Differential Coding for MIMO and Cooperative Communications

Manav R. Bhatnagar

DISSERTATION IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF PHILOSOPHIAE DOCTOR

Department of Informatics
Faculty of Mathematics and Natural Sciences
University of Oslo

Oslo 2008

Series of dissertations submitted to the
Faculty of Mathematics and Natural Sciences, University of Oslo
Nr. 782

ISSN 1501-7710

Cover: Inger Sandved Anfinsen.
Printed in Norway: AiT e-dit AS, Oslo, 2008.

Produced in co-operation with Unipub AS.
The thesis is produced by Unipub AS merely in connection with the
thesis defence. Kindly direct all inquiries regarding the thesis to the copyright
holder or the unit which grants the doctorate.

Unipub AS is owned by
The University Foundation for Student Life (SiO)

Preface

This dissertation has been submitted to the Faculty of Mathematics and Natural Sciences at the University of Oslo in partial fulfillment of the requirements for the degree *Philosophiae Doctor*. The most of this work was carried out at UNIK- University Graduate Center, Kjeller, Norway and some parts are done at University of Minneasota, Minneapolis, USA and Indian Institute of Technology, Delhi, India. This work was fully supported financially by the Research Council of Norway in the framework of the "OptiMO" project under Grant 176773/S10. My supervisor has been Prof. Are Hjørungnes.

The symbol usage may vary from one paper to another as the papers included in this dissertation are *not* published/submitted/revised at the same time.

Acknowledgments

I would first like to thank my supervisor Prof. Are Hjørungnes for all his efforts he put for me being his first Ph.D. student. All of my work has equal contribution of Prof. Hjørungnes. He was a big motivating force behind this herculean task I finished in last couple of years. I cannot forget him in rest of my life.

The almighty God is also thanked for blessing me with nice people around me. I have a firm belief that God has always helped me during this work whenever I reached to the depth of depression.

Next, I must thank my friend Dr. Lingyang Song for the help he provided in accomplishing my research work. He is one of the nicest people I came across in my life. We had a very good time at UNIK discussing the research issues during tea, lunch, and dinner.

The administration at UNIK specially Kristin Scheen, Hellfrid O. Newman, Gerd Haugen Mariniusson, Trond Dragland, Tuhta Ismailova, and

Ivar Jardar Aasen must be thanked for helping me all the time. Their kind cooperation kept my life hassle free and let me concentrate more over my research and studies. I am also thankful to my friends Mohammad Mushfiquer Rahman Chowdhury, Elin Sundby Boysen, Behrouz Maham, Walid Saad, and Najeeb Elahi. A special thank goes to Hilde Skjevling and Frode Bøhagen for providing me help in preparing Latex set-up for the dissertation.

I also express my gratitude to Prof. G. B. Giannakis and Prof. Ranjan Bose for the help they provided for finishing this work.

At last, I would like to thank my wife Arti M. K. for being a guiding force for my research career. Because of her support and continuous motivation I have reached at this point of my life. I also want to thank my son Kushagra for loving me even if I could not spend much time with him during last couple of years. I would also like to thank my parents, my brothers Dr. Anubhav and Vaibhav, my sister Dr. Supriti, and nephew Atulit for providing me support when I needed it.

Manav R. Bhatnagar
Oslo, June 17, 2008

Abstract

Multiple-input multiple-output (MIMO) wireless communication systems have been studied a lot in the last ten years. They have many promising features like array gain, diversity gain, spatial multiplexing gain, interference reduction, and improved capacity as compared to a single-input single-output (SISO) systems. However, the increasing demand of high data-rate in current wireless communications systems motivated us to investigate new rate-efficient channel coding techniques. In this dissertation, we study differential modulation for MIMO systems. Differential modulation is useful since it avoids the need of channel estimation by the receiver and saves valuable bandwidth with a slight symbol error-rate (SER) performance loss. The effect of channel correlation over differential MIMO system has not been studied in detail so far. It has been shown in the literature that a linear memoryless precoder can be used to improve the performance of coherent MIMO system over correlated channels. In this work, we implement precoded differential modulation for non-orthogonal and orthogonal space-time blocks codes (STBCs) over arbitrarily correlated channels. We design precoders based on pair-wise error probability (PEP) and approximate SER for differential MIMO system.

The carrier offsets, which result because of the movement of the receiver or transmitter and/or scatterers, and mismatch between the transmit and receive oscillators, are a big challenge for the differential MIMO system. The carrier offsets make the flat fading channel behave as a time-varying channel. Hence, the channel does *not* remain constant over two consecutive STBC block transmission time-intervals, which is a basic assumption for differential systems and the differential systems break down. Double-differential coding is a key technique which could be used to avoid the need of both carrier offset and channel estimation. In this work, we propose a double-differential coding for full-rank and square orthogonal space-time block codes (OSTBC) with M-PSK constellation. A suboptimal

decoder for the double-differentially encoded OSTBC is obtained. We also derive a simple PEP upper bound for the double-differential OSTBC. A precoder is also designed based on the PEP upper bound for the double-differential OSTBC to make it more robust against arbitrary MIMO channel correlations.

Cooperative communication has several promising features to become a main technology in future wireless communications systems. It has been shown in the literature that the cooperative communication can avoid the difficulties of implementing actual antenna array and convert the SISO system into a virtual MIMO system. In this way, cooperation between the users allows them to exploit the diversity gain and other advantages of MIMO system at a SISO wireless network. A cooperative communication system is difficult to implement in practice because it generally requires that all cooperating nodes must have the perfect knowledge of the channel gains of all the links in the network. This is infeasible in a large wireless network like cellular system. If the users are moving and there is mismatch between the transmit and receive oscillators, the resulting carrier offset may further degrade the performance of a cooperative system. In practice, it is very difficult to estimate the carrier offset perfectly over SISO links. A very small residual offset error in the data may degrade the system performance substantially. Hence, to exploit the diversity in a cooperative system in the presence of carrier offsets is a big challenge. In this dissertation, we propose double-differential modulation for cooperative communication systems to avoid the need of the knowledge of carrier offset and channel gain at the cooperating nodes (relays) and the destination. We derive few useful SER/bit error rate (BER) expressions for double-differential cooperative communication systems using decode-and-forward and amplify-and-forward protocols. Based on these SER/BER expressions, power allocations are also proposed to further improve the performance of these systems.

List of Publications

This dissertation is based on the following five papers, referred to in the text by letters (A-E).

A. M. R. Bhatnagar, A. Hjørungnes, and L. Song, "Precoded Differential Orthogonal Space-Time Modulation over Correlated Ricean MIMO Channels," *IEEE Journal of Selected Topics in Signal Processing*, in the issue "MIMO-Optimized Transmission Systems for Delivering Data and Rich Content", volume 2, issue 2, pages 124 - 134, April 2008.

B. M. R. Bhatnagar, A. Hjørungnes, and L. Song, "Differential Coding for Non-orthogonal Space-Time Block Codes with Non-Unitary Constellations in Arbitrarily Correlated Rayleigh Channels," conditionally accepted for publication in *IEEE Transactions on Wireless Communications* (subject to reviewers' and editors' final approval of the revised version submitted 19-03-2008).

C. M. R. Bhatnagar, A. Hjørungnes, and L. Song, "Double Differential Orthogonal Space-Time Block Codes for Arbitrarily Correlated Rayleigh Channels with Carrier Offsets," conditionally accepted for publication in *IEEE Transactions on Wireless Communications* (subject to reviewers' and editors' final approval of the revised version under preparation).

D. M. R. Bhatnagar, A. Hjørungnes, and L. Song, "Cooperative Communications over Flat Fading Channels with Carrier Offsets: A Double-Differential Modulation Approach", *EURASIP Journal on Advances in Signal Processing*, in special issue on "Wireless Cooperative Networks", volume 2008, article ID 531786, 11 pages, doi:10.1155/2008/531786.

E. M. R. Bhatnagar, A. Hjørungnes, R. Bose, and L. Song, "Double-Differential Decode-and-Forward Cooperative Communications over

Nakagami-m Channels with Carrier Offsets" in Proc. for *Sarnoff Symposium 2008*, pages 1-5, Princeton, NJ, USA, April 2008.

Contents

Paper C: Double-Differential Orthogonal Space-Time Block Codes for Arbitrarily Correlated Rayleigh Channels with Carrier Offsets 123

Paper E: Double - Differential Decode - and - Forward Cooperative Communications over Nakagami-m Channels with Carrier Offsets 187

List of Figures

List of Tables

Abbreviations

AAF	Amplify-and-forward
AP	Access point
AWGN	Additive white Gaussian noise
BER	Bit error rate
BFSK	Binary frequency shift keying
BPSK	Binary phase shift keying
BS	Base station
BW	Band-width
CDMA	Code division multiple access
CFO	Carrier frequency offset
CRC	Cyclic redundancy check
CSI	Channel state information
CSIT	Channel state information at transmitter
d	Destination
dB	Decibel
DAF	Decode-and-forward
DD	Double-differential
DDAAF	Double-differential amplify-and-forward
DDDAF	Double-differential decode-and-forward
DDOSTBC	Double-differential orthogonal space-time block code
DDSTBC	Double-differential space-time block code
DOSTBC	Differential orthogonal space-time block code
DoA	Direction-of-arrival
DSTBC	Differential space-time block code
EGC	Equal gain combining
EMRC	Emulated maximum ratio combining
EVD	Eigen value decomposition
FDMA	Frequency division multiple access
Hz	Hertz
i.i.d.	Independent and identically distributed

IEEE	Institute of Electrical and Electronics Engineers
LOS	Line of sight
MIMO	Multiple-input multiple-output
ML	Maximum likelihood
MRC	Maximum ratio combining
MS	Mobile station
MSE	Mean square error
OSTBC	Orthogonal space-time block code
p.d.f.	Probability distribution function
PAM	Pulse amplitude modulation
PEP	Pair-wise error probability
PSK	Phase shift keying
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
r	Relay
Rx	Receiver
s	Source
SER	Symbol error rate
SISO	Single-input single-output
SNR	Signal-to-noise ratio
STBC	Space-time block code
STC	Space-time coding
SVD	Singular value decomposition
TDMA	Time division multiple access
Tx	Transmitter

Part I

Introduction

Introduction

Digital communication using MIMO wireless link, has emerged as one of the most significant technical breakthroughs in modern communications [1–3]. The topic has been explored so intensively by communications engineers in the last ten years that it does not need an introduction. A key feature of MIMO systems is the ability to turn multipath propagation, traditionally a pitfall of wireless transmission, into a benefit for the user. A well-designed MIMO effectively takes advantage of random fading and when available, multipath delay spread for increasing data-rates. In this chapter, we briefly introduce the MIMO channel, space-time coding, differential modulation, precoding, and cooperative communications.

1 MIMO System

MIMO systems are capable of providing much better performance than SISO system by using multiple antennas separated by such a distance that independent channel realizations are possible. Information theoretic investigations in the past many years [4–6] have shown that very high ca-

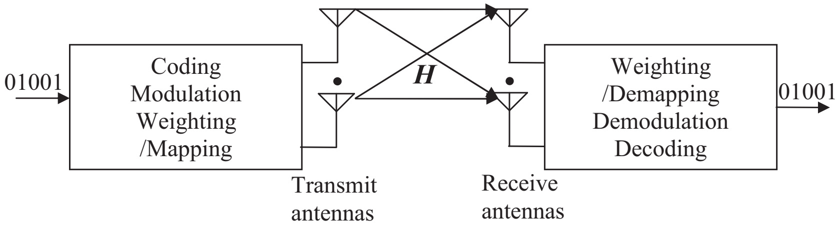


Figure 1.1: Block diagram of a MIMO system.

pacities can be obtained by employing multiple antenna elements at both the transmitter and the receiver in a wireless system. Fig. 1.1 shows a block diagram of a general wireless MIMO system [7]. A compressed digital source in the form of a binary data stream is fed to a simplified transmitting block encompassing the functions of error control coding and (possibly joined with) mapping to complex modulation symbols (quaternary phase-shift keying (QPSK), M-QAM, etc.). The latter produces several separate symbol streams which range from independent to partially redundant to fully redundant. Each is then mapped onto one of the multiple transmit antennas. The mapping operation may include linear spatial weighting called precoding of the antenna elements or linear antenna space-time coding. After upward frequency conversion, filtering, and amplification, the signals are launched into the wireless channel. At the receiver, the signals are captured by possibly multiple antennas and demodulation and demapping operations are performed to recover the message. The level of intelligence, complexity, and a priori channel knowledge used in selecting the coding and antenna mapping algorithms can vary a great deal depending on the application. This determines the class and performance of the multi-antenna solution that is implemented.

1.1 System Model

Consider a MIMO system with n_t transmit and n_r receive antennas. Let $\boldsymbol{H}$ be an $n_r \times n_t$ complex-valued baseband channel matrix and $\boldsymbol{S}_k$ be the $b \times n$ space-time block code (STBC) matrix transmitted at time k, which will be introduced in Section 2, and b and n are the spatial and temporal dimensions of the STBC. The received data $n_r \times n$ matrix $\boldsymbol{Y}_k$ is

$$\boldsymbol{Y}_k = \boldsymbol{H}\boldsymbol{F}\boldsymbol{S}_k + \boldsymbol{Q}_k, \tag{1.1}$$

where $\boldsymbol{Q}_k$ is an $n_r \times n$ matrix, containing additive white complex-valued Gaussian noise (AWGN), whose elements are independent and identically distributed (i.i.d.) Gaussian random variables with zero mean and variance σ^2. The matrix $\boldsymbol{F} \in \mathbb{C}^{n_t \times b}$ is a full memoryless precoder matrix. The channel $\boldsymbol{H}$ is block-fading channel which is assumed to be constant over the transmission period of $\boldsymbol{S}_k$. In addition, $\boldsymbol{H}$, $\boldsymbol{S}_k$, and $\boldsymbol{Q}_k$ are statistically independent of each other.

