Quantized Beamforming Technique for LTE-Advanced Uplink

Young Ju Kim* and Xun Li

Chungbuk National University
Cheongju, Chungbuk, Republic of Korea
{yjkim,xunli}@cbnu.ac.kr

Abstract. Long term evolution (LTE) standard for uplink transmission is based on single carrier frequency division multiple access (SC-FDMA) to maintain low peak-to-average power ratio (PAPR), which is very valuable for the practical handset design. Recently the usage of codebook-based precoding is thoroughly discussed for the LTE-Advanced (LTE-A) uplink. Among the various precoding schemes, equal gain transmission (EGT) is proposed in this paper because it does not increase any PAPR. Especially, considering nonlinear transmit power amplifier model in uplink, EGT is superior to any other precoding schemes. Theoretical analysis of precoding schemes' PAPR is presented under quasistatic flat fading channel, and link-level bit error rate (BER) is simulated to corroborate the anticipated results.

Keywords: SC-FDMA, LTE-A, uplink, MIMO.

1 Introduction

3rd generation partnership project (3GPP) release 8 standardization, which is called LTE, adopts quite different modulation and multiple access techniques from 3GPP's previous versions such as wideband code division multiple access (WCDMA) and high speed packet access (HSPA) [1][2][3]. Orthogonal frequency division multiple access (OFDMA) and SC-FDMA are employed as downlink and uplink multiple access techniques respectively [4]. Also the notable thing is the fact that SC-FDMA has lower PAPR than OFDMA, which make a small and low cost handset design possible. Meanwhile, the 1st workshop of LTE-A held in Shenzhen, April 2008, proposed advanced key techniques for higher average throughput, cell-edge throughput, and spectrum efficiency, compared to LTE. Then 3GPP approved LTE-A study from June 2008 [5]-[11]. One of the key techniques for LTE-A is applying multi-input multi-output (MIMO) technique for uplink which is a promising technique with many benefits [12][14][15].

When user equipment (UE) moves at a low speed less than 60 km/hr, codebook-based closed-loop MIMO can enhance uplink performances. Conventionally,

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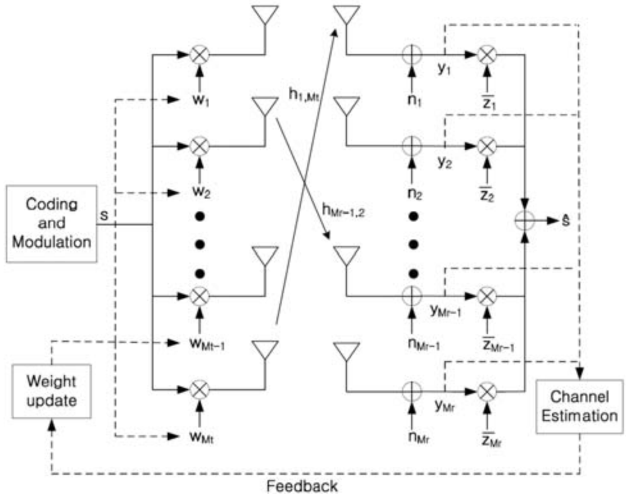


Fig. 1. Block diagram of precoding and combining method in MIMO systems

various codebook design employ maximum ratio transmission (MRT) technique because it shows the optimum received signal-to-noise ratio (SNR) [16]. But in terms of uplink transmission, it can deteriorate PAPR. So in this paper quantized equal gain transmission (EGT) is newly considered for LTE-A uplink because of its perfect PAPR property [17]. Moreover, non-linear transmit power amplifier model is also considered to verify the effect of PAPR in the link-level BER simulations. It can be expected that because MRT-based codebook make the transmit signal level fluctuate, EGT-based codebook outperforms MRT codebook in nonlinear power amplifier channel model.

This paper is organized as follows: Section 2 makes a brief overview of codebook-based precoding scheme. Section 3 describes the precoding method for SC-FDMA system. Section 4 investigates how the PAPR can be obtained in SC-FDMA in quasistatic flat fading channel. In Section 5, we exhibit BER simulation results considering nonlinear transmit amplifier model. Finally, our conclusions are provided in Section 6.

