Eckhard Ohlmer

Channel-Adaptive Multiple-Input Multiple-Output Transmission: A Receiver-Centric View

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Channel-Adaptive Multiple-Input Multiple-Output Transmission: A Receiver-Centric View

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Abstract

Channel-adaptive multi-antenna transmission is among the most promising concepts to cope with the ever increasing demand of multimedia applications for reliable, high-rate, low-latency wireless data connections. Practical constraints, such as **spatially correlated propagation paths**, decreasing the performance of low-complexity receivers on the one hand, and **imperfect channel knowledge**, causing erroneous adaptation and a reduction of the receiver performance on the other hand, render the application of this concept challenging. This dissertation focusses on the receiver analysis and the rate adaptation design subject to both practical constraints.

The first part of this work encompasses a **comparative analysis of four receiver types** with regard to their respective data rates in spatially correlated channels and under perfect channel knowledge.

Two parallel receivers and two successive cancelation-detection receivers, each characterized by a different receiver complexity and latency, are investigated. Symbol-level mutual information expressions for discrete and Gaussian signal alphabets as well as bit-level mutual information expressions are derived for each receiver. Analytical approximations and numerical evaluations support the assessment of the receiver characteristics in spatially correlated channels.

Transmitter-side linear precoding techniques complement the receiver analysis. A study of codebook based precoding techniques is followed by a study of existing mutual information maximizing precoding approaches for discrete signal alphabets. These are extended for application with parallel receivers in point-to-point and point-to-multi-point transmission setups.

The second part of this work is devoted to the problem of **rate adaptation** for a low-complexity parallel and a successive cancelation-detection receiver **impaired by imperfect channel state information** during adaptation and during detection.

First, a statistical model of outdated and noisy channel state information is derived in order to study its impact on the detection performance. Fundamental mechanisms are exposed by introducing appropriate approximations. Following, the work focusses on rate adaptation for a future transmission. The rate is adapted based on outdated and noisy channel state information. Likewise, the future transmission is impaired by imperfect channel knowledge.

An adaptation concept for multi-antenna transmission is presented which exploits an approximate statistical characterization of the channel quality. The concept can be successfully applied in order to trade-off data rate and outage probability. One of the main results is that the error propagation of the sequential interference cancelation receiver can be carefully adjusted in order to maintain its data rate gain as compared to the parallel receiver - even under imperfect channel knowledge.

Finally, an extension of the proposed adaptation concept to multi-carrier transmission and ARQ techniques is presented.

Zusammenfassung

Die kanaladaptive Mehrantennenübertragung stellt eines der vielversprechendsten Konzepte dar, um den rapide steigenden Bedarf von Multimediaapplikationen an hochratigen und verlässlichen Datenverbindungen mit geringer Latenz zu decken. Praktische Randbedingungen, wie **räumlich korrelierte Ausbreitungspfade** und die damit verbundenen Leistungseinbußen niedrig-komplexer Empfänger auf der einen Seite, sowie die **imperfekte Kenntnis des Mobilfunkkanals** und die damit verbundene senderseitige Fehladaption auf der anderen Seite, stehen diesem Ziel jedoch diametral entgegen. Beide Themenkomplexe bilden den Schwerpunkt dieser Dissertation.

Den ersten Teil der Arbeit bildet eine **vergleichende Analyse vier prinzipieller Empfängertypen** bezüglich der jeweils erreichbaren Datenrate in räumlich korrelierten Kanälen. Dabei wird perfekte Kanalkenntnis vorausgesetzt.
Es werden zwei parallele Empfänger und zwei sequentielle Interferenzreduktionsempfänger mit jeweils unterschiedlicher Komplexität und Detektionslatenz untersucht. Ratenausdrücke auf Symbolebene mit diskreter und Gauß'scher Modulation sowie auf Bitebene werden abgeleitet. Die Untersuchung und Bewertung des Empfängerverhaltens unter räumlicher Korrelation stützt sich sowohl auf analytische Approximationen als auch auf numerische Auswertungen.
Nachfolgend werden senderseitige lineare Vorkodierungstechniken in die Empfängeranalyse einbezogen. Neben Codebuch-basierten Verfahren werden auch existierende Ansätze Datenraten-maximierender Vorkodierungsverfahren für diskrete Symbolalphabete untersucht und auf parallele Empfänger in Punkt-zu-Punkt und Punkt-zu-Mehrpunkt Übertragungsszenarien erweitert.

