Abstract

In this paper, we propose an efficient symbol detection algorithm for space-frequency OFDM (SF-OFDM) transmit diversity scheme and present the implementation results of the SF-OFDM WLAN baseband processor with the proposed algorithm. When the number of sub-carriers in SF-OFDM scheme is small, the interference between adjacent sub-carriers may be neglected. The proposed algorithm eliminates this interference in a parallel manner and obtains a considerable performance improvement over the conventional detection algorithm. The bit error rate (BER) performance of the proposed detection algorithm is evaluated by the simulation. In the case of 2 transmit and 2 receive antennas, at BER = 10^{-4} the proposed algorithm obtains about 3 dB gain over the conventional detection algorithm. The packet error rate (PER) link throughput, and coverage performance of the SF-OFDM WLAN with the proposed detection algorithm are also estimated. For the target throughput at 80% of the peak data rate, the SF-OFDM WLAN achieves the average SNR gain of about 5.95 dB and the average coverage gain of 3.98 meter. The SF-OFDM WLAN baseband processor with the proposed algorithm was designed in a hardware description language and synthesized to gate-level circuits using 0.18μm 1.8V CMOS standard cell library. With the division-free architecture, the total logic gate count for the processor is 945K. The real-time operation is verified and evaluated using a FPGA test system.

Keywords: Space-Frequency OFDM transmit diversity scheme, symbol detection, WLAN.

I. Introduction

The tremendous growth in WLANs has generated much interest in technologies that provide higher data rates and greater system capacities. The current IEEE 802.11a standards, based on coded orthogonal frequency division multiplexing (COFDM), support up to 54Mbps transmission rate at 5GHz band. However, high-speed internet, video, and multi-media applications have created a need for even higher
bandwidth efficiency and reliability from the next generation WLAN system\(^a\).

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 shown a high potential for the greatly improved system performance over flat fading channels with reasonable complexity.\(^b\)

A number of orthogonal transmit diversity schemes have been proposed.\(^d\) 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 a critical factor for the reliable 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 \(^6\), respectively. In the ST-OFDM scheme, since adjacent OFDM symbols are encoded for the diversity gain, good performance is obtained over slow fading channel such as in an indoor environment. However, encoding between OFDM symbols results in large encoding and decoding processing delays which are not compliant with the short inter-frame space (SIFS) timing requirements for IEEE 802.11 MAC protocol’s acknowledgement packets.\(^7\) In the case of the SF-OFDM scheme, due to encoding among adjacent sub-carrier symbols, small delays are obtained in the encoding and decoding processing.\(^8\). However, for the performance gain, SF-OFDM requires a large number of sub-carriers, typically 512 or 1024.\(^9\) Therefore, the SF-OFDM scheme is not adequate for the systems with a few sub-carriers such as WLANs.

In this paper, we propose an efficient symbol detection algorithm for the SF-OFDM scheme and present the implementation results of the SF-OFDM WLAN baseband processor with the proposed algorithm. By eliminating the interference caused by a few sub-carriers, the proposed detection algorithm shows a considerable performance improvement over the conventional detection algorithm. Also, the SF-OFDM WLAN system with the proposed algorithm supports a better throughput and coverage performance than the conventional IEEE 802.11a system.

This paper is organized as follows. In Section II, the system model with SF-OFDM transmit diversity scheme is introduced, and the proposed detection algorithm is described in Section III. Performance analysis results such as PER, link throughput, and coverage are shown in Section IV, and implementation results of the SF-OFDM WLAN baseband processor with the proposed algorithm are presented in Section V. Finally, Section VI concludes the paper.

## II. System Model

In this paper, we consider two-branch SF-OFDM transmit diversity scheme as the convenient benchmarking case. However, the proposed algorithm can be extended to other transmit/receive antenna cases. A block diagram of the two-branch SF-OFDM system is shown in Fig. 1.

Consider two adjacent sub-carriers \(k\) and \(k+1\) (\(k=0, 2, 4; \cdots, N-2\)) for transmission. For the 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.