1.2 Model of Correlated Channels

Let us consider a flat block-fading correlated Rice-fading channel model [8] with n_t transmit and n_r receive antennas. Let $\boldsymbol{R}$ be a general $n_t n_r \times n_t n_r$ positive semi-definite autocorrelation matrix for the fading part of the channel coefficients and $\sqrt{\frac{K}{(1+K)}}\bar{\boldsymbol{H}}$ be the mean value of the channel coefficients. The mean value corresponds to the line of sight (LOS) component of the MIMO channels. The factor $K \geq 0$ is called Ricean factor [8]. A channel realization of the Ricean correlated MIMO channels can be given as

$$\mathrm{vec}\left(\boldsymbol{H}\right) = \sqrt{\frac{K}{K+1}}\mathrm{vec}\left(\bar{\boldsymbol{H}}\right) + \sqrt{\frac{1}{K+1}}\mathrm{vec}\left(\boldsymbol{H}_{\mathrm{F}}\right), \tag{1.2}$$

where $\boldsymbol{H}_{\mathrm{F}}$ is the fading part of the MIMO channels. The matrix $\boldsymbol{H}_{\mathrm{F}}$ can be expressed in terms of $\boldsymbol{R}$ as $\mathrm{vec}\left(\boldsymbol{H}_{\mathrm{F}}\right) = \boldsymbol{R}^{1/2}\mathrm{vec}\left(\boldsymbol{H}_w\right)$, where $\boldsymbol{R}^{1/2}$ is the unique positive semi-definite square root [9] of the correlation matrix $\boldsymbol{R} = \mathbb{E}\left[\mathrm{vec}\left(\boldsymbol{H}_{\mathrm{F}}\right)\mathrm{vec}^{\mathcal{H}}\left(\boldsymbol{H}_{\mathrm{F}}\right)\right]$, which is assumed to be invertible, and $\boldsymbol{H}_w$ is an $n_r \times n_t$ matrix consisting of complex Gaussian circularly distributed and independent components with unit variance and zero mean. As $\mathrm{vec}\left(\boldsymbol{H}_w\right) \sim \mathcal{CN}\left(\mathbf{0}_{n_t n_r \times 1}, \boldsymbol{I}_{n_t n_r}\right)$, it follows that $\mathrm{vec}\left(\boldsymbol{H}\right) \sim \mathcal{CN}\left(\sqrt{\frac{K}{(1+K)}}\mathrm{vec}\left(\bar{\boldsymbol{H}}\right), \frac{1}{1+K}\boldsymbol{R}\right)$. A correlation model for arbitrarily correlated Rayleigh fading MIMO channels can be obtained by setting LOS component zero or letting $K = 0$.

Kronecker Model: A special case of the model given above is the Kronecker model, which can be represented as [8, Eq. (3.26)]

$$\boldsymbol{R} = \boldsymbol{R}_t^{\mathcal{T}} \otimes \boldsymbol{R}_r, \tag{1.3}$$

where $\boldsymbol{R}_r$ is the $n_r \times n_r$ receive correlation matrix and $\boldsymbol{R}_t$ is the $n_t \times n_t$ transmit correlation matrix. Hence, the MIMO channel $\boldsymbol{H}$ following the Kronecker model can be represented as

$$\boldsymbol{H} = \sqrt{\frac{K}{K+1}}\bar{\boldsymbol{H}} + \sqrt{\frac{1}{K+1}}\boldsymbol{R}_r^{\frac{1}{2}}\boldsymbol{H}_w\boldsymbol{R}_t^{\frac{1}{2}}. \tag{1.4}$$

The Kronecker model is appropriate for the scenarios where only the objects surrounding the transmitter and the receiver cause the correlation of the local antenna elements, while they have no impact on the correlation at the other end of the link. However, the generalized model of correlation, which takes into account the coupling between transmit and receive sides, characterizes the realistic channels more accurately [10].

2 Space-Time Coding

Space-time coding is a systematic transmission technique that can use multiple transmit antennas in an optimized manner. The space-time coding can extract the total available spatial diversity in the MIMO channel through appropriate construction of the transmitted space-time codewords without any channel knowledge at the transmitter. The STBCs proposed so far can be broadly divided into three categories 1) Orthogonal STBC, 2) Quasi-orthogonal STBC, and 3) Non-orthogonal STBC. Another scheme for space-time diversity coding is delay diversity [11] which converts spatial diversity into frequency diversity by transmitting the data signal from the first antenna and a delayed replica thereof from the second antenna. However, we will discuss only STBC schemes in this section as we used them in our work.

2.1 Orthogonal Space-Time Block Codes

Alamouti [1] discovered a remarkable space-time block coding scheme for transmission with two antennas. This scheme supports maximum-likelihood (ML) detection based only on linear processing at the receiver. Let s_1 and s_2 be the two symbols to be transmitted in two time intervals. According to Alamouti's scheme, the following data matrix is transmitted through the two transmit antennas in two consecutive time intervals:

$$\boldsymbol{S}_k = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}. \tag{1.5}$$

It is assumed that the MIMO channel remains constant over the transmission period of $\boldsymbol{S}_k$. As $\boldsymbol{S}_k\boldsymbol{S}_k^{\mathcal{H}} \propto \boldsymbol{I}_2$, ML decoding of s_1 and s_2 can be done separately [1]. This reduces the decoding complexity to a large extent. The Alamouti code was the first orthogonal space-time block code (OSTBC) proposed. Alamouti's scheme was generalized to higher number of transmit antennas in [3, 12, 13]. There, a general technique for constructing OSTBCs for more than two transmit antennas that provide the maximum diversity promised by the number of transmit and receive antennas was developed. These codes retain the simple ML decoding algorithm based on only linear processing at the receiver [1]. It is also shown that for real signal constellations, i.e., M-PAM, OSTBCs with transmission rate one can be constructed [3, 12, 13]. However, for general complex constellations like M-QAM or M-PSK, it is proved in [12, Subsection V-D] that OSTBC with transmission rate one and simple linear processing that will give the maximum diversity gain with more than two transmit antennas does not exist. However, it is possible to construct OSTBCs with complex constellations with rate less than one. For example, assuming that the transmitter uses four transmit antennas, a rate 1/2 OSTBC is given by [12, Eq. (38)] and a rate 3/4 OSTBC was proposed in [14, Eq. (41)], which interestingly may *save* on power due the inclusion of some zeros in the transmission.

2.2 Quasi-Orthogonal Space-Time Block Codes

In order to gain the advantages of OSTBCs with higher data rates, Quasi-Orthogonal Space-Time Block Codes (QSTBC) were proposed in [15–19]. QOSTBC can be used with more than two transmit antennas with pairwise decoding complexity. A QOSTBC code matrix for four transmit antenna can be written as [16, 18]

$$\boldsymbol{S}_k = \begin{bmatrix} s_1 & s_2^* & s_3^* & s_4 \\ s_2 & -s_1^* & s_4^* & -s_3 \\ s_3 & s_4^* & -s_1^* & -s_2 \\ s_4 & -s_3^* & -s_2^* & s_1 \end{bmatrix}. \tag{1.6}$$

For any quasi-orthogonal code with four transmit antennas, let us define $\mathcal{U} = \{\mathcal{U}_1, \mathcal{U}_2, \mathcal{U}_3, \mathcal{U}_4\}$, where $\mathcal{U}_i$ denotes the i-th column of the code. We can always divide $\mathcal{U}$ into two pairs $\{\mathcal{U}_i, \mathcal{U}_j\}$ and $\{\mathcal{U}_{i'}, \mathcal{U}_{j'}\}$, each pair having two distinct columns such that $\{\mathcal{U}_i, \mathcal{U}_j\} \cup \{\mathcal{U}_{i'}, \mathcal{U}_{j'}\} = \mathcal{U}$ and $\{\mathcal{U}_i, \mathcal{U}_j\} \cap \{\mathcal{U}_{i'}, \mathcal{U}_{j'}\} = \emptyset$. The two subspaces, each of which is created by two columns in each pair, are orthogonal to each other. The orthogonality of the subspaces of quasi-orthogonal codes results in the possibility of decoding pairs of symbols independently. As a matter of fact, this is the rationale behind all the quasi-orthogonal codes. Therefore, quasi-orthogonal STBCs provide the pairwise decoding complexity. We note that the rate of the QOSTBC for four transmit antennas is one while the maximal possible rate of orthogonal codes for four transmit antennas is 3/4. However, the QOSTBC of (1.6) can provide the diversity of two only. It is shown in [20–23] that with rotated constellations the quasi-orthogonal codes can also achieve full diversity. As a result, rotated quasi-orthogonal codes for four transmit antennas can achieve full diversity and full rate at the same time.

2.3 Non-Orthogonal STBC

Some examples of non-orthogonal high-rate codes are full-diversity, high-rate STBC from division algebras [24], STBC based on Number Theory [25], Golden codes [26], and the perfect STBC [27]. In these STBCs, the entries in the code matrix $\boldsymbol{S}_k$ are linear combinations of the elements of M-QAM or M-PSK constellations. These higher order constellations are optimized to maximize the coding gain. Therefore, the algebraic high-rate codes perform better than the OSTBC. We will briefly review some of the famous high-rate STBC in this section.

2.3.1 Full-Diversity, High-Rate STBC from Division Algebras

Proposition 1: Let $\mathbb{F}$ be a field and z be an indeterminate (of the type $e^{\jmath\theta}$). Also, let $\mathbb{F}(z)$ be the rational function field over $\mathbb{F}$ in the indeterminate z, i.e., it is the set of quotients of polynomials in z with entries from $\mathbb{F}$. Then, for any integer $n_t \geq 1$, the polynomial $x^{n_t} - z$ is irreducible in the ring $\mathbb{F}(z)[x]$ and the code matrices of the form:

$$\begin{bmatrix} f_0 & zf_{n_t-1} & \cdots & zf_1 \\ f_1 & f_0 & \cdots & zf_2 \\ \vdots & \vdots & \ddots & \vdots \\ f_{n_t-1} & f_{n_t-2} & \cdots & f_0 \end{bmatrix}, \tag{1.7}$$

where $\{f_0, f_1, .., f_{n_t-1}\} \in \mathbb{F}$, form a set, which has the property that the difference of any two matrices in it will have full rank.

Refer [24] for a proof.

Equation (1.7) forms the basis of a full rate (rate-1) STBC for n_t transmit antennas. Next, consider the rational function $\mathbb{Q}(\omega_m, z)$ over $\mathbb{Q}(\omega_m)$ in the indeterminate z, where ω_m is the m-the root of the unity and $\mathbb{Q}$ is the field of rational numbers. Let $\mathbb{Q}(\omega_m)$ denote the extension of $\mathbb{Q}$ using the minimal polynomial $x^{n_t} - \omega_m$. Then, $x^{n_t} - z$ is irreducible over $\mathbb{Q}(\omega_m, z)$ and by this minimal polynomial we can obtain the STBC as follows:

$$\boldsymbol{S}_k(z) = \begin{bmatrix} f_0(z) & zf_{n_t-1}(z) & \cdots & zf_1(z) \\ f_1(z) & f_0(z) & \cdots & zf_2(z) \\ \vdots & \vdots & \ddots & \vdots \\ f_{n_t-1}(z) & f_{n_t-2}(z) & \cdots & f_0(z) \end{bmatrix}, \tag{1.8}$$

where $\{f_i(z)\} \in \mathbb{Q}(\omega_m)[z]$. In this STBC, the entries in the code matrix $\boldsymbol{S}_k(z)$ are polynomials in z, which can be of any order and each $f_i(z)$ being a polynomial of the following form:

$$f_i(z) = \sum_{l=0}^{R-1} f_{i,l} z^l \ \ \forall f_{i,l} \in \mathbb{Q}(\omega_m). \tag{1.9}$$

We get a rate-R STBC.

Example 1: This example illustrates a rate-2, 2×2 full rank STBC over the QPSK signal set.

$$\boldsymbol{S}_k(z) = \frac{1}{\sqrt{2}} \begin{bmatrix} f_{0,0} + f_{0,1}z & z\left(f_{1,0} + f_{1,1}z\right) \\ f_{1,0} + f_{1,1}z & f_{0,0} + f_{0,1}z \end{bmatrix}, \tag{1.10}$$

where $\forall f_{i,k} \in$ QPSK Constellation and $i, j \in \{0, 1\}$. The size of the code is 256 and its bit rate is 4 bits per channel use. The scaling factor of $1/\sqrt{2}$ is used to normalize the average power transmitted by each antenna. The optimum value of z, found by computer simulation, is $e^{\jmath 0.52}$ [24]. The coding gain of this code is 0.136, which is about 2.5 times the coding gain of rate-1 code. Apparently, this code uses the symbols $\{f_i(z)\}$ drawn from an optimized 16-point non-unitary constellation. In addition, this code is non-orthogonal since $\boldsymbol{S}_k(z)\boldsymbol{S}_k^H(z)$ is not proportional to $\boldsymbol{I}_2$, therefore, the symbols cannot be decoded separately.

2.3.2 Space-Time Code Based on Number Theory

These non-orthogonal space-time codes are proposed in [25]. The construction of these codes is as follows:

$$\boldsymbol{S}_k = \frac{1}{\sqrt{2}} \begin{bmatrix} s_1 + \phi s_2 & \theta\left(s_3 + \phi s_4\right) \\ \theta\left(s_3 - \phi s_4\right) & s_1 - \phi s_2 \end{bmatrix} \ \forall s_i \in \text{QAM constellation}, \tag{1.11}$$

where $\phi = e^{\jmath\lambda}$ and $\theta^2 = \phi$. When $s_i \in$ 4-QAM, these codes utilize the optimized 16-point constellation similar to [24]. The 8-QAM STBC of [25] utilizes optimized 64-point constellation.

2.3.3 Golden Codes

The other important class of non-orthogonal STBCs are the Golden codes [26]. The algebraic construction yields codewords of the Golden code of the form

$$\boldsymbol{S}_k = \frac{1}{\sqrt{5}} \begin{bmatrix} \left(s_1 + s_2\theta\right)\alpha & \alpha\left(s_3 + s_4\theta\right) \\ \jmath\bar{\alpha}\left(s_3 + s_4\bar{\theta}\right) & \bar{\alpha}\left(s_1 + s_2\bar{\theta}\right) \end{bmatrix} \ \forall s_i \in \text{QAM constellation}, \tag{1.12}$$

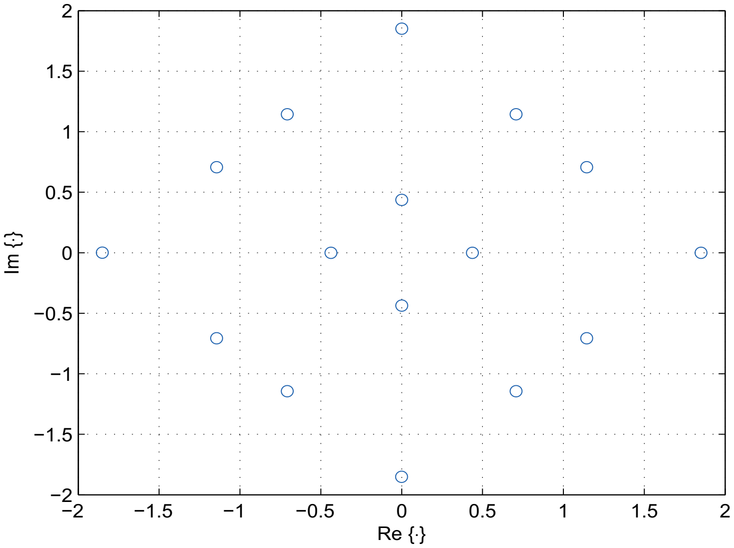


Figure 1.2: Optimized 16-point constellation of Golden codes of [26].

where $\alpha = 1 + \jmath(1-\theta)$, $\bar{\alpha} = 1 + \jmath\big(1-\bar{\theta}\big)$, $\theta = \frac{1+\sqrt{5}}{2}$ and $\bar{\theta} = \frac{1-\sqrt{5}}{2}$. The Golden codes not only improve the spectral efficiency but also achieve the diversity-multiplexing trade-offs [28]. The optimized 16-point constellation used by the Golden codes is shown in Fig. 1.2.

