Novel Feedback Calculation Technique for Improved Transmit Scheme

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Abstract. *Extended balanced space-time block coding (EBSTBC) is able to achieve large coding gain and guarantee full diversity for any number of transmit antennas. Performance of the EBSTBC has been improved with improved transmit scheme (ITS) which is combination of the EBSTBC with transmit antenna selection. Performance of the ITS with a limited number of feedback bits approaches to performance of ideal beamforming which requires ideal channel state information at the transmitter. However, the calculation of feedback information at the receiver employs exhaustive searching scheme which is very complex and energy inefficient process. In this work, a low complexity and energy efficient feedback information scheme for the ITS receiver is proposed. Theoretical and simulation results show that the calculation complexity of feedback information is decreased more than 87% and the proposed scheme yields the same bit error rate performance with the ITS. Moreover, the proposed scheme requires very low addition memory with respect to alternative schemes.*

Keywords

Extended balanced space-time coding, feedback calculation, low complexity, energy efficiency.

1. Introduction

Multiple-input–multiple-output (MIMO) systems have enormous channel capacity gain, and are subject to enormous interest in wireless communication. Moreover, space-time coding techniques have been developed for the MIMO systems. Orthogonal space-time block coding (OSTBC) is one of the space-time coding methods. The OSTBC provides two advantages: Full diversity and low decoding complexity [1]. The OSTBC method does not achieve full rate and full diversity more than two transmit antennas [2]. In [3], balanced space-time block coding (BSTBC) has been proposed that achieve full rate and full diversity for arbitrary number of transmit antennas when limited number of feedback bits is available at the transmitter. But, the BSTBC does not yield higher coding gain. To increase the coding gain of the BSTBC, extended balanced space-time block coding (EBSTBC) has been proposed [4], [5]. However, the calculation of feedback information at receiver employs exhaustive searching scheme which is highly complex and consumes large amount of energy. In [6], the calculation complexity of the feedback information is decreased for the EBSTBC.

In the EBSTBC scheme, all available transmit antennas are employed to achieve full diversity and to maximize the coding gain. Using all available antennas is not an ideal solution because one of the path gains contributes to the diversity gain only and does not contribute to the coding gain. In [7], [8], an improved transmit scheme (ITS) has been proposed. In the ITS, one out of N transmit antennas does not transmit and one out of N transmit antennas which maximizes the received signal-to-noise ratio (SNR) at the receiver doubles the power of the antenna. The performance of the ITS approaches less than 1 dB to the ideal beamforming performance which requires ideal channel state information (CSI) at the transmitter [7], [8].

In the ITS, selecting optimum code and selecting N-1 antennas out of N antennas can be achieved via exhaustive search which is very complex and consumes lots of energy. Since the ITS selects not only optimum code but also optimum transmit antennas, the proposed technique in [6] cannot be achieved for the ITS. In this paper, we propose a low complexity and energy efficient feedback calculation technique at the receiver. The complexity analysis and detailed simulations show that the calculation complexity of feedback information is decreased strictly, and the same performance is obtained. In addition, we can decrease exhaustive search complexity of the ITS with using limited number of additional memory blocks.

In the following section, system model is described, in the third section, the ITS is explained, in the fourth section, low complexity feedback calculation scheme is presented, in the fifth section, alternative schemes are presented for performance comparison, in the sixth section, complexity analysis of the ITS, the proposed method and alternative schemes is given, in the seventh section, performance analysis is presented. In the last section, the results of the paper and the conclusion are written.

In the paper, the following notations are used: * denotes the conjugate operation; Re{.} is the real part of the

{.}. The operator ceil{.} rounds to the smallest integer greater than or equal to its argument. The operator max{.} returns the largest of its operands and the operator min{.} returns the minimum of its operands.

2. System Model

The system model consists of a base station with N transmit antennas and a mobile user with a single antenna. It can be assumed that all channels are frequency flat Rayleigh fading channel where channel gains are circularly complex Gaussian random variables and statistically independent from each other. The parameter h_i is the channel coefficient from the ith antenna of the base station to the mobile user where i=1, 2,.., N.

