

Enhancing MIMO Capacity Through Space-Time Coding: Analysis And Design Framework

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Abstract - Space-time coding combines time and space to generate codewords, transmitting signals in both time and space domains. This leads to not only diversity and coding gains but also reduces the impact of multipath fading, resulting in high spectral efficiency. This paper examines the challenges in implementing space-time coding to enhance the capacity of MIMO systems. It analyzes the principle, design objectives, and criteria of space-time coding, providing a basic design framework, based on the space-time coding (STC) system model. STC and MIMO have proven to be effective in improving system capacity, reliability, and overall performance in wireless communication. They have been applied in various fields such as wireless local area networks (WLANs), cellular networks, satellite communication, and wireless body area networks (WBANs). The use of space-time coding in 5G massive multi-antenna technology improves diversity and gain, resulting in higher communication throughput, leading to increased research in the field.

Keywords - Space Time Coding (STC), Massive Multiple Input Multiple Output (MMIMO) Systems, Transmit Diversity, 5th Generation Wireless Systems (5G)

Received: 14 December 2022; Accepted: 09 February 2023; Published: 16 March 2023

I. INTRODUCTION

The demand for communication services has increased dramatically with the fast-paced development of wireless communication technology. To meet this demand, it has become essential to optimize the utilization of spectrum resources to achieve greater bandwidth and higher rates. To accomplish this, 5G systems employ various advanced communication technologies such as ultra-dense networks, spectrum sharing, millimeter-wave or milliwave technology, IoT, and MIMO technology [1,2]. Among these, MIMO technology has received widespread recognition and implementation in practice [3-5].

Space-time coding is an important technology for improving the error performance in multi-antenna transmission. It combines error control coding, modulation, and transmission diversity by using both space and time, making it a suitable technology for multi-antenna transmission. MIMO systems consists of two categories: spatial multiplexing systems and space-time coding systems, based on the objectives of increasing transmission rate (efficiency) and obtaining diversity gain (reliability)[6]. Space-time coding is one way of implementing MIMO technology and has been utilized in various communication systems, ranging from the original MIMO system to the current massive MIMO (MMIMO) system [7,8].

II. LITERATURE REVIEW

A. Initial STC in MIMO System

MIMO technology is a method that uses multiple antennas at both the sender and receiver to create multiple communication links simultaneously. This results in enhanced channel capacity and better utilization of the spectrum without requiring increased transmission power or more spectrum resources. Since its debut, MIMO has opened up a wider range of possibilities for improvement and flexible usage in wireless communication.

Massive MIMO, which utilizes large antenna arrays, plays a crucial role in 5G as it improves the spectrum efficiency and network performance of 5G systems, helping to achieve the goal of gigabit throughput [9,10]. Research in the field of information theory supports the use of multi-element antenna arrays at both ends of a wireless link in a MIMO system, resulting in significant improvement in communication capacity .

The successful deployment of Space-Time Coding (STC) in MIMO systems necessitates multiple antennas at both the sender and receiver. STC is a type of signal coding that utilizes antenna array processing to boost MIMO performance [11]. In the mid-1980s, Winters was the first to acknowledge the significance of antenna diversity in wireless communication capacity. Moreover, the development of MIMO and STC has led to the creation of new technologies such as beamforming, cooperative communication, and network MIMO, among others. The combination of MIMO and STC has greatly influenced the development of wireless communication and continues to drive innovation in this field.

B. Principle of Space-Time Coding

Space-time coding is a widely used technique in systems with multiple transmit antennas. It enables the transmission of signals through different antennas at the same time to achieve spatial diversity and through the same subchannel at different times to achieve time diversity. This separation of time and location creates unique space-time properties that increase the reliability of the transmission. Space-time coding reduces the bit error rate and improves the bandwidth utilization by doubling system capacity without the need for additional bandwidth resources [12].

Space-time coding includes a variety of techniques, such as transmit diversity, receive diversity, channel coding, signal modulation, etc. The combination of these techniques results in improved data rate in MIMO systems and higher channel capacity [13]. In space-time coding, the input high-speed information bit stream is transformed into several low-speed bit streams, each of which is independently coded and modulated, and then mapped to different transmit antennas. At the receiver, the information is extracted using multiple confidence channels that take into account the differences in multipath fading characteristics.

C. Design Objectives of Space-time Coding

Space-time coding is designed for use in multi-path and multi-collision communication environments. To maximize the benefits of the multipath effect, the antennas used for transmission and reception should be placed far apart.