2.3.4 Comparison of Orthogonal and Non-Orthogonal STBC

Fig. 1.3 shows the SER versus SNR performance comparison of the same rate (4 bits/sec/Hz) OSTBC [1] and the non-orthogonal STBCs of [24–26] with two transmit and one receive antennas. It can be seen from Fig. 1.3 that the Golden code [26] provides the best symbol error rate (SER) performance. In addition, non-orthogonal codes of [24–26] perform better than the OSTBC. From Fig. 1.3, it is obvious that the diversity of all STBCs is two but the coding gain is improved by the non-orthogonal codes.

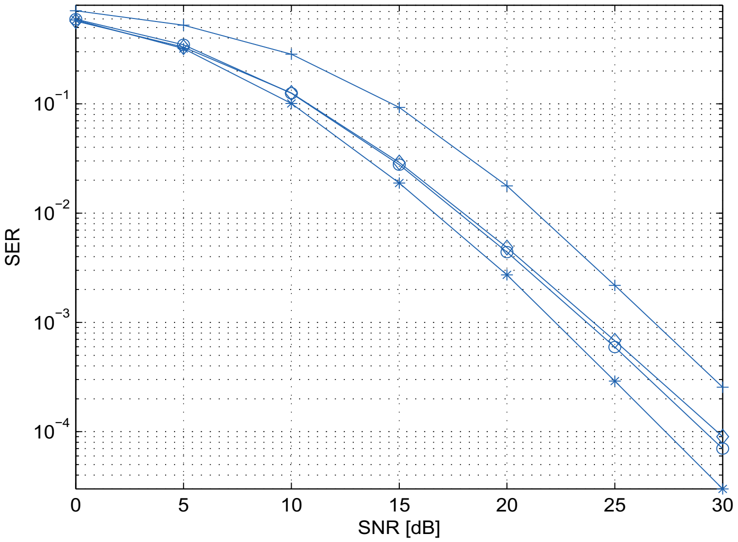


Figure 1.3: SER versus SNR performance of OSTBC $-+-$, STBC of [24] $-\diamond-$, STBC of [25] $-\circ-$, and STBC of [26] $-*-$.

3 Precoding for MIMO System

Precoding is a processing technique that exploits channel state information at the transmitter (CSIT) by operating on the signal before transmission. A linear precoder essentially functions as a multi-mode beamformer, matching the data to be transmitted to the channel. It is shown in [29–31] that a linear precoder with partial CSIT improves the capacity. Precoding design varies depending on the types of CSIT and the performance criterion. The following are the possible precoder design criteria:

- Maximization of the channel ergodic capacity
- Minimization of the error exponent
- Minimization of the pairwise error performance (PEP)
- Minimization of the detection mean square error (MSE)
- Minimization of the SER

- Minimization of the BER
- Maximization of the received SNR

Precoder design by maximizing the channel ergodic capacity has been studied extensively for various scenarios: perfect CSIT [32], mean CSIT [33–36], transmit covariance CSIT [33, 37, 38], both transmit and receive covariance CSIT [39, 40], and both mean and transmit covariance CSIT [41]. Most of the earlier precoder designs focused on the perfect CSIT, by jointly optimizing both linear precoder and linear decoder based on MSE, SNR, or BER [42–45]. However, recently, partial CSIT is considered more relevant for a precoder design. Precoder with mean CSIT was designed to maximize the received SNR [32], or minimize the SER [46], the MSE [47], or the PEP [48–50]. Precoding with transmit covariance CSIT was similarly developed to minimize the PEP [51], the SER [52], or the MSE [53]. Precoding for both mean and transmit covariance CSIT has been developed to minimize the PEP [54]. Most of these previous works assume that the channel correlation follows a Kronecker correlation model [8, Eq. (3.26)]. Precoder design is discussed over arbitrarily correlated MIMO channels [10] for minimizing the PEP upper bound in [55] and the SER in [56, 57]. The point to be noted here is that all of these works consider a coherent receiver which has perfect knowledge of the channel gain coefficients. In [58], an eigen-beamforming based precoder is designed for a differential multiple-input single-output (MISO) system by considering the Kronecker model with only transmitter correlations and no receiver correlation.

4 Differential Modulation

Differential modulation introduces memory in the transmitted data. This memory can be utilized at the receiver to estimate the transmitted data without knowing the channel coefficients. This property is very important for high speed wireless system as the channel estimation requires a significant amount of training data. Moreover, the estimates of the channel become poor when the channel is fading fast. Hence, the differential modulation can be used for fast fading channels in order to avoid the need of channel estimates at the receiver and to increase the data rate.

4.1 Differential Modulation for SISO Systems

Let $z\left[n\right]$ denotes the symbol belonging to the unit-norm M-PSK constellation $\mathcal{A}$ to be transmitted at time n. In differential modulation, the transmitted time-series $p[n]$ is obtained from $z[n]$ as follows:

$$p\left[n\right] = p\left[n-1\right] z\left[n\right], \tag{1.13}$$

with $p\left[0\right] = 1$. As $\left|z\left[n\right]\right| = 1$ for the unit-norm M-PSK symbols, it follows from (1.13) that $\left|p\left[n\right]\right| = 1$. The received data when $p[n]$ was sent over a channel h is

$$y[n] = \sqrt{\rho} h p[n] + e[n], \quad n = 0, 1, \ldots, \tag{1.14}$$

where ρ is the average transmitted power. The ML decoding of $z[n]$ is performed as follows [59]:

$$\hat{z}[n] = \arg \max_{z \in \mathcal{A}} \operatorname{Re}\left\{y[n] y^*[n-1] z^*\right\}, \tag{1.15}$$

where arg denotes the argument of the complex number, max represents maximum value, and $\operatorname{Re}\{\cdot\}$ returns the real part of the complex quantity. It can be seen from (1.15) that the ML decoder does not need the information about the channel h for decoding of the transmitted data $z[n]$ and the decision is based on two consecutively received data samples $y[n-1]$ and $y[n]$. Hence, by differential encoding, we can avoid the need of channel gain estimation at the receiver if the channel stays constant for two consecutive channel uses. In this way, the transmission of training data can be avoided and the overall data-rate is increased. However, the differential system works 3 dB poorer than the coherent system with perfect channel knowledge [59, 60].

4.2 Differential Modulation for MIMO Systems

The differential coding for MIMO systems was first reported in [61]. In [61], a differential encoding for MIMO system employing M-PSK constellation is suggested. The differential code is transmitted through Alamouti STBC. It is shown in [61] that the decoding of this differential code can be done coherently or non-coherently. However, this scheme is only applicable to two transmit antennas. A differential modulation scheme for MIMO systems based on a class of unitary matrices which follow group structure is proposed in [62, 63]. A special case of a unitary group is diagonal unitary matrices. The differential encoding is extended to MIMO systems using OSTBC in [64, 65] as follows: Let $\boldsymbol{S}_k$ be an $n_t \times n_t$ OSTBC data matrix obtained at block k from $\boldsymbol{s}_k = \left[s_{k,1}, s_{k,2}, \ldots, s_{k,n_s}\right]^{\mathcal{T}}$, $s_{k,t} \in M$-PSK constellation, $n_s \leq n_t$, and $\|\boldsymbol{s}_k\|^2 = 1$. A differentially encoded data matrix $\boldsymbol{D}_k \in \mathbb{C}^{n_t \times n_t}$

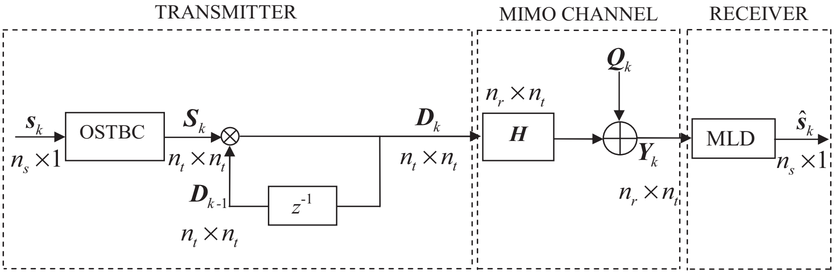


Figure 1.4: Block diagram of a differential MIMO system.

can be obtained from $\boldsymbol{S}_k$ as shown in Fig. 1.4

$$\boldsymbol{D}_k = \boldsymbol{D}_{k-1}\boldsymbol{S}_k. \tag{1.16}$$

A maximum-likelihood decoder (MLD) which takes the decision based on two consecutively received data matrices $\boldsymbol{Y}_{k-1}$ and $\boldsymbol{Y}_k$ without channel knowledge is derived as

$$\hat{\boldsymbol{S}}_k = \arg\min_{\boldsymbol{S}_k \in \Xi} \|\boldsymbol{Y}_k - \boldsymbol{Y}_{k-1}\boldsymbol{S}_k\|^2 , \tag{1.17}$$

where Ξ is the set of all OSTBC matrices, consisting of symbols belonging to the M-PSK constellation and $\|\cdot\|^2$ denotes Frobenius norm. It is assumed that the channel $\boldsymbol{H}$ remains constant over the transmission period of $\boldsymbol{D}_k$ and $\boldsymbol{D}_{k-1}$.

Differential-OSTBC with M-QAM constellation is discussed in [66–70]. Let $s_{k,t}$ belongs to the M-QAM constellation, then $\|\boldsymbol{s}_k\|^2$ varies from one block to the other. Here, if we apply the differential encoding of (1.16), the peak power will fluctuate from one differential block to the other and might become very large. Hence, we need to modify the differential encoding for the non-unitary constellations. This is done by sending a modified $\boldsymbol{D}_k$ at block k as [66, 67]

$$\boldsymbol{D}_k = \boldsymbol{D}_{k-1}\frac{\boldsymbol{S}_k}{\|\boldsymbol{s}_{k-1}\|}, \tag{1.18}$$

where $\|\cdot\|^2$ denotes Euclidean norm of vector. The normalization by $\|\boldsymbol{s}_{k-1}\|$ in (1.18) is done for maintaining a constant average transmit power. If

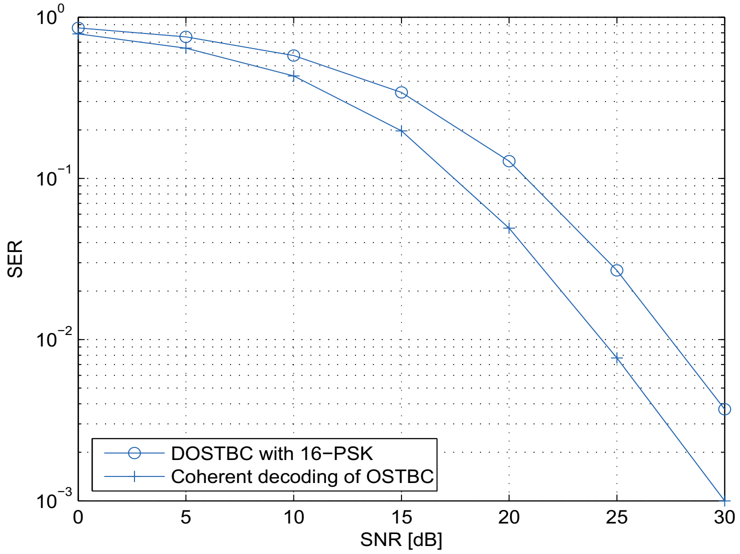


Figure 1.5: Performance of DOSTBC as compared to the coherent detector.

we use $\|\boldsymbol{s}_k\|$ for normalization in the place of $\|\boldsymbol{s}_{k-1}\|$ in (1.18), then the instantaneous power will also become constant and the scheme will work similar to the DOSTBC with M-PSK and looses coding gain. It can be further noticed from (1.18) that zero cannot be put at the signal alphabet as $\|\boldsymbol{s}_{k-1}\| \neq 0$ in (1.18). The following suboptimal differential decoder is used for decoding $\boldsymbol{S}_k$ which assumes that the previously received data $\boldsymbol{Y}_{k-1}$ as an estimate of the channel [66, 67]:

$$\hat{\boldsymbol{S}}_k = \arg\min_{\boldsymbol{S}_k \in \Xi} \left\| \boldsymbol{Y}_k - \boldsymbol{Y}_{k-1} \frac{\boldsymbol{S}_k}{\|\boldsymbol{s}_{k-1}\|} \right\|^2, \tag{1.19}$$

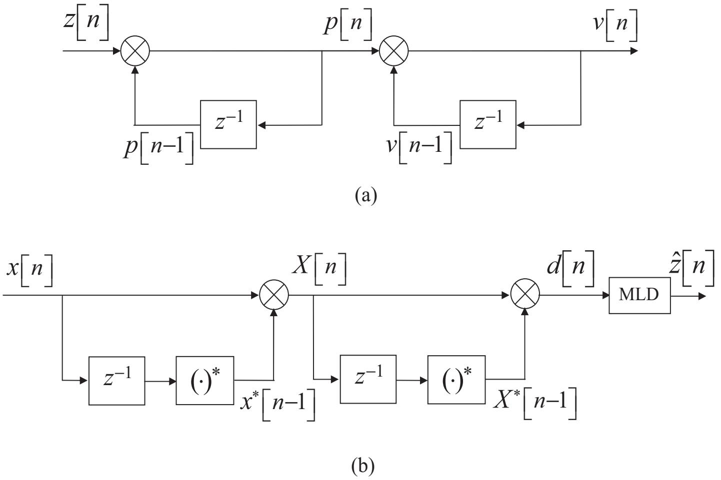
where Ξ is the set of all OSTBC matrices, consisting of symbols belonging to the finite M-QAM constellation. In [68, 69], the differential coding for MIMO systems with unitary constellations presented in [61] is extended to the MIMO system with with non-unitary constellations. However, this scheme is only applicable to two transmit antennas. Contrary to [66, 67], a row-wise differential encoding is used in [68, 69]. The differentially encoded symbols are transmitted by Alamouti code. The major limitation of this scheme is that the receiver requires the knowledge of channel power and signal power to decode the data. The channel power is estimated by buffering many samples (normally $L \geq 100$) of the received data and then finding the average autocorrelation of the received data sequence. These methods introduce a delay in making decisions and the performance of the receiver may degrade for fastly varying channels, which do not remain constant for many symbol durations.