It is also assumed that the channels are quasi-static. That is to say, the fading coefficients remain constant over the duration of one frame. The mobile user is assumed to have perfect knowledge of its own channels with using a pilot tone. The noise can be modeled as additive white Gaussian whose components are circular complex random variable with zero-mean and variance σ^2. The base station transmitted data bits are mapped by streams of y bits into M-ary phase shift keying (M-PSK) symbols where $M = 2^y$.

3. Improved Transmit Scheme

The ITS can be obtained as an extension of Alamouti`s code first or second column. The first column extension is selected to obtain minimum decoding delay. Since one of the path gain antenna does not contribute the coding gain, to maximize the received SNR, the ITS uses N-1 transmit antennas out of N transmit antennas and doubles the power of an antenna which maximizes the received SNR.

$$\boldsymbol{C} = \boldsymbol{X}\boldsymbol{W}. \tag{1}$$

Here $\boldsymbol{X}$ is the Alamouti`s code first column and $\boldsymbol{W}$ is the 1xN matrix. The following example shows how to generate the ITS for three transmit antennas. Consider the ITS pair with transmission matrix

$$\boldsymbol{C}_1 = \begin{bmatrix} s_1 & 0 & as_1 \\ -s_2^* & 0 & -as_2^* \end{bmatrix} \tag{2}$$

where $a = e^{j2\pi m/q}$, q is the extension level, s_1 and s_2 are transmitted symbols and m = 0, 1,…q-1. k bits of feedback is needed to select the feedback a where k = ceil{$\log_2 q$}. The columns and rows of $\boldsymbol{C}_1$ denote symbols transmitted from the first and third transmit antennas in two signaling intervals, respectively. $\boldsymbol{C}_1$ is obtained from the Alamouti`s code first column using (1) where

$$\boldsymbol{X} = \begin{bmatrix} s_1 \\ -s_2^* \end{bmatrix}, \quad \boldsymbol{W} = \begin{bmatrix} 1 & 0 & a \end{bmatrix}. \tag{3}$$

The decoding of $\boldsymbol{C}_1$ can be achieved as follows. Assume that first path gain is selected for maximizing the received SNR at the mobile user and the base station transmits the code $\boldsymbol{C}_1$. Then, the received signals at the first and second time intervals at the mobile user are as follows:

$$\begin{aligned} r_1 &= \frac{1}{\sqrt{3}}\left(\sqrt{2}h_1 s_1 + ah_3 s_1\right) + \eta_1, \\ r_2 &= \frac{1}{\sqrt{3}}\left(-\sqrt{2}h_1 s_2^* - ah_3 s_2^*\right) + \eta_2 \end{aligned} \tag{4}$$

where η_i i=1,2 is the complex zero-mean additive white Gaussian noise samples with the variance $N_0/2$ per dimension and the factor $\frac{1}{\sqrt{3}}$ maintains constant transmit power constraint. The estimates of s_1 and s_2 are obtained by linear processing from

$$\begin{aligned} \hat{s}_1 &= \left(\sqrt{2}h_1 + ah_3\right)^* r_1, \\ \hat{s}_2 &= -\left(\sqrt{2}h_1 + ah_3\right) r_2^*. \end{aligned} \tag{5}$$

Replacing (4) into (5) yields

$$\hat{s}_i = \frac{1}{\sqrt{3}}\left(2\left|h_1\right|^2 + \left|h_3\right|^2 + 2\sqrt{2}\,\mathrm{Re}\left\{ah_1^* h_3\right\}\right) s_i + \hat{\eta}_i \quad i=1,2 \tag{6}$$

where $\hat{\eta}_1 = \left(\sqrt{2}h_1 + ah_3\right)^* \eta_1$ and $\hat{\eta}_2 = -\left(\sqrt{2}h_1 + ah_3\right)\eta_2^*$.