Im zweiten Teil der Arbeit wird die **Adaption der Übertragungsrate** für einen parallelen Empfänger und einen sequentiellen Empfänger **unter imperfekter Kanalkenntnis** während der Adaption und während des Datenempfangs untersucht.
Basierend auf einem statistischen Modell veralteter und verrauschter Kanalkenntnis wird zunächst deren Einfluss auf die Detektion analysiert. Approximationen dienen der einfachen Darstellung wesentlicher Mechanismen. Darauf aufbauend beschäftigt sich die Arbeit mit Ratenadaption für eine zukünftige Übertragung. Dabei basiert die Ratenadaption auf veralteter und verrauschter Kanalkenntnis. Die zukünftige Übertragung ist gleichermaßen durch imperfekte Kanalkenntnis gestört.
Für die Mehrantennenübertragung wird ein Konzept vorgestellt, welches auf einer approximativen statistischen Beschreibung der Kanalqualität beruht. Das Konzept erlaubt, die Ausfallwahrscheinlichkeit und die Datenrate kontrolliert zu steuern. Als wesentliches Ergebnis kann die Fehlerfortpflanzung des sequentiellen Interferenzreduktionsempfängers kontrolliert und dessen Gewinn gegenüber dem parallelen Empfänger auch unter imperfekter Kanalkenntnis erhalten werden.
Abschließend wird gezeigt, wie das vorgestellte Adaptionskonzept auf Mehrträgerübertragungsverfahren und ARQ-Verfahren erweitert werden kann.

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Contents

Chapter 1

Introduction

1.1 Motivation

The mobile communications landscape has been subject to changes in user demand and service-architecture through the last decades, driven by advances in the semiconductor industry, in display and battery design, and in signal processing, to name only a few. Most notably, the once dominating share of traditional, low-rate voice telephony traffic is in constant decline and will account for only 1.5 % of the over-all mobile traffic in 2015 [Cis11]. High-performance, yet affordable mobile devices such as smart phones, laptops and e-readers have gained a dominant market position by now. These multimedia application capable devices, featuring high resolution displays and large memory, turned out to be mobile traffic multipliers. High-rate video applications are becoming the largest mobile traffic source with a projected share of over 60 % in 2015 [Cis11]. Interactivity on top of the video content adds stringent latency requirements which altogether poses a formidable challenge to wireless system designers.

In principle, data rates may be increased by improving the signal quality, e.g., through denser networks, increased transmit power or a higher quality of analogue components, or by increasing the number of communication channels, e.g., by adding frequency resources or multiple antennas. Naturally, frequency resources for coverage oriented mobile communications, currently ranging from 450 MHz (global system for mobile communications (GSM) [3GP11b]) up to almost 6 GHz (wireless local area networks [IEE09]) are limited and, therefore, expensive.

Not surprisingly, multiple antenna transmission, boosting data rates by transmitting multiple data streams in parallel, has been in the focus of a vast number of research activities during the past 15 years. Numerous advances, reaching from fundamental information theoretic results over signal processing through to proof-of-concept activities, render the multiple antenna concept ready for practical application. Upcoming cellular systems standards such as 3GPP LTE-Advanced [3GP11a] and mobile WiMAX [Ahm11] already allow for up to eight antennas at either side of the communication link.

However, the benefits of multiple antenna systems come at the cost of both an increased hardware complexity as well as an increased signal processing complexity, depending on the particular transmitter and receiver algorithms.

The performance versus computational resource, implementation and debugging effort, and energy consumption trade-off raises the question **about the data rate gain which can be harvested by investing in a more complex receiver type.**

Another important design aspect arises from the confined space which is available for integrating multiple antennas into a small mobile device. Closely spaced antennas cause the wireless channels, connecting different transmit-receive antenna pairs, to be correlated. In particular, low complexity receiver algorithms are known to be susceptible to spatial correlation.
The previous question readily extends to **what is the impact of spatial correlation on the data rate considering different transmitter-receiver algorithms?**

