Near-Capacity Multi-Functional MIMO Systems:

Sphere-Packing, Iterative Detection and Cooperation

by

L. Hanzo, O. R. Alamri, M. El-Hajjar, N. Wu

We dedicate this monograph to the numerous contributors of this field, many of whom are listed in the Author Index

The classic Shannon-Hartley law suggests that the achievable channel capacity increases logarithmically with the transmit power. By contrast, the MIMO capacity increases linearly with the number of transmit antennas, provided that the number of receive antennas is equal to the number of transmit antennas. With the further proviso that the total transmit power is increased proportionately to the number of transmit antennas, a linear capacity increase is achieved upon increasing the transmit power, which justifies the spectacular success of MIMOs...

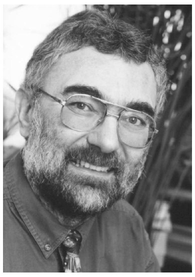
School of Electronics and Computer Science
University of Southampton
Southampton SO17 1BJ
United Kingdom

Contents

II Coherent Versus Differential Turbo-Detection of Single-User and Cooperative MIMOs 209

7 Linear Dispersion Codes – An EXIT Chart Perspective 211

About the Authors



Lajos Hanzo (http://www-mobile.ecs.soton.ac.uk) FREng, FIEEE, FIET, DSc received his degree in electronics in 1976 and his doctorate in 1983. During his 31-year career in telecommunications he has held various research and academic posts in Hungary, Germany and the UK. Since 1986 he has been with the School of Electronics and Computer Science, University of Southampton, UK, where he holds the chair in telecommunications. He has co-authored 17 books on mobile radio communications totalling in excess of 10 000, published in excess of 800 research papers, acted as TPC Chair of IEEE conferences, presented keynote lectures and been awarded a number of distinctions. Currently he is directing an academic research team, working on a range of research projects in the field of wireless multimedia communications sponsored by industry, the Engineering and Physical Sciences Research Council (EPSRC) UK, the European IST Programme and the Mobile Virtual Centre of Excellence (VCE), UK. He is an enthusiastic supporter of industrial and academic liaison and he offers a range of industrial courses. He is also an IEEE Distinguished Lecturer as well as a Governor of both the IEEE ComSoc and the VTS. He is the acting Editor-in-Chief of the IEEE Press. For further information on research in progress and associated publications please refer to http://www-mobile.ecs.soton.ac.uk

Osamah Rashed Alamri received his B.S. degree with first class honours in electrical engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, in 1997, where he was ranked first with a 4.0 GPA. In 2002, he received his M.S. degree in electrical engineering from Stanford University, California, USA. Mr. Alamri submitted his PhD thesis in October 2006 and published in excess of 20 research papers while working towards his PhD degree with the Communications Group, Shool of Electronics and Computer Science, University of Southampton, UK. His research interests include sphere packing modulation, space-time coding, turbo coding and detection, multidimensional mapping and MIMO systems. At the time of writing he is continuing his investigations as a post-doctoral researcher.

Mohammed El-Hajjar received the B.Eng. degree (with Distinction) in Electrical Engineering from the American University of Beirut (AUB), Lebanon, and the M.Sc. degree (with Distinction) in Radio Frequency Communication Systems from the University of Southampton, UK. Since October 2005, he has been working towards his Ph.D. degree with the Communications Group, School of Electronics and Computer Science, University of Southampton, U.K. Mohammed is the recepient of several academic awards from the AUB as well as the University of Southampton. His research interests include sphere packing modulation, space-time coding, differential space-time spreading, adaptive transceiver design and cooperative communications. In 2008 he completed his PhD thesis and joined Ensigma in Chepstow, Wales, UK as wireless system architect.

Nan Wu received his B.Eng in Electronics Engineering in 2003 from Dalian University of Technology, China. He then moved to the UK and received his M.Sc degree (with Distinction) and PhD from the University of Southampton, UK in 2004 and 2008, respectively. His research interests are in the areas of wireless communications, including space-time coding, channel coding and cooperative MIMO systems. In September 2008 he joined the National Institute of Standards and Technology (NIST) in the USA as a guest researcher working on cross-layer designs.

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[1] For detailed contents and sample chapters please refer to http://www-mobile.ecs.soton.ac.uk

Preface

The family of recent wireless standards included the optional employment of MIMO tyechniques. This was motivated by the observation according to the classic Shannon-Hartley law the achievable channel capacity increases logarithmically with the transmit power. By contrast, the MIMO capacity increases linearly with the number of transmit antennas, provided that the number of receive antennas is equal to the number of transmit antennas. With the further proviso that the total transmit power is increased proportionately to the number of transmit antennas, a linear capacity increase is achieved upon increasing the transmit power, which justifies the spectacular success of MIMOs...

Hence this volume explores recent research advances in MIMO techniques as well as their limitations. The basic types of multiple antenna-aided wireless systems are classified and their benefits are characterised. We also argue that under realistic propagation conditions, when for example the signals associated with the MIMO elements become correlated owing to shadow fading, the predicted performance gains may substantially erode. Furthermore, owing to the limited dimensions of shirt-pocket-sized handsets the employment of multiple antenna elements at the mobile station is impractical. In this scenario only the family of distributed MIMO elements relying on the cooperation of potentially single-element mobile stations is capable of eliminating the correlation of the signals impinging on the MIMO elements, as it will be discussed in the book. The book also reports on a variety of avantgarde hybrid MIMO designs to set out promising future research directions.

Our intention with the book is:

1. First, to pay tribute to all researchers, colleagues and valued friends, who contributed to the field. Hence this book is dedicated to them, since without their quest for better MIMO solutions for wireless communications this monograph could not have been conceived. They are too numerous to name here, hence they appear in the author index of the book. Our hope is that the conception of this monograph on the topic will provide an adequate portrayal of the community's research and will further fuel this innovation process.

2. We expect to stimulate further research by exposing open research problems and by collating a range of practical problems and design issues for the practitioners. The coherent further efforts of the wireless research community is expected to lead to the solution of the range of outstanding problems, ultimately providing us with flexible MIMO-aided wireless transceivers exhibiting a performance close to information theoretical limits.

Chapter 1

Problem Formulation, Objectives and Benefits

The objective of this light-hearted introductory chapter is to provide a brief rudimentary exposure of the pivotal aspects of the book. Our treatment in this chapter is conceptual, rather than mathematically motivated, with the objective of characterizing the attainable diversity gains, multiplexing gains and beamforming gains. All issues touched upon in this chapter will be revisited in a more rigorous mathematical approach in the remaining chapters.

Digital communication exploiting multiple-input multiple-output (MIMO) wireless channels has recently attracted considerable attention as one of the most significant technical breakthroughs in modern communications. Soon after its invention, the technology seems to have the potential to be part of large-scale standards-driven commercial wireless products and networks such as broadband wireless access systems, wireless local area networks (WLAN), third-generation (3G) networks and beyond [1]. The 3G systems are expected to have the capability to support circuit and packet data at high bit rates. Rates of 144 kilobits/second or higher in high mobility (vehicular) traffic, 384 Kbits/second for pedestrian traffic, and 2 Megabits/second or higher for indoor traffic are targeted [2]. Wireless systems that employ multiple antennas provide a promising platform for achieving such high rates because of the improved bit/symbol capacity compared to the single-input single-output systems [3].

As shown in Figure 1.1, MIMO systems can be defined as wireless communication systems for which the transmitting end as well as the receiving end is equipped with multiple antenna elements. The basic concept of MIMO is that the transmitted signals from all transmit antennas are *combined* at each receive antenna element in such a way to improve the Bit Error Rate (BER) performance or the data rate (bits/sec) of the transmission. Both the network's quality of service and the operator's revenues can be increased significantly because of this advantage of MIMO systems. One can think of MIMO systems as an extension to smart antennas. However, the idea of using antenna arrays for improving the wireless transmission was introduced several decades ago.

Space-time processing (STP) is the core concept of MIMO systems. Time is the natural dimension of digital communication data. Space refers to the spatial dimension inherent in the use of multiple spatially distributed antennas. Most of the current interest in space-time coding (STC) is driven by discoveries in the late 1980s and early 1990s that multiple antennas can exploit a rich wireless scattering environment and benefit from the multi-path fading nature of the wireless channel. Current research mostly focuses on channel modelling and measurement, and on the design of modulation and coding techniques that take into consideration the two-dimensional nature of STP (i.e. the space and time dimensions) [4].

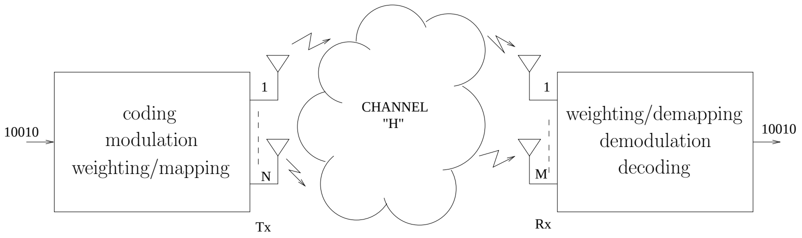

Figure 1.1: MIMO wireless transmission system

1.1 The Wireless Channel and the Concept of Diversity

The key characteristics of the mobile radio channel in contrast to the Gaussian channel are small-scale fading and multipath propagation [5]. Small-scale fading, which is usually simply called fading, refers to the rapid fluctuation of signal strength over a short travel distance or period of time. Fading is primarily caused by multipath propagation of the transmitted signal, which creates replicas of the transmitted signal that arrive at the receiver with different delays. These versions of the transmitted signal combine either constructively or destructively at the receiver resulting in fluctuation in amplitude and phase of the resultant signal. Other factors that influence the small-scale fading include speed of the mobile, speed of the surrounding objects and the transmission bandwidth of the signal [5]. During severe fading, the transmitted signal cannot be determined by the receiver unless some less attenuated version of it is available at the receiver. This usually can be achieved by introducing some sort of diversity in the transmitted signal. The three most common diversity techniques are [6]:

- **Temporal Diversity**: An example of temporal diversity is channel coding with time interleaving. The receiver is provided with several versions of the transmitted signal as redundancy in the temporal domain.

- **Frequency Diversity**: This type of diversity is based on the phenomenon that the structure of multipath propagation depends on the frequency of the transmitted wave. Thus redundancy in the frequency domain provides the receiver with several replicas of the transmitted signal that experience different fading at any particular time instance.

- **Antenna or Space Diversity**: In order to create space diversity, several spatially separated or differentially polarised antennas are employed. This would generate redundancy of the transmitted signal in the spatial domain, where each replica would undergo different propagation path. In this context, diversity order refers to the number of decorrelated spatial branches available at the transmitter or receiver, where the probability of losing a signal decreases exponentially with increasing diversity order.

It is always desirable to employ all forms of diversity in order to combat the adverse effects of the wireless channel [7]. However, it becomes sometimes impractical to employ a particular type of diversity in a specific situation [8]. For example, temporal diversity is ineffective in slow fading channels especially for delay-sensitive applications. In addition, antenna diversity at the mobile unit induces design impracticality. The most common systems that employ different types of diversity techniques for the sake of improving the performance of wireless transmission/reception are STC and MIMO schemes. Next, a brief historical overview on space-time coding and MIMO systems will be presented summarising the main contributions in this field.

1.2 Diversity and Multiplexing Tradeoffs in Multi-functional MIMO Systems

1.2.1 Classification of Multiple-Input Multiple-Output Systems

Again, our objective in this light-hearted section is to provide a brief conceptual overview of the material discussed in significantly more detail in Parts I and III of the book. More specifically, we will briefly consider the design alternatives of different Multiple-Input Multiple-Output (MIMO) schemes, while considering the attainable diversity gains, multiplexing gains and beamforming gains. Our easy-reading conceptual treatment in this section aims for avoiding the rigor of mathematics, which is left for the detailed approach of the remaining chapters.

Here we would like to commence with a brief classification of different MIMO schemes, which are categorised as *diversity techniques, multiplexing schemes, multiple access arrangements and beamforming techniques*. We then introduce two *multi-functional MIMO families*. These multi-functional MIMOs are capable of combining the benefits of several MIMO schemes and hence they attain an improved performance in terms of both their Bit Error Ratio (BER) as well as throughput. The first multi-functional MIMO family represents the recently proposed Layered Steered Space-Time Codes (LSSTC), which combines the triple benefits of Space-Time Block Codes (STBC), Vertical Bell Labs Layered Space-Time (V-BLAST) schemes and beamforming. The other multi-functional MIMO scheme is referred to as Layered Steered Space-Time Spreading (LSSTS) that combines the benefits of Space-Time Spreading (STS), V-BLAST and beamforming with those of the generalised Multi-Carrier Direct Sequence Code Division Multiple Access (MC DS-CDMA). We also compare the attainable diversity, multiplexing and beamforming gains of the different MIMO schemes in order to document the advantages of the multi-functional MIMOs over conventional MIMO schemes.

Recently, there has been an urging demand for flexible and bandwidth-efficient transceivers capable of supporting the explosive expansion of the Internet and the continued dramatic increase in demand for high-speed multimedia wireless services. Advances in channel coding made it feasible to approach Shannon's capacity limit in systems equipped with a single antenna [9], but fortunately these capacity limits can be further extended with the aid of multiple antennas. Recently, Multiple-Input Multiple-Output (MIMO) systems have attracted considerable research attention and it is considered as one of the most significant technical breakthroughs in contemporary communications.

Explicitly, the MIMO schemes can be categorised as diversity techniques, multiplexing schemes, multiple access methods, beamforming as well as multi-functional MIMO arrangements, as shown in Figure 1.2. Spatial diversity can be attained by employing multiple antennas at the transmitter or the receiver. Multiple antennas can be used to transmit and receive appropriately encoded replicas of the same information sequence in order to achieve diversity and hence to obtain an improved BER performance. In the context of diversity techniques, the antennas are spaced as far apart as possible, so that the signals transmitted to or received by the different antennas experience independent fading and hence we attain the highest possible diversity gain.

A simple spatial diversity technique, which does not involve any loss of bandwidth, is constituted by the employment of multiple antennas at the receiver, where several techniques can be employed for combining the independently fading signal replicas, including Maximum Ratio Combining (MRC), Equal Gain Combining (EGC) and Selection Combining (SC), as shown in Figure 1.2. Several transmit - rather than receive - diversity techniques have also been proposed in the literature [10–13], as shown in Figure 1.2. In [10] Alamouti proposed a witty transmit diversity technique using two transmit antennas, whose key advantage was the employment of low-complexity single-receive-antenna-based detection, which avoids the more complex joint detection of multiple symbols. The decoding algorithm proposed in [10] can be generalised to an arbitrary number of receive antennas using MRC, EGC or SC. Alamouti's achievement inspired Tarokh *et*

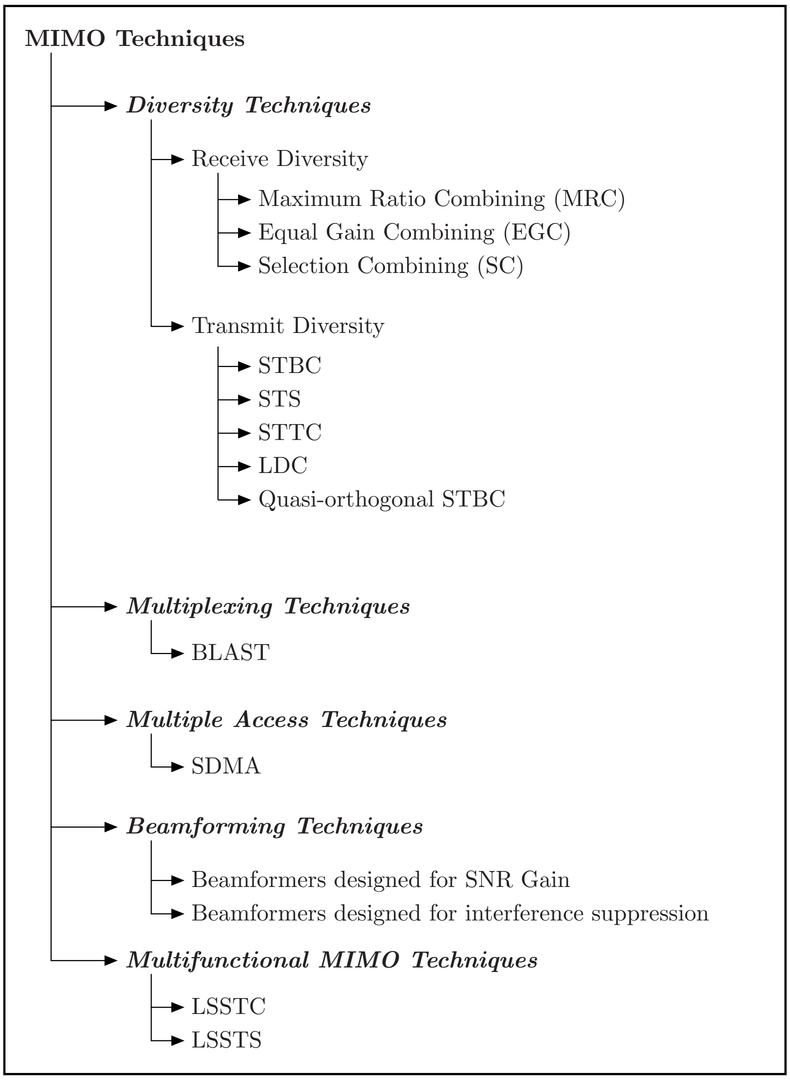

Figure 1.2: Classification of MIMO Techniques.

al. [11] to generalise the concept of transmit diversity schemes to more than two transmit antennas, contriving the generalised concept of Space-Time Block Codes (STBC). The family of STBCs is capable of attaining the same diversity gain as Space-Time Trellis Codes (STTC) [12] at a lower decoding complexity, when employing the same number of transmit antennas. However, a disadvantage of STBCs when compared to STTCs is that they employ unsophisticated repetition-coding and hence provide no coding gain. Furthermore, inspired by the philosophy of STBCs, Hochwald *et al.* [14] proposed the transmit diversity concept known as Space-Time Spreading (STS) for the downlink of Wideband Code Division Multiple Access (WCDMA) that is capable of achieving the highest possible transmit diversity gain.

Regretfully, the STBC and STS designs of [11,14] contrived for more than two transmit antennas result in a reduction of the achievable throughput per channel use. An alternative idea invoked for constructing full-rate STBCs for complex-valued modulation schemes and more than two antennas was suggested in [15]. Here the strict constraint of perfect orthogonality was relaxed in favour of achieving a higher data rate. The resultant STBCs were referred to as quasi-orthogonal STBCs [15].

The STBC and STS designs offer - at best - the same data rate as an uncoded single-antenna system, but they provide an improved BER performance compared to the family of single-antenna-aided systems by providing diversity gains. In contrast to this, several high-rate space-time transmission schemes having a normalised rate higher than unity have been proposed in the literature. For example, high-rate space-time codes that are linear both in space and time, namely the family of the so-called Linear Dispersion Codes (LDC), was proposed in [13]. LDCs provide a flexible trade-off between emulating space-time coding and/or spatial multiplexing.

