The Enhanced Decoding Method for QO-SFBC System in Frequency Selective Fading Channel Environment

Young-il Min
School of Information and Communications Engineering, Sungkyunkwan University, Suwon, Korea
Email: bashbabar@ece.skku.ac.kr

Hwan-min Park, Jun-hee Jang, Keun-dea Kim, and Hyung-jin Choi
School of Information and Communications Engineering, Sungkyunkwan University, Suwon, Korea
DMC R&D Center, SAMSUNG Electronics, CO., LTD, Korea
Email: hwanmin.park@samsung.com, hellojjh@ece.skku.ac.kr, rootbig@chol.com, hjchoi@ece.skku.ac.kr

Abstract—In this paper, we propose an enhanced decoding method to improve the performance of the quasi orthogonal (QO)-space frequency block coding (SFBC) in frequency selective fading channel environment. Generally, QO-SFBC obtains full diversity gain with more than two transmit antennas by using the constellation rotation in flat fading channel. However, QO-SFBC provides less diversity gain in frequency selective fading channel, because the discrepancy of channel frequency responses (CFRs) at adjacent subcarriers causes additive interferences. Although the conventional method using the simple averaging scheme for all CFRs at adjacent subcarriers can be effective for mitigating interferences, it is not quite robust to variation of CFRs, especially in high Doppler frequency environments. Therefore, to achieve better diversity gain in frequency selective fading channel environment, the selective averaged QO-SFBC decoding method based on mathematical analysis considering each CFR of elements in QO-SFBC encoding block is proposed. By using computer simulation, we show that the proposed method can provide better performance compared with the conventional methods and verify that the proposed method is attractive and suitable for implementation with stable operation when frequency selectivity is high.

Index Terms—QO-SFBC, CFR, LTE, MIMO, MMSE, ZF

I. INTRODUCTION

The 3rd generation partnership project (3GPP) has launched the study item of evolved-universal terrestrial radio access (E-UTRA), which is aiming for the long term evolution-advanced (LTE-A). In E-UTRA (4G), the goal of peak data rate is up to 1 Gbps for the downlink. Additionally, mobile broadband wireless access (MBWA) such as LTE-A is to operate reliably in different types of environments: macro, micro, and pico-cellular; urban, suburban, and rural; indoor and outdoor. In other words, the LTE-A is supposed to have better quality and coverage, be more power- and bandwidth-efficient, and be deployed in diverse environments [1]-[3].

In most scattering environments, antenna diversity is a practical, effective and, hence, a widely applied technique for improving the quality of the received signal. The classical approach is to use multiple antennas at the receiver and perform combining or selection and switching in order to improve the quality of the received signal. The major problem with using the receive diversity approach is the cost, size, and power consumption of the user equipment (UE). As a result, diversity techniques have almost exclusively been applied to base stations to improve their reception quality. It is therefore more economical to add equipment to base stations rather than the UEs. For this reason, diversity schemes are also very attractive. Therefore, transmit diversity method with multiple-input multiple-output (MIMO) is indispensable for higher data rate, and 3GPP LTE-Advanced employs multi-antenna technology combined with cooperative relaying system [3].

Recently, some interesting approaches for MIMO have been suggested. In 1998, Alamouti designed space time block coding (STBC)/SFBC, which are simple transmit diversity techniques for systems having two transmit antennas. If STBC/SFBC is orthogonal STBC/SFBC (OSTBC/OSFBC), this method provides full diversity and requires simple linear operations at both transmission and reception side. Unfortunately, OSTBC/OSFBC suffers from a reduced code rate when complex signal constellations and more than two transmit antennas are used. Therefore, improved STBC/SFBC design, that can achieve full transmit diversity and a higher code rate, is needed with using more than two antennas. To this end, QO-STBC/SFBC with constellation rotation has been proposed, that is able to achieve full code rate in flat fading channel environment [3]-[7].
However, the performance of QO-SFBC is degraded by inter-carrier interference (ICI) that is caused by frequency selective fading channel in mobile communications. This is because the QO-SFBC scheme disregards frequency selectivity of the channel by assuming that CFRs of adjacent subcarriers in coding block are the same. To solve this problem, we propose an efficient channel estimation and symbol decoding method, which can overcome the difference between CFRs of the adjacent subcarriers in coding block by applying the selective average scheme. The proposed method can be applied to any existing QO-SFBC scheme. In this paper, we consider QO-SFBC with ABBA code which is used in more than two transmit antennas in order to increase the data transmission rate in the downlink without much increase in system complexity [8], [9].

This paper is organized as follows. In Section II, the LTE specification about MIMO which is considered in this paper is presented. In Section III, STBC/SFBC scheme for two transmit antennas is described. In Section IV, QO-SFBC techniques with constellation rotation and full CFR method which achieve full diversity in four transmit antennas are described and we analyzed problems of the conventional QO-SFBC schemes in frequency selective fading channel. In Section V, we proposed an effective decoding scheme based on mathematical analysis considering each CFR of an element in QO-SFBC encoding block. The results of performance comparison are presented in Section VI and a conclusion is drawn in Section VII.

