공간-주파수 OFDM 전송 다이버시티 기법을 위한 효율적인 심볼 검출 알고리즘

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Efficient Symbol Detection Algorithm for Space-Frequency OFDM Transmit Diversity Scheme

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요 약

본 논문에서는 공간-주파수 OFDM (SF-OFDM) 전송 다이버시티 기법을 위한 효율적인 심볼 검출 알고리즘이 제안되었다. SF-OFDM 전송 다이버시티 기법에서 부반송파의 수가 적은 경우 부채널간 간섭이 발생하게 되며, 이러한 간섭은 다이버시티 시스템의 성능을 크게 저하시킨다. 제안된 알고리즘은 부채널간 간섭을 병렬 혹은 순차적으로 제거함으로써 기존 알고리즘에 비해 큰 성능 이득을 얻는다. 컴퓨터 모의실험을 통한 비트오류율 (BER) 성능 평가 결과, 두개의 송수신 안테나를 사용하는 경우, 10^{-4}의 BER에서 약 3 dB의 성능 이득을 얻을 수 있음을 확인하였다. 제안된 알고리즘이 적용된 심볼 검출기는 하드웨어 설계 언어를 통해 설계되었고, 0.18um 1.8V CMOS 표준 셀 라이브러리를 이용하여 합성되었다. 제시된 하드웨어 구조와 함께 설계된 SF-OFDM-PIC 심볼 검출기는 약 140K개의 논리 게이트로 구성되었고, SF-OFDM-SIC 검출기는 129K개의 논리 게이트로 합성되었다.

Key Words : SF-OFDM, transmit diversity, symbol detection, wireless LANs

ABSTRACT

In this paper, we propose two efficient symbol detection algorithms for space-frequency OFDM (SF-OFDM) transmit diversity scheme. When the number of sub-carriers in SF-OFDM scheme is small, the interference between adjacent sub-carriers may be generated. The proposed algorithms eliminate this interference in a parallel or sequential manner and achieve a considerable performance improvement over the conventional detection algorithm. The bit error rate (BER) performance of the proposed detection algorithms is evaluated by the simulation. In the case of 2 transmit and 2 receive antennas, at BER=10^{-4} the proposed algorithms achieve the gain improvement of about 3 dB. The symbol detectors with the proposed algorithms are designed in a hardware description language and synthesized to gate-level circuits with the 0.18um 1.8V CMOS standard cell library. With the division-free architecture, the proposed SF-OFDM-PIC and SF-OFDM-SIC symbol detectors can be implemented using 140K and 129K logic gates, respectively.

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Ⅰ. Introduction

The next generation wireless communication systems are expected to provide high-speed, spectrally efficient and reliable communication. Achieving these goals in wireless environment presents several challenges. Recently, the multiple transmit and receive antenna schemes have been proposed as an efficient solution for future wireless systems. Among them, transmit diversity schemes have attracted much attention since they greatly improve the system performance over flat fading channels with reasonable complexity overhead[1]-[2].

A number of orthogonal transmitter diversity schemes have been proposed[3]-[4]. However, the large delay spreads in non-flat fading channels such as frequency-selective multi-path channels destroy the orthogonality of the received signals, which is critical to the operation of the diversity systems. Using orthogonal frequency division multiplexing (OFDM), the channel impulse response can be considered to be flat within each sub-carrier. Therefore, transmit diversity schemes with OFDM can be effectively used in non-flat fading channels.

Two transmit diversity schemes with OFDM, the space-time OFDM (ST-OFDM) and the space-frequency OFDM (SF-OFDM), are described in [5] and [6]. Both the ST-OFDM and SF-OFDM are based on the transmit diversity scheme proposed by Alamouti[7]. The SF-OFDM transmit diversity scheme is better than the ST-OFDM scheme over fast fading environment, and it has lower latency in encoding and decoding processing[8]-[9]. However, in order to achieve the performance gain, the SF-OFDM requires a large number of sub-carriers, typically 512 or 1024. If the number of sub-carriers is not sufficiently large, the interference between sub-carriers may be generated and it seriously degrades the overall system performance. Therefore, the SF-OFDM scheme is not adequate for systems with a small number of sub-carriers such as wireless LANs. In this paper, we propose two efficient symbol detection algorithms that eliminate the interference effectively using parallel interference cancellation (PIC) and sequential interference cancellation (SIC) scheme for multi-user detection (MUD) in CDMA system[10]. By eliminating the interference caused by the small number of sub-carriers in a parallel or sequential manner, the proposed detection algorithms show a considerable performance improvement over the conventional detection algorithm.

