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A Review on STBC Design with Two Transmit Antennas

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Abstract: Detection schemes that can outperform the conventional Orthogonal Space-Time Block Code (STBC) in real practical situations (imperfect CSI, time-varying fast fading channels, spatially correlated channels, ...) are investigated. This article focuses on the case of 2×1 and 2×2 MIMO systems, which are attractive in IoT and industrial communications due to multiple antennas design cost and need of fast prototyping. Indeed, large MIMO arrays are not suitable for reconfigurable intelligent surface (RIS) and 5G Reduced Capability (RedCap) devices where coding/decoding complexity has to be low. The optimization of 2×2 MIMO systems is therefore receiving renewed interest.

Keywords: space-time block code; multiple-input multiple-output (MIMO); fast fading channels; spatially correlated channels

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1. Introduction

Using multiple antennas at the transmitter and receiver terminal can improve the performance (data rate, spectral efficiency, bit error rate, ...) of a communication system and provide diversity in a fading environment without increasing the transmitting power. Diversity is a metric used to evaluate the reliability of communication systems with multiple antennas at the designing phase of these MIMO (multiple-input multiple-output) systems. In the last ten years, MIMO systems featuring a massive number of antennas have been studied for possible adoption by the 5G NR standard. This so-called massive MIMO technology is facing the challenges of high hardware cost, high energy consumption, and high decoding complexity.

In Rel-17, 3GPP has introduced Reduced Capability (RedCap) devices [1]. The goal is to have lower device cost and complexity for specific connected objects and industrial sensors. RedCap devices may have compact form factor with reduced number of antennas. Indeed, reducing the number of receiving antennas allows to simplify the RF (radio frequency) design (amplifier, mixer, local oscillator, ...) and therefore reduces the RF cost.

Another technology that can fulfill the need of low cost and high energy efficiency in specific MIMO communication systems is reconfigurable intelligent surface (RIS) [2]. RIS systems can actually manipulate the parameters of electromagnetic (EM) waves, such as amplitude and phase, in a real-time programmable manner, without the need for conventional RF chains. A RIS-based Alamouti space-time coding was implemented in [3]. The authors state that RISs will allow considerable cost reduction for 2×1 and 2×2 MIMO systems.

The OSTBC (orthogonal space-time block code) code proposed by Alamouti in 1998 [4] is the most adopted solution when implementing 2×1 and 2×2 MIMO systems. The

Alamouti code is the only OSTBC that can achieve full spatial rate when the constellation has complex values in the 2×1 case [5]. The rate of a STBC is defined by the number of different symbols transmitted per antenna divided by the number of time slots used to transmit those symbols. The Alamouti scheme transmits two symbols (and their redundant copies) every two time slots. This gives rate one, also called full rate.

Another attractive feature of the Alamouti code is that the receiver terminal can perform a maximum likelihood decoding with low complexity (linear processing instead of exponential) if CSI (channel state information) is known at the receiver terminal. For any communication system, the Maximum Likelihood decoding rule is based on exhaustive search over all possible code words used to find the symbol that minimizes a metric based on Euclidean distance. While Maximum Likelihood causes high decoding complexity for large number of transmit antennas, the optimum Maximum Likelihood decoder is very simple for 2×1 OSTBC: it consists in a matched filter and a symbol-by-symbol detector.

In many MIMO research works, such as [6, 7, 8, 9], an ideal channel estimation is used in the calculations, by considering that the channel changes very slowly. This assumption lead to a systematic usage of the original Alamouti code to develop new decoders because it can achieve full-rate and full-diversity transmission in 2×1 MISO (multiple-input-single-output) systems and its implementation is simple. However, according to my literature review, better STBC decoders could be built in case of mobile channels, typically present in satellite and vehicular communications. Such channels are time-varying fast-fading channels. They cause spatial correlation between two transmit antennas and perfect CSI at the receiver terminal is not realistic. Sometimes no CSI is available at all because of limited on board resources accessible at the receiver terminal. In addition, a real system may experience significant latencies due to processing overheads. Low decoding complexity is therefore needed to reduce these latencies.