For three transmit antennas, a code and a transmit antenna which doubles the transmit power, are selected according to the following criteria

$$max\begin{Bmatrix} \left(2\left|h_1\right|^2 + \left|h_2\right|^2 + 2\sqrt{2}\,\mathrm{Re}\left\{ah_1^* h_2\right\}\right), \left(2\left|h_2\right|^2 + \left|h_1\right|^2 + 2\sqrt{2}\,\mathrm{Re}\left\{ah_1^* h_2\right\}\right), \\ \left(2\left|h_1\right|^2 + \left|h_3\right|^2 + 2\sqrt{2}\,\mathrm{Re}\left\{ah_1^* h_3\right\}\right), \left(2\left|h_3\right|^2 + \left|h_1\right|^2 + 2\sqrt{2}\,\mathrm{Re}\left\{ah_1^* h_3\right\}\right), \\ \left(2\left|h_2\right|^2 + \left|h_3\right|^2 + 2\sqrt{2}\,\mathrm{Re}\left\{ah_2^* h_3\right\}\right), \left(2\left|h_3\right|^2 + \left|h_2\right|^2 + 2\sqrt{2}\,\mathrm{Re}\left\{ah_2^* h_3\right\}\right) \end{Bmatrix}. \tag{7}$$

When the term $2\left|h_1\right|^2 + \left|h_2\right|^2 + 2\sqrt{2}\,\mathrm{Re}\left\{ah_1^* h_2\right\}$ maximizes the received SNR, transmission matrix $\boldsymbol{C}_2$ and the first transmit antenna are selected for where

$$\boldsymbol{C}_2 = \begin{bmatrix} s_1 & as_1 & 0 \\ -s_2^* & -as_2^* & 0 \end{bmatrix}. \tag{8}$$

The $\boldsymbol{C}_2$ and the second transmit antenna are selected if the term $2\left|h_2\right|^2 + \left|h_1\right|^2 + 2\sqrt{2}\,\mathrm{Re}\left\{ah_1^* h_2\right\}$ maximizes the received SNR. The $\boldsymbol{C}_1$ and the first transmit antenna are selected if the term $2\left|h_1\right|^2 + \left|h_3\right|^2 + 2\sqrt{2}\,\mathrm{Re}\left\{ah_1^* h_3\right\}$ is chosen. If the term $2\left|h_3\right|^2 + \left|h_1\right|^2 + 2\sqrt{2}\,\mathrm{Re}\left\{ah_1^* h_3\right\}$ maximizes the received SNR, the $\boldsymbol{C}_1$ and the third transmit antenna are selected. When the term $2\left|h_2\right|^2 + \left|h_3\right|^2 + 2\sqrt{2}\,\mathrm{Re}\left\{ah_2^* h_3\right\}$ maximizes the received SNR, transmission matrix $\boldsymbol{C}_3$ and the second transmit antenna are selected where

$$\boldsymbol{C}_3 = \begin{bmatrix} 0 & s_1 & as_1 \\ 0 & -s_2^* & -as_2^* \end{bmatrix}. \tag{9}$$

Lastly, the term $2|h_3|^2 + |h_2|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_2^* h_3\}$ is selected, the $\boldsymbol{C}_3$ and the third transmit antenna are chosen.

For four transmit antennas, there are four different types of coding matrix for the ITS. These coding matrices are shown below.

$$\boldsymbol{C}_1 = \begin{bmatrix} s_1 & as_1 & bs_1 & 0 \\ -s_2^* & -as_2^* & -bs_2^* & 0 \end{bmatrix} \quad \boldsymbol{C}_2 = \begin{bmatrix} s_1 & as_1 & 0 & bs_1 \\ -s_2^* & -as_2^* & 0 & -bs_2^* \end{bmatrix}$$
$$\boldsymbol{C}_3 = \begin{bmatrix} s_1 & 0 & as_1 & bs_1 \\ -s_2^* & 0 & -as_2^* & -bs_2^* \end{bmatrix} \quad \boldsymbol{C}_4 = \begin{bmatrix} 0 & s_1 & as_1 & bs_1 \\ 0 & -s_2^* & -as_2^* & -bs_2^* \end{bmatrix} \tag{10}$$