Throughout this paper, normal letters indicate scalar quantities and boldface fonts denote matrices and vectors, respectively. For any matrix \( M \), we write its conjugate transpose as \( M^\dagger \).

II. SYSTEM MODEL

LTE frames are 10 ms in duration and they are divided into 10 subframes with each subframe 1.0 ms long. Each subframe is further divided into two slots, each of 0.5 ms duration. Slots consist of either 6 or 7 OFDM symbols, depending on whether the normal or extended cyclic prefix (CP) is employed. The LTE physical layer (PHY) specification is designed to accommodate bandwidths from 1.25 MHz to 20 MHz OFDM was selected as the basic modulation scheme because of its robustness in the presence of severe multipath fading. In this paper, we consider OFDM system of 1024 FFT size allocated to 10 MHz bandwidth. Basic parameters are summarized in Table I [10].

LTE considers SFBC for downlink (DL) transmit diversity method, and Fig. 1 shows the principle of the downlink reference signal structure for 4 multi-antennas of 3GPP LTE MIMO transmission. This structure is adapted to the SFBC method. Specific predefined resource elements in the time-frequency domain are carrying the reference signal sequence. As shown in Fig. 1, reference signals are transmitted on equally spaced subcarriers within the first and third from the last OFDM symbol of each slot. A receiver must get an accurate channel impulse response (CIR) from each transmit antenna. Therefore, when a reference signal is transmitted from an antenna port, other antenna ports in the cell are idle. The reference signals are sent on every sixth subcarrier. CIR estimates for subcarriers that do not have the reference signals are computed via interpolation.

III. STBC/SFBC SCHEME

The STBC/SFBC scheme is the simplest type of spatial codes that exploit the diversity offered in systems with several transmit antenna. In 1998, Alamouti designed a simple transmission diversity technique for systems with two transmit antennas [4]. This method provides full diversity and requires simple linear operations at both transmission and reception side [3], [4].

<table>
<thead>
<tr>
<th>Transmission BW (MHz)</th>
<th>1.4</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subframe duration</td>
<td>1.0 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>15 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subframe frequency (MHz)</td>
<td>1.92</td>
<td>3.84</td>
<td>7.68</td>
<td>15.36</td>
<td>23.04</td>
<td>30.72</td>
</tr>
<tr>
<td>FFT Size</td>
<td>128</td>
<td>256</td>
<td>512</td>
<td>1024</td>
<td>1536</td>
<td>2048</td>
</tr>
<tr>
<td>Number of occupied subcarrier</td>
<td>73</td>
<td>181</td>
<td>301</td>
<td>601</td>
<td>901</td>
<td>1201</td>
</tr>
</tbody>
</table>

Table I. PARAMETERS FOR DOWNLINK TRANSMISSION SCHEME
In a system with two transmit antennas and one receive antenna, the optimal STBC/SFBC codeword \( \mathbf{S} \) is

\[
\mathbf{S} = \begin{bmatrix} x_1 & x_2 \\ x_2 & x_1 \end{bmatrix}
\]

(1)

where \( x_1 \) and \( x_2 \) are transmitted symbols and row of \( \mathbf{S} \) represents either a time instance for STBC or frequency tone signal for SFBC and column of \( \mathbf{S} \) represents an antenna port index. Assuming a flat fading channel, the 2×1 vector of the received signal \( \mathbf{r} \) is

\[
\mathbf{r} = \mathbf{S} \mathbf{h} + \mathbf{n}
\]

(2)

where \( \mathbf{h} \) is 2×1 vector of CFR and \( h_i \) is the CFR from the \( i \)-th transmit antenna \((i = 1, 2) \) to the receiver. \( \mathbf{n} \) is 2×1 vector of additive white Gaussian noise (AWGN).

Assuming the channel is not varying over the size of the codeword, the received signal equation for the STBC/SFBC codeword in (2) may be rewritten in terms of an equivalent signal model as

\[
\mathbf{r}^{\prime} = \mathbf{H} \mathbf{x} + \mathbf{n}
\]

(3)

where the received signal during the second symbol period is conjugated, and \( \mathbf{x} \) is 2×1 vector of the transmitted signal and the equivalent channel matrix \( \mathbf{H} \) is

\[
\mathbf{H} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}
\]

(4)

If \( \mathbf{H} \) were orthogonal, i.e., \( \mathbf{H}^H \mathbf{H} \) were a diagonal matrix, this code could be optimally detected by left-multiplying the receive signal vector in (3) by \( \mathbf{H}^H \) (what is known as the matched filtering approach). The received signal is simply decoded using \( \mathbf{H}^H \) and decoding process is represented as

\[
\hat{\mathbf{x}} = \mathbf{H}^H \mathbf{r} = \mathbf{H}^H \mathbf{H} \mathbf{x} + \mathbf{H}^H \mathbf{n}
\]

(5)

\[
\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} h_1 r_1 + h_2 r_2 \\ h_2^* r_1 - h_1^* r_2 \end{bmatrix} = \begin{bmatrix} |h_1|^2 + |h_2|^2 & 0 \\ 0 & |h_1|^2 + |h_2|^2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} h_1^* r_1 - h_2^* r_2 \\ h_2 r_1 - h_1 r_2 \end{bmatrix} \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}
\]

(5)

where \( \hat{\mathbf{x}} \) is 2×1 vector of the estimated symbol from transmitted signal and \(|h_1|^2 + |h_2|^2\) shows a diversity gain of the STBC/SFBC scheme.