2 Overview of Codebook-Based Precoding

This paper treats closed-loop precoding showing better performance than open-loop precoding in pedestrian channel environment. Closed-loop schemes include explicite and implicit channel state information (CSI) feedback. The explicit CSI feedback is that the quantized channel information is directly delivered to the transmitter by receiver, while implicit one is that the receiver determines and delivers the proper index among the weighting vectors of the codebook which is known by both transmitter and receiver. In WiMAX, multi-rank MRT-based codebooks are proposed when the numbers of transmit antennas are 2, 3 and 4 [18] [19]. LTE release 8 also has MRT-based codebooks for downlink. And codebooks were proposed by some companies for LTE-A uplink [7]. In [17], EGT is also precisely studied by David Love and the generation of EGT-based codebook is also detailed in six steps.

Fig. 1 shows how CSI feedback is performed in precoded MIMO systems. M_t and M_r is the number of transmit antennas and receive antennas, respectively. w is precoding vector, $l(1 \leq l \leq M_t)$ is transmit antenna index, while $k(1 \leq k \leq M_r)$ is receive antenna index. The received signal y_k could be expressed as the following [16] [17]:

$$y_k = \left(\sum_{l=1}^{M_t} h_{k,l} w_l \right) s + n_k, \tag{1}$$

where $h_{k,l}$ is memoryless fading channel and n_k is AWGN noise at kth receive antenna. The data received by the kth receive antenna, y_k, is multiplied by $\overline{z_k}$. The weighted output of each of the M_r receive antennas is then combined. This formulation allows the equivalent system to be written in matrix form as the following [17]:

$$\widehat{s} = \left(z^H H w \right) s + z^H n, \tag{2}$$

where $\mathbf{w} = [w_1, w_2, \cdots, w_{M_t}]^T$, $\mathbf{z} = [z_1, z_2, \cdots, z_{M_r}]^T$, $\mathbf{n} = [n_1, n_2, \cdots, n_{M_r}]^T$ and $\mathbf{H}$ denotes the $M_r \times M_t$ matrix having coordinate (k, l), which is equal to $h_{k,l}$. Furthermore, $[\cdot]^T$ and $[\cdot]^H$ represent transposition and conjugate transposition, respectively. For the sake of achieving optimum performances, $\mathbf{w}$ and $\mathbf{z}$ should be chosen as a function of the channel estimate to maximize the receive Signal to Noise Ratio (SNR) [16],[20].

The receiver can estimate and send back CSI to the transmitter. But due to a limited feedback channel capacity, it is impossible to send back high precision CSI to the transmitter in most systems. Only quantized CSI or well designed codebook's index within L bits can be sent back. In multiple-input single-output (MISO) system, which can be more easily understood than MIMO, the optimal precoding vector with MRT scheme w_{MRT} is given by [16]:

$$w_{MRT} = \sqrt{M_t} \frac{h^H}{\|h\|_F^2}, \tag{3}$$

where $h = [h_1, h_2, \cdots, h_{M_t}]$ and $\|\cdot\|_F^2$ represents the Frobenius norm. In case of EGT scheme, the optimal precoding vector w_{EGT} is given by [17]:

$$w_{EGT} = \frac{1}{\sqrt{M_t}} e^{j\theta}, \tag{4}$$

where

$$\theta \in \arg\max_{\vartheta \in [0, 2\pi)} \left\| H e^{j\vartheta} \right\|. \tag{5}$$

Texas instruments proposed a Householder-based codebook with potential complexity reduction in [13], whose codebook for Rank 1 transmission with 3 bits feedback is generated by following

$$V_{21}(\theta, \varphi) = \begin{bmatrix} \cos(\theta) \\ \sin(\theta)\exp(j\varphi) \end{bmatrix} \tag{6}$$

where $\theta = \tan^{-1}\{1/3, 3, 3/4, 3/4, 3/4, 4/3, 4/3, 4/3,\}$, and $\varphi = \{0, 0, 0, \pi/3, 2\pi/3, \pi, 4\pi/3, 5\pi/3\}$.

The upper bound of system performance is achievable if $z = Hw/\|Hw\|_2$. In codebook based precoding system with codebook size 2^L, the codebook index k could be determined by following equation

$$k = \arg\max_{1 \le k \le 2^L} |Hw(k)|_1 \tag{7}$$

The codebook search algorithm and performance comparison between MRT and EGT with codebook is studied by the authors in [21].

