Combining Beamforming With Space-time Block Coding in Massive MIMO System

Minjie Li*, Jinlong Zhan, Man Wang & Shuai Zhang
School of Communications and Information Engineering, Xi’an University of Posts and Telecommunications, Shanxi, Xi’an, China

ABSTRACT: An eigen-beamforming combined space-time block coding technique is proposed in massive MIMO systems. At the transmitter, utilize massive MIMO to form orthogonal beams, and then space-time block code is transmitted on these beams. At the receiver, space-time block code is decoded according to traditional decoding algorithm. The proposed technique can obtain diversity gain and beamforming gain simultaneously. Simulation results confirm the validity of the proposed technique.

Keywords: massive MIMO; Space-time block coding (STBC); beamforming (BF)

1 INTRODUCTION

Multiple-input multiple-output (MIMO) techniques have been utilized in modern wireless networks to improve reliability and capacity. In recent years, with the rapid development of high data rate service, massive MIMO has aroused extensive concern and research, because it can greatly enhance the data transmission rate and simplify the required signal processing [1].

The most popular approaches in a MIMO system are space time block coding (STBC) and beamforming. STBC can obtain space diversity gain to improve reliability by deploying a diversity antenna system. Beamforming can get beamforming gain to improve coverage range and suppress the inter-cell interference by utilizing the beamforming antenna array [2].

In order to improve the performance of system employing STBC, beamforming may be combined with STBC to achieve both space diversity gain and beamforming gain [9]. In this paper, an eigen-beamforming combined space-time block coding technique is proposed in massive MIMO systems. At the transmitter, utilize massive antennas to form four orthogonal beams, and then four branch space-time block codes are transmitted on these beams. At the receiver, space-time block code is decoded according to traditional decoding algorithm. Therefore, the proposed technique can achieve diversity gain promised by conventional STBC as well as beamforming gain provided by eigen-beamforming.

The rest of the paper is organized as follows. First, the four-branch STBC system is briefed in section 2, then the proposed technique is detailed in section 3, and the optimal beamformer achieving both full diversity gain and beamforming gain is derived in this section. In section 4, simulations are conducted to evaluate the proposed technique. Finally the paper is concluded in section 5.

2 STBC

The STBC originally proposed by Alamouti [3] used two transmit antennas of complex orthogonal design to achieve full diversity gain. With the increasing number of transmit antennas, STBC are designed to achieve 1/2 of the maximum possible transmission rate for any number of transmit antennas [4]. In this paper, the system with four transmit antennas and one receive antenna is taken as an example to illustrate.

STBC with four transmit antennas and one receive antenna is shown in Figure 1, where \( s_1, s_2, s_3, s_4 \) are modulated signals. \( h_i, i=1, 2, 3, 4 \) are channel coefficients from the \( i \)th transmit antenna to receive antenna.

After QPSK modulation, the STBC encoder chose four modulated symbols as a group to obtain a space-time coding matrix [5-6].

*Corresponding author: 936995854@qq.com
\[
s = \begin{bmatrix}
s_1 & -s_2 & -s_3 & -s_4 & s_1' & -s_2' & -s_3' & -s_4'
s_2 & s_1 & s_4 & -s_3 & s_1' & s_4' & -s_3' & s_1'
s_3 & -s_4 & s_1 & s_2 & -s_3 & s_1' & s_2' & -s_3'
s_4 & s_3 & -s_2 & s_1 & s_4 & -s_3 & s_1' & s_2'
\end{bmatrix}
\] (1)

the output of encoder is transmitted from four transmit antennas during eight successive emission periods, (where \((\cdot)^*\) denotes complex conjugate).

