Ibrahim A. Bello
Basel Halak

Algorithms and VLSI Implementations of MIMO Detection

Springer

Algorithms and VLSI Implementations of MIMO Detection

Ibrahim A. Bello • Basel Halak

Algorithms and VLSI Implementations of MIMO Detection

Springer

Ibrahim A. Bello
Dyson Technology Ltd.,
Bristol, UK

Basel Halak
University of Southampton
Southampton, UK

ISBN 978-3-031-04511-0 ISBN 978-3-031-04512-7 (eBook)
https://doi.org/10.1007/978-3-031-04512-7

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

To our families and friends...

Preface

The use of multiple antennas at the transmitter and receiver of a wireless communication system, otherwise known as multiple-input multiple-output (MIMO), has been one of the most significant milestones in the field of wireless communications in the past few decades. MIMO offers several advantages to wireless communications systems, including increased diversity and an increased throughput using the same bandwidth as single-antenna systems. Presently, wireless communications standards supporting several megabits-per-second in throughput have been developed and are in use in many consumer products. However, despite these advantages, the complexity of the signal detection at the receiver in a MIMO system is exacerbated as a result of the multiple interferences at each receiver antenna. The maximum likelihood (ML) detector, which offers the optimal bit error rate performance, has a prohibitive complexity that scales exponentially with the number of antennas and is not suitable for hardware implementation.

Several algorithms have been proposed in the literature to implement MIMO signal detection with low complexity. These include linear detection algorithms, such as zero-forcing and minimum mean squared error, as well as non-linear detection schemes, such as lattice-reduction-based techniques and also tree search detection. The main objective of this book is to provide a broad overview of these algorithms while highlighting their VLSI implementation aspects. Given the importance of low power consumption in modern communications, we will pay special attention to the notable techniques proposed in the literature to achieve low-power and low-complexity hardware implementations of MIMO detection algorithms. Furthermore, we will provide hardware design examples and results, supplemented with several MATLAB code examples, which we hope will help the reader quickly gain an understanding and appreciation of this very interesting research topic.

Bristol, UK — Ibrahim A. Bello
Southampton, UK — Basel Halak
February 2022

Acknowledgements

We would like to thank colleagues and staff at the University of Southampton for their support towards the completion of this book. In particular, we would like to acknowledge the fruitful discussions and collaborations we had with Prof Mark Zwolinski and Dr Mohammed El-Hajjar on several publications in this research area. We would also like to acknowledge the Petroleum Technology Development Fund (PTDF), Nigeria, for their financial support. Finally, we would like to thank the Springer Nature editorial team for their guidance throughout the publication process.

Contents

About the Authors

Ibrahim A. Bello obtained his bachelor's degree in electrical and electronics engineering from Abubakar Tafawa Balewa University, Nigeria, in 2006, MSc (with distinction) in microelectronic systems and telecommunications from the University of Liverpool in 2010, and PhD in electronics and electrical engineering from the University of Southampton in 2017. In 2019, he joined the Department of Engineering Science at the University of Oxford, where he conducted research on an EPSRC-funded project investigating smart energy systems. Dr Bello was previously at Ahmadu Bello University, lecturing on various courses in software development and digital systems design. In 2022, he joined Dyson Technology Ltd. as a senior embedded software engineer. He retains a keen research interest in wireless communications, hardware implementation of digital signal processing algorithms, and the Internet of Things.

Basel Halak is an associate professor and the director of the embedded systems and IoT program at the University of Southampton. Dr Halak is a visiting scholar at the Technical University of Kaiserslautern, an industrial fellow of the Royal Academy of Engineering, a senior fellow of the Higher Education Academy, and a national teaching fellow of Advance HE UK. He has written more than 100 refereed conference and journal papers and authored 4 books. His research expertise includes hardware security, digital design, and embedded systems. Dr Halak serves on several technical programme committees such as HOST, IEEE DATE, DAC, IVSW, ICCCA, ICCCS, MTV, and EWME. He is an associate editor of *IEEE Access* and an editor of the *IET Circuits, Devices and System* journal. He is also a member of the hardware security working group of the World Wide Web Consortium (W3C).

Acronyms

API	Application Programming Interface
ASM	Algorithmic State Machine
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CMOS	Complementary Metal Oxide Semiconductor
FPGA	Field Programmable Gate Array
FSM	Finite State Machine
Gbps	Gigabits per Second
HDL	Hardware Description Language
HLS	High Level Synthesis
IDE	Integrated Development Environment
LSB	Least Significant Bit
LTE	Long-Term Evolution
Mbps	Megabits per Second
MIMO	Multiple-Input Multiple-Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
MSB	Most Significant Bit
PED	Partial Euclidean Distance
QAM	Quadrature Amplitude Modulation
RTL	Register Transfer Level
SD	Sphere Decoder
SINR	Signal-to-Interference-Plus-Noise Ratio
SNR	Signal-to-Noise Ratio
STBC	Space Time Block Code
V-BLAST	Vertical-Bell Laboratories Layered Space-Time
VCD	Value Change Dump
VLSI	Very-Large-Scale Integration
ZF	Zero-Forcing

List of Figures

List of Tables

Chapter 1
Introduction

1.1 Chapter Overview

The chapter is organised as follows. In Sect. 1.2, MIMO technology is introduced. In Sect. 1.3, we will discuss the basic setup of a multiple-antenna wireless system. In Sect. 1.4, we will discuss MIMO detection generally and present an overview of prominent MIMO detection algorithms. In Sect. 1.5, we will present the design flow for the algorithm-to-hardware conversion, which will be used throughout the book. In Sect. 1.6, we highlight a number of design tradeoffs to be considered when implementing the MIMO detector in hardware. The overview of the book and scope of the work is presented in Sect. 1.7. Finally, the chapter is concluded in Sect. 1.8.

1.2 Introduction

One of the main bottlenecks of the capacity of a wireless communication system is the channel bandwidth. The relationship between the channel capacity and the bandwidth is captured in the famous Shannon–Hartley channel equation as follows [1]:

$$C = B\log_2\left(1 + \frac{S}{N}\right), \tag{1.1}$$

where C represents the channel capacity in bits per second, B denotes the bandwidth in Hertz, and $\frac{S}{N}$ is the signal-to-noise (SNR) ratio, which is a dimensionless ratio of the signal-to-noise power. It is clear that if the channel bandwidth can be increased, then the channel capacity, or the maximum data rate at which a wireless communication could occur at an arbitrarily low error rate, could be increased as well. Since bandwidth is both limited and expensive, there is a clear motivation to

I. A. Bello, B. Halak, *Algorithms and VLSI Implementations of MIMO Detection*,
https://doi.org/10.1007/978-3-031-04512-7_1