논문 2007-44TC-5-4

상향 링크 고속 페이딩 채널에서의 중계기 기반 단일 반송파 전송을 위한 분산 주파수 공간 블록 부호화 기법

(Distributed SFBC for Relay-Assisted Single Carrier Transmission over Uplink Fast Fading Channels)

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(Dae-Young Seol, Ui-Kun Kwon, and Gi-Hong Im)

요 약

사용자 단말기는 크기상의 제약 때문에, 다중 송신 안테나를 이용한 공간 다이버시티를 얻는데 어려움이 있다. 본 논문에서는 단일 반송파 변조 방식 기반의 사용자 단말이 낮은 하드웨어적인 복잡도를 유지하면서, 중계기의 도움을 받아 공간 다이버시티를 얻는 기법을 제안한다. 중계기는 사용자 단말로부터 받은 신호에 주파수 공간 블록 부호화를 수행하여 기지국으로 전송한다. 이때 주파수 공간 블록 부호화는 주파수 영역이 아닌 등가의 시간 영역에서의 신호 처리를 통해 낮은 계산 복잡도로 구현된다. 사용자 단말과 중계기로부터 신호를 수신한 기지국은 다중 경로 페이딩을 고려한 주파수 영역 등화를 수행한다. 제안된 기법은 기존의 시공간 부호화 기반의 중계 방식에 비해 고속 페이딩 채널에서 개선된 성능을 갖는데, 사용자 단말의 이동 속도를 고려한 시뮬레이션을 통해 이를 확인할 수 있었다.

Abstract

This paper proposes a distributed space-frequency block code (SFBC) for relay-assisted single carrier frequency-domain equalization (SC-FDE). The proposed technique achieves spatial diversity gain over fast fading channels without the complexity of multiple antennas. The mobile equipment of the proposed system has a very simple transmitter structure with constant amplitude transmit sequences, which is desirable especially for uplink communications. In order to obtain spatial diversity, the transmit sequence of relay is efficiently generated in the time domain, which is equivalent to the SFBC. Further, efficient implementation of relay and destination structures is also presented. Extensive simulation results show that the proposed system significantly outperforms the distributed space-time block code (D-STBC) SC-FDE over fast fading channels.

Keywords : Single-carrier frequency domain equalization (SC-FDE), orthogonal frequency division multiplexing (OFDM), distributed space-frequency block code (D-SFBC), relay.

Ⅰ. Introduction

Single-carrier frequency-domain equalization (SC-FDE) has similar structure and performance as orthogonal frequency division multiplexing (OFDM), and was shown to be an attractive solution for broadband wireless communications[1]. This SC-FDE is preferred for the uplink transmission, because its transmit structure at mobile equipment is very simple. Moreover, the peak-to-average power ratio (PAPR) of transmitted sequences of SC-FDE is much lower than that of OFDM, and thus the required dynamic range of power amplifier is smaller and the battery life time is longer than that of OFDM[1][2].

Space-time coding is a communication technique for wireless systems, which realizes spatial diversity by introducing temporal and spatial correlations into

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※ 본 연구는 삼성종합기술원의 지원으로 수행되었음.
접수일자: 2007년5월1일, 수정완료일: 2007년5월14일

the signals transmitted from different antennas[3]-[6]. Most significantly, Alamouti proposed a simple space-time block code (STBC) for two transmit antennas, guaranteeing full spatial diversity and full rate over frequency-flat channels[3]. STBC combined with SC-FDE was presented by Al-Dhahir, which is based on the Alamouti scheme for frequency selective channels[5]. The major drawback of the STBC SC-FDE, however, is that the channel is assumed to be constant for two consecutive block intervals[7][8]. Therefore, the system breaks down when used in a time-varying mobile environment. In order to mitigate the fast fading distortion caused by high-speed mobility, Jang et. al. recently proposed space-frequency block code (SFBC) combined with SC-FDE[7]. Although the SFBC SC-FDE achieves spatial diversity gain over fast fading channels, it introduces 3dB PAPR increase over two transmit antennas, and additional computational complexity at the transmitter.