This paper is organized as follows. In Section II, the system model for SF-OFDM transmit diversity scheme is introduced, and the proposed detection algorithms are described in Section III. Numerical simulation results are shown in Section IV, and implementation results of proposed algorithms are presented in Section V. Finally, Section VI concludes the paper.

Ⅱ. System Model

In this paper, two-branch SF-OFDM transmit diversity scheme is considered in convenience. However, the proposed algorithm can be extended to other cases involving more than two transmit/receive antennas. A block diagram of the two-branch SF-OFDM system is shown in Fig. 1.

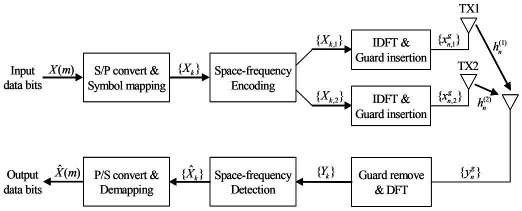

Fig 1. Block diagram of the two-branch SF-OFDM system.

Consider two adjacent sub-carriers k and $k+1$ ($k=0, 2, 4,..., N-2$) for transmission. For sub-carrier k, $X_{k,1}=X_k$ and $X_{k,2}=X_{k+1}$ are transmitted from transmit antenna 1 (TX1) and antenna 2 (TX2), respectively; for sub-carrier $k+1$, $X_{k+1,1}=-X_{k+1}^*$ and $X_{k+1,2}=X_k^*$ are transmitted from TX1 and TX2, respectively.

With perfect synchronization, the discrete Fourier transform (DFT) outputs at the receiver for the sub-carriers k and $k+1$ are given by

$$\begin{aligned} Y_k &= H_k^{(1)} \cdot X_{k,1} + H_k^{(2)} \cdot X_{k,2} + N_k \\ &= H_k^{(1)} \cdot X_k + H_k^{(2)} \cdot X_{k+1} + N_k \end{aligned} \tag{1}$$

$$\begin{aligned} Y_{k+1} &= H_{k+1}^{(1)} \cdot X_{k+1,1} + H_{k+1}^{(2)} \cdot X_{k+1,2} + N_{k+1} \\ &= H_{k+1}^{(1)} \cdot (-X_{k+1}^{*}) + H_{k+1}^{(2)} \cdot X_k^{*} + N_{k+1}, \end{aligned} \tag{2}$$

where $H_k(i)$ with $i=1$ or 2 denotes the DFT of the channel impulse response from transmit antenna i to the receiver and N_k denotes the DFT of additive white Gaussian noise (AWGN) corresponding to the sub-carrier k. After conjugating (2), the DFT outputs for the sub-carriers k and $k+1$ can be written in the matrix notation,

$$\begin{aligned} \mathbf{Y} = \begin{pmatrix} Y_k \\ Y_{k+1}^{*} \end{pmatrix} &= \begin{pmatrix} H_k^{(1)} & H_k^{(2)} \\ H_{k+1}^{(2)*} & -H_{k+1}^{(1)*} \end{pmatrix} \cdot \begin{pmatrix} X_k \\ X_{k+1} \end{pmatrix} + \begin{pmatrix} N_k \\ N_{k+1}^{*} \end{pmatrix} \\ &= \mathbf{H} \cdot \mathbf{X} + \mathbf{N}. \end{aligned} \tag{3}$$

In (3), with the assumption that the complex channel gains between adjacent sub-carriers are approximately constant, the matrix $\mathbf{H}$ is orthogonal, i.e.

