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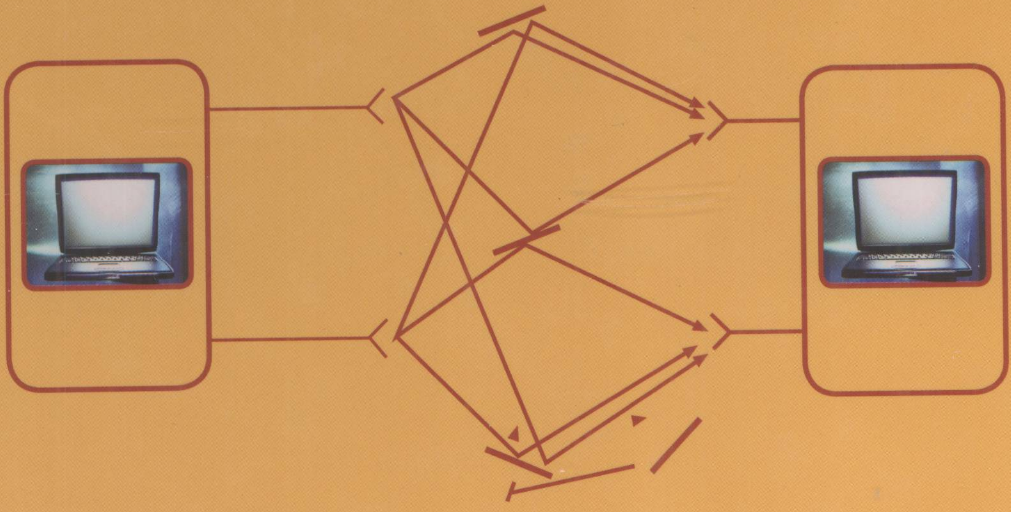
Space-Time Layered Information Processing for Wireless Communications



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SPACE-TIME LAYERED INFORMATION PROCESSING FOR WIRELESS COMMUNICATIONS

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A JOHN WILEY & SONS, INC., PUBLICATION

Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data:

Sellathurai, Mathini, 1968-
Space-time layered information processing for wireless communications / by Mathini Sellathurai and Simon Haykin.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-471-20921-8
1. Space time codes. 2. MIMO systems. I. Haykin, Simon S., 1931- II. Title.
TK5103.4877.S45 2009
621.3840285′572–dc22

2009005657

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

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INTRODUCTION

1.1 BRIEF HISTORICAL NOTES

In the last decade of the twentieth century, two groundbreaking ideas were published, which, in their own individual ways, have shaped many facets of digital communications and signal processing in both theoretical and practical terms.

The first idea on turbo codes was presented at the 1993 IEEE International Conference on Communications (ICC) that was held in Geneva, Switzerland, in May of that year. At that conference, Berrou, Glavieux, and Thitimajshima presented a paper entitled "Near Shannon Limit Error-Correcting Coding and Decoding: Turbo Codes," and with it the ever-expanding field of turbo-information processing was born [17].

Then, three years later, Foschini published a paper entitled "Layered Space-Time Architecture for Wireless Communication in a Fading Environment When Using Multi-Element Antennas" in the *Bell Laboratories Technical Journal* [43]. With the publication of this second paper, the ever-expanding field of multiple-input multiple-output (MIMO) wireless communications was born.

Although entirely different in their theory and applications, turbo-information processing and MIMO wireless communications, share two common points:

- They were both ideas conceived as a result of "thinking outside of the box" and were initially received with a skepticism by experts in the field.

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- Since their invention in the 1990s, they have both evolved at an unprecedented pace, reaching a state of maturity in just over a decade.

The particular form of MIMO wireless communications described in Foschini's paper was named the "Bell Labs Layered Space-Time (BLAST)" architecture. With the early formulations of the two ideas, turbo processing and BLAST architecture, it was logical that these two ideas be combined into what we now refer to as "Turbo-BLAST," on which research was initiated when the first author of this book joined the senior author as a Ph.D. student in 1998. Indeed, it was Sellathurai's thesis, entitled "Turbo-BLAST, A Novel Technique for Multi-Transmit and Multi-Receive Wireless Communications," and subsequent publications that led to the writing of this book. Simply put, Turbo-BLAST offers the advantage of building a layered space-time wireless communication system that is both spectrally and computationally efficient.