For four transmit antennas, a code and a transmit antenna which doubles the transmit power, are selected according to the following criteria

$$\max\begin{Bmatrix} \left(2|h_1|^2 + |h_2|^2 + |h_3|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_1^*h_2 + bh_1^*h_3 + a^*bh_2^*h_3\}\right), \\ \left(|h_1|^2 + 2|h_2|^2 + |h_3|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_1^*h_2 + bh_1^*h_3 + a^*bh_2^*h_3\}\right), \\ \left(|h_1|^2 + |h_2|^2 + 2|h_3|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_1^*h_2 + bh_1^*h_3 + a^*bh_2^*h_3\}\right), \\ \left(2|h_1|^2 + |h_2|^2 + |h_4|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_1^*h_2 + bh_1^*h_4 + a^*bh_2^*h_4\}\right), \\ \left(|h_1|^2 + 2|h_2|^2 + |h_4|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_1^*h_2 + bh_1^*h_4 + a^*bh_2^*h_4\}\right), \\ \left(|h_1|^2 + |h_2|^2 + 2|h_4|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_1^*h_2 + bh_1^*h_4 + a^*bh_2^*h_4\}\right), \\ \left(2|h_1|^2 + |h_3|^2 + |h_4|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_1^*h_3 + bh_1^*h_4 + a^*bh_3^*h_4\}\right), \\ \left(|h_1|^2 + 2|h_3|^2 + |h_4|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_1^*h_3 + bh_1^*h_4 + a^*bh_3^*h_4\}\right), \\ \left(|h_1|^2 + |h_3|^2 + 2|h_4|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_1^*h_3 + bh_1^*h_4 + a^*bh_3^*h_4\}\right), \\ \left(2|h_2|^2 + |h_3|^2 + |h_4|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_2^*h_3 + bh_2^*h_4 + a^*bh_3^*h_4\}\right), \\ \left(|h_2|^2 + 2|h_3|^2 + |h_4|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_2^*h_3 + bh_2^*h_4 + a^*bh_3^*h_4\}\right), \\ \left(|h_2|^2 + |h_3|^2 + 2|h_4|^2 + 2\sqrt{2}\,\mathrm{Re}\{ah_2^*h_3 + bh_2^*h_4 + a^*bh_3^*h_4\}\right) \end{Bmatrix}$$

where $b = e^{j2\pi m/q}$. (11)

4. Low Complexity Feedback Calculation Scheme

In the ITS, when the base station is equipped with three transmit antennas, a code and a transmit antenna which doubles the transmit power, are selected with using (7). The proposed technique calculates a transmit antenna which doubles the transmit power as follows:

$$X = \arg\max_i \left\{|h_i|^2\right\},\ i = 1,2,3. \tag{12}$$

The proposed technique determines a transmit antenna which does not transmit as follows:

$$Y = \arg\min_i \left\{|h_i|^2\right\},\ i = 1,2,3. \tag{13}$$

Then, the proposed technique finds feedback information (a) with using (14).

$$\max\left\{\mathrm{Re}\left\{ah_X^* h_Z\right\}\right\} \text{ where } X, Z \in 1,2,3 \text{ and } X, Z \neq Y. \tag{14}$$

In the ITS, when the base station is equipped with four transmit antennas, a code and a transmit antenna which doubles the transmit power, are selected with using (11). The proposed technique calculates a transmit antenna which doubles the transmit power as follows:

$$X = \arg\max_i \left\{|h_i|^2\right\},\ i = 1,2,3,4. \tag{15}$$

The proposed technique determines a transmit antenna which does not transmit as follows:

$$Y = \arg\min_i \left\{|h_i|^2\right\},\ i = 1,2,3,4. \tag{16}$$

Then, the proposed technique finds feedback information (a, b) with using (17).

$$\max\left\{\mathrm{Re}\left\{ah_X^* h_Z + bh_X^* h_T + a^* bh_Z^* h_T\right\}\right\} \tag{17}$$

where $X, Z, T \in 1, 2, 3, 4$ and $X, Z, T \neq Y$.