![Fig. 1. Block diagram of two-branch SF-OFDM system.](image-url)
With perfect synchronization, the discrete Fourier transform (DFT) outputs at the receiver for sub-carriers $k$ and $k+1$ are given by

$$Y_k = H_k^{(0)} \cdot X_k + H_k^{(0)} \cdot X_{k+1} + N_k$$

$$Y_{k+1} = H_{k+1}^{(0)} \cdot (-X_{k+1}) + H_{k+1}^{(0)} \cdot X_k + N_{k+1},$$

where $H_k^{(0)}$ with $i \in \{1, 2\}$ denotes the DFT of the channel impulse response from transmit antenna $i$ to the receiver and $N_k$ denotes the DFT of AWGN. After conjugating (2), the DFT outputs can be written in the matrix notation,

$$Y = \begin{pmatrix} Y_k \\ Y_{k+1} \end{pmatrix} = \begin{pmatrix} H_k^{(0)} & H_k^{(0)} \\ H_{k+1}^{(0)} & -H_{k+1}^{(0)} \end{pmatrix} \cdot \begin{pmatrix} X_k \\ X_{k+1} \end{pmatrix} + \begin{pmatrix} N_k \\ N_{k+1} \end{pmatrix}$$

$$= H \cdot X + N$$

(3)

Assuming that the complex channel gains between adjacent sub-carriers are approximately constant, the matrix $H$ in (3) is orthogonal, i.e.,

$$H^H H = \begin{pmatrix} |H_k^{(0)}|^2 + |H_{k+1}^{(0)}|^2 & H_k^{(0) \ast} \cdot H_k^{(2)} - H_{k+1}^{(0) \ast} \cdot H_{k+1}^{(2)} \\ H_k^{(0) \ast} \cdot H_k^{(2)} - H_{k+1}^{(0) \ast} \cdot H_{k+1}^{(2)} & |H_k^{(2)}|^2 + |H_{k+1}^{(2)}|^2 \end{pmatrix}$$

$$= \begin{pmatrix} c_k & 0 \\ 0 & c_{k+1} \end{pmatrix} = c_k \cdot I_2$$

(4)

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

$$\hat{X} = Q(X) = Q\left( \frac{H^H \cdot Y}{c_k} \right) = Q\left( X + \frac{H^H \cdot Y}{c_k} \right)$$

(5)

where $(0^H$ and $Q)$ denote the conjugate transpose and the quantization operation. 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 $H$ is non-orthogonal, i.e.,

$$H^H H = \begin{pmatrix} |H_k^{(0)}|^2 + |H_{k+1}^{(0)}|^2 & H_k^{(0) \ast} \cdot H_k^{(2)} - H_{k+1}^{(0) \ast} \cdot H_{k+1}^{(2)} \\ H_k^{(0) \ast} \cdot H_k^{(2)} - H_{k+1}^{(0) \ast} \cdot H_{k+1}^{(2)} & |H_k^{(2)}|^2 + |H_{k+1}^{(2)}|^2 \end{pmatrix}$$

$$= \begin{pmatrix} \tilde{c}_k & \tilde{c}_{k+1} \\ \tilde{c}_{k+1} & \tilde{c}_{k+1} \end{pmatrix} \neq c_k \cdot I_2,$$

(6)

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

$$X = \begin{pmatrix} X_k \\ X_{k+1} \end{pmatrix} = \begin{pmatrix} X_k + \frac{c_k}{e_k} \cdot X_{k+1} + H_k^{(0) \ast} \cdot N_k + H_k^{(2) \ast} \cdot N_{k+1} \\ X_{k+1} + \frac{c_{k+1}}{e_{k+1}} \cdot X_k + H_{k+1}^{(0) \ast} \cdot N_k + H_{k+1}^{(2) \ast} \cdot N_{k+1} \end{pmatrix}$$

(7)

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

### III. Proposed Detection Algorithm

The proposed algorithm achieves the performance gain by eliminating the interference between adjacent sub-carriers with the parallel interference cancellation (PIC) method. Table 1 describes the proposed detection algorithm. After a symbol as expressed in (5) is detected in steps 1 and 2, the interference terms are cancelled in parallel in step 3. Finally, the transmitted symbols are detected in step 4.

Fig. 2 depicts the block diagram of the proposed detection algorithm. As shown in this figure, the proposed algorithm requires slightly more