Employing multiple antennas in uplink communications is restricted, due to the limitation of size and complexity of the mobile equipment. Cooperative diversity overcomes these problems without additional complexity of multiple antennas and provides an effective means of improving spectral and power efficiencies[9][10]. Mheidat et. al. extended conventional STBC SC-FDE in a distributed fashion, so called D-STBC SC-FDE, for practical implementation of cooperative networks[11]. For fast fading channels, the conventional SFBC SC-FDE can also be extended in a distributed fashion, but still holds the disadvantages of increased PAPR and computational complexity. In this paper, we propose a new D-SFBC SC-FDE, where operations in relay are processed in the time domain, for uplink fast fading channels. The proposed D-SFBC SC-FDE achieves the same diversity gain as the conventional D-SFBC SC-FDE without any increase of PAPR and computational complexity at the mobile equipment, while only the transmitted sequences of relay have 3dB PAPR increase. It is desirable especially for the infra- structure-based relay scenario. The corresponding destination structure and frequency domain equalization are also presented.

The remainder of this paper is organized as follows. In Section Ⅱ, the conventional SFBC SC-FDE and the distributed SFBC SC-FDE are described. Then, the proposed D-SFBC SC-FDE and its efficient implementation method are presented in Section Ⅲ. Simulation results are shown in Section Ⅳ, and conclusions are given in Section Ⅴ.

Ⅱ. Conventional and Distributed SFBC SC-FDE Systems

1. Conventional SFBC SC-FDE

The SFBC system codes across two transmit antennas and over two adjacent subcarriers instead of two consecutive block intervals. Unlike an OFDM, the SFBC cannot be directly applicable to a single carrier system, because its transmit sequences are processed in the time domain, not in the frequency domain. To obtain SFBC single carrier signals, transmit sequences for respective antennas are processed in the time domain as follows[7].

Firstly, a block of QAM or PSK modulated information symbols, $\mathrm{x}=[x(0),\ldots,x(N-1)]^T$, is separated into two blocks with the length $N/2$, i.e., $[x(0),\ldots,x(N/2-1)]^T$ and $[x(N/2),\ldots,x(N-1)]^T$. Each block is repeated to form $\mathrm{x}^{\mathrm{A}}=[x^A(0),\ldots,x^A(N-1)]^T$ and $\mathrm{x}^{\mathrm{B}}=[x^B(0),\ldots,x^B(N-1)]^T$ as

$$\begin{aligned}\mathrm{x}^{\mathrm{A}}&=cat([x(0),\ldots,x(N/2-1)]^T,\\&\qquad[x(0),\ldots,x(N/2-1)]^T),\\\mathrm{x}^{\mathrm{B}}&=cat([x(N/2),\ldots,x(N-1)]^T,\\&\qquad[x(N/2),\ldots,x(N-1)]^T)\end{aligned}\tag{1}$$

where $cat(\mathrm{a},\mathrm{b})$ denotes the vertical concatenation of two column vectors, a and b. The frequency domain representations of x^{A} and x^{B} can be written as $\mathrm{X}^{\mathrm{A}}=\mathrm{W}\mathrm{x}^{\mathrm{A}}$ and $\mathrm{X}^{\mathrm{B}}=\mathrm{W}\mathrm{x}^{\mathrm{B}}$, where W is an $N\times N$ orthonormal discrete Fourier transform (DFT) matrix. Since x^{A} and x^{B} are formed by a concatenation of identical column vectors, odd components of the X^{A} and X^{B} are zero, i.e.,

$$X^{A(B)}(2k+1)=0,\quad 0\le k\le \frac{N}{2}-1. \tag{2}$$

The transmit sequence of each antenna in the frequency domain, X_i, $i=1,2$, is formed as

$$\begin{aligned} X_1(k)&=\frac{1}{\sqrt{2}}(X^A(k)+X^B(k-1)_N),\\ X_2(k)&=\frac{1}{\sqrt{2}}(-X^{B^*}(k)+X^{A^*}(k-1)_N) \end{aligned} \tag{3}$$

where $(\cdot)^*$ denotes the complex-conjugate operation. Note from (2) and (3) that the adjacent subcarriers of each transmit antenna are SFBC coded as follows

$$\begin{bmatrix} X_1(2l) & X_1(2l+1)\\ X_2(2l) & X_2(2l+1)\end{bmatrix}=\frac{1}{\sqrt{2}}\begin{bmatrix} X^A(2l) & X^B(2l)\\ -X^{B^*}(2l) & X^{A^*}(2l)\end{bmatrix}. \tag{4}$$

