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Performance analysis of zero-forcing precoding with signal space diversity under antenna correlation☆

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ABSTRACT

We consider a multiantenna transmission system where the transmitter and receiver respectively have M and two antennas. Specifically, zero-forcing precoding is employed at the transmitter based on a possibly imperfect channel state information (CSI). The channel estimation is carried out at the transmitter using pilot signals sent from the receiver. Adopting a dual-stream transmission structure, the error performance of the system is enhanced by resorting to signal space diversity (SSD). The performance of the proposed system with binary phase shift keying modulation is studied under a slow flat Rayleigh fading scenario with uncorrelated transmit antennas and correlated receive antennas. We separately examine two cases: the perfect CSI and imperfect CSI at the transmitter. In the former scenario, we provide an exact closed-form expression on the bit error probability (BEP) of the proposed approach. A tight approximation on the BEP of the proposed scheme is presented for the latter scenario. The case with distinct channel estimation qualities for the two subchannels is also considered in the second scenario. The proper rotation angles for the BPSK signal constellation are analytically obtained such that the derived expressions on the BEP are minimized under both cases. We show that the inclusion of SSD into the original scheme yields a noteworthy improvement on the BEP performance with only an insignificant increase in complexity and no additional use of bandwidth/time slots. It is also shown that the proposed technique is more immune against the channel estimation errors as compared to the original method.

1. Introduction

Multiple-input multiple-output (MIMO) systems have become an indispensable part of emerging communication standards. This fact can be attributed partly to the potential in MIMO systems that renders simultaneous transmission of multiple substreams possible without need of additional bandwidth/time slots. In a single-user communication scenario with sufficient scattering, a MIMO system with t antennas at the transmitter and r antennas at the receiver (a t-by-r MIMO system) offers a channel capacity that linearly grows with the minimum of t and r [1]. In such a point-to-point scenario, the exact channel capacity is contingent on the amount of channel state information (CSI) at the transmitter. If no CSI exists at the transmitter, the optimum transmission approach is to transmit independent data streams over t transmit antennas [1]. On the other hand, the capacity can be achieved by using eigenmodes of the channel when the transmitter has full CSI [1,2]. Unfortunately, these capacity-achieving techniques suffer from high complexity. When the channel matrix is full-rank, a low-complexity scheme called zero-forcing beamforming (ZFBF) can convert a t-by-r MIMO system into a system with $\min(t, r)$ parallel independent subchannels. Hence, ZFBF can attain the full spatial multiplexing gain [3–7]. ZFBF exploits the spatial dimensions inherent in the channel matrix to cancel interference among distinct substreams. To this end, a linear processing is performed on the substreams either at the transmitter (zero-forcing precoding, ZFP) or at the receiver (zero-forcing receive beamforming). The beamforming weight vectors required for the linear processing in ZFBF can be obtained from the Moore–Penrose pseudoinverse of the channel matrix [8]. Unlike vertical Bell Labs layered space–time (V-BLAST) algorithm, there exists no possibility of error propagation among substreams in a ZFBF system. Despite the mentioned advantages, the noise boosting feature involved in a ZFBF system places it at a disadvantage in terms of error performance. This loss in error performance emanates from the selection of the beamforming weight vectors. It becomes problematic especially for low signal-to-noise ratio (SNR) values.

In this work, we resort to signal space diversity (SSD) to compensate for the error performance loss in ZFP. We show that the error performance of ZFP can be improved by utilizing SSD (also known as modulation diversity) with no extra bandwidth/time slots, no extra power, and almost no additional complexity. The

☆ A similar scenario with receive beamforming and only transmit antenna correlation was presented at Int. Conf. Electric. and Electron. Eng. (ELECO), 2017, Bursa, Turkey.

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idea behind SSD has been presented first in [9]. For two-dimensional modulation techniques with constant envelope property, SSD relies on a two-step procedure. First, it is guaranteed that each symbol in the signal constellation can uniquely be identified by any of its two components. The second step ensures that both components of a transmitted symbol experience independent fades through the channel. The first condition can be managed by properly rotating the signal constellation [10]. The second condition is generally accomplished by using component interleaving and deinterleaving blocks at the transmitter and receiver, respectively [10–12]. When these two conditions are satisfied, a dual diversity can be obtained for two-dimensional modulation schemes [10–12].