IV. QO-SFBC TECHNIQUES

A. QO-SFBC with Constellation Rotation

In the previous section, we investigated the STBC/SFBC schemes. It is known, however, that similar complex orthogonal code design does not exist for more than two transmit antennas [8]; therefore, STBC/SFBC schemes for higher number of antennas either have lower code rates or are based on QO codes. As an example among 4×4 schemes with symbol rate \( R_s = 1 \) for \( N_t = 4 \) antennas and \( N_R = 4 \) symbol periods or \( N_t = 4 \) frequency tones, we consider the following 4×4 QO-STBC/SFBC code matrix, especially called ABBA code, which is information-optimal, and could be constructed to perform well at high SNR as well [4][11].

\[
\mathbf{S} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ -x_4 & x_3 & -x_2 & x_1 \\ -x_3 & x_4 & x_1 & x_2 \end{bmatrix} = \begin{bmatrix} S_A & S_B \\ S_B^\dagger & S_A^\dagger \end{bmatrix}
\]

(6)

However, ABBA code suffers from loss of diversity gain due to the coupling between symbols in the codewords. In order to overcome its non-orthogonality which decreases the signal to interference plus noise ratio (SINR) by inducing interference between the symbols, QO-STBC/SFBC techniques can be combined with maximum likelihood (ML) or iterative cancellation scheme using a least minimum mean square error (LMMSE) algorithm but the complexity of the receiver design is significantly increased. Therefore, other ways including constellation expansion, symbol rotation and angle feedback are proposed to improve the diversity gain [11]-[19].

Ref. [14] considers the following 4×4 QO-SFBC code matrix similar to the ABBA code with constellation rotation. Note that four symbols in (7) are multiplied by \( g \) which is equivalent to rotation by an angle \( \theta \), where \( g = e^{j\theta} \).

\[
\mathbf{S} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ gx_3 & x_4 & x_1 & x_2 \\ -x_4^* & g^* x_3^* & -g^* x_2^* & x_1^* \end{bmatrix}
\]

(7)

In flat fading channel, the 4×1 vector of the received signal \( \mathbf{r} \) is

\[
\mathbf{r} = \mathbf{S} \mathbf{h} + \mathbf{n}
\]

(8)

\[
\begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ gx_3 & x_4 & x_1 & x_2 \\ -x_4^* & g^* x_3^* & -g^* x_2^* & x_1^* \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{bmatrix}
\]

The assumed channel is not varying over the size of the codeword in (8), the received signal is expressed as \( \mathbf{H} \mathbf{x} + \mathbf{n} \) using the equivalent channel matrix that can be described as
which can be described as consisting of CFRs which are expressed as number. In [14], a scheme with new QO-SFBC codeword can be orthogonalized and can become nearly zero when the precoding constant \( g \) is applied. We see in (10) that \( \delta = 0 \) when \( g = e^{i\theta} \) and \( \theta = 2\pi \times \angle(\alpha) \), where \( \angle(\cdot) \) denotes the argument of a complex number.

\[
\delta = \alpha - g^* \alpha^* , \quad \text{where} \quad \alpha = h_k^* h_{k+1} + h_{k+2}^* h_{k+3}^* \quad (11)
\]

With full information of such angles by feedback, this new OQ-SFBC codeword can be orthogonalized and can achieve the full diversity. In [14], a scheme with \( \theta = \pi/2 \) was shown to give the best open-loop performance.

However, the diversity performance of OQ-SFBC with constellation rotation is degraded due to the frequency selectivity of CFR because the CFRs of SFBC are not flat in the practical channel [11]. So the channel vector at (8) must be represented as a matrix instead of a vector. The element of the practical channel matrix is given by

\[
h'_k = [h_k(k) \ h_{k+1}(k) \ h_{k+2}(k) \ h_{k+3}(k)] \quad (12)
\]

where \( k \) is subcarrier index, and \( h'_k \) is defined as consisting of CFRs \( h_k(k) \) for 4 consecutive subcarriers in OQ-SFBC codeword. Finally, the channel vector in (8) can be modified by using coefficients \( a_j, b_j, c_j, \) and \( d_j \) as, which can be described as

\[
h' = \begin{bmatrix}
h'_1 \\
h'_2 \\
h'_3 \\
h'_4
\end{bmatrix} = \begin{bmatrix}
a_1 h_1 & a_2 h_1 & a_3 h_1 & a_4 h_1 \\
b_1 h_2 & b_2 h_2 & b_3 h_2 & b_4 h_2 \\
c_1 h_3 & c_2 h_3 & c_3 h_3 & c_4 h_3 \\
d_1 h_4 & d_2 h_4 & d_3 h_4 & d_4 h_4
\end{bmatrix}
\]