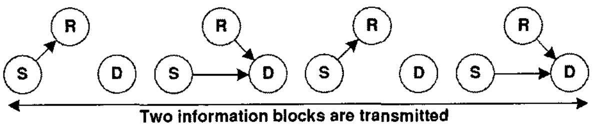
Using the DFT symmetry and frequency shift properties[13], i.e., $x^*(-n)_N \Leftrightarrow X^*(k)$, and $W_N^n x(n) \Leftrightarrow X(k+1)$, $n,k=0,1,\dots,N-1$, the single carrier SFBC sequences of two transmit antennas, $\mathrm{x}_1=[x_1(0),\dots,x_1(N-1)]^T$ and $\mathrm{x}_2=[x_2(0),\dots,x_2(N-1)]^T$, are obtained in time domain as follows

$$\begin{aligned} x_1(n)&=\frac{1}{\sqrt{2}}(x^A(n)+W_N^{-n}x^B(n)),\\ x_2(n)&=\frac{1}{\sqrt{2}}(-x^{B^*}(-n)_N+W_N^{-n}x^{A^*}(-n)_N) \end{aligned} \tag{5}$$

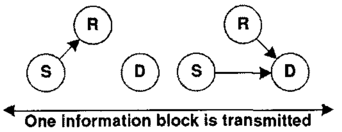
where $W_N^n=e^{-j(2\pi n/N)}$.

2. Distributed SFBC SC-FDE

Mheidat et. al. extended an STBC SC-FDE system in a distributed fashion with single relay[11]. They consider all underlying links experience frequency selective fading, where the channel impulse responses (CIRs) for the source-to-relay (S→R), relay-to-destination (R→D), and source-to-destination (S→D) links are given by $\mathrm{h_{SR}}=[h_{SR}(0),\dots,h_{SR}(L_{SR})]^T$, $\mathrm{h_{RD}}=[h_{RD}(0),\dots,h_{RD}(L_{RD})]^T$, and $\mathrm{h_{SD}}=[h_{SD}(0),\dots,h_{SD}(L_{SD})]^T$, respectively. In the system, the source communicates with the relay during the first signaling interval, while the destination does not receive the direct signals from the source. Then, both the relay and source communicate with the destination in the second signaling interval, using a protocol proposed by Nabar et. al.[12] (see Fig. 1). The performance of the D-STBC SC-FDE, however, dramatically deteriorates in a fast fading environment, since the channels are assumed to be constant for four consecutive blocks[11]. In order to overcome this problem, the conventional SFBC SC-FDE can be easily extended in a distributed fashion. The D-SFBC SC-FDE completes the transmission of one information block within two time slots, while the D-STBC SC-FDE requires four time slots for the transmission of two information blocks. Although the D-SFBC SC-FDE is robust against fast fading channels, it has disadvantages compared with the D-STBC SC-FDE, in view of PAPR and computational complexity. Note from (5) that each transmit sequence of SFBC SC-FDE shows 3dB PAPR increase by adding two time domain signals, and requires N complex multiplications and additions. High PAPR requires large dynamic range of the transmit power amplifier and reduces the power efficiency, and thus the cost of mobile equipment is increased and the battery life time is decreased. To cope with these problems, we propose a new relay-assisted D-SFBC SC-FDE for uplink transmission in the next section.



(a) D-STBC



(b) D-SFBC

그림 1. D-STBC와 D-SFBC를 위한 프로토콜
Fig. 1. Protocols for D-STBC and D-SFBC.

Ⅲ. Proposed D-SFBC SC-FDE

1. Transmission Model of the Proposed D-SFBC SC-FDE

Conceptual block diagram of the proposed D-SFBC

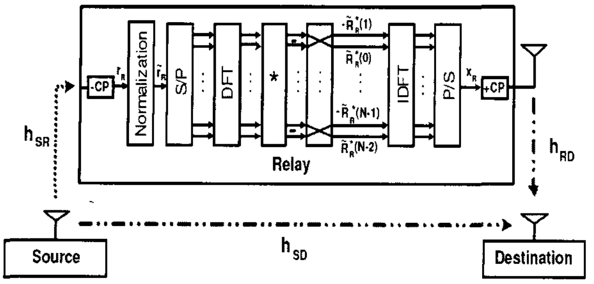


그림 2. D-SFBC SC-FDE를 위한 개념도

Fig. 2. Conceptual block diagram of relay-assisted D-SFBC SC-FDE.

