Smart Antennas in Wireless Networks: 
System Issues and Performance Limits

Rickard Stridh

TRITA−S3−SB−0301
ISSN 1103-8039
ISRN KTH/SB/R - - 03/01 - - SE

Signal Processing
Department of Signals, Sensors and Systems
Royal Institute of Technology (KTH)
Stockholm, Sweden, 2003

Submitted to the School of Electrical Engineering, Royal Institute of Technology, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
Abstract

This work deals with performance limits when using smart antennas in future wireless systems. The current evolution in the field of wireless communication implicates a substantially increased demand on transport capacity. Smart antennas is one very powerful means to fulfill these demands. In this work the use of smart antennas, deployed at either the access point or both the access point and the mobile terminal is investigated.

In order to find out how the evolution within wireless communication will continue during the ten years to come, a scenario analysis is performed where driving forces are identified and scenarios are created.

The system aspects of uplink and downlink communications utilizing smart antenna algorithms are investigated. For the uplink case, the impact of different smart antenna algorithms on a packet switched radio interface is investigated. In the downlink case, the use of joint optimal beamforming and power control is examined and compared to suboptimal downlink algorithms. Further, an algorithm for admission control is introduced and evaluated and the issue of optimal access point assignment is assessed.

The extension to use smart antennas with both multiple transmitters and multiple receivers, i.e dual arrays, can provide high link capacity in future wireless systems. An analysis of indoor environment channel measurements in the 5.8 GHz band is performed and the possible increase in link capacity is examined. It is found that in the measured indoor environment, the scattering is sufficiently rich to provide substantial link capacity increase and that moderate intra-antenna-element distances is enough to give this capacity increase.

It is concluded that smart antennas promise substantial capacity increase and remains a strong enabling technology for future systems for wireless communication.
Acknowledgments

Many people have contributed to my research work during the last five years. First and foremost I want to thank my supervisor Professor Björn Ottersten for introducing me to the research area and for his guidance through the years. His neverending enthusiasm for research and vast knowledge in the research area has been a great inspiration. I also want to thank Dr. Stefan Parkvall, who provided the contact with KTH and Björn in the first place. Thanks to all current and former colleagues at the Signal Processing Group for fruitful discussions concerning any topic and for providing a great research environment. I am especially thankful to my co-authors Dr. Mats Bengtsson and Tekn.Lic. Kai Yu. Thanks to Karin Demin for making the administration work at all times.

The cooperation and networking in the Personal Computing and Communications program (PCC) has been a great inspiration. Especially I want to thank The Fourth Generation Wireless Group (4GW) headed by Professor Jens Zander and all PCC friends who have given me wider knowledge and a great research network. I want to acknowledge the financial support from the Swedish Foundation for Strategic Research (SSF) through the PCC program.

I want to thank Dr. Peter Karlsson and Dr. Christian Bergljung, Telia Research AB in Malmö, for giving me the opportunity to work with their extensive channel measurement data.

My friends and family have been an important support for me. I am most grateful to my parents Carin and Lars-Åke for all encouragements and support and to my brother Martin for all discussions through the years. Last and certainly most, thanks to my wife Anna for your love and support and for always being there.

Rickard Stridh
Stockholm, January 2003
Contents

1 Introduction 1
  1.1 Background ................................. 1
  1.2 Scope ...................................... 2
  1.3 Methodology ................................. 3
  1.4 Highlights .................................. 4
  1.5 Outline and Contribution .................. 5

2 Future Generation Wireless Communication 9
  2.1 Introduction ................................. 9
  2.2 Personal Computing and Communication ...... 10
  2.3 4th Generation Wireless Infrastructures - 4GW ... 10
  2.4 Research Approach .......................... 11
  2.5 Identified Trends ............................ 12
  2.6 Scenario Summary ........................... 13
    2.6.1 Anything Goes! ............................ 13
    2.6.2 Big Brother Protects you from Little Brothers .... 14
    2.6.3 Pocket Computing .......................... 14
    2.6.4 Scenarios in Trend Space .................. 14
  2.7 Working Assumptions ....................... 15
  2.8 Some Key Research Issues in 4GW .......... 18
  2.9 Summary .................................... 19