STBCs and STTCs are capable of providing diversity gains for the sake of improving the achievable system performance. However, this BER performance improvement is often achieved at the expense of a rate-loss, since STBCs and STTCs may result in a throughput-loss compared to single-antenna-aided systems. As a design alternative, a specific class of MIMO systems was designed for improving the attainable spectral efficiency of the system by transmitting different signal streams independently over each of the transmit antennas, hence resulting in a multiplexing gain. This class of MIMOs subsumes Bell Labs' Layered Space-Time (BLAST) scheme and its relatives [16]. The BLAST scheme aims for increasing the system throughput in terms of the number of bits per symbol that can be transmitted in a given bandwidth at a given integrity.

In contrast to the family of BLAST schemes, where multiple antennas are activated by a single user for increasing the user's throughput, Space Division Multiple Access (SDMA) [17] employs multiple antennas for the sake of supporting multiple users. SDMA exploits the unique user-specific Channel Impulse Response (CIR) of the different users for separating their received signals. On the other hand, in beamforming arrangements [17] typically $\lambda/2$-spaced antenna elements are used for the sake of creating a spatially selective transmitter/receiver beam, where λ represents the carrier's wavelength. Beamforming is employed for providing a beamforming gain by mitigating the effects of various interfering signals, provided that they arrive from sufficiently different directions. Additionally, beamforming is capable of suppressing the effects of co-channel interference, hence allowing the system to support multiple users by angularly separating them. Again, this angular separation becomes feasible only on condition, if the corresponding users are separable in terms of the angle of arrival of their beams.

Finally, multi-functional MIMOs, as the terminology suggests, combine the benefits of several MIMO schemes including diversity gains, multiplexing gains as well as beamforming gains. As mentioned earlier, V-BLAST is capable of achieving the maximum attainable multiplexing gain, while STBC can achieve the full achievable antenna diversity gain facilitated by the number of independently fading diversity channels. Hence, it was proposed in [18] to combine these two techniques in order to provide both antenna diversity and spectral efficiency gains. Furthermore, the combined array processing proposed in [18] was improved in [19] by optimising the decoding order of the different antenna layers. An iterative decoding algorithm was proposed in [19] that results in achieving the full receive diversity gain for the combined V-BLAST STBC system facilitated by the number of independently fading diversity channels. On the other hand, in [20] the authors presented a transmission scheme referred to as Double Space-Time Transmit Diversity (D-STTD), which consists of two STBC layers at the transmitter that is equipped with four transmit antennas, while the receiver is equipped with two antennas. Furthermore, in order to achieve additional performance gains, beamforming has been combined both with spatial diversity as well as spatial multiplexing techniques. STBC has been combined with beamforming in order to attain an improved SNR gain in addition to the diversity gain [21].

This contribution provides a light-hearted perspective on further research advances in the field of multi-functional MIMO systems and demonstrates how diversity, multiplexing and beamforming gains are achieved by multi-functional MIMOs. More explicitly, in Section 1.2.2 we elaborate on the design of two novel multi-functional MIMOs, that are characterised by diversity gain, multiplexing gain as well as beamforming gain. In Section 1.2.3 we quantify the achievable performance of the different MIMO schemes. A comparison of the different MIMO schemes expressed in terms of their diversity, multiplexing and beamforming gains is presented in Section 1.2.4, followed by our brief conclusions.

1.2.2 Multi-functional MIMO Systems

Space-time codes have been designed for the sake of attaining the highest possible diversity gain, where the diversity order of STBC schemes is $(N_t \times N_r)$, where N_t is the number of transmit antennas and N_r represents the number of receive antennas. However, the STBC schemes were not designed for attaining any multiplexing gain; quite the contrary, in some STBC designs there is a rate loss, which results in a reduced throughput in comparison to Single-Input Single-Output (SISO) systems. On the other hand, the V-BLAST scheme was designed for attaining the maximum achievable multiplexing gain equal to the number of transmit antennas, although it does not attain a high diversity gain. Therefore, the appealing concept of multi-functional MIMO schemes designed for combining the benefits of STBC and BLAST schemes arises, in order to provide both diversity and multiplexing gains. Below we describe two novel multi-functional MIMO schemes that can attain diversity gain, multiplexing gain and beamforming gain, while employing low-complexity linear receivers.

1.2.2.1 Layered Steered Space-Time Codes

The first multi-functional MIMO scheme combines the benefits of the V-BLAST scheme, of STBCs as well as of beamforming. Thus, the proposed system benefits from the multiplexing gain of V-BLAST, from the diversity gain of STBCs and from the SNR gain of the beamformer. This multi-functional MIMO scheme was referred to as a Layered Steered Space-Time Code (LSSTC) [22].

A block diagram of the proposed LSSTC scheme is illustrated in Figure 1.3. The system's architecture in Figure 1.3 has N_t transmit Antenna Arrays (AA) spaced sufficiently far apart in order to experience independent fading and hence to achieve transmit diversity. The L_{AA} number of elements of each of the AAs are spaced at a distance of $\lambda/2$ for the sake of achieving a beamforming gain. Furthermore, the receiver is equipped with $N_r \geqslant N_t$ antennas. According to Figure 1.3, a block of B input information symbols is serial-to-parallel converted to K groups of symbol streams of length B_1, B_2, $\cdots$, B_K, where $B_1 + B_2 + \cdots + B_K = B$. Each group of B_k symbols, $k \in [1, K]$, is then encoded by a component space-time code STC_k associated with m_k transmit AAs, where $m_1 + m_2 + \cdots + m_K = N_t$.

The L_{AA}-dimensional spatio-temporal CIR vector spanning the mth transmitter AA, $m \in [1, \cdots, N_t]$, and the nth receiver antenna, $n \in [1, \cdots, N_r]$, can be expressed as $\mathbf{h}_{nm}(t) = \mathbf{a}_{nm}(t)\delta(t - \tau_k)$, where τ_k is the signal's delay and $\mathbf{a}_{nm}(t)$ is the CIR of the mnth link between the mth AA and the nth receive antenna. Based on the assumption that the array elements are separated by half a wavelength, we have $\mathbf{a}_{nm}(t) = \alpha_{nm}(t) \cdot \mathbf{d}_{nm}$, where $\alpha_{nm}(t)$ is a Rayleigh faded envelope and $\mathbf{d}_{nm}$ is an L_{AA}-dimensional vector, whose elements are based on the Direction Of Arrival (DOA) of the signal to the receiver. As for the AA-specific DOA, we consider a scenario where the distance between the transmitter and the receiver is significantly higher than that between the AAs and thus we can assume that the signals arrive at the different AAs in parallel, i.e. the DOA at the different AAs is the same. In this scenario, the MRC-criterion based transmit beamformer, which constitutes an effective solution to maximising the antenna gain, is the optimum beamformer.

The decoder applies Group Successive Interference Cancellation (GSIC) based on the Zero Forcing (ZF) algorithm [18] for decoding the received signal. The most beneficial decoding order of the STC layers is determined on the basis of detecting the highest-power layer first for the sake of a high correct detection probability. For simplicity, let us consider the case of $K = 2$ STBC layers, where layer 1 is detected first, which allows us to eliminate the interference caused by the signal of layer 2. However, the proposed concept is applicable to arbitrary STCs and to an arbitrary number of layers K. For this reason, the decoder of layer 1 has to compute a matrix $\mathbf{Q}$, so that we have $\mathbf{Q} \cdot \widehat{\mathbf{H}}_2 = 0$, where $\widehat{\mathbf{H}}_2$ represents the channel matrix of the second STBC layer whose nmth element is α_{nm}. Therefore, the decoder computes an orthonormal basis for the left null space of $\widehat{\mathbf{H}}_2$ and assigns the vectors of the basis to the rows of $\mathbf{Q}$. Multiplying $\mathbf{Q}$ by the received signal matrix

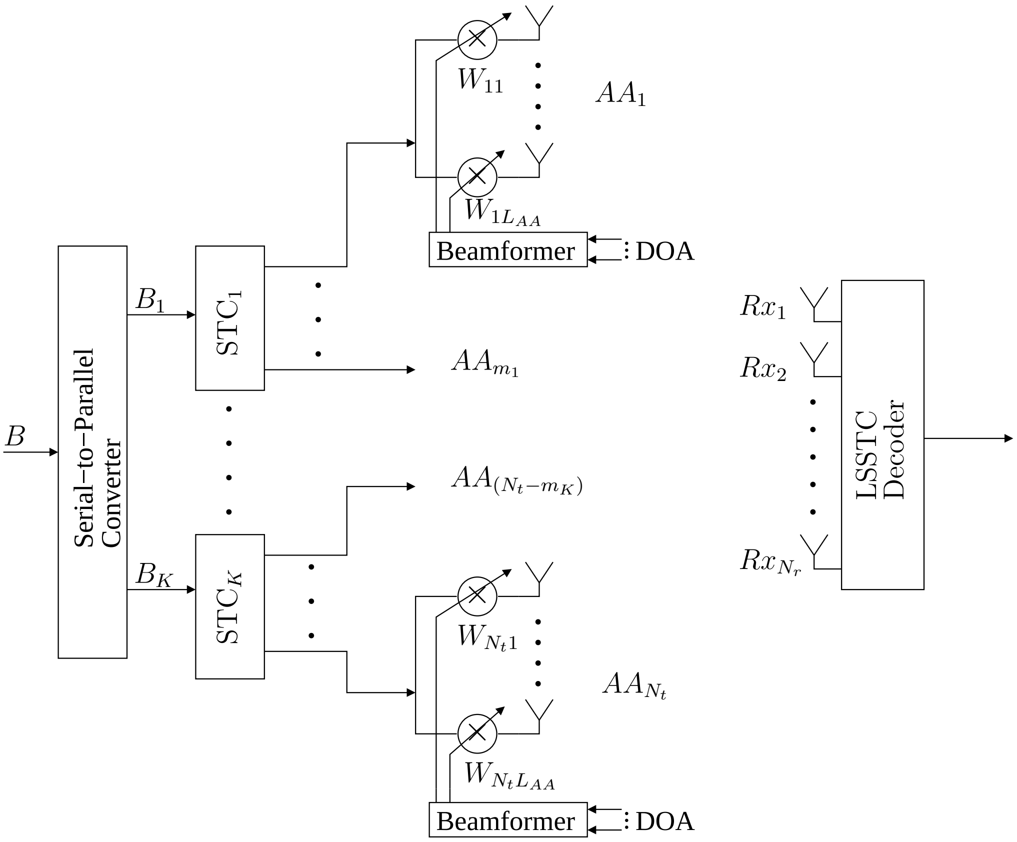

Figure 1.3: Layered steered space-time code system block diagram.

Y suppresses the interference of layer 2 originally imposed on layer 1 and generates a signal which can be decoded using Maximum Likelihood (ML) STBC detection. Then, the decoder subtracts the remodulated contribution of the decoded symbols of layer 1 from the composite twin-layer received signal **Y**. Finally, the decoder applies direct STBC decoding to the second layer, since the interference imposed by the first layer has been eliminated. This group-interference cancellation procedure can be generalised to arbitrary N_t and K values.

1.2.2.2 Layered Steered Space-Time Spreading

The LSSTC scheme of Section 1.2.2.1 combines the benefits of V-BLAST, STBC and beamforming and hence is characterised by a diversity gain, a multiplexing gain as well as a beamforming gain. However, a drawback of the LSSTC scheme is the fact that the number of receive antennas N_r should be at least equal to the number of transmit antennas N_t. This condition is not very practical for employing shirt-pocket sized Mobile Stations (MS) that are limited in size and complexity. The LSSTC scheme can be applied in a scenario where two Base Stations (BS) cooperate or a BS is communicating with a MIMO-aided laptop. Therefore, in order to allow communication between a BS and a MS accommodating less antennas than the transmitting BS while employing simple linear receivers, the Layered Steered Space-Time Spreading (LSSTS) scheme described below can be employed.

A block diagram of the LSSTS scheme is shown in Figure 1.4. The LSSTS scheme combines the benefits of V-BLAST, STS and beamforming with generalised MC DS-CDMA [23] for the sake of achieving a multiplexing gain, a spatial and frequency diversity gain as well as a beamforming

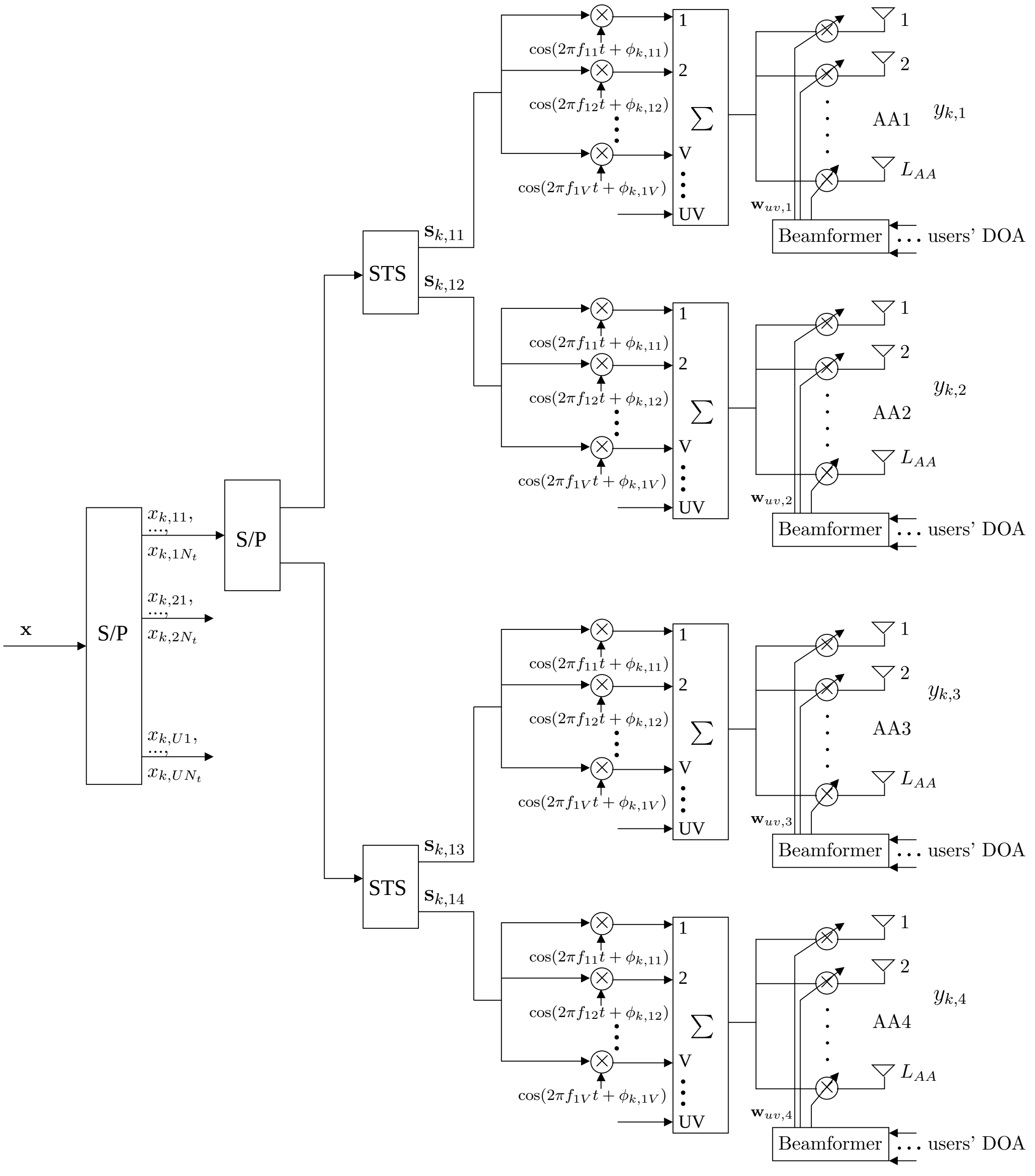

Figure 1.4: The k_{th} user's LSSTS aided Generalised MC DS-CDMA transmitter model.

gain. The LSSTS scheme described in this section employs N_t=4 transmit antennas and N_r=2 receive antennas and employs a linear receiver to decode the received signal.

The system architecture employed in Figure 1.4 for the proposed scheme is equipped with N_t=4 transmit AAs spaced sufficiently far apart in order to experience independent fading. The L_{AA} number of elements of each of the AAs are spaced at a distance of $\lambda/2$ for the sake of achieving beamforming. The system can support K users transmitting at the same time and using the same carrier frequencies, while they can be differentiated by the user-specific spreading code $\bar{\mathbf{c}}_k$, where $k \in [1, K]$. Additionally, in the generalised MC DS-CDMA system considered, the subcarrier frequencies are arranged in a way that guarantees that the same STS signal is spread to and hence transmitted by the specific V number of subcarriers having the maximum possible frequency separation, so that they experience independent fading and achieve the maximum attainable frequency diversity.

The system considered employs the generalised MC DS-CDMA scheme of [23] using UV number of subcarriers. The transmitter schematic of the kth user is shown in Figure 1.3, where a block of UN_t data symbols $\mathbf{x}$ is Serial-to-Parallel (S/P) converted to U parallel sub-blocks. Afterwards, each set of N_t symbols is S/P converted to G=2 groups, where each group is encoded using the N_{tg}=2 antenna-aided STS procedure of [14], where the transmitted signal is spread to N_{tg} transmit antennas with the aid of the orthogonal spreading codes of $\{\bar{\mathbf{c}}_{k,1}, \bar{\mathbf{c}}_{k,2}, \cdots, \bar{\mathbf{c}}_{k,N_tg}\}$, k=$1, 2, ..., K$. The spreading codes $\bar{\mathbf{c}}_{k,1}$ and $\bar{\mathbf{c}}_{k,2}$ are generated from the same user-specific spreading code $\bar{\mathbf{c}}_k$ as in [14]. The discrete symbol duration of the orthogonal STS codes is $N_{tg}N_e$, where N_e represents the kth user's TD spreading factor.

The UN_t outputs of the UG number of STS blocks modulate a group of subcarrier frequencies $\{f_{u,1}, f_{u,2}, ..., f_{u,V}\}$. Since each of the U sub-blocks is spread to and hence conveyed with the aid of V subcarriers, a total of UV number of subcarriers are required in the MC DS-CDMA system considered. The UV number of subcarrier signals are superimposed on each other in order to form the complex-valued modulated signal for transmission. Finally, according to the kth user's channel information, the UVN_t signals of the kth user are weighted by the transmit weight vector $\mathbf{w}_{uv,n}^{(k)}$ determined for the uvth subcarrier of the kth user, which is generated for the nth AA. Assuming that the system employs a modulation scheme transmitting D bits-per-symbol, then the bandwidth efficiency of the LSSTS aided Generalised MC DS-CDMA system is given by $2UD$ bits-per-channel-use.

The uvth CIR considered in the case of LSSTS is the same as that considered in the previous section for LSSTC. Assuming that the K users' data are transmitted synchronously over a dispersive Rayleigh fading channel, decoding is carried out in two steps, first SIC is performed according to [20], followed by the STS decoding procedure of [14].

Finally, after combining the k=1st user's identical replicas of the same signal transmitted by spreading over V number of subcarriers, the decision variables corresponding to the symbols transmitted in the uth sub-block can be expressed as $\widetilde{x}_{1,u} = \sum_{v=1}^{V} \widetilde{x}_{1,uv}$. Therefore, the decoded signal has a diversity order of $2V$. More explicitly, second order spatial diversity is attained from the STS operation and a diversity order of V is achieved as a benefit of spreading by the generalised MC DS-CDMA scheme, where the subcarrier frequencies are arranged in a way that guarantees that the same STS signal is spread to and hence transmitted by the specific V number of subcarriers having the maximum possible frequency separation, so that they experience as independent fading as possible.