SC-FDE is shown in Fig. 2. The transmit sequence of the source (mobile equipment), x_S^1, is equal to the information block x, i.e., $x_S^1 = x$. In the first time slot, the source transmits x_S^1 after appending a cyclic prefix (CP) with length L_{SR}, making the channel matrix circulant. At the relay, removing the CP, the received signal is given by

$$r_R = \sqrt{E_{SR}} H_{SR} x_S^1 + n_R \tag{6}$$

where ESR represents the average energy available at the relay, H_{SR} is an $N \times N$ circulant channel matrix with entries $[H_{SR}]_{k,l} = h_{SR}((k-l)_N)$, and n_R is a complex additive white Gaussian noise (AWGN) vector with each entry having zero-mean and variance of N0/2 per dimension. (n)N represents n (mod N). Path loss and shadowing effects in S→R link are included into ESR for simplicity. The received signal, r_R, is normalized as $\tilde{r}_R = r_R / \sqrt{E_{SR} + N_0}$, to ensure unit average energy, and the discrete Fourier transform of $\tilde{r}_R$ is processed like below

$$\begin{bmatrix} X_R(2l) \\ X_R(2l+1) \end{bmatrix} = \begin{bmatrix} -\tilde{R}_R^*(2l+1) \\ \tilde{R}_R^*(2l) \end{bmatrix}, \quad l = 0, 1, \ldots, \frac{N}{2} - 1 \tag{7}$$

where X_R is the transmit signal of the relay in frequency domain, and $\tilde{R}_R = W\tilde{r}_R$. Changing the signs of the odd components and permutating the even and odd components can be conducted by multiplying the following matrices, S and P, respectively.

$$S = I_{\frac{N}{2} \times \frac{N}{2}} \otimes \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \quad P = I_{\frac{N}{2} \times \frac{N}{2}} \otimes \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \tag{8}$$

where $I_{\frac{N}{2} \times \frac{N}{2}}$ is the $\frac{N}{2} \times \frac{N}{2}$ identity matrix, and $\otimes$ denotes the Kronecker product. Then, the transmit signal of the relay can be represented as

$$\begin{aligned} x_R &= W^H PS\{W\tilde{r}_R\}^* \\ &= \sqrt{\frac{E_{SR}}{E_{SR} + N_0}} W^H PS\{WH_{SR} x_S^1\}^* + n_R' \end{aligned} \tag{9}$$

where (·)H denotes the complex-conjugate transpose, and W^H is an inverse DFT matrix.

In the second time slot, the source and the relay transmit x_S^2, remaining the same as x_S^1, and x_R after appending a CP with length $L = \max(L_{SD}, L_{RD})$. At the destination, removing the CP, the received signal is given by

$$\begin{aligned} r_D &= \sqrt{E_{RD}} H_{RD} x_R + \sqrt{E_{SD}} H_{SD} x_S^2 + n_D \\ &= \sqrt{\frac{E_{RD} E_{SR}}{E_{SR} + N_0}} H_{RD} W^H PS\{WH_{SR} x\}^* \\ &\quad + \sqrt{E_{SD}} H_{SD} x + n_D + \sqrt{E_{RD}} H_{RD} n_R' \end{aligned} \tag{10}$$

where n_D is a complex AWGN vector with each entry having zero-mean and variance of N0/2 per dimension.

2. Destination structure of the Proposed D-SFBC SC-FDE

By omitting $\sqrt{E_{RD} E_{SR} / (E_{SR} + N_0)}$, the first term of (10) can be written as

$$H_{RD} W^H PS\{WH_{SR} x\}^* = W^H \Lambda_{RD} PS \Lambda_{SR}^* \{Wx\}^* \tag{11}$$

where $\Lambda_{SR} (= WH_{SR} W^H)$ and $\Lambda_{RD} (= WH_{RD} W^H)$ are $N \times N$ diagonal matrices. Both Λ_{SR}^* and S are diagonal matrices, and thus (11) can be rewritten as

$$W^H \Lambda_{RD} PS \Lambda_{SR}^* \{Wx\}^* = W^H \Lambda_{RD} P \Lambda_{SR}^* S \{Wx\}^* \tag{12}$$