The SER versus SNR performance of differential MIMO system with 16-PSK signal constellation, Alamouti STBC [1], 2 transmit, and 1 receive antennas is shown in Fig. 1.5. It can be seen from Fig. 1.5 that the differential MIMO system works 3 dB poorer than the coherent decoder with perfect channel knowledge.

5 Double-Differential Modulation

If there is a carrier offset due to a mismatch between the transmit and receive oscillators or relative motion of the receiver and transmitter, the channel does not remain stationary over two consecutive time-periods, which is an assumption in differential coding. In such cases, the performance of the differential scheme degrades substantially. The presence of carrier offset is an important practical and theoretical problem for wireless communication systems.

Double-differential (DD) modulation [59, 71–73] is a key differential technique to remove the effect of carrier offset from the communication system. It differs from single differential modulation in the sense that the decoder uses *three* consecutively received data samples for decoding the current symbol. Two levels of single differential modulation are employed at the transmitter as shown in Fig. 1.6 (a) and a simple heuristic decoder [72, Eq. (15)] is used at the receiver to find the estimate of the transmitted data as shown in Fig. 1.6 (b). It has been shown in [72, Section III] that the heuristic decoder coincides with the maximum likelihood decoder (MLD) under the assumption that the product of two zero-mean white circularly symmetric Gaussian noise terms in the decision variable is also zero-mean white circularly symmetric Gaussian. *It is also assumed that the channel and the carrier offset remain constant over at least three consecutive time intervals.*



(a)

(b)

Figure 1.6: Double-differential (a) encoder and (b) decoder.

5.1 Double-Differential Modulation for MIMO Systems

A DD schemes for MIMO channels is presented in [74]. The double-differential (DD) scheme of [74] utilizes diagonal unitary matrices for transmission of data. It can be seen as an extension of the differential STBC proposed in [62] to the double-differential case. We will briefly describe the DD scheme of [74] here.

5.1.1 Double-Differential Encoding

Let $\boldsymbol{D}_k$ be a $n_t \times n$ code matrix to be transmitted in block k, where n_t is the number of transmit antennas and n is the number of time-intervals used for the transmission of $\boldsymbol{D}_k$. Then $\boldsymbol{D}_k$ must satisfy the following property [74]:

$$\boldsymbol{D}_k \boldsymbol{D}_k^{\mathcal{H}} = n\boldsymbol{I}_{n_t}, \ \ \forall k \geq 0. \tag{1.20}$$

In order to maximize the transmission rate, n is chosen such that $n = n_t$.

Let $\mathcal{G}$ be any finite group of $n \times n$ unitary and *diagonal* matrices such

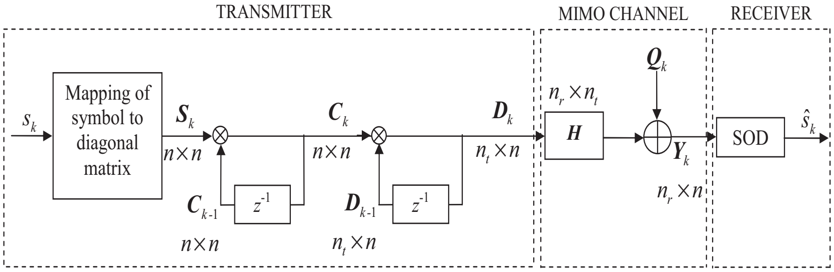


Figure 1.7: Block diagram of a double-differential MIMO system of [74].

that

$$\boldsymbol{S}_k \boldsymbol{S}_k^{\mathcal{H}} = \boldsymbol{I}_n, \ \ \forall \boldsymbol{S}_k \in \mathcal{G}. \tag{1.21}$$

The double-differentially modulated data matrix $\boldsymbol{D}_k$ is obtained as shown in Fig. 1.7

$$\boldsymbol{D}_k = \boldsymbol{D}_{k-1} \boldsymbol{C}_k, \ \ \forall k \geq 1, \tag{1.22}$$

where $\boldsymbol{C}_k$ obeys the following recursion:

$$\begin{aligned} \boldsymbol{C}_k &= \boldsymbol{C}_{k-1} \boldsymbol{S}_k, \ \ \forall k \geq 2, \\ \boldsymbol{C}_1 &= \boldsymbol{I}_n. \end{aligned} \tag{1.23}$$

In the second recursion, the data matrix $\boldsymbol{S}_k \in \mathcal{G}$ conveys the information symbols.

5.1.2 Choice of S_k

In order to implement the DD encoding of [74], $\boldsymbol{S}_k \in \mathcal{G}$ must satisfy the following properties:

- $\mathcal{G}$ must consist of only *diagonal* unitary matrices.
- Let $s_k \in \mathcal{A}$ be the symbol to be transmitted at time k, where $\mathcal{A}$ is a signal constellation with cardinality M. Then $\mathcal{G}$ must have the same cardinality as that of $\mathcal{A}$. Hence, $\mathcal{G}$ must consist of M different diagonal unitary matrices.

- Let $\mathcal{G} = \{\boldsymbol{S}_0, \boldsymbol{S}_1, \ldots, \boldsymbol{S}_{M-1}\}$ and $\mathcal{A} = \{s_0, s_1, \ldots, s_{M-1}\}$, there must be the following one-to-one (ordered) mapping between the elements of $\mathcal{A}$ and $\mathcal{G}$:

  $$s_i \longleftrightarrow \boldsymbol{S}_i, \;\; \forall i \in \{0, 1, \ldots, M-1\}\,. \tag{1.24}$$

  Hence, knowing or detecting $\boldsymbol{S}_k$ at the receiver, determines uniquely s_k.

5.1.3 Model for Time Varying Channel

Consider a MIMO system with n_t transmit and n_r receive antennas. Let $h_{m,n}$ be the channel gain between m-th receive and n-th transmit antenna and $\boldsymbol{D}_k$ be the k-th transmitted $n_t \times n_t$ DD encoded matrix. Let $\omega_m \in [-\pi, \pi>$ be the random carrier offset between the transmit antennas and the m-th receive antenna, which is independent of block k, and assumed to be constant over the transmission period of at least *three* DD encoded matrices $\boldsymbol{D}_k$. The received data $\boldsymbol{y}_{m,k} \in \mathbb{C}^{1\times n_t}$ at the m-th receiver antenna corresponding to the $\boldsymbol{D}_k$, $k \geq 0$, is [65, Eq. (9.7.14)], [74, Eq. (7)]

$$\boldsymbol{y}_{m,k} = \exp\left(\jmath\omega_m n_t k\right)\boldsymbol{h}_m \boldsymbol{D}_k \boldsymbol{\Omega}_m + \boldsymbol{q}_{m,k}, \tag{1.25}$$

where $\boldsymbol{\Omega}_m = \operatorname{diag}\{1, \exp\{\jmath\omega_m\}, \ldots, \exp\{\jmath\omega_m(n_t-1)\}\}$ is a diagonal matrix with diag$\{\cdot\}$ as diagonalization operator, $\boldsymbol{h}_m$ = $[h_{m,1}, \ldots, \;\; h_{m,n_t}]$ is an $1 \times n_t$ row vector consisting of channel coefficients between the transmit antennas and m-th receive antenna, and $\boldsymbol{q}_{m,k} \in \mathbb{C}^{1\times n_t}$ contains additive white complex-valued Gaussian noise (AWGN), whose elements are i.i.d. Gaussian random variables with zero mean and variance σ^2. The channel $\boldsymbol{H} = [\boldsymbol{h}_1^{\mathcal{T}}, \boldsymbol{h}_2^{\mathcal{T}}, \ldots, \boldsymbol{h}_{n_r}^{\mathcal{T}}]^{\mathcal{T}}$ is assumed to be constant over the transmission period of at least same *three* DD encoded matrices for which the carrier offset remains constant.

A generalized model of flat fading channels with carrier offsets is given in [65, Eq. (9.7.1)], where each pair of transmit and receive antenna has different carrier offset. However, it is elaborated in [74] that if the receiver is sufficiently far away from the transmitter such that all transmit antennas share a common angle of arrival then all channels between the transmit antennas and a receive antenna m can be assumed to be perturbed by a single carrier offset ω_m. Under this assumption the generalized model of time varying channel [65, Eq. (9.7.1)] reduces into [65, Eq. (9.7.14)], [74, Eq. (7)]. This argument is also supported in [65].

5.1.4 Decoding of Double-Differential Codes

The decoding of $\boldsymbol{S}_k$ at the m-the receive antenna can be performed on the basis of three consecutively received data samples $\boldsymbol{y}_{m,k-2}$, $\boldsymbol{y}_{m,k-1}$, and $\boldsymbol{y}_{m,k}$. A maximum-likelihood (ML) decoder should maximize the joint probability distribution function (p.d.f.) of $\boldsymbol{y}_{m,k-2}$, $\boldsymbol{y}_{m,k-1}$, and $\boldsymbol{y}_{m,k}$. It is shown in [74, Subsection III-A] that the ML decoder of the DD codes of [74] is not feasible as it depends upon the value of the carrier offsets. Hence, a suboptimal decoder (SOD) is obtained in [74, Subsection III-B] as follows:

$$\hat{\boldsymbol{S}}_k = \arg\max_{\boldsymbol{S}\in\mathcal{G}} \sum_{m=1}^{n_r} \mathrm{ReTr}\left\{\left\{\mathrm{diag}\left\{\boldsymbol{y}_{m,k}^{\mathcal{H}}\boldsymbol{y}_{m,k-1}\right\}\mathrm{diag}^{*}\left\{\boldsymbol{y}_{m,k-1}^{\mathcal{H}}\boldsymbol{y}_{m,k-2}\right\}\right.\right. \\ \left.\left. \times\mathrm{diag}^{-1}\left\{\boldsymbol{y}_{m,k}^{\mathcal{H}}\boldsymbol{y}_{m,k} + 2\boldsymbol{y}_{m,k-1}^{\mathcal{H}}\boldsymbol{y}_{m,k-1} + \boldsymbol{y}_{m,k-2}^{\mathcal{H}}\boldsymbol{y}_{m,k-2}\right\}\boldsymbol{S}\right\}\right\}, \quad (1.26)$$

where diag $\{\boldsymbol{Z}\}$ returns a diagonal matrix with all off-diagonal elements of $\boldsymbol{Z}$ set to zero. It can be seen form (1.26) that the decoding is independent of the carrier offsets and the channel gains. However, in contrast to the SISO case, the decoder of (1.26) is suboptimal.

5.1.5 Diagonal Unitary Group Design

The PEP of the suboptimal decoder proposed in [74] is obtained in [74, Eq. (42)]. It is shown in [74] that the PEP of the DD code can be expressed at high SNR as

$$\Pr\left(\boldsymbol{S}_k^0 \to \boldsymbol{S}_k\right) = \left[\Lambda_{dd}E_b/(4\sigma^2)\right]^{-L_{dd}n_r}, \quad (1.27)$$

where $\boldsymbol{S}_k^0$ is the transmitted diagonal matrix, $\boldsymbol{S}_k$ is the decoded diagonal matrix, E_b is the energy per bit, and L_{dd} is the transmit diversity advantage defined as [74, Eq. (43)]

$$L_{dd} \triangleq \mathrm{rank}\left\{\left(\boldsymbol{S}_k^0 - \boldsymbol{S}_k\right)\left(\boldsymbol{S}_k^0 - \boldsymbol{S}_k\right)^{\mathcal{H}}\right\} \leq n, \quad (1.28)$$

where rank $\{\boldsymbol{Z}\}$ returns the rank of matrix $\boldsymbol{Z}$, and Λ_{dd} is the coding advantage defined as [74, Eq. (44)]

$$\Lambda_{dd} \triangleq \frac{\log_2 M}{4n_t}\det\left\{\left(\boldsymbol{S}_k^0 - \boldsymbol{S}_k\right)\left(\boldsymbol{S}_k^0 - \boldsymbol{S}_k\right)^{\mathcal{H}}\right\}^{1/n_t}. \quad (1.29)$$

In order to optimize the performance of the decoder, L_{dd} and Λ_{dd} must be maximized. An optimized code design criteria is proposed in [74, Sec-

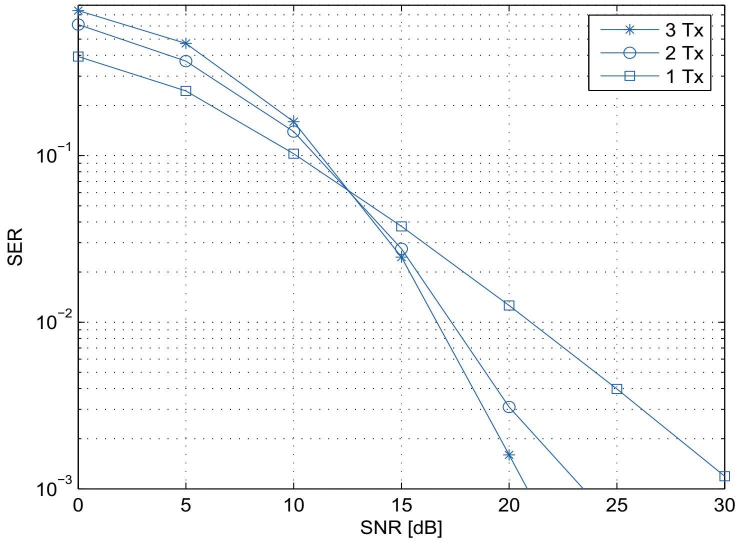


Figure 1.8: Performance of DD codes of [74] for different number of transmit antennas.

tion IV]. According to this criteria, the diagonal unitary group is specified as [74, Eq. (46)]

$$\mathcal{G} = \left[\boldsymbol{I}_n, \boldsymbol{\mathcal{Z}}, \ldots, \boldsymbol{\mathcal{Z}}^{M-1}\right], \tag{1.30}$$

where $\boldsymbol{\mathcal{Z}}$ is the $n \times n$ diagonal matrix [74, Eq. (47)]

$$\boldsymbol{\mathcal{Z}} = \begin{bmatrix} z_M^{k_1} & 0 & \dots & 0 \\ 0 & z_M^{k_2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & z_M^{k_n} \end{bmatrix}, \tag{1.31}$$

where $z_M = \exp\left(2\pi\jmath/M\right)$ and $k_1, k_2, ..., k_{n_t}$ are positive odd integer numbers which can be decided by optimizing the transmit diversity advantage and the coding advantage. It can be seen that the diagonal OSTBC of (1.31) utilizes n time intervals to transmit *one* M-ary symbol.

