Blind recognition of MIMO-SFBC based on Symbolic eigenvalue*

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Abstract. In the blind recognition of air frequency block code signals, a blind recognition algorithm of MIMO-SFBC based on symbolic eigenvalue was proposed to solve the problems of poor recognition performance and large number of samples under the condition of low SNR. According to the symbol correlation characteristics of different air frequency block codes in frequency domain, the eigenvector sequences of different air frequency block codes are derived, symbolic eigenvalue are estimated by binary hypothesis testing, and different coding types are distinguished by decision tree classification recognition algorithm. Simulation results show that the algorithm does not need prior information such as modulation prediction, and has good recognition performance under low SNR and small sample conditions, and can be applied to engineering fields such as cognitive radio.

Keywords: Blind recognition; Space Frequency Block Code (SFBC); The Decision tree classification; MIMO.

1. Introduction

Communication signal blind processing technology is a hot topic in academic and engineering circles[1]Blind recognition of communication signals has been widely used in both military and civil fields[2-3]. Spatial frequency block codes (SFBC) encode data streams jointly at the transmitter, and introduce redundancy into different antennas and carrier frequencies to obtain spatial and frequency diversity, thus effectively reducing the symbol error rate[4], greatly improves the transmission performance of the system, and has been incorporated into several wireless standards, such as LTE[5]And WiMax[6]. Blind recognition of air frequency block code refers to the technology that only USES the air frequency coding method used by the receiving end when the receiving end does not know the channel state information (CSI).It is an urgent field to be conquered in the field of communication reconnaissance countermeasure. It can provide effective technical support for MIMO countermeasure technology and has important research and military application value.

At present, blind recognition methods for MIMO system codes are mainly space-time block codes (STBC), and blind recognition of space-frequency block codes is a new research field. Literature [7]-[10] are all studies on space-time block codes. Literature [7] proposes a blind recognition algorithm based on high-order cumulant, but this algorithm can only identify SM and AL STBC codes. Literature [8] proposed a blind RECOGNITION algorithm of STBC based on Kolmogorov-Smirnov detection, but...
the recognition effect of this algorithm is poor under the condition of low SNR. Literature [9] proposes a blind STBC recognition of fourth-order delay vector, and identifies the coding type of STBC by determining whether the fourth-order cumulant of the received signal under different delay vectors is 0. Literature [10] proposed a blind recognition algorithm based on fourth-order cyclic cumulant. STBC was identified by detecting the cycle frequency. However, this algorithm had high computational complexity and only recognized 4 STBC codes.

The coding matrix of space frequency block code is similar to that of space time block code, which uses space and frequency diversity, while space time block code uses space and time diversity. Because the two kinds of codes use different diversity gain, the algorithm will inevitably be affected when the blind recognition method of space-time block code is directly applied to the space-time block code. Therefore, the air frequency block code needs blind recognition algorithm suitable for its own coding characteristics. At present, literature on air frequency block code mainly analyzes its structure and performance. Literature [11] and literature [12] respectively propose a MIMO system transmission mode based on air frequency block code. Literature [13] and literature [14] respectively introduce the space-frequency block code coding technology and system structure in frequency-selective fading channel. Literature [15] analyzes the performance of space-frequency block codes in fading channels. Literature [16] proposed an algorithm for blind recognition of SFBC-OFDM, and extracted the features of SFBC-OFDM by using autocorrelation matrix. Literature [17] proposed to identify SFBC-OFDM by using the redundant features of two-dimensional frequency domain. Literature [18] uses random matrix and subspace to identify SFBC-OFDM, but these three algorithms are not suitable for blind MIMO-SFBC recognition. Literature [19] proposes a blind recognition method of MIMO-SFBC based on singular value iteration. By comparing the estimated symbol vector of single carrier and double carrier, the coding type of space frequency block code is determined. Simulation results show that this algorithm can recognize SFBC coding type, but the recognition effect is poor under the condition of low SNR.