Since the channel frequency responses (CFRs) between adjacent subcarriers are approximately constant, i.e., $\Lambda_{SR}(2k) \approx \Lambda_{SR}(2k+1)$ for large N[7], (12) can be changed as

$$\begin{aligned}\mathrm{W}^{\mathrm{H}}\Lambda_{\mathrm{RD}}\mathrm{P}\Lambda_{\mathrm{SR}}^{*}\mathrm{S}\{\mathrm{Wx}\}^{*} &\cong \mathrm{W}^{\mathrm{H}}\Lambda_{\mathrm{RD}}\Lambda_{\mathrm{SR}}^{*}\mathrm{PS}\{\mathrm{Wx}\}^{*}\\ &= \mathrm{W}^{\mathrm{H}}\Lambda_{\mathrm{EQ}}\mathrm{PS}\{\mathrm{Wx}\}^{*}\end{aligned} \tag{13}$$

where $\Lambda_{\mathrm{EQ}}(=\Lambda_{\mathrm{RD}}\Lambda_{\mathrm{SR}}^{*})$ is the equivalent CFR.

With the normalization as in [11], the noise can be handled as complex AWGN having zero-mean and variance of $N_0/2$ without affecting the signal-to-noise ratio (SNR). After normalization, we have

$$\mathrm{r}_{\mathrm{D}}^{'} = \sqrt{\gamma_1}\,\mathrm{W}^{\mathrm{H}}\Lambda_{\mathrm{EQ}}\mathrm{PS}\{\mathrm{Wx}\}^{*} + \sqrt{\gamma_2}\,\mathrm{H}_{\mathrm{SD}}\mathrm{x} + \mathrm{n} \tag{14}$$

where γ_1 and γ_2 are defined as

$$\begin{aligned}\gamma_1 &= \frac{(E_{SR}/N_0)E_{RD}}{1+E_{SR}/N_0+\sum_{m=0}^{L_{RD}}|h_{RD}(m)|^2E_{RD}/N_0},\\ \gamma_2 &= \frac{(1+E_{SR}/N_0)E_{SD}}{1+E_{SR}/N_0+\sum_{m=0}^{L_{RD}}|h_{RD}(m)|^2E_{RD}/N_0}.\end{aligned} \tag{15}$$

Then, the frequency domain representation of $\mathrm{r}_{\mathrm{D}}^{'}$ is obtained by multiplying W as follows

$$\mathrm{R}_{\mathrm{D}}^{'} = \sqrt{\gamma_1}\,\Lambda_{\mathrm{EQ}}\mathrm{PSX}^{*} + \sqrt{\gamma_2}\,\Lambda_{\mathrm{SD}}\mathrm{X} + \mathrm{N} \tag{16}$$

We can divide (16) into even and odd components as

$$\begin{aligned}R_D^{'}(2k) &= -\sqrt{\gamma_1}\,\Lambda_{EQ}(2k)X^{*}(2k+1)\\ &\quad + \sqrt{\gamma_2}\,\Lambda_{SD}(2k)X(2k)+N(2k),\\ R_D^{'*}(2k+1) &= \sqrt{\gamma_1}\,\Lambda_{EQ}^{*}(2k+1)X(2k)\\ &\quad + \sqrt{\gamma_2}\,\Lambda_{SD}^{*}(2k+1)X^{*}(2k+1)+N^{*}(2k+1),\end{aligned} \tag{17}$$

and (17) can be changed in the matrix form as

$$\begin{aligned}\mathrm{R}_{\mathrm{k}}^{'} &= \begin{bmatrix} R_D^{'}(2k) \\ R_D^{'*}(2k+1)\end{bmatrix}\\ &\cong \begin{bmatrix} \Lambda_{SD}^{'}(2k) & -\Lambda_{EQ}^{'}(2k) \\ \Lambda_{EQ}^{'*}(2k) & \Lambda_{SD}^{'*}(2k)\end{bmatrix}\begin{bmatrix} X(2k) \\ X^{*}(2k+1)\end{bmatrix}+\begin{bmatrix} N(2k) \\ N^{*}(2k+1)\end{bmatrix}\\ &= \Lambda_{\mathrm{k}}^{'}\mathrm{X}_{\mathrm{k}}^{'}+\mathrm{N}_{\mathrm{k}}^{'}\end{aligned} \tag{18}$$