1.2.3 Expected Performance and Discussions

In this section we compare the BER performance of the different MIMO schemes to that of the SISO system. We compare BPSK modulated systems, while considering transmissions over correlated Rayleigh fading channels associated with a normalised Doppler frequency of 0.01.

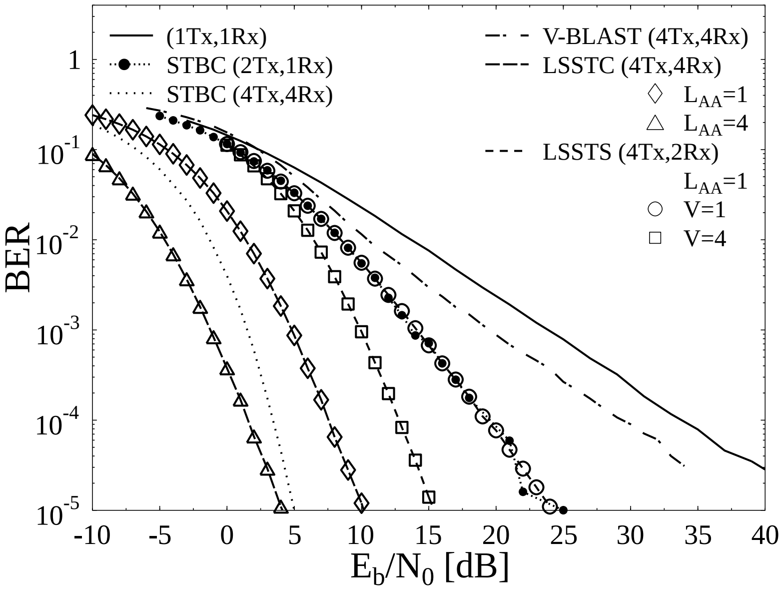

Figure 1.5: BER performance comparison of the SISO, STBC, V-BLAST, LSSTC and LSSTS schemes, while communicating over a correlated Rayleigh fading channel associated with a normalised Doppler frequency of f_d=0.01.

Table 1.1: Comparison of the gains achieved by various MIMO schemes.

	N_t	N_r	L_{AA}	V	Number of Layers	Diversity Order	Multiplexing Order	Beamforming Order
STBC	2	N_r	1	1	1	$2 \times N_r$	1	1
	4	N_r	1	1	1	$4 \times N_r$	1/2	1
	8	N_r	1	1	1	$8 \times N_r$	1/2	1
V-BLAST ZF-SIC	2	2	1	1	2	1	2	1
	4	4	1	1	4	1	4	1
	8	8	1	1	8	1	8	1
LSSTC	4	4	L_{AA}	1	2	4	2	L_{AA}
	8	8	L_{AA}	1	2	16	1	L_{AA}
	8	8	L_{AA}	1	4	4	4	L_{AA}
LSSTS	4	2	L_{AA}	V	2	$2 \times V$	2	L_{AA}

According to Figure 1.5, the V-BLAST system employing (N_t, N_r)=$(4, 4)$ antennas has a slightly better BER performance than the SISO system, despite its quadrupled throughput. Also observe in Figure 1.5 that the slope of the BER curves of both the V-BLAST and of the SISO system is similar, which suggests that V-BLAST does not attain a high diversity gain, but it is capable of attaining a high multiplexing gain. Additionally, Figure 1.5 shows that the STBC system employing (N_t, N_r)=$(2, 1)$ attains a better BER performance than the SISO and V-BLAST schemes due to the diversity gain attained by the STBC. Further diversity gain can be attained by the four-antenna aided STBC employing four receive antennas, which results in a diversity order of 16. As shown in Figure 1.5 the four-antenna-aided STBC scheme employing four receive antennas is capable of attaining around 15 dB gain at a BER of 10^{-5} over the twin-transmit-antenna aided STBC system using N_r=1. However, a drawback of the four-antenna aided system is that it results in a throughput loss, where four symbols are transmitted in eight time slots, resulting in a rate of 1/2.

Observe in Figure 1.5 that the LSSTS scheme employing (N_t, N_r)=$(4, 2)$ and V=1 attains an identical BER performance to that of the twin-transmit-antenna aided STBC system. This means that the LSSTS scheme employing V=1 has a diversity order of 2 similar to the twin-antenna aided STBC. On the other hand, the LSSTS scheme attains twice the throughput of the twin-transmit-antenna aided STBC scheme. Additionally, when V is increased from 1 to 4, the achievable BER performance improves due to the additional frequency diversity gain attained.

A further performance improvement is attained by the LSSTC scheme in conjunction with (N_t, N_r)=$(4, 4)$ compared to the LSSTS scheme. The LSSTC scheme employs more antennas than the LSSTS scheme and hence attains both a higher diversity order as well as a better BER performance. Furthermore, Figure 1.5 shows the performance improvements attained by beamforming, where the LSSTC scheme employing L_{AA}=4 attains around 6 dB performance improvement at a BER of 10^{-5} over its counterpart employing L_{AA}=1, provided that the DOA is perfectly known. Finally, a comparison between the STBC and LSSTC schemes using (N_t, N_r)=$(4, 4)$ reveals that the STBC arrangement attains a better performance than the LSSTC scheme employing L_{AA}=1. This is due to the fact that the STBC scheme has a higher diversity gain, while the LSSTC scheme attains a throughput that is 4 times that of its STBC counterpart.

1.2.4 Diversity versus Multiplexing Tradeoffs in MIMO Systems

According to our previous discussions, different MIMO schemes have different structures and hence a different BER as well as throughput performance. Explicitly, the STBC scheme is capable of attaining the highest possible spatial diversity gain, while having no multiplexing gain, in fact, some STBC structures result in a throughput loss. On the other hand, the V-BLAST scheme is capable of achieving the maximum possible multiplexing gain, while attaining a low diversity gain, depending on the choice of the V-BLAST decoder employed. Furthermore, we have introduced the LSSTC and LSSTS multi-functional MIMO designs that are capable of attaining diversity, multiplexing as well as beamforming gains.

Table 1.1 compares the diversity, multiplexing and beamforming gains of the different MIMO schemes for different configurations. In Table 1.1, N_t and N_r stand for the number of transmit and receive antennas, respectively, while L_{AA} represents the number of elements per transmit AA and V denotes the number of subcarriers employed by the generalised MC DS-CDMA system. Additionally, the number of layers represents the number of antenna layers that is used for transmitting different data symbols at the same time, for the sake of attaining a multiplexing gain.

As shown in Table 1.1, the STBC schemes are capable of attaining a full diversity order of $(N_t \times N_r)$, while achieving no multiplexing or beamforming gain. By contrast, in the case of four-antenna and eight-antenna aided STBC schemes, the multiplexing gain is 1/2, resulting in half the throughput of the SISO scheme. For example, in the four-antenna aided STBC scheme, four symbols are transmitted in eight time slots and similarly for the eight-antenna aided STBC scheme, eight complex-valued symbols are transmitted in 16 time slots. On the other hand, as shown in Table 1.1, the V-BLAST scheme can attain a multiplexing gain of N_t, since the different antennas transmit different symbols in the same time slot. For example, for the V-BLAST scheme employing (N_t, N_r)=$(4, 4)$, the transmitter transmits four different symbols from the four different antennas in the same time slot, which results in a quadrupled multiplexing gain in comparison to that of the SISO scheme. Observe in Table 1.1 that the diversity order of V-BLAST employing the ZF-SIC is 1 for different (N_t, N_r) configurations. The diversity order of the V-BLAST scheme employing ZF-SIC is $(N_r - N_t + 1)$.

The LSSTC scheme combines the benefits of STBC, V-BLAST as well as of beamforming, as discussed earlier. This becomes clear in Table 1.1, where it is shown that the LSSTC scheme attains a diversity gain, a multiplexing gain as well as a beamforming gain. In the case of the (N_t, N_r)=$(4, 4)$ configuration, two twin-antenna STBC layers are implemented, which results in a diversity order of 4 and a multiplexing order of 2. This is due to the fact that four symbols are transmitted from the four transmit antennas in two time slots. Additionally, when L_{AA} elements are used per AA, then a beamforming gain can be attained. In the (N_t, N_r)=$(8, 8)$ configuration, two different schemes can be implemented. The first scheme is a two-layer one with each layer constituted of a four-antenna STBC scheme. The other configuration employs four layers of the twin-antenna STBC scheme. The two configurations result in the different diversity and multiplexing gains shown in Table 1.1.

Finally, in the LSSTS scheme four transmit and two receive antennas are employed, where the transmit antennas are separated into two STS layers. The diversity order achieved by the LSSTS scheme is $(2 \times V)$ as discussed in Section 1.2.2.2. The multiplexing order of the LSSTS scheme is 2, since four symbols are transmitted in two time slots. Moreover, the LSSTS scheme is capable of attaining a beamforming gain, when $L_{AA} > 1$ elements per AA are used.

In this section a brief classification of MIMO schemes was presented based on their attainable diversity, multiplexing or beamforming gains. We also investigated the design of multi-functional MIMO schemes that are capable of combining the benefits of several MIMO schemes and hence attaining diversity, multiplexing as well as beamforming gains. More explicitly, we introduced two multi-functional MIMO schemes: LSSTC and LSSTS. The LSSTC combines the benefits of STBC, V-BLAST as well as beamforming, while the LSSTS combines the advantages of STS, V-BLAST and beamforming with those of generalised MC DS-CDMA, while supporting multiple users. Finally, a comparison between the BER performance as well as the diversity, multiplexing and beamforming gains of the different MIMO schemes reveals that multi-functional MIMOs are capable of attaining an improved performance over STBC and V-BLAST schemes.

1.3 Coherent vs. Non-Coherent Detection for STBCs Using Co-located and Cooperative Antenna Elements

1.3.1 Motivation

Again, our objective in this conceptually motivated section is to provide a brief overview of the material discussed in intricate detail in Part II of the monograph. More specifically, we will briefly consider the design alternatives of various STBCs documented in the open literature, focussing our attention on the so-called orthogonal design approach and on the layered method. We introduce the generalized concept of the linear dispersion space-time coding architecture, which allows us to strike a compromise between the above-mentioned two approches. We will also demonstrate that the powerful linear dispersion structure is capable of unifying the entire suite of existing schemes. As a further benefit, it offers extra design flexibility so that diverse system requirements can be satisfied. Furthermore, after characterizing the fundamental relationship between STBCs and Differential STBCs (DSTBCs), we highlight the benefits of non-coherently detected schemes, which are capable of exploiting the advantages of multiple antennas, while circumventing the potentially excessive burden of multi-antenna channel estimation. Additionally, we will demonstrate that the linear dispersion structure can also be applied in systems, where the multiple-antenna array is formed in a distributed fashion by multiple single-antenna-aided cooperating mobile stations. Hence, the design of co-located and cooperative MIMO systems aiming for achieving diversity is linked from a linear dispersion perspective.

As argued above, apart from employing multiple antennas at the transmitter and receiver in a 'co-located' fashion, a Virtual Antenna Array (VAA) may also be formed by a group of cooperating single-antenna-aided mobile stations. The resultant cooperative MIMO system is capable of offering similar degrees of freedom to those of a co-located MIMO system having independently fading signal impinging on the antenna elements. In other words, the distributed MIMO elements are capable of mimicking the functionality of the co-located MIMO elements.

The advantage of a MIMO system can be exploited in two ways: to increase the reliability of the system by providing a diversity gain [24] and/or to increase the data rate by providing multiplexing gain [24]. In fact, it has been shown that there is a fundamental tradeoff between the achievable diversity gain and the attainable multiplexing gain for a given MIMO system [24]. The term spatial multiplexing gain refers to the fact that one can use multiple antennas to achieve a higher throughput at the cost of an increased SNR requirement. On the other hand, the concept of spatial diversity is to provide multiple independently fading replicas of the transmitted signal for the receiver with the aid of the MIMO channel. If indeed these replicas are faded independently, it is unlikely that all copies of the transmitted signal are in a deep fade simultaneously. Therefore, the receiver is expected to reliably decode the transmitted signal using these independently faded received signals. Finally, apart from the 'spatial' dimension, diversity can also be achieved in both the temporal as well as the frequency domains.

In many practical scenarios, reliable wireless communications may not be guaranteed, even when multiple antennas have been employed. For example, when large-scale shadow fading contaminates the wireless links, all the channels tend to fade together rather than independently, hence eroding the achievable diversity gain. Therefore, the concept of 'cooperative diversity' [25] has been proposed in the literature, which is a technique designed for providing diversity using the single antennas of other nodes in the cellular network as 'virtual' antennas.

In this section the design philosophies of spatial-diversity-oriented Space-Time Block Codes (STBCs) designed for open-loop MIMO systems are presented from a unique linear dispersion perspective. More explicitly, Section 1.3.2 demonstrates various design guidelines of STBCs and presents a general framework to unify all the existing coherently detected STBCs found in the open literature. Section 1.3.3 exploits the linkage between coherently detected STBCs and non-coherently detected STBCs having no Channel State Information (CSI), which enables our general framework to incorporate the subclass of differential encoding/decoding techniques. Similarly, Section 1.3.4 examines the fundamental linkage between co-located and cooperative MIMO systems. Hence, cooperative STBCs can be created by applying the general linear dispersion framework. The expected performance is illustrated in Section 1.3.5, along with the related brief conclusions.

1.3.2 Evolution of Space-Time Block Codes

In order to exploit both the spatial as well as temporal domains offered by a MIMO system, STBCs transmit a signal matrix $\mathbf{S}$ conveying the source information. For a MIMO system having M transmit and N receive antennas, a STBC scheme can be designed to transmit Q symbols using T channel slots. The STBC scheme may be described by the parameter combination $(MNTQ)$ having the normalized throughput of $R = Q/T$. In other words, the concept of STBCs is to design a set of matrices $\mathbf{S}$ satisfying both the throughput as well as diversity order requirements under certain complexity constraints. However, the number of matrices to be designed may become excessive, when the system is operating at a high normalized throughput facilitated by a high number of antennas. This challenge was mainly addressed from two perspectives in the open literature, namely from the orthogonal and the layered approaches, both of which will be highlighted below.

1.3.2.1 Orthogonal Approach

The 'orthogonal' approach was first proposed in [10], which was later generalized in [26]. The philosophy behind Orthogonal STBCs (OSTBCs) is that the space-time signal matrix $\mathbf{S}$ has to be an orthogonal/unitary matrix, where the orthogonality embedded in $\mathbf{S}$ is capable of decoupling the transmitted multi-antenna-coded symbol streams into independent single-antenna symbols. For example, Alamouti's scheme [10] can be characterized as follows:

$$\mathbf{G}_2 = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix}. \tag{1.1}$$

Although the associated single-stream decoding procedure is appealing, the orthogonality of the multi-antenna streams limits the choice of modulation schemes and restricts the antenna configurations supported. Hence, the OSTBCs are unable to reach a high normalized throughput. On the other hand, when relaxing the above-mentioned orthogonality of the OSTBCs, a potentially higher normalized throughput can be achieved, as exemplified by the family of Quasi-Orthogonal STBCs (QOSTBCs) [15].

Furthermore, the design of OSTBCs involves the inevitable throughput versus diversity gain tradeoff characterized in [27]. This is because each spatial and temporal slot is used to convey either a new symbol to increase the throughput or a redundant symbol to attain diversity. However, with the aid of the recent advances in high-throughput full-diversity [1] STBCs [28], it has been shown that it is not necessary to sacrifice the throughput in favor of achieving diversity or vice versa. The philosophy of these schemes is that they impose redundancy on the space-time codeword, but additional diversity gain can be achieved by spreading the information across both the spatial and temporal domains. We will elaborate on this idea in more detail using Linear Dispersion Codes (LDCs) [28] [29] in Section 1.3.2.3.

1.3.2.2 Layered Approach

The motivation of introducing a 'layered' structure into the STBCs is that of supporting high-throughput communications, as exemplified by schemes such as Bell Labs' Layered-Space-Time (BLAST) architecture [16]. Although conventional BLAST-type schemes were not designed for achieving diversity, they provide a new insightful angle for STBC designs. For example, the $\mathbf{G}_2$ STBC of Equation (1.1) can be considered as a scheme consisting two layers. The first layer only conveys the information symbol s_1, which is 'repetition-coded' and mapped to one of the diagonals of Equation (1.1). The second layer contains the symbol s_2, which is mapped to the other diagonal of Equation (1.1). Each layer occupies half of the four spatial and temporal slots and the inherent orthogonality enables the receiver to separate the two layers to facilitate simple single-layer decoding. Since having more layers has the promise of an increased normalized throughput, the question of how many layers can a STBC codeword accommodate arises. In the literature, the authors of [30] proposed a class of STBCs employing a unitary Time Variant Linear Transformation (TVLT), which is capable of transmitting using T layers, while maintaining a normalized throughput of $R = M$. Furthermore, high-throughput Threaded Algebraic Space-Time Block Codes (TASTBCs) [31] were proposed in order to support up to M number of adaptively reconfigurable layers. One of the intriguing features of both TVLTs and TASTBCs is that both of them are capable of achieving the full attainable spatial diversity order of MN, while maintaining a high throughput. This is guaranteed by mapping the signals of each layer across all the antennas,

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[1] Using the average pairwise symbol error probability analysis technique [26], it follows that the maximum attainable diversity order of a STBC scheme designed for an $(M \times N)$-element MIMO system is $D_{full} = MN$.

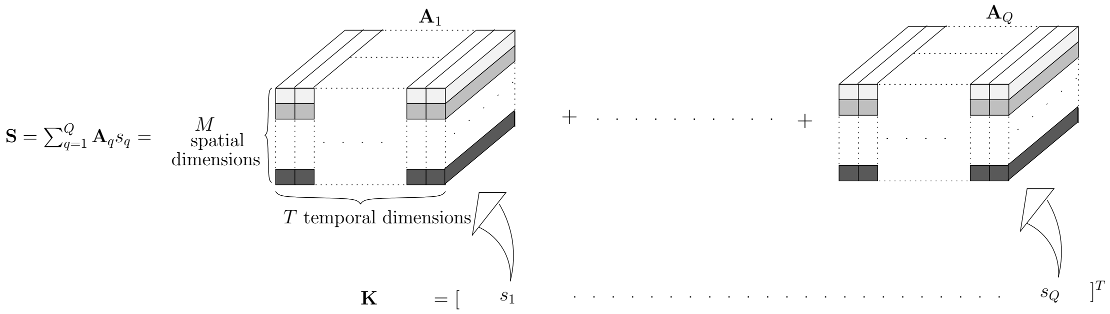

Figure 1.6: The space-time codeword **S** employing the linear dispersion structure.

in order to achieve spatial diversity, as exemplified in Equation (1.1). Again, this philosophy will be further augmented using the linear dispersion structure below.