Supposed channel fading coefficients are unchanged in eight periods. The received signals are expressed as

\[
R = HS + n = \begin{bmatrix} r_1, r_2, r_3, r_4, r_5, r_6, r_7, r_8 \end{bmatrix}^T \tag{2}
\]

Where

\[
H = \begin{bmatrix}
h_1 & h_2 & h_3 & h_4 \\
h_2 & -h_1 & h_4 & -h_3 \\
h_3 & h_4 & -h_2 & -h_1 \\
h_4 & -h_3 & h_1 & h_2 \\
h_1' & h_2' & h_3' & h_4' \\
h_2' & -h_1' & h_4' & -h_3' \\
h_3' & -h_4' & h_1' & h_2' \\
h_4' & h_3' & -h_2' & -h_1'
\end{bmatrix}
\] (3)

\[s = (s_1, s_2, s_3, s_4)^T\] denotes transmit signal vector, and \(n\) represents \(8 \times 1\) vector of i.i.d. \(CN(0, \sigma^2)\) additive complex Gaussian noise.

Assume all the modulated signals are equi-probable in constellation, and the combined signal can be expressed as

\[
S = (S_1, S_2, S_3, S_4) = H^n R_1 = H^n H s + H^n n
\]

\[
= \begin{bmatrix}
2\sum_{j=1}^{4}|h_j|^2 & 0 & 0 & 0 \\
0 & 2\sum_{j=1}^{4}|h_j|^2 & 0 & 0 \\
0 & 0 & 2\sum_{j=1}^{4}|h_j|^2 & 0 \\
0 & 0 & 0 & 2\sum_{j=1}^{4}|h_j|^2
\end{bmatrix} s + H^n n \tag{4}
\]

These combined signals are then sent to the maximum likelihood decoder [7]. For signal \(S\), the following decision criteria are used.

\[
\hat{s}_1 = \arg\min_{s_1 \in X} d^2(S, s_1)
\]

\[
\hat{s}_2 = \arg\min_{s_2 \in X} d^2(S, s_2)
\]

\[
\hat{s}_3 = \arg\min_{s_3 \in X} d^2(S, s_3)
\]

\[
\hat{s}_4 = \arg\min_{s_4 \in X} d^2(S, s_4)
\]

where \(X\) is all possible signal collection in the adopted modulated constellation.

3 COMBINED BF WITH STBC IN MASSIVE MIMO SYSTEMS

The idea of the combination of space-time block coding (STBC) and smart antenna was proposed to obtain the full diversity order as well as beamforming gain. The performance of mobile communication with antenna array depends on the DOA and angular spread.

For the system of combining BF with STBC using single-array and multiple arrays was proposed in [8-9], where it assumed small number of transmit antenna. In this paper, an eigen-beamforming combined four branch STBC technique is proposed in massive MIMO systems. For simplicity, only a single-cell system, with one BS (equipped with massive antennas) and a single-antenna user is considered. The schematic diagram of the proposed technique is shown in Figure 2 and 3. In Figure 3, the element number for one array is \(N\).

The output of four branch STBC encoder is weighted by four beamformers, which are denoted \(w_1\), \(w_2\), \(w_3\), and \(w_4\), respectively. Followed by a signal

---

**Figure 1. Schematic diagram of four transmit and one receive antenna STBC system.**
combiner which performs a simple sum function to produce a vector $\mathbf{x}$, which can be expressed as

$$\mathbf{x} = \mathbf{w}_1^H s_1 + \mathbf{w}_2^H s_2 + \mathbf{w}_3^H s_3 + \mathbf{w}_4^H s_4$$  \hfill (6)$$

Finally, the vector $\mathbf{x}$ is transmitted through massive number antennas (64 or 128). Suppose the wireless channel is flat fading, and consists of $L$ spatially separated paths, whose fading coefficients and direction of arrival (DOA) for each path are given as $\{\sqrt{\beta} h_i, \theta_i\}$, $i=1, 2, 3, 4, \ldots, L$ the equivalent channel response can be expressed as $[10-11]$

$$\mathbf{h} = \sum_{i=1}^{L} \sqrt{\beta} h_i \bullet \mathbf{a}(\theta_i)$$ \hfill (7)$$