5. Alternative Schemes

There are several alternative schemes which combine limited feedback schemes with space-time coding. In [9], an open-loop extended orthogonal space-time coding (EO-STBC) for three and four transmit antennas are presented. Since the EO-STBC does not use any feedback, the diversity may not be full. In order to achieve full diversity, closed-loop extended orthogonal space-time block codes (CL EO-STBCs) use N-2 feedback bits to rotate the phases of the signals for certain antennas to ensure that the full diversity is achieved during the whole transmission [9]. The disadvantage of the CL EO-STBCs is that the phase angles are quantized to two levels (0 or π). In phase feedback based extended space-time block codes (PFB-ESTBC), the phase angles are quantized arbitrary levels [10]. Then, these levels are fed back from the mobile user to the base station. The mobile user needs ceil$\{(N\text{-}2)\log_2 q\}$ feedback bits ($N \geq 3$).

In the partial phase combining (PPC), quantized phase difference of channel coefficients is fed back to the base station [11]. The base station utilizes this information to maximize average received SNR by steering the transmitted signals and reducing the phase difference between received signals. The mobile user needs ceil$\{(N\text{-}1)\log_2 q\}$ feedback bits ($N \geq 2$). Beamforming (BF) needs ideal CSI at the base station and it requires unlimited feedback from the mobile user [12]. However, the bandwidth of feedback channel is limited. In this case, the mobile user should quantize the CSI in the form of transmit beamforming vector and inform it to the base station through a low-rate, limited bandwidth feedback channel [13].

6. Complexity Analysis

In this section we give a comparison of the computational complexity of the ITS [8], the ITS with using additional memory, the PFB-ESTBC [10], the PFB-ESTBC with using additional memory, the EBSTBC [4], the EBSTBC with additional memory, the PPC [11], the PPC with additional memory, the proposed method without using additional memory, and proposed method with using additional memory in calculating the feedback response. We provide memory requirements of all schemes fairly in mobile environments. Additional memory is used to keep the results of former calculations to use them in the following calculations thus reducing computational work load.

In this section, floating-point operation (FLOP) is used as the computational unit, and every real addition, real multiplication or comparison is taken as 1 FLOP. Tab. 1 presents the memory requirements without additional memory and memory requirements with additional memory for the PFB-ESTBC [10], the EBSTBC [4], the PPC [11], the ITS [8], and the proposed method. Due to fair comparison, proposed method without additional memory usage is added. When four transmit antennas are present at the base station, memory requirements of the EBSTBC and the PPC are proportional to q^2 and the proposed scheme requires minimum memory among all schemes. This situation can be seen from Fig. 1.

	$N = 3$	
	Without additional memory usage	With additional memory usage
PFB-ESTBC [10]	$2q + 5$	$2q + 5$
EBSTBC [4]	$2q + 7$	$4q + 7$
PPC [11]	$4q + 7$	$6q+7$
ITS [8]	$2q + 7$	$2q + 17$
Proposed Method	$2q + 9$	$2q + 12$
	$N = 4$	
	Without additional memory usage	With additional memory usage
PFB-ESTBC [10]	$4q + 7$	$6q+7$
EBSTBC [4]	$4q + 9$	$7q^2 + 15q+9$
PPC [11]	$6q + 9$	$3q^2+9q+9$
ITS [8]	$4q + 9$	$4q + 30$
Proposed Method	$4q + 11$	$4q + 15$

Tab. 1. Memory requirements without additional memory and memory requirements with additional memory for $N = 3$ and $N = 4$.

Tab. 2 presents computational complexity analysis without additional memory usage. When choosing $q = 32$, $N = 3$ and $N = 4$, the proposed scheme without additional memory requires 2.82% and 1.46% more memory than ITS without additional memory [8]. On the other hand, complexity of the proposed scheme without additional memory is decreased 91.12% and 93.61% with respect to the ITS without additional memory [8].

