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VLSI Circuits for MIMO Preprocessing

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Abstract

Multiple-input multiple-output (MIMO) technology employs multiple antennas at both ends of the wireless link and constitutes one of today's most promising approaches to increase the throughput by exploiting the limited radio frequency resources in an unprecedentedly efficient way – without additional transmit power expenditure or increase in channel bandwidth. Combined with broadband modulation schemes such as orthogonal frequency-division multiplexing (OFDM), MIMO provides a powerful and attractive solution for high-throughput wireless home, office, and metropolitan area networks.

Unfortunately, the adoption of these modern wireless communication technologies significantly increases the signal processing complexity – most prominently at the receiver. Therefore, the practical realization of MIMO signal processing algorithms ultimately calls for dedicated very large scale integration (VLSI) circuits. However, even state-of-the-art process technologies for integrated circuits do not allow for implementation of mathematically optimal algorithms. Hence, we are urged to resort to suboptimal reduced-complexity solutions, which are still specifically optimized for their target application.

This work focuses on VLSI circuits for MIMO preprocessing, with a strong emphasis on sorted QR decomposition (SQRD). The thesis introduces several preprocessing algorithms and describes the quality metrics having been employed for subsequent algorithm optimizations for hardware implementation. Moreover, it shows the exploration of the fixed-point VLSI design space for various SQRD architectures including the assessment of finite-precision effects. The corresponding VLSI implementation results in UMC 0.18 µm 1P/6M CMOS technology provide reference figures for throughput and silicon complexity.

Zusammenfassung

Multiple-input multiple-output (MIMO) Technologie benutzt in drahtlosen Kommunikationssystemen sowohl sende- als auch empfangsseitig mehrere Antennen und stellt eine der vielversprechendsten Ansätze zur Steigerung des Datendurchsatzes auf enorm effiziente Art und Weise dar – und dies ohne Erhöhung der Sendeleistung oder Steigerung der Kanalbandbreite. In Kombination mit Breitband-Modulationsarten wie orthogonal frequency-division multiplexing (OFDM) bietet MIMO eine attraktive Lösung für drahtlose Hochleistungsnetzwerke im Heim- und Bürobereich, sowie in urbanen Umgebungen an.

Leider bringt der Einsatz dieser modernen Kommunikationstechnologien eine signifikante Komplexitätssteigerung der Signalverarbeitung mit sich – vornehmlich im Empfänger. Deshalb werden für die praktische Umsetzung der MIMO Signalverarbeitungsalgorithmen dedizierte integrierte Schaltungen benötigt. Doch auch die modernsten Prozesstechnologien erlauben es nicht, mathematisch optimale Algorithmen den Anforderungen entsprechend umzusetzen. So ist man gezwungen, sich auf suboptimale Lösungen zu fokussieren, welche aber trotzdem hinsichtlich ihres Einsatzbereichs gezielt optimiert werden.

Diese Arbeit behandelt integrierte Schaltungen für MIMO Signalvorverarbeitung, mit Fokus auf sortierter QR Zerlegung. Mehrere Algorithmen werden eingeführt und die Qualitätsmetriken beschrieben, welche für die nachfolgenden Optimierungen hinsichtlich der Schaltungsintegration verwendet wurden. Zusätzlich wird die Entwurfsraumexploration für verschiedene Architekturen aufgezeigt, mit Einbezug von Quantisierungseffekten aufgrund reduzierter numerischer Präzision. Die daraus entstandenen integrierten Schaltungen stellen Referenzgrössen für Durchsatz und Integrationskomplexität dar.

Contents

Chapter 1

Introduction

The rapid evolution of wireless communication technologies, the worldwide efforts for standardization and interoperability, and the proliferation of corresponding affordable integrated circuits for mobile devices have made wireless communication so far a success story. During the last two decades, the opportunities of wireless communication not only established a multi-billion dollar market, which still exhibits ferocious growth potential, but have also led to a fast-paced technology penetration into virtually every electronic product. By using advanced process and manufacturing technologies, the development of highly integrated and cost-effective wireless communication chipsets became possible. The advances in circuit integration ultimately enabled the design of compact mobile electronic devices allowing for pervasive wireless connectivity. On the other hand, the formation of new standards for infrastructure networks prepared the grounds for ubiquitous mobile Internet access. While wireless local area networks (WLANs) seek to replace high-speed wired connections for home, office and public hot-spot environments, wireless metropolitan area networks (WMANs) focus on substitution of wired last-mile connections.