This article is an overview of existing methods to efficiently implement STBC schemes for 2×1 MISO and 2×2 MIMO systems in the following cases:

- need of processing overheads reduction
- partial or unknown CSI at the receiver terminal
- spatial correlation between the transmit antennas

This manuscript could be used as a guide to help engineers who need to choose the right STBC-based technique for their work.

2. Channel state information aspect

2.1. Design without CSI knowledge

In some situation, channel estimation is not suitable. For instance, CSI may be inaccurate when the coherence time of the channel is small. Sometimes CSI may not be available because of limited on board resources accessible at the receiver terminal. Methods not requiring the estimation of CSI can be a solution. Non-coherent schemes, also known as differential schemes, are an example. Tarokh and Jafarkhani [10] proposed the DSTBC (differential STBC). This code is based on the Alamouti code and can achieve full rate and full diversity without CSI knowledge. This DSTBC scheme is more resistant to the channel variation, but the signal-to-noise ratio (SNR) is degraded by approximately 3 dB from that of Alamouti STBC in slow fading environment. Ettus USRPs (Universal Software Radio Peripherals) are used in [11] to prototype a DSTBC-based 2 × 1 MISO communication system.

Fan [12] proposed an improved version of the original DSTBC with two transmit antennas by using a multiple symbol differential detection method for BPSK, QPSK and 8-PSK signals. For three-pair symbols case, it can provide more than 1 dB SNR gain at the price of a slight increase of the decoding complexity. Later, authors in [13] proposed to extend Fan work with more than three blocks, which increase the decoding complexity. They were able to reduce the decoder complexity by designing a multiple differential feedback detection.

2.2. Joint channel estimation and symbol decoding

Many theoretical works on wireless communication, such as the Alamouti code [4], deal with the optimization of symbol decoding assuming perfect CSI. However, in practice, CSI is just an estimate. The channel estimator quality influences the bit-error-rate (BER) performance of STBC-based MIMO systems and better performance can be obtained by jointly estimating the channel and decoding the symbols.

The channel estimation process can be supervised or unsupervised. Supervised channel estimation can be based on pilot symbols, also known as training sequences. Knowing two channel parameters is needed to perform coherent detection in 2 × 1 Alamouti systems. This can be done by means of using pilot symbols. However, their usage reduces the system throughput and wastes energy during the signal transmission because these training sequences do not carry useful information [14]. The 2×2 version of the Alamouti decoder employs maximum ratio combining (MRC) at the receiver terminal and requires knowledge about four channel parameters, which reduce even more the system throughput and therefore reduce the system spectral efficiency. This problem has led researchers to find new STBC decoding strategies that can reduce the usage of pilot symbols. For instance, authors in [15] have implemented a new STBC scheme for 2×2 MIMO systems with joint channel estimation and symbol decoding. It has better BER, without increasing the number of pilot symbols.

Another strategy to mitigate the system throughput limitation problem, is to use unsupervised techniques, also known as Blind Source Separation (BSS) techniques [16]. They allow channel coefficients estimation without pilot symbols. These techniques can be employed if the transmitted signals are statistically independent. Several authors have proposed BSS methods tailored to the classical OSTBC scheme [17, 18, 19]. However, authors in [20] pointed out that all these methods do not allow unique identification of a channel due to phase ambiguity and proposed a novel blind channel identification technique tailored to their custom full diversity space–time block code for 2×1 MISO systems, with optimal Maximum Likelihood decoding.

A last point I want to mention about channel estimation algorithms is their complexity. It is an important challenge in wireless communication systems because a high decoding complexity at the receiver terminal implies more power consumption and delay. In many standards, such as Wi-Fi and 3GPP standards, channel estimation is done every time the receiver decodes a new frame, even if it is not really necessary. Indeed, a new channel estimate is only needed when there is a significant fluctuation of the channel state or of the SNR. Authors in [14] proposed a process including a decision rule to automatically determine the time instants when CSI must be again updated. Their solution reduces the computational complexity of both supervised and blind channel estimation in the 2×1 Alamouti scheme and does not sacrifice the Symbol Error Rate (SER).

