An Efficient ICI Cancellation Method for Cooperative STBC-OFDM Systems

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Abstract. In this paper, an efficient inter carrier interference (ICI) cancellation method for cooperative space time block coded orthogonal frequency division multiplexing (STBC-OFDM) system is presented. In cooperative STBC-OFDM system, ICI cancellation is needed because ICI due to the separated local oscillators always exists. To solve the complexity problem of matrix inversion operation in zero forcing method which shows the best performance, ICI cancellation method using sparse matrix decomposition (SMD) has been proposed. However, overall complexity is increased in proportion to the third order of required tap size which also increases in proportion to FFT size or carrier frequency offsets (CFOs). Considering implementation issue, the conventional method still has not sufficiently overcome the performance versus complexity trade-offs. Therefore, we propose an ICI cancellation method that focuses on solving practical complexity problem of conventional method. The proposed method adaptively decides the required tap size of each sparse matrix through signal to interference and noise ratio (SINR) measurement to reduce the complexity of conventional method, and we verified that the proposed method improves the performance versus complexity trade-offs compared with conventional method.

Keywords: Equalization, Frequency offset, ICI cancellation, STBC, OFDM.

1 Introduction

Spatial diversity offers prominent benefits in link reliability and spectral efficiency through the use of multiple antennas at the transmitter and/or receiver side [1], [2]. Unfortunately, the use of multiple-antenna techniques might not be practical for some reasons; especially due to the antenna size and power constraints. For this reason, recently, there has been significant interest in a class of techniques known as cooperative communication, which allows single-antenna mobiles to reap some of the benefits of multiple-antenna systems by cooperation of in-cell users [3], [4].

Since space time block codes (STBC) were developed originally for frequency flat channels [2], an effective way to use them on frequency selective channels is to use them along with orthogonal frequency division multiplexing (STBC-OFDM) [5]. By using space time coded with OFDM, frequency selective channel is converted into multiple frequency flat channels.

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However, due to the distributed nature of cooperative STBC-OFDM system, each of the transmitters has a separate local oscillator, and synchronization becomes a difficult problem or requires feedback process to achieve. Furthermore, due to the physically separated local oscillators, different CFOs are received in one receiver antenna, and they cannot be easily assumed identical. Therefore, inter carrier interference (ICI) cancellation process is always needed in cooperative STBC-OFDM systems, because ICI caused by residual CFOs always exists at the receiver side.

Generally, zero forcing method has the best performance by multiplying the inversion of ICI matrix to the received signal. However it requires very high implementation complexity for matrix inversion. Therefore, in order to solve the complexity problem of matrix inversion operation, many proposals have been presented [6]-[9]. Some of the proposals achieve the complexity reduction, such as simplified zero forcing (ZF) method using sparse matrix decomposition (SMD), and iterative ICI cancellation method using the iterative operation of ICI estimation and cancellation [8], [9].

Especially, the ICI cancellation method which uses SMD can reduce the complexity of matrix inversion, because the major portion of ICI components are distributed in the diagonal or near diagonal position of ICI matrix [7], and the inversion operation of ICI matrix can be approximated by using SMD proposed in [10]. However, considering time-varying multi-path fading channel, it still have not sufficiently overcome the performance versus complexity trade-offs.

Therefore, in this paper, we propose an efficient ICI cancellation method which can efficiently reduce the practical complexity of conventional method without performance loss by using adaptive sparse matrix decomposition (ASMD).

This paper is organized as follows. In Section 2, we introduce the cooperative STBC-OFDM system model and ICI problem. The proposed ICI cancellation method using adaptive sparse matrix decomposition method is described in Section 3. In Section 4, the results of performance and complexity comparisons between the conventional method and the proposed method are presented. A brief conclusion is drawn in Section 5.

2 System Model

The cooperative communication system considered in this paper includes one source node, one destination node, and one of relay node. The basic premise in this work is that source and relay have information of their own to send, and would like to cooperate in order to send this information to the receiver according to the cooperative STBC scheme as shown in Fig. 1. That is, we do not consider signal distortion in the source-to-relay link. In Fig. 1, two consecutive symbols on subcarrier k, $X_{k,0}$ and $X_{k,1}$, are encoded and transmitted from the source and the relay antenna, respectively, to obtain the diversity order 2.