3 Precoding Methods for SC-FDMA Uplink

The basic idea of SC-FDMA could be regarded as discrete fourier transform (DFT)-spread OFDMA, where time domain data symbols are transformed to frequency domain by M-point DFT operation and subcarrier mapping has to be done before going through N-point OFDM modulator, where N is much larger than M. When $Q = N/M$, Q denotes band spreading factor. Users of SC-FDMA system occupy different subcarriers in frequency domain. Thus the overall transmit signal performs like a single carrier signal, PAPR is inherently low at each user equipment compare to the case of OFDMA. Let $\{x_m : m = 0, 1, \cdots, M-1\}$ be data symbols to be modulated. Then, $\{X_k : k = 0, 1, \cdots, M-1\}$ are frequency domain DFT processed samples and $\{y_n : n = 0, 1, \cdots, M-1\}$ represents the OFDM modulated time domain samples. They could be expressed as

$$X_k = \sum_{m=0}^{M-1} x_m e^{-j2\pi \frac{m}{M} k} \tag{8}$$

$$y_n = \frac{1}{N} \sum_{l=1}^{N-1} Y_l e^{j2\pi \frac{n}{N} l}, \tag{9}$$

where $\{Y_l : l = 0, 1, \cdots, N-1\}$ is the frequency domain samples after subcarrier mapping. Interleaved FDMA (IFDMA) and localized FDMA (LFDMA) subcarrier mapping schemes are under consideration as the uplink communications in this paper, which were illustrated in [22]. In IFDMA, DFT transformed signals are allocated over the entire bandwidth with equidistance between occupied subcarriers, whereas consecutive subcarriers are occupied by the DFT outputs in LFDMA. At each user equipment, zeros are occupied in unused subcarriers as the block diagram is shown in Fig. 3. For IFDMA,

$$Y_l = \begin{cases} \widehat{X}_{l/Q}, l = Q \cdot k (0 \le k \le M-1) \\ 0, otherwise \end{cases} \tag{10}$$

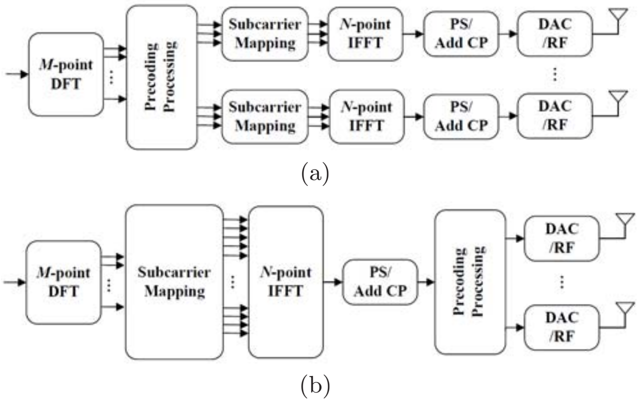
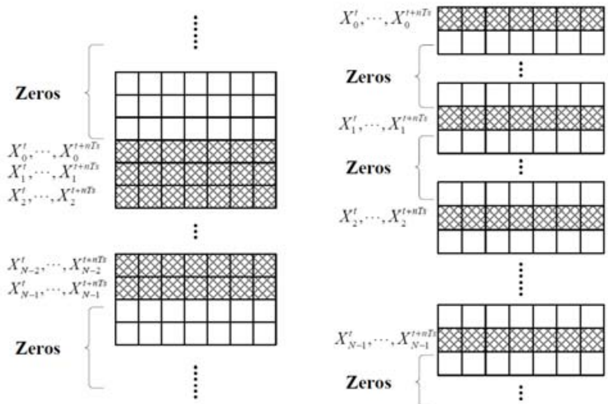


Fig. 2. Block diagram of a spatial multiplexing SC-FDMA MIMO system: (a) Precoding in frequency domain, (b) Precoding in time domain



(a) (b)

Fig. 3. Subcarrier mapping modes: (a) Localized FDMA, (b) Interleaved FDMA

and for LFDMA,

$$Y_l = \begin{cases} \widehat{X}_l, 0 \leq l \leq M-1 \\ 0, M \leq l \leq N-1 \end{cases}, \tag{11}$$

We have two schemes to implement the precoding operation, precoding in frequency domain as shown in Fig. 2(a), and precoding in timedomain as shown in Fig. 2(b).

In case of precoding in frequency domain, $\{\widehat{X}_l : l = 0, 1, \cdots, M-1\}$ in (11) are frequency domain precoded samples, and precoding vector $\{W_k : k = 0, 1, \cdots, M-1\}$ should be determined according to the channel frequency response, $\widehat{X}_k = W_k \cdot X_k$. The transmit samples are OFDM modulated samples $\widehat{y}_n = y_n$.

