Space Time Block Codes for MIMO systems: History to Recent Developments

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Abstract: *Multi Input Multi Output (MIMO) communication is a proven technique to increase the throughput, diversity gain and increase the energy gain by reducing the energy consumption of the wireless network. Space time diversity used in MIMO systems is a technique to mitigate multipath fading. The same information is transmitted over multiple channels that fade independently. So, space time diversity is achieved. Transmit space time diversity is achieved if the transmitter has knowledge of the channel. But, if the transmitter does not know the channel then it is necessary to code across both space and time to achieve diversity which is termed as space time coding. In this article, we discuss the developments in MIMO systems and Space Time Block Coding Techniques for MIMO systems, over the years.*

Keywords: Space time block codes, diversity, fading, relay channel, user cooperation

1. Introduction

Wireless networks are designed to provide high voice quality and services at very high data bit rate. At the same time, they should be deployable in any environment and must be bandwidth efficient. Further, they should provide mobility, portability, minimum interference from other users, privacy and security. The major challenge to meet all these expectations is posed by time varying multipath fading [1], [2]. So, it is necessary to understand the behavior of wireless channel. In wireless channels, there are many different paths through which a signal is propagated between transmitter and receiver. The interference between two or more versions of the transmitted signal which arrive at the receiver at slightly different times causes fading. The resulting signal generally varies widely in amplitude and phase. Time varying multipath fading can be slow or fast; frequency selective or frequency flat [3]-[5]. Due the destructive addition of multipaths, the fading channel suffers from sudden decline in power. This can lead to deep fades and reliable recovery of the signal at the receiver becomes immensely difficult. In other words, if the ratio of signal power to noise power (SNR) at the receiver falls below a certain threshold, it leads to outage. The most effective technique to mitigate fading is through power control. But, the requirement of the transmitter dynamic range and knowledge of the channel which results in throughput degradation and complexity made this approach unpopular [3].The technique of diversity is used to mitigate the effects of multipath fading. It provides different replicas of transmitted signal to receiver. If these replicas fade independently, the possibility of all experiencing deep fading simultaneously is very low.

Diversity can be implemented in space (spatial), time (temporal), frequency, using different directional antennas (angular) and using different polarizations to transmit the same signal (polarization) diversity[6]-[10]. In many situations, however, the channel is both significantly frequency selective and time varying i.e. the wireless channel can be assumed to be quasi static and frequency flat. The system engineers can deploy multiple antennas at both transmitter and receiver to achieve spatial diversity.

Relay networks have the capability of providing spatial diversity to mitigate the effects of fading, thereby providing robustness gain [11]-[13]. It is practically not feasible to place multiple antennas on a small size terminal. A single antenna receiver can therefore use relay nodes as virtual antennas. Besides providing spatial diversity in Multiple Input Multiple Output (MIMO) systems [14] and [15] the capacity of wireless channel also grows manifold with the number of transmit and receive antennas and offers multiplexing gain [3], [5].

In a two-way cooperative MIMO system, relays can be passive i.e. they do not transmit their own data but rather choose to cooperatively listen. In another case, a user can act as relay and can transmit other users' data when idle [16]-[20]. Cooperative MIMO which is also referred to as distributed, virtual or networked MIMO, uses cooperating nodes with multiple antennas to emulate a virtual antenna array. In a large set of single antenna relay nodes, only a small set of relay nodes are active at any given time. Such type of MIMO systems are studied in [21], [22], and find applications in ad- hoc and sensor networks employing decode and forward relaying. A new class of Distributed space time block codes (DSTBC) is suggested in [23] which enable efficient node cooperation in networks with large number of relay nodes. In practice, such code design is often very difficult to realize due to the distributed and ad-hoc nature of cooperative links as compared to codes designed for co-located MIMO systems [24]-[26]. Single selection opportunistic relaying with decode-and-forward (DaF) and amplify-and-forward (AaF) strategies, is presented in [27]. Here distributed relay selection algorithms are used for outage optimal opportunistic relaying and outage probability is analyzed under an aggregate power constraint. But, such schemes often require large cooperation overhead.

One of the key problems in cooperative system is the requirement of a global channel state information (CSI) [28], [29]. When CSI is known, pair of neighboring nodes can cooperatively beamform [30] towards final destination to increase capacity and enhance performance of multi antenna system [16]. Optimal channel estimation and training design for two way AaF relay networks is proposed in [31]. Novel

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channel estimation for two hop MIMO relay systems using parallel factor analysis is discussed in [32]. The proposed algorithm provides destination node full knowledge of all channel matrices and at the same time requires lesser number of training blocks, yields less estimation error, and is applicable to both one way and two way MIMO relay systems with single and multiple relay nodes. Other recent works on channel estimation problem for multi relay MIMO systems using tensor approach can be found in [33]-[37]. Comparison of different channel estimation schemes for MIMO two way relaying system is done in [38]. A rate efficient two phase training protocol for cascaded channel estimation, required for maximum likelihood (ML) detection [3], [4], [5], [42], [45] has been recently proposed in [39]. But, it requires a complex maximum likelihood detector.