\[
F' = H' \mathbf{H} = \begin{bmatrix}
f_{11} & f_{12} & f_{13} & f_{14} \\
f_{21} & f_{22} & f_{23} & f_{24} \\
f_{31} & f_{32} & f_{33} & f_{34} \\
f_{41} & f_{42} & f_{43} & f_{44}
\end{bmatrix}
\]

\[
F' = H' \mathbf{H}' = \begin{bmatrix}
h'_1 \\
h'_2 \\
h'_3 \\
h'_4
\end{bmatrix} = \begin{bmatrix}
h_1 & h_2 & h_3 & h_4 \\
h_1^* & h_2^* & h_3^* & h_4^* \\
h_1 g & h_2^* & h_3 & h_4 \\
h_1 g & h_2^* & h_3 & h_4 \\
h_1 g & h_2^* & h_3 & h_4 \\
h_1 g & h_2^* & h_3 & h_4 \\
h_1 g & h_2^* & h_3 & h_4 \\
h_1 g & h_2^* & h_3 & h_4
\end{bmatrix}
\]

\[
F' = \begin{bmatrix}
f_{11}' & f_{12}' & f_{13}' & f_{14}' \\
f_{21}' & f_{22}' & f_{23}' & f_{24}' \\
f_{31}' & f_{32}' & f_{33}' & f_{34}' \\
f_{41}' & f_{42}' & f_{43}' & f_{44}'
\end{bmatrix}
\]

\[
F' = \begin{bmatrix}
af & bf & cf & df \\
a^* h_1 & b^* h_2 & c^* h_3 & d^* h_4 \\
a^* h_1 + h_2 h_4 & b^* h_2 + h_3 h_4 & c^* h_3 + h_4 h_4 & d^* h_4 + h_1 h_4
\end{bmatrix}
\]

where \( a_j, b_j, c_j, \) and \( d_j \) are represented as

\[
\begin{align*}
a_j &= h_1(k+j)/h_1(k) \\
b_j &= h_2(k+j)/h_2(k) \\
c_j &= h_3(k+j)/h_3(k) \\
d_j &= h_4(k+j)/h_4(k)
\end{align*}
\]

For simplicity of expression, \( a_0, b_0, c_0, \) and \( d_0 \) are omitted below from here, because they are all 1.

By considering the variation of channel over the size of codeword, the matrix \( F' \) can be expressed as

\[
\begin{align*}
f_{11}' &= |h_1|^2 + l h_1^* h_1 + c_1 |h_1|^2 + d_1^* |h_1|^2 \\
f_{12}' &= (1-a_1) h_1 h_2 + g(d_2 - c_2) h_1 h_4 \\
f_{13}' &= h_1 h_2 + h_1 h_3 + g a_2 h_4 h_1 + g b_2 h_4 h_2 \\
f_{14}' &= (1-a_3) h_1 h_4 + (b_3 - c_3) h_1 h_3
\end{align*}
\]

\[
\begin{align*}
f_{22}' &= |h_2|^2 + |h_2|^2 + c_2^* |h_2|^2 + d_2^* |h_2|^2 \\
f_{23}' &= (1-b_1) h_2 h_3 + g(c_3 - d_3) h_2 h_4 \\
f_{24}' &= g a_1 h_2 h_1 + g b_1 h_2 h_4 + c_1 h_2 h_3 + h_2 h_4
\end{align*}
\]

\[
\begin{align*}
f_{33}' &= |h_3|^2 + |h_3|^2 + c_3^* |h_3|^2 + d_3^* |h_3|^2 \\
f_{34}' &= (1-c_1) h_3 h_4 + g(b_3 - a_3) h_3 h_2 \\
f_{44}' &= a_1^* |h_4|^2 + b_2^* |h_4|^2 + c_4^* |h_4|^2 + d_4^* |h_4|^2
\end{align*}
\]

In (15), the diagonal elements of the matrix \( F' \) indicate the diversity of MIMO system. If the MIMO system has full diversity, the matrix \( F' \) is diagonal matrix and off-diagonal elements which mean co-antenna interference become nearly zero.

However, in practical channel environments with frequency selectivity, the coefficients \( a_j, b_j, c_j, \) and \( d_j \) are varied and the additional interferences between antennas are generated when we decode using only some CFR such as \( h_1, h_2, h_3, \) and \( h_4 \) in SFBC codeword. Even if...
we use the constellation rotation $g$, $f_1^r$, $f_2^r$, $f_4^r$, and $f_2^r$ are not zero. Therefore, the QO-SFBC system in practical channel needs a modified QO-SFBC decoding method considering the frequency selectivity of CFR.

**B. QO-SFBC with Conventional CFR**

**Averaging method**

In order to mitigate interferences which are generated by the difference between the decoding matrix $H^D$ of QO-SFBC and the CFR of practical channel $H^E$, the decoding matrix by applying averaging method to each QO-SFBC decoding block is considered [20].