In this paper, a blind recognition algorithm of MIMO-SFBC based on feature vector sequence is proposed. First, by analyzing SFBC coding characteristics, feature vector sequences of different SFBC codes are calculated in the frequency domain, and estimated value of feature vector sequence is obtained through binary hypothesis testing. Different SFBC coding types are identified by decision tree classification recognition algorithm. The algorithm proposed in this paper can recognize 6 different SFBC codes without prior information such as modulation mode. Simulation results show that the algorithm can achieve good recognition effect under the conditions of small samples and low SNR.

2. Signal Model

2.1. Transmitting signal model
Assume that the transmitting antennas in the MIMO-SFBC wireless communication system belong to the same linear modulation, QPSK, BPSK or M-QAM, and \( M \geq 4 \).

At the sending end, after modulation, the information symbol flow enters into the SFBC encoder and becomes the channel parallel data. After IFFT transformation, it is sent out through the antenna. Assume that the transfer symbols are independent and uniformly distributed, and that the average modulation symbol energy is 1. The modulated data symbol stream is parsed into symbol data blocks, and there are symbols in each sequence, and the transmission time slot is, and can be expressed as, and the signal matrix vector at the transmitter can be expressed as:

\[
\mathbf{C}(S) = [A_1, S, \ldots, A_L] \quad (1)
\]

Where, represents the SFBC coding matrix of the transmitter. \( A_i (0 \leq i \leq L) \)
2.2. Channel Model
First, confirm that you have the correct template for your paper size. This template has been tailored for output on the A4 paper size. If you are using US letter-sized paper, please close this file and download the Microsoft Word, Letter file. In this section, power delay distribution (PDP) is used to quantitatively and qualitatively analyze the characteristics of the channel model. PDP describes the distribution of the average power of the received signal at each path, where the power at each path is given by the ratio of the power at that path to the power at the first path [20].

The PDP of IEEE802.11 frequency selective fading channel follows the exponential model, and the Impulse Response of the channel is expressed by the output of Finite Impulse Response (FIR) filter.

Assuming that the power mean of the tap in the P channel is 0 and the variance is, its impulse response can be expressed as \( \sigma_p^2 / 2 \)

\[
h_p = Z_1 + j \cdot Z_2, \quad p = 0, 1, L, \quad p_{max}
\]

Where, \( Z_1 \) and \( Z_2 \) is an independent and \( Z_i : N(0, \sigma_i^2 / 2), i = 1, 2 \) identically distributed Gaussian random variable, namely.

The power of each channel tap is

\[
\sigma_p^2 = \sigma_0^2 e^{-pT_\eta/\sigma_i}
\]

Where, is the power of the first tap, and its power value is \( \sigma_0^2 \).

The tapped delay line model USES a set of fading generators with an average power of 1. The types of fading generation can be selected, such as exponential model or IEEE802.11, and the generators are independent of each other. Referring to the PDP in the channel model, since the PDP is based on the actual measurement in a specific environment, the delay may not be an integer multiple of the sampling period, so the tap is adjusted by means of rounding or tap difference, and the path number and power of each path are guaranteed to remain unchanged. Add the corresponding propagation delay to each channel, multiply each distinguishable path by its corresponding attenuation coefficient, and add these propagation paths to form a frequency selective fading channel, whose pulse at time T can be expressed as:

\[
h_p(t, \tau) = \sum_{i=0}^{\text{path}-1} a_i(t, \tau)e^{-j\nu_0\tau_i(t)+\phi_i(t, \tau)} \delta(\tau - \tau_i(t))
\]

2.3. Receiving signal model
At the receiving end, FFT transformation is performed on the received signal. After the synchronization is completed, the signal model of the V carrier of the received signal can be expressed as

\[
Y(v) = H_v \cdot S(v) + W(v)
\]

Where, \( S(v) \) represents the Signal sequence of the VTH hairstyle, \( H_v \) represents the transmission channel matrix, and \( W(v) \) represents the Gaussian white noise existing in the channel.