During even symbol period, $X_{k,0}$ and $X_{k,1}$ are transmitted from the source antenna and relay antenna, and during odd symbol period, $(-X_{k,1})^*$ and $(X_{\mathrm{k},0})^*$ are transmitted from the source antenna and the relay antenna, where $(\cdot)^*$ denotes the complex conjugate operation.

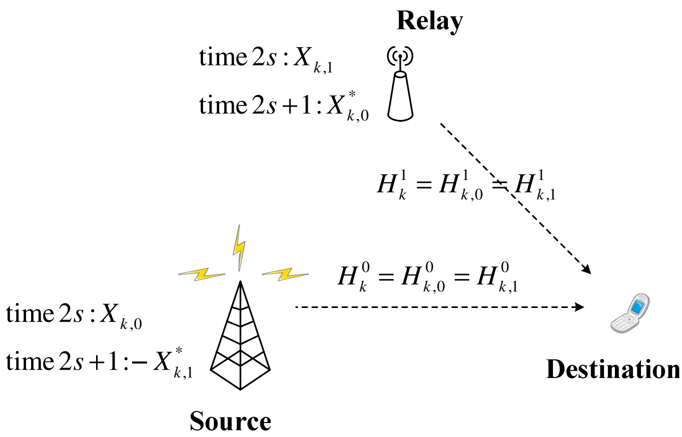


Fig. 1. Schematic representation of cooperative STBC-OFDM system

With the assumption of $H_k^j = H_{k,0}^j = H_{k,1}^j$, which is a case of quasi-static channel for two symbol period, the received signal $Y_{k,i}$ for symbol duration 0 and 1 (i=0,1) can be expressed as

$$\begin{aligned} Y_{k,0} &= H_k^0 \cdot X_{k,0} + H_k^1 \cdot X_{k,1} + W_k^0, \\ Y_{k,1} &= H_k^0 \cdot \left(-X_{k,1}\right)^* + H_k^1 \cdot \left(X_{k,0}\right)^* + W_k^1, 0 \le k \le N-1 \end{aligned} \tag{1}$$

where N is FFT size, $H_{k,i}^j$ is channel frequency response (CFR) of received signal on the j-th link, and W_k^j is zero-mean white Gaussian noise with variance σ^2.

From (1), we can easily obtain diversity gain by using simple linear combination as described in [2]

$$\begin{aligned} \hat{X}_{k,0} &= \left(H_k^0\right)^* \cdot Y_{k,0} + H_k^1 \cdot \left(Y_{k,1}\right)^* \\ &= \left(\left|H_k^0\right|^2 + \left|H_k^1\right|^2\right) \cdot X_{k,0} + \left(H_k^0\right)^* \cdot W_k^0 + H_k^1 \cdot \left(W_k^1\right)^* \\ \hat{X}_{k,1} &= \left(H_k^1\right)^* \cdot Y_{k,0} - H_k^0 \cdot \left(Y_{k,1}\right)^* \\ &= \left(\left|H_k^0\right|^2 + \left|H_k^1\right|^2\right) \cdot X_{k,1} + \left(H_k^1\right)^* \cdot W_k^0 - H_k^0 \cdot \left(W_k^1\right)^*. \end{aligned} \tag{2}$$

With the residual CFOs, the received signal for symbol duration 0 and 1 can be expressed as [6]

$$Y_{k,0} = \Gamma_0^0 \cdot H_k^0 \cdot X_{k,0} + \Gamma_0^1 \cdot H_k^1 \cdot X_{k,1} + \sum_{\substack{i=0 \\ i \neq k}}^{N-1} \left(\Gamma_{k-i}^0 \cdot H_i^0 \cdot X_{i,0} + \Gamma_{k-i}^1 \cdot H_i^1 \cdot X_{i,1} \right) + W_k^0$$

$$Y_{k,1} = -\Gamma_0^0 \cdot H_k^0 \cdot X_{k,1}^* + \Gamma_0^1 \cdot H_k^1 \cdot X_{k,1}^* + \sum_{\substack{i=0 \\ i \neq k}}^{N-1} \left(-\Gamma_{k-i}^0 \cdot H_i^0 \cdot X_{i,0}^* + \Gamma_{k-i}^1 \cdot H_i^1 \cdot X_{i,1}^* \right) + W_k^1 \quad (3)$$