1.2 TURBO-INFORMATION PROCESSING

The turbo-coding scheme, originally formulated by Berrou, Glavieux, and Thitimajshima, is a codec, in which the encoder and decoder distinguish themselves from the traditional codecs in two fundamental ways:

1. The encoder consists of two parallel constituent encoders with an interleaver between them, as depicted in Figure 1.1. The purpose of the interleaver is to randomize the incoming stream of bits to ensure that the respective inputs of the two constituent encoders are as dissimilar as practically possible.
2. Correspondingly, the decoder consists of two constituent decoders separated by an interleaver and a de-interleaver, forming a closed-loop feedback system in the manner depicted in Figure 1.2. The interleaver and de-interleaver are positioned inside the decoder in such a way that the inputs applied to

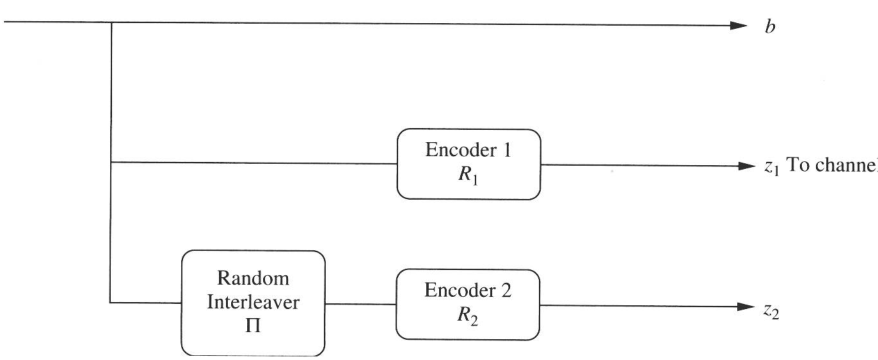

Figure 1.1 Turbo encoder.

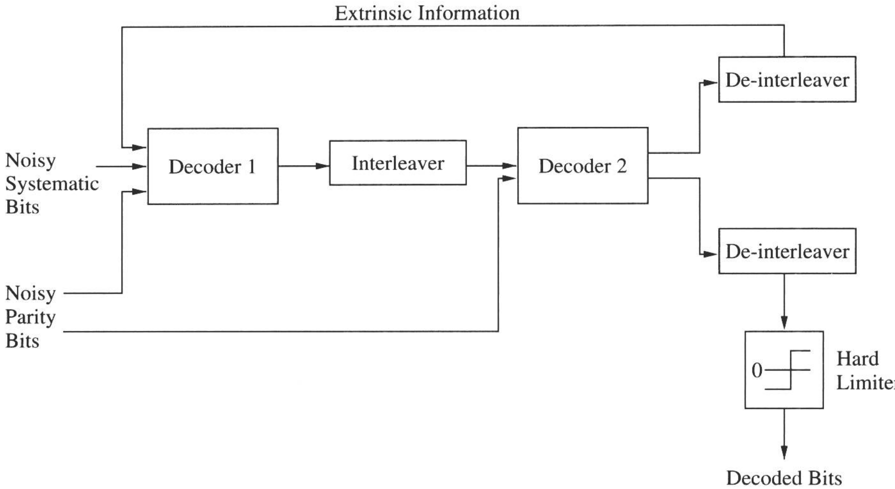

Figure 1.2 Turbo decoder.

each constituent decoder correspond to the pertinent constituent encoder. In particular, each constituent decoder operates on three different inputs:

- The systematically encoded (message) bits
- The parity-check bits associated with the systematic bits
- The information bits produced by the other constituent decoder about the likely values of the received message bits.

The turbo decoder of Figure 1.2 is an iterative decoder. An important novel feature of this decoder is the application of feedback around all of the components constituting the decoder. Another important feature that is equally novel, in its own way, is the notion of extrinsic information that is basic to the operation of the turbo decoder. The extrinsic information, generated by a decoding stage for a set of systematic (message) bits, is defined as the difference between the log-likelihood ratio computed at the output of that particular decoding stage and the intrinsic information represented by the log-likelihood ratio fed back to the input of the decoding stage. In effect, extrinsic information is the incremental information gained by exploiting the dependencies that exist between a specific message bit and the incoming raw data bits processed by the decoder. Thus, in a loose sense, we may view the role of extrinsic information in turbo decoding as the "error signal" in a conventional closed-loop feedback system.

The concept of turbo codes was originally conceived by Berrou, Glavieux, and Thitimajshima in the context of channel codes, with the primary purpose of approaching the Shannon limit in a computationally efficient manner. Today, this concept is being applied not only in channel coding, but also in source coding, joint source-channel coding, channel equalization, synchronization, and MIMO wireless communications. For an important survey of these applications to turbo-information processing, the reader is referred to the special issue of the *Proceedings of the IEEE*, vol. 95, July 2007 [141].