Space-time coding helps improve the performance of wireless communication systems by exploiting the characteristics of the environment, such as the multipath effect and the spatial and temporal correlation of transmission signals. This approach helps to minimize the impact of multipath fading, which is a major challenge in wireless communication, and enhance spectral efficiency. By providing both diversity gain and coding gain, space-time coding can significantly improve the transmission reliability and increase the capacity of the communication system. The research in this area has evolved over time, starting with a focus on designing the transmitted signals to be both spatially and temporally independent, and later shifting to using only time-domain coding with multiple independent transmit antennas. The challenge in this area of research is to find ways to effectively manage and eliminate interference between the received signals [14].

III. RESEARCH METHODOLOGY

A. Analysis of Space-Time Coding Design Criteria

The focus of this paper is to design a communication system code in the additive Gaussian white noise (AWGN) channel with slow Rayleigh fading. Since the channel characteristics are known, the method of decoding the encoded information at the receiver is maximum likelihood decoding.

At the receiving end of the communication system, the maximum likelihood method is used for decoding, and its performance is generally measured by the paired error probability. When the current form is established, there will be paired errors:

$$\|r - Hc\|_F^2 \geq \|r - Hc'\|_F^2 \quad (1)$$

Where, c' is the error estimate code word selected by the decoder, and $\|\cdot\|_F^2$ is the norm operation symbol.

If the channel parameter H_t and the received signal r are respectively:

$$H_t = \begin{bmatrix} h'_{1,1} & h'_{1,2} & \cdots & h'_{1,N_T} \\ h'_{2,1} & h'_{2,2} & \cdots & h'_{2,N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h'_{N_R,1} & h'_{N_R,2} & \cdots & h'_{N_R,N_T} \end{bmatrix} \quad (2)$$

$$r = H_t c + n \quad (3)$$

Substituting (2) and (3) into formula (1) and simplifying it to obtain:

$$\sum_t \sum_{m=1}^{N_R} 2 \operatorname{Re} \left\{ (n_t^m)^* \sum_{n=1}^{N_T} h_{mn}^t (c_t^n - c_t'^n) \right\} \geq \sum_t \sum_{m=1}^{N_R} \left| \sum_{n=1}^{N_T} h_{mn}^t (c_t^n - c_t'^n) \right|^2 = d_0^2(c, c') \quad (4)$$

Assuming that the receiver has an ideal CSI, the equal sign in equation (4) holds[15].

$d_0^2(c, c')$ is the corrected Euclidean distance between the actual transmitted space-time codeword and the error-estimated codeword, which can also be expressed as:

$$d_0^2(c, c') = \sum_m \sum_n \lambda_n |\beta_{m,n}|^2 \quad (5)$$

The codeword difference matrix can be expressed as: $B(c, c')_{N_T \times N_T} = c - c'$, and the codeword distance matrix is $A(c, c')_{N_T \times N_T} = B(c, c') \cdot B^T(c, c')$. Where λ_n is the eigenvalue of the codeword distance matrix $A(c, c')$, and v_n is the eigenvector of $A(c, c')$. $\beta_{m,n} = h_m \cdot v_n$. h_m is the row vector of H .

The upper limit of conditional paired error probability based on H , according to the research of (Vahid Tarokh, 1998) and (B Vucetic, J Yuan, 2003), there are two cases (R is the rank of $A(c, c')$.) according to the difference of RN_R value.

When RN_R is large, the upper limit of paired error probability is:

$$p(c, c') \leq 1/2 \exp \left(1/2 \left(\frac{E_s}{4N_0} \right)^2 N_R \sum_{i=1}^R \lambda_i^2 - \frac{E_s}{4N_0} N_R \sum_{i=1}^R \lambda_i \right) \cdot Q \left(\frac{\frac{E_s}{4N_0} \sqrt{N_R \sum_{i=1}^R \lambda_i^2} - \frac{\sqrt{N_R \sum_{i=1}^R \lambda_i}}{\sqrt{\sum_{i=1}^R \lambda_i^2}}}{\sqrt{\sum_{i=1}^R \lambda_i^2}} \right) \quad (6)$$

$Q(x)$ is the auxiliary error function, $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt$.