1.3.2.3 Linear Dispersion Codes

At this stage of our discussions, the challenge of STBC design becomes that of finding an appropriate way of relaxing the orthogonality, while maintaining the maximum diversity order of MN. Alternatively, we may cast this design dilemma as contriving a 'layered' structure capable of exploiting all the spatial and temporal diversity resources available for a single layer, while supporting multiple layers. Remarkably, these design objectives may be satisfied by the family of LDCs proposed by Hochwald and Hassibi [29]. The revolutionary concept of LDCs [28] [29] invokes a matrix-based linear modulation framework, where each space-time transmission matrix $\mathbf{S}$ is generated by a linear combination of so-called dispersion matrices and the weights of the components are determined by the associated transmitted symbol vector. More explicitly, given an information symbol vector $\mathbf{K} = [s_1, s_2, \ldots, s_Q]^T$ constituted by symbols of an arbitrary modulation constellation, the transmitted space-time matrix $\mathbf{S}$ may be defined as [28] $\mathbf{S} = \sum_{q=1}^{Q} \mathbf{A}_q s_q$, where each symbol s_q is dispersed to the M spatial- and T temporal dimensions using a specific dispersion matrix $\mathbf{A}_q \in \zeta^{M \times T}$ and $\mathbf{S}$ is attained by the linear combination of all the weighted dispersion matrices. The schematic of the LDCs is specifically visualized in Figure 7.4.

Hence, it is beneficial to revisit the OSTBCs of Section 1.3.2.1 using the linear dispersion structure of Figure 1.6. More explicitly, if each individual dispersion matrix $\mathbf{A}_q$ is an orthogonal matrix and the set of dispersion matrices are orthogonal to each other, the resultant space-time codeword $\mathbf{S}$ has to be an orthogonal/unitary matrix achieving full diversity [32]. This design philosophy is that of the family of Linear STBCs (LSTBCs) [32]. Furthermore, by appropriately choosing the set of dispersion matrices depicted in Figure 1.6, the degree of orthogonality can be adjusted, leading to an increased design flexibility.

When compared to the layered STBCs discussed in Section 1.3.2.2, the LDCs of Figure 1.6 consist of Q layers corresponding to the number of symbols transmitted per space-time block. Since the parameter Q is unrestricted, LDCs are capable of supporting an arbitrary number of layers. Furthermore, rather than using only some of the $(M \times T)$ slots available, each layer of the LDCs spans all the dimensions available, resulting in a high number of legitimate dispersion matrices. However, it may not be feasible to perfectly separate the high number of superimposed layers, unless sophisticated multi-stream receivers are used.

In summary, the LDCs of Figure 1.6 subsume all the above-mentioned space-time block codes exhibiting diverse characteristics by simply employing different sets of dispersion matrices. Hence, the LDCs provide a natural framework for satisfying diverse design criteria. Below, we offer a range of further remarks concerning LDCs.

- LDCs are suitable for arbitrary transmit and receive antenna configurations, combined with arbitrary modulation schemes;
- The maximum achievable diversity order of an LDC scheme is $N \cdot \min(M, T)$. This implies that increasing T beyond M does not provide any further advantage in terms of an increased diversity, whereas having $T < M$ could decrease the maximum achievable spatial diversity order. As expected, the receive diversity order is determined by the number of receive antennas N alone. For the proof of the theorem please refer to [28].
- Every transmitted signal launched from each antenna is the linear combination of all the information symbols weighted by a set of dispersion matrices of Figure 1.6, which ensures that different replicas of the same information symbol are attainable. In other words, LDCs demonstrate that spatial diversity can also be achieved without transmitting redundant information at the cost of reducing the normalized throughput R.
- All the dispersion matrices $\mathbf{A}_q$ of Figure 1.6 can be described with the aid of the a single Dispersion Character Matrix (DCM) χ specified by $\chi = [vec(\mathbf{A}_1), vec(\mathbf{A}_2), \ldots, vec(\mathbf{A}_Q)]$, where the $vec()$ operation represents the vertical stacking of the columns of an arbitrary matrix. The benefit of using a single DCM is that there is no need to design Q number of separate dispersion matrices.
- The linear nature of Figure 1.6 enables the receiver to recover the source information, provided that the CSI is perfectly known at the receiver.

As far as the design of the set of dispersion matrices or the DCM is concerned, in their original form, the LDCs [29] were optimized to maximize the ergodic capacity. In practice, the channel's input is constituted by non-Gaussian symbols, such as discrete-amplitude PSK and QAM signals, where a Discrete-input Continuous-output Memoryless Channel (DCMC) is encountered. Therefore, the more pertinent DCMC capacity is employed to optimize the LDCs [33]. Naturally, other optimization criteria can also be imposed on the DCM. For example, the authors of [28] specifically designed the LDCs to maximize the ergodic capacity, while maintaining a low BER. On the other hand, LDCs can also be optimized using the so-called determinant criterion [26], where having a non-vanishing determinant is guaranteed.

1.3.3 Differential STBCs Using Colocated Antenna Elements

The primary focus of the codes discussed in Section 1.3.2 has been the case, where the receiver has the knowledge of the CSI. In practice, the knowledge of the CSI is typically acquired using a channel sounding sequence, which has an exponentially increasing complexity as a function of the number of antennas. Furthermore, the relative frequency of estimating the channel has to be increased proportionately to the Doppler frequency. Finally, an excessive number of training symbols may be required. Hence, precious transmit power as well as valuable bandwidth are wasted. Therefore, differentially encoded low-complexity schemes, dispensing with pilot-based channel estimation and invoking non-coherent detection became attractive.

The conventional Differential PSK (DPSK) designed for single antenna aided systems differentially encodes the information between successive transmission symbols, thus the information can be recovered without the knowledge of the CSI, provided that the CSI does not change substantially between them. A DPSK scheme is constituted by the serial concatenation of a PSK modulator and a differential encoder. Here, we extend this philosophy to multiple antenna aided systems and the schematic of the resultant Differential STBC (DSTBC) system is portrayed in Figure 1.7.

More explicitly, the 'space-time mapper' of Figure 1.7 maps the n-th differentially encoded transmission matrix $\mathbf{S}_n$ to all the spatial and temporal slots, whereas the 'differential encoder' of Figure 1.7 correlates the consecutive transmission matrices by $\mathbf{S}_n = \mathbf{S}_{n-1} \cdot \mathbf{X}_n$, where $\mathbf{X}_n$ is the

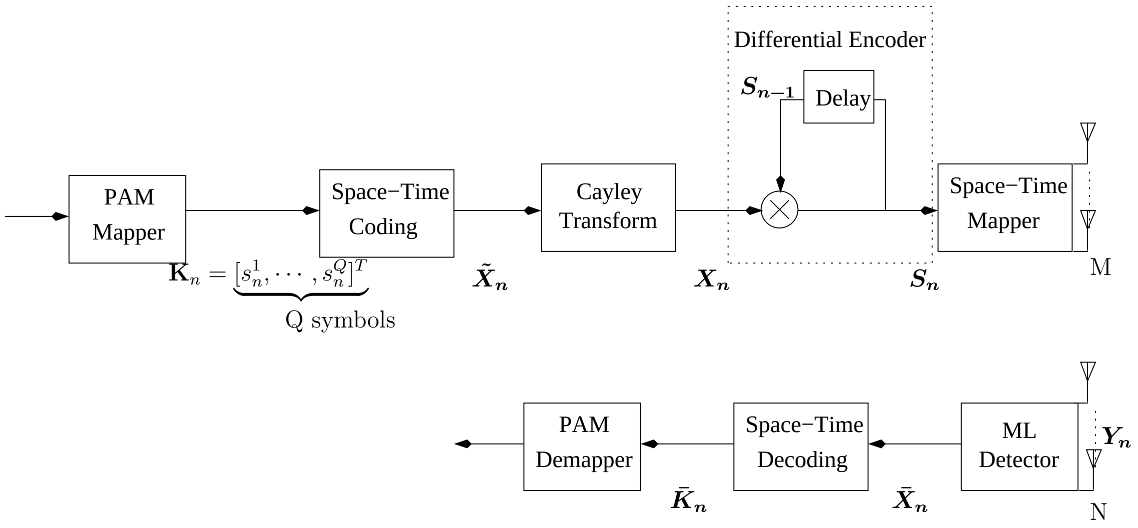

Figure 1.7: Schematic of a DLDC($MNTQ$) scheme equipped with M transmit and N receive antennas and employing the Cayley transform, while transmitting Q symbols over T time slots using $\mathbf{S}_n$.

space-time coded information matrix. Furthermore, this differential encoding process restricts the set of matrices $\mathbf{X}_n$ to be unitary, otherwise, the product $\mathbf{S}_n = \mathbf{X}_n\mathbf{X}_{n-1}\cdots\mathbf{X}_1$ may become zero, infinity, or both in different spatial and temporal directions. **In other words, the challenge of designing DSTBCs can be described as that of designing a family of STBCs, where all the space-time matrices $\mathbf{X}_n$ are unitary.**

Recall that the OSTBCs detailed in Section 1.3.2.1 generate orthogonal/unitary matrices by default, hence they become natural candidates for employment in DSTBC designs. Since the LDCs exhibit a high design flexibility as demonstrated in Section 1.3.2.3, it is desirable to retain the linear dispersion architecture in the differential design. Hence, the 'space-time encoding' block of Figure 1.7 is configured to generate space-time codewords $\tilde{\mathbf{X}}_n$ obeying the linear dispersion structure of Figure (1.6). However, even if each individual dispersion matrix is a unitary matrix, there is no guarantee that their weighted sum $\tilde{\mathbf{X}}_n$ will automatically become a unitary matrix. Hence, the 'Cayley transform' [13] block of Figure 1.7 is introduced in order to provide an efficient way of projecting the linearly-structured matrix $\tilde{\mathbf{X}}_n$ into a unique unitary matrix $\mathbf{X}_n$, which potentially facilitates the differential encoding of Figure 1.7. Apart from its additional computational complexity, the Cayley transform requires the employment of real-valued modulation schemes in order to generate the unitary matrices. Also note that the DSTBCs typically suffer from a 3dB penalty in comparison to the STBCs having perfect CSI, owing to the doubled equivalent channel noise encountered during the detection.

In summary, the design of DSTBCs based on coherently detected STBCs is facilitated by the 'unitary' constraint. Furthermore, the philosophy of LDCs may be extended to the differential encoding domain and the resultant Differential Linear Dispersion Codes (DLDCs) based on the Cayley transform [34] provide a general framework for DSTBCs. Consequently, DLDCs are capable of supporting arbitrary antenna configurations as well as a dynamically reconfigurable throughput. Similarly to LDCs, all the dispersion matrices of a DLDC scheme can be characterized by a single DCM. On the other hand, the performance of DLDCs is affected by the rate of Doppler-induced channel fluctuations.

1.3.4 Cooperative STBCs Using Distributed Antenna Elements

The STBC techniques detailed in Sections 1.3.2 and 1.3.3 provide promising solutions in the context of co-located MIMO systems requiring reliable wireless communications at high rates. However, it may not always be practical to accommodate multiple antennas at the mobile stations, owing to cost, size and other hardware limitations. A further limitation of having co-located MIMO elements is that even at relatively large element separations their elements may not benefit from independent fading, when subjected to shadow-fading imposed for example by large-bodied vehicles or other shadowing local paraphernalia. As a remedy, the concept of cooperative MIMOs have been proposed for cellular systems as an attempt to attain a better communication efficiency beyond that permitted by a single node's resources. More specifically, a group of mobile nodes, known as relays, 'shares' their antennas with other users to create a VAA to provide spatial diversity gain.

Owing to the philosophical similarities between the cooperative MIMO and the co-located MIMO systems, numerous space-time block coding techniques have been 'transplanted' into relay-aided schemes in order to achieve cooperative diversity, based on either Amplify-and-Forward (AF) strategies or Decode-and-Forward (DF) arrangements. It was Laneman and Wornell [25] who first proposed to employ OSTBCs for cooperative MIMO systems, where each relay transmits according to a different column of the orthogonal STBC matrix. In this section, we focus our attention on the employment of the LDC structure in the context of cooperative MIMO systems, namely in twin-layer Cooperative LDCs (CLDCs).

Figure 1.8 portrays the schematic of the cooperation-aided UpLink (UL) system using the above-mentioned twin-layer CLDC. As seen in Figure 1.8, each transmission block consists of two intervals, namely the broadcast interval of duration T_1 and the cooperation interval of length T_2. This scheme supports the cooperation of M number of relays transmitting Q information symbols per block to the base station equipped with N receive antennas, provided that the total number of channel uses T obeys $T = T_1 + T_2$.

The assumptions and the rationale of this model are summarized as follows:

- All the relays of Figure 1.8 are assumed to transmit synchronously. Quasi-synchronous transmissions can be accomplished, when the relative delays between the relays are significantly shorter than the symbol duration;
- All the nodes of Figure 1.8 are assumed to have a single antenna and hence operate in half-duplex mode, i.e. at any point of time, a node can either transmit or receive. This constraint is imposed, in order to prevent the high-power transmit signal from contaminating the low-power received signal, for example, by the non-linear distortion-induced out-of-bound emissions routinely encountered at the transmitter.
- All the relays of Figure 1.8 transmit and receive on the same frequency as the source node, in order to avoid wasting or occupying additional bandwidth;
- No communication is permitted between the relays, in an effort to minimize the total network traffic. The relays may use the same previously unallocated time-slot for their reception and transmission;
- Since the simple AF strategy is adopted, only linear combination operations are performed at the relays before retransmitting the signals dispersed to the cooperating MIMO elements to the BS;
- We confine the total number of channel uses of the twin-layer CLDC scheme of Figure 1.8 to T. Hence, by appropriately adjusting the parameters T_1 or T_2, different degrees of freedom can be provided for the broadcast interval as well as for the cooperation interval;
- At any given time, the total transmit power of the twin-layer CLDC scheme of Figure 1.8 is normalized to unity.

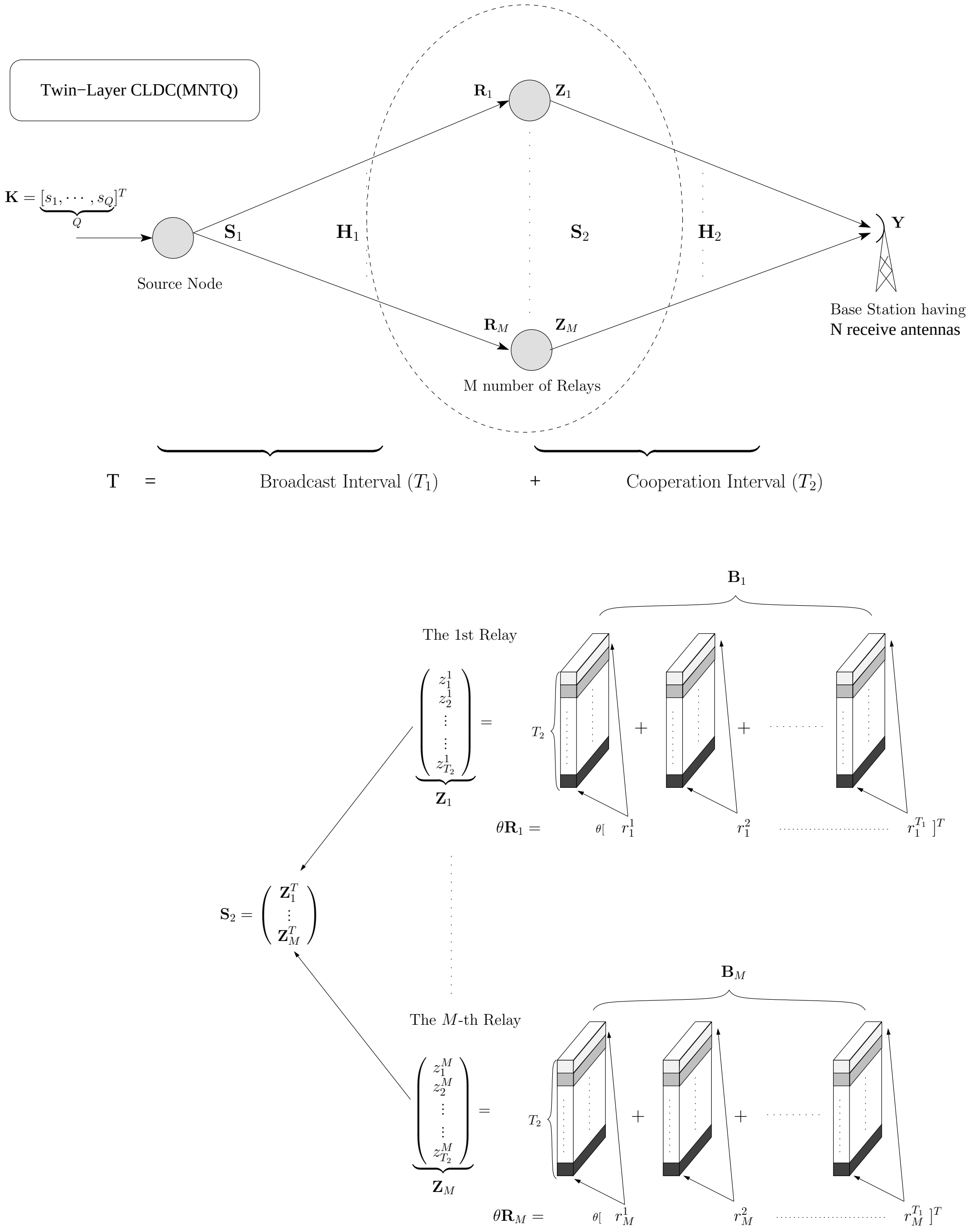

Figure 1.8: Schematic of the cooperation-aided uplink system employing twin-layer Cooperative Linear Dispersion Codes (CLDCs).

During the broadcast interval T_1, the first-layer dispersion matrix χ_1 is responsible for dispersing the source information vector $\mathbf{K} = [s_1, \ldots, s_Q]^T$ to all the T_1 temporal slots. The resultant space-time codeword $\mathbf{S}_1$ of Figure 1.8 is transmitted through independent source-to-relay Rayleigh fading channels. The received signal vector of the m-th relay is $\mathbf{R}_m$. During the cooperation interval T_2, the relays form a VAA and cooperatively transmit the space-time codeword $\mathbf{S}_2$ of Figure 1.8 to the BS based on CLDC's second-layer dispersion matrix. More explicitly, the process of forming the cooperative space-time codeword $\mathbf{S}_2$ for the cooperation interval is also visualized in Figure 1.8. Each relay contributes one row of the cooperative space-time codeword $\mathbf{S}_2$ by dispersing the corresponding normalized received signal vector $\theta\mathbf{R}_m = \theta[r_m^1, \ldots, r_m^{T_1}]^T$ to the available T_2 temporal slots using the pre-assigned dispersion matrix. Again, the dispersion matrices from all the relays can be characterized by a single DCM χ_2. Hence, the receiver can recover the source information by exploiting the linearity of the CLDCs, provided that the CSI as well as the dispersion matrices χ_1 and χ_2 are known at the receiver. Since only T_2 time slots are used for achieving cooperative diversity and the relays only have access to the noisy version of the transmitted information, the maximum achievable diversity order of the CLDCs becomes $D \approx N \cdot \min(M, T_2)$.

Hence, we conclude that the fundamental difference between cooperative and co-located MIMO systems is the existence of the broadcast interval, which is used by the relays to attain preferably perfect but typically imperfect source information, depending on the specific cooperation strategy employed. As a result, instead of employing a single DCM as in the LDC scheme, the CLDC scheme requires a pair of DCMs (χ_1, χ_2) in order to characterize the transmission regime of both the broadcast interval and of the cooperation interval, respectively.

