_{cp} = \mathbf{F}^H\mathbf{\Lambda}\mathbf{F} \tag{7}$$

where $\mathbf{\Lambda}$ is the channel frequency response, and $\mathbf{F}$ is defined as a discrete Fourier transform (DFT) matrix. The received signal block $\mathbf{Y}$ after DFT can be written as

$$\mathbf{Y}(n) = \mathbf{F}\mathbf{y}(n) = \mathbf{\Lambda}\mathbf{F}\mathbf{x}(n) + \mathbf{F}\mathbf{n}(n) \tag{8}$$

Finally, after the frequency domain equalizer $\mathbf{W}$ and IDFT processing, we can get the detected signal $\hat{\mathbf{x}}(n)$

$$\hat{\mathbf{x}}(n) = \mathbf{F}^H\mathbf{W}\mathbf{Y}(n) = \mathbf{F}^H\mathbf{W}\mathbf{\Lambda}\mathbf{F}\mathbf{x}(n) + \mathbf{F}^H\mathbf{W}\mathbf{F}\mathbf{n}(n) \tag{9}$$

where $(\cdot)^H$ stands for the conjugate transpose. The equalizer $\mathbf{W}$ consists of ZF and MMSE equalizers.

(1) Zero Forcing (ZF)

$$\mathbf{W} = \mathbf{W}_{ZF} = \mathbf{\Lambda}^{-1} \tag{10}$$

(2) Minimum Mean Square Error (MMSE)

$$\mathbf{W} = \mathbf{W}_{MMSE} = \left(\mathbf{\Lambda}^H\mathbf{\Lambda} + \sigma_n^2/\sigma_x^2\mathbf{I}_{N\times N}\right)^{-1}\mathbf{\Lambda}^H \tag{11}$$

where σ_n^2 and σ_x^2 are the variance of noise and signal.

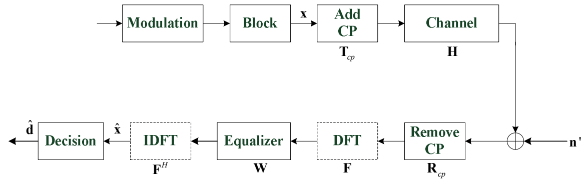

Figure 1. Block diagram of SCBT system.

B. Time Domain Pre-equalization System

In this section, we introduce two pre-equalization systems, which are performed in the transmitter. First, the digital modulation signal block pre-processed by equalizer then adds the CP to overcome multipath channel effect. After CP discarding at the receiver, the received signal can be detected. The two pre-equalization systems are expressed as follows.

(1) Pre-ZF system

First we assume $\mathbf{x}$ is the modulated signal and $\mathbf{H}_c$ is a circulant matrix of channel, the pre-ZF equalization $\mathbf{W}_{ZF}$ is given by

$$\mathbf{W}_{ZF} = \mathbf{H}_c^{-1} \tag{12}$$

Therefore, after pre-equalizer, the precoding signal $\tilde{\mathbf{x}}$ can be written as

$$\tilde{\mathbf{x}} = \mathbf{W}_{ZF}\mathbf{x} \tag{13}$$

Passing through the channel and discarding the CP, the received signal can be written as

$$\mathbf{y} = \mathbf{H}_c\mathbf{W}_{ZF}\mathbf{x} + \mathbf{n} = \mathbf{x} + \mathbf{n} \tag{14}$$

where $\mathbf{H}_c = \mathbf{R}_{cp}\mathbf{H}\mathbf{T}_{cp}$ is defined in (7).

(2) Pre-MMSE system

Pre-MMSE system structure is similar as pre-ZF system, we only need to change the weight matrix into $\mathbf{W}_{MMSE}$, where $\mathbf{W}_{MMSE}$ is given by

$$\mathbf{W}_{MMSE} = \mathbf{H}_c^H(\mathbf{H}_c^H\mathbf{H}_c + \sigma_n^2/\sigma_x^2\mathbf{I})^{-1} \tag{15}$$

so the precoding signal $\tilde{\mathbf{x}}$ can be written as

$$\tilde{\mathbf{x}} = \mathbf{W}_{MMSE}\mathbf{x} \tag{16}$$

Passing through the channel and discarding the CP, the received signal can be written as

$$\begin{aligned} \mathbf{y} &= \mathbf{H}_c\mathbf{W}_{MMSE}\mathbf{x} + \mathbf{n} \\ &= \mathbf{H}_c\mathbf{H}_c^H(\mathbf{H}_c^H\mathbf{H}_c + \sigma_n^2/\sigma_x^2\mathbf{I})^{-1}\mathbf{x} + \mathbf{n} \end{aligned} \tag{17}$$