$$\Gamma_k^j = \frac{\sin\left(\pi \cdot \varepsilon_j\right)}{N \cdot \sin\left(\pi\left(\varepsilon_j - k\right)/N\right)} \cdot \exp\left(j\pi\varepsilon_j \left(N - 1/N\right) - j\pi\left(\varepsilon_j - k\right)/N \right)$$

where ε_j is the residual CFO from the j-th link which is normalized by the subcarrier spacing, and the second parts in (3) means the ICI components represented by a sum for $i \neq k$ on subcarrier k caused by CFOs.

Fig. 2 shows the performance degradations caused by ICI in cooperative STBC-OFDM systems. In spite of perfect channel estimation, from Fig. 2, we can see that there are severe performance degradations due to the loss of orthogonality between subcarriers.

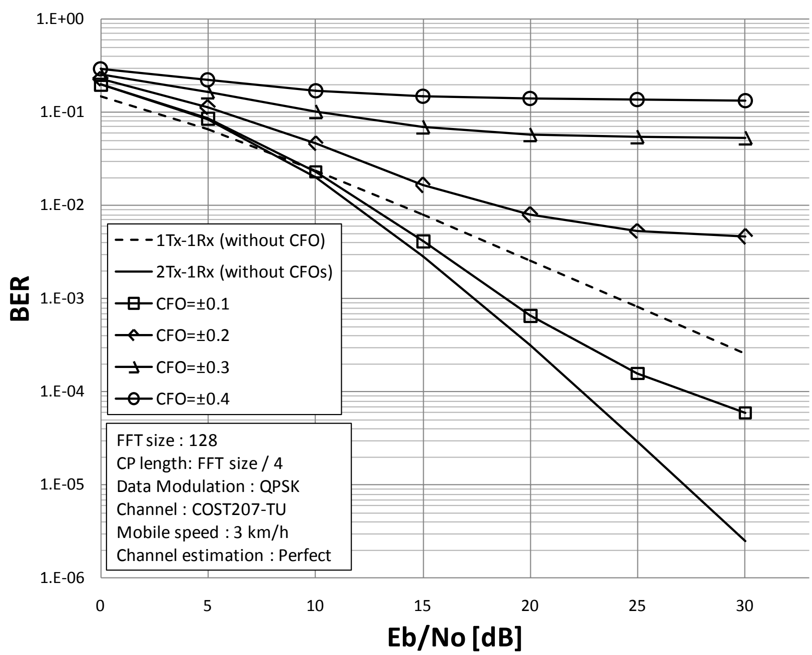


Fig. 2. Performance degradations caused by ICI in cooperative STBC-OFDM systems

3 An Efficient ICI Cancellation Method

Equation (3) can be expressed as matrix form in (4).

$$\begin{bmatrix}\mathbf{Y}_0\\ \mathbf{Y}_1^*\end{bmatrix}=\begin{bmatrix}\mathbf{A} & \mathbf{B}\\ \mathbf{C} & \mathbf{D}\end{bmatrix}\begin{bmatrix}\mathbf{X}_0\\ \mathbf{X}_1\end{bmatrix}+\begin{bmatrix}\mathbf{W}_0\\ \mathbf{W}_1^*\end{bmatrix}$$

$$\mathbf{Y}_i=\begin{bmatrix}Y_{0,i}\\ Y_{1,i}\\ \vdots\\ Y_{N-1,i}\end{bmatrix},\mathbf{X}_i=\begin{bmatrix}X_{0,i}\\ X_{1,i}\\ \vdots\\ X_{N-1,i}\end{bmatrix},\mathbf{W}_i=\begin{bmatrix}W_{0,i}\\ W_{1,i}\\ \vdots\\ W_{N-1,i}\end{bmatrix} \tag{4}$$

where **A**, **B**, **C**, and **D** are $N\times N$ size sub-matrices.