Six typical SFBC signals are selected in this paper, and their coding matrix is shown as follows:

SM - SFBC[21]: SM is SFBC transmitted by a set of symbols through the antennas. The length of the code matrix is shown in Formula (7) : \( n, n, L = 1 \)

\[
C^{SM}(S) = [s_1, s_2, L , s_j]^T, j = 1, L , N_p
\]

AL - SFBC[21]: AL code is SFBC transmitted by two transmitting antennas with a set of 2 symbols. The code matrix length is shown in Equation (8) : \( L = 2 \)
SFBC3(1) is [22]. A set of three symbols is SFBC transmitted by three transmission antennas. The length of the code matrix is shown in Formula (9): \( L = 4 \)

\[
C_{\text{SFBC}(1)}^\text{SFBC} = \begin{bmatrix}
 s_1 & -s_3^* & s_2^* & 0 \\
 s_2 & s_1^* & 0 & -s_3^* \\
 s_3 & 0 & -s_1 & s_2^*
\end{bmatrix}^T
\]  

SFBC3(2) [23] is a set of three symbols transmitted by three transmission antennas. The length of the code matrix is shown in Equation (10): \( L = 4 \)

\[
C_{\text{SFBC}(2)}^\text{SFBC} = \begin{bmatrix}
 s_1 & 0 & -s_3 \\
 0 & s_1 & s_2 \\
 -s_2 & -s_3 & s_1
\end{bmatrix}
\]  

SFBC3(3) [23] is a set of four symbols transmitted by three transmission antennas. Length of code matrix: \( L = 8 \)

The encoding method is shown in Equation (11):

\[
C_{\text{SFBC}(3)}^\text{SFBC} = \begin{bmatrix}
 s_1 & -s_3 & -s_4 & s_3^* & -s_2 & s_1^* & -s_3 & -s_4 \\
 s_2 & s_1 & s_4 & -s_3 & s_2^* & s_1^* & s_3 & -s_4 \\
 s_3 & -s_4 & s_2 & s_1 & s_3^* & -s_1 & s_2 & s_4 \\
 s_4 & -s_3 & s_1 & s_2 & -s_4 & s_3 & s_1 & s_2^*
\end{bmatrix}
\]  

SFBC4 [24] is a set of four symbols transmitted by four transmission antennas. The encoding method of code matrix length is shown in Equation (12): \( L = 8 \)

\[
C_{\text{SFBC}(4)}^\text{SFBC} = \begin{bmatrix}
 s_1 & -s_3 & -s_4 & s_3^* & -s_2 & s_1^* & -s_3 & -s_4 \\
 s_2 & s_1 & s_4 & -s_3 & s_2^* & s_1^* & s_3 & -s_4 \\
 s_3 & -s_4 & s_2 & s_1 & s_3^* & -s_1 & s_2 & s_4 \\
 s_4 & -s_3 & s_1 & s_2 & -s_4 & s_3 & s_1 & s_2^*
\end{bmatrix}
\]  

3. Eigenvector sequence detection algorithm

In this section, the channel of adjacent carriers is first analyzed. Then the eigenvector sequences of different SFBC signals are taken as the recognition features and the values of the eigenvector sequences in the sequences are estimated by binary hypothesis testing. Finally, the coding type of SFBC signal is determined by the minimum distance between the estimated and theoretical values calculated by Euclidean distance criterion.

The adjacent carrier channel is assumed to be a quasi-static MIMO channel, represented by the matrix \( N \times N \) \( H \). Because the channel fading severity of adjacent carriers is almost the same, the channel matrix is approximately the same.

The \( k \) group can be expressed as:

\[
Y_k = H_k \cdot S_k + W_k
\]  

Where, \( W_k \) is gaussian additive white noise. In order to convenient expression, another signal \( S(k) \) is used to express, the length of the vector \( S \) on behalf of the expression of the first \( n \) contiguous carrier modulation symbols. Therefore, the matrix can be expressed as \( \tilde{S} \left[ \text{Re}(S), \text{Im}(S) \right] \), where the vector \( \left[ \hat{A}_1, \hat{A}_2, \hat{A}_3, \hat{A}_4 \right] \) \( \text{Re}(\hat{g}) \) represents the real part of the variable \( S \) and \( \text{Im}(\hat{g}) \) represents the imaginary part of the variable.