$$\begin{aligned} \mathbf{H}^H \mathbf{H} &= \begin{pmatrix} H_k^{(1)} & H_k^{(2)} \\ H_{k+1}^{(2)*} & -H_{k+1}^{(1)*} \end{pmatrix}^H \cdot \begin{pmatrix} H_k^{(1)} & H_k^{(2)} \\ H_{k+1}^{(2)*} & -H_{k+1}^{(1)*} \end{pmatrix} \\ &= \begin{pmatrix} \left|H_k^{(1)}\right|^2 + \left|H_{k+1}^{(2)}\right|^2 & H_k^{(1)*} \cdot H_k^{(2)} - H_{k+1}^{(1)*} \cdot H_{k+1}^{(2)} \\ H_k^{(1)} \cdot H_k^{(2)*} - H_{k+1}^{(1)} \cdot H_{k+1}^{(2)*} & \left|H_{k+1}^{(1)}\right|^2 + \left|H_k^{(2)}\right|^2 \end{pmatrix} \\ &= \begin{pmatrix} c_k & 0 \\ 0 & c_k \end{pmatrix} = c_k \cdot \mathbf{I}_2. \end{aligned} \tag{4}$$

Using (4), the transmitted symbol vector can be simply detected as follows:

$$\hat{\mathbf{X}} = Q(\tilde{\mathbf{X}}) = Q\left(\frac{\mathbf{H}^H \cdot \mathbf{Y}}{c_k}\right) = Q\left(\mathbf{X} + \frac{\mathbf{H}^H \cdot \mathbf{N}}{c_k}\right), \tag{5}$$

where $(\cdot)^H$ and $Q(\cdot)$ denote the conjugate transpose and the quantization (slicing) operation appropriate to the constellation used, respectively. However, in the case that the number of sub-carriers is small, the channel gains between adjacent sub-carriers are not constant, and the matrix $\mathbf{H}$ is non-orthogonal, i.e.

$$\mathbf{H}^H \mathbf{H} = \begin{pmatrix} c_k & e_k \\ e_{k+1} & c_{k+1} \end{pmatrix} \neq c_k \cdot \mathbf{I}_2, \tag{6}$$

where $e_k^{*} = e_{k+1}$. Therefore, by (6) the decision statistic vector can be rewritten as

$$\tilde{\mathbf{X}} = \begin{pmatrix} \tilde{X}_k \\ \tilde{X}_{k+1} \end{pmatrix} = \begin{pmatrix} X_k + \dfrac{e_k}{c_k} \cdot X_{k+1} + \dfrac{H_k^{(1)*} \cdot N_k + H_{k+1}^{(2)} \cdot N_{k+1}^{*}}{c_k} \\ X_{k+1} + \dfrac{e_{k+1}}{c_{k+1}} \cdot X_k + \dfrac{H_k^{(2)*} \cdot N_k - H_{k+1}^{(1)} \cdot N_{k+1}^{*}}{c_{k+1}} \end{pmatrix}. \tag{7}$$

The second term of each element in vector is the interference between adjacent sub-carriers. This interference seriously degrades the system performance of the SF-OFDM scheme.

Ⅲ. Proposed Detection Algorithm

As already mentioned, the proposed algorithms, called SF-OFDM-PIC and SF-OFDM-SIC, achieve the performance gain by eliminating the interference between adjacent sub-carriers with PIC or SIC schemes. The SF-OFDM-PIC eliminates the interference in parallel while the SF-OFDM-SIC does it in a sequential manner. Table 1 describes the SF-OFDM-PIC detection algorithm(for the brevity, $k=1$ is assumed). After the symbol is detected as expressed in (5) in steps 1 and 2, the interference terms are cancelled in parallel in step 3. Finally, the transmitted symbols are detected in step 4.