3. Influence of the channel type on STBC design

3.1. Time-varying fast fading channel

The Maximum Likelihood decoding techniques proposed for the original Alamouti decoder rely on the assumption that the channel fading is quasi-static: the channel gains stay constant within a frame but might vary from one block to another. Using the original Alamouti decoder requires periodical updates of CSI. This can be done by sending pilot signals. The channel should change very slowly to be considered constant until the next training period. While this assumption is most of the time reasonable, it does not hold true for applications with high mobility like satellite and vehicular communications. For example, in a train, if a mobile phone moves at a speed of 500 Km/h and the carrier frequency is 2 GHz, the Doppler shift is 800 Hz, which causes considerable inter-symbol interferences (ISI) [21]. In this situation, a time-selective fading channels model is more appropriate. This channel is not static and the channel matrix is not an orthogonal matrix, i.e. there is a temporal correlation between consecutive symbols. When the channels are highly time-varying, the Alamouti scheme causes additional ISI between the two transmit antennas. Consequently, time-varying fast-fading channels induce considerable performance loss when the Alamouti decoder is used at the receiver [22].

Authors in [22] showed that the linear Maximum Likelihood decoder (i.e. the conventional decoder of 2×1 and 2×2 OSTBC) is not a good choice in a fast fading environment. Indeed, this detector is not a true Maximum Likelihood detector anymore if the channel is not static over consecutive transmission periods.

Authors in [23] proposed a Minimum Mean Square Error (MMSE) detector, which features noise and interference components removal. This detector can therefore enhance the performance of the 2×1 Alamouti scheme over time-varying fast fading channels. However, their decoder is not a maximum-likelihood decoder.

Tran and Sesay [21] proposed a novel maximum-likelihood decoder of OSTBC for wireless communications over time-selective fading channels. The proposed decoder computes the decision statistics using CSI and fully suppresses the inter-transmit-antenna interference (ITAI). The authors have also shown that their decoder becomes optimal in the Maximum Likelihood sense for OSTBC when the channel is quasi-static.

However, authors in [24] pointed out that Tran and Sesay decoder does not suppress noise and proposed a detector using a MMSE method to suppress both noise and interference. Authors in [25] proposed a QR-based detection scheme of OSTBC for very fast fading channels. The proposed detection scheme employs a QR decomposition on the channel matrix and solves the noise problem of Tran and Sesay decoder.

3.2. Spatially correlated channel

The performance of STBCs has been mainly studied when the MIMO channel is spatially uncorrelated. In practice, spatial correlation can be caused by sparse scattering environments. Moreover, the 2×2 STBC case leads to significant cross-correlations between RX or between TX signals and reduce the MIMO systems performance. When designing a communication system, the space between the antennas should be at least half a wavelength to guarantee that the path estimates are uncorrelated. However, in mobile communications, the mobile terminal is small in size and placing multiple antennas on it can lead to correlation at the antennas because there is not enough space between them. A solution is to use multiple transmit antennas on the base station and only one antenna for the mobile. This allows to implement 2×1 STBC schemes. However, 2×2 STBC schemes that have satisfying performance (even with some correlation at the antennas) could be designed to increase the diversity gain. Paulraj et al. [26] proposed a modified MIMO channel matrix under the spatial correlation effect at both transmitter and receiver to study the impact of channel spatial correlation. They concluded that most STBC schemes's performances deteriorate under spatially correlated fading channels. Research on robust STBCs with respect to spatial correlation is still an active topic.

In LTE-Advanced (LTE-A) systems, user equipment (UE) is imposed two transmit antennas and a code with two antennas and three time slots is required. The classical Alamouti code cannot therefore be applied. Kuhestani et al. [27] proposed a full-rate linear dispersion STBC tailored to correlated Rayleigh fading channels and appropriate for LTE-A systems. Their code designed for two transmit antennas provide better performance than the classical Alamouti code.

Finally, STBC-based communication system designers should wonder if the channel state information is available at the transmitter. If it is the case, the combination of STBCs and precoding techniques can be used to enhance the performance of the original Alamouti code by adapting the data encoding in function of the channel state. Phan et al. [28] have designed precoders for space-time coded systems over correlated Rayleigh fading channels.

3.3. Backscatter channel

Backscatter channel models are used for experiments involving battery-free connected objects in future Internet-of-Things (IoT) networks. These devices require no internal battery and almost zero maintenance. The drawback of backscatter communications is channel deep fading. The MIMO backscatter channel can be modeled as a two-way channel with forward links and backscatter links.