3 Smart Antennas 21
  3.1 Introduction ............................... 21
  3.2 The Wireless Channel ....................... 24
    3.2.1 Spatial Channel Models .................... 24
    3.2.2 Multiple-Input-Multiple-Output Channels .... 25
  3.3 Receiver and Transmitter Strategies ........ 26
## Contents

3.3.1 Sensor Array Processing .......................... 27
3.3.2 Beamforming ................................. 27
3.4 System Aspects ...................................... 29
  3.4.1 Uplink vs. Downlink .......................... 30
  3.4.2 Packet Switching Aspects ....................... 31
3.5 Summary ............................................. 32

I Smart Antennas in Wireless Systems ........................ 33

4 Data Models ............................................ 35
  4.1 Introduction ........................................ 35
  4.2 Signal Model ....................................... 35
    4.2.1 Uplink Communication ......................... 36
    4.2.2 Downlink Communication ....................... 37
  4.3 Spatial Channel Models ................................ 38
    4.3.1 Scalar Channel Factors ....................... 38
    4.3.2 Local Scattering Channel Model ............... 39
  4.4 Receiver and Transmitter Strategies ................... 39
    4.4.1 Antenna Models ............................... 39
    4.4.2 Uplink Receiver Strategies .................. 41
    4.4.3 Downlink Transmitter Strategies .............. 42
  4.5 System Aspects ..................................... 42
    4.5.1 Traffic Models ............................... 42
    4.5.2 Cellular Model ............................... 42
    4.5.3 Systems Simulations Issues .................. 43
  4.4 Approximation for Gaussian Distributed Scattering ... 44
    4.4.1 Derivation of Covariance Matrix for a UCA with Gaussian Distributed Scattering .... 44

5 Uplink Beamforming with Packet Switching .................. 47
  5.1 Introduction ........................................ 47
  5.2 System and Analysis ................................ 48
    5.2.1 Traffic Model .................................. 48
    5.2.2 Channel and Receiver models .................. 48
    5.2.3 Beamforming ................................... 49
    5.2.4 Outage Calculations ............................ 51
    5.2.5 Throughput .................................... 52
    5.2.6 Simulations .................................... 52
  5.3 Results ............................................. 53
5.3.1 Theoretic Model and Idealized beamformers . . . . . . . 53
5.3.2 Combining Methods . . . . . . . . . . . . . . . . . . . . . 54
5.3.3 Latency and Delay Issues . . . . . . . . . . . . . . . . 55
5.4 Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . 56
5.A Derivation of Outage Probability for the Idealized Beam- 
former . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 58

6 Downlink Beamforming - a System View 61
6.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . 61
6.2 System Assumptions . . . . . . . . . . . . . . . . . . . . . . 62
6.2.1 System Model . . . . . . . . . . . . . . . . . . . . . . . 62
6.2.2 Signal Model . . . . . . . . . . . . . . . . . . . . . . . 64
6.3 Beamforming . . . . . . . . . . . . . . . . . . . . . . . . . . 65
6.3.1 Suboptimal Beamforming Methods . . . . . . . . . . 65
6.3.2 Power Control . . . . . . . . . . . . . . . . . . . . . . 67
6.3.3 Joint Optimal Beamforming and Power 
Control . . . . . . . . . . . . . . . . . . . . . . . . . 67
6.3.4 Joint Optimal Beamforming, Power Control and 
Access Point Assignment . . . . . . . . . . . . . . . . 68
6.4 Semidefinite Optimization . . . . . . . . . . . . . . . . . . 69
6.4.1 Introduction to Optimization over Semidefinite 
Convex Cones . . . . . . . . . . . . . . . . . . . . . . . . . 69
6.4.2 Solution of the Beamforming Problem . . . . . . . . . 70
6.4.3 Terminal Admission . . . . . . . . . . . . . . . . . . . 71
6.4.4 Implementation Aspects . . . . . . . . . . . . . . . . . 72
6.5 Results . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 73
6.5.1 Simulation Setup . . . . . . . . . . . . . . . . . . . . . . 73
6.5.2 Outage and Throughput . . . . . . . . . . . . . . . . . 74
6.5.3 Performance without Admission Control . . . . . . . 75
6.5.4 Fade Margin . . . . . . . . . . . . . . . . . . . . . . . 77
6.5.5 Performance with Random Admission Control . . . . 79
6.5.6 Performance with Heuristics Admission Control 
and Access Point Assignment . . . . . . . . . . . . . . . 80
6.5.7 An Example of a CDMA-like System . . . . . . . . . . 82
6.5.8 An Example on Optimal Access Point Assignment . 84
6.5.9 Admission Control Fairness . . . . . . . . . . . . . . . 85
6.6 Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 87
6.A Simulation Parameters . . . . . . . . . . . . . . . . . . . . 92
Chapter 1