1.3 MIMO WIRELESS COMMUNICATIONS

In a wireless environment, the transmitted signal reaches the intended receiver via a multiplicity of propagation paths; hence, the resulting components of the wireless channel output may end up adding in a destructive manner. Such a situation may result in serious degradation in the performance of the wireless communication system. This multipath phenomenon is commonly referred to as channel fading. To overcome the degrading effects of channel fading, it is common practice to use diversity. The basic idea of this technique is to provide the receiver with a set of independently faded replicas of the transmitted signal in the hope that at least one of them will have been received in a reasonably correct manner.

Diversity can be realized in a variety of ways under one of three basic headings:

1. Diversity on receive
2. Diversity on transmit
3. Diversity on both transmit and receive

In MIMO wireless communications, it is the third form of diversity that is employed. Specifically, the transmitter employs an array of antenna elements, and the receiver employs another array of antenna elements of its own. These two antenna arrays may embody different numbers of antenna elements.

The interesting properties of a MIMO wireless communication system are summarized as follows:

1. Under certain environmental conditions, fading is viewed not as a nuisance, but rather as a possible environmental source of performance improvement.
2. The combined use of space diversity at both the transmit and receive ends of the MIMO wireless link may provide the basis for an increase in channel capacity or spectral efficiency of the system.
3. Unlike the use of conventional techniques to increase channel capacity, in MIMO wireless communications the increase in channel capacity is achieved by increasing computational complexity while, at the same time, keeping the primary communication resources (i.e., total transmit power and channel bandwidth) constant.

These are remarkable properties.

Figure 1.3 shows the block diagram of a MIMO wireless link, where n_t is the number of transmit antennas and n_r is the number of receive antennas. Suppose now we make two assumptions:

1. The wireless link is modeled as a narrowband flat-fading channel.

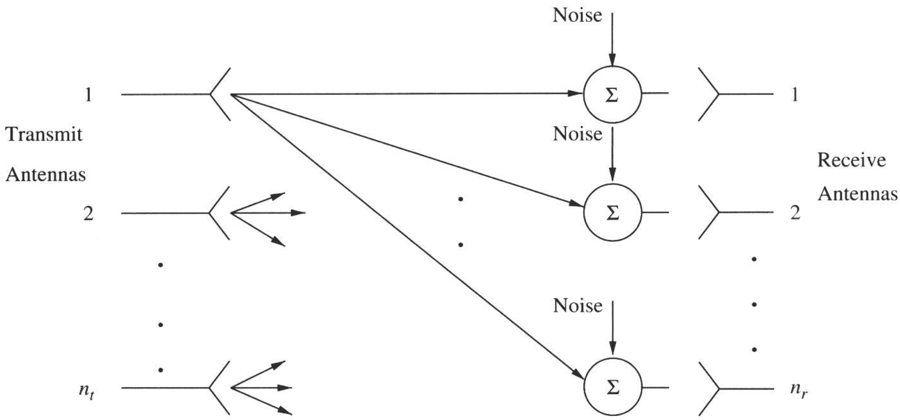

Figure 1.3 Schematic a of MIMO wireless link.

2. The number of transmit antennas and the number of receive antennas have a common value denoted by N.

Under these special conditions, we find that as N approaches infinity, the (ergodic) capacity of the MIMO channel grows asymptotically (at least) linearly with N, as shown by

$$\lim_{N\to\infty} \frac{C}{N} \geq \text{constant} \tag{1.1}$$

where C denotes the channel capacity. This asymptotic result teaches us that, by increasing the computational complexity of a MIMO wireless communication system through the use of multiple antennas at both the transmit and receive ends of a wireless link, we are able to increase the spectral efficiency of the link for more than is possible by conventional means (i.e., increasing the signal-to-noise ratio). Indeed, it is this important result that is responsible for the increasing interest in the deployment of MIMO wireless links.

1.4 ORGANIZATION OF THE BOOK

Two major motivations for MIMO wireless communication research exist. On the one hand, information theorists wish to understand the ultimate limits of bandwidth-efficient digital wireless communications system by exploiting the MIMO technology. They attempt to find techniques that attain Shannon's capacity limit. On the other hand, a communication engineer wishes to design techniques that are practically feasible and also to achieve a significant portion of the great capacity promised by information theory. The two motivations are certainly not mutually exclusive and are slowly converging to provide a more principled approach to MIMO wireless communication.