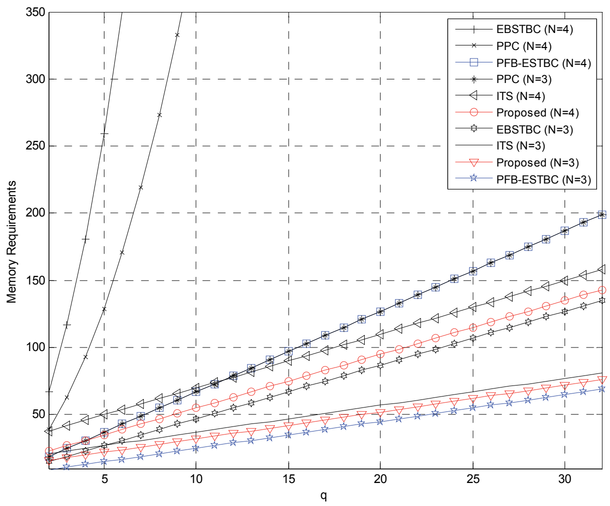

Fig. 1. Memory requirements for N=3 and N=4.

	$N = 3$			
	Multiplication	Addition	Comparison	Total
PFB-ESTBC [10]	$6q$	$3q$	q-1	$10q$-1
EBSTBC [4]	$18q$	$9q$	$3q$	$30q$
PPC [11]	$22q^2$	$13q^2$	q^2-1	$36q^2$-1
ITS [8]	$66q$	$48q$	$6q$-1	$120q$-1
Proposed Method	$6q$+12	$3q$+6	q+3	$10q$+21
	$N = 4$			
PFB-ESTBC [10]	$22q^2$	$13q^2$	q^2-1	$36q^2$-1
EBSTBC [4]	$124q^2$	$73q^2$	$21q^2$	$218q^2$
PPC [11]	$48q^3$	$29q^3$	q^3-1	$78q^3$-1
ITS [8]	$348q^2$	$204q^2$	$12q^2$-1	$564q^2$-1
Proposed Method	$22q^2$+16	$13q^2$+8	q^2+5	$36q^2$+29

Tab. 2. Computational complexity analysis results without additional memory usage for N=3 and N=4.

In addition, we diminish the complexity of exhaustive search [8] with using additional memory. Tab. 3 depicts computational complexity analysis with additional memory usage. When choosing $q = 32$, $N = 3$ and $N = 4$, the ITS with additional memory usage requires 14% and 15% more memory than ITS without additional memory usage [8]. However, complexity of the ITS with additional memory usage is diminished 69.55% and 92.14% with regard to the ITS without additional memory [8]. The proposed method with additional memory usage requires 7% and 4.38% more memory than ITS without additional memory usage. However, complexity of the proposed method with additional memory usage is reduced 91.38% and 96.71% with respect to the ITS without additional memory. Comparison of proposed method and other schemes′ computational complexity with using additional memory usage can be found in Fig. 2. The proposed scheme and PFB-ESTBC requires minimum additional memory and very low feedback calculation complexity for three and four transmit antennas.

	$N=3$			
	Multiplication	Addition	Comparison	Total
PFB-ESTBC [10]	$6q$	$3q$	q-1	$10q$-1
EBSTBC[4]	$14q$	$7q$	$3q$	$24q$
PPC [11]	$10q^2+12q$	$7q^2+6q$	q^2-1	$18q^2+18q-1$
ITS [8]	$17q+6$	$13q+12$	$6q-1$	$36q+17$
Proposed Method	$6q+6$	$3q+3$	$q+2$	$10q+11$
	$N=4$			
PFB-ESTBC [10]	$10q^2+12q$	$7q^2+6q$	q^2-1	$18q^2+18q-1$
EBSTBC [4]	$20q^2+34q$	$21q^2+17q$	$21q^2$	$62q^2+51q$
PPC [11]	$30q^2+18q$	$5q^3+15q^2+9q$	q^3-1	$6q^3+45q^2+27q-1$
ITS [8]	$19q^2+28q+8$	$12q^2+14q+26$	$12q^2-1$	$43q^2+42q+33$
Proposed Method	$10q^2+12q+8$	$7q^2+6q+4$	q^2+4	$18q^2+18q+18$

Tab. 3. Computational complexity analysis results with additional memory usage for $N=3$ and $N=4$.