Traditionally, the performance of MMSE equalizer is better than ZF at the receiver side because of the noise enhancement problem in ZF equalizer. However, the MMSE equalizer makes a trade-off between zero-ISI and noise enhancement, so the problem of noise enhancement can be overcome. But, according to (14), it is note that the performance of pre-ZF is equivalent to the AWGN channel. The simulation result is shown in Figure 2. Assume the length of the signal block is 64, multipath numbers is L=6, the length of CP is 16, and we use QPSK as our modulation type. It is note that the performance of pre-ZF is better than Pre-MMSE about 7dB at BER= 2×10^{-7} and slightly poorer than QPSK AWGN about 1dB because of the CP loss. Finally, we can see the performance of pre-equalization is better than post-equalizer at the receiver side. This is due to the problem of noise enhancement for the equalization at the receiver side. Although the pre-equalization can acquire better performance, but it should do the inverse matrix operation, which will cause the computation load too high. Thus, we will try to reduce the computation load at the following sections

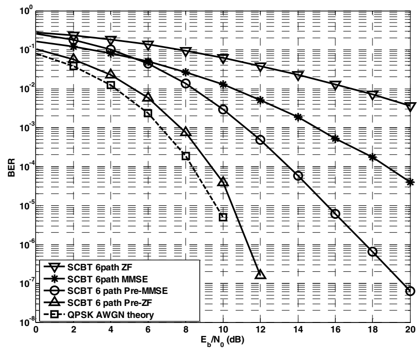

Figure 2. BER performance: ZF/MMSE in the receiver versus Pre-ZF/Pre-MMSE.

III. Upper-Triangular Dirty Paper Coding

In this section, referred to [5], [7], an upper-triangular dirty paper coding (UDPC) is proposed to do pre-processing.

A. Design of Upper Triangular Dirty Paper Coding

Figure 3 is the block diagram of UDPC for SCBT system.

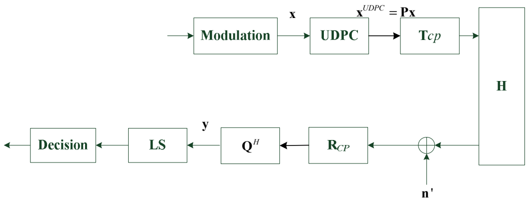

Figure 3. Block diagram of UDPC for SCBT system.

UDPC can be implemented when all the channel states are known at the transmitter side. UDPC is a method of preceding the data such that the effect of the known interference can be canceled. That is, the interference due to the first up to (k-1) signals is canceled in the course of precoding the kth signal. To do the UDPC, first the channel matrix $\mathbf{H}_c$ can be QR-decomposed as

$$\mathbf{H}_c = \begin{bmatrix} \mathbf{q}_1 \\ \vdots \\ \mathbf{q}_N \end{bmatrix} \begin{bmatrix} r_{11} & \cdots & r_{1N} \\ 0 & \ddots & \vdots \\ 0 & 0 & r_{NN} \end{bmatrix} = \mathbf{QR} \tag{18}$$

From [5], we can get precoding matrix in UDPC being a scaled inverse matrix of the upper triangular matrix which is obtained from the channel gain matrix, i.e.,

$$\mathbf{P} = \begin{bmatrix} r_{11} & \cdots & r_{1N} \\ 0 & \ddots & \vdots \\ 0 & 0 & r_{NN} \end{bmatrix}^{-1} \begin{bmatrix} r_{11} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & r_{NN} \end{bmatrix} = \mathbf{R}^{-1}\mathbf{D} \tag{19}$$

The signal after UDPC precoding can be expressed as

$$\begin{aligned} x_1^{UDPC} &= x_1 - \frac{r_{12}}{r_{11}} x_2^{UDPC} \cdots - \frac{r_{1N}}{r_{11}} x_N^{UDPC} \\ &\vdots \\ x_{N-1}^{UDPC} &= x_{N-1} - \frac{r_{(N-1)(N)}}{r_{(N-1)(N-1)}} x_N^{UDPC} \\ x_N^{UDPC} &= x_N \end{aligned} \tag{20}$$

From (18)-(20), the received signal $\mathbf{y}$ can be written as

$$\mathbf{y} = \mathbf{Q}^H \mathbf{H}_c \mathbf{x}^{DPC} + \mathbf{n} = \mathbf{Q}^H \mathbf{H}_c \mathbf{Px} + \mathbf{n} = \mathbf{Dx} + \mathbf{n} \tag{21}$$

Finally, the least square (LS) algorithm can be used for the received signal in (21) to detect the transmit signal.