Table 1. SF-OFDM-PIC Detection Algorithm

Step	Operation
1	$\tilde{X}_1 = X_1 + (e_1 / c_1) \cdot X_2 + N_1'$, $\tilde{X}_2 = X_2 + (e_2 / c_2) \cdot X_1 + N_2'$
2	$\bar{X}_1 = Q(\tilde{X}_1)$, $\bar{X}_2 = Q(\tilde{X}_2)$
3	$\breve{X}_1 = \tilde{X}_1 - (e_1 / c_1) \cdot \bar{X}_2$, $\breve{X}_2 = \tilde{X}_2 - (e_2 / c_2) \cdot \bar{X}_1$
4	$\hat{X}_1 = Q(\breve{X}_1)$, $\hat{X}_2 = Q(\breve{X}_2)$

The SF-OFDM-SIC detection algorithm sequentially eliminates the interference by order of the post detection SNR (PDSNR). Since the symbol that has a large PDSNR is more reliable, that symbol is detected first and cancelled. In (5), the PDSNR of the i th transmitted symbol is given by

$$PDSNR(X_i) = \frac{E_s/2}{\frac{|e_i|^2}{c_i^2}\cdot\frac{E_s}{2} + \frac{N_0}{c_i}} = \frac{1}{\frac{|e_i|^2}{c_i^2} + \frac{2}{c_i}\cdot\frac{1}{E_s/N_0}}, \tag{8}$$

where E_s and N_0 denote the symbol energy and the noise power spectral density, respectively. Since the effects of the interference are remarkably large in the high SNR region (see Figs. 4-7), (8) can be approximated as

$$PDSNR(X_i) \cong \frac{c_i^2}{|e_i|^2}. \tag{9}$$

However, since the denominator in (9) is constant over all i, the ordering process is performed by comparing the powers of c_1 and c_2. That is, if the power of c_1 is larger than that of c_2, the symbol X_1 is detected first otherwise, the symbol X_2 would be detected first. The SF-OFDM-SIC detection algorithm is described in Table 2. It is assumed that the symbol X_1 is detected first and X_2 is detected next.

Figs. 2 and 3 depict the block diagram of the SF-OFDM-PIC and SF-OFDM-SIC detection algorithms, respectively. As shown in these figures, since the proposed algorithms have additional computations such as divisions, one may think that they are too complex. However, through a little modification with a scaled constellation, the additional divisions can be removed, and therefore, their computational complexity can be acceptable(see the section V)

Table 2. SF-OFDM-SIC Detection Algorithm

Step	Operation
1	$\tilde{X}_1 = X_1 + (e_1/c_1)\cdot X_2 + N_1'$, $\tilde{X}_2 = X_2 + (e_2/c_2)\cdot X_1 + N_2'$
2	Compare the powers of c_1 and c_2 ($c_1^2 > c_2^2$)
3	$\bar{X}_1 = Q(\tilde{X}_1)$
4	$\breve{X}_2 = \tilde{X}_2 - (e_2/c_2)\cdot \bar{X}_1$
5	$\hat{X}_2 = Q(\breve{X}_2)$
6	$\breve{X}_1 = \tilde{X}_1 - (e_1/c_1)\cdot \hat{X}_2$
7	$\hat{X}_1 = Q(\breve{X}_1)$

Ⅳ. Simulation Results

The BER performance of the proposed detection algorithms was evaluated by the simulation. We consider a 16QAM-OFDM system with 64 subcarriers and in a slow time-varying multi-path fading channel generated according to the channel model A for HIPERLAN/2[11]. It is assumed that the channel state information (CSI) is available at the receiver except for for the case in Fig. 7.

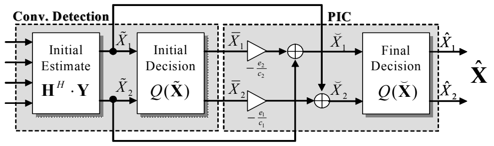

Fig 2. Block diagram of the SF-OFDM-PIC algorithm.

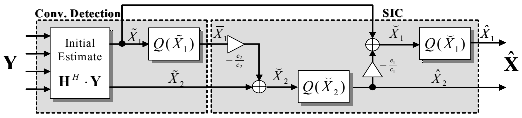

Fig 3. Block diagram of the SF-OFDM-SIC algorithm.