2. An Overview

2.1 Space Time Block Codes & Space Time Trellis Codes

The goal of the space time coding is to achieve maximum diversity which is the product of transmitting antennas and receiving antennas in an MIMO system. When the channel is unknown, space time block codes (STBC) can provide maximum diversity, coding gain, high throughput and lower encoding and decoding complexity [40]. The decoding complexity should be low as the mobile transceiver has a limited available battery power. Space time trellis coding (STTC) proposed in [41] combines signal processing at the receiver with coding techniques used for multiple transmit antennas. Alamouti suggested a rate one orthogonal space time block coding (OSTBC) scheme for two transmit and one receive antennas in [42]. The codes provided full diversity and simple decoding using only linear processing. But, there is a loss in performance compared to STTC. Alamouti scheme is still more appealing due to its simplicity in implementation, albeit, with some performance penalty. STBC introduced in [43], [44] generalized the transmission scheme suggested by Alamouti to arbitrary number of antennas and is able to achieve full diversity. The performance of STBC is evaluated further in [45] and details of encoding and decoding procedures have been provided. Real and complex orthogonal designs for STBC based on Radon and Hurwitz theories, and theory of amicable designs [46], are suggested in [43]. Damen et al. suggested construction of space time codes based on number theory in [47]. It is a class of STBCs that provides full diversity with no mutual information penalty. Design of STBCs based on groups and their representation theory have been reported in [48]-[51]. STBCs constructed using Division Algebras and Field Extensions can also be found in literature [52]-[55].

Although, OSTBC can provide full diversity at low computational cost, it suffers loss in capacity for multiple receive antennas and when code rate is less than one. Moreover, complex orthogonal designs that provide full rate and full diversity are impossible to be designed for more than two transmit antennas [43]. To design full rate codes for complex constellations, quasi orthogonal space time block codes (QOSTBC) were proposed in [56], [57]. Here, the separate decoding property is relaxed. It is possible to construct rate one full diversity QOSTBC by using rotated

versions of the symbols. Such codes are called rotated QOSTBCs [58]-[64]. STBCs provide full diversity and low decoding complexity but do not provide large coding gains. On the other hand STTCs are designed to provide full diversity and high coding gain at the expense of higher decoding complexity [65], [66]. High coding gains can also be achieved if STBC is concatenated with outer trellis code designed for AWGN channel. Such codes are called Super orthogonal space time trellis codes (SOSTTC) [67], [68]. SOSTTC considers STBC as modulation schemes for multiple transmit antennas. The outer trellis code for slow fading channel are usually based on the set partitioning concepts of Ungerboeck codes [69] for the additive white Gaussian noise (AWGN) channel [70]. The codes discussed so far, use different channel estimation techniques for detection. The transmitter sends the pilot signals during training phase and receiver uses them to estimate the channel [71]. In all these, quasi static fading is assumed. But, the problem becomes worse for fast fading channels.

2.2 Differential Space Time Modulation

Differential space time modulation employs differential modulation schemes for MIMO channels that neither requires channel knowledge nor pilot symbols, for detection of symbols [72]-[75].

However, if there is a career offset due to the mismatch between transmit and receive clock or relative motion of the receiver and transmitter, the channel does not remain stationary over two consecutive time periods. In such cases, the performance of differential detection scheme degrades significantly. To overcome this problem, Bhatnagar et al. proposed a double differential modulation scheme in [76] for cooperative wireless communication over fast fading Nakagami-m channels.

2.3 Spatial Multiplexing

To achieve highest possible throughput, Spatial Multiplexing (SM) is used. Foschini introduced multilayered space-time architecture in [77]. Since then, different space time architectures have been proposed such as the Bell Labs Layered Space Time architectures (BLAST) [78], [79]. In the SM scheme, the input is demultiplexed into N separate streams and each stream is transmitted from an independent antenna. As a result, the throughput increases N-fold as N symbols per channel are transmitted from N transmit antennas. But, the diversity gain suffers and hence, SM is better suited for high data rate systems operating at relatively high SNRs. On the other hand, STBC is more appropriate for transmitting at low rates and low SNRs. Sphere Decoding (SD) [80] instead of ML decoding, is used in SM. In ML detection, a search for closest integer lattice point to the given vector is performed. So, ML detection reduces to solving an integer least squares problem. In some applications like SM, the complexity in decoding grows exponentially making ML detection computationally intractable. SD limits the number of possible codewords by considering only those codewords (lattice points) that are within a sphere centered at received signal vector. The closest lattice point inside the sphere would also be the closest lattice point for the whole lattice. The problem of finding the closest lattice point to the point of interest is discussed in [81]-[83]. Another approach to design receivers with low decoding

complexity than ML decoding is to use equalization techniques to separate different symbols [3], [84]. Combination or hybrid of SM and STBC is generally used to achieve maximum possible diversity and higher throughput [85], [86].