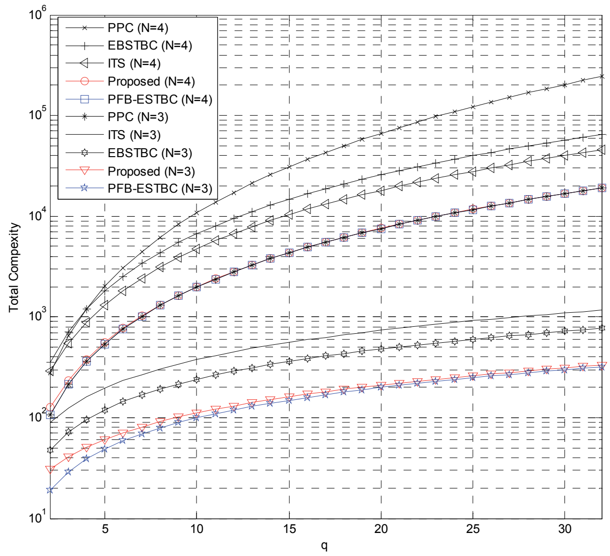

Fig. 2. Total feedback calculation complexity with using additional memory for $N=3$ and $N=4$.

7. Performance Evaluations

The bit error probabilities of the ITS and proposed method sets are evaluated for quaternary phase-shift keying (QPSK) modulation by computer simulations. The wireless channel is described in Section 2. The frame length is 130 symbol duration. For comparison, bit error rate (BER) curves of the EBSTBC, partial phase combining (PPC), open-loop extended orthogonal space-time block coding (EO-STBC), phase feedback based extended space-time block codes (PFB ESTBC) and beamforming are also included in Fig. 3-4.

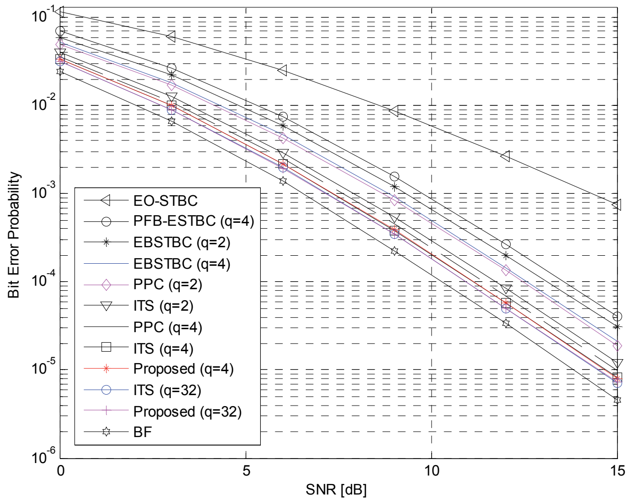

Fig. 3. Bit-error probabilities for three transmit antennas.