This book is concerned about both of these motivations. In particular, Chapter 2 presents the MIMO channel capacity limits and Chapter 3–6 describe unconstrained signaling techniques, exemplified by the BLAST architectures, whose aim is to increase the channel capacity by using standard channel codes.

Chapter 2 is devoted to the spectral efficiency of MIMO channels under various channel conditions. We provide the information theory concepts and capacity limits of MIMO channels over Rayleigh fast fading and quasi-static fading. In particular, we derive the MIMO channel capacity from the first principle assuming that the receiver has knowledge of the channel state. In this scenario, when the wireless communication environment is endowed with rich scattering, the information capacity of the wireless channel is roughly proportional to the number of transmit or receive antennas, whichever is smaller. That is to say, we have the potential to achieve a spectacular increase in spectral efficiency, with the channel capacity of the link being roughly doubled by doubling the number of antennas at both ends of the link.

In Chapter 3, we describe a family of MIMO wireless communication systems popularized as BLAST architectures. In particular, BLAST architectures use standard one-dimensional error-correction codes and low-complexity interference-cancellation schemes to construct and decode powerful two-dimensional space-time codes. These MIMO systems offer spectacular increases in spectral efficiency, provided that three conditions are met:

- The system operates in a rich scattering environment.
- Appropriate coding structures are used.
- Error-free decisions are available in the interference-cancellation schemes, which, in turn, assumes the combined use of arbitrarily long (and therefore powerful) error-correction codes and perfect decoding.

The material presented herein focuses on three specific implementations of BLAST, depending on the type of coding employed:

- Diagonally layered space-time architecture known as diagonal BLAST or simply D-BLAST, which provides the standard framework for MIMO wireless communications;
- A simplified version of BLAST known as vertical BLAST or V-BLAST, which is the first practical implementation of MIMO wireless communications demonstrating a spectral efficiency as high as 40 bits/s/Hz in real time with significant reduction in system complexity;
- Stratified D-BLAST.

In Chapter 4, we review the framework of the turbo principle and its applications in space-time channels. In particular, we describe serial and parallel concatenated turbo codes and their iterative decoders, soft-in/soft-out modules, which are exemplified by the BCJR algorithm that performs maximum *a posteriori* estimation on a bit-by-bit basis in the decoding of turbo codes and their lower complexity and numerically less sensitive approximations, the extraction of extrinsic information. The turbo decoding principle features prominantly in Chapters 5 and 6.

In Chapter 5, we describe the Turbo-BLAST architecture which is suitable for for high-throughput wireless communications, exploiting the following basic ideas:

- A random layered space-time coding scheme, which is based on the use of independent block coding and space-time interleaving.
- A turbo-like receiver, also known as an iterative interference cancellation and decoding receiver.

In particular, we show how the turbo principles applied to BLAST architectures can significantly improve overall system performance.

In Chapter 6, we discuss another important class of MIMO architecture, known as turbo-MIMO systems, where the layer code construction is based on space-time bit-interleaved coded modulation (ST-BICM). Turbo-MIMO is a highly effective system when used in conjunction with receivers employing iterative detection and decoding. This chapter also presents three recent low-complexity detection schemes:

- Minimum mean-squared based soft-interference cancellation;
- Low complexity implementations of sphere detections;
- Iterative tree search detection;
- List-sphere detection.

The chapter includes the analysis of flat and frequency-selective fading channels for Turbo-MIMO.

2

MIMO CHANNEL CAPACITY

2.1 INTRODUCTION

The major concern in wireless communications research is to provide techniques that use the frequency spectrum, which is a scarce resource, efficiently. The basic information theory result reported in a pioneering paper [45] by Foschini and Gans showed that great spectral efficiency can be achieved through the use of multiple-input, multiple-output (MIMO) wireless systems. The major conclusion of their work is that the capacity of a multiple-transmit, multiple-receive system far exceeds that of a single-antenna system. In particular, in a Rayleigh flat-fading environment, a MIMO link has an asymptotic capacity that increases linearly with the number of transmit and receive antennas, provided that the complex valued propagation coefficients between all pairs of transmit and receive antennas are statistically independent and known to the receiver.

This chapter presents a detailed discussion of the channel capacity limits of different MIMO wireless channels systems. In particular, we derive the MIMO channel capacity from first principles, assuming that the receiver has knowledge of the channel state. In this scenario, when the wireless communication environment is endowed with rich scattering, the information capacity of the wireless channel is roughly proportional to the number of transmit or receive antennas, whichever is less. That is to say, we have a spectacular increase in spectral efficiency, with the channel capacity of the link being roughly doubled by doubling the number of antennas at both ends of the link.

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