If the precoding operation is implemented in time domain, $\widehat{X}_l = X_l$. The precoding vector $\{w_n : n = 0, 1, \cdots, N-1\}$ should be determined according channel impulse response, and the transmit samples after precoding operation becomes $\widehat{y}_n = w_n \cdot y_n$. These two precoding implementations could obtain the same performance if we assume the CSI is perfectly known by the receiver, and ignore the equalization complexity difference between in frequency domain and in time domain. Finally, the transmit samples in time domain could be expressed as the following by substituting (10) and (11) to (9):

$$\hat{y}_{n,LFDMA} = \begin{cases} \frac{1}{N}\sum\limits_{l=1}^{N-1} W_l X_l e^{j2\pi\frac{n}{N}l}, \mathrm{FD-precoding} \\ w_n \frac{1}{N}\sum\limits_{l=0}^{N-1} X_l e^{j2\pi\frac{n}{N}l}, \mathrm{TD-precoding} \end{cases} \tag{12}$$

$$\hat{y}_{n,IFDMA} = \begin{cases} \frac{1}{N}\sum\limits_{l=1}^{N-1} W_{l/Q} X_{l/Q} e^{j2\pi\frac{n}{N}l}, \mathrm{FD-precoding} \\ w_n \frac{1}{N}\sum\limits_{l=0}^{N-1} X_{l/Q} e^{j2\pi\frac{n}{N}l}, \mathrm{TD-precoding} \end{cases} \tag{13}$$

4 PAPR of SC-FDMA in Quasistatic Flat Fading Channels

The PAPR of precoded SC-FDMA is analyzed under the quasistatic flat fading channel. Since quasistatic channel means the fading coefficient is constant over a OFDM symbole period, precoded weighting vector is also constant under the period. The PAPR of transmit signal could be expressed as

$$PAPR = \frac{\max\left|\widehat{y}_n\right|^2}{E\left[\left|\widehat{y}_n\right|^2\right]} = \frac{\max\left|W_n\widehat{X}_n\right|^2}{E\left[\left|W_n\widehat{X}_n\right|^2\right]}. \tag{14}$$

Considering flat fading channel, the precoding vector for each subcarrier is equivalent in one OFDM symbol due to the channel is frequency non-selective. Therefore, (13) could be rewritten as

$$PAPR = \frac{\max\left|W\widehat{X}_n\right|^2}{E\left[\left|W\widehat{X}_n\right|^2\right]} = \frac{\left|W\right|^2\cdot\max\left|\widehat{X}_n\right|^2}{\left|W\right|^2\cdot E\left[\left|\widehat{X}_n\right|^2\right]}. \tag{15}$$

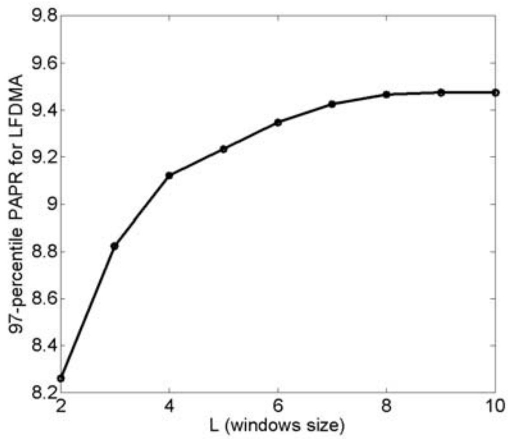


Fig. 4. CCDF curve of PAPR for the obervation window size L

From (14), we could know that it is meaningless to calculate the PAPR in one OFDM symbol. However, it is meaningful to calculate PAPR with several symbols. we set the observation windows size to be L, the new PAPR represents as the following:

$$PAPR = \frac{\max\limits_{0\leq l\leq L-1, 0\leq n\leq N-1} \left| W_l \widehat{X}_{Nl+n} \right|^2}{\frac{1}{L}\cdot\frac{1}{N}\sum\limits_{l=0}^{L-1}\sum\limits_{n=0}^{N-1}\left| W_l \widehat{X}_{Nl+n} \right|^2}. \tag{16}$$