Today's latest mobile applications in conjunction with omni-present multimedia content and the growing number of wireless users keep up the demand for ever increasing wireless data rates. At the same time, users are asking for improved coverage, regardless of being at crowded places or remote locations. Unfortunately, the scarce radio frequency resources do not allow for meeting the insatiable throughput demands by simply allocating more channel bandwidth or by increasing transmit power. New concepts and key technologies need to be evolved in order to pave the way for satisfying the increasing demand for high-throughput wireless access solutions.

1.1 Key Technologies

New technologies for wireless communication have constantly been invented and evolved since the foundation of wireless data transmission through practical laboratory experiments in the 19th century by Heinrich R. Hertz and Nikola Tesla. In the following, two key technologies for present and future wireless communication are introduced and their basic operating principles are explained.

1.1.1 MIMO

In the late 1990s, it was discovered that wireless communication systems using multiple antennas at both transmitter and receiver gain significant advantages from multi-path propagation in a rich-scattering environment [1]. While conventional single-antenna communication systems, also known as single-input single-output (SISO), only rely on time and frequency as fundamental degrees of freedom[1], multi-antenna wireless communication technology, commonly referred to as multiple-input multiple-output (MIMO), additionally exploits the spatial dimension [2,3]. By making best use of this diversity in degrees of freedom, MIMO signaling techniques [4] for wireless communication allow for higher data rates, increase in range and coverage, and higher link reliability at the same overall transmit power expenditure and employed channel bandwidth. In other words, MIMO technology increases the spectral efficiency compared to conventional single-antenna systems by transmitting more data during the same time with similar expenses in bandwidth and transmit power. Thereby, the increase in channel capacity grows linearly with the minimum

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[1] For conventional SISO systems, coding can be considered as a virtual degree of freedom derived from time and frequency.

number of transmit and receive antennas – a fact that is reflected in throughput and spectral efficiency if properly exploited.

Principle of Operation

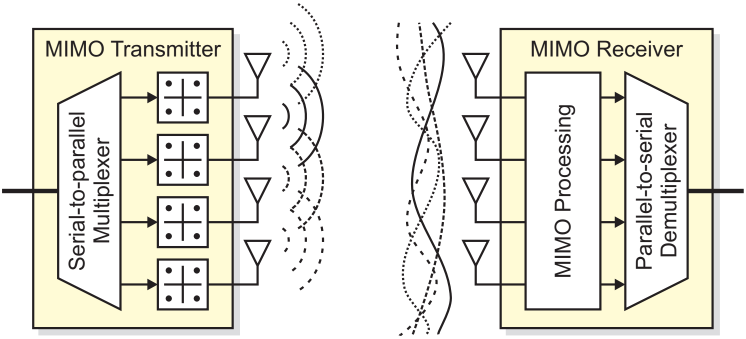

Figure 1.1: Operating principle of MIMO wireless communication.

As illustrated in Fig. 1.1, a high-rate data stream is split into several low-rate streams in the transmitter. After modulation, the individual low-rate streams are transmitted from multiple antennas simultaneously and in the same frequency band. At the receiver, a unique superposition of all transmitted streams is acquired from every receive antenna. After demodulation, the MIMO processing block performs the separation of the individual data streams from the superimposed receive signals. At the end, the recovered low-rate streams are recombined such as to form again a high-rate data stream.

For MIMO wireless communication systems, it is crucial that all antennas are decorrelated amongst each other, and hence, experience independent fading. On one hand, this can be achieved by ensuring to have a distance of at least half a wavelength between every antenna, or by applying antennas with different polarizations. On the other hand, one must seek to attain channel conditions that allow for multi-path propagation such that the signals picked up at the individual receive antennas exhibit unique spatial signatures and therefore render the separation of the individual data streams in the receiver possible.

Only the fruition of these important requirements allow MIMO technology to actually perform in practice and to deliver on its promises.

Gains of MIMO Technology

The prospects of MIMO technology reside in the variety of gains amenable for exploitation by applying appropriate signaling schemes and corresponding communication system architectures. In the following, a summary about the advantages of MIMO is given.