A decoding matrix of the QO-SFBC with CFR averaging method for equalization can be expressed as

$$\bar{F}^D = \left[ \begin{array}{cccc} \bar{a} h_i^* & \bar{b} h_i^* & \bar{c} h_i^* & \bar{d} h_i^* \\ \bar{b} h_i^* & -\bar{a} h_i^* & \bar{d} h_i^* & -\bar{c} h_i^* \\ \bar{c} h_i^* & \bar{d} h_i^* & \bar{a} h_i^* & \bar{b} h_i^* \\ \bar{d} h_i^* & -\bar{c} h_i^* & \bar{b} h_i^* & -\bar{a} h_i^* \end{array} \right]$$

where the averaged coefficients $\bar{a}$, $\bar{b}$, $\bar{c}$, and $\bar{d}$ for each CFR between the $i$th transmit antenna and the received antenna are determined as

$$\bar{a} = \frac{1}{N_p} \left( \sum_{j=0}^{N_p-1} a_j \right), \quad \bar{b} = \frac{1}{N_p} \left( \sum_{j=0}^{N_p-1} b_j \right),$$

$$\bar{c} = \frac{1}{N_p} \left( \sum_{j=0}^{N_p-1} c_j \right), \quad \bar{d} = \frac{1}{N_p} \left( \sum_{j=0}^{N_p-1} d_j \right)$$

(21)

where $N_p$ is the number of consecutive frequency tones in QO-SFBC. For QO-SFBC with decoding matrix $\bar{F}^D$, the averaged matrix $\bar{F}^D$ can be expressed as

$$\bar{F}^D = H^D \bar{F}^E$$

(22)

where elements of $\bar{F}^D$ are represented as

$$\bar{F}_{ij}^D = \left[ \begin{array}{cccc} \bar{a} h_i^* & \bar{b} h_i^* & \bar{c} h_i^* & \bar{d} h_i^* \\ \bar{b} h_i^* & -\bar{a} h_i^* & \bar{d} h_i^* & -\bar{c} h_i^* \\ \bar{c} h_i^* & \bar{d} h_i^* & \bar{a} h_i^* & \bar{b} h_i^* \\ \bar{d} h_i^* & -\bar{c} h_i^* & \bar{b} h_i^* & -\bar{a} h_i^* \end{array} \right]$$

(23)

Compared with that of the QO-SFBC with constellation rotation method, new cross-terms are added to the co-antenna interference elements of $\bar{F}^D$. For example, the term, $(d_j - c_{j'})$, of $f_{j2}^r$ is changed into $(\bar{c} d_j - c_{j'} \bar{d})$ of $\bar{f}_{j2}^r$. $c_j$ and $d_j$ are determined by the property of statistically independent channel. And $c_j$ has little difference with $\bar{c}$. Therefore, the following condition of formula $Pr(\bar{c} d_j - c_{j'} \bar{d} = 0) > Pr(d_j - c_{j'} = 0)$ is established.

Although the conventional method using the simple averaging scheme for each CFR at adjacent subcarriers in coding block can be effective for mitigating interference, it is not quite robust to variation of CFRs in coding block and satisfy reliable performance anymore, especially in high Doppler frequency environment.

**V. THE PROPOSED METHODS**

In this section, we present an enhanced decoding method to improve the performance and achieve better diversity gain in not only frequency selective fading channel environment but also high Doppler frequency environments.

**A. The Effect of Time-Varying Channel**

In the previous section, the researches for QO-STBC/SFBC schemes have been focused on the receiver design over the single path flat fading channel or time-invariant frequency selective channel. However, in practical wireless mobile communications, channel variations arise mainly due to not only multipath delay but also Doppler frequency shift that is caused by mobile movement. In such condition, mobility causes the channel to be fast time-varying channel, wherein the time-stationary channel assumption no longer holds. Moreover, the channel variation owing to Doppler frequency shift during one OFDM symbol destroys the orthogonality among the subcarriers and leads to the ICI. Therefore, the OFDM system performance degradation is caused by Doppler frequency shift [21].

Generally, in the absence of ICI, the channel matrix of each CFR between the $i$th transmit antenna and the received antenna, in the frequency domain, is diagonal. Hence, by using (12), we can describe the channel matrix as a vector. However, in the presence of ICI, it makes the
channel matrix full and usually is formulated in terms of ICI coefficient matrix with each CFR component at adjacent subcarriers. Assuming that the number of subcarriers is sufficiently large, we may invoke the central limit theorem and model the residual ICI as Gaussian noise. Also, in case Jakes’ model is assumed for the Doppler spectrum, the well-known formula for the ICI power caused by Doppler is obtained as

\[ P_{IC1} = \frac{\sigma^2}{6} f_d^2 \]  

(27)

where \( f_d = f_0 / \Delta f \) is the normalized Doppler, i.e., the actual Doppler \( f_0 \) divided by the subcarrier spacing \( \Delta f \) [22][23].