When RN_R is small, the upper limit of paired error probability is:

$$p(c, c') \leq \left(\prod_{i=1}^R \lambda_i \right)^{-N_R} \left(\frac{E_s}{4N_0} \right)^{-RN_R} \quad (7)$$

Equations (6) and (7) are directly related to RN_R [16,17]. Thus, the design criteria of STC in slow Rayleigh fading channel are obtained:

- 1) Rank criterion: let $B(c, c')$ be full rank to obtain full diversity gain $N_T \times N_R$.
- 2) Determinant criterion: maximize the minimum value of the determinant of $A(c, c')$, that is, maximize the product $\prod_{n=1}^r \lambda_n$ of the minimum non-zero eigenvalues of $A(c, c')$ to ensure that the minimum coding gain distance of the code is maximum, so as to obtain high coding gain.
- 3) Trace criterion: maximize the minimum value of $\|B(c, c')\|_F^2$ to obtain high coding gain.

We can use the above Space-Time Coding Design Criteria to determine the performance of the designed space-time codeword. For example, in the famous Alamouti space-time coding scheme, the determinant of the error matrix will never be equal to 0: $\det B(c, c') \neq 0$, because the multiple signals sent by multiple transmitting antennas at the same time are orthogonal to each other [15,18]. So when $c \neq c'$, $B(c, c')$ is always a full rank matrix (satisfying the rank criterion). At the same time, all eigenvalues of the codeword distance matrix $A(c, c')$ are also greater than 0 (satisfying the determinant criterion), so Alamouti code can obtain full diversity, and its diversity gain is $N_T \times N_R$. That is to say, Alamouti space-time coding matrix satisfies the rank criterion and determinant criterion, and is a superior space-time coding scheme.

The design criteria demonstrated above are those proposed by Tarokh et al. to reduce the bit error rate of information transmission. Using these three criteria, we can design a coding scheme with maximum coding gain, thus obtaining a lower bit error rate, making more correct bits transmitted per unit time, and maximizing channel capacity.

In fact, these criteria were initially proposed to design STBC (space-time block coding) with excellent performance, so that STBC first has full diversity characteristics, and then maximize its coding gain.

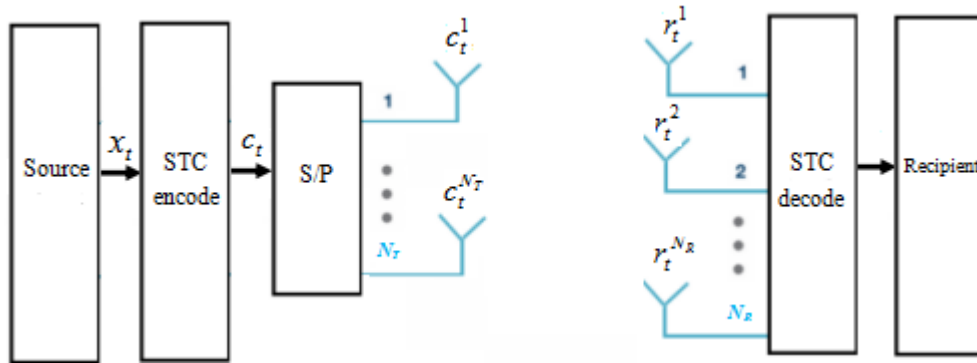
The coding gain is a measure of the power gain of the coding system relative to the non-coding system with the same diversity gain and the same error probability. The above criteria ultimately maximize the minimum distance between

codewords. Therefore, in the process of designing space-time codewords, under the premise of following the design criteria, the key problem of STC becomes how to better combine with diversity technology [19].

IV. RESULTS AND DISCUSSIONS

A. Model of Space Time Coding System

Space-time coding involves the combination of signals for transmission, using a two-dimensional approach to information processing. To enhance the capacity and speed of wireless communication systems, multiple antennas are utilized for transmitting and receiving signals, which is referred to as spatial diversity[20]. This improves the overall performance. To enable diverse reception, correlations between signals transmitted from different antennas in both the time and space domains are introduced. Figure 1 provides a visual representation of a typical space-time coding system model, which comprises a source, an STC encoder, a serial to parallel converter, an STC decoder, and a sink..



$$c_t = (c_t^1, c_t^2, \dots, c_t^{N_T})^T \xrightarrow{H_{N_R \times N_T}} (r_t^1, r_t^2, \dots, r_t^{N_R})^T$$