where $\Lambda_{\mathrm{SD}}^{'}=\sqrt{\gamma_1}\,\Lambda_{\mathrm{SD}}$ and $\Lambda_{\mathrm{EQ}}^{'}=\sqrt{\gamma_2}\,\Lambda_{\mathrm{EQ}}$. From (18), we can now derive a linear combination receiver under the minimum mean square error (MMSE) criterion. The resultant equation is similar to that of the maximal ratio combining (MRC) receiver with the two branch diversity system, which is

$$\begin{aligned}\mathrm{Y}_{\mathrm{k}} &= \Lambda_{\mathrm{k}}^{'\mathrm{H}}\mathrm{R}_{\mathrm{k}}^{'} = \begin{bmatrix}\tilde{\Lambda}(k) & 0 \\ 0 & \tilde{\Lambda}(k)\end{bmatrix}\mathrm{X}_{\mathrm{k}}^{'}+\Lambda_{\mathrm{k}}^{'\mathrm{H}}\mathrm{N}_{\mathrm{k}}^{'}\\ \tilde{\Lambda}(k) &= \gamma_1|\Lambda_{EQ}(2k)|^2+\gamma_2|\Lambda_{SD}(2k)|^2\\ \widehat{X_k} &= (\Lambda_k^{'H}\Lambda_k^{'}+\frac{1}{SNR}\mathrm{I}_2)^{-1}\mathrm{Y}_{\mathrm{k}} = \begin{bmatrix}\hat{X}(2k) \\ \widehat{X^{*}}(2k+1)\end{bmatrix}\end{aligned} \tag{19}$$

Note that decisions of the SC-FDE are made in the time domain, although channel equalization is performed in the frequency domain. Therefore, the estimate of the information symbols can be obtained as

$$\hat{\mathrm{x}} = \mathrm{W}^{\mathrm{H}}\hat{\mathrm{X}} \tag{20}$$

where $\hat{\mathrm{X}} = [\hat{X}(0),\hat{X}(1),\ldots,\hat{X}(N-1)]^T$.

3. Efficient Implementation of the Relay

In Fig. 2, the relay requires DFT/IDFT operations to code over adjacent subcarriers. In this subsection, we give an efficient implementation method of the relay, generating the same transmit sequence without DFT/IDFT operations, by processing the received signals in time domain. The procedure of time domain processing is explained as follows.

1) *Conjugation*: Using the DFT symmetry property, the time domain representation of $\tilde{\mathrm{R}}_{\mathrm{R}}^{*}$ in (7) is given by

$$r_c(n) = \widetilde{r_R^{*}}(-n)_N \tag{21}$$

2) *Separation of even and odd subcarriers*: To code over adjacent subcarriers, we should separate the even and odd components of the $\mathrm{R}_{\mathrm{C}}(=\tilde{\mathrm{R}}_{\mathrm{R}}^{*})$. Even (odd) components of the R_{C} can be easily separated by multiplying a sequence $\mathrm{D}_{\mathrm{e}}(\mathrm{D}_{\mathrm{o}})$ in frequency domain as follows

$$R_{e(o)}(k) = R_c(k)D_{e(o)}(k) \tag{22}$$

where $\mathrm{D}_{\mathrm{e}}=[1,0,\ldots,1,0]_{1\times N}^{T}$, $\mathrm{D}_{\mathrm{o}}=[0,1,\ldots,0,1]_{1\times N}^{T}$. Using the fact that the multiplication of sequences in frequency domain corresponds to the circular

표 1. 소스 및 중계기에서의 한 블록 전송을 위해 필요한 복소수 곱셈 연산 횟수 비교

Table 1. A Comparison of computational complexity for transmission of one information block. (The number of complex multiplications at source and relay)

	Diversity scheme	Source	Relay
OFDM	STBC	$\frac{N}{2}log_2N \times 2$	-
	SFBC	$\frac{N}{2}log_2N \times 2$	-
SC-FDE	STBC [5]	-	-
	Conventional SFBC [7]	2N	-
	Proposed SFBC	-	N*

*The computational complexity of the relay is reduced from $\frac{N}{2}log_2N\times2$ to N, by using (27).