Fig. 4 shows the complementary culdative distribution function (CCDF) result of PAPR with various windows size L using Monte Carlo simulation. The CCDF is the probability that PAPR is higher than a certain PAPR value $PAPR_o$. The souce samples are modulated by QPSK and mapped with LFDMA scheme. The codebook is WiMAX rank 1 codebok which designed for 2 transmit antenna and single user. The observation windows size is increase from 2 to 10. In this simulation, the $PAPR_o$ is determined by the probability is 97-percentage. Another simulation shows the $PAPR_o$ which is determined by the probability is 99.9-percentage in Table 1. Therefore, $L = 10$ would be approprate to reflect the impact of precoding to PAPR of SC-FDMA system. With this consideration, Fig. 5 shows the CCDF comparison of IFDMA and LFDMA with different codebook, including EGT codebook, MRT codebook (WiMAX), LTE Release 8 downlink codebook, and TI codebook which was proposed by TI company for LTE-A. Raised cosine filter is used at the transmitter for pulse shaping, with over sampling factor is 8 and roll-off factor is 0.5. Fig. 5 shows that SC-FDMA has lowest PAPR with EGT codebook for precoding, and IFDMA mapping scheme outperforms LFDMA mapping scheme.

Table 1. 99.9-percentile PAPR for the observation window size L

L	99.9% PAPR for LFDMA (dB)
2	8.262
4	9.122
6	9.347
8	9.465
10	9.471

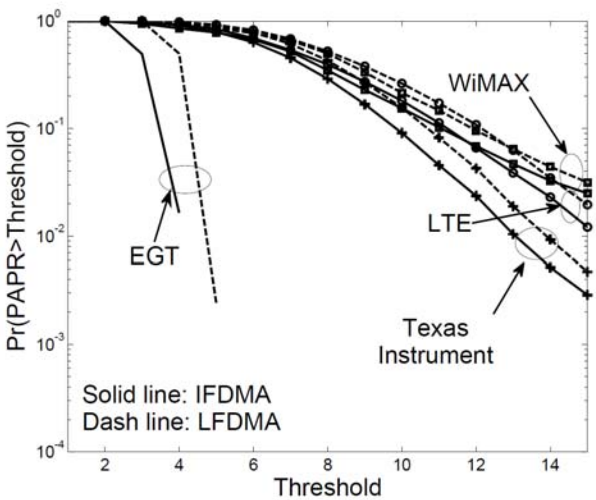


Fig. 5. CCDFs of IFDMA and LFDMA with Raised-cosine roll-off factor $\alpha = 0.5$

5 System Parameters and BER Simulation Results

For this section, we simulated the average probability of bit error with varous codebook. Jakes' model is used as wireless channel with 3km/h and 60km/h of UE's velocity. Perfect channel estimation and ideal synchronization at the receiver is considered, and there is no correlation between transmit antennas and receive antennas since enough antenna space is assumed. The system carrier frequency is 2.0 GHz, symbol rate is 7.68 million symbols/sec which is usually used in LTE-A. PMI related parameters are error-free precoding matrix indicator (PMI) with 1ms delay. We considered $M_r = M_t = 2$. We let the bandwidth expansion factor $Q = 4$, and $M = 512$ and $N = 2048$. Raised-cosine filter is used for pulse shaping with 8x oversampling. More details about simulation parameter are listed in Table 2.

Table 2. Simulation parameters for PAPR and BER

Bandwidth	5MHz
Carrier frequency	2GHz
Data rate	7.68Mbps
Channel for PAPR	Quasistatic Rayleigh fading
Channel for BER	Jakes' model
Tx antenna	2
Modulation	QPSK
Channel estimation	Ideal
DFT size (M)	16/512 (PAPR/BER)
IFFT size (N)	512/2048 (PAPR/BER)
Precoding codebook	EGT/WiMAX/LTE/TI
Oversampling factor	8
Pulse shaping	Raised cosine filter

To approximate the effect of nonlinear power amplifier in the transmitter, we adopt Rapp's model for amplitude conversion which could be represent as

$$g(A) = \frac{A}{(1 + A^{2p})^{1/(2p)}}. \tag{17}$$

Fig. 6 illustrate the relation between amplitude of the normalized input signal A and amplitude of output signal $g(A)$ when the nonlinear characteristic factor $p = 3$. The phase conversion of the power amplifier is neglected in this paper.