B. Tomlinson-Harashima Precoding in UDPC System

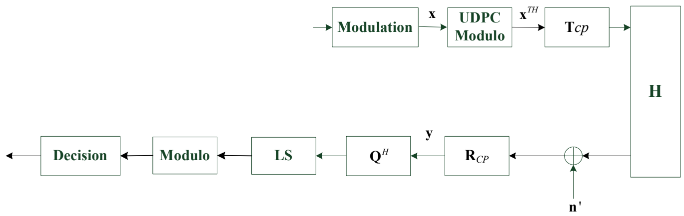

Figure 4. Block diagram of UDPC and THP for SCBT system.

UDPC at the transmitter side is very similar to decision feedback equalization (DFE) at the receiver side. After precoding, the PAPR of the transmitted signals increase very seriously. It may cause power amplifier working in the non-linear area and degrade system performance. Therefore, the combination of UDPC and symmetric modulo operation turns out to be equivalent to Tomlinson-Harashima precoding (THP) [5], [8]. Figure 4 is a block diagram of UDPC system with THP. THP is used to reduce the PAPR of precoding system. Consider the precoding in the two-dimensional case. In M-ary QAM with a square constellation, the real and imaginary parts of a symbol are bounded by [-A, A) with $A = \sqrt{M}$, as illustrated in figure 5, the symmetric modulo operation is defined as

$$\operatorname{mod}_A(x) = x - 2A\lfloor (x + A + jA)/2A \rfloor \tag{22}$$

where $\lfloor \ \rfloor$ stands for floor function. The above modulo operation can be interpreted as a method to find integer values, a and b, such that the following inequalities are satisfied:

$$-A - jA \le \operatorname{mod}_A(x) = x + 2A \cdot a + j2A \cdot b < A + jA \tag{23}$$

the modulo operation in (22) can be expressed as

$$\operatorname{mod}_A(x) = x + 2A \cdot a + j2A \cdot b \tag{24}$$

To simplify the exposition, we consider a simple case of UDPC combined with THP (UDPC-THP). Let $\{x_i^{TH}\}_{i=1}^{3}$ denote the TH precoding signal. Referring to (20) and the modulo operation in (22), THP data can be represented as

$$x_3^{TH} = \operatorname{mod}_A(x_3) = x_3 \tag{25}$$

$$x_2^{TH} = \operatorname{mod}_A(x_2 - \frac{r_{23}}{r_{22}} x_3^{TH}) \tag{26}$$

$$x_1^{TH} = \operatorname{mod}_A(x_1 - \frac{r_{12}}{r_{11}} x_2^{TH} - \frac{r_{13}}{r_{11}} x_3^{TH}) \tag{27}$$

Furthermore, the interpretation in (24) gives the following expression for the TH-precoding signals:

$$x_3^{TH} = x_3 \tag{28}$$

$$x_2^{TH} = x_2 - \frac{r_{23}}{r_{22}} x_3^{TH} + 2A \cdot a_2 + j2A \cdot b_2 \tag{29}$$

$$x_1^{TH} = x_1 - \frac{r_{12}}{r_{11}} x_2^{TH} - \frac{r_{13}}{r_{11}} x_3^{TH} + 2A \cdot a_1 + j2A \cdot b_1 \tag{30}$$

For the transmitted signal $\mathbf{T}_{cp}\mathbf{x}^{TH} = \mathbf{T}_{cp}[x_1^{TH} x_2^{TH} x_3^{TH}]^T$, after the channel fading , CP discarding and $\mathbf{Q}^H$ operation, the received signal is given as

$$\mathbf{y} = \mathbf{Q}^H \mathbf{H}_c \mathbf{x}^{TH} + \mathbf{n} = \mathbf{R}\mathbf{x}^{TH} + \mathbf{n} \tag{31}$$

Since $x_3^{TH} = x_3$, the signal detection for y_3 is obvious. The received signal of y_2 is given as

$$y_2 = r_{22} x_2^{TH} + r_{23} x_3^{TH} + n_2 \tag{32}$$

Next, substituting (29) into (32) leads to

$$y_2 = r_{22}(x_2 + 2A \cdot a_2 + j2A \cdot b_2) + n_2 \tag{33}$$

Defining $\widehat{y}_2$ as a scaled version of y_2, i.e.,

$$\widehat{y}_2 = \frac{y_2}{r_{22}} = x_2 + 2A \cdot a_2 + j2A \cdot b_2 + \frac{n_2}{r_{22}} \tag{34}$$