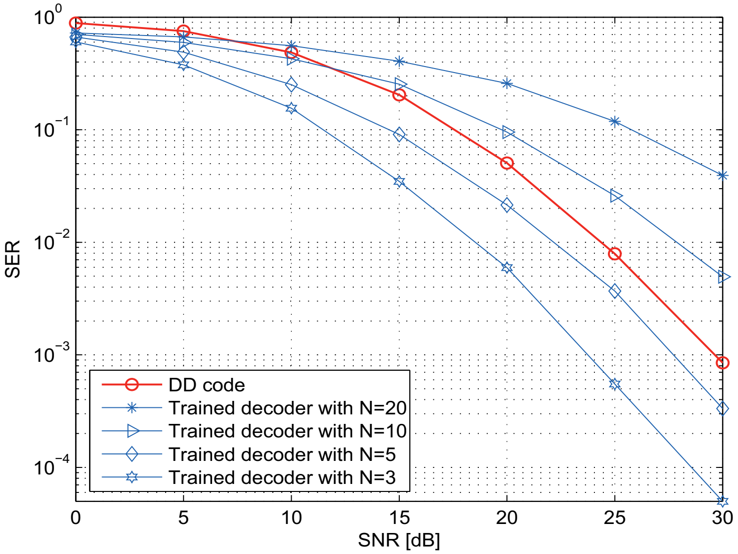


Figure 1.9: Comparison of DD codes of [74] and trained decoder of [65, 75] with two transmit and one receive antennas.

The performance of the DD codes of [74] for different number of transmit antennas is shown in Fig. 1.8. The transmission rate is kept constant at 1 bit/sec/Hz and the transmit power is also kept unity per time interval. It can be seen from Fig. 1.8 that DD coding of [74] achieves diversity gain of n_t. However, as the number of transmit antennas increases, the performance of these codes degrades for SNR less than 12.5 dB.

5.1.6 Comparison of Double-Differential Decoder with Trained Decoder

A training based decoder which estimates the carrier offsets and channel gains using the training data is proposed in [65, 75]. A comparison of the double-differential scheme of [74] and the same rate training based method of [65, 75] is shown in Fig. 1.9 for fast fading channels which remain constant over three blocks of consecutively transmitted OSTBC.

The carrier offset also varies randomly from one frame (three consecutive blocks) to another. It can be seen from Fig. 1.9 that trained decoder performs better than the double-differential scheme over fast fading channels which remain constant for three OSTBC matrices. We have also shown the performance of the trained decoder [65, 75] with relatively slower fading channels which remain constant for N equal to 5, 10, and 20 OSTBC blocks. It can be seen that the training based scheme of [65, 75] losses performance over slowly fading channels. However, the double-differential code of [74] does not loose performance as it is independent of the block length of the channel as long as it is constant over three blocks.

6 Cooperative Communications

In the last few of years, it has been shown that cooperative communication is a promising technique for providing transmit diversity and improved capacity without a physical antenna array [76]. The cooperation between the users helps them share the system resources in an optimized manner and all of them achieve better quality of service. Cooperative communication has several promising features to become a main technology in future wireless communications systems. It has been shown in the literature [76, 77] that the cooperative communication can avoid the difficulties of implementing actual antenna array and convert the SISO system into a virtual MIMO system. In this way, cooperation between the users allows them to exploit the diversity gain and other advantages of MIMO system at a SISO wireless network.

The basic ideas behind cooperative communications can be traced back to the work of Cover and El Gamal [78] on the information theoretic properties of the relay channel. This work analyzes the capacity of a three-node network consisting of a source, a destination, and a relay under the assumption of additive white Gaussian noise (AWGN) broadcast channel.

6.1 Cooperative Protocols

Many cooperative protocols have been proposed in last seven years. However, there are three key protocols 1) Decode-and-Forward (DAF), 2) Amplify-and-Forward (AAF), and 3) Coded Cooperation. We concentrated over the cooperative systems with DAF and AAF protocols in our work.

In the DAF protocol, an user (source) is needed to select another user who agrees to relay its data to the destination [76, 79]. The source sends information to the destination and relay as well. The relay decodes the data sent by the source and retransmits the decoded data to the destination. Hence, the destination has two received replicas of the same data and the quality of reception is expected to improve. To avoid the wrong relaying of data, some intelligence could be included into the relay terminal to make a decision about the quality of reception. The source may apply *ideal* cyclic redundancy check (CRC) codes [80] over the transmitted data for this. Using CRC, the relay can judge whether it has received the signal correctly or not, hence, it can stop relaying wrong data and the performance of the cooperative system is improved. In [81], the SER performance analysis for the coherent DAF relaying protocol for M-PSK and M-QAM modulation is performed.

To avoid the problem of error propagation, a hybrid DAF method is proposed in [82] where, at time instance when the fading channel has high instantaneous SNR, the users detect and forward their partners data, however, when the channel has low SNR, users revert to a non-cooperative mode. It is a form of selection relaying [83]. Another method to avoid the error propagation called incremental relaying is proposed in [83], where the destination decides whether it needs relaying or not.

In the AAF protocol, the relaying terminal acts non-regeneratively over the received data. It amplifies the received data such that an instantaneous or average power constraint is satisfied and forwards toward the destination. This protocol was proposed and analyzed in [83]. It has been shown in [83] that for the two-user case, this method achieves diversity order of two, which is the best possible outcome at high SNR.

The coded cooperation [84–87] integrates cooperative signaling with the channel coding. In this protocol, an N-bit codeword transmission time is divided into two different parts N_1 and N_2 called frames. The users transmit their data in the N_1 frames with CRC bits using TDMA, FDMA, or CDMA, to the destination and their partners. If the partner decodes the data of the user correctly, it transmits this data in the N_2 frame. If partner fails in decoding, it only transmits parity bits in the N_2 frame. A detailed performance analysis of coded cooperation is performed in [85].

It is obvious from the discussion above that for the implementation of the coherent cooperative system, it is required that a node in the cooperative network must possess the information about the channels of the other links in the network. This requirement is difficult to satisfy in practice due to a lot of signaling about the channel values in the system.

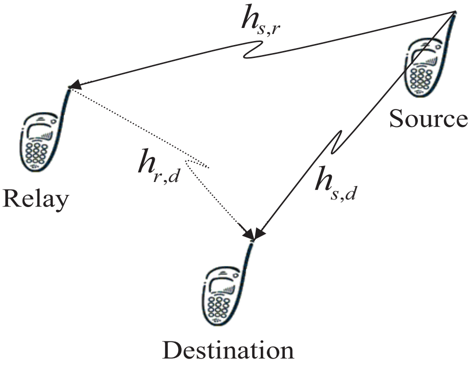


Figure 1.10: Cooperative communication system.

6.2 Differential Modulation for Cooperative Communications

In a differential cooperative system, it is not required that nodes possess information about the channel of the other links. Hence, differential modulation can eliminate training and avoid the difficulty of practical implementation of the cooperative systems with a small loss in the performance. Differential modulation for cooperative system with single source-destination pair with relay under DAF protocol with BPSK constellation is proposed over Rayleigh channels in [88] and Nakagami-m channels in [89]. The maximum-likelihood (ML) decoder for differentially modulated binary frequency shift keying (BFSK) signal transmitted through multiple regenerative relays is found in [90, 91]. Differential modulation with the AAF protocol over Rayleigh fading channels is proposed in [92, 93] and over Nakagami-m channels in [94]. In [92, 94], a limited case of BPSK modulation is treated, whereas, in [93], an expression of approximate BER of differential cooperative communications system with M-PSK constellation is derived.

6.2.1 Differential Transmission for Cooperative System

Let us consider a basic cooperative communication system, which consists of one source (s), one relay (r), and one destination (d) terminal as shown in Fig. 1.10. Each of them can either transmit or receive a signal at a time. The transmission of the data from the source to the destination terminal is furnished in two phases. In the first phase, the source broadcasts data to the destination and the relay. The relay decodes/amplifies the received data and retransmits it to the destination, in the second phase. To avoid the interference, source and relay use orthogonal channels for transmission [83]. For ease of presentation we assume that in both phases, the source and relay transmit stream of data through TDMA. In the TDMA scheme, the source has to remain silent in the second phase in order to maintain the orthogonality between the transmissions. However, in the FDMA or the CDMA schemes, the source and the relay can transmit at the same time.

If we use differential modulation in the cooperative communications system, the data received during the *first phase* at the destination is

$$x_{s,d}\left[n\right] = \sqrt{P_1} h_{s,d} p\left[n\right] + e_{s,d}\left[n\right], \quad n = 0, 1, \ldots, \tag{1.32}$$

and at the relay is

$$x_{s,r}\left[n\right] = \sqrt{P_1} h_{s,r} p\left[n\right] + e_{s,r}\left[n\right], \quad n = 0, 1, \ldots, \tag{1.33}$$

where P_1 is the power transmitted by the source, $h_{s,d}$ and $h_{s,r}$ are the channel gains, $e_{s,d}\left[n\right]$ and $e_{s,r}\left[n\right]$ are complex-valued AWGN noise on the two links, and $p[n]$ is differentially modulated signal obtained from $z[n]$ belonging to the unit-norm M-PSK constellation $\mathcal{A}$ and to be transmitted at the time n, similar to (1.13).

During the *second phase* the source remains silent and the relay demodulates or amplifies/scales the received data of (1.33) and retransmits such that the received signal by the destination in the second phase is:

$$x_{r,d}\left[l\right] = \sqrt{P_2} h_{r,d} p_{r,d}\left[l\right] + e_{r,d}\left[l\right], \quad l = 0, 1, \ldots, \tag{1.34}$$

where l is the time index which is used in the place of n to show the difference in time of the first and second phases, $p_{r,d}\left[l\right]$ is the unit variance signal transmitted by the relay, $h_{r,d}$ is the channel gain, $e_{r,d}\left[l\right]$ is the complex-valued AWGN noise, and P_2 is the average transmission power during the second phase.

In the case of DAF cooperative system employing differential BPSK modulation, i.e., $z[n] = \pm 1$, the relay first differentially decodes the transmitted data similar to (1.15) based on two consecutively received data samples $x_{s,r}[n]$ and $x_{s,r}[n-1]$ [88, 89]. Next, the decoded bits are differentially encoded before transmission

As $|p[n]| = 1$, it can be seen from (1.33), that the average power of $x_{s,r}[l]$ is $P_1\sigma_{s,r}^2 + \sigma^2$, where $\sigma_{s,r}^2$ is the variance of $h_{s,r}$, and σ^2 is the variance of the AWGN noise $e_{s,r}[l]$, hence, in the case of AAF cooperative system $p_{r,d}[l]$ is given as [92–94]

$$p_{r,d}[l] = \frac{x_{s,r}[l]}{\sqrt{P_1\sigma_{s,r}^2 + \sigma^2}}. \tag{1.35}$$

It can be seen from (1.35) that $p_{r,d}[l]$ is a unit-variance signal.

6.2.2 Differential Decoding for Cooperative System

An ML decoder for differential DAF cooperative system at the destination is derived in [88–91]. For AAF based differential cooperative system following linear combiner is proposed in [92–94]:

$$d[k] = x_{s,d}^*[n-1]x_{s,d}[n] + \frac{1+\bar{\gamma}_{s,r}}{1+\bar{\gamma}_{s,r}+\bar{\gamma}_{r,d}}x_{r,d}^*[l-1]x_{r,d}[l], \tag{1.36}$$

where $k = n = l$, $\bar{\gamma}_{s,r} = P_1\sigma_{s,r}^2/\sigma^2$ is the average SNR of the link between the source and the relay, and $\bar{\gamma}_{r,d} = P_2\sigma_{r,d}^2/\sigma^2$ is the average SNR of the link between the relay and the destination. The decision is made as follows:

$$\hat{z}[n] = \arg\max_{z\in\mathcal{A}} \operatorname{Re}\{d[n]z^*\}. \tag{1.37}$$

It can be seen from (1.37) that decoding of $z[n]$ can be done without exact channel knowledge at the receiver.

6.2.3 Differential Modulation for Cooperative System Based on OS-TBC

A differential scheme based on Alamouti STBC [1] for uplink DAF cooperative channels is proposed in [95, 96]. A simple DAF based cooperative system consisting of two users and one destination (base-station) is considered for differential modulation. Both users act as relays for each other. Only BPSK constellation is used for transmission. The signals of both users are transmitted through orthogonal phases (I and Q). Let $s_1$ands_2 belong to BPSK constellation be the data of the first and the second user, respectively. The transmission of the Alamouti code from users to the base-station (BS) is performed in three time-slots. In first time-slot, User one differentially encodes s_1 and broadcasts to User two and the BS. Then User two decodes s_1. In the next time interval, User two differentially encodes s_2 and broadcasts to User one and the BS on the orthogonal phase Q. User one decodes s_2. In the third time interval, User one differentially encode the estimated data of User two, i.e., $\hat{s}_2$, keeps it on the Q phase, and transmits a negative and conjugate version of it to the BS. In the same time interval, User two differentially encodes $\hat{s}_1$ and transmits a conjugate version of it to the BS. A differential decoder based on the received data in six consecutive time intervals is derived in [95, 96]. In the case of using the DAF protocol, the BER versus SNR performance of this scheme suffers from error floor when the direct transmission SNR is greater than the interuser SNR. To avoid the problem of error floor it is assumed in [95, 96] that each transmitted message uses CRC bits such that the relay can perfectly know whether it has decoded the transmitted signal correctly or not. The performance of the differential scheme improves with CRC bits and selection and incremental relaying [83]. A BER analysis for this scheme is also performed in [96] assuming perfect relaying.

In [97], a generalized differential scheme based on unitary space-time block codes is proposed assuming single source destination pair with more than two ($U > 2$) relays in between. The whole transmission is divided into two phases consisting of several time intervals. In the first phase, symbols are transmitted using differential encoding to the relays. The relays decode the symbols differentially. Then N relays are selected which have perfectly decoded the transmitted symbols, where $N \leq U$. The symbol vector is mapped into an unitary space-time matrix $\boldsymbol{G}_k$ which belongs to a finite unitary matrix group $\mathcal{G}$, where k denotes the k-th block. Each of the N relays separately encodes $\boldsymbol{G}_k$ into the corresponding row of the differential code matrix $\boldsymbol{D}_k$. Let $\boldsymbol{D}_{k-1} = [\boldsymbol{d}_{k-1,1}^{\mathcal{T}}, \boldsymbol{d}_{k-1,2}^{\mathcal{T}}, \ldots, \boldsymbol{d}_{k-1,N}^{\mathcal{T}}]^{\mathcal{T}}$, then the i-th relay obtains $\boldsymbol{d}_{k,i}$ as $\boldsymbol{d}_{k,i} = \boldsymbol{d}_{k-1,i}\boldsymbol{G}_k$. A PEP upper bound is also obtained for the differential cooperative system in [97]. The idea of [97] is generalized in [98] by including direct link between the source and the relay.