2.4 MIMO-OFDM

MIMO-Orthogonal Frequency Division Multiplexed (MIMO-OFDM) systems [3], [5], [87], [88] are designed for frequency selective fading channels. A frequency selective channel provides an additional degree of diversity called frequency diversity i.e. the code could operate over space, time and frequency. Thus, maximum diversity can be achieved by transmitting symbols through different antennas and different frequencies. MIMO-OFDM systems still does not provide maximum possible diversity gain because frequency diversity and correlation among subcarriers are ignored in such systems. Space time coded OFDM (STC-OFDM) system designed in [89]-[92] is another approach for transmission over MIMO channels using OFDM. A STC-OFDM also known as space frequency code replaces time with OFDM frequencies in the structure of space time codes.

3. Recent Developments

STBC designs based on quadratic field extensions for two transmitting antennas are reported in [93]. The average codeword error rate of the proposed optimal quadratic STBC is lower than the optimal cyclotomic [94] and golden STBCs [95]. Full diversity non coherent Alamouti based Toeplitz STBCs are proposed in [96]. The proposed codes use the Alamouti coding scheme and the Toeplitz matrix structure to construct a non coherent non unitary STBC. These codes outperform differential codes. Natarajan et al. proposed full diversity multi group decodable STBCs with rate greater than one in [97]. For group g greater than or equal to 3, these are the first instances of multi group decodable codes having rate greater than one reported in the literature. S. Zhao et al. proposed a concatenated scheme with Polar codes [98]-[100] and STBC named Polar-STBC scheme in [101]. The proposed scheme inherits the advantages of Polar codes that can achieve high capacity and low encoding and decoding complexity; at the same time, sufficient diversity gain is also achieved due to concatenation with STBCs.

STBCs that provide full rate and achieve high spectral efficiency, transmit linear combinations of information symbols through every transmit antenna. But, inappropriate choice of coefficients for linear combination may lead to increased processing bits and peak to average power ratio (PAPR) values. Integer Space Time Codes of [102] utilizes integer coefficients in the code structure to reduce the number of processing bits and PAPR values.

STBCs find applications in multi-static/MIMO radar systems also as they allow the use of non-orthogonal waveforms while providing waveform diversity with full signal separation. But, use of STBCs necessitates the assumption of a stationary or immobile target. A modified adaptive block coding scheme suggested in [103] alleviates the issue of target Doppler shifts. The proposed scheme attempts to reduce the ambiguity in detection at lower antenna transmit power too. Le et al. recently proposed a spatially modulated OSTBC (SM-OSTBC) scheme in [104] that is based on the concept of spatial constellation codewords (SC) [107]. The proposed scheme generates transmit codeword matrices by multiplying SC matrices with OSTBC codeword matrices. The proposed SM-OSTBC scheme is able to achieve high spectral efficiency; low decoding complexity and second order transmit diversity by satisfying the non vanishing determinant property [95], [105], [106]. STBCs for MIMO channels have been constructed by Salomon et al. in [108], by concatenating orthogonal designs with diversity transforms (DT) [109]. DT spreads the channel alphabets without sacrificing information rate, bandwidth or Euclidean distance. The distribution of the obtained code alphabet becomes Gaussian like leading to high diversity gain. It has low implementation complexity and high transmission rate. Recently, an efficient MIMO scheme with signal space diversity for future mobile communications is proposed in [110]. It uses rotated modulation and space time component interleaver, and attempts to jointly optimize channel coding and modulation. At the same time, it maximizes achievable rate for MIMO systems and improves link reliability and energy efficiency.

4. Conclusion

Use of STBCs for MIMO systems have generated lot of interest for increasing spectral efficiency and improved performance in wireless communication systems. Although, lot of work has been carried out in the area of STBC-MIMO systems and literature is now extensively available but orthogonal designs suggested by Alamouti [42], Tarokh et al. [44], [45], [71] remain popular and are still relevant in the present context; as orthogonal designs lead to simple, optimal receiver structure due to the possibility of decoupled detection along orthogonal dimensions of space and time.

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