$\hat{x}_2$ can be detected with the modulo operation

$$\hat{x}_2 = \mathrm{mod}_A(\widehat{y}_2) \tag{35}$$

If the noise component in (34) is small enough to meet the following condition:

$$-A \le x_2 + \frac{n_2}{r_{22}} < A \tag{36}$$

Then, (35) turns out to be

$$\hat{x}_2 = \mathrm{mod}_A(\widehat{y}_2) = \widehat{y}_2 - 2A(a_2 + jb_2) = x_2 + \frac{n_2}{r_{22}} \tag{37}$$

From (31), the received signal of y_1 is given as

$$y_1 = r_{11} x_1^{TH} + r_{12} x_2^{TH} + r_{13} x_3^{TH} + n_1 \tag{38}$$

Substituting (28)-(30) into (38), the received signal y_1 can be expressed as

$$\begin{aligned} y_1 &= r_{11} x_1^{TH} + r_{12} x_2^{TH} + r_{13} x_3^{TH} + n_1 \\ &= r_{11}(x_1 + 2A \cdot a_1 + j2A \cdot b_1) + n_1 \end{aligned} \tag{39}$$

Next, same as the detection of $\hat{x}_2$ in (34)-(35), the signal $\hat{x}_1$ can be detected as

$$\hat{x}_1 = \mathrm{mod}_A(\widehat{y}_1) = \widehat{y}_1 - 2A(a_1 + jb_1) = x_1 + \frac{n_1}{r_{11}} \tag{40}$$

where

$$\widehat{y}_1 = \frac{y_1}{r_{11}} = x_1 + 2A \cdot a_1 + j2A \cdot b_1 + \frac{n_1}{r_{11}} \tag{41}$$

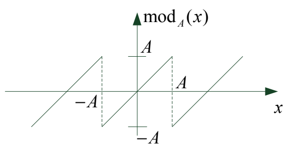

Figure 5. Illustration of symmetric modulo operation (real part of x).

C. *Water Filling Algorithm in UDPC System*

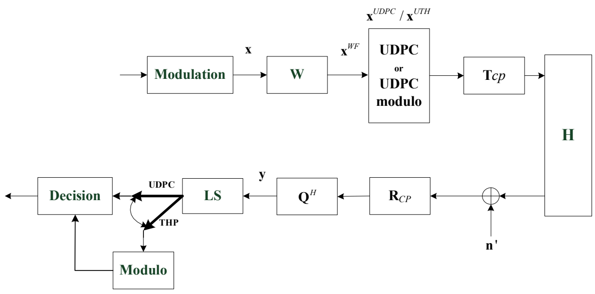

Figure 6. Block diagram of UDPC/UDPC-THP with water filling algorithm for SCBT system.

The conventional water filling algorithm [9] is used to assign the transmitted power allocation according to different subcarriers channel in frequency domain. In this section, because the UDPC-THP system will be degraded by the deep fading composite channel r_{ii}, the dynamic channel on/off assignment via the water filling algorithm is proposed to enhance bit error rate (BER) performance. That is, the water filling algorithm is used to turn off the transmit signals corresponding to the deep fading composite time-domain channels. The block diagram of UDPC/UDPC-THP with water filling algorithm is depicted in Figure 6. Let **W** be the water filling matrix is defined as $\mathbf{W} = diag\{w_1, ..., w_N\}$ where $diag\{.\}$ is the diagonal matrix, and

$$w_i = \sigma_n^2 (\tilde{\mu} - \frac{1}{|r_{ii}|})^+ \;\; => \;\; w_i = \begin{cases} 1, w_i > 0 \\ 0, w_i \le 0 \end{cases} \tag{42}$$

$$\tilde{\mu} = \frac{1}{N}(\frac{P}{\sigma_n^2} + \sum_{i=1}^{N} \frac{1}{|r_{ii}|}) \text{ and } \frac{P}{\sigma_n^2} = 10^{\frac{SNR}{10}} \tag{43}$$

Simply speaking, when $w_i = 0$, it represents that no data will be transmitted. On the contrary, when $w_i = 1$, all data will be transmitted normally.

IV. Computer Simulations

In this section, simulation results are conducted to demonstrate the performance of the proposed UDPC system. Table 1 is the system parameters. All the simulations are assuming perfectly known the channel state information at the transmitter.