He et al. [29] have suggested that there may exist simple Space–Time Codes, which were ignored in the conventional channel but would be preferred in the backscatter channel. They proposed a 2×2 STBC scheme simpler than the Alamouti code that performs well in the backscatter channel. It considerably reduces the tag circuit complexity, which makes it a good choice for low cost and hardware-limited backscatter devices in the future IoT networks. Besides, Luan et al. [30] showed that a rotation of the classical Alamouti code can increase the availability for backscattering signals.

4. Optimality criteria for 2×2 MIMO systems

4.1. Channel capacity maximization

The Alamouti scheme can be used to achieve capacity and full-rate when there is one receive antenna but not when there is more than one. The Alamouti code still achieves full-diversity transmission in 2×2 MIMO systems but with half rate. A code rate is quantified by the spatial multiplexing gain. Hence, many researchers have built new STBC schemes to maximize the spatial multiplexing gain, which gives full rate codes.

In addition, in the case of 2×2 MIMO communication systems, OSTBC schemes, such as the Alamouti scheme, do not preserve the mutual information between the received and the transmit signal vectors due to the induced space-time correlation on the channel matrix. Hence, OSTBC does not achieve channel capacity in 2×2 MIMO and is only half rate. In other words, orthogonal designs are not suitable for very-high-rate communications [31]. Authors in [31] proposed a 2×2 full-rate full-diversity linear dispersion space-time block code (STBC) to overcome this problem. This non-orthogonal STBC scheme can achieve channel capacity.

4.2. Optimum diversity-multiplexing gain tradeoff

The Alamouti scheme achieves the diversity-multiplexing gain tradeoff in the case of a single receive antenna. A sufficient condition for a space-time code to achieve the optimal diversity-multiplexing gain tradeoff for a 2×2 MIMO channel with an arbitrary fading is the nonvanishing determinant (NVD) property, also known as non-vanishing coding gain property: the coding gain does not depend on the constellation size [32]. Some researchers proposed non-orthogonal STBC schemes that satisfy this condition, while keeping maximum spatial diversity. The Golden code [33] has optimum coding gain and achieve the optimum diversity-multiplexing gain tradeoff for all PAM or QAM constellations. This code is currently the best for 4-QAM constellation.

Ghaderipoor et al. STBC [32] is the best code for PAM constellations, such as BPSK and 4-PAM (non-complex symbols). It outperforms the Golden code in the case of PAM constellations but has still high complexity (non linear complexity) at the receiver terminal. Indeed, the ML decoding of these codes require sphere decoding technique, which is computationally demanding.

4.3. Full rate codes with low decoding complexity

Many researchers have tried to reduce the decoding complexity of STBCs for 2×2 MIMO communication systems, while keeping the full-rate and full-diversity advantage. In case of BPSK symbols, Bidaki et al. [34] code, also known as full-rate linear-receiver (FRLR) STBC, has the same performance as Ghaderipoor et al. STBC, while allowing low complexity (linear complexity) at the receiver terminal.

Authors in [35] proposed a new 2×2 full-rate full-diversity linear dispersion STBC that achieves the optimal diversity-multiplexing gain (DMG) tradeoff. Their maximum-likelihood decoder has a low computational complexity with respect to other full-rate STBCs.

Authors in [36] proposed a new STBC design for 2×2 MIMO systems that does not achieve the optimum diversity-multiplexing tradeoff. However, their code has maximum-diversity, maximum-capacity and maximizes the coding gain. Their design has lower complexity Maximum Likelihood decoding. Indeed, it is quadratic in the constellation size whereas design complexity of the Golden code is proportional to the fourth order of the signal constellation size.

5. Conclusions

In this paper, STBC-based detection schemes that can outperform the classical Alamouti STBC were studied. Various performance criteria were considered. The robustness to imperfect CSI, to time-varying fast fading channels and to spatially correlated channels were studied. The channel capacity maximization for 2×2 MIMO communication systems was discussed. The decoding complexity was also taken into account because it is an important aspect for reconfigurable intelligent surface and 5G RedCap devices. It should be pointed out that many communications engineering works resort to the classical Alamouti scheme, while the STBC-based schemes mentioned in this paper may be more appropriate depending on the considered performance criteria.

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