Figure 1. model of space time coding system

B. Analysis of The Transmitting Model of Space-Time Coding System

In this baseband STC communication system, at each time t , the source bitstream x_t (composed of m binary information symbols) is first sent to the space-time encoder, and x_t can be expressed as:

$$x_t = (x_t^1, x_t^2, \dots, x_t^m) \tag{8}$$

The encoder first maps the m binary information symbols into modulation symbols, and then sends them to the

serial/parallel converter (S/P) to form $c = \dots \begin{bmatrix} c_1^1 & c_2^1 & \dots & c_t^1 \\ c_1^2 & c_2^2 & \dots & c_t^2 \\ \vdots & \vdots & \ddots & \vdots \\ c_1^{N_T} & c_2^{N_T} & \dots & c_t^{N_T} \end{bmatrix}$. Where N_T parallel symbol sequences c_t can be

expressed as $N_T \times 1$ -column vectors:

$$c_t = (c_t^1, c_t^2, \dots, c_t^{N_T})^T \tag{9}$$

Where, T represents the transposition of the matrix. Then the N_T parallel output symbols $c_t^i \ 1 \leq i \leq N_T$, correspond to the i th transmitting antenna, and are simultaneously transmitted by the N_T antennas within the same time width T_{sec} . The vector of coded modulation symbols corresponding to different antennas is space-time symbol.

The spectrum utilization of the system is:

$$\eta = \frac{r_b}{B} = m \quad \text{bit/s/Hz} \quad (10)$$

In the formula, r_b is the data speed and B is the channel bandwidth. The visible equation (10) is equal to the spectral utilization of the encoding system of a single transmitting antenna.

Assuming that the channel of this wireless mobile communication system is memory-less, then the link from each transmitting antenna to each receiving antenna can be represented by a flat fading model. At time t , the $N_T \times N_R$ MIMO channel can be represented by a channel matrix H_t .

C. Analysis of The Receiver System Model of Space-Time Coding System

At the receiving end of the system, each signal on the root receiving antenna is a superposition of the noise after the signal sent by the root transmitting antenna is attenuated by the attenuation channel. The noise column vector n_t at the receiver may be expressed as:

$$n_t = (n_t^1, n_t^2, \dots, n_t^{N_R})^T \quad (11)$$

In the formula, n_t^j is the noise component of the j ($1 \leq j \leq N_R$) root receiving antenna at time t , which is a zero-mean complex Gaussian random variable with a one-sided power spectral density of N_0 .

Therefore, at time t , the received signal column vector on the root receiving antenna may be expressed as:

$$r_t = H_t c_t + n_t = (r_t^1, r_t^2, \dots, r_t^{N_R})^T \quad (12)$$

The receiving signal on the j th receiving antenna at time t is expressed as:

$$r_t^j = \sum_{i=1}^{N_T} H_t^j \cdot c_t^i + n_t^j \quad (13)$$

It is assumed that the receiver obtains the ideal channel state information (CSI), and the decoder estimates the emission information sequence using the maximum-likelihood algorithm[21]. The judgment measure is:

$$d = \sum_t \sum_{j=1}^{N_R} \left| r_t^j - \sum_{i=1}^{N_T} h_{j,i}^t \cdot c_t^i \right|^2 \quad (14)$$

The decoder selects codewords with minimum judgment measures as the output.

V. CONCLUSION

This study examines MIMO technology, with a particular emphasis on space-time coding as a key component of the MIMO system. The space-time coding system model is introduced and subsequently its design criteria are studied. In addition, the mathematical models of the transmitter and receiver in a MIMO system are presented to provide a thorough grasp of space-time coding design.

Effective implementation of space-time coding requires several antennas at both the transmitter and receiver, as the production of codewords in both temporal and spatial dimensions is necessary. In order to optimize the error performance of multi-antenna transmission, error control coding, modulation, transmission diversity, and spatial and temporal 2D transmission signals are generated concurrently. The objective of space-time coding is to maximize diversity gain, coding gain, and realized capacity while maintaining a simple decoding method. For improved performance, integrating space-time coding into 5G systems and future wireless networks is a critical factor to consider.

As codewords must be formed in both temporal and spatial dimensions, the successful operation of space-time coding requires the use of several antennas at the transmitter and receiver. In conjunction with error control coding, modulation, transmission diversity, and spatial diversity, spatial and temporal 2D transmission signals are produced to improve the

error code performance of multi-antenna transmission. The design goal of space-time encoding is to obtain the maximum diversity gain ($N_T \times N_R$), the maximum encoding gain, and the maximum realized capacity, while having the simplest decoding algorithm [22]. How to better integrate space-time coding technology or its integration with other technologies into 5G system and next generation wireless system is very important[23,24].

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