7 Contribution of the Included Papers

This dissertation consists of five papers numbered with letters (A-E). In this section, we present a brief summary of these papers.

7.1 Paper A

M. R. Bhatnagar, A. Hjørungnes, and L. Song, "Precoded Differential Orthogonal Space-Time Modulation over Correlated Ricean MIMO Channels," *IEEE Journal of Selected Topics in Signal Processing*, in the issue "MIMO-Optimized Transmission Systems for Delivering Data and Rich Content", volume 2, issue 2, pages 124 - 134, April 2008.

In Paper A, we give a more comprehensive presentation of the results we presented in [99, 100]. We study differential modulation for MIMO system with correlated channels in this paper. The MIMO system utilizes OSTBC with M-PSK, M-QAM, or M-PAM signal constellation. It is assumed that the MIMO channel is arbitrarily correlated Ricean channel. The mathematical model of the arbitrarily correlated Ricean MIMO channel, given in Subsection 1.2, is followed. It is observed that the channel correlation degrades the performance of the differential system. To improve the performance of the differential system we introduce a linear memoryless precoder matrix at the transmitter.

A major contribution of this paper is that we derive approximate SER expressions of the differential OSTBC (DOSTBC) with a full precoder. These SER expressions are applicable to precoded DOSTBC with M-PSK, M-QAM, or M-PAM. It is observed by simulations that these approximate SER expressions are able to predict the behavior of the differential system very closely from moderate to high SNR values. These SER expressions are approximate since we have neglected two terms in the decision variable which depend upon the transmitted data. However, these terms have diminishing effect at SNR above 6dB.

Another major contribution of this paper is that we have designed a full memoryless precoder for the differential system employing OSTBC using M-PSK, M-QAM, or M-PAM signal constellations. The precoder is designed to minimize the approximate SER of the differential system. The precoder design presented in this paper is much more generalized than [58]. In [58], a eigen-beamforming based precoder is designed to minimize the Chernoff bound of the approximate SER of DOSTBC using M-PSK signal constellation only. It is also assumed in [58] that only transmit correlation exists in a multiple-input single-output (MISO) system which follows the Kronecker model. However, our precoder design is applicable to a more general system employing multiple transmit and multiple receive antennas, M-PSK, M-QAM, and M-PAM, and non-Kronecker correlation model. The proposed precoder also provides better SER versus SNR performance than [58].

7.2 Paper B

M. R. Bhatnagar, A. Hjørungnes, and L. Song, "Differential Coding for Non-orthogonal Space-Time Block Codes with Non-Unitary Constellations in Arbitrarily Correlated Rayleigh Channels," conditionally accepted for publication in *IEEE Transactions on Wireless Communications* (subject to reviewers' and editors' final approval of the revised version submitted 19-03-2008).

This paper generalizes the idea of differential modulation for MIMO system to the non-orthogonal space-time block coding. Initial results of differential coding for non-orthogonal STBC were published in [101]. In Paper B, we propose precoded differential modulation for non-orthogonal STBC. The non-orthogonal STBC like [24–26] have generated interest since the last seven years. These codes are important as they are generally available for arbitrary number of transmit antennas, whereas, OSTBCs with complex symbols are available for limited number of transmit antennas only [12]. Despite of their decoding complexity, non-orthogonal codes like Golden codes [26] are able to achieve the diversity-multiplexing trade-off [28]. Moreover, these codes also perform better than the same rate OSTBC as shown in Subsection 2.3.4. These codes utilize optimized non-unitary constellations in order to maximize the coding gain. The optimized signal constellation is drawn from regular QAM constellations through algebraic structures.

We derive an ML decoder of the differential non-orthogonal STBC using optimized non-unitary signal constellations. It is shown that this ML decoder is far more general than the suboptimal decoders used in the conventional differential systems employing OSTBCs. The proposed decoder is applicable to non-orthogonal and orthogonal STBCs with unitary and non-unitary signal constellations. We also derived a ML decoder of OSTBC with QAM constellation.

As another contribution, we study the effect of channel correlation on the performance of the differential system employing non-orthogonal STBCs. We assume an arbitrarily correlated channel model for Rayleigh fading MIMO channels. This model can be derived from the correlation model discussed in Subsection 1.2 with $K = 0$. We introduce a full memoryless precoder matrix at the transmitter to improve the performance of the differential system. A key feature of the proposed precoding is that the receiver does not need to know the precoder matrix for the decoding of the data. We obtained an upper bound of the PEP for the precoded differential system.

A full memoryless linear precoder is designed to minimize the PEP upper bound. We utilized the results given in [102] about the matrix derivation to find the first order derivative of the objective function. As it is difficult to find a close form solution for precoder, we suggest an iterative optimization algorithm. The precoder design proposed in this paper performs better than the conventional precoder design [58] of differential MIMO systems.

7.3 Paper C

M. R. Bhatnagar, A. Hjørungnes, and L. Song, "Double-Differential Orthogonal Space-Time Block Codes for Arbitrarily Correlated Rayleigh Channels with Carrier Offsets," conditionally accepted for publication in *IEEE Transactions on Wireless Communications* (subject to reviewers' and editors' final approval of the revised version under preparation).

In this paper, we consider differential modulation over flat-fading channels with carrier offsets. The carrier offsets can be present due to the mismatch between the transmit and receive oscillators or relative movement of the transmitter and the receiver. The existence of carrier offsets makes the flat-fading channels behave as time varying channels which do not remain stationary over two consecutively transmitted data matrices, which is a basic assumption in differential coding. In order to implement a pure differential system, we need to bypass the estimation of the carrier offset and the channel gains. This can be done by double-differential modulation.

A model of the time varying channel given in Subsection 5.1.3 is used. We propose double-differential encoding for MIMO systems which is applicable to square OSTBC with M-PSK constellation. This encoding is more general than the previously proposed double-differential encoding for MIMO system [74] since the later one is applicable for *diagonal* unitary matrices only. Hence, the conventional DD code cannot utilize the space and time dimensions fully and this results in low data rate. By using any square OSTBC in DD encoding we are able to exploit more coding gain than [74].

Another contribution is that we derived a suboptimal decoder of the proposed double-differential OSTBC (DDOSTBC) which is able to decode the OSTBC data linearly. The decision is independent of the channel and the carrier offset knowledge. A PEP analysis is also conducted for the DDOSTBC and we obtain an upper bound of the PEP.

Finally, we consider the effect of channel correlation on the performance of the DDOSTBC. In order to improve its performance over arbitrarily correlated Rayleigh fading channels with carrier offsets, we introduce a full memoryless precoder in the transmitter. The precoder is designed to minimize an upper bound of the PEP. We have used an iterative method to obtain the optimized precoder matrix.

Our DDOSTBC gains substantial improvement in terms of SER as compared to the DD codes of [74]. In addition, our precoder also works fairly well over correlated channels. Hence, this paper presents differential coding in a much more generalized framework than the conventional work of [74]. Some initial results over DDOSTBC are presented in [103].

7.4 Paper D

M. R. Bhatnagar, A. Hjørungnes, and L. Song, "Cooperative Communications over Flat Fading Channels with Carrier Offsets: A Double-Differential Modulation Approach", *EURASIP Journal on Advances in Signal Processing*, in special issue on "Wireless Cooperative Networks", volume 2008, article ID 531786, 11 pages, doi:10.1155/2008/531786.

In Paper D, we implement a cooperative system which is perturbed by random carrier offsets. The approach presented in this paper is novel as we consider double-differential modulation for cooperative network in order to avoid the knowledge of channel gain and carrier offsets at each node in the network. A cooperative network is more vulnerable to the carrier offsets as compared to the MIMO system if the cooperation is among the mobile users. The sources, relays, and destinations can be moving and it is not possible to have perfect match between oscillators of two nodes in the network. If a training based method is used, it is very deficient in the terms of bandwidth and data rate. Moreover, exact estimation of the carrier offsets is difficult.

It is shown by simulation in Paper D, that in the presence of the random carrier offsets, the conventional differential scheme breaks down. We consider the AAF protocol with double-differential modulation over Nakagami-m channels. A maximum ratio combining (MRC) based receiver is obtained at the destination which includes instantaneous channel coefficients. As in a pure differential system, the nodes cannot possess the exact channel knowledge, therefore, we replace the channel gains by their variances and propose an emulated MRC (EMRC) receiver.

In paper [73], we show that there is an analogy between the single and double-differential modulation and SER expressions of DD modulation can be obtained from the analytical results of single differential modulation. In Paper D, we used the analogy between the single and double-differential modulation to find approximate BER expressions of the double-differential AAF (DDAAF) system. We also obtained the p.d.f. of the effective channel of the cooperative link (source-relay-destination) for arbitrary value of $m \geq 0.5$. A closed-form (without integral) expression of the approximate BER of DDAAF system with BPSK is obtained for general Nakagami-m. We also obtain an upper bound of the BER for M-PSK signal constellation. In addition, a numerical power allocation is suggested to minimize the upper bound of the BER. The proposed DD cooperative system with one source-destination pair and one relay, achieves the maximum possible diversity of two.

7.5 Paper E

M. R. Bhatnagar, A. Hjørungnes, R. Bose, and L. Song, "Double-Differential Decode-and-Forward Cooperative Communications over Nakagami-m Channels with Carrier Offsets" in Proc. for *Sarnoff Symposium 2008*, pages 1-5, Princeton, NJ, USA, April 2008.

In paper E, we give a more comprehensive presentation of the results we presented in paper [104]. We consider a decode-and-forward based cooperative system for implementation of double-differential modulation over Nakagami-m channels in Paper E. It is assumed that ideal CRC bits are added in each message such that the relay can know whether it has decoded the data correctly or not. The relay only cooperates if it decodes the data correctly. We propose a linear combiner of the diversity branches at the destination. A comparison is performed between the MRC and the proposed combiner.

A major contribution of this paper is that we obtain an upper bound of the SER of double-differential DAF (DDDAF) system with M-PSK over

Nakagami-m channels. We have also proposed a closed-form analytical power distribution for Rayleigh channels and a numerical power distribution for Nakagami-m channels to minimize the upper bound of SER for DDDAF system.

8 Main Contributions of the Dissertation

The main contributions of this dissertation can be summarized as follows:

- Found approximate SER expressions for DOSTBC with unitary and non-unitary constellations over arbitrarily correlated Ricean MIMO channels.
- Design of a precoder based on the approximate SER to improve the performance of DOSTBC over arbitrarily correlated Ricean channels.
- Derived a ML decoder for differentially encoded non-orthogonal STBC with optimized non-unitary constellations which is also applicable for OSTBC with PSK and QAM constellations.
- Designed precoder based on the PEP upper bound for improving the performance of the differential *non-orthogonal* STBC over arbitrarily correlated Rayleigh channels. The proposed precoder also works well with differential OSTBC.
- Proposed a double-differential encoding and decoding of square OSTBC with M-PSK constellation.
- Found a PEP upper bound for DDOSTBC over arbitrarily correlated Rayleigh channels.
- Designed precoder based on the PEP upper bound in order to improve the performance of the DDOSTBC over arbitrarily correlated Rayleigh MIMO channels.
- Implemented double-differential modulation for wireless cooperative communication systems with random carrier offsets using the DAF and AAF protocols.
- Derived approximate SER/BER expressions for DDDAF and DDAAF cooperative systems.
- Obtained optimized power allocations for DDDAF and DDAAF cooperative systems.

9 Suggestions for Future Research and Extensions

In this section, we will discuss some issues that can be interesting to investigate in the future.

In this dissertation, we implement differential modulation of square and full-rank STBC. A natural extension of this work is to implement differential coding of arbitrary STBC. We obtained approximate SER expressions for DOSTBC by ignoring two terms in the decision variables which depend upon the original signal. However, in the future, exact SER expressions for the DOSTBC with unitary and non-unitary constellations might be possible to derive by including these two neglected terms in the analysis. As an extension of our work of differential coding for non-orthogonal STBC, one can try to find exact or approximate SER expressions for these differential codes. In addition, the differential non-orthogonal STBC can be implemented in cooperative networks in a distributed manner.

As an extension of our work over DDOSTBC, double-differential coding for *arbitrary* STBC might be possible to implement. An important extension might be to find the ML decoder of the double-differentially modulated OSTBC. Furthermore, the precoder designs can be obtained for differential and double-differential STBCs over correlated key-hole or Nakagami-m channels in future.

Exact SER/BER expressions for DDDAF and DDAAF cooperative systems might be possible to derive as an extension of the work presented in this dissertation. In our work, we have discussed the DDDAF and DDAAF schemes for a single source-destination pair with one relay. The proposed DD schemes might be possibly extended to a more general case of multiple source-destination pairs with multiple relay terminals in future. In addition, closed-form solutions of optimized power allocation for DDAAF and DDDAF schemes over general Nakagami-m fading channels might be possibly obtained in future.

10 Journal and Conference Contributions during Ph.D. Studies

During the Ph.D. studies, the author has contributed to the following journals and conference publications:

List of journal publications during Ph.D.:

- M. R. Bhatnagar, A. Hjørungnes, and L. Song, *"Precoded Differential Orthogonal Space-Time Modulation over Correlated Ricean MIMO Channels,"* IEEE Journal of Selected Topics in Signal Processing, in the issue "MIMO-Optimized Transmission Systems for Delivering Data and Rich Content", volume 2, issue 2, pages 124 - 134, April 2008.
- M. R. Bhatnagar, A. Hjørungnes, and L. Song, *"Cooperative Communications over Flat Fading Channels with Carrier Offsets: A Double-Differential Modulation Approach,"* EURASIP Journal on Advances in Signal Processing, in special issue on "Wireless Cooperative Networks", volume 2008, article ID 531786, 11 pages, doi:10.1155/2008/531786.
- L. Song, A. Hjørungnes, P. Yahampath, and M. R. Bhatnagar, *"Transceiver Design for Spatial Multiplexing Based on Pre-Whitening Detector,"* IEEE Transactions on Vehicular Technology, accepted 06.03.2008 for publication.
- M. R. Bhatnagar, A. Hjørungnes, and L. Song, *"Precoded DOSTBC over Rayleigh Channels,"* EURASIP Research Letters in Communications, volume 2007, article ID 16438, 5 pages, DOI:10.1155/2007/16438.
- M. R. Bhatnagar, A. Hjørungnes, and L. Song, *"Differential Coding for Non-orthogonal Space-Time Block Codes with Non-Unitary Constellations in Arbitrarily Correlated Rayleigh Channels,"* IEEE Transactions on Wireless Communications, conditionally accepted for publication subject to reviewers' and editors' final approval of the revised version submitted 19-03-2008.
- M. R. Bhatnagar, A. Hjørungnes, and L. Song, *"Double-Differential Orthogonal Space-Time Block Codes for Arbitrarily Correlated Rayleigh Channels with Carrier Offsets,"* IEEE Transactions on Wireless Communications, conditionally accepted for publication subject to reviewers' and editors' final approval of the revised version under preparation.
- M. R. Bhatnagar and A. Hjørungnes, *"Differential Relay Strategies over Downlink Channel in Two-User Cooperative Communication System,"* Wireless Personal Communications, Springer, submitted 17.04.2008 for publication.