Table 1: System simulated parameters

Parameter	Specification
Modulation type	QPSK
Subcarriers number	64
Multipath number	6
Channel model	Equal Gain Rayleigh Fading Channel
CP length	16

The performance of UDPC and UDPC-THP systems is shown in Figure 7. The UDPC-THP system is slightly poorer than UDPC system with a degradation of only about 2 dB, due to the received signal with noise in (34) and (41) conducted the incorrectness of the modulo operation in (37) and (40). Next, for the PAPR comparison, the performance of UDPC and UDPC-THP systems is shown in Figure 8. It is obvious that the UDPC-THP system can provide lower PAPR performance than the UDPC system about 5 dB at $Pr=10^{-3}$. It confirms that the modulo operation can assist the UDPC-THP system with the constrained transmit power.

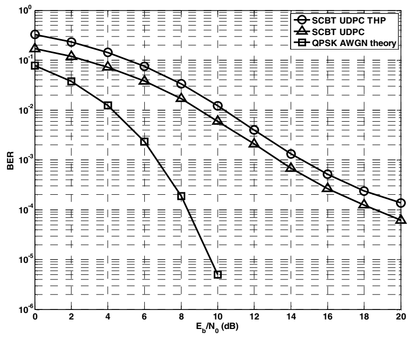

Figure 7. BER performance of UDPC/UDPC-THP for SCBT system.

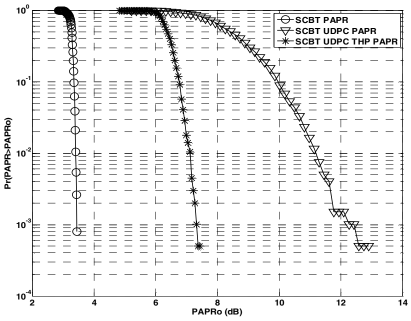

Figure 8. PAPR comparison of UDPC/UDPC-THP for SCBT system.

Finally, to investigate the performance of the proposed UDPC and UDPC-THP systems with water filling algorithm, the performances are shown in Figure 9 and 10. To overcome the error floor problem in Figure 7, the water filling algorithm is proposed to turn off the signal transmission for the weak composite fading channel. The result in Figure 9 shows the off-subchannel probability of UDPC system with water filling algorithm for different E_b/N_0. It is note that, when E_b/N_0=0dB, the off-subchannel probability is about 7%. Moreover, when E_b/N_0=20dB, only 0.5% transmission signal is turned off.

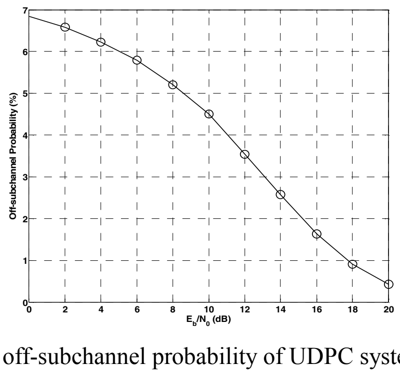

Figure 9. The off-subchannel probability of UDPC system with water filling algorithm for different E_b/N_0.

Next, as shown in Figure 10, at E_b/N_0>12dB, the proposed system with water filling algorithm can provide better performance than the UDPC/UDPC-THP system. Finally, the above simulation results confirm that the proposed UDPC-THP system with water filling algorithm is able to offer lower PAPR and better BER performances than UDPC system.

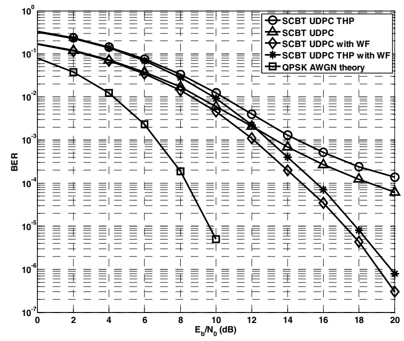

Figure 10. BER performance of UDPC/UDPC-THP with water filling algorithm for SCBT system.

V. CONCLUSIONS

The precoding algorithms with the pre-equalization and pre-cancellation techniques are proposed for SCBT system. First, we propose a UDPC precoding technique to pre-equalize the multipath channel fading and then adopt THP technique in order to acquire low PAPR. Finally, the UDPC-THP with water filling algorithm is proposed to combat the deep fading effect and enhance the BER performance. Simulation results confirm that the proposed algorithms can attain the excellent BER performance and provide low PAPR performance.

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