The inclusion of SSD into single-input single-output systems has been widely investigated [9–15]. When used with a two-dimensional signal constellation such as phase-shift keying modulation or quadrature amplitude modulation, SSD has been demonstrated to entail no increase in the decoding complexity [12]. Lately, SSD has also been combined with MIMO systems [16–27]. Some of these studies employ the component interleaver/deinterleaver blocks functioning over time domain [20–23]. Note that with the component interleaver/deinterleaver blocks, the interleaving depth must be greater than the channel coherence time in order to have independent fading among the components of the transmitted symbol. This condition can be quite troublesome for the transmission of latency-sensitive data. Alternatively, the independence between the fading coefficients affecting the components of a transmitted symbol can also be ensured by transmitting the components of each modulated symbol over different transmit antennas [16–19,24–27]. The idea of transmitting two components of a signal point from different transmit antennas is first proposed in [16]. Coordinate interleaved orthogonal design has been introduced in [16] and shown to achieve full-diversity, full-rate, and single-symbol maximum likelihood decodability for the systems using complex signal constellations [17]. When CSI is available at both ends, a technique called coordinate interleaved spatial multiplexing (CISM) has been demonstrated to augment the diversity order of a MIMO system by transmitting multiple data streams over the eigenmodes of the channel [18]. SSD has also been incorporated into V-BLAST algorithm in [19] to augment the diversity order of the system. The performance of precoded bit-interleaved coded modulation spatial multiplexing MIMO system with spatial component interleaver is studied in [20] where CISM technique is combined with channel coding and SSD. In [21], the performance of orthogonal space–time block codes with SSD is studied for Nakagami-m fading channels. SSD has been incorporated into a V-BLAST system with orthogonal frequency-division multiplexing in [22] and the performance of the system over Rayleigh fading channels has been evaluated by means of simulations. A bit-interleaved coded modulation system with spatial division multiplexing has been combined with SSD over frequency selective Rayleigh fading channels [23]. A coded MIMO system relying on SSD has been introduced in [24] for block-fading channels. This scheme has been shown to accomplish full spatial multiplexing and diversity gains via simulations. By assuming the existence of perfect CSI at the transmitter, SSD has been integrated into a ZFP system with uncorrelated antennas at both ends in [25]. Zero-forcing receive beamforming is integrated with SSD under an open-loop (no CSI at the transmitter) scenario for uncorrelated antennas [26] and for antenna correlation only at the transmit side [27]. The work in [27] inspects the error performance only by computer simulations. In [28], a cooperative two-cell downlink transmission framework with SSD is suggested for the cell boundary users. Unlike the prior related studies, we combine an M-by-2 ZFP system with SSD over slow flat Rayleigh fading channels with receive antenna correlation. For the sakes of generality and practicality, we analyze both perfect and imperfect CSI at the transmitter cases. We show how the performance of ZFP can be improved by utilizing SSD with almost no extra complexity under these two scenarios. The performance of zero-forcing receive beamforming is analyzed in [29] under the presence of channel estimation errors at the receiver. As different from the work in [29], the inclusion of SSD necessitates an analysis based on the joint distribution of the subchannel gains, which may not be independent. With imperfect CSI, the error performance of the system is limited by the error floor. We demonstrate that the proposed scheme considerably lowers the error floor. Instead of using time domain component interleaving/deinterleaving blocks, we exploit the existence of multiple antennas to ensure independent fades between the components of the transmitted symbol. Hence, the proposed scheme is especially attractive for systems with relatively long coherence time. The performance of the proposed technique is inspected in slow flat Rayleigh fading channels with binary phase shift keying (BPSK) modulation and antenna correlation only at the receive side. A closed-form expression on the bit error probability (BEP) for the proposed scheme is presented. This expression becomes exact when CSI at the transmitter is perfect. In the other case, it yields a pretty tight approximation on the BEP. The appropriate rotation angles for the BPSK signal constellation are obtained based on the derived expressions.

The remaining of the paper is organized as follows. Section 2 introduces the system model. In Section 3, the proposed scheme is described. A number of numerical results are presented in Section 4. Finally, Section 5 concludes the paper. Throughout the paper, the matrices and column vectors are denoted by uppercase and lowercase bold letters, respectively. The operators $\mathrm{E}[.]$, $|.|$, $(.)^H$, $\|.\|$, $\Re\{.\}$, $\Im\{.\}$, and $\exp(.)$ stand for the expectation, absolute value, Hermitian transpose, Euclidean norm, real part of a complex number, imaginary part of a complex number, and exponential function, respectively. Also, $\mathbb{C}$, j, and $[\mathbf{A}]_{i,k}$ respectively refer to the set of all complex numbers, $\sqrt{-1}$, and (i, k) element of the matrix $\mathbf{A}$. The probability density function (PDF) of a random variable X is represented by $f_X(x)$ and we denote the joint PDF of two random variables X and Y by $f_{X,Y}(x, y)$. Additionally, $f_{X,Y}(a, b)$ means that the variables x and y are respectively replaced with the variables a and b in the joint PDF of X and Y.

2. System model

We assume a single-user MIMO transmission system with two simultaneous substreams and a time-division duplex mode of operation. The transmitter and receiver are equipped with M and two antennas ($M \geq 2$), respectively. The received complex baseband signal at the receiver is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{1}$$

where $\mathbf{H}$ is the 2-by-M channel matrix with its (i, k) entry, i.e., $[\mathbf{H}]_{ik} \in \mathbb{C}$, denoting the fading coefficient between the kth transmit antenna and ith receive antenna. Additionally, the vector $\mathbf{x} \in \mathbb{C}^{M\times 1}$ denotes the transmitted baseband signal. It is aimed to simultaneously transmit two independently modulated symbols $s_i = s_{iI} + js_{iQ}$ ($i \in \{1, 2\}$) where the subscripts I and Q refer to the corresponding in-phase (I) and quadrature (Q) components, respectively. The modulated symbols are obtained from a rotated BPSK signal constellation where the counter-clockwise rotation angle θ satisfies $0 < \theta < \pi/2$ in radian. We also have a per-bit energy constraint such that $|s_i|^2 = E_b$ with E_b standing for the energy per bit. Additionally, $\mathbf{n} \in \mathbb{C}^{2\times 1}$ represents additive white Gaussian noise (AWGN) at the receiver such that $\mathrm{E}\{\mathbf{n}\mathbf{n}^H\} = N_0\mathbf{I}$. Here, N_0 denotes the one-sided power spectral density of the AWGN at each receive antenna and $\mathbf{I}$ is the identity matrix. We adopt a slow flat Rayleigh fading scenario with rich scattering and