The ICI can be easily reduced by increasing the subcarrier spacing, i.e., making OFDM symbol shorter. However, since the CP in OFDM systems needs to be long enough to guarantee that no inter-symbol interference (ISI) is experienced, the improved Doppler performance comes at a cost of increased overhead [22]. Furthermore, according LTE specification [10], it is not appropriate because the subcarrier spacing is fixed by 15 kHz for normal subframe.

Therefore, the QO-SFBC system in practical channel needs an enhanced QO-SFBC decoding method considering not only the frequency selectivity of CFR but also ICI effect caused by Doppler frequency shift to improve the performance and achieve better diversity gain by maximizing the interference reduction effect.

**B. QO-SFBC with Selective CFR Averaging method**

The proposed method is composed through statistical calculation of CFRs and can be applied to most QO-SFBC code with four transmit antennas. The enhanced decoding matrix for equalization is expressed as

\[
\bar{H}' = \begin{bmatrix}
\bar{a}_1^* h_1^* & \bar{b}_1 h_1 & \bar{c}_1^* h_1^* & \bar{d}_1 h_1 \\
\bar{b}_2 h_2 & \bar{a}_2^* h_2^* & \bar{d}_2^* h_2 & \bar{c}_2^* h_2^* \\
\bar{c}_3^* h_3 & \bar{d}_3^* h_3 & \bar{a}_3^* h_3^* & \bar{b}_3 h_3 \\
\bar{d}_4 h_4 & \bar{c}_4^* h_4 & \bar{b}_4^* h_4 & \bar{a}_4^* h_4^*
\end{bmatrix}
\]

(28)

where the modified selective averaged coefficients \( \bar{a}_j, \bar{b}_j, \bar{c}_j, \) and \( \bar{d}_j \) for each CFR between the \( j \)th transmit antenna and the received antenna are determined as

\[
\begin{align*}
\bar{a}_0 &= a_0 + a_1 + a_2 + a_3 \\
\bar{a}_1 &= a_0 + a_1 + a_2 + a_3 \\
\bar{a}_2 &= a_0 + a_1 + a_2 + a_3 \\
\bar{a}_3 &= a_0 + a_1 + a_2 + a_3 \\
\bar{b}_0 &= a_0 + a_1 + a_2 + a_3 \\
\bar{b}_1 &= a_0 + a_1 + a_2 + a_3 \\
\bar{b}_2 &= a_0 + a_1 + a_2 + a_3 \\
\bar{b}_3 &= a_0 + a_1 + a_2 + a_3 \\
\bar{c}_0 &= a_0 + a_1 + a_2 + a_3 \\
\bar{c}_1 &= a_0 + a_1 + a_2 + a_3 \\
\bar{c}_2 &= a_0 + a_1 + a_2 + a_3 \\
\bar{c}_3 &= a_0 + a_1 + a_2 + a_3 \\
\bar{d}_0 &= a_0 + a_1 + a_2 + a_3 \\
\bar{d}_1 &= a_0 + a_1 + a_2 + a_3 \\
\bar{d}_2 &= a_0 + a_1 + a_2 + a_3 \\
\bar{d}_3 &= a_0 + a_1 + a_2 + a_3
\end{align*}
\]

(29)

For QO-SFBC with decoding matrix \( \bar{H}' \), the matrix \( \bar{F}' \) is can be expressed as

\[
\bar{F}' = \bar{H}' H'
\]

\[
\begin{bmatrix}
\bar{a}_1^* h_1^* & \bar{b}_1 h_1 & \bar{c}_1^* h_1^* & \bar{d}_1 h_1 \\
\bar{b}_2 h_2 & \bar{a}_2^* h_2^* & \bar{d}_2^* h_2 & \bar{c}_2^* h_2^* \\
\bar{c}_3^* h_3 & \bar{d}_3^* h_3 & \bar{a}_3^* h_3^* & \bar{b}_3 h_3 \\
\bar{d}_4 h_4 & \bar{c}_4^* h_4 & \bar{b}_4^* h_4 & \bar{a}_4^* h_4^*
\end{bmatrix}
\]

(30)

where elements of \( \bar{F}' \) matrix are represented as

\[
\bar{F}'_1 = \begin{bmatrix}
\bar{a}_1^* h_1^* & \bar{b}_1 h_1 & \bar{c}_1^* h_1^* & \bar{d}_1 h_1 \\
\bar{b}_2 h_2 & \bar{a}_2^* h_2^* & \bar{d}_2^* h_2 & \bar{c}_2^* h_2^* \\
\bar{c}_3^* h_3 & \bar{d}_3^* h_3 & \bar{a}_3^* h_3^* & \bar{b}_3 h_3 \\
\bar{d}_4 h_4 & \bar{c}_4^* h_4 & \bar{b}_4^* h_4 & \bar{a}_4^* h_4^*
\end{bmatrix}
\]