In parallel with the real and imaginary parts in Formula (13), the carrier parallel matrix is obtained and vectorized, and it can be obtained as follows:
\[ \hat{y}_n = (I_2 \otimes \overline{H}) \tilde{c}(S) + \tilde{w}_n \] (14)

Where, \( \hat{y}_n \) denotes the vectorization, \( \tilde{w}_n \) denotes the channel vectorization matrix, and \( Y_k W_k \) is only related to the structure of SFBC, \( \overline{H} \) denotes the kron product.

Since additive noise and propagation symbols have zero mean value:

\[ \mathbb{E}[v] = 0 \] (15)

The covariance matrix of adjacent carriers can be expressed as:

\[ \sum_{\nu} = \mathbb{E} \begin{bmatrix} \nu S \nu S^T \end{bmatrix} = (I_2 \otimes \overline{H}) \mathbb{E} \begin{bmatrix} \nu S \nu S^T \end{bmatrix} + \mathbb{E} \begin{bmatrix} \nu W \nu W^T \end{bmatrix} \] (16)

Obviously, the combination of coding matrix and modulation symbol vector \( S \) can be extended to matrix products. The matrix \( M_c \) combines the coding matrix, and equation (16) can be expressed as:

\[ \sum_{\nu} = \frac{1}{2} (I_2 \otimes \overline{H}) M_c M_c^T (I_2 \otimes \overline{H}^T) + \frac{\sigma_w^2}{2} I_{4N_r} \] (17)

Obviously, \( (I_2 \otimes \overline{H}) M_c \) is a column full rank matrix, and the rank of the matrix is \( 2n \).

Eigenvalue decomposition \( \sum_{\nu} \) is performed for the covariance matrix, whose eigenvalues are represented by \( \lambda_i \geq \lambda_{4N_r} \), wherein, \( 2n \) are the eigenvalues of the signal, and the remaining eigenvalues \( 4N_r - 2n \) correspond to the eigenvalues of the noise. Where the smallest eigenvalue \( \lambda_{4N_r} = \frac{\sigma_w^2}{2} \) is equal to theta, which is \( \frac{\sigma_w^2}{2} \).

The ratio of the eigenvalues of the adjacent carrier covariance matrix is calculated to obtain the eigenvalue ratio vector \( F \), and the ordinal number of the largest element is taken as the estimated symbol number \( j_p \). Then the estimated symbol of the next carrier \( j_{p+1} \) is calculated, and the eigenvector \( P = [p_1, p_2, p_3, p_4] \) is obtained by continuing to slide the frequency domain window for \( N \) times.

SM - SFBC: analysis of the two transmitting antenna, on the assumption of adjacent carrier transmission symbol for SM - SFBC, modulation symbols can be expressed as, the smallest eigenvalue of \( 4N_r - 4 \). In this sampling, the estimated number of symbols on the carrier is equal to 4, and in the next receiving carrier, the estimated number of symbols on the modulation symbol carrier is also 4, which is because sm-SFBC has no correlation between groups. In the case of 2 transmitting antennas, the number of symbols carried on the adjacent carriers is all 4. When the frequency domain window slides, the sm-SFBC feature vector sequence can be expressed as:

\[ P_{sm} = [4, 4, 4, 4, 4, 4, 4, 4] \]

AL-SFBC: It is assumed that al-SFBC generation signals are transmitted on adjacent carriers.

In AL-SFBC coding, the number of symbols on a packet carrier is 2, and the number of symbols carried by adjacent carriers of the same packet is still 2. On the next receiving carrier, there is no correlation between the carrier packet symbols, so the number of symbols carried is 4.

\[ C^{al}(S) = \begin{bmatrix} s_1^2 & s_2^2 \\ -s_1^* s_2 & s_1^* s_2 \end{bmatrix} \] Therefore, the eigenvector sequence of AL-SFBC is \( P_{al} = [2, 4, 2, 4, 2, 4, 2, 4] \).