Where $h_i$ and $\sqrt{\beta}$ represent small-scale and large-scale fading coefficients, respectively. $\alpha_i$ and $\phi_i$ are small fading amplitude and phase, $\mathbf{a}(\theta_i)$ is the downlink array steering vector at DOA $\theta_i$ and defined as (ULA)

$$\mathbf{a}(\theta_i) = \left[ 1, e^{j \frac{2\pi}{\lambda} d \sin \theta_i}, \ldots, e^{j \frac{2\pi}{\lambda} (M-1)d \sin \theta_i} \right]^T$$ \hfill (8)$$

Where $\lambda$ is the wavelength and $d$ is the distance between adjacent antenna elements. $N$ is the number of massive transmit antenna. The downlink channel covariance matrix can be represented as $[12]$

$$\mathbf{R} = \mathbb{E} [\mathbf{h} \bullet \mathbf{h}^H] = \sum_{i=1}^{L} \mathbb{E} \left[ |h_i|^2 \right] \mathbf{a}(\theta_i) \mathbf{a}^H(\theta_i)$$ \hfill (9)$$

$w_1, w_2, w_3,$ and $w_4$ are set to be the corresponding eigen vector to the four large eigen value of the downlink channel covariance matrix $[12]$.

For simplicity set $L=8$, in the case of combining BF
with STBC using single-array, the virtual MIMO channel is constructed as
\[ k_i = w_i^H h_i (i = 1, 2, 3, 4) \]
\[ h_i = \frac{\sqrt{\beta_i}}{\sum_{j=1}^4 \sqrt{\beta_j}} a(\theta_i) \]  

The received signal can be represented as
\[ y_i = k_i s_i + k_2 s_2 + k_3 s_3 + k_4 s_4 + n_i \]
\[ y_2 = -k_1 s_1 - k_3 s_3 + k_4 s_4 + n_2 \]
\[ y_3 = -k_1 s_1 + k_2 s_2 - k_3 s_3 + k_4 s_4 + n_3 \]
\[ y_4 = -k_1 s_1 - k_2 s_2 + k_3 s_3 - k_4 s_4 + n_4 \]
\[ y_5 = k_1 s_1 + k_2 s_2 + k_3 s_3 - k_4 s_4 + n_5 \]
\[ y_6 = -k_1 s_1 + k_2 s_2 - k_3 s_3 + k_4 s_4 + n_6 \]
\[ y_7 = -k_1 s_1 - k_2 s_2 + k_3 s_3 - k_4 s_4 + n_7 \]
\[ y_8 = -k_1 s_1 - k_2 s_2 - k_3 s_3 + k_4 s_4 + n_8 \]  

While the case of using multiple arrays, the virtual MIMO channel is the similar as single-array
\[ k_i = w_i^H (h_i + h_s) \]
\[ h_i = w_i^H (h_i + h_s) \]  

The received signal shown below are similar as single-array
\[ y_i = k_1 s_i + k_2 s_2 + k_3 s_3 + k_4 s_4 + n_i \]
\[ y_2 = -k_1 s_1 - k_2 s_2 + k_3 s_3 + k_4 s_4 + n_2 \]
\[ y_3 = -k_1 s_1 + k_3 s_3 - k_2 s_2 + k_4 s_4 + n_3 \]
\[ y_4 = -k_1 s_1 - k_3 s_3 + k_2 s_2 + k_4 s_4 + n_4 \]
\[ y_5 = k_1 s_1 + k_2 s_2 + k_3 s_3 - k_4 s_4 + n_5 \]
\[ y_6 = -k_1 s_1 + k_2 s_2 - k_3 s_3 + k_4 s_4 + n_6 \]
\[ y_7 = -k_1 s_1 - k_2 s_2 + k_3 s_3 + k_4 s_4 + n_7 \]
\[ y_8 = -k_1 s_1 - k_2 s_2 + k_3 s_3 - k_4 s_4 + n_8 \]  

The decoding algorithm is the same as described in section 2, i.e. the maximum likelihood decoder. Because of the similarity, in this letter, we only describe the detection of single-array.