The attribute *mobile* to communications already suggests that the wireless channel quality typically changes in the course of a transmission, e.g., as users or reflecting objects move. Adapting the transmission parameters accordingly is key to an efficient use of scarce spectral resources but is also key to reliable communications. Different applications are characterized by different requirements regarding data rate, latency, and reliability which need to be traded-off.
In many relevant situations, the channel changes sufficiently slow, allowing to adapt the transmission to the instantaneous channel conditions rather than to the average statistical channel properties. Therefore, current and upcoming wireless standards include fast receiver-transmitter feedback loops which establish partial information about the channel conditions at the transmitter, subject to a few milliseconds delay only.
Nevertheless, adaptation parameters have to be computed based on information which is uncertain to some extent. Adapting, for instance, the data rate overly conservative guarantees reliable communications but entails a data rate loss, hence rendering the transmission inefficient. Adapting the data rate too optimistic entails an opposing effect and may cause high transmission latencies due to required retransmissions. Adaptation becomes particularly challenging for multi-antenna transceivers, depending on the transmitter and receiver algorithms of choice.
The question arises about **how to adapt the transmission** and **what is the performance of different receiver types if adaptation is possible but based on uncertain information?**

1.2 Outline and Contribution

The central theme of this thesis can be traced back to algorithmic works on link adaptation for point-to-point, 3GPP-LTE MIMO-OFDM systems [OF09, OF10]. These works soon revealed the need for modeling and analyzing channel-adaptive multi-antenna transmission using information theoretic tools as a prerequisite to designing adaptation algorithms. The information theoretic receiver analysis of channel-adaptive multi-antenna systems is, therefore, in the focus of this thesis. In addition, field trial experiments [OHB+10], designed and conducted in the course of this work, motivated to investigate the impact of spatial correlation on the receiver performance in greater detail.

This thesis comprises two main parts. Mutual information based models and comparisons of different receiver types, given perfect adaptation of the transmission parameters, are captured in Chapters 3 and 4. Model and impact of channel uncertainty and related adaptation concepts are developed in Chapter 5. More specifically, the thesis is structured as follows:

Chapter 2 summarizes background information. The concept of mutual information and its operational meaning are introduced. Multi-antenna channel models, channel capacity and transmission concepts as well as the impact of spatial correlation are reviewed. The chapter is concluded with the system model for use in the remainder of this work.

Chapter 3 focusses on a mutual information based multi-antenna receiver comparison. Expressions for the achievable rate of different receiver types with Gaussian and discrete channel input signal alphabets are derived. Two principle receiver types are distinguished: parallel detection and successive cancelation-detection receivers. A low and a high complexity variant of each receiver type is modeled and receiver equivalences are outlined. Several approximations provide analytical insight into the mechanisms behind the receiver performance in presence of spatially correlated channels. The chapter concludes with the model and the additional impact of binary coding which is assessed from a mismatched receiver perspective.

Chapter 4 extends the analysis in Chapter 3 towards the receiver performance with linear precoding at the transmitter. Fundamental mechanisms when using precoding are discussed. A receiver comparison using code book based precoding is presented, followed by data rate maximizing optimal precoding for discrete signal alphabets. This thesis adds to the state of the art by extending recent results for optimal precoding to parallel receivers. An interesting application of these results to point-to-multi-point transmission systems is presented.

Chapter 5 addresses the model and impact of channel uncertainty for the low complexity variants of parallel and successive cancelation detection receivers. The first part models and analyzes the impact of imperfect channel state information during detection and discusses the consequences of spatial correlation and receiver mismatch in that regard. The second part develops a rate adaptation concept with regard to the model, developed in the first part. This concept allows to trade-off data rate and outage probability. By using this concept it is shown that successive cancelation-detection receivers can provide significant performance gains, even under channel uncertainty. The second part concludes with an extension of the adaptation concept to parallel and independent channels, e.g., distributed subcarriers in a broadband OFDM system. The third part discusses the combination of the adaptation concept with a retransmission protocol.

Chapter 6 summarizes key results and outlines future research directions.

Numerous authors have added to the theory of single-user, point-to-point multi-antenna transmission. This thesis contributes a comparative view on different receiver types from different perspectives which can be rarely found in the literature. By far, this work cannot be comprehensive. Main limitations include the restriction to narrow-band, point-to-point, Gaussian channels, the restriction of numerical results to small antenna numbers, and the restriction to an information theoretic treatment.

As a prerequisite, the reader is assumed to be familiar with the concept of mutual information and achievable rates, the spatial multiplexing concept, basic channel modeling, basic linear algebra and stochastic processes.