$$\mathbf{A}=\begin{bmatrix}\Gamma_0^0H_0^0 & \Gamma_{-1}^0H_1^0 & \cdots & \Gamma_{1-N}^0H_{N-1}^0\\ \Gamma_1^0H_0^0 & \Gamma_0^0H_1^0 & \cdots & \Gamma_{2-N}^0H_{N-1}^0\\ \vdots & \vdots & \ddots & \vdots\\ \Gamma_{N-1}^0H_0^0 & \Gamma_{N-2}^0H_1^0 & \cdots & \Gamma_0^0H_{N-1}^0\end{bmatrix}\ \mathbf{B}=\begin{bmatrix}\Gamma_0^1H_0^1 & \Gamma_{-1}^1H_1^1 & \cdots & \Gamma_{1-N}^1H_{N-1}^1\\ \Gamma_1^1H_0^1 & \Gamma_0^1H_1^1 & \cdots & \Gamma_{2-N}^1H_{N-1}^1\\ \vdots & \vdots & \ddots & \vdots\\ \Gamma_{N-1}^1H_0^1 & \Gamma_{N-2}^1H_1^1 & \cdots & \Gamma_0^1H_{N-1}^1\end{bmatrix} \tag{5}$$

$$\mathbf{C}=\begin{bmatrix}\Gamma_0^{1*}H_0^{1*} & \Gamma_{-1}^{1*}H_1^{1*} & \cdots & \Gamma_{1-N}^{1*}H_{N-1}^{1*}\\ \Gamma_1^{1*}H_0^{1*} & \Gamma_0^{1*}H_1^{1*} & \cdots & \Gamma_{2-N}^{1*}H_{N-1}^{1}\\ \vdots & \vdots & \ddots & \vdots\\ \Gamma_{N-1}^{1*}H_0^{1*} & \Gamma_{N-2}^{1*}H_1^{1*} & \cdots & \Gamma_0^{1*}H_{N-1}^{1}\end{bmatrix}\ \mathbf{D}=\begin{bmatrix}-\Gamma_0^{0*}H_0^{0*} & -\Gamma_{-1}^{0*}H_1^{0*} & \cdots & -\Gamma_{1-N}^{0*}H_{N-1}^{0*}\\ -\Gamma_1^{0*}H_0^{0*} & -\Gamma_0^{0*}H_1^{0*} & \cdots & -\Gamma_{2-N}^{0*}H_{N-1}^{0*}\\ \vdots & \vdots & \ddots & \vdots\\ -\Gamma_{N-1}^{0*}H_0^{0*} & -\Gamma_{N-2}^{0*}H_1^{0*} & \cdots & -\Gamma_0^{0*}H_{N-1}^{0*}\end{bmatrix}.$$

Ignoring system complexity, for the perfect cancellation of ICI, we can simply multiply the inverse of ICI matrix to the received signal matrix (zero forcing method). However, as you can see in (4), the implementation complexity of the inversion operation of $2N\times 2N$ size ICI matrix is too high.

To reduce the complexity of matrix inversion operation in zero forcing method, [7] proposed the ICI cancellation method using SMD introduced in [10]. The major portion of ICI components in (5) are distributed in the diagonal or near diagonal position of ICI matrix. Therefore, by using SMD, inversion of ICI matrix can be transmitted into a series of inversions of its diagonal sub-blocks as illustrated in Fig. 3.

By using the SMD method, (4) can be approximated as

$$\begin{bmatrix}\grave{\mathbf{Y}}_{n.0}\\ \grave{\mathbf{Y}}_{n,1}^*\end{bmatrix}=\begin{bmatrix}\mathbf{A}_n & \mathbf{B}_n\\ \mathbf{C}_n & \mathbf{D}_n\end{bmatrix}\begin{bmatrix}\grave{\mathbf{X}}_{n,0}\\ \grave{\mathbf{X}}_{n,1}\end{bmatrix}+\begin{bmatrix}\grave{\mathbf{W}}_{n,0}\\ \grave{\mathbf{W}}_{n,1}\end{bmatrix}$$

$$\grave{\mathbf{X}}_{n,i}=\begin{bmatrix}X_{n,0} & X_{n+1,0} & \cdots & X_{n+2q,0}\end{bmatrix}^T \tag{6}$$