<table>
<thead>
<tr>
<th>Step</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\hat{x}<em>k = \hat{x}<em>k + (e_k/c_k) \cdot X</em>{k+1}, N_k \hat{x}</em>{k+1} = \hat{x}<em>{k+1} (e</em>{k+1}/c_{k+1}) \cdot X_k + N_k$</td>
</tr>
<tr>
<td>2</td>
<td>$\hat{X}<em>k = Q(\hat{X}<em>k)$, $\hat{X}</em>{k+1} = Q(\hat{X}</em>{k+1})$</td>
</tr>
<tr>
<td>3</td>
<td>$\hat{x}<em>k = \hat{x}<em>k - (e_k/c_k) \cdot \hat{X}</em>{k+1}, \hat{x}</em>{k+1} = \hat{x}<em>{k+1} (e</em>{k+1}/c_{k+1}) \cdot \hat{x}_k$</td>
</tr>
<tr>
<td>4</td>
<td>$\hat{X}<em>k = Q(\hat{X}<em>k)$, $\hat{X}</em>{k+1} = Q(\hat{X}</em>{k+1})$</td>
</tr>
</tbody>
</table>

| Table 1. Proposed Symbol Detection Algorithm. |

Fig. 2. Block diagram of the proposed detection algorithm.
Fig. 3. BER performance for 2 TX and 1 RX.

Fig. 4. BER performance for 2 TX and 2 RX.

Fig. 5. BER performance for 2 TX, 2 RX, and imperfect channel estimation.

The BER performance for the case of 2 TX and 2 RX is depicted in Fig. 4. The results similar to the case of 2 TX and 1 RX are observed. At BER = 10^{-4} the proposed algorithm obtains about 3 dB gain over the conventional algorithm and also achieves perfectly the same performance as the ST-OFDM.

Fig. 5 shows the performance for the case of imperfect channel estimation. A least square (LS) estimation with orthogonal space-time pilot matrices \[11\] is used. Like the results in Fig. 3, the proposed algorithm shows a considerable performance improvement over the conventional algorithm.

IV. Performance Analysis Results

The PER performance of the conventional IEEE 802.11a WLAN and the SF-OFDM based WLAN with the proposed detection algorithm are shown in Fig. 6. The transmission modes 5-8, that support the peak data rates of 24-54 Mba/s, in IEEE 802.11a standards\[12\] are considered. As shown in this figure, at PER = 10^{-1} the SF-OFDM based WLAN with the proposed algorithm achieves the SNR gain of about 5-8 dB over the conventional IEEE 802.11a WLAN system for transmission modes.

By this SNR gain, the link throughput performance is improved as shown in Fig. 7. The link throughput is estimated by the methods in \[13\]-\[14\]. Assuming
that the target throughput is set to 80% of the peak data rate, the SF-OFDM based WLAN obtains the SNR gain of about 4.6-7.0 dB over the conventional IEEE 802.11a WLAN.

Like the improvement of the link throughput, the coverage (operating range) performance is also enhanced as shown in Fig. 8. With the target throughput at 80% of the peak data rate, the conventional WLAN has the coverage of about 12.9-18.9 meter as the transmission modes, while the SF-OFDM based WLAN has the coverage of about 17.5-22.1 meter.

The comparison results of the PER, link throughput, and coverage performance are summarized in Table II. For the target throughput at 80% of the peak data rate, the SF-OFDM based WLAN achieves the average SNR gain of about 5.95 dB and average coverage gain of 3.98 meter.

V. Implementation of SF—OFDM WLAN

Baseband Processor

The block diagram of the SF-OFDM WLAN baseband processor is depicted in Fig. 9.

The transmitted baseband signals consist of packets composed of a preamble followed by OFDM symbols. The preamble in [11] is used for synchronization and channel estimation. Forward error correction is provided through the use of a rate 1/2 constraint length 7 convolutional code with selectable puncturing to provide rates of 2/3, 3/4, and 5/6. The coded bits are interleaved to prevent error bursts from being fed into the Viterbi decoder since the decoder does not work very well with burst errors. The interleaved coded bits are grouped together to form symbols. The symbols are modulated with one of BPSK, QPSK, 16QAM, and 64QAM.

The modulated symbols are encoded by the SF—OFDM encoder as transmission modes in Table III. The SF-OFDM encoded symbols are OFDM—modulated by 64-point inverse FFT (IFFT). Each output of the IFFT is converted to a serial sequence...
표 2. 목표 throughput를 위한 SNR 및 coverage 비교
Table 2. Comparison of the required SNR and coverage for the target throughput.