(31)

\[
\bar{F}'_2 = \begin{bmatrix}
\bar{a}_1^* h_1^* & \bar{b}_1 h_1 & \bar{c}_1^* h_1^* & \bar{d}_1 h_1 \\
\bar{b}_2 h_2 & \bar{a}_2^* h_2^* & \bar{d}_2^* h_2 & \bar{c}_2^* h_2^* \\
\bar{c}_3^* h_3 & \bar{d}_3^* h_3 & \bar{a}_3^* h_3^* & \bar{b}_3 h_3 \\
\bar{d}_4 h_4 & \bar{c}_4^* h_4 & \bar{b}_4^* h_4 & \bar{a}_4^* h_4^*
\end{bmatrix}
\]

(32)

\[
\bar{F}'_3 = \begin{bmatrix}
\bar{a}_1^* h_1^* & \bar{b}_1 h_1 & \bar{c}_1^* h_1^* & \bar{d}_1 h_1 \\
\bar{b}_2 h_2 & \bar{a}_2^* h_2^* & \bar{d}_2^* h_2 & \bar{c}_2^* h_2^* \\
\bar{c}_3^* h_3 & \bar{d}_3^* h_3 & \bar{a}_3^* h_3^* & \bar{b}_3 h_3 \\
\bar{d}_4 h_4 & \bar{c}_4^* h_4 & \bar{b}_4^* h_4 & \bar{a}_4^* h_4^*
\end{bmatrix}
\]

(33)

\[
\bar{F}'_4 = \begin{bmatrix}
\bar{a}_1^* h_1^* & \bar{b}_1 h_1 & \bar{c}_1^* h_1^* & \bar{d}_1 h_1 \\
\bar{b}_2 h_2 & \bar{a}_2^* h_2^* & \bar{d}_2^* h_2 & \bar{c}_2^* h_2^* \\
\bar{c}_3^* h_3 & \bar{d}_3^* h_3 & \bar{a}_3^* h_3^* & \bar{b}_3 h_3 \\
\bar{d}_4 h_4 & \bar{c}_4^* h_4 & \bar{b}_4^* h_4 & \bar{a}_4^* h_4^*
\end{bmatrix}
\]

(34)

Compared with the QO-SFBC using CFR averaging method, the proposed method adopts the selective average-term by eliminating the unnecessary factors from the full average-term in (21). For example, \( \bar{a}_0 \) is included in \( \bar{a}_0 | h_1^2 | 0 \) of \( f_{11}^* \), \( \bar{a}_0^* - a_1^* b_0 h_1 h_2^* \) of \( f_{12}^* \), and \( \bar{a}_0^* - a_1^* b_0 h_1 h_2^* \) of \( f_{14}^* \). If \( \bar{a}_0 \) is close to \( a, a_1 \), and \( a_3 \), then \( \bar{a}_0 | h_1^2 | 0 \) \( f_{11}^* \), \( \bar{a}_0^* - a_1^* b_0 h_1 h_2^* \) of \( f_{12}^* \), and \( \bar{a}_0^* - a_1^* b_0 h_1 h_2^* \) of \( f_{14}^* \) are established. In this way, \( \bar{a}_1, \bar{b}_1, \bar{c}_1, \) and \( \bar{d}_1 \) can be
determined by the property of statistically independent channels. Therefore, interference power is decreased, and so overall diversity gain is increased.

Fig. 2 shows mean square error (MSE) performance comparison between the conventional methods and the proposed method to minimize the interference caused by Doppler in time-varying channel. MSE is defined as

\[ \text{MSE}(a_j) = \mathbb{E}[|a_j - a_j|^2], \text{ using conventional w/o CFR avg.} \]

\[ \text{MSE}(\tilde{a}) = \mathbb{E}[|a_i - \tilde{a}|^2], \text{ using conventional CFR avg.} \]

\[ \text{MSE}(\tilde{a}_j) = \mathbb{E}[|a_i - \tilde{a}_j|^2], \text{ using proposed CFR avg.} \]

(35)

where the calculated MSE is proportional to the interference power. From Fig. 2, we can see that interference power increases with increasing Doppler frequency and we can expect the decoding performance to depend on Doppler effects. Also, we can find that the performances of conventional methods are seriously degraded due to ICI in high mobile speed environment. On the other hand, in case of the proposed method, it can be closer to considered coefficient than other schemes by minimizing the ICI component.

VI. SIMULATION RESULT

In this section, we present the simulation results which are performed under 4Tx-1Rx MIMO system based on 3GPP LTE specification [10]. The simulation parameters are given in Table II.

Convolutional encoder has code rate 1/2 and constraint length 7, and the number of quantization bits is 4, i.e. \( q = 4 \), for soft decision. We consider 1024-FFT mode. Employed channel profile models are COST207 Typical Urban (TU)-6 and ITU Pedestrian A (PEDA). For the MIMO receiver algorithm, the minimum mean square error (MMSE) and zero forcing (ZF) are considered in this section.

Fig. 4 shows coded BER performance comparisons between the proposed method and the conventional methods in PEDA channel without Doppler frequency. From the result, we can see that there is no performance differences between the proposed and the conventional methods in PEDA channel because the PEDA channel is flat fading channel. Therefore, we can verify that both the proposed method and the conventional methods can achieve full diversity if full CSI is provided in PEDA channel environment.