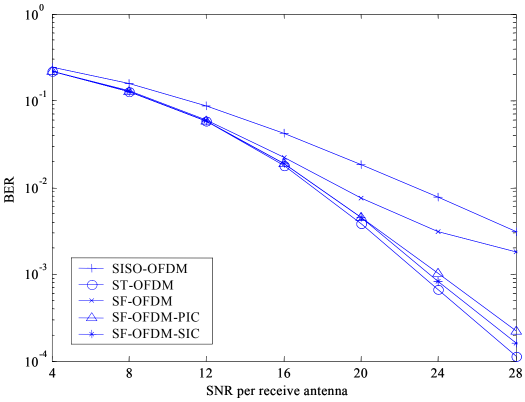

Fig 4. BER performance for SISO-OFDM, ST-OFDM, SF-OFDM, SF-OFDM-PIC and SF-OFDM-SIC with 2 transmit and 1 receive antennas.

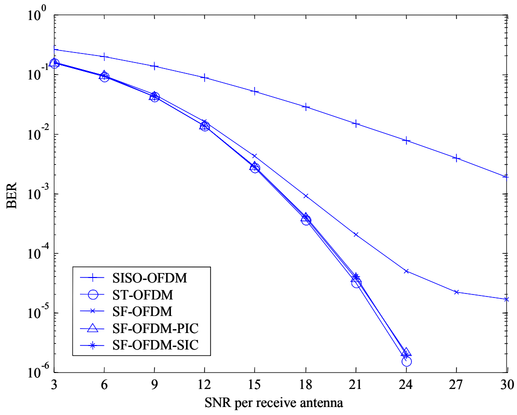

Fig 5. BER performance for 2 TX and 2 RX.

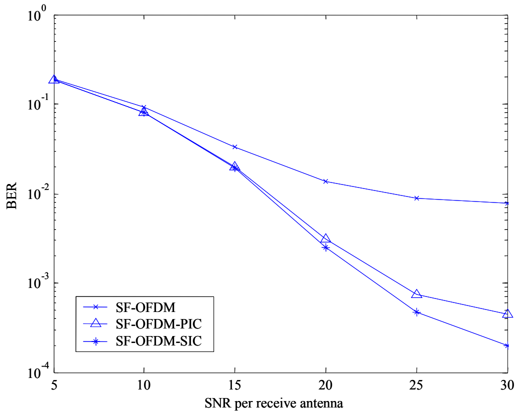

Fig 6. BER performance for 3 TX and 1 RX.

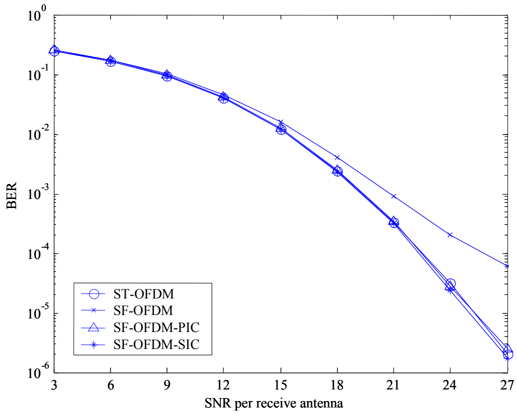

Fig 7. BER performance for 2 TX, 2 RX, and imperfect channel estimation.

Fig. 4 shows the BER performance of the single-input single-output OFDM(SISO-OFDM), ST-OFDM, SF-OFDM, SF-OFDM-PIC and SF OFDM-SIC for the case of 2 TX and 1 RX. It can be observed that at BER=10^{-3} the proposed algorithms achieve the gain improvement of about 6-7 dB over the conventional SF-OFDM and maintain nearly the same performance as the ST-OFDM.

The BER performance for the case of 2 TX and 2 RX is depicted in Fig. 5. The results similar to the case of 2 TX and 1 RX are observed. At BER=10^{-4} the proposed algorithms achieve the gain of about 3 dB over the conventional algorithm while maintaining the same performance as the ST-OFDM. From the results in Figs. 4 and 5, we can see that the SF-OFDM-SIC algorithm is only slightly better than SF-OFDM-PIC algorithm. The reason for the marginal improvement is simply that the effects of the ordered cancellation become relatively insignificant, since the number of transmit antennas is just two. However, with more than two antennas, the performance gain of the SF-OFDM-SIC algorithm increases as shown in Fig. 6. In this simulation, the transmission matrix in[12] was used for the case of 3 TX and 1 RX.