Array gain refers to the gain achieved by using multiple antennas in order to coherently combine individual receive signals from different antennas at the receiver. Array gain essentially improves the average receive signal-to-noise ratio (SNR) and mainly allows to extend the range of operation of communication devices. This technique can be applied to every device individually, irrespective of the number of antennas of the counterpart.

Diversity gain constitutes the gain achieved by taking advantage of multi-path propagation in order to mitigate fading. In other words, diversity gain accounts for the effects of spatio-temporal fluctuations of the receive signal by exploiting the diversity of signal propagation across multiple, independently fading paths. Effectively, diversity gain increases the stability of the receive signal and therefore improves link reliability and quality of service (QoS). For MIMO communication, diversity gain may be exploited in the spatial (antenna), temporal (time), or spectral (frequency) dimensions and can also be addressed jointly by employing appropriate space-time (ST) coding techniques [5].

Spatial multiplexing gain represents the gain that allows for a linear increase in data rate by transmitting multiple independent data streams concurrently and in the same frequency band. The linear increase is defined by the amount of parallel transmitted data streams and thereby limited by the minimum number of transmit and receive antennas.

For example, a simple scheme that primarily exploits diversity gain is antenna selection. This multi-antenna scheme chooses only the

Chapter 2

Algorithms for MIMO Preprocessing

The first part of this chapter introduces the system model and the simulation methodology combined with the quality metric for performance assessment. The second part provides an overview of several MIMO signal processing algorithms, with emphasis on MIMO preprocessing.

2.1 System Model

Applying OFDM as broadband modulation technique has an advantage which is of particular importance for the system model: The fundamental property of OFDM – to decompose a wide-band frequency-selective channel into several, closely spaced, orthogonal subcarriers experiencing frequency-flat fading – allows for breaking up the broadband system into a set of independent narrow-band MIMO systems. Each individual narrow-band MIMO system can then be modeled as depicted in Fig. 2.1.

Throughout this thesis, we consider a MIMO system with M_T transmit and M_R receive antennas, and we further assume $M_R \geqslant M_T$. The $M_R \times M_T$-dimensional complex-valued matrix $\mathbf{H}$ represents the

Chapter 3

Optimizations for Implementation

This chapter covers the different aspects of algorithm optimization for hardware implementation. It elaborates on fixed- and floating-point number formats and associated dynamic range aspects, and introduces building blocks for implementing Givens rotation in hardware. For each MIMO preprocessing algorithm, the specific optimizations are discussed and the associated impact on BER performance is shown.

3.1 Algorithm Implementation Aspects

The efficient implementation of algorithms in hardware requires to consider various algorithmic and implementation-specific aspects. In the following, the most important aspects for algorithm optimization with respect to subsequent implementation are discussed.

3.1.1 Number Format and Dynamic Range

The appropriate choice of the number format constitutes a very important aspect for algorithm implementation in hardware. The number representation not only determines the numeric precision and the dynamic range for the input values and the associated data path,

Chapter 4

VLSI Architectures

The previous chapter discussed the optimization efforts for algorithm implementation in fixed-point number format and showed the corresponding numeric precision requirements and fixed-point quantization settings. On the basis of these findings, this chapter continues the systematic exploration of the design space on architectural level to derive suitable VLSI architectures for MIMO preprocessing algorithms.

4.1 Architectural Aspects

The implementation of a given algorithm or functionality in hardware can be realized using different VLSI architectures and different target technologies. The decision for implementing a specific architecture is dependent on various constraints and limitations such as maximum circuit size, minimum throughput requirements, real-time constraints, power budget, availability of macro cells or intellectual property (IP) modules in the target technology, processing or memory resources to be shared, maximum number of I/O pads, interface protocols, or flexibility of functional adaptations for design re-use. In order to find the most appropriate hardware solution for a specific application, architectural transformations [51] are the key to explore the prospects and drawbacks for each architectural alternative. In the end, it is crucial to choose a VLSI architecture, which is in line with both,

Chapter 5

Real-Time Testbed

This chapter outlines the hardware components and the system architecture of a real-time 4×4 MIMO-OFDM testbed developed during a research project called multiple-access space-time coding testbed (MASCOT). The partitioning of the MIMO physical layer (PHY) on the hardware is shown and a brief overview of the medium access control (MAC) layer is given. The extensions for QRD-based MIMO preprocessing are described including the preprocessing architecture and the deployment of the MMSE-SQRD ASIC to the testbed.