Fig. 5 and Fig. 6 show coded BER performance comparisons between the proposed method and the conventional methods in COST207 TU6 channel without and with Doppler frequency, respectively. Even though we assume that full CSI is provided, the performance of QO-SFBC is degraded in COST207 TU6 channel because of discrepancy between CFRs at adjacent subcarriers. However, we can see that the proposed method has better performance than the conventional methods, especially in high Doppler frequency environments. Also a MMSE receiver shows better performance than ZF receiver because MMSE receiver considering noise variance can suppress interference more effectively. From these results, we can verify that the proposed method can get more

<table>
<thead>
<tr>
<th>TABLE II. SIMULATION PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameters</strong></td>
</tr>
<tr>
<td>Carrier frequency</td>
</tr>
<tr>
<td>Bandwidth</td>
</tr>
<tr>
<td>Sampling frequency</td>
</tr>
<tr>
<td>Number of subcarrier (K)</td>
</tr>
<tr>
<td>Number of occupied subcarrier</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
</tr>
<tr>
<td>Mobile speed</td>
</tr>
<tr>
<td>Data modulation type</td>
</tr>
<tr>
<td>Channel model</td>
</tr>
</tbody>
</table>

**Figure 2.** MSE performance comparisons for various mobile speeds

**Figure 3.** Probability Distribution Function of Interference Power
reliable performance than conventional methods when mobile channel environment causes large discrepancy of CFRs at adjacent subcarriers.

VII. CONCLUSION

In this paper, we proposed an enhanced QO-SFBC decoding. The proposed method can reduce co-antenna interference effectively in frequency selective fading channel environment by applying modified CFR averaging method. The performance results show that the proposed method has better performance than the conventional methods, especially in mobile channel environment which causes large discrepancy of CFRs at adjacent subcarriers. Consequently, the proposed method is attractive and suitable for implementation of 4G system such as LTE/LTE-A with stable operation when frequency selectivity is high.

ACKNOWLEDGMENT

“This research was supported by the MKE (The Ministry of Knowledge Economy), Korea, under the ITRC (Information Technology Research Center) support program supervised by the NIPA (National IT Industry Promotion Agency)” (NIPA-2010-C1090-1011-0005)

REFERENCES


Young-il Min received the B.S.E.E. degree in the school of Information and communication Engineering from Sungkyunkwan University, Korea in 2009. Since 2009, he has been working towards the M.S.E.E. degree in Mobile System Engineering at Sungkyunkwan University. His research field includes mobile communication system engineering, cooperative communication system, OFDM, MIMO, and signal processing for synchronization.

Hwan-min Park received the B.S.E.E. degree in the school of Information and communication Engineering and M.S.E.E. degree in Mobile System Engineering from SungKyunKwan University, Korea in 2008 and 2010 respectively. Since 2010, he worked DMC R&D Center, Modem H/W Lab., Samsung Electronics Co. Ltd., Suwon, Korea, as an Engineer. His research field includes mobile communication system engineering, cooperative communication system, OFDM, MIMO, and signal processing for synchronization.

Jun-hee Jang received the B.S.E.E. degree in the school of Electrical and Computer Engineering and M.S.E.E. degree in Mobile System Engineering from SungKyunKwan University, Korea in 2007 and 2009 respectively. Since 2009, he has been working towards the Ph.D. degree in Mobile System Engineering at SungKyunKwan University. His research field includes mobile communication system engineering, adaptive modulation & coding, CDMA, OFDM, MIMO, and signal processing for synchronization.

Keun-dae Kim received the B.S.E.E and M.S.E.E degrees in the school of Electronic Engineering from the Sungkyunkwan University, Korea, in 1994 and 1996, respectively. From 1996 to 2001, he was a assistant research engineer of Central Research Center of Dacom (now LGT) and researched the CDMA, PCS, WLL and IMT-2000 system. From 2001, he is a senior officer of KEIT (Korea Evaluation Institute of Industrial Technology) in South Korea and is managing National R&D researches of next generation mobile communication (3.9G, 4G, B4G, etc). His research interests JGPP LTE Modem, WiBro platform technologies, multi-hop relay and etc.

Hyung-jin Choi received the B.S.E.E. degree from Seoul National University, Korea in 1974, the M.S.E.E degree from the Korea Advanced Institute of Science, Korea in 1976, and Ph. D degree in Electrical Engineering (communications major) from the University of Southern California, Los Angeles in 1982. From 1976 to 1979, he worked for the Central Research Lab. of the Gold Star Co., Seoul, Korea, as a research engineer. From 1983 to 1989, he worked for the Lincom Corp., Los Angeles, California. Since March 1989, he has been a faculty member with the Department of Electronics Engineering (now, School of Information and Communication Engineering), SungKyunKwan University, Korea and currently holds the rank of Professor. His main field of interests includes mobile radio engineering, satellite communications, communication system engineering, and digital modulation/demodulation with associated signal processing and synchronization.