1.3.5 Performance for Imperfect Channel Estimates and Shadow-Fading

In this section, we provide a set of comparisons between the family of LDCs, DLDCs and CLDCs in order to evaluate their advantages as well as limitations, when communicating in *small*-scale or *large*-scale fading scenarios as well as when having *perfect* or *imperfect* CSI at the receiver. All the simulation parameters were listed in Table 1.2. Observe in Table 1.2 that we set $M = T$ and assume that the channels were subjected to Rayleigh fading having $f_d = 10^{-2}$ in order to enable the adequate operation of the DLDCs based on the Cayley transform. Hence, the group of LDCs and DLDCs have the potential to achieve the full attainable diversity order of $D = N \cdot \min(M, T)$ [28] in comparison to the reduced maximum diversity order $D \approx N \cdot \min(M, T_2)$ of the CLDCs.

For Comparison A of Table 1.2, Figure 1.9 characterizes the achievable throughput of the group of LDCs, DLDCs and CLDCs recorded at BER=10^{-4}, when the wireless channels were subjected to *small*-scale Rayleigh fading and *perfect* CSI was available at the receiver. Observe in Figure 1.9 that the class of LDCs is capable of operating at the lowest SNR at a certain throughput. The group of DLDCs suffers from the usual 3dB SNR penalty in comparison to that of the LDCs, since no CSI was exploited. The family of CLDCs operates at SNRs further away from that of the LDCs, owing to their reduced achievable diversity order as well as due to having the noisy rather than perfect version of the source information.

For Comparison B of Table 1.2, Figure 1.10 characterizes the effective throughput of the LDCs, the DLDCs and the CLDCs of Table 1.2 recorded at BER=10^{-4}, when the wireless channels were subjected to *small*-scale Rayleigh fading and the receiver has *imperfect* CSI. We assume that the channel estimation errors obey the Gaussian distribution and the degree of the CSI estimation errors is governed by the ratio ω (dB) with respect to the received signal power. Hence, the perfect CSI scenario corresponds to $\omega = -\infty$. Observe in Figure 1.10 that the family of DLDCs demonstrated a significant advantage over the LDCs at a high throughput, even when the channel estimation errors were as low as $\omega = -10$dB. Since the group of CLDCs has an error floor higher than BER=10^{-4}, the associated throughput curve was omitted from Figure 1.10. This phenomenon suggested that the CLDCs are more sensitive to the channel estimation errors than

Table 1.2: Comparison of the LDCs of Section 1.3.2.3, the DLDCs of Section 1.3.3 and the CLDCs of Section 1.3.4, when communicating over small-scale/large-scale fading channels and having perfect/imperfect CSI at the receiver.

	LDC	**DLDC**	**CLDC**
M	3	3	3
N	2	2	2
T	3	3	$T_1 = 1, T_2 = 2$
Q	1,2,3	1,2,3	1,2,3
Modulation	BPSK	BPSK	BPSK
Mapping	Gray mapping	Gray mapping	Gray mapping
Detector	ML	ML	ML
Doppler frequency	$f_d = 10^{-2}$	$f_d = 10^{-2}$	$f_d = 10^{-2}$
Diversity	$D = 6$	$D = 6$	$D \approx 4$
Comparison A	*Small*-scale Rayleigh fading, *perfect* CSI in Figure 1.9		
Comparison B	*Small*-scale Rayleigh fading, *imperfect* CSI in Figure 1.10		
Comparison C	*Large*-scale shadowing, *perfect* CSI in Figure 1.11		

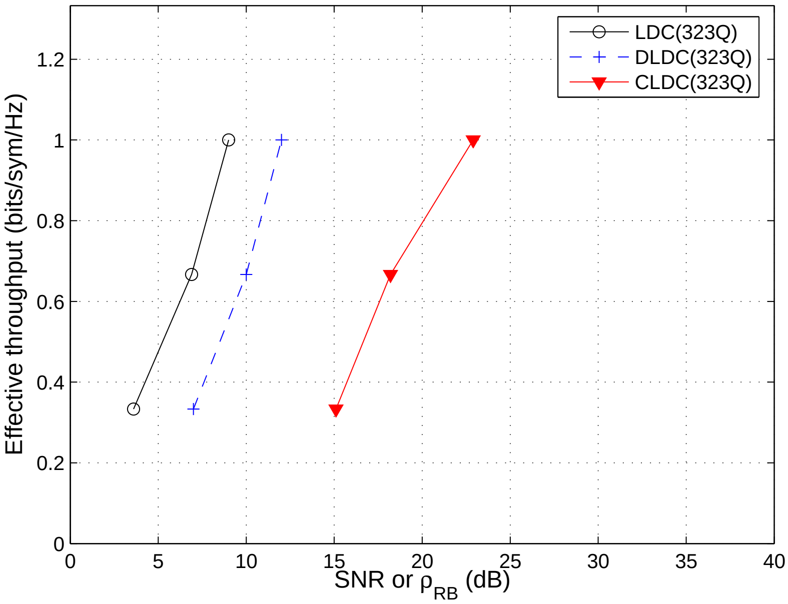

Figure 1.9: Throughput comparison for the LDCs of Section 1.3.2.3, the DLDCs of Section 1.3.3 and the CLDCs of Section 1.3.4 recorded at BER$=10^{-4}$, when communicating over *small*-scale Rayleigh fading channels and assuming that the *perfect* CSI was known by the receiver. All the system parameters were summarized in Table 1.2.

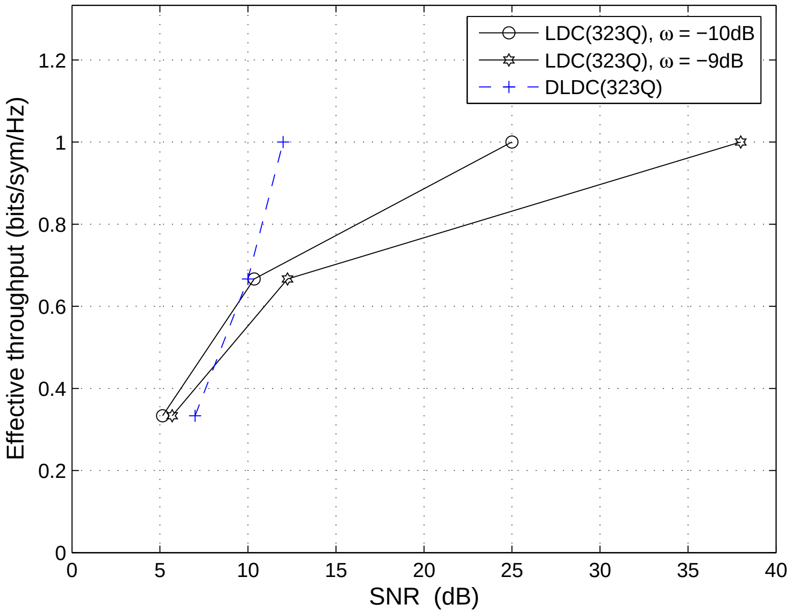

Figure 1.10: Throughput comparison for the LDCs of Section 1.3.2.3, the DLDCs of Section 1.3.3 and the CLDCs of Section 1.3.4 recorded at BER=10^{-4}, when communicating over *small*-scale Rayleigh fading channels and having *imperfect* CSI governed by ω (dB). All the system parameters were summarized in Table 1.2.

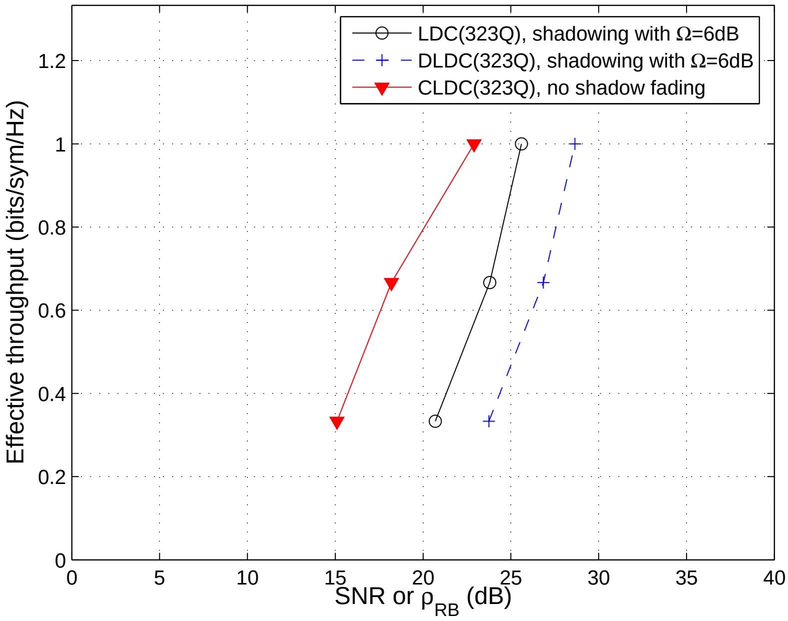

Figure 1.11: Throughput comparison for the LDCs of Section 1.3.2.3, the DLDCs of Section 1.3.3 and the CLDCs of Section 1.3.4 recorded at BER=10^{-4}, when the channels were subjected to *large*-scale shadowing and assuming that the *perfect* CSI was known at the receiver. All the system parameters were summarized in Table 1.2.

the LDCs. This is because the CLDCs require the CSI knowledge of both the source-to-relay and the relay-to-destination channels in comparison to the classic single-phase direct transmission regime of co-located MIMO systems.

Finally, in Comparison C of Table 1.2, Figure 1.11 characterizes the throughput of the LDCs, the DLDCs and the CLDCs of Table 1.2 recorded at BER=10^{-4}, when the communication channels were subjected to *shadowing* and the receiver had access to *perfect* CSI. The shadow fading effect was assumed to have log-normal distribution and was governed by a random Gaussian variable having zero mean and a standard deviation of Ω (dB). Observe in Figure 1.11 that the family of CLDCs designed for the cooperative MIMO systems has the best ability to combat the effect of large-scale shadowing with the aid of relays. Compared to the small-scale Rayleigh fading performance curves of Figure 1.9, the SNR required for the group of LDCs in Table 1.2 to maintain a BER of 10^{-4} increased by about 17dB, even though the receiver had access to perfect CSI.

Again, our investigations indicate that the LDCs obeying the structure of Figure 1.6 are ideal for small-scale fading environments, when near-perfect CSI is available. On the other hand, the DLDCs having the structure of Figure 1.7 constitute the most appropriate solution, when the CSI is unavailable or the channel estimation would impose severe errors. Finally, when large-scale shadowing dominates the achievable performance, the family of CLDCs obeying the structure of Figure 1.8 remains capable of maintaining reliable wireless communications.

In conclusion of this brief section, the design guidelines of diverse STBCs schemes found in the open literature were considered. More explicitly, we demonstrated that the linear dispersion structure unifies the orthogonal approach as well as the layered architecture. The flexibility of the LDCs allows them to be designed according to diverse constraints and to be adopted to various MIMO scenarios. Furthermore, the linkage between STBCs and DSTBCs may be established with the aid of the 'unitary' constraint, which enables us to invoke the LDC structure also in the differential encoding domain. In the case of cooperative MIMO systems, the flexible linear structure remains applicable, but an additional dipersion character matrix is required to characterize the transmissions during the broadcast interval. Finally, the rudimentary performance results provided explicitly demonstrated the suitable application scenarios for the various LDCs, DLDCs and CLDCs considered.

1.4 Historic Perspective and Sate-of-the-art Contributions

1.4.1 Colocated MIMO Techniques

MIMO systems exhibit higher capacity than single-antenna-aided systems. Multiple antennas can be used to provide diversity gains and hence a better BER performance or multiplexing gains, in order to attain a higher throughput. Additionally, multiple antennas can be used at the transmitter or receiver in order to attain a beamforming gain. On the other hand, multiple antennas can be employed in order to attain diversity gains, multiplexing gains as well as beamforming gains as shown in Figure 1.2. The terminology of colocated MIMOs refers to the systems, where the multiple antennas are located at the same transmitter or receiver station. In the sequel, we give an overview of the family of multiple antennas, when used for achieving diversity, multiplexing or beamforming gains.

1.4.1.1 Diversity Techniques

Communication in the presence of channel fading has been one of the grand research challenges in recent times. In a fading channel, the associated severe attenuation often result in decoding errors. A natural way of overcoming this problem is to allow the receiver to have several replicas of the same transmitted signal, while assuming that at least some of them are not severely attenuated.

Year	**Author(s)**	**Contribution**
1959	Brennan [35]	introduced and provided analysis for the three combining techniques: selection combining, maximum ratio combining and equal gain combining.
1991	Wittneben [36]	proposed a bandwidth-efficient transmit diversity technique, where different base stations transmit the same signal.
1993	Wittneben [37]	proposed a modulation diversity scheme in a system equipped with multiple transmit antennas.
	Seshadri *et al.* [38]	proposed a transmit diversity scheme that was inspired by the delay diversity design of Wittneben [37].
1994	Winters [39]	proved that the diversity advantage of the scheme proposed in [36] is equal to the number of transmit antennas.
1996	Eng *et al.* [40]	Compared several diversity combining techniques in a Rayleigh fading transmission with coherent detection and proposed a new second order selection combining technique.
1998	Alamouti [10]	discovered a transmit diversity scheme using two transmit antennas with simple linear processing at the receiver.
	Tarokh *et al.* [12]	proposed a complete study of design criteria for maximum diversity and coding gains in addition to the design of space-time trellis codes.
1999	Tarokh *et al.* [11, 26]	generalised Alamouti's diversity scheme [10] to more than two transmit antennas.
	Guey [41]	derived the criterion for designing the maximum transmit diversity gain.
2001	Hochwald *et al.* [14]	proposed the twin-antenna-aided space-time spreading scheme.
	Jafarkhani *et al.* [15]	designed rate-one STBC codes which are quasi-orthogonal and provide partial diversity gain.
2002	Hassibi *et al.* [13]	proposed the LDCs that provide a flexible trade-off between space-time coding and spatial multiplexing.
	Stoica *et al.* [42]	compared the performance of STBC when employing different estimation/detection techniques and proposed a blind detection scheme dispensing with the pilot symbols transmission for channel estimation.

Table 1.3: Major coherent spatial diversity techniques (Part 1).

This technique is referred to as diversity, where it is possible to attain diversity gains by creating independently fading signal replicas in the time, frequency or spatial domain.

Spatial diversity can be attained by employing multiple antennas at the transmitter or the receiver. Multiple antennas can be used to transmit and receive the same information sequence in order to achieve diversity and hence to obtain an improved BER performance. A simple spatial diversity technique, which does not involve any loss of bandwidth, is constituted by the employment of multiple antennas at the receiver. In case of narrowband frequency-flat fading, the optimum combining strategy in terms of maximising the SNR at the combiner output is Maximum Ratio Combining (MRC) [9, 35, 43]. Additionally, other combining techniques have been proposed in the literature, as shown in Figure 1.2, including Equal Gain Combining (EGC) [35] and Selection Combining (SC) [9]. All the three combining techniques are said to achieve full diversity order, which is equal to the number of receive antennas [40].

On the other hand, the idea of transmit diversity corresponds to the transmission of the same signal over multiple transmit antennas at the same time within the same bandwidth. The first

Year	**Author(s)**	**Contribution**
2003	Wang *et al.* [44]	derived upper bounds for the rates of complex orthogonal STBCs.
	Su *et al.* [45]	introduced the concept of combining orthogonal STBC designs with the principle of sphere packing.
2005	Zhang *et al.* [46]	derived the capacity and probability of error expressions for PSK/PAM/QAM modulation with STBC for transmission over Rayleigh-, Ricean- and Nakagami-fading channels.
2006	Liew *et al.* [47]	studied the performance of STTC and STBC in the context of wideband channels using adaptive orthogonal frequency division multiplex modulation.
2007	Alamri *et al.* [48]	modified the SP demapper of [45] for the sake of accepting the *a priori* information passed to it from the channel decoder as extrinsic information.
2008	Luo *et al.* [49]	combined orthogonal STBCs with delay diversity and designed special symbol mappings for maximising the coding advantage.

Table 1.4: Major coherent spatial diversity techniques (Part 2).

bandwidth-efficient transmit diversity scheme was proposed in [36] and it was shown that the diversity advantage of this scheme is equal to the number of transmit antennas [39, 50, 51]. In [10] Alamouti discovered a witty transmit diversity technique using two transmit antennas, whose key advantage was the employment of simple linear processing at the receiver, which is based on Maximum-Likelihood (ML) detection. The decoding algorithm proposed in [10] can be generalised to an arbitrary number of receive antennas using MRC, EGC or SC. Alamouti's achievement inspired Tarokh *et al.* [11, 26] to generalise the transmit diversity scheme to more than two transmit antennas, contriving the concept of Space-Time Block Codes (STBC). The family of STBCs is capable of attaining the same diversity gain as Space-Time Trellis Codes (STTC) [12, 52] at lower decoding complexity, when employing the same number of transmit antennas. However, a disadvantage of STBCs when compared to STTCs is that they provide no coding gain [9], as documented for example in [47].

Inspired by the philosophy of STBCs, Hochwald *et al.* [14] proposed the transmit diversity concept known as Space-Time Spreading (STS) for the downlink of Wideband Code Division Multiple Access (WCDMA) [53] that is capable of achieving the highest possible transmit diversity gain. The STBC and STS designs contrived for higher number of transmit antennas results in a reduction of the achievable transmission rate and hence in a reduction of the attainable bandwidth efficiency. An alternative idea for constructing full-rate STBCs for complex modulation schemes and more than two antennas was pursued in [15, 51]. Here the strict constraint of perfect orthogonality was relaxed in favour of a higher data rate. The resultant STBCs were referred to as quasi-orthogonal STBCs [15].

The STBC and STS designs offer at best the same data rate as an uncoded single-antenna system, but they provide an improved BER performance as compared to the family of single-antenna-aided systems by providing diversity gains. In contrast to this, several high-rate space-time transmission schemes having a normalised rate higher than one have been proposed in the literature. For example, high-rate space-time codes that are linear in space and time, namely the so-called Linear Dispersion Codes (LDC), were proposed in [13]. LDCs provide a flexible trade-off between achieving space-time coding and spatial multiplexing.

Additionally, the concept of combining orthogonal transmit diversity designs with the principle of Sphere Packing (SP) was introduced by Su *et al.* [45] in order to maximise the achievable coding advantage, where it was demonstrated that the proposed SP aided STBC scheme was capable of outperforming the conventional orthogonal design based STBC schemes of [10, 11]. A further

Year	Author(s)	Contribution
1998	Tarokh *et al.* [54]	proposed a detection algorithm for the Alamouti scheme [10] dispensing with channel estimation.
1999	Tarokh *et al.* [55]	proposed a differential encoding/decoding of Alamouti's scheme [10] with PSK constellations.
2000	Hochwald *et al.* [56]	proposed a differential modulation scheme for transmit diversity based on unitary space-time codes.
	Hughes [57]	proposed a differential modulation scheme that is based on group codes.
2001	Jafarkhani *et al.* [58]	proposed a differential detection scheme for the multiple antenna STBC [11].
2002	Schober *et al.* [59]	proposed non-coherent receivers for differential space-time modulation (DSTM) that can provide satisfactory performance in fast fading unlike the conventional differential schemes that perform poorly in fast fading.
2003	Hwang *et al.* [60,61]	extended the scheme of [58] to QAM constellations.
2004	Nam *et al.* [62]	extended the scheme of [60, 61] to four transmit antennas and QAM constellations.
2005	Zhu *et al.* [63]	proposed a differential modulation scheme based on quasi-orthogonal STBCs, which when compared with that of [58] results in a lower BER and provides full diversity.
2007	Song *et al.* [64]	proposed a new class of quasi-orthogonal STBCs and presented a simple differential decoding scheme for the proposed structures that avoids signal constellation expansion.