$$\text{where } \grave{\mathbf{Y}}_{n,i}=\begin{bmatrix}Y_{n,0} & Y_{n+1,0} & \cdots & Y_{n+2q,0}\end{bmatrix}^T \quad ,0<n\le N-(2q+1)$$

$$\grave{\mathbf{W}}_{n,i}=\begin{bmatrix}W_{n,0} & W_{n+1,0} & \cdots & W_{n+2q,0}\end{bmatrix}^T$$

where n is sparse matrix index, $2q+1$ is the tap size of diagonal sub-blocks, and $\mathbf{A}_\mathrm{n}$ is shown in (7). $a_{n,n}$ is the elements of **A**, $\mathbf{B}_n$, $\mathbf{C}_n$, and $\mathbf{D}_n$ can be obtained similarly [7].

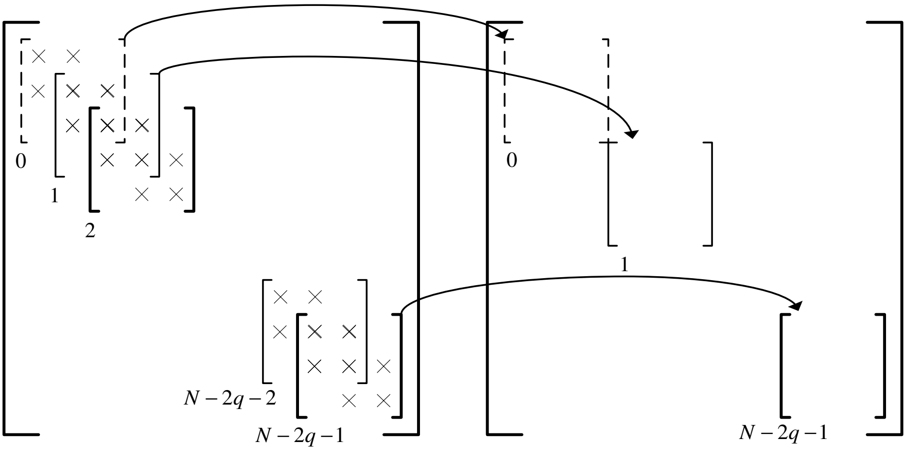


Fig. 3. Sparse matrix decomposition proposed in [10]

$$\mathbf{A}_n = \begin{bmatrix} a_{n,n} & a_{n,n+1} & \cdots & a_{n,n+q} & \cdots & & 0 \\ a_{n+1,n} & a_{n+1,n+1} & & & & & \vdots \\ \vdots & & & & & & 0 \\ a_{n+q,n} & & & & & & a_{n+q,n+2q} \\ 0 & & & & & & \vdots \\ \vdots & & & & & a_{n+2q-1,n+2q-1} & a_{n+2q-1,n+2q} \\ 0 & & \cdots & a_{n+2q,n+q} & \cdots & a_{n+2q,n+2q-1} & a_{n+2q,n+2q} \end{bmatrix} \tag{7}$$

Therefore, mitigation of ICI is accomplished by multiplying the inversion of sparse matrix as follows

$$\begin{bmatrix} \hat{\mathbf{X}}_{n,0} \\ \hat{\mathbf{X}}_{n,1} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_n & \mathbf{B}_n \\ \mathbf{C}_n & \mathbf{D}_n \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{Y}_{n,0} \\ \mathbf{Y}^*_{n,1} \end{bmatrix} = \begin{bmatrix} \mathbf{X}_{n,0} \\ \mathbf{X}_{n,1} \end{bmatrix} + \begin{bmatrix} \mathbf{A}_n & \mathbf{B}_n \\ \mathbf{C}_n & \mathbf{D}_n \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{W}_{n,0} \\ \mathbf{W}_{n,1} \end{bmatrix}. \tag{8}$$

In the case of the above SMD method, although the total number of complex multiplications for the matrix inversion is reduced from $(2N)^3$ to $(N-2q)\cdot(2(2q+1))^3$, required complexity remains high because the tap size q increases as increasing CFOs and FFT size N.

However, considering time and frequency selectivity due to mobile movement and multi-path delay, respectively, each subcarriers are unequally interfered each other. Therefore, there is no necessity for the size of sparse matrix to be fixed. If each sparse matrix has adequately small tap size q^* within maximum tap size q depending on the amount of ICI from each neighboring subcarriers, the total amount of complex multiplications for the matrix inversion is reduced to less than $(N-2q)\cdot(2(2q+1))^3$.