Introduction

1.1 Background

In 1837, it was first possible for the general public in Sweden to send and receive data messages and the system used was actually wireless but not really mobile. This year, the optical telegraph system was built in Sweden. Ten years later Morse’s telegraph was introduced and line-of-sight was no longer required, but instead a wire was required. Alexander Graham Bell filed his patent on the telephone in 1876, which introduced speech in telecommunication, and in 1895 Marconi transmits a message over radio. Thus the main components of modern telecommunication was created. Both speech and data could be transmitted over either wired or wireless infrastructures. However, speech and data would be separated through many years.

After these inventions the evolution has been substantial. First, the one link was organized into a system with more users. Second, the offered quality of service and capacity increased. Third, an increasing proportion of the connections became wireless and the equipment portable and so the users went mobile.

During the 90s, the development was enormous. Still, the mobile communication systems are mainly used for speech. In parallel to the wireless development the evolution of the Internet has taken place. With this development millions of people are connected to the global data network and thus creating needs for enormous data transportation. Combining the evolutions of wireless communications and the Internet into the Mobile Internet, implicates a demand for very high data rates in wireless sys-
tems in the future. Today the Global System for Mobile Communication (GSM) and General Packet Radio Service (GPRS), and corresponding systems in other parts of the world, handle most of this Mobile Internet together with systems for Wireless Local Area Networks. Concurrently, corresponding capabilities for both speech and data, but with higher capacity, are built into the Third Generation Mobile Communication (3G), Universal Mobile Telephone System (UMTS), that has started its deployment in Japan Europe and USA. In parallel to this evolution based on the speech branch of mobile communication, the data communication branch introduces Bluetooth and Wireless Local Area Network (WLAN) systems like HiperLAN2 and IEEE802.11a/g/h.

For the future it is impossible to look another 100 years ahead, but starting off today, it may be possible to foresee some issues for the ten years to come. The three steps above are still valid and more people, want more capacity, more wireless for each day. It is of interest to provide a system that has large coverage, is easy to deploy and offers some flexibility regarding capacity and Quality of Service (QoS). At the same time there is a non-technical development, in the world today, that interact with the technical evolution. Thus technical as well as economical, social and regulation issues need to be taken into account.

For the future generation wireless systems, it is foreseen that current systems will still be operated, but supplemented with new systems meeting new requirements [FGL’99]. The requirements may be locally higher bit rate, different Quality of Service requirements and transparency between different infrastructures as well as new services and a variety of new terminal devices.

This thesis will investigate how some of these requirements may be fulfilled using Smart Antennas, i.e. antenna arrays at either access point, terminal or both in combination with advanced signal processing.

1.2 Scope

The main scope of this work is to provide limits for wireless communication systems, equipped with antennas arrays at either or both of access point and mobile terminal sides.

This work is performed within the Personal Computing and Communication (PCC) program, described in Chapter 2. The vision for all work within the PCC program has been Personal multimedia communication to all at the same cost as fixed telephony today. This vision imposes an
drastic increase of the wireless infrastructure, but also a decrease in cost