Similarly, the signal-number eigenvectors of other SFBC signals can be constructed, as shown in FIG. 5(a)-(d). SFBC3\((1)\)s: SFBC3 \( P_{sfc3}^{(1)} = [3, 3, 3, 3, 3, 3, 3, 3] \) (2)s: SFBC3 \( P_{sfc3}^{(2)} = [3, 3, 3, 5, 3, 3, 3, 3] \) (3), the eigenvector sequence of SFBC4 is: \( P_{sfc4}^{(3)} = [4, 4, 4, 4, 4, 4, 4, 4] \) \( P_{sfc4}^{(4)} = [4, 4, 4, 4, 4, 4, 4, 4] \)

To sum up, the encoding type of SFBC can be distinguished by recognizing the feature vector of the received signal.

The sample covariance matrix of the k and K + 1 adjacent carriers can be expressed as:
The eigenvalues are denoted by $l_{\frac{k}{2}} \geq L \geq l_{\frac{N_x}{2}}$.

The test statistics of adjacent carriers are constructed as

$$U_{k}^{(k)} = \frac{1}{4N_x-2} \sum_{x=1}^{N_x} \sum_{|n|<l} \rho_{n}$$

(19)

$U_k$ A statistic, representing the threshold value of an eigenvalue, $\eta_q$.

The threshold value can be expressed by the inverse function of the Probability of false Alarm (PFA):

$$\eta_q = f^{-1}(pf_a)$$

(20)

$$pf_a = \int_{q}^{\infty} \left( \frac{1}{2\pi \delta^2} \right) e^{-\frac{x^2}{2\delta^2}} dx$$

(21)

In order to automatically identify SFBC signal type, decision tree classification algorithm was used for identification. $P=[p_1, p_2, p_3, p_4, L, p_n]$

**Figure 1.** Decision Tree Classification and recognition algorithm

The decision tree classification and recognition algorithm is shown in Figure 1. In the first step, the decision is made according to the $2i-1$ estimated symbol number of the received signal. If it is 2, the minimum Euclidean distance decision is adopted to identify al-SFBC code, $p_{2i-1}$.

If equal to 4, the signal is divided into a subset to be recognized, including SM-SFBC and SFBC3 $\Theta$, SFBC4 and other three SFBC codes; If equal to 3, the signal is divided into a subset to be recognized, including SFBC3 $\Theta$, SFBC4 and other three SFBC codes. Step 2: According to the $8i$ estimated symbol number in the subset of the signals to be recognized, three codes can be distinguished. When equal to 4, al-SFBC codes can be identified by using the minimum Euclidean distance decision. $p_{4i}$.

When it's equal to 6, it identifies SFBC3 $\Theta$ Code; When it's equal to 8, SFBC4 is determined; According to the $4i$ estimated symbol number in the subset of the signals to be recognized, two codes can be distinguished. When equal to 5, SFBC3 can be identified $p_{4i}(1)$; When it's equal to 4, it identifies SFBC3 $\Theta$.

Among them, the minimum European distance judgment criterion is distance $d_c$, which can be expressed as:

$$d_c = \sqrt{\sum_{k \in \Sigma} (P(k) - P_{SFBC}(k))^2}$$

(22)
4. Simulation experiment and analysis

4.1. Simulation 1 algorithm identification performance
Under the simulation conditions in Section 3.1, this section discusses and analyzes the average recognition probability of the eigenvector algorithm and the correct recognition probability of the six SFBC codes. As shown in FIG. 2, the recognition performance of the algorithm for SFBC encoding type improves with the increase of SNR. In this paper, the recognition probability of the algorithm is above 96% at 4dB. The recognition performance of different SFBC signals is shown in Figure 9, and the correct recognition probability is adopted to measure the performance of the algorithm. As can be seen from Figure 3, SM-SFBC has the highest recognition rate, SFBC3(1) and SFBC3(2) due to the presence of 0 value in the coding matrix and the large structural similarity, the two coding methods are difficult to identify. Under low SNR, the recognition performance is poor, but at 8dB, the recognition performance can reach about 95%.

![Recognition probability](image)

**Figure 2.** Average probability of Correct Recognition of the algorithm

![Recognition probability](image)

**Figure 3.** Correct recognition probability of Different SFBC algorithms

4.2. Simulation 2 algorithm identifies the relationship between performance and number of samples
The relationship between the number of samples and the average recognition rate of the algorithm is shown in figure 10, 512, 1024, 2048. With the increase of the number of samples N, the statistical
characteristics of the received signal become more obvious and the estimation value of the eigenvector sequence becomes more accurate, thus improving the performance of the algorithm.