Fig. 7 shows the performance for the case of imperfect channel estimation. Least square (LS) estimation with orthogonal space-time pilot matrices[13] is used. Like the results in Fig. 4, the proposed algorithms show a considerable performance improvement over the conventional algorithm.

Ⅴ. Implementation

As shown in Figs. 2 and 3, the proposed algorithms require additional division operations. Since the division circuits require much larger combinational logic delays, the design of the pipeline architecture incorporating them is very difficult. However, since the divisors, ck and $ck+1$, in the proposed algorithms are positive scalar, the division-free implementation with the scaled constellation as reported in [14]-[15] can be possible. A modified SF-OFDM-PIC algorithm for the division-free implementation is depicted in Table 3. It can be observed that the division operation is removed. Similarly, a division-free SF-OFDM-SIC algorithm can also be derived.

Table 3. Modified SF-OFDM-PIC Detection Algorithm

Step	Operation
1	$X_1' = c_1 \cdot X_1 + e_1 \cdot X_2 + N_1',\ X_2' = c_2 \cdot X_2 + e_2 \cdot X_1 + N_2'$
2	$\overline{X}_1 = Q(X_1', c_1),\ \overline{X}_2 = Q(X_2', c_2)$
3	$X_1'' = \tilde{X}_1 - e_1 \cdot \overline{X}_2,\ X_2'' = \tilde{X}_2 - e_2 \cdot \overline{X}_1$
4	$\hat{X}_1 = Q(X_1'', c_1),\ \hat{X}_2 = Q(X_2'', c_2)$

Figs. 8 and 9 show the hardware architectures of the SF-OFDM-PIC and SF-OFDM-SIC detection algorithms. As shown in these figures, with a division-free architecture, the complexity overhead for the proposed algorithm is just a couple of additions, multiplications and decision units. Table 4 depicts the comparison results of the conventional detector, the proposed SF-OFDM-PIC, and SF-OFDM-SIC detector for the logic gates and power consumption with a 0.18um 1.8V standard cell library. From these results, it is more clearly confirmed that the complexity overhead of the proposed algorithms is acceptable.

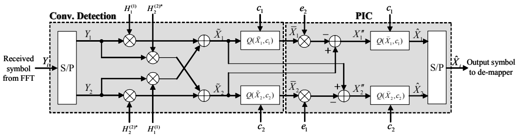

Fig 8. Hardware architecture of the SF-OFDM-PIC detection algorithm.

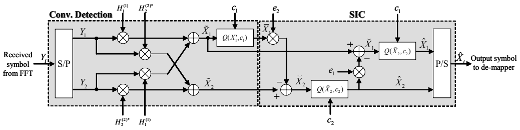

Fig 9. Hardware architecture of the SF-OFDM-SIC detection algorithm

Table 4. Comparison Results for Logic Gates and Power Consumption

	SF-OFDM Detector	SF-OFDM-PIC Detector	SF-OFDM-SIC Detector
Logic Gates	93K	140K	129K
Power (mW)	43.5	54.9	55.1

Ⅵ. Conclusion

In this paper, we propose two efficient symbol detection algorithms for the SF-OFDM transmit diversity scheme and present the implementation results. By eliminating the interference caused by a small number of sub-carriers, the proposed algorithms, the SF-OFDM-PIC and the SF-OFDM-SIC, achieve the performance gain over the conventional algorithm. The BER performance of the proposed detection algorithms is evaluated by the simulation. In the case of 2 transmit and 2 receive antennas, at BER=10^{-4} the proposed algorithms achieve the gain ofabout 3 dB. The symbol detectors with the proposed algorithms are designed in a hardware description language and synthesized to gate-level circuits with the 0.18um 1.8V CMOS standard cell library. With the division-free architecture, the proposed SF-OFDM-PIC and SF-OFDM-SIC symbol detectors can be implemented using 140K and 129K logic gates, respectively. Since the proposed algorithms remove the interference caused by a few sub-carriers and provide an excellent diversity advantage, the SF-OFDM scheme with the proposed algorithms will be very attractive for systems with a small number of sub-carriers such as wireless LANs

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