convolution in time domain, the time domain representation of $\mathrm{R_e}$ and $\mathrm{R_o}$ can be obtained as follows

$$r_e(n) = r_c(n) \ *_N \ \delta_e(n),$$
$$r_o(n) = r_c(n) \ *_N \ \delta_o(n) \tag{23}$$

where $*_N$ represents the N-point circular convolution, and $\delta_e = \mathrm{W^H D_e}$, $\delta_o = \mathrm{W^H D_o}$. Note that $\delta_e(n) = 0$ and $\delta_o(n) = 0$ except $n = 0, \frac{N}{2}$ as follows

$$\delta_e(n) = \begin{cases} \frac{1}{2}, & n = 0 \text{ or } \frac{N}{2} \\ 0, & otherwise \end{cases},$$
$$\delta_o(n) = \begin{cases} \frac{1}{2}, & n = 0 \\ -\frac{1}{2}, & n = \frac{N}{2} \\ 0, & otherwise \end{cases} \tag{24}$$

Therefore, instead of circular convolution, the $\mathrm{r_e}$ and $\mathrm{r_o}$ in (23) can be obtained by adding two time domain signals as follows

$$r_e(n) = \frac{1}{2}r_c(n) + \frac{1}{2}r_c(n - N/2)_N$$
$$r_o(n) = \frac{1}{2}r_c(n) - \frac{1}{2}r_c(n - N/2)_N \tag{25}$$

3) *Shift and Summation of sequences*: Now the transmit sequence of relay can be obtained from $\mathrm{r_e}$ and $\mathrm{r_o}$ by using the frequency shift property as follows

$$x_R(n) = r_e(n) \times W_N^{-n} - r_o(n) \times W_N^{n} \tag{26}$$

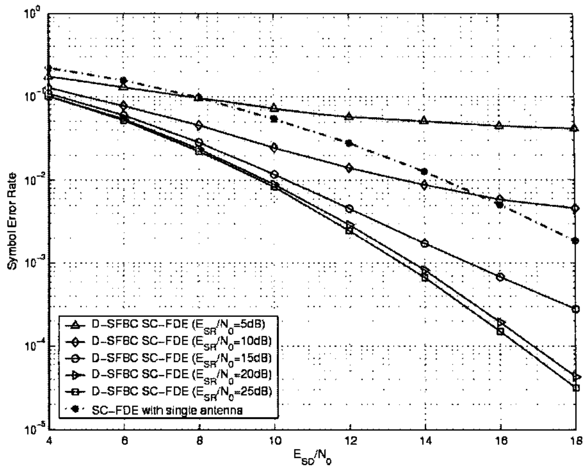


그림 3. E_{SR}/N_0에 대한 D-SFBC SC-FDE의 SER 성능

Fig. 3. SER performance of D-SFBC SC-FDE for different E_{SR}/N_0 (N=256, QPSK, fdts=0.001).

Further, substituting (25) into (26), $\mathrm{x_R}$ can be rewritten as

$$\begin{aligned} x_R(n) &= \frac{1}{2}r_c(n)(W_N^{-n} - W_N^{n}) \\ &\quad + \frac{1}{2}r_c(n-N/2)_N(W_N^{-n} + W_N^{n}) \\ &= r_c(n) \times j\sin(2\pi n/N) \\ &\quad + r_c(n-N/2)_N \times \cos(2\pi n/N). \end{aligned} \tag{27}$$

Note from (27) that we have directly obtained the transmit sequence of relay, $\mathrm{x_R}$, in the time domain, using the received signals from the source. It requires 2N multiplications of real by complex values, instead of DFT and IDFT operations. Due to the addition of two time domain signals, $\mathrm{x_R}$ may have peak power at the sample time, $n = N(2k+1)/8$, $k = 0,1,2,3,$, where the $|\cos(2\pi n/N)|$ and $|\sin(2\pi n/N)|$ are $1/\sqrt{2}$, and the PAPR is increased by 3dB. Table I compares the computational complexity of the distributed systems, summarizing the number of complex multiplications at source and relay. Two multiplications of real by complex values are counted as one complex multiplication. The overall complexity of the proposed system is half of the conventional SFBC SC-FDE, with no additional complexity at the source.

IV. Simulation Results

The symbol-error rate (SER) performance of the distributed systems (the D-STBC SC-FDE and the proposed D-SFBC SC-FDE) is investigated through computer simulations. We consider uncoded systems with the block size N=256, QPSK constellation, 3MHz bandwidth, and 3.1GHz carrier frequency. All underlying links experience frequency-selective channels, where S→R and S→D links are modeled as 4-path, and R→D link is 2-path with a uniform delay power profile. We assume that the channel state information (CSI) is known at the destination, and the S→D and R→D links are balanced, i.e., perfect power control.