![Figure 4. Relationship between sample size and algorithm performance](image1)

4.3. Simulation 3 identifies the relationship between the performance and the number of receiving antennas $N_r$

The influence of the number of receiving antennas on the algorithm performance is shown in Figure 5. The more the number of receiving antennas, the better the algorithm's recognition performance will be. When the number of receiving antennas is 12, the recognition rate can reach nearly 100% at 0dB. According to equations (19)-(20), as the number of antennas increases, the variance estimation of noise becomes more accurate, so the algorithm has a better recognition effect.

![Figure 5. Relationship between average recognition probability of algorithm and number of receiving antennas](image2)

4.4. Simulation 4 The relationship between algorithm performance and false alarm probability

The influence of false alarm probability on algorithm performance is shown in Figure 7, where the false alarm probability is 0.1, 0.01 and 0.001 respectively. $\Pr_f$. According to the figure, when the false alarm probability is 0.001, the algorithm has the best performance. According to Equation (22), when the false alarm probability increases, the threshold $\gamma_q$ decreases and the performance of the algorithm improves accordingly.

![Figure 6. Relationship between average recognition probability of algorithm and number of receiving antennas](image3)
4.5. Simulation 5 Relationship between algorithm performance and modulation mode

The algorithm's recognition performance under four different modulation modes of QPSK, BPSK, 8PSK and 16QAM is measured by the average recognition probability, as shown in Figure 8. It can be seen that there is almost no difference in algorithm performance under different modulation modes, so the algorithm in this paper does not need to predict the modulation mode information of the transmitted signal.

4.6. Simulation 6 algorithm and other algorithms comparison

The algorithm in this paper is compared with the singular value iterative algorithm in literature [19], as shown in Figure 9. Under the same simulation setting conditions, the received sample is 1024 and the modulation method is QPSK, so the performance of the algorithm in this paper is better. In this paper, the algorithm can achieve a recognition rate of more than 96% when it is 4dB, while the singular value iterative algorithm can only achieve a recognition probability of 96% when it is 12dB. However, the information theory criterion algorithm has limited recognition ability under the condition of receiving sample number. Especially in the case of low SNR, the recognition performance of the proposed algorithm is about 40% better than that of the singular value iterative algorithm. The computational complexity of this algorithm is $O(N\log N)$, while that of the algorithm in reference [17] is $O(n^2)$. In summary, the performance of the algorithm in this paper is better, and it can be identified under the conditions of small samples and low SNR, which also reduces the computational complexity of the recognition algorithm.
5. Conclusion
In this paper, MIMO-SFBC blind recognition algorithm based on eigenvector sequence is proposed. Six SFBCS including different code length and transmitting antenna number are studied. Based on the symbol correlation characteristics of space frequency block codes in the frequency domain, the eigenvector sequences of different space frequency block codes are derived, the eigenvector sequences are estimated by binary hypothesis testing of the sequence, and different coding types are identified by the minimum Euclidean distance criterion and decision tree classification method.

The simulation results show that the proposed algorithm does not need prior information such as predictive noise and debugging mode. Compared with the existing algorithms, the proposed algorithm also achieves better recognition performance under the conditions of low SNR and small samples, and can be applied to engineering fields such as cognitive radio.