From this point of view, we propose an adaptive sparse matrix decomposition (ASMD) method which is based on a kind of SINR measurement to adaptively decide the efficient tap size q^*. Without loss of generality, we assume that all transmitted signals have average power 1, i.e., $E[\boldsymbol{X}^H\boldsymbol{X}]=\boldsymbol{I}$, where $(\quad)^H$ denotes the Hermitian transpose.

In the proposed ASMD method, the decision procedure of efficient tap size q^*_n of the n-th sparse matrix can be expressed as

$$\Psi_n^j = \begin{cases} \min\left\{ u \left| \dfrac{\left|\Gamma^j_{\pm(u+1)} \cdot H_{k\pm(u+1)}\right|^2}{\left|\Gamma^j_0 \cdot H_k\right|^2} < \Psi^j_q \right.\right\}, \; u = 0,1,\cdots q-1, \\ q, \text{ if } \dfrac{\left|\Gamma^j_{\pm(u+1)} \cdot H_{k\pm(u+1)}\right|^2}{\left|\Gamma^j_0 \cdot H_k\right|^2} \geq \Psi^j_q \text{ for all } u = \{0,1,\cdots,q-1\} \end{cases} \tag{9}$$

$$\Psi^j_q = \left(\left|\Gamma^j_q\right|^2 + \sigma^2\right) \Big/ \left|\Gamma^j_0\right|^2, k = n+q$$

where $\left|\Gamma^j_{\pm(u+1)} \cdot H_{k\pm(u+1)}\right|^2 \Big/ \left|\Gamma^j_0 \cdot H_k\right|^2$ means signal to interference ratio (SIR) of the k-th subcarrier to the $\pm(u+1)$-th subcarrier in frequency selective fading channel with CFO, Ψ^j_q is based on SINR of the k-th subcarrier to the $(k+q)$-th subcarrier in frequency flat channel, and noise power σ^2 is inserted to the threshold Ψ^j_q to reduce unnecessary operation in low signal to noise ratio (SNR) environments.

From (8) and (9), with the assumption of quasi-static channel for two symbol period, efficient tap size q^*_n of n-th sparse matrix can be determined as follows

$$q^*_n = \max\left\{\Psi^j_n\right\} \tag{10}$$

Therefore, by using the proposed ASMD method, the total amount of complex multiplications for ICI cancellation in cooperative STBC-OFDM systems can be approximately reduced from $(N-2q)\cdot\left(2(2q+1)\right)^3$ to $(N-2q)\cdot\left(1+2\cdot4\cdot(q^*+1)+\left(2\left(2q^*+1\right)\right)^3\right)$, $q^*\leq q$. For each (N-2q) times of sparse matrix, $1+2\cdot4\cdot(q`+1)$ times of complex multiplication is needed for the calculation of k-th subcarrier power $\left|\Gamma^j_0 \cdot H_k\right|^2$ and SINR comparisons.

4 Simulation Results

In this section, we investigate the performance of the proposed method on multipath channel for cooperative STBC-OFDM system. The simulation parameters used in this paper are shown in Table 1. The multi-path fading channel is generated by COST 207 TU model and in order to avoid inter symbol interference (ISI) we set the length of cyclic prefix (CP) long enough.

Table 1. Simulation parameters

Parameters	Values
FFT size	128
Cyclic prefix (CP) length	FFT size / 4
System bandwidth	FFT size * 15 kHz
Subcarrier spacing	15 kHz
Center frequency	2 GHz
Channel model	COST 207 TU
Channel estimation	Perfect
Data modulation	QPSK
Normalized frequency offsets	± 0.1