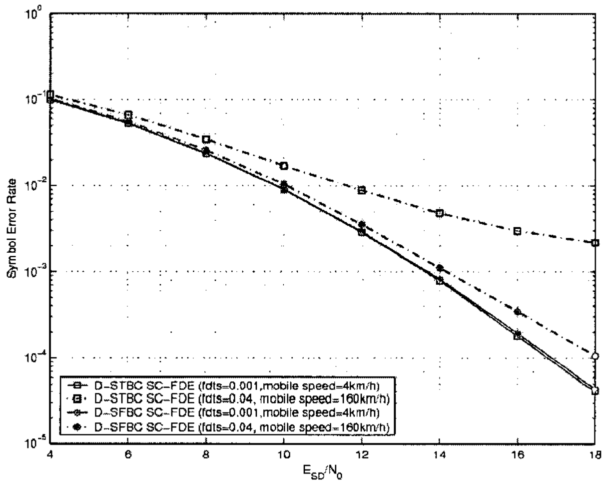


그림 4. D-STBC SC-FDE와 D-SFBC SC-FDE의 SER 성능 비교

Fig. 4. SER performance of D-STBC and D-DFBC SC-FDEs (N=256, QPSK, E_{SR}/N_0=20dB).

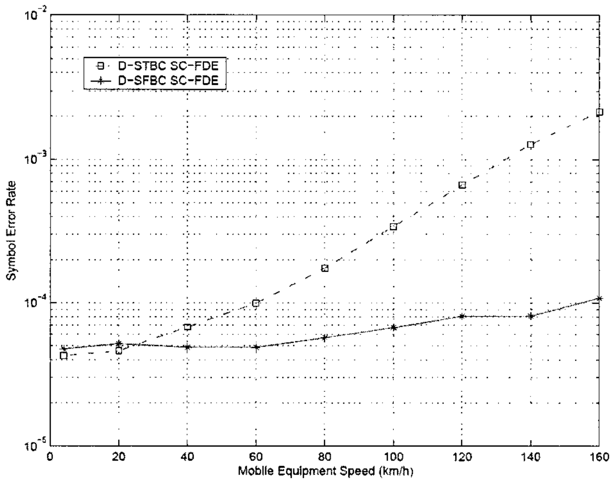


그림 5. 사용자 단말의 속도에 대한 D-STBC SC-FDE와 D-SFBC SC-FDE의 SER 성능 비교

Fig. 5. SER performance of D-STBC and D-DFBC SC-FDEs for different mobile equipment speeds (N=256, QPSK, E_{SR}/N_0=20dB).

Fig. 3 shows the performance of the proposed D-SFBC SC-FDE for E_{SR}/N_0=5, 10, 15, 20, and 25dB. For comparison, the performance of SC-FDE with single antenna is also shown in the figure. It is observed that the proposed system provides diversity order of 2, at high E_{SR}/N_0. However, at low E_{SR}/N_0, it is even worse than that of the SC-FDE with single antenna. Note that this is an inherent disadvantage of the distributed systems[11]. Fig. 4 compares the performance of the D-STBC SC-FDE and the proposed D-SFBC SC-FDE over slow fading (normalized Doppler frequency (fdts) = 0.001) and fast fading (fdts = 0.04) channels, which correspond to the mobile equipment speeds of 4 and 160 km/h, respectively. Fig. 5 shows the performance of the two systems for different mobile equipment speeds at E_{SR}/N_0 = 20dB and E_{SD}/N_0 = 18dB. Note from Figs. 4 and 5 that the proposed D-SFBC SC-FDE significantly outperforms the D-STBC SC-FDE, when there exists severe Doppler spread.

V. Conclusions

This paper proposed a distributed space-frequency block code (SFBC) for relay-assisted single carrier frequency-domain equalization (SC-FDE). The proposed system achieves spatial diversity without the complexity of multiple antennas. Mobile equipment transmits original single carrier signals without any additional processing, which is desirable especially for uplink transmission in view of PAPR and computational complexity. Efficient implementation of relay and the corresponding destination structure were also presented. Simulation results show that the proposed system considerably outperforms the distributed space-time block code (D-STBC) SC-FDE over fast fading channels.

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