In order to get maximal SNR, we try to maximize (14) subject to (15) based on conventional STBC detection
\[ E [w_i^H h_i^2 + w_i^H h_i^2 + w_i^H h_i^2 + w_i^H h_i^2] \]
\[ w_i^H w_1 + w_i^H w_2 + w_i^H w_3 + w_i^H w_4 = 1 \]  

The combined signal can be expressed as
\[ S_i = K s_i = K^H K s + K^H n \]  

Where
\[
K = \begin{bmatrix}
  k_1 & k_2 & k_3 & k_4 \\
  k_5 & -k_1 & k_4 & -k_3 \\
  k_6 & -k_4 & k_3 & -k_5 \\
  k_7 & k_6 & k_5 & k_4 \\
  k_8 & k_7 & k_6 & k_5
\end{bmatrix}
\]
\[ s = (s_1, s_2, s_3, s_4)^T, \quad y = (y_1, y_2, y_3, y_4, y_5, y_6, y_7, y_8)^T \]  

\[ \text{denotes transmit and receive signal vector, respectively, and } n \text{ represents } 8 \times 1 \text{ vector of i.i.d. } \mathcal{CN}(0, \sigma^2) \text{ additive complex Gaussian noise.} \]

As shown in (10), \( w_i \) \((i=1, 2, 3, 4) \) are set to be \( a(\theta) \) \((i=1, 2, 3, 4) \). Similar components in the equation can be denoted as array gain \( \varepsilon \), which is only dependent on beamwidth and the sidelobe level. However, \( \varepsilon \) is sensitive to its variance.

\[ \varepsilon \propto \|w_i^H a(\theta)|^2, l_1 = i, l_2 = 9 - i (i=1,2,\cdots,8) \]  

As can be seen from the equation (18), direction of arrival and angular spread have a significant effect on the array gain, resulting in system performance has greatly changed, and the specific effects described later simulation.

4 SIMULATION RESULTS

In order to verify previous theoretical results, numerical analysis and simulations are provided in this section. The typical values and simulation parameters are presented in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data frame length</td>
<td>N=64</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK</td>
</tr>
<tr>
<td>Symbol period</td>
<td>T=8</td>
</tr>
<tr>
<td>Energy per symbol</td>
<td>( \varepsilon^2 )</td>
</tr>
<tr>
<td>Power per noise</td>
<td>( \sigma^2 )</td>
</tr>
<tr>
<td>Receive antenna</td>
<td>1</td>
</tr>
<tr>
<td>Array element spacing</td>
<td>( \lambda/2 )</td>
</tr>
<tr>
<td>Spatially separated paths</td>
<td>( L=8 )</td>
</tr>
</tbody>
</table>

It is assumed that the data frame length is \( N=64 \) (after modulation). The flat fading channel between each transmit antenna and receive antenna is Rayleigh faded with uniform power delay profile. Under the assumption of a quasi-stationary channel, the channel is constant during eight symbol period. Additive Gaussian noise with zero-mean and variance \( \sigma^2 \) is assumed and the definition of SNR is \[ SNR = \varepsilon^2 / \sigma^2 \].
where $\epsilon^2$ is the energy per symbol. At the receiver, perfect symbol/carrier synchronization and perfect channel state information are assumed to be available. And only one receive antenna is assumed.

angular spread have a significant impact on the performance of the system. While the impact of DOA and angular spread can be minimized in multi-arrays system. So the multiple arrays have a slight better performance.

5 CONCLUSIONS

In this paper, an eigen-beamforming combined four branch space-time block coding technique is proposed in massive MIMO systems. Both the theoretical analysis and simulation results confirm that the proposed technique can obtain diversity gain and beamforming gain simultaneously. For simplicity, one cell and one user is considered, multi-cells and multi-users will be considered in the following work.

ACKNOWLEDGEMENT

This work was supported in part by the National Science and Technology Major Project of the Ministry of Science and Technology of China (2014ZX 0300 3005-003), in part by the National Natural Science Foundation of China-Youth Program (61501371-F010401), and in part by the Natural Science Foundation of Shanxi Province of China (2011JM8027).
REFERENCES