<table>
<thead>
<tr>
<th>TX mode</th>
<th>Thr. (Mbit/s)</th>
<th>802.11a</th>
<th>Proposed</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SNR (dB)</td>
<td>Coverage (meter)</td>
<td>SNR (db)</td>
<td>Coverage (meter)</td>
</tr>
<tr>
<td>5</td>
<td>19.2</td>
<td>12.9</td>
<td>18.9</td>
<td>8.3</td>
</tr>
<tr>
<td>6</td>
<td>28.8</td>
<td>17.3</td>
<td>15.8</td>
<td>10.7</td>
</tr>
<tr>
<td>7</td>
<td>38.4</td>
<td>19.6</td>
<td>14.5</td>
<td>14.0</td>
</tr>
<tr>
<td>8</td>
<td>43.2</td>
<td>22.2</td>
<td>12.9</td>
<td>15.2</td>
</tr>
<tr>
<td>Average</td>
<td>59.5</td>
<td>3.98</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

그림 9. SF-OFDM WLAN 기지대역 프로세서의 블록도
Fig. 9. Block diagram of the SF-OFDM WLAN baseband processor with the proposed detection algorithm.

표 3. 전송 모드
Table 3. Transmission modes.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Peak data rate</th>
<th>Modulation</th>
<th>Coding rate</th>
<th>MIMO scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 Mbit/s</td>
<td>BPSK</td>
<td>1/2</td>
<td>SF-OFDM</td>
</tr>
<tr>
<td>2</td>
<td>9 Mbit/s</td>
<td>BPSK</td>
<td>3/4</td>
<td>SF-OFDM</td>
</tr>
<tr>
<td>3</td>
<td>12 Mbit/s</td>
<td>QPSK</td>
<td>1/2</td>
<td>SF-OFDM</td>
</tr>
<tr>
<td>4</td>
<td>18 Mbit/s</td>
<td>QPSK</td>
<td>3/4</td>
<td>SF-OFDM</td>
</tr>
<tr>
<td>5</td>
<td>24 Mbit/s</td>
<td>16QAM</td>
<td>1/2</td>
<td>SF-OFDM</td>
</tr>
<tr>
<td>6</td>
<td>36 Mbit/s</td>
<td>16QAM</td>
<td>3/4</td>
<td>SF-OFDM</td>
</tr>
<tr>
<td>7</td>
<td>48 Mbit/s</td>
<td>64QAM</td>
<td>2/3</td>
<td>SF-OFDM</td>
</tr>
<tr>
<td>8</td>
<td>54 Mbit/s</td>
<td>64QAM</td>
<td>3/4</td>
<td>SF-OFDM</td>
</tr>
</tbody>
</table>

and a cyclic prefix (CP) is added. After the CP is added, each OFDM symbol is clipped to reduce the effective peak-to-average power ratio (PAPR) for non-linear power amplifier.

In the receiver, an all-digital AGC detects RF amplifier gain error. After AGC tuning, time and frequency synchronization is performed. After the CP removal and FFT, interpolation-based channel estimation is performed to estimate the channel frequency response. Next, the transmitted symbols are detected by the SF-OFDM detector with the proposed algorithm.

As shown in Fig. 2, the proposed algorithm requires additional division operations. Since the division circuits require a much larger combinational logic delay, the design of the pipeline architecture incorporating them is very difficult. However, since the divisors, \( a_1 \) and \( a_2 \), in the proposed algorithm are positive scalars, the division-free implementation with the scaled constellation in [14]-[15] can be possible.

Modified algorithm for the division-free implementation is depicted in Table IV. It can be observed that the division operation is removed.

Fig. 10 shows the hardware architecture of the proposed detection algorithm. As shown in this figure, the proposed algorithm was implemented without additional division circuits.

The results of logic synthesis and power analysis for the symbol detector with the modified division-free architecture using the 0.18um 1.8V CMOS standard cell library are shown in Table V. Power consumption is simulated using DesignPower.
### VI. Conclusion

In this paper, we propose an efficient symbol detection algorithm for the SF-OFDM scheme and present the implementation results of the SF-OFDM WLAN baseband processor with the proposed algorithm. The BER performance of the proposed detection algorithm was evaluated by simulation. In the case of 2 transmit and 2 receive antennas, at BER=10^{-4} the proposed algorithm obtains about 3 dB gain over the conventional detection algorithm. The PER, link throughput, and coverage performance of the SF-OFDM WLAN with the proposed detection algorithm are estimated. For the target throughput at 80% of the peak data rate, the SF-OFDM WLAN achieves the average SNR gain of about 5.95 dB and the average coverage gain of 3.98 meter. The SF-OFDM WLAN baseband processor with the proposed algorithm is implemented with the 0.18um 1.8V CMOS standard cell library. With the division-free architecture, the total logic gate count for the processor is 945 K. Since the SF-OFDM WLAN with the proposed algorithm shows a considerable performance improvement over the conventional IEEE 802.11a WLAN, it can be a highly promising solution for the next generation WLAN.

### 참고 문헌