Table 1.5: Major differential spatial diversity techniques.

advance was proposed in [48], where the SP demapper of [45] was modified for the sake of accepting the *a priori* information passed to it from the channel decoder as extrinsic information. The major coherent spatial diversity techniques are summarised in Tables 1.3 and 1.4.

A common feature of all the above-mentioned schemes is that they use coherent detection, which assumes the availability of accurate Channel State Information (CSI) at the receiver. In practice, the CSI of each link between each transmit and each receive antenna pair has to be estimated at the receiver either blindly or using training symbols. However, channel estimation invoked for all the antennas substantially increases both the cost and complexity of the receiver. Furthermore, when the CSI fluctuates dramatically from burst to burst, an increased number of training symbols has to be transmitted, potentially resulting in an undesirably high transmission overhead and wastage of transmission power. Therefore, it is beneficial to develop low-complexity techniques that do not require any channel information and thus are capable of mitigating the complexity of MIMO-channel estimation.

A detection algorithm designed for Alamouti's scheme [10] was proposed in [54], where the channel encountered at time instant t was estimated using the pair of symbols detected at time instant $t-1$. The algorithm, nonetheless, has to estimate the channel during the very first time instant using training symbols and hence is not truly differential. Tarokh and Jafarkhani [55, 65] proposed a differential encoding and decoding algorithm for Alamouti's scheme [10] using real-valued phasor constellations and hence the transmitted signal can be demodulated both with or without CSI at the receiver. The resultant differential decoding aided non-coherent receiver performs within 3 dB from the coherent receiver assuming perfect channel knowledge at the receiver. The differential scheme of [55] was restricted to complex-valued PSK modulation. The twin-antenna-aided differential STBC scheme of [55] was extended to QAM constellations in [60, 61].

Differential STBC (DSTBC) schemes designed for multiple antennas were proposed in [58] for real-valued constellations. Afterwards, the authors of [60, 62] developed a DSTBC scheme that supports non-constant modulus constellations combined with four transmit antennas. This extension, however, requires the knowledge of the received power in order to appropriately normalise the received signal. The received power was estimated blindly using the received differentially encoded signals without invoking any channel estimation techniques or transmitting any pilot symbols. In [56], a differential modulation scheme was proposed for the sake of attaining transmit diversity based on unitary space-time codes [66]. The proposed scheme can be employed in conjunction with an arbitrary number of transmit antennas. Around the same time, a similar differential scheme was also proposed in [57] based on the employment of group codes.

Zhu *et al.* [63] proposed a differential modulation scheme based on quasi-orthogonal STBCs, which were compared to that of [58] and resulted in a reduced BER as a benefit of providing full diversity. Additionally, a new class of quasi-orthogonal STBCs was proposed in [64], which presented a simple differential decoding scheme that avoids signal constellation expansion. The major contributions on differential spatial diversity techniques are summarised in Table 1.5.

1.4.1.2 Multiplexing Techniques

STBC and STTC are capable of providing diversity gains for the sake of improving the achievable system performance. However, this BER performance improvement is often achieved at the expense of a rate loss since the STBC and STTC may result in a throughput loss compared to single-antenna-aided systems. As a design alternative, a specific class of MIMO systems was designed for improving the attainable spectral efficiency of the system by transmitting the signals independently from each of the transmit antennas, hence resulting in a multiplexing gain.

The basic principle of spatial multiplexing can be summarised as follows. The source bit sequence at the transmitter side is split into N_t sequences, which are modulated and then transmitted simultaneously from the N_t transmit antennas using the same carrier frequency. At the receiver side, interference cancellation is employed in order to separate the different transmitted signals. In the case of narrowband frequency flat fading, there are several decoding algorithms designed for interference cancellation at the receiver side of the spatial multiplexing systems. The different receivers can be characterised by a tradeoff between the achievable performance and the complexity imposed. A low-complexity receiver is constituted by the Zero-Forcing (ZF) or the Minimum Mean Square Error (MMSE) technique [67,68]. However, when we employ the ZF receiver, the attainable BER performance is typically poor in addition to imposing the condition that the number of receive antennas should be at least equal to the number of transmit antennas. The optimum receiver is the Maximum Likelihood (ML) receiver [69], which is capable of achieving full diversity gain, i.e. the same diversity order, as the number of receive antennas. However, a major drawback of the ML receiver is its complexity that grows exponentially with the number of transmit antennas and the number of bits per symbol employed by the modulation scheme. Fortunately, the complexity of the ML decoders can be reduced by employing sphere decoders [70–72] that are capable of achieving a similar performance to the ML decoders at a fraction of their complexity.

In [73] Foschini proposed a multi-layer MIMO structure, known as the Diagonal Bell Labs Layered Space-Time (D-BLAST) scheme[2], which is in principle capable of approaching the substantial capacity of MIMO systems. The D-BLAST signal may be subjected to low-complexity linear processing for decoding the received signals. However, the diagonal approach suffers from a potentially high implementation complexity that led Wolniansky *et al.* to propose another version of BLAST, which is known as Vertical BLAST (V-BLAST) [16]. In V-BLAST, each transmit antenna simultaneously transmits independent data over the same carrier frequency band. At the receiver side, provided that the number of receive antennas is higher than or equal to the number

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[2] The diagonal approach implies that the signal mapped to the consecutive antenna elements is delayed in time, which has the potential of subjecting the delayed signal components of a space-time symbol to more independent fading, hence leading to a potential diversity gain.

Year	Author(s)	Contribution
1996	Foschini *et al.* [73]	studied the encoding and decoding of the diagonal BLAST structure.
1998	Wolniansky *et al.* [16]	introduced the vertical BLAST architecture for reducing the implementation complexity of the diagonal approach.
1999	Golden *et al.* [74]	provided the first real-time BLAST demonstrations.
2001	Benjebbour *et al.* [75]	introduced the minimum mean square error receiver for V-BLAST and introduced an ordering scheme for improving the attainable performance.
2002	Sellathurai *et al.* [76]	studied the combination of BLAST architecture with that of a turbo code to improve its performance.
2003	Wubben *et al.* [77]	proposed a detector for improving the attainable performance of V-BLAST.
2004	Zhu *et al.* [78]	proposed a complexity-reduction algorithm for BLAST detectors.
2005	Huang *et al.* [79]	proposed a new detection algorithm for BLAST based on the concept of particle filtering and provided a near ML performance at a reasonable complexity.

Table 1.6: Major spatial multiplexing techniques.

of transmit antennas, a low complexity *serial* decoding algorithm may be applied to detect the transmitted data. The V-BLAST transceiver is capable of providing a substantial increase of a specific user's effective bit-rate without the need for any increase in the transmitted power or the system's bandwidth. However, its impediment is that it was not designed for exploiting transmit diversity. Furthermore, the decision errors of a particular antenna's detector propagate to other bits of the multi-antenna symbol, when erroneously cancelling the effects of the sliced bits from the composite signal. The V-BLAST detector first selects the layer[3] with the largest SNR and estimates the transmitted bits of that layer, while treating the other layers as interference. The detected symbol is then subtracted from the received signal and then the layer with the second highest SNR is selected for decoding. The procedure is repeated for all the layers. The BER performance of each layer is different and it depends on the received SNR of each layer. The first decoded layer has the highest SNR, while the layers detected later have a higher diversity order, since they suffer from less interference.

The BLAST detection algorithm is based on Successive Interference Cancellation (SIC), which was originally proposed for multiuser detection in CDMA systems [80]. Several BLAST detectors have been proposed in the literature for either reducing the complexity [81–86] or for improving the attainable BER performance [77, 87–92]. An alternative design approach contrived for spatial multiplexing using less receive antennas than transmit antennas was proposed in [93] based on group Maximum A Posteriori (MAP) detection. In [76, 94] a spatial multiplexing scheme referred to as Turbo-BLAST was proposed, which uses quasi-random interleaving in conjunction with an iterative receiver structure, in order to separate the individual layers. The major spatial multiplexing techniques are summarised in Table 1.6.

1.4.1.3 Beamforming Techniques

According to Sections 1.4.1.1 and 1.4.1.2, it becomes clear that multiple antennas can be used for the sake of attaining either spatial diversity or spatial multiplexing gains. However, multiple antennas can also be used in order to improve the Signal-to-Noise Ratio (SNR) at the receiver or the Signal-to-Interference-plus-Noise Ratio (SINR) in a multi-user scenario. This can be achieved

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[3] The layer in the case of the V-BLAST corresponds to each of the transmit antennas.

by employing beamforming techniques [17, 95]. Beamforming constitutes an effective technique of reducing the multiple access interference, where the antenna gain is increased in the direction of the desired user, whilst reducing the gain towards the interfering users.

In a wireless communications scenario the transmitted signals propagate via several paths and hence are received from different directions/phases at the receiver. If the directions of the different propagation paths are known at the transmitter or the receiver, then beamforming techniques can be employed in order to direct the received beam pattern in the direction of the specified antenna or user [96, 97]. Hence, significant SNR gains can be achieved in comparison to a single antenna system. On the transmitter side, when the Direction of Arrival (DOA) of the dominant paths at the receiver is known for the transmitter, then the transmit power is concentrated in the direction of the target user, where less power is wasted in the other directions.

On the other hand, beamforming can be used in order to reduce the co-channel interference or multiuser interference. When using beamforming, each user adjusts his/her beam pattern to ensure that there are nulls in the directions of the other users, while there is a high directivity in the direction of the desired receiver [17, 98]. Hence, the system attains an SINR gain.

1.4.1.4 Multi-functional MIMO Techniques

V-BLAST is capable of achieving full multiplexing gain, while STBC can achieve full antenna diversity gain. Hence, it was proposed in [18] to combine the two techniques to provide both antenna diversity and spectral efficiency gains. More specifically, it was proposed that the antennas at the transmitter be partitioned into layers, where each layer uses STBC. At the receiver side, successive group interference cancellation can be applied to each layer before decoding the signals using ML STBC decoding. Therefore, by combining V-BLAST and STBC, an improved transmit diversity gain can be achieved as compared to pure V-BLAST, while ensuring that the overall bandwidth efficiency is higher than that of pure STBC due to the independence of the signals transmitted by different STBC layers. Furthermore, the combined array processing proposed in [18] was improved in [19] by optimising the decoding order of the different antenna layers. An iterative decoding algorithm was proposed in [19] that results in a full receive diversity gain for the combined V-BLAST STBC system.

In [20] the authors presented a transmission scheme referred to as Double Space-Time Transmit Diversity (D-STTD), which consists of two STBC layers at the transmitter that is equipped with four transmit antennas, while the receiver is equipped with two antennas. The decoding of D-STTD presented in [20] is based on a linear decoding scheme presented in [110], where the authors provided a broad overview of space-time coding and signal processing designed for high data rate wireless communications. A two-user scheme was presented in [110], where each user is equipped with a twin-antenna-aided STBC scheme transmitting at the same carrier frequency and in the same time slot. A two-antenna-aided receiver was implemented for the sake of decoding the two users' data, while eliminating the interference imposed by the users on each others' data. An extension to the idea of combining interference cancellation with STBC techniques was presented in [100, 102], where the STBC and interference cancellation arrangements were combined with CDMA for the sake of increasing the number of users supported by the system. A zero-forcing decoder designed for the D-STTD was presented in [107] for the sake of reducing the decoding complexity. Finally, the authors of [101, 111] presented further results that compare the performance of STBC versus D-STTD and extended the applicability of the D-STTD scheme to more than two STBC layers.

Furthermore, in order to achieve additional performance gains, beamforming has been combined with spatial diversity as well as spatial multiplexing techniques. STBC has been combined with beamforming in order to attain a higher SNR gain in addition to the diversity gain [21, 104, 105, 112–114]. In [21], the authors combined conventional transmit beamforming with STBC, assuming that the transmitter has partial knowledge of the channel and derived a performance criterion for a frequency-flat fading channel. In addition, a particularly efficient solution was developed in [21]

Year	**Author(s)**	**Contribution**
1998	Naguib *et al.* [99]	presented a multi-user scenario where each user employs STBC and the receiver applies interference cancellation for eliminating the co-channel interference and then uses ML decoding for the STBC of each user.
1999	Tarokh *et al.* [18]	proposed to combine STBC with V-BLAST in order to provide both antenna diversity and spectral efficiency gains.
2000	Huang *et al.* [100]	extended the idea of combining interference cancellation with STBC to multiuser scenarios using CDMA.
2001	Stamoulis *et al.* [101]	proposed a simple decoder for the two-user system, where each user employs STBC and showed how the decoder can be extended to more users and then extended the results for frequency-selective channels.
2002	Onggosanusi *et al.* [20]	presented the Double Space-Time Transmit Diversity scheme, which consists of two STBC blocks at the transmitter that is equipped with four antennas, while the receiver is equipped with two antennas.
	Jongren *et al.* [21]	combined conventional transmit beamforming with STBC assuming that the transmitter has partial knowledge of the channel and derived a performance criteria for improving the system performance.
	Huang *et al.* [102]	introduced a transmission scheme that can achieve transmit diversity and spatial separation and proposed a generalisation of the V-BLAST detector for CDMA signals.
	Soni *et al.* [103]	designed a hybrid downlink technique for achieving both transmit diversity and transmit beamforming combined with DS-CDMA.
2003	Liu *et al.* [104]	combined the twin-antenna-aided Alamouti STBC with ideal beamforming in order to show that the system can attain a better performance while keeping full diversity and unity rate.
2004	Tao *et al.* [19]	improved the design of [18] by optimising the decoding order of the different antenna layers. Also proposed an iterative decoder than can achieve full diversity.
	Zhu *et al.* [105]	compared the performance of two systems combining beamforming with STBC, while using a single or two antenna arrays and studied the effect of the DOA on the performance of the two schemes.

Table 1.7: Major multi-functional MIMO techniques (Part 1).

Year	Author(s)	Contribution
2005	Zhao *et al.* [106]	compared the performance of the combined diversity and multiplexing systems while employing ZF, QR and MMSE group interference cancellation techniques.
	Lee *et al.* [107]	proposed a computationally efficient ZF decoder for the double space-time transmit diversity scheme [20] that achieves similar performance to the conventional ZF decoder but with less complexity.
2007	Sellathurai *et al.* [108]	investigated the performance of multi-rate layered space-time coded MIMO systems and proposed a framework where each of the layers is encoded independently with different rates subject to equal per-layer outage probabilities.
2008	Ekbatani *et al.* [109]	combined STBC and transmit beamforming while using limited-rate channel state information at the transmitter. Also proposed a combined coding, beamforming and spatial multiplexing scheme over multiple-antenna multi-user channels that enables a low-complexity joint interference cancellation.
	Luo *et al.* [49]	considered a new class of full-diversity STCs that consist of a combination of delay transmit diversity with orthogonal STBCs and specially designed symbol mappings.

Table 1.8: Major multi-functional MIMO techniques (Part 2).

for the specific case of independently fading channel coefficients. More explicitly, the transmission scheme of [21] combines the benefits of conventional beamforming with those of orthogonal STBC. Furthermore, in [105] the performance of combined beamforming and STBC has been analysed as a function of the number of antenna array groups. Explicitly, Zhu *et al.* [105] compared the performance of the system combining beamforming with STBC, while using either a single or two antenna arrays and studied the effect of the DOA on the attainable system performance. Finally, multiplexing techniques have been combined with beamforming techniques in [115–117]. The major multi-functional MIMO techniques are summarised in Tables 1.7 and 1.8.

1.4.2 Distributed MIMO Techniques

Wireless channels suffer from multipath propagation of the signals that results in channel fading. Employing multiple transmit antennas is a beneficial method that can be used for counteracting the effects of the channel fading by providing diversity gains. Transmit diversity results in a significantly improved BER performance, when the different transmit antennas are spatially located so that the paths arriving from each transmit antenna to the destination experience independent fading, which can be achieved by having a distance between the different antennas, which is significantly higher than the carrier's wavelength. However, considering a handheld mobile phone, it is not a feasible option to position the transmit antennas far enough in order to achieve independent fading. On the other hand, the spatial fading correlation caused by insufficiently high antenna spacing at the transmitter or receiver of a MIMO system results in a degradation of both the achievable capacity and the BER performance of MIMO systems. The problem of correlation of the transmit signals can be circumvented by introducing a new class of MIMOs also referred to as distributed MIMOs or cooperative communications [118, 119].

The basic idea behind cooperative communications can be traced back to the idea of the relay channel which was introduced in 1971 by Van der Meulen [120]. Cover and El Gamal [121] characterised the relay channel from an information theoretic point of view. In [123] Sendonaris *et al.* generalised the conventional relay model, where there is one source, one relay and one

Year	**Author(s)**	**Contribution**
1971	Meulen [120]	investigated a simple 3-node relay channel incorporating a transmitter, a relay and a receiver using a time-sharing approach.
1979	Cover *et al.* [121]	characterised the relay channel from an information theoretic point of view.
1983	Willems [122]	introduced a partially cooperative communications scenario where the encoders are connected by communication links with finite capacities, which permit both encoders to communicate with each other. The paper also established the capacity region of the multiple access channel with partially cooperating encoders.
1998	Sendonaris *et al.* [123]	generalised the relay model to multiple nodes that transmit their own data as well as serve as relays for each other.
2001	Laneman *et al.* [124]	built upon the classical relay channel and exploited space diversity available at distributed antennas through coordinated transmission and processing by cooperating radios.
2002	Hunter *et al.* [125]	proposed a user cooperation scheme for wireless communications in which the idea of cooperation was combined with the existing channel coding methods.
	Dohler *et al.* [126]	introduced the concept of virtual antenna arrays that emulates Alamouti's STBC for single-antenna-aided cooperating users.
2003	Sendonaris *et al.* [118, 119]	presented a simple user-cooperation methodology based on a DF signalling scheme using CDMA.
	Laneman *et al.* [25]	developed space-time coded cooperative diversity protocols for exploiting spatial diversity in a cooperation scenario, which can also be used for higher spectral efficiencies than repetition-based schemes.
	Valenti and Zhao [127, 128]	proposed a turbo coding scheme in a relay network.
2004	Laneman *et al.* [129]	developed and analysed cooperative diversity protocols and compared the DF, AF, selection relaying and incremental relaying.
	Nabar *et al.* [130]	analysed the spatial diversity performance of various signalling protocols.
	Janani *et al.* [131]	presented two extensions to the coded cooperation framework [125]: increased the diversity of coded cooperation via ideas borrowed from space-time codes and applied turbo codes in the proposed relay framework.

Table 1.9: Major distributed MIMO techniques (Part 1).