Fig. 3 presents the bit error probabilities of the ITS with extension level 2 (ITS ($q=2$)), the ITS with extension level 4 (ITS ($q=4$)), the ITS with extension level 32 (ITS ($q=32$)), the proposed method with extension level 4 (Proposed ($q=4$)) and the proposed method with extension level 32 (Proposed ($q=32$)) for three transmit antennas. The extended orthogonal space-time block codes (EO-STBC) yield the worst performance among all schemes due to the fact that the extended orthogonal space-time block codes do not employ the feedback. Compared to the phase feedback based extended space-time block codes with extension level 4 (PFB-ESTBC ($q=4$)), the EBSTBC with extension level 2 (EBSTBC ($q=2$)) provides an SNR advantage of approximately 0.43 dB for a BER value of $1\text{x}10^{-4}$. However, the EBSTBC with extension level 4 (EBSTBC ($q=4$)) provides approximately 0.56 dB better performance than the EBSTBC with extension level 2 (EBSTBC ($q=2$)). The partial phase combining with extension level 2 (PCC ($q=2$)) provides approximately 0.11 dB better performance than the EBSTBC with extension level 4 (EBSTBC ($q=4$)). The ITS with extension level 2 (ITS ($q=2$)) provides approximately 0.75 dB better performance than the partial phase combining with extension level 2 (PCC ($q=2$)). If one may extend feedback with four levels, the partial phase combining (PPC ($q=4$)) yields approximately 1.07 dB better than the partial phase combining with two levels (PPC ($q=2$)) and the ITS (ITS ($q=4$)) yields approximately 1.33 dB better performance than the partial phase combining with two levels (PPC ($q=2$)). The ITS with extension level 4 (ITS ($q=4$)) which requires 5 bits of feedback yields only 0.87 dB worse performance than the beamforming (BF 3:3) which requires ideal feedback at the base station. Compared to the ITS, the proposed method yields the same bit error rate (BER) performance.

Fig. 4 presents the bit error probabilities of the ITS with extension level 2 (ITS ($q=2$)), the ITS with extension level 4 (ITS ($q=4$)), the ITS with extension level 32 (ITS

($q = 32$)), the proposed method with extension level 4 (Proposed ($q = 4$)) and the proposed method with extension level 32 (Proposed ($q = 32$)) for four transmit antennas. The ITS with extension level 4 (ITS ($q = 4$)) which requires 8 bits of feedback yields only 0.75 dB worse performance than the beamforming (BF 3:3) which requires ideal feedback at the base station. Once again, the proposed method yields the same BER performance as the performance of the ITS.

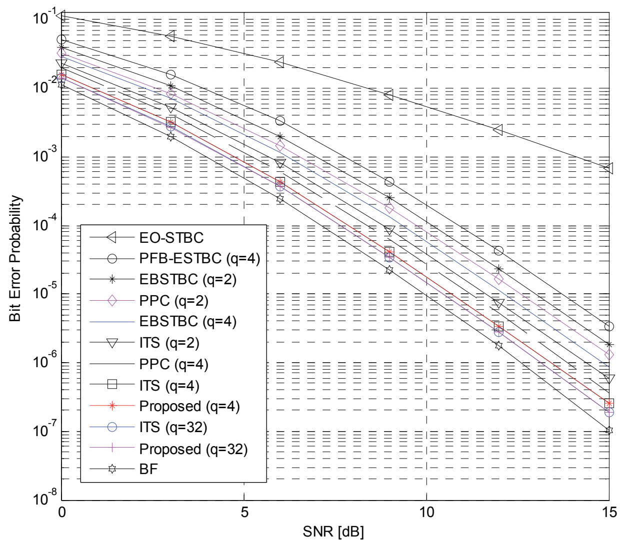

Fig. 4. Bit-error probabilities for four transmit antennas.

8. Conclusions

Performance of the ITS with a limited feedback approaches to ideal beamforming performance. In the ITS, the calculation of feedback information at the receiver employs exhaustive searching scheme which is very complex and consumes large amount of energy. In this paper, we propose a low-complexity and energy efficient calculation scheme for ITS receiver. The complexity for calculating the feedback information of the proposed scheme is decreased more than 87% compared to the scheme in [8], while achieving the same BER performance. The proposed scheme is valuable for power limited mobile terminals. Moreover, we utilize limited number of additional memory blocks for diminishing complexity of feedback information calculation at the original ITS scheme. Namely, using limited number of additional memory blocks, the complexity of original ITS is greatly decreased. Compared to the alternative schemes, the proposed schemes yields better performance with a limited number of memory elements.

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