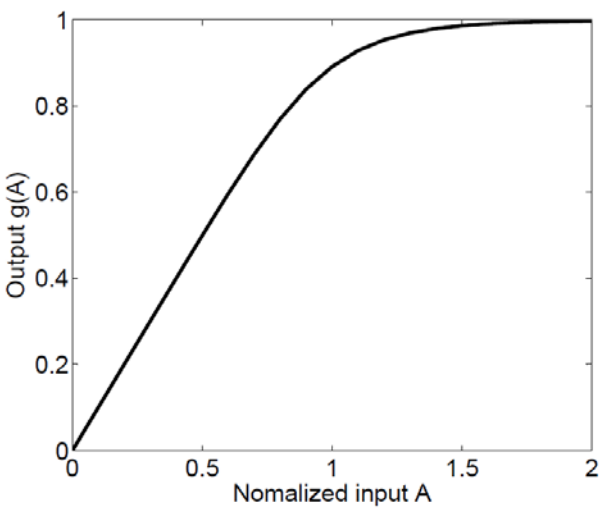


Fig. 6. Input-output relation curve of the Rapp's model when $p = 3$

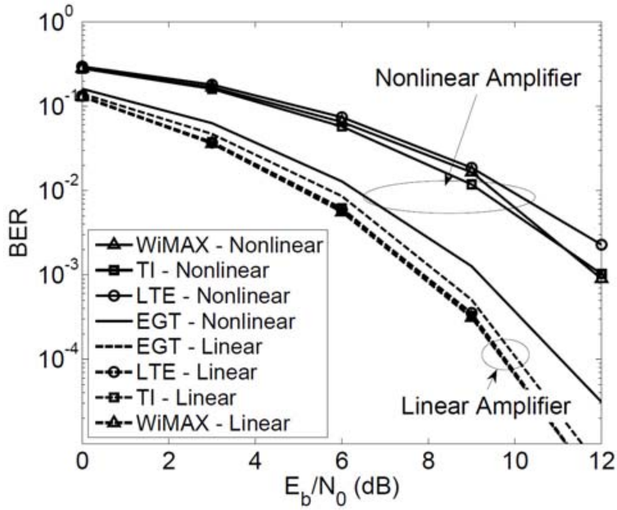


Fig. 7. BER performance of LFDMA with QPSK, velocity is 3km/h

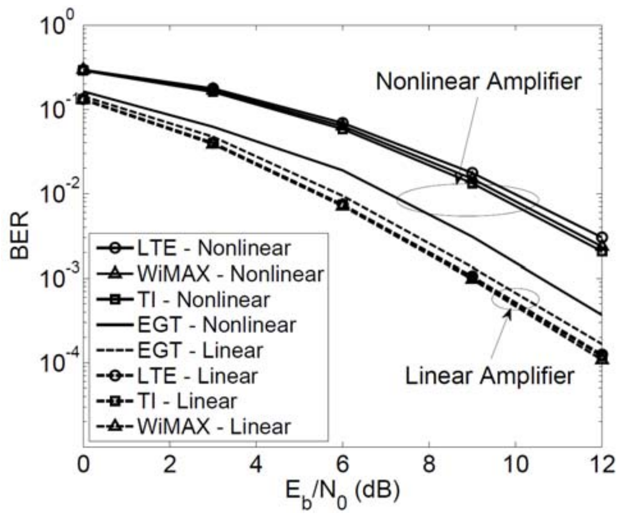


Fig. 8. BER performance of LFDMA with QPSK, velocity is 60km/h

Fig. 7 illustrates the BER performances of LFDMA with different precoding schemes. At the receiver, maximal ratio combining (MRC) scheme is used who provids upper bound receive diversity. Although, when the linear amplifier is considered at the transmitter, EGT scheme performs worse than other codebook almost 1dB. But when the nonlinear amplifier is under consideration, it outperforms other schemes by almost 3dB at a 10^{-3} BER, while other scheme's signal suffering nonlinear power distortion much more seriously. Fig. 8 shows the BER comparison of SC-FDMA system with UE's velocity is 60km/h. Due to feedbacked daley, all BER performances are degraded with high velocity of UEs. However, the performance based on EGT codebook still outperforms other scheme when nonlinear power amplifier is under consideration.

6 Conclusions

In this paper, we have investigated how the precoding schemes impact on the PAPR of SC-FDMA system. Conventional MRT-based methods and newly proposed EGT-based method were carefuly examined. We showed that precoding schemes could increase the PAPR for SC-FDMA signals but EGT does not cause any signal variations. In the BER simulations including non-linear transmit power amplifier model, EGT-based precoding scheme outperforms any other MRT-based ones. In order to maintain the low PAPR advantages of SC-FDMA compared to OFDMA, precoding schems should be cautiously designed, and EGT can be a good technique for LTE-A uplink employing MIMO SC-FDMA.

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