Year	**Author(s)**	**Contribution**
2004	Stefanov *et al.* [132]	analysed the performance of channel codes that are capable of achieving the full diversity provided by user cooperation in the presence of noisy interuser channels.
2005	Azarian *et al.* [133]	proposed cooperative signalling protocols that can achieve the diversity-multiplexing tradeoff.
	Sneessens *et al.* [134]	proposed a soft decode-and-forward signalling strategy that can outperform the conventional DF and AF.
	Hu *et al.* [135]	proposed Slepian-Wolf cooperation that exploits distributed source coding technologies in wireless cooperative communication.
	Yu [136]	compared the AF and DF signalling schemes in practical scenarios.
2006	Hunter *et al.* [137, 138]	developed the idea of coded cooperation [125] by computing BER and FER bounds as well as the outage probability of coded cooperation.
	Li *et al.* [139]	employed soft information relaying in a BPSK modulated relay system employing turbo coding.
	Hu *et al.* [140]	proposed Wyner-Ziv cooperation as a generalisation of the Slepian-Wolf cooperation [135] with a compress-and-forward signalling strategy.
	Hϕst-Madsen [141]	derived upper and lower bounds for the capacity of four-node ad hoc networks with two transmitters and two receivers using cooperative diversity.
2007	Bui *et al.* [142]	proposed soft information relaying where the relay LLR values are quantised, encoded and superimposedly modulated before being forwarded to the destination.
	Khormuji *et al.* [143]	improved the performance of the conventional DF strategy by employing constellation rearrangement in the source and the relay.
	Bao *et al.* [144]	combined the benefits of AF and DF and proposed a new signalling strategy referred to as decode-amplify-forward.
	Xiao *et al.* [145]	introduced the concept of network coding in cooperative communications.

Table 1.10: Major distributed MIMO techniques (Part 2).

destination, to multiple nodes that transmit their own data as well as serve as relays for each other. The scheme of [123] was referred to as "user cooperation diversity". Sendonaris *et al.* presented in [118, 119] a simple user-cooperation methodology based on a Decode-and-Forward (DF) signalling scheme using CDMA. In [124] the authors reported data rate gains and a decreased sensitivity to channel variations, where it was concluded that cooperation effectively mimics the multi-antenna scenario with the aid of single-antenna terminals. Dohler *et al.* [126] introduced the concept of Virtual Antenna Arrays (VAA) that emulates Alamouti's STBC for single-antenna-aided cooperating users. Space-time coded cooperative diversity protocols for exploiting spatial diversity in a cooperative scenario was proposed in [25].

Cooperative communications has been shown to offer significant performance gains in terms of various performance metrics, including diversity gains [25, 129, 149] as well as multiplexing gains [133]. Hunter *et al.* [125] proposed the novel philosophy of coded cooperation schemes, which combine the idea of cooperation with the classic channel coding methods. Extension to the framework of coded cooperation was presented in [131], where the diversity gain of coded cooperation was increased with the aid of ideas borrowed from the area of space-time codes. Additionally, a turbo coded scheme was proposed in [131] in the framework of cooperative communications. Furthermore, the analysis of the performance benefits of channel codes in a coded cooperation aided

Year	Author(s)	Contribution
2008	Yue *et al.* [146]	compared the multiplexed coding and superposition coding in the coded cooperation system.
	Zhang *et al.* [147]	proposed a distributed space-frequency coded cooperation scheme for communication over frequency-selective channels.
	Wang *et al.* [148]	introduced the complex field network coding approach that can mitigate the throughput loss in the conventional signalling schemes and attain full diversity gain.

Table 1.11: Major distributed MIMO techniques (Part 3).

scenario was performed in [132]. Laneman *et al.* [129] developed and analysed cooperative diversity protocols and compared the DF, Amplify-and-Forward (AF), selection relaying and incremental relaying signalling strategies.

Recently, there has been substantial research interest in the idea of soft relaying, where the relay passes soft information to the destination. In [134], it was argued that the DF signalling loses soft information and hence, it was proposed to use soft DF signalling, where all operations are performed using the Log-Likelihood Ratio (LLR) based representation of soft information. It was shown in [134] that the soft DF philosophy outperforms the DF and the AF signalling strategies. In [142] soft DF was also used, where the soft information was quantised, encoded and superimposed before transmission to the destination. In [139] soft information based relaying was employed in a turbo coding scheme, where the relay derives parity checking BPSK symbol estimates for the received source information and forwards the symbols to the destination. In [134, 139, 142] soft information relaying has been used, where it was shown that soft DF attains a better performance than hard DF. Furthermore, in [135, 140] distributed source coding techniques have been adopted for employment in wireless cooperative communications in order to improve the attainable performance. The major distributed MIMO techniques are summarised in Tables 1.9, 1.10 and 1.11.

1.5 Iterative Detection Schemes and Their Convergence Analysis

The concept of concatenated codes has been proposed in [150]. However, at the time of its conception it was deemed to have an excessive complexity and hence it failed to initiate immediate research interest. It was not until the discovery of turbo codes [151] that efficient iterative decoding of concatenated codes became a reality at a low complexity by employing simple constituent codes. Since then, the appealing iterative decoding of concatenated codes has inspired numerous researchers to extend the technique to other transmission schemes consisting of a concatenation of two or more constituent decoding stages [152–168].

For example, in [159] iterative decoding was invoked for exchanging extrinsic information between a soft-output symbol detector and an outer channel decoder in order to combat the effect of Inter-Symbol Interference (ISI). In [160] iterative decoding was carried out by exchanging information between an outer convolutional decoder and an inner Trellis Coded Modulation (TCM) decoder. The authors of [161, 162] presented a unified theory of Bit-Interleaved Coded Modulation (BICM). On the other hand, the employment of the iterative detection principle in [163] was considered for iterative soft demapping in the context of BICM, where a soft demapper was used between the multilevel demodulator and the channel decoder. In addition, iterative multiuser detection and channel decoding was proposed in [167] for CDMA schemes. Finally, in [168] an iteratively detected scheme was proposed for the Rayleigh fading MIMO channel, where an orthogonal STBC scheme was considered as the inner code combined with an additional block code

Year	Author(s)	Contribution
1966	Forney [150]	promoted concatenated codes.
1974	Bahl *et al.* [169]	invented the Maximum A-Posteriori (MAP) algorithm.
1993	Berrou *et al.* [151]	invented the turbo codes and showed that the iterative decoding is an efficient way of improving the attainable performance.
1995	Robertson *et al.* [170]	proposed the log-MAP algorithm that results in similar performance to the MAP algorithm but with significantly lower complexity.
	Divsalar *et al.* [152]	extended the turbo principle to multiple parallel concatenated codes.
1996	Benedetto *et al.* [153]	extended the turbo principle to serially concatenated block and convolutional codes.
1997	Benedetto *et al.* [160]	proposed an iterative detection scheme where iterations were carried out between the outer convolutional code and an inner TCM decoders.
	Caire *et al.* [161, 162]	presented the BICM concept with its design rules.
	Li *et al.* [164–166]	presented the BICM with iterative detection scheme.
1998	Benedetto *et al.* [154, 171]	studied the design of multiple serially concatenated codes with interleavers.
	Brink *et al.* [163]	introduced a soft demapper between the multilevel demodulator and the channel decoder in an iteratively detected coded system.
1999	Wang *et al.* [167]	proposed iterative multiuser detection and channel decoding for coded CDMA systems.
2000	Divsalar *et al.* [172, 173]	employed unity-rate inner codes for designing low-complexity iterative detection schemes suitable for bandwidth and power limited systems having stringent BER requirements.
	ten Brink [174]	proposed the employment of EXIT charts for analysing the convergence behaviour of iteratively detected systems.
2001	Lee [175]	studied the effect of precoding on serially concatenated systems with ISI channels.
	ten Brink [176, 177]	extended the employment of EXIT charts to three-stage parallel concatenated codes.
	EL Gamal *et al.* [178]	used SNR measures for studying the convergence behaviour of iterative decoding.

Table 1.12: Major concatenated schemes and iterative detection (Part 1).

Year	**Author(s)**	**Contribution**
2002	Tüchler *et al.* [179]	simplified the computation of EXIT charts.
	Tüchler *et al.* [180]	compared several algorithms predicting the decoding convergence of iterative decoding schemes.
	Tüchler *et al.* [181]	extended the EXIT chart analysis to three-stage serially concatenated systems.
2003	Sezgin *et al.* [168]	proposed an iterative detection scheme where a block code was used as an outer code and STBC as an inner code.
2004	Tüchler *et al.* [182]	proposed a design procedure for creating systems exhibiting beneficial decoding convergence depending on the block length.
2005	Lifang *et al.* [183]	showed that non-square QAM can be decomposed into parity-check block encoder having a recursive nature and a memoryless modulator. Iterative decoding was implemented with an outer code for improving the system performance.
	Brännström *et al.* [184]	considered EXIT chart analysis for multiple concatenated codes using 3-dimensional charts and proposed a way for finding the optimal activation order.
2008	Maunder *et al.* [185]	designed irregular variable length codes for the near-capacity design of joint source and channel coding aided systems.

Table 1.13: Major concatenated schemes and iterative detection (Part 2).

as the outer channel code.

It was shown in [186] that a recursive inner code is needed in order to maximise the interleaver gain and to avoid the average BER floor, when employing iterative decoding. This principle has been adopted by several authors designing serially concatenated schemes, where unity-rate inner codes were employed for designing low complexity iterative detection aided schemes suitable for bandwidth- and power-limited systems having stringent BER requirements [172, 173, 175, 183, 187].

Semi-analytical tools devised for analysing the convergence behaviour of iteratively decoded systems have attracted considerable research attention [172, 174, 177–180, 184, 188, 189]. In [174], ten Brink proposed the employment of the so-called EXtrinsic Information Transfer (EXIT) characteristics for describing the flow of extrinsic information between the soft-in soft-out constituent decoders. The computation of EXIT charts was further simplified in [179] to a time averaging, when the PDFs of the information communicated between the input and output of the constituent decoders are both symmetric and consistent. A tutorial introduction to EXIT charts can be found in [188]. The concept of EXIT chart analysis has been extended to three-stage concatenated systems in [176, 181, 184]. The major contributions on iterative detection and its convergence analysis are summarised in Tables 1.12 and 1.13.

1.6 Outline and Novel Aspects of the Monograph

1.6.1 Outline of the Book

Having briefly reviewed the literature of space-time coding, concatenated schemes, iterative decoding and having studied the convergence behaviour of iterative schemes, let us now outline the organisation of the book.

- **Chapter 2: Space-Time Block Code Design using Sphere Packing**
  In this chapter, we consider the theory and design of space-time block codes using sphere packing modulation, referred to here as (STBC-SP). We first summarise the design criteria

of space-time coded communication systems in Section 2.2. In Section 2.3, we emphasise the design criteria relevant for time-correlated fading channels, where both the pairwise error probability as well as the corresponding design criterion are presented in Section 2.3.2. In Section 2.4, orthogonal space-time designs combined with sphere packing modulation are considered for space-time signals, where the motivation behind the adoption of sphere packing modulation in conjunction with orthogonal design is discussed in Section 2.4.2. Section 2.4.4 discusses the problem of constructing a sphere packing constellation having a particular size L. The capacity of STBC-SP schemes employing $N_t = 2$ transmit antennas is derived in Section 2.4.5, demonstrating that STBC-SP schemes exhibit a higher capacity than conventionally modulated STBC schemes. Finally, the performance of STBC-SP schemes is presented in Section 2.5, demonstrating that STBC-SP schemes are capable of outperforming STBC schemes that employ conventional modulation (i.e. PSK, QAM).

- **Chapter 3: Turbo Detection of Channel-Coded STBC-SP Schemes**
  In this chapter, we demonstrate that the performance of STBC-SP systems can be further improved by concatenating sphere packing aided modulation with channel coding and performing demapping as well as channel decoding iteratively. The sphere packing demapper of [190] is further developed for the sake of accepting the *a priori* information passed to it from the channel decoder as extrinsic information. Two realisations of a novel bit-based iterative-detection aided STBC-SP scheme are presented, namely a recursive systematic convolutional (RSC) coded turbo-detected STBC-SP scheme and a binary LDPC-coded turbo-detected STBC-SP arrangement. Our system overview is provided in Section 3.2. In Section 3.3, we show how the STBC-SP demapper is modified for exploiting the *a priori* knowledge provided by the channel decoder, which is essential for the employment of iterative demapping and decoding. EXIT chart analysis is invoked in Section 3.4 in order to study and design the turbo-detected schemes proposed in Section 3.2. We propose 10 different anti-Gray mapping (AGM) schemes that are specifically selected from all the possible mapping schemes for $L = 16$ in order to demonstrate the different extrinsic information transfer characteristics associated with different bit-to-symbol mapping schemes. The slope of the EXIT curves corresponding to the different AGM schemes increases gradually in fine steps. This attractive characteristic is a result of the multi-dimensional constellation mapping and having this property is essential for the sake of designing near-capacity turbo detected systems. The performance of the turbo-detected bit-based STBC-SP schemes is presented in Section 3.5, where we investigate the relation between the achievable BER and the mutual information at the input as well as at the output of the outer decoders. Additionally, the predictions of our EXIT chart analysis are verified by generating the actual decoding trajectories and BER curves. The effect of interleaver depth is also addressed, since matching the predictions of the EXIT chart analysis is only guaranteed, when employing large interleaver depths. The BER performance of the proposed channel-coded STBC-SP scheme is compared to that of an uncoded STBC-SP scheme [190] and to that of a channel-coded conventionally modulated STBC scheme.

- **Chapter 4: Turbo Detection of Channel-Coded DSTBC-SP Schemes**
  In Chapter 2 and Chapter 3, we assume that the channel state information is perfectly known at the receiver. This, however, requires sophisticated channel estimation techniques, which imposes excess cost and complexity. In Chapter 4, we consider the design of novel sphere packing modulated differential STBC schemes, referred to here as DSTBC-SP, that require no channel estimation, where we describe in Section 4.2.1 how DSTBC schemes are constructed using sphere packing modulation. The performance of uncoded DSTBC-SP schemes is considered in Section 4.2.2, where we compare the performance of different DSTBC-SP schemes against equivalent conventional DSTBC schemes under various channel conditions. Simulation results are provided for systems having different BPS rates in conjunction with appropriate conventional and sphere packing modulation schemes. In Section 4.3, we propose

novel bit-based RSC-coded turbo-detected DSTBC-SP schemes. The system's architecture is outlined in Section 4.3.1. The EXIT chart analysis of Section 3.4 is employed in Section 4.3.2 in order to design and analyse the convergence behaviour of the proposed turbo-detected RSC-coded DSTBC-SP schemes. In Section 4.3.3, we investigate the performance of the proposed RSC-coded DSTBC-SP schemes. The actual decoding trajectories and BER performance curves are also provided, when using various interleaver depths.

- **Chapter 5: Three-Stage Turbo-Detected STBC-SP Schemes**
  The conventional two-stage turbo-detected schemes introduced in Chapter 3 suffer from a BER floor, preventing them from achieving infinitesimally low BER values, since the inner coding stage is of non-recursive nature. In Chapter 5, we circumvent this deficiency by proposing a three-stage turbo-detected STBC-SP scheme, where a rate-1 recursive inner precoder is employed to avoid having a BER floor. Section 5.2 provide a brief description of the proposed three-stage system. We consider three different types of channel codes for the outer encoder, namely a repeater, an RSC code and an irregular convolutional code (IRCC). Our 3D EXIT chart analysis is presented in Section 5.3.2, where its simplified 2D projections are provided in Section 5.3.3. In Section 5.3.4, we employ the powerful technique of EXIT tunnel-area minimisation for near-capacity operation. More specifically, we exploit the well-understood properties of conventional 2D EXIT charts that a narrow but nonetheless open EXIT-tunnel represents a near-capacity performance. Consequently, we invoke IRCCs for the sake of appropriately shaping the EXIT curves by minimising the area within the EXIT-tunnel using the procedure of [182, 191]. In Section 5.4, an upper bound on the maximum achievable rate is calculated based on the EXIT chart analysis. More explicitly, a procedure is proposed for calculating a tighter upper bound of the maximum achievable bandwidth efficiency of STBC-SP schemes based on the area property of the EXIT charts discussed in Section 5.3.4. The design procedure is summarised in Algorithm 5.1. The performance of the three-stage turbo-detected STBC-SP schemes is demonstrated and characterised in Section 5.5, where we discuss the actual decoding trajectories, BER performance and the effect of interleaver depth on the achievable performance. We also investigate the E_b/N_0 distance to capacity for the three-stage RSC-coded as well as for the IRCC-coded STBC-SP schemes, when employing various interleaver depths and using different number of three-stage iterations. Finally, in Section 5.5.5, the performance of both the three-stage RSC-coded and IRCC-coded STBC-SP schemes are compared, when employing various interleaver depths, while using different number of three-stage iterations.

- **Chapter 6: Symbol-Based Channel-Coded STBC-SP Schemes**
  In all previous chapters, iterative decoding is employed at the bit-level. By contrast, in this chapter, we explore a range of further design options and propose a purely symbol-based scheme, where symbol-based turbo detection is carried out by exchanging extrinsic information between an outer non-binary LDPC code and a rate-1 non-binary inner precoder. The motivation behind the development of this symbol-based scheme is that a reduced transmit power may be required, when symbol-based rather than bit-based iterative decoding is employed [192]. The system's architectures of the proposed symbol-based and turbo-detected scheme and its equivalent bit-based scheme are presented in Section 6.2. Symbol-based iterative decoding is discussed in Section 6.3, where it is demonstrated how the *a priori* information is removed from the decoded *a posteriori probability* with the aid of symbol-based element-wise division for the sake of generating the *extrinsic probability*. Section 6.4 provides our non-binary EXIT chart analysis. More specifically, in Section 6.4.1 we demonstrate, how non-binary EXIT charts can be generated without generating an L-dimensional histogram [193] since the complexity of this operation may become higher than conducting full-scale BER or SER simulations, when the number of bits per symbol is high. In Section 6.4.2, we address the problem of generating the *a priori* symbol probabilities, when

the binary bits within each non-binary symbol are assumed be either independent or not. Accordingly, a detailed procedure is described in Section 6.4.2.2 for creating the *a priori* symbol probabilities, when the binary bits of each non-binary symbol may no longer be assumed to be independent. The results of our non-binary EXIT chart analysis are provided in Section 6.4.3, where the EXIT charts of both the symbol-based and bit-based schemes are compared demonstrating that the symbol-based schemes require a lower transmit power and a lower number of decoding iterations for achieving a performance comparable to that of their bit-based counterparts. The performance of the symbol-based and bit-based LDPC-coded STBC-SP schemes is investigated in Section 6.5, in terms of the actual decoding trajectories and the attainable BER performance. The effect of employing various interleaver depths or, equivalently, LDPC output block lengths on the achievable performance is also considered in Section 6.5.