5.1 Prototyping Platform

In the following, the individual hardware components of the modular prototyping platform for the real-time 4×4 MIMO-OFDM testbed are described. The entire testbed was initially built on three different boards, called VAMP, BAT, and WING, before being extended with an additional board carrying two MMSE-SQRD ASICs.

5.1.1 VAMP Board

The main component and the largest board of the prototyping platform is called Virtex-II Pro astonishing multi-purpose (VAMP) board and is depicted in Fig. 5.1. It has been developed during a master's

Chapter 6

Summary and Conclusions

Spurred by the rapid growth of the Internet, the evolution of new wireless communication technologies, and the global efforts for standardization, mobile communication has become a worldwide success story. The corresponding development and proliferation of affordable integrated circuits for wireless communication prepared the grounds for today's thriving markets in mobile information exchange. With respect to mobile networking, MIMO and OFDM have established themselves as key technologies for next-generation wireless broadband communications. This thesis has focused on the VLSI implementation of selected MIMO preprocessing algorithms, which are mandatory for wireless communication systems comprised of more advanced detection schemes, such as SIC detection or tree-search-based variants achieving ML or near-ML error rate performance. Although MIMO preprocessing represents only a small spot in the vast design space for wireless communication, this thesis intends to provide a few answers concerning the practical implementation of future broadband communication systems based on MIMO and OFDM.

Appendix A

Supplemental Information

A.1 Building Blocks

A.1.1 Linear & SIC Detection

Linear and SIC detection based on direct matrix inversion (DMI) for multiple data streams are illustrated as conceptual block diagrams (which may serve as a basis for implementation) in Fig. A.1 on the left and right side, respectively. While the linear variant only employs a combined equalization and slicing stage, the SIC variant additionally requires a back-substitution and cancellation stage. The input signals for the MIMO detection blocks depicted in Fig. A.1 are estimator matrix $\mathbf{G}$, channel matrix $\mathbf{H}$, and received symbol vector $\mathbf{y}$. The estimated receive symbol vector after slicing is represented by $\hat{\mathbf{s}}$ and constitutes the detection result before demapping to binary-valued data. In general, the block-internal iterator is represented by variable j, which is used for computing a single entry $\hat{s}_i$ with $i = 1, 2, \ldots, M_T$ of symbol vector estimate $\hat{\mathbf{s}}$.

As already indicated by the block diagrams in Fig. A.1, DMI-based linear MIMO detection allows for a parallel implementation of equalization and slicing for individual data streams. On the other hand,

Appendix B

Notation and Acronyms

Symbols

M_T	number of transmit antennas
M_R	number of receive antennas
$\mathbf{H}$	$M_R \times M_T$-dimensional MIMO channel matrix
$\bar{\mathbf{H}}$	$(M_R{+}M_T) \times M_T$-dimensional augmented MIMO channel matrix
$\mathbf{Q}$	$M_R \times M_T$-dimensional unitary matrix
$\mathbf{R}$	$M_T \times M_T$-dimensional upper-right triangular matrix
$\mathbf{P}, \mathbf{M}$	$M_T \times M_T$-dimensional permutation matrix
$\mathbf{P}^{1/2}$	$M_T \times M_T$-dimensional square-root matrix
$\mathbf{U}$	$M_R \times M_T$-dimensional real-valued matrix
$\mathbf{W}$	matrix containing weight vectors
$\mathbf{Z}$	composite matrix, also called pre-array
$\mathbf{I}_n$	n-dimensional identity matrix
$\mathbf{s}$	M_T-dimensional transmitted MIMO symbol vector
$\hat{\mathbf{s}}$	estimate of the transmitted MIMO symbol vector
$\mathbf{n}$	M_R-dimensional additive white Gaussian noise vector
$\mathbf{y}$	M_R-dimensional received MIMO symbol vector
$\hat{\mathbf{y}}$	received MIMO symbol vector $\mathbf{y}$ pre-multiplied with $\mathbf{Q}^H$

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