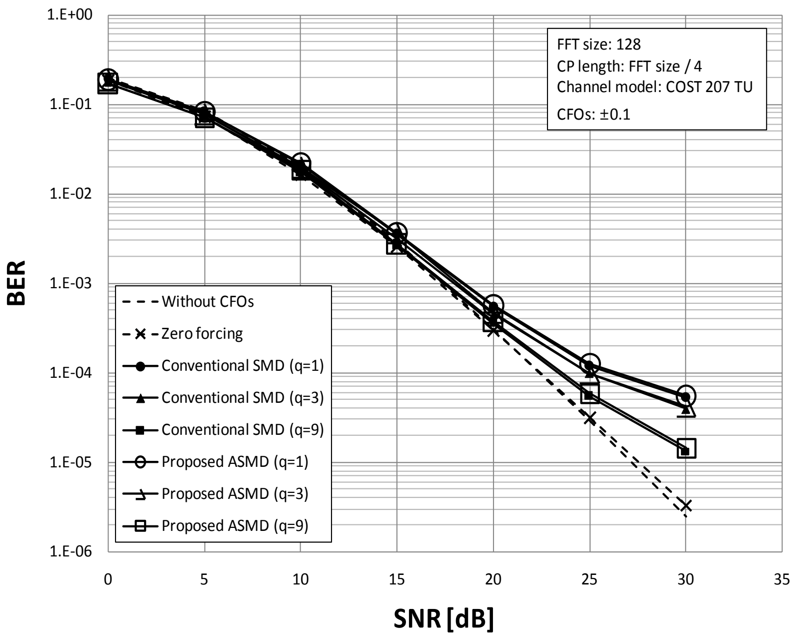
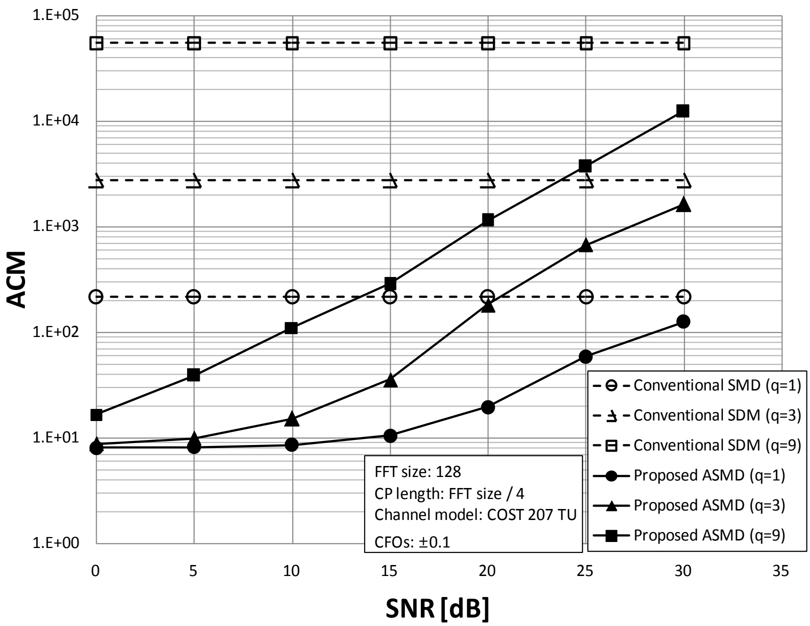


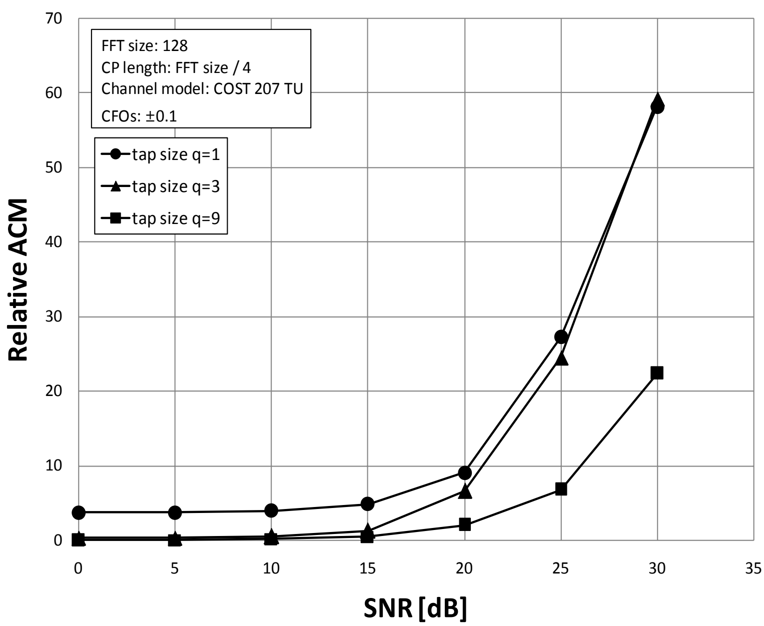
Fig. 4. BER performance of ICI cancellation methods versus SNR