List of conference publications during Ph.D.:

- M. R. Bhatnagar, A. Hjørungnes, and R. Bose, *“Precoded DDOSTBC with Non-Unitary Constellations over Correlated Rayleigh Channels with Carrier Offsets,”* In Proc. for IEEE International Symposium on Information Theory (ISIT 2008), Toronto, Ontario, Canada, Jul. 2008.
- L. Song, R. de Lamare, A. Hjørungnes, M. R. Bhatnagar, and A. Burr, *“Approximate ML Serial Detector Based on Tomlinson–Harashima Pre-Equalization,”* In Proc. for IEEE Vehicular Technology Conference (VTC Spring 2008), Singapore, May 2008.
- L. Song, A. Hjørungnes, and M. R. Bhatnagar, *“Pre-Equalization and Precoding Design for Frequency-Selective Fading Channels,”* In Proc. for IEEE International Conference on Communications (ICC 2008), Beijing, China, May 2008.
- M. R. Bhatnagar, A. Hjørungnes, R. Bose, and L. Song, *“Double-Differential Decode-and-Forward Cooperative Communications over Nakagami-*m *Channels with Carrier Offsets,”* In Proc. for IEEE Sarnoff Symposium 2008, Nassau Inn in Princeton, NJ, USA, Apr. 2008.
- M. R. Bhatnagar, A. Hjørungnes, and L. Song, *“Double-Differential Coding for Orthogonal Space-Time Block Codes,”* In Proc. for IEEE The 33rd International Conference on Acoustics, Speech, and Signal Processing (ICASSP 2008), Las Vegas, USA, Mar.-Apr. 2008.
- M. R. Bhatnagar, A. Hjørungnes, and L. Song, *“Amplify-and-Forward Cooperative Communications Using Double-Differential Modulation over Nakagami-m Channels,”* In Proc. for IEEE Wireless Communications and Networking Conference (WCNC 2008), Las Vegas, USA, Mar.-Apr. 2008.
- M. R. Bhatnagar, M.K. Arti, R. Bose, A. Hjørungnes, and L. Song, *“Time Efficient Multi-User Relay Strategy for Cooperative MIMO Networks,”* In Proc. for The 10th International Symposium on Wireless Personal Multimedia Communications (WPMC 2007), Jaipur, India, Dec. 2007.
- L. Song, A. G. Burr, M. R. Bhatnagar, and A. Hjørungnes, *“Differential Modulation Based on Double Space Time Transmit Diversity Architecture,”* In Proc. for The 10th International Symposium on Wireless Personal Multimedia Communications (WPMC 2007), Jaipur, India, Dec. 2007.

- M. R. Bhatnagar, A. Hjørungnes, and L. Song, *"Precoding of Differential OSTBC in Arbitrarily Correlated MIMO Channels,"* In Proc. for Asilomar Conference on Signals, Systems, and Computers, CA , USA, Nov. 2007.
- L. Song, A. Hjørungnes, P. Yahampath, and M. R. Bhatnagar, *"Precoder Design for V-BLAST Schemes Based on Pre-Whitening Detector,"* In Proc. for Asilomar Conference on Signals, Systems, and Computers, CA, USA, Nov. 2007.
- M. R. Bhatnagar and A. Hjørungnes, *"Double-Differential Modulation for Decode-and-Forward Cooperative Communications,"* In Proc. for IEEE International Conference on Signal Processing and Communications (ICSPC 2007), Dubai, UAE, Nov. 2007.
- L. Song, A. Hjørungnes, and M. R. Bhatnagar, *"Linear Pre-Whitening Detector for Space-Time Block Codes over Time-Selective Fading Channels,"* In Proc. for IEEE International Symposium on Wireless Communication Systems 2007 (ISWCS 2007), Trondheim, Norway, IEEE, Oct. 2007.
- M.K. Arti, R. Bose, M. R. Bhatnagar, and A. Hjørungnes, *"Relay Strategies for high-rate Space-Time Code in Cooperative MIMO Networks,"* In Proc. for IEEE International Symposium on Wireless Communication Systems (ISWCS 2007), Trondheim, Norway, IEEE, Oct. 2007.
- M. R. Bhatnagar and A. Hjørungnes, *"Downlink Cooperative Communication Using Differential Relaying,"* In Proc. for IEEE International Symposium on Wireless Communication Systems (ISWCS 2007), Trondheim, Norway, IEEE, Oct. 2007.
- L. Song, A. Hjørungnes, A. G. Burr, and M. R. Bhatnagar, *"Differential Tranceiver Design for Quasi-Orthogonal Space-Time Block Codes,"* In Proc. for IEEE International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM 2007). Shanghai, China, Sep. 2007.
- M. R. Bhatnagar and A. Hjørungnes, *"SER Expressions for Double-Differential Modulation,"* In Proc. for IEEE Information Theory Workshop (ITW 2007), Bergen, Norway, IEEE, Jul. 2007.
- M. R. Bhatnagar, A. Hjørungnes, and L. Song, *"Non-Orthogonal Differential Space-Time Block Code with Non-Unitary Constellations,"* In

Proc. for IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC 2007), Helsinki, Finland, IEEE, Jun. 2007.

References

[1] S. M. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[2] V. Tarokh, N. Seshadri, and A. R. Calderbank, “Space–time codes for high data rate wireless communications: Performance criterion and code construction,” *IEEE Trans. Inform. Theory*, vol. 44, no. 2, pp. 744–765, Mar. 1998.

[3] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, “Space-time block coding for wireless communications: Performance results,” *IEEE J. Select. Areas Commun.*, vol. 17, no. 3, pp. 451–460, Mar. 1999.

[4] İ. E. Telatar, “Capacity of multi-antenna Gaussian channels,” *AT&T-Bell Laboratories Internal Technical Memo*, pp. 1–28, June 1995.

[5] J. Foschini, “Layered space-time architecture for wireless communications in a fading environment,” *Bell Labs Tech. J.*, vol. 1, no. 2, pp. 41–59, 1996.

[6] J. Foschini and M. Gans, “On the limit of wireless communications in a fading environment when using multiple antennas,” *Wireless Personal Communications*, vol. 6, no. 3, pp. 311–335, Mar. 1998.

[7] D. Gesbert, M. Shafi, D. Shiu, P. J. Smith, and A. Naguib, “From theory to practice: An overview of MIMO space-time coded wireless systems,” *IEEE J. Select. Areas Commun.*, vol. 21, no. 3, pp. 281–302, Apr. 2003.

[8] A. Paulraj, R. Nabar, and D. Gore, *Introduction to Space-Time Wireless Communications.* Cambridge, UK: Cambridge University Press, 2003.

[9] R. A. Horn and C. R. Johnson, *Topics in Matrix Analysis*. Cambridge University Press Cambridge, UK, 1991, reprinted 1999.

[10] E. Bonek, H. Özcelik, M. Herdin, W. Weichselberger, and J. Wallace, "Deficiencies of a popular stochastic MIMO radio channel model," *Proc. Int. Symp. on Wireless Personal Multimedia Communications*, Oct. 2003, Yokosuka, Japan.

[11] N. Seshadri and J. H. Winters, "Two signaling schemes for improving the error performance of frequency-division-duplex (FDD) transmission systems using transmitter antenna diversity," *Int. J. Wireless Inform. Netw.*, vol. 1, pp. 49–60, Jan. 1994.

[12] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Trans. Inform. Theory*, vol. 45, no. 5, pp. 1456–1467, July 1999.

[13] G. Ganesan and P. Stoica, "Space-time diversity using orthogonal and amicable orthogonal designs," *Wireless Personal Communications*, vol. 18, no. 2, pp. 165–178, Aug. 2001.

[14] ——, "Space-time block codes: A maximum SNR approach," *IEEE Trans. Inform. Theory*, vol. 47, no. 4, pp. 1650–1656, May 2001.

[15] O. Tirkkonen, A. Boariu, and A. Hottinen, "Minimal nonorthogonality rate one space-time block codes for 3+ Tx antennas," *Proc. IEEE 6th Int. Symp. Spread-Spectrum Techniques and Applications*, pp. 429–432, Sep. 2000, New Jersey, USA.

[16] H. Jafarkhani, "A quasi-orthogonal space-time block code," *IEEE Trans. Commun.*, vol. 49, no. 1, pp. 1–4, Jan. 2001.

[17] C. Papadias and G. Foschini, "Capacity-approaching space-time codes for system employing four transmitter antennas," *IEEE Trans. Inform. Theory*, vol. 49, no. 3, pp. 726–733, Mar. 2003.

[18] C. Mecklenbräuker and M. Rupp, "On extended Alamouti schemes for space-time coding," *Proc. Int. Symp. on Wireless Personal Multimedia Communications*, pp. 115–119, Oct. 2002, Honolulu, Hawaii.

[19] A. Boarui and D. M. Ionescu, "A class of nonorthogonal rate-one space-time block codes with controlled interference," *IEEE Trans. Wireless Commun.*, vol. 2, no. 2, pp. 270–276, Mar. 2003.

[20] H. Jafarkhani and N. Hassanpour, “Super-quasi-orthogonal space-time trellis codes for four transmit antennas,” *IEEE Trans. Wireless Commun.*, vol. 4, no. 1, pp. 215–227, Jan. 2005.

[21] O. Tirkkonen, “Optimizing space-time block codes by constellation rotations,” *Proc. Finnish Wireless Communications Workshop*, pp. 59–60, Oct. 2001, Tampere, Finland.

[22] W. Su and X. Xia, “Signal-constellations for quasi-orthogonal space-time block codes with full diversity,” *IEEE Trans. Inform. Theory*, vol. 50, no. 10, pp. 2331–2347, Oct. 2004.

[23] N. Sharma and C. B. Papadias, “Improved quasi-orthogonal codes through constellation rotation,” *IEEE Trans. Commun.*, vol. 51, no. 3, pp. 332–335, Mar. 2003.

[24] B. A. Sethuraman, B. S. Rajan, and V. Shashidhar, “Full-diversity, high-rate space-time block codes from division algebras,” *IEEE Trans. Inform. Theory*, vol. 49, no. 10, pp. 2596–2616, Oct. 2003.

[25] M. O. Damen, A. Tewfik, and J. C. Belfiore, “A construction of a space-time code based on number theory,” *IEEE Trans. Inform. Theory*, vol. 48, no. 3, pp. 753–760, Mar. 2002.

[26] J. C. Belfiore, G. Rekaya, and E. Viterbo, “The Golden code: A 2×2 full-rate space-time code with non-vanishing determinants,” *IEEE Trans. Inform. Theory*, vol. 51, no. 4, pp. 1432–1436, Apr. 2005.

[27] S. Yang, J. C. Belifiore, G. Rekaya, and B. Othman, “Perfect space-time block codes for parallel MIMO channels,” *Proc. Int. Symp. on Information Theory*, pp. 1949–1953, Jul. 2006, Seattle, Washington, USA.

[28] L. Zheng and D. N. C. Tse, “Diversity and multiplexing a fundamental tradeoff in multiple antenna channels,” *IEEE Trans. Inform. Theory*, vol. 49, no. 5, pp. 1073–1096, May 2003.

[29] C. Shannon, “Channels with side information at the transmitter,” *IBM J. Res. Develop.*, vol. 2, no. 4, pp. 289–293, Oct. 1958.

[30] G. Caire and S. Shamai, “On the capacity of some channels with channel state information,” *IEEE Trans. Inform. Theory*, vol. 45, no. 6, pp. 2007–2019, Sep. 1999.

[31] M. Skoglund and G. Jöngren, “On the capacity of a multiple-antenna communication link with channel side information,” *IEEE J. Select. Areas Commun.*, vol. 21, no. 3, pp. 395–405, Apr. 2003.

[32] T. M. Cover and J. A. Thomas, *Elements of Information Theory.* New York, USA: Wiley, 1991.

[33] A. Narula, M. Lopez, M. Trott, and G. Wornell, “Efficient use of side information in multiple antenna data transmission over fading channels,” *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1423–1436, Oct. 1998.

[34] E. Visotsky and U. Madhow, “Space-time transmit precoding with imperfect feedback,” *IEEE Trans. Inform. Theory*, vol. 47, no. 6, pp. 2632–2639, Sep. 2001.

[35] S. Venkatesan, S. Simon, and R. Valenzuela, “Capacity of a Gaussian MIMO channel with nonzero mean,” *Proc. IEEE Veh. Tech. Conf. (VTC'03)*, pp. 1767–1771, Oct. 2003, Orlando, Florida, USA.

[36] D. Hösli and A. Lapidoth, “The capacity of a MIMO Ricean channel is monotonic in the singular values of the mean,” *In Proc. 5th Int. ITG Conf. Source and Channel Coding*, Jan. 2004, Erlangen-Nuremberg, Germany.

[37] S. A. Jafar and A. Goldsmith, “Multiple-antenna capacity in correlated Rayleigh fading with channel covariance information,” *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, pp. 990–997, May 2005.

[38] E. Jorswieck and H. Boche, “Optimal transmission strategies and impact of correlation in multi-antenna systems with different types of channel state information,” vol. 52, no. 12, pp. 3440–3453, Dec. 2004.

[39] ——, “Channel capacity and capacity-range of beamforming in MIMO wireless systems under correlated fading with covariance feedback,” *IEEE Trans. Wireless Commun.*, vol. 3, no. 5, pp. 1543–1553, Sep. 2004.

[40] A. Tulino, A. Lozano, and S. Verdu, “Capacity-achieving input covariance for single user multi-antenna channels,” *IEEE Trans. Wireless Commun.*, vol. 5, no. 3, pp. 662–671, Mar. 2006.

[41] M. Vu and A. Paulraj, "On the capacity of MIMO wireless channels with dynamic CSIT," *IEEE J. Select. Areas Commun.*, vol. 25, no. 7, pp. 1269–1283, Sep. 2007.

[42] H. Sampath, P. Stoica, and A. Paulraj, "Generalized linear precoder and decoder design for MIMO channels using the weighted MMSE criterion," *IEEE Trans. Commun.*, vol. 49, no. 12, pp. 2198–2206, Dec. 2001.

[43] A. Scaglione, P. Stoica, S. Barbarossa, G. B. Giannakis, and H. Sampath, "Optimal designs for space-time linear precoders and decoders," *IEEE Trans. Signal Process.*, vol. 50, no. 5, pp. 1051–1064, May 2002.

[44] D. Palomar, J. Cioffi, and M. Lagunas, "Joint Tx-Rx beamforming design for multicarrier MIMO channels: A unified framework for convex optimization," *IEEE Trans. Signal Process.*, vol. 51, no. 9, pp. 2381–2401, Sep. 2003.

[45] Y. Ding, T. N. Davidson, J.-K. Zhang, Z.-Q. Luo, and K. M. Wong, "Minimum BER block precoders for zero-forcing equalization," *Proc. IEEE Int. Conf. Acoust., Speech, Signal Proc.*, vol. 3, pp. 2261–2264, May 2002, Orlando, FL, USA.

[46] S. Zhou and G. B. Giannakis, "Optimal transmitter eigen-beamforming and space-time block coding based on channel mean feedback," *IEEE Trans. Signal Process.*, vol. 50, no. 10, pp. 2599–2613, Oct. 2002.

[47] E. Jorswieck, A. Sezgin, H. Boche, and E. Costa, "Optimal transmit strategies in MIMO Ricean channels with MMSE receiver," *Proc. IEEE Veh. Tech. Conf. (VTC'04)*, vol. 5, pp. 3787–3791, Sep. 2004, Los Angeles, CA, USA.

[48] G. Jöngren, M. Skoglund, and B. Ottersten, "Combining beamforming and orthogonal space-time block coding," *IEEE Trans. Inform. Theory*, vol. 48, no. 3, pp. 611–627, Mar. 2002.

[49] L. Liu and H. Jafarkhani, "Combining beamforming and quasi-orthogonal space-time block coding using channel mean feedback," *Proc. IEEE GLOBECOM*, vol. 4, pp. 1925–1930, Dec. 2003, San Fransico, USA.

[50] ——, “Application of quasi-orthogonal space-time block codes in beamforming,” *IEEE Trans. Signal Process.*, vol. 53, no. 1, pp. 54–63, Jan. 2005.

[51] H. Sampath and A. Paulraj, “Linear precoding for space-time coded systems with known fading correlations,” *IEEE Commun. Lett.*, vol. 6, no. 6, pp. 239–241, June 2002.

[52] S. Zhou and G. B. Giannakis, “Optimal transmitter eigen-beamforming and space-time block coding based on channel correlations,” *IEEE Trans. Inform. Theory*, vol. 49, no. 7, pp. 1673–1690, July 2003.

[53] T. Haustein and H. Boche, “Optimal power allocation for MSE and bit-loading in MIMO systems and the impact of correlation,” *Proc. IEEE Int. Conf. Acoust., Speech, Signal Proc. (ICASSP’03)*, vol. 4, pp. 405–408, Apr. 2003, Hong Kong, China.

[54] M. Vu and A. Paulraj, “Optimal linear precoders for MIMO wireless correlated channels with non-zero mean in space-time coded systems,” *IEEE Trans. Signal Process.*, vol. 54, no. 6, pp. 2318–2332, Jun. 2006.

[55] A. Hjørungnes, D. Gesbert, and J. Akhtar, “Precoding of space-time block coded signals for joint transmit-receive correlated MIMO channels,” *IEEE Trans. Wireless Commun.*, vol. 5, no. 2, pp. 492–497, Feb. 2006.

[56] A. Hjørungnes and D. Gesbert, “Precoded orthogonal space-time block codes over correlated Ricean MIMO channels,” *IEEE Trans. Signal Process.*, vol. 55, no. 2, pp. 779–783, Feb. 2007.

[57] ——, “Precoding of orthogonal space-time block codes in arbitrarily correlated MIMO channels: Iterative and closed-form solutions,” *IEEE Trans. Wireless Commun.*, vol. 6, no. 3, pp. 1072–1082, Mar. 2007.

[58] X. Cai and G. B. Giannakis, “Differential space-time modulation with eigen-beamforming for correlated MIMO fading channels,” *IEEE Trans. Wireless Commun.*, vol. 54, no. 9, pp. 1279–1288, Apr. 2006.

[59] M. K. Simon, S. M. Hinedi, and W. C. Lindsey, *Digital Communication Techniques: Signal Design and Detection.* NJ, USA: Prentice-Hall, 1994.

[60] J. G. Proakis, *Digital Communications*, 4th ed. Singapore: McGraw-Hill, 2001.

[61] V. Tarokh and H. Jafarkhani, “A differential detection scheme for transmit diversity,” *IEEE J. Select. Areas Commun.*, vol. 18, no. 7, pp. 1169–1174, Jul. 2000.

[62] B. L. Hughes, “Differential space time modulation,” *IEEE Trans. Inform. Theory*, vol. 46, no. 7, pp. 2567–2578, Nov. 2000.

[63] B. M. Hochwald and W. Sweldens, “Differential unitary space-time modulation,” *IEEE Trans. Commun.*, vol. 48, no. 12, pp. 2041 – 2052, Dec. 2000.

[64] G. Ganesan and P. Stoica, “Differential modulation using space-time block codes,” *IEEE Signal Process. Lett.*, vol. 9, no. 2, pp. 57–60, Feb. 2002.

[65] E. G. Larsson and P. Stoica, *Space-Time Block Coding for Wireless Communications*. Cambridge, UK: Cambridge University Press, 2003.

[66] M. Tao and R. S. Cheng, “Differential space time block codes,” *Proc. IEEE GLOBECOM*, pp. 1098–1102, Nov. 2001, S. Antonio, Texas, USA.

[67] Z. Chen, G. Zhu, J. Shen, and Y. Liu, “Differential space time block codes from amicable orthogonal designs,” *Proc. IEEE Wireless Communications and Networking Conf. (WCNC 2003)*, pp. 768–772, Mar. 2003, New Orleans, Louisiana, USA.

[68] C. S. Hwang, S. H. Nam, J. Chung, and V. Tarokh, “Differential space time block codes using qam constellations,” *In Proc. of 14-th IEEE Int. Symp. on Personal, lndoor and Mobile Radio Communication*, pp. 1693–1697, Sep. 2003, Beijing, China.

[69] ——, “Differential space time block codes using nonconstant modulus constellations,” *IEEE Trans. Signal Process.*, vol. 51, no. 11, pp. 2955–2964, Nov. 2003.

[70] G. Bauch and A. Mengi, “Non-unitary orthogonal differential space-time modulation with non-coherent soft output detection,” *In Proc. IEEE 62th Veh. Technol. Conf. (VTC’05-Fall)*, Sep. 2005, Dallas, USA.

[71] M. K. Simon and D. Divsalar, “On the implementation and performance of single and double differential detection schemes,” *IEEE Trans. Commun.*, vol. 40, no. 2, pp. 278–291, Feb. 1992.

[72] P. Stoica, J. liu, and J. Li, “Maximum-likelihood double differential detection clarified,” *IEEE Trans. Inform. Theory*, vol. 50, no. 3, pp. 572–576, Mar. 2004.

[73] M. R. Bhatnagar and A. Hjørungnes, “SER expressions for double differential modulation,” *Proc. IEEE Inform. Theory Workshop*, pp. 203–207, Jul. 2007, Bergen, Norway.

[74] Z. Liu, G. B. Giannakis, and B. L. Hughes, “Double differential space-time block coding for time-selective fading channels,” *IEEE Trans. Commun.*, vol. 49, no. 9, pp. 1529–1539, Sep. 2001.

[75] P. Stoica and G. Ganesan, “Trained space-time block decoding for flat fading channels with freqency offsets,” *In Proc. of the 11-th European Signal Processing Conference (EUSIPCO)*, vol. 2, pp. 417–420, Sep. 2002, Toulouse, France.

[76] A. Sendonaris, E. Erkip, and B. Aazhang, “User cooperation diversity — Part I: System description,” *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1938, Nov. 2003.

[77] A. Nosratinia, T. E. Hunter, and A. Hedayat, “Cooperative communication in wireless networks,” *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[78] T. M. Cover and A. A. El Gamal, “Capacity theorems for the relay channel,” *IEEE Trans. Inform. Theory*, vol. 25, no. 4, pp. 572–584, Sept. 1979.

[79] A. Sendonaris, E. Erkip, and B. Aazhang, “User cooperation diversity — Part II: Implementation aspects and performance analysis,” *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1939–1948, Nov. 2003.

[80] P. Merkey and E. C. Posner, “Optimum cyclic redundancy codes for noisy channels,” *IEEE Trans. Inform. Theory*, vol. 30, no. 6, pp. 865–867, Nov. 1984.

[81] W. Su, A. K. Sadek, and K. J. R. Liu, “Ser performance analysis and optimal power allocation for decode-and-forward cooperation protocol in wireless networks,” *Proc. IEEE Wireless Communications and Networking Conf.*, pp. 984–989, Mar. 2005, New Orleans, LA USA.

[82] J. N. Laneman, G. W. Wornell, and D. N. C. Tse, “An efficient protocol for realizing cooperative diversity in wireless networks,” *Proc. Int. Symp. on Information Theory*, p. 294, Jun. 2001, Washington, DC, USA.

[83] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behaviour,” *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 389–400, Dec. 2004.

[84] T. E. Hunter and A. Nosratinia, “Cooperative diversity through coding,” *Proc. Int. Symp. on Information Theory*, p. 220, Jul. 2002, Laussane, Switzerland.

[85] ——, “Diversity through coded cooperation,” *IEEE Trans. Wireless Commun.*, vol. 5, no. 2, pp. 283–289, Feb. 2006.

[86] M. Janani, A. Hedayat, T. E. Hunter, and A. Nosratinia, “Coded cooperation in wireless communications: Space-time transmission and iterative decoding,” *IEEE Trans. Signal Process.*, vol. 52, no. 2, pp. 362–371, Feb. 2004.

[87] T. E. Hunter and A. Nosratinia, “Coded cooperation under slow fading, fast fading, and power control,” *In Proc. Asilomar Conference on Signals, Systems, and Computers*, Nov. 2002, Pacific Grove, CA, USA.

[88] Q. Zhao and H. Li, “Performance of differential modulation with wireless relays in Rayleigh fading channels,” *IEEE Commun. Lett.*, vol. 9, no. 4, pp. 343–345, Apr. 2005.

[89] ——, “Performance of decode-based differential modulation for wireless relay networks in Nakagami-m channels,” *in Proc. 2006 IEEE Int. Conf. Acoustics, Speech, Signal Processing*, pp. 673–675, May 2006, Toulouse, France.

[90] D. Chen and J. N. Laneman, “Noncoherent demodulation for cooperative diversity in wireless systems,” *Proc. IEEE GLOBECOM*, pp. 32–35, Nov.-Dec. 2004, Dallas, Texas USA.

[91] ——, “Cooperative diversity for wireless fading channels without channel state information,” *In Proc. 48-th Asilomar Conf. Signals, Systems, and Computers*, pp. 1307–1312, Nov. 2004, Monterey, CA, USA.

[92] Q. Zhao and H. Li, “Performance of differential modulation with wireless relays in rayleigh fading channels,” *IEEE Commun. Lett.*, vol. 9, no. 4, pp. 343–345, Apr. 2005.

[93] T. Himsoon, W. Su, and K. J. R. Liu, “Differential transmission for amplify-and-forward cooperative communications,” *IEEE Signal Process. Lett.*, vol. 12, no. 9, pp. 597–600, Sep. 2006.

[94] Q. Zhao and H. Li, “Performance analysis of an amplify-based differential modulation for wireless relay networks under Nakagami-m fading channels,” *Proc. IEEE Int. Workshop on Signal Process. Advances in Wireless Communications (SPAWC’05)*, pp. 211–215, Jun. 2005, New York, NY, USA.

[95] P. Tarasak, H. Minn, and V. K. Bhargava, “Differential modulation for two-user cooperative diversity systems,” *Proc. IEEE GLOBECOM*, pp. 3389–3393, Nov.-Dec. 2004, Dallas, Texas, USA.

[96] ——, “Differential modulation for two-user cooperative diversity systems,” *IEEE J. Select. Areas Commun.*, vol. 23, no. 9, pp. 1891–1900, Sep. 2005.

[97] Y. Zhang, “Differential modulation schemes for decode-and-forward cooperative diversity,” *Proc. IEEE Int. Conf. Acoust., Speech, Signal Proc. (ICASSP’05)*, vol. 4, pp. 918–920, Mar. 2005, Philadelphia, PA, USA.

[98] G. Wang, Y. Zhang, and M. Amin, “Differential distributed space-time modulation for cooperative networks,” *IEEE Trans. Wireless Commun.*, vol. 5, no. 11, pp. 3097–3108, Nov. 2006.

[99] M. R. Bhatnagar, A. Hjørungnes, and L. Song, “Precoding of differential OSTBC in arbitrarily correlated MIMO channels,” *In Proc. Asilomar Conference on Signals, Systems, and Computers*, Nov. 2007, Monterey, CA, USA.

[100] ——, “Precoded DOSTBC over Rayleigh channels,” *EURASIP Research Letters in Communications*, vol. 2007, no. 16438, pp. 1–5, Oct. 2007.

[101] ——, “Non-orthogonal differential space-time block code with non-unitary constellations,” *In Proc. of 8-th IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC’07)*, pp. 1–5, Jun. 2007, Helsinki, Finland.

[102] A. Hjørungnes and D. Gesbert, “Complex-valued matrix differentiation: Techniques and key results,” *IEEE Trans. Signal Process.*, vol. 55, no. 6, pp. 2740–2746, Jun. 2007.

[103] M. R. Bhatnagar, A. Hjørungnes, and L. Song, “Double differential orthogonal space-time modulation,” *In Proc. of IEEE Conference on Acoustics, Speech, and Signal Processing (ICASSP’08)*, pp. 1–4, Mar.-Apr. 2008, Las Vegas, NV, USA.

[104] M. R. Bhatnagar, R. Vishwanath, and V. Bhatnagar, “Performance analysis of space time codes in flat fading MIMO channels with offsets,” *EURASIP J. Wireless Comm. and Net.*, vol. 2007, no. 30548, p. 7, Apr. 2007.