- **Chapter 7: IR-PLDCs for Co-located MIMO Antenna Elements**
  The theory and design of LDCs designed for co-located MIMO systems is investigated and a novel irregular near-capacity scheme using LDCs as the *inner* constituent code is proposed. Section 7.2 presents LDC models suitable for describing OSTBCs and for non-orthogonal STBCs. Furthermore, a novel method of optimizing the LDCs according to their DCMC capacities is proposed. In Section 7.3, the relationship between various STBC designs and LDCs is exploited in detail, demonstrating the flexibility of the linear dispersion framework. Table 7.3 specifically characterizes the evolution of STBCs in terms of their rate, diversity and flexibility. As far as channel-coded schemes concerned, Section 7.4 investigates various design issues related to two-stage concatenated convolutional coded LDCs as well as to three-stage precoder-assisted LDCs with the aid of EXIT chart, including their maximum achievable rates and their iteration parameters. Section 7.5 investigates the irregular code design principle originally derived for IRCCs and employ a similar concept to design a family of IrRegular Precoded Linear Dispersion Codes (IR-PLDCs) as the *inner* constituent code of a SCC. In Sections 7.5.1 to 7.5.3, different degrees of irregularity are imposed on both the *inner* IR-PLDCs and the *outer* IRCCs.

- **Chapter 8: IR-PDLDCs for Co-located MIMO Antenna Elements**
  In Chapter 8, we exploit the linear dispersion structure in the context of non-coherently detected MIMO systems as well as characterize the effective throughput achieved by an irregular SCC scheme. In Section 8.2, the multi-antenna aided DSTBC's system architecture is derived from the conventional single-antenna aided Differential Phase Shift Keying (DPSK) scheme, followed by the characterization of the fundamental relationship between STBCs and DSTBCs in Section 8.2.3. After characterizing the performance of DSTBCs based on various orthogonal constraints in Section 8.3, Section 8.4 proposes the family of DLDCs based on the Cayley transform. In Section 8.5, we introduce the concept of Sphere Packing (SP) modulation [194] and jointly design the SP modulation and DSTBCs. The convolutional-coded SP-aided DSTBC scheme of Figure 8.18 is capable of approaching the capacity at a specific SNR. Finally, in Section 8.6 the irregular design philosophy is imposed on both the *inner* and *outer* codes. Again, the resultant IRCC-coded IrRegular Precoded Differential Linear Dispersion Codes (IR-PDLDCs) of Figure 8.25 has the potential of operating near the attainable capacity across a wide range of SNRs.

- **Chapter 9: IR-PCLDCs for Cooperative MIMO Systems**
  In Chapter 9, we apply the linear dispersion structure to the family of relay-aided cooperative schemes and characterize the maximum achievable throughput achieved by the irregular system. More explicitly, Section 9.1 justifies the need for cooperation and portrays the system architecture in Figure 9.2. The mathematical model of the proposed twin-layer CLDCs as well as the rationale of our assumptions are discussed in Sections 9.2.1 to 9.2.3. The fundamental link between LDCs and CLDCs is exploited in Section 9.2.4, followed by their achievable performance recorded in Section 9.2.5. Similarly, we impose the irregular design

philosophy in the context of cooperative MIMO systems in Section 9.3. The resultant IRCC-coded IrRegular Precoded Cooperative Linear Dispersion Codes (IR-PCLDCs) of Figure 9.16 become capable of achieving a flexible effective throughput according to the SNR encountered, while maintaining an infinitesimally low BER.

- **Chapter 10: Differential Space-Time Spreading**
  This chapter introduces the idea of differential space-time spreading and its combination with Sphere-Packing (SP) modulation. The chapter first reviews the concept of differential encoding in Section 10.2. It is shown that differential encoding requires no channel state information at the receiver and thus eliminates the complexity of channel estimation at the expense of a 3 dB performance loss compared to the coherently detected system assuming perfect CIR recovery at the receiver. In Section 10.3, we outline the encoding and decoding processes of the differential space-time spreading scheme, when combined with conventional modulation schemes such as PSK and QAM. In Section 10.3.3, the philosophy of DSTS using sphere packing modulation is introduced based on the fact that the diversity product of the DSTS design is improved by maximising the Minimum Euclidean Distance (MED) of the DSTS symbols, which is motivated by the fact that SP has the best known MED in the real-valued space. Section 10.3.4 discusses the problem of constructing a sphere packing constellation having a particular size L. The capacity of DSTS-SP schemes employing $N_t = 2$ transmit antennas is derived in Section 10.3.6, followed by the performance characterisation of a twin-antenna-aided DSTS scheme in Section 10.3.7, demonstrating that the DSTS scheme is capable of providing full diversity. Our results demonstrate that DSTS-SP schemes are capable of outperforming DSTS schemes dispensing with SP.

  The four-antenna-aided DSTS design is characterised in Section 10.4, where it is demonstrated that the DSTS scheme can be combined with conventional real- and complex-valued constellations as well as with SP modulation. It is also shown that the four-dimensional SP modulation scheme is constructed differently in the case of two transmit antennas than when employing four transmit antennas. The capacity of the four-antenna-aided DSTS-SP scheme is also derived for different spectral efficiency systems, while employing a variable number of receive antennas in Section 10.4.5. Finally, Section 10.4.6 presents the simulation results obtained for the four-antenna-aided DSTS scheme, when combined with conventional as well as SP modulations.

- **Chapter 11: Turbo Detection of Channel-Coded DSTS Schemes**
  In this chapter, two realisations of a novel iterative-detection aided DSTS-SP scheme are presented, namely an iteratively detected RSC-coded DSTS-SP scheme as well as an iteratively detected RSC-coded and URC precoded DSTS-SP arrangement. The iteratively detected RSC-coded DSTS-SP scheme is described in detail in Section 11.2. In Section 11.2.1, we show how the DSTS-SP demapper was modified for exploiting the *a priori* knowledge provided by the channel decoder, which is essential for the employment of iterative detection.

  The concept of EXIT charts is introduced in Section 11.2.2 as a tool designed for studying iterative detection aided schemes. Then, we propose a novel technique for computing the maximum achievable bandwidth efficiency of the system based on EXIT charts in Section 11.2.3, followed by a discussion of the system's performance. Section 11.2.5 presents an application of the iteratively detected RSC-coded DSTS-SP system, where an Adaptive Multi-Rate WideBand (AMR-WB) source codec was employed by the system in order to demonstrate the attainable performance improvements.

  Additionally, in Section 11.3 we propose an iteratively detected RSC-coded and URC-precoded DSTS-SP scheme that is capable of eliminating the error floor exhibited by the system of Section 11.2, which hence performed closer to the system's achievable capacity. In Section 11.3.1 we present an overview of the system operation, followed by a discussion of the results in Section 11.3.2. In Section 11.3.3 we present an application of the proposed system, while employing Irregular Variable Length Codes (IrVLC) as our outer code for the sake of achieving a near-capacity performance.

- **Chapter 12: Adaptive Differential Space-Time-Spreading-Assisted Turbo-Detected Sphere Packing Modulation**
  In this chapter we propose a novel adaptive DSTS aided system that exploits the advantages of differential encoding, iterative decoding, as well as SP modulation, while adapting the system parameters for the sake of achieving the highest possible bandwidth efficiency, as well as maintaining a given target BER. The proposed adaptive DSTS-SP scheme benefits from a substantial diversity gain, while using four transmit antennas without the need for pilot-assisted channel envelope estimation and coherent detection. The proposed scheme reaches the target BER of 10^{-3} at an SNR of about 5 dB and maintains it for SNRs in excess of this value, while increasing the effective throughput. The system's bandwidth efficiency varies from 0.25 bits/sec/Hz to 16 bits/sec/Hz.

- **Chapter 13: Layered Steered Space-Time Codes**
  In this chapter, we propose a multi-functional MIMO scheme, that combines the benefits of Vertical Bell Labs Layered Space-Time (V-BLAST) codes, of space-time codes as well as of beamforming. Thus, the proposed system benefits from the multiplexing gain of the V-BLAST, from the diversity gain of the space-time codes and from the SNR gain of the beamformer. The MIMO scheme is referred to as Layered Steered Space-Time Codes (LSSTC). To further enhance the attainable system performance and to maximise the coding advantage of the proposed transmission scheme, the system is also combined with multi-dimensional SP modulation.

  In Section 13.2 we outline the encoding and decoding processes of this multi-functional MIMO scheme when combined with conventional as well as SP modulation schemes. Then, in Section 13.3 we quantify the capacity of the proposed multi-functional MIMO and present the capacity limits for a system employing $N_t = 4$ transmit antennas, $N_r = 4$ receive antennas and a variable number L_{AA} of elements per Antenna Array (AA). Furthermore, in Section 13.4.3 we quantify the upper bound of the achievable bandwidth efficiency of the system based on the EXIT charts obtained for the iteratively detected system.

  To further enhance the attainable system performance, the proposed MIMO scheme is serially concatenated with both an outer code and a URC, where three different receiver structures are presented by varying the iterative detection configuration of the constituent decoders/demapper. In Section 13.4.1 we provide a brief description of the iteratively detected two-stage RSC-coded LSSTC-SP scheme, where extrinsic information is exchanged between the outer RSC decoder and the inner URC decoder, while no iterations are carried out between the URC decoder and the SP demapper. The convergence behaviour of the iterative-detection-aided system is analysed using EXIT charts in Section 13.4.1.1. In Section 13.4.1.2, we employ the powerful technique of EXIT tunnel-area minimisation, for the sake of achieving a near-capacity operation. Consequently, we invoke IrCCs for the sake of appropriately shaping the EXIT curves by minimising the area within the EXIT-tunnel using the procedure of [179, 182].

  In Section 13.4.2 we present an iteratively detected three-stage RSC-coded LSSTC scheme, where extrinsic information is exchanged between the three constituent decoders, namely the outer RSC decoder, the inner URC decoder as well as the demapper. 3D EXIT charts are presented in Section 13.4.2.1, followed by Section 13.4.2.2, where the simplified 2D projections of the 3D EXIT charts were provided. Finally, in Section 13.5 we discuss our performance results and characterise the three iteratively detected LSSTC schemes proposed. Explicitly, the SP aided system is capable of operating within 0.9 dB, 0.6 dB and 0.4 dB from the maximum achievable rate limit. However, to operate within 0.6 dB from the maximum achievable rate limit, the system imposes twice the complexity compared to a system operating within 0.9 dB from this limit. On the other hand, to operate as close as 0.4 dB from the maximum achievable rate limit, the system imposes 20 times higher complexity in comparison to the one operating within 0.9 dB from the maximum achievable rate limit. The proposed design principles are applicable to an arbitrary number of antennas and diverse antenna configurations as well as modem schemes. By contrast, the QPSK modulated three-stage iteratively detected system is capable of operating within 1.54 dB from the maximum achievable rate limit and thus the SP modulated system outperforms its QPSK aided counterpart by about 1 dB at a BER of 10^{-6}.

- ▶ **Chapter 14: Downlink LSSTS Aided Generalised MC DS-CDMA**
  A multi-functional multiuser MIMO scheme that combines the benefits of V-BLAST, of STS, of generalised MC DS-CDMA as well as of beamforming is presented. The proposed system is referred to as Layered Steered Space-Time Spreading (LSSTS) aided generalised MC DS-CDMA, which benefits from a multiplexing gain, a spatial diversity gain, a frequency diversity gain and a beamforming gain.
  In Section 14.2 the proposed LSSTS scheme's transmitter structure is characterised and then the decoding process is illustrated. Afterwards, in order to increase the number of users supported by the system, Frequency Domain (FD) spreading is applied in the generalised MC DS-CDMA in addition to the Time Domain (TD) spreading action of the STS. A user-grouping technique is employed that minimises the FD interference coefficient for the users in the same TD group.

  To further enhance the achievable system's performance, the proposed MIMO scheme is serially concatenated with an outer code combined with a URC, where three different iteratively detected systems are presented in Section 14.4. EXIT charts are used to study the convergence behaviour of the proposed systems and in Section 14.4.1 we propose an LLR post-processing technique for the soft output of the QPSK demapper in order to improve the achievable system performance. In Section 14.5 we discuss our performance results and characterise the three proposed iteratively detected schemes, while employing N_t=4 transmit AAs, N_r=2 receive antennas, L_{AA} number of elements per AA, V number of subcarriers supporting K users.

- ▶ **Chapter 15: Distributed Turbo Coding**
  A cooperative communication scheme referred to as Distributed Turbo Coding (DTC) is presented. In the proposed scheme, two users are cooperating, where each user's transmitter is constituted by an RSC code and an interleaver followed by a SP mapper. In Section 15.2 we provide an overview of cooperative communications and the background of the major cooperative signalling strategies including AF, DF and coded cooperation. In Section 15.3 the DTC scheme is presented, where a two-phase cooperation scheme is proposed. In the first phase, the two users exchange their data, while in the second phase the two users simultaneously transmit their data to the base station. In Section 15.4 we characterise the attainable system performance and study the effects of varying the inter-user channel characteristics on the performance of the uplink DTC scheme.

- ▶ **Chapter 16: Conclusions and Future Research Ideas**

  This chapter summarises the main findings of the book, giving cognizance to the current trends in the research community and outlines a range of suggestions for future research.

1.6.2 Novel Aspects of the Book

The book is based on a diverse range of publications, which were listed at the back of the book as well as in the Author Index and covers the following novel research aspects:

- The achievable performance of several STBC-SP schemes employing various sphere packing constellation sizes L was investigated, where the constellation points were first chosen based on a minimum energy criterion. Then, an exhaustive computer search was conducted in order to find the set of L points having the highest MED from the entire set of constellation points satisfying the minimum energy criterion.

- A turbo-detected sphere packing modulation aided STBC scheme was proposed, where the sphere packing demapper was further developed for the sake of accepting the *a priori* information passed to it from the channel decoder as extrinsic information [195, 196].
- In order to portray the different EXIT characteristics associated with different bit-to-SP-symbol mapping schemes, 10 different anti-Gray mapping (AGM) schemes were developed that were specifically selected from all the possible mapping schemes available for $L = 16$. The slope of the EXIT curves corresponding to the different AGM schemes increases gradually in fine steps demonstrating the advantages of multi-dimensional constellation mapping. Exhibiting a gradually increasing EXIT characteristic is essential for the sake of designing near-capacity turbo-detected systems. The proposed turbo-detected STBC-SP scheme was optimised using using EXIT charts [197].
- A differential turbo-detected sphere packing modulation aided STBC scheme that requires no channel state information was proposed and its performance was optimised using EXIT charts [198].
- A three-stage serially concatenated turbo-detected STBC-SP scheme was proposed that is capable of achieving infinitesimally low BER values, where the performance was no longer limited by a BER floor. The convergence behaviour of the three-stage system was analysed and designed with the aid of 3D EXIT charts and their 2D projections, resulting in a near-capacity performance [199, 200].
- A procedure was proposed for calculating a tighter upper bound on the maximum achievable bandwidth efficiency of concatenated schemes based on the so-called 'area property' of the EXIT charts [199, 200].
- A purely symbol-based scheme was proposed, where symbol-based turbo detection was carried out by exchanging extrinsic information between an outer non-binary LDPC code and a rate-1 non-binary inner precoder. The convergence behaviour of the proposed symbol-based scheme was analysed using novel symbol-based EXIT charts [48, 201–203].
- Llinear dispersion codes were used in order to unify the family of orthogonal and non-orthogonal STBC designs. This unified structure enables us to examine existing STBCs from a novel perspective. More explicitly, we characterized the linkage between existing STBCs found in the open literature and LDCs in terms of both their mathematical representations and their design philosophies. Furthermore, we proposed to optimize the LDCs from a capacity maximization perspective, namely by maximizing the LDCs' Discrete-input Continuous-output Memoryless Channel (DCMC) capacity.
- We demonstrated the fundamental relationship between STBCs and DSTBCs, which enables us to extend the STBC design philosophy to DSTBCs. Furthermore, the Cayley transform [13] was introduced as an efficient way of constructing unitary matrices for their description. The resultant Differential Linear Dispersion Codes (DLDCs) based on the Cayley transform exhibited similar characteristics to those of their coherently detected LDC counterparts.
- The fundamental relationship between co-located and cooperative MIMO systems has been investigated, which is facilitated by the establishment of the broadcast interval. In other words, CSTBCs are designed to provide spatial diversity with the aid of a two-phase transmission regime. Hence, we proposed the family of twin-layer Cooperative Linear Dispersion Codes (CLDCs), which inherited the flexible linear dispersion structure and were specifically designed to exploit the above-mentioned two-phase transmission regime.

- A quantitative comparative study of LDCs, DLDCs and CLDCs is conducted, since all of them are based on the linear dispersion structure. Our investigations suggested that the family of LDCs is suitable for co-located MIMO systems employing coherent detection. The class of DLDCs is more applicable, when no CSI is available at the receiver. When relay-aided cooperative transmission is necessary to avoid the performance erosion imposed by shadow fading, our specifically designed twin-layer CLDCs are more beneficial.

- The concept of irregular coding [204] was documented and it was extended to a broad range of systems. More explicitly, the irregular design principle was applied in the context of the inner code of a serial concatenated coding scheme. The resultant inner IrRegular Precoded LDC (IR-PLDC) scheme facilitates the system's near-capacity operation across a wide range of SNRs. Similarly, we proposed the IR-DLDCs for non-coherent MIMO systems and IR-CLDCs for cooperative MIMO systems.

- A Differential Space-Time Spreading (DSTS) scheme is proposed, which is advocated for the sake of achieving a high transmit diversity gain in a multi-user system, while eliminating the complexity of MIMO channel estimation. Additionally, the system is combined with multi-dimensional Sphere Packing (SP) modulation, which is capable of maximising the coding advantage of the transmission scheme by jointly designing and detecting the sphere-packed DSTS symbols. The capacity of the DSTS-SP scheme is quantified analytically, where it is shown that the DSTS-SP system attains a higher capacity than its counterpart dispensing with SP [205–207].

- Iteratively detected DSTS-SP schemes are designed for near-capacity operation, where EXIT charts are used for analysing the convergence behaviour of the iterative detection. The outer code used in the iterative detection aided systems is a Recursive Systematic Convolutional (RSC) code, while the inner code is SP mapper in the first system and a Unity Rate Code (URC) in the second system, where the URC is capable of eliminating the error floor present in the BER performance of the system dispensing with URC [205, 208–210].

- An algorithm is devised for computing the maximum achievable rate of the DSTS system using EXIT charts, where the maximum achievable rate obtained using EXIT charts matches closely with the analytically computed capacity [205].

- An adaptive DSTS-SP scheme is proposed in order to maximise the system's throughput. The adaptive scheme exploits the advantages of differential encoding, iterative decoding as well as SP modulation. The achievable integrity and bit rate enhancements of the system are determined by the following factors: the specific transmission configuration used for transmitting data from the four antennas, the spreading factor used and the RSC encoder's code rate [211].

- The merits of V-BLAST, STC and beamforming are amalgamated in a Layered Steered Space-Time Coded (LSSTC) multi-functional MIMO scheme for the sake of achieving a multiplexing gain, a diversity gain as well as a beamforming gain. Additionally, the capacity of the LSSTC-SP scheme is quantified analytically [212].

- Furthermore, in order to characterise the LSSTC scheme, three iteratively detected LSSTC-SP receiver structures are proposed, where iterative detection is carried out between the outer code's decoder, the intermediate code's decoder and the LSSTC-SP demapper. The three systems are capable of operating within 0.9, 0.4 and 0.6 dB from the maximum achievable rate limit of the system. A comparison between the three iteratively detected schemes reveals that a carefully designed two-stage iterative detection aided scheme is capable of operating sufficiently close to capacity at a lower complexity, when compared to a three-stage system employing RSC or a two-stage system employing an Irregular Convolutional Code (IrCC) as the outer code [22, 213].