Fig. 4 shows the bit error rate (BER) performances comparisons between conventional SMD and proposed ASMD for ICI cancellation. From Fig. 4, we can see that zero forcing method shows almost the same performance with and without CFOs. Also, we can see that each performance of the proposed ASMD method is very close to that of the conventional SMD method for the same number of taps.

Fig. 5 shows the average number of complex multiplications (ACM) and relative ACM for matrix inversion per each subcarrier. In Fig 5, in low SNR environment, overall ACM is dramatically reduced by using proposed ASMD, because threshold Ψ_q^j depends on the noise variance σ^2 $\left(\sigma^2 \approx 1\right)$. And in high SNR environment, Ψ_q^j



(a) ACM versus SNR



(b) Relative ACM versus SNR

Fig. 5. Complexity comparisons between conventional SMD and proposed ASMD

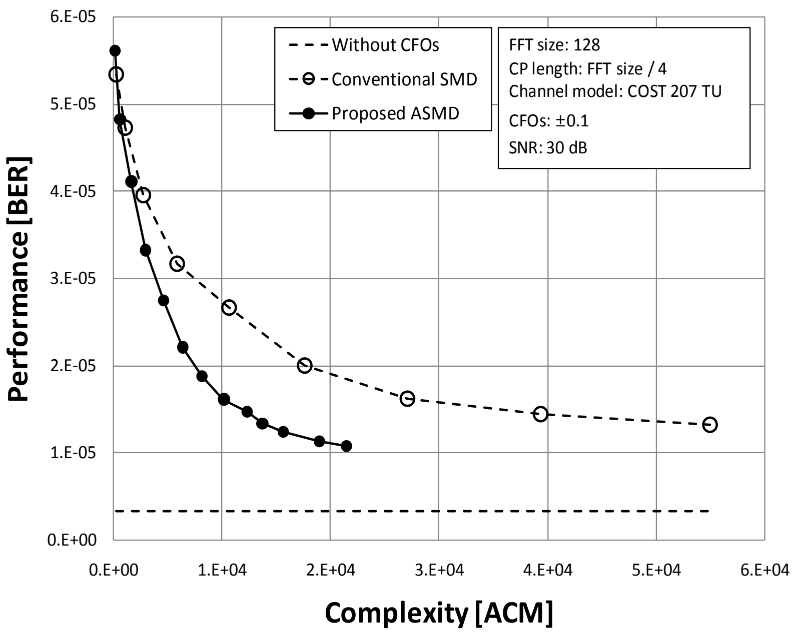


Fig. 6. BER performances versus AMC

depends on the SIR of at each subcarriers $\left(\sigma^2 \approx 0\right)$. Therefore, although the ACM of the proposed ASMD method increases in proportion to SNR, it is always lower than the conventional SMD method, and the relative ACM ratio improves as the number of taps increases.

Fig. 6 compares performance versus complexity trade-offs of conventional SMD method and proposed ASMD method at SNR=30 dB environment. As shown in Fig 6, both conventional and proposed method, the more performance is improved, the more complexity is needed for the same amount of performance enhancement, because the amount of ICI on the k-th subcarrier from the $(k+q)$-th subcarrier is described in the form of sinc function. However, we can see that the proposed ASMD method efficiently improves performance versus complexity trade-offs compared with the conventional SMD method by SINR measurement and adaptive tap allocation.

5 Conclusions

In this paper, we proposed an efficient ICI cancellation method for cooperative STBC-OFDM system. Through the frequency domain SINR measurement and adaptive tap allocation, we showed that the overall complexity for ICI cancellation can be efficiently reduced with approximately same performance compared with the conventional method. We expect that the proposed ASMD scheme can be applicable for various ICI suppression or cancellation methods.

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