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References
[1] Patil V M, Patil S R. Correction to: Signal Detection in Cognitive Radio Networks over AWGN and Fading Channels[J]. International Journal of Wireless Information Networks, 2018, 25(1):87-87.
[2] Kumar M, Majhi S. Joint signal detection and synchronization for OFDM based cognitive radio networks and its implementation[J]. Wireless Networks, 2019, 25(2):699-712.
[3] Fernando X, Sultana A, Hussain S, et al. Resource Allocation in OFDM-Based Cognitive Radio Systems[M]. Cooperative Spectrum Sensing and Resource Allocation Strategies in Cognitive Radio Networks. 2019.
[4] CHEN Hong. Principle and Key technology of MIMO-OFDM System [J]. China Radio, 2006(10): 57-62.
[5] S. Sesia, I. Toufik, and M. Baker, LTE: the UMTS long term evolution. [M]Wiley Online Library, 2009.
[6] bwmeta.element.ieee. 802.16m-2011. IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Broadband Wireless Access Systems Amendment 3: Advanced Air Interface[J]. 2011.
[7] Ling Q, Zhang L, Yan W, et al. Hierarchical space–time block codes signals classification using higher order cumulants[J]. Chinese Journal of Aeronautics, 2016, 29(3): 754-762.

[8] Lin H W, Yu K Y, Zhong Z G, et al. Blind Identification of Space-time Block Coding (STBC) Using Single Receive Antenna over Frequency-selective Fading Channels[C]. International Conference on Wireless Communication and Sensor Networks (WCSN 2016). Atlantis Press, 2016.

[9] ZHANG Limin, YAN Wenjun, LING Qing. A space time block code recognition method under a single receiving antenna [J]. Acta Electronica & Information Technology, 2015, 37(11).

[10] Zhang Limin, LING Qing, YAN Wenjun. Research on blind Recognition Algorithm of Space-time Block Code based on High-order Cumulant [J]. Journal of Communications, 2016, 037(005):1

[11] BA Haitao, XU Ruifeng, ZONG Ming. Short-wave MIMO communication System based on air frequency Block Code [J]. Ship Electronic Engineering, 2010, 30(9):103-105.

[12] Jiang Jing, SUN Yunfeng, ZHI Zhou. A multi-input multi-output transmission method based on air frequency block coding: CN.101547065

[13] Song Gao-Jun, Zhou Zhong-zhong, ZHONG Jun. Space-frequency block coding in frequency selective correlation channels [J]. Journal of Circuits and Systems, 2005, 10(2):71-74.

[14] Lu S, Narasimhan B, Al-Dhahir N. A Novel SFBC-OFDM Scheme for Doubly Selective Channels[J]. IEEE Transactions on Vehicular Technology, 2009, 58(5):2573-2578.

[15] Qiu Xin, ZHANG Xiaoli. Performance Analysis of OFDM system based on space-time Block Code and Space-frequency block Code [J]. Communications Management and Technology, 2014(1).

[16] Mohamed Marey, Octavia A. Dobre. Automatic Identification of Space-Frequency Block Coding for OFDM Systems[M]. IEEE Press, 2017.

[17] Gao M, Li Y, Mao L. Blind Identification of SFBC-OFDM Signals Using Two-Dimensional Space-Frequency Redundancy[C] GLOBECOM 2017 - 2017 IEEE Global Communications Conference. IEEE, 2017.

[18] Gao M, Li Y, Dobre O A. Blind Identification of SFBC-OFDM Signals Using Subspace Decompositions and Random Matrix Theory[J]. IEEE Transactions on Vehicular Technology, 2018:1-1.

[19] Guo Song. Research on Blind Recognition Algorithm of Space-Frequency Block Code Based on Singular value Iteration [D]. Xidian University, Xi'an: 2014.

[20] Guo Yanzhen. Modeling and Simulation of highly mobile wireless Channel based on relevant Nakagami-M fading [D]. Southwest Jiaotong University, Chengdu: 2011.

[21] Lin Hongwen, YU Keyuan, ZHONG Zhaogen. A Review of space-time Block Code blind recognition technology in Selective Fading Channels [J]. Computer and Digital Engineering, 2017(5).

[22] Alamouti S M. A simple transmit diversity technique for wireless communications[J]. 1998,16(8):1451–8. DOI:10.1109/9780470546543.ch2

[23] Tarokh V, Jafarkhani H, Calderbank A R. Space-time block codes from orthogonal designs[J]. IEEE Transactions on Information theory, 1999, 45(5): 1456-1467.

[24] Choqueuse V, Yao K, Collin L, et al. Hierarchical space-time block code recognition using correlation matrices[J]. IEEE Transactions on Wireless Communications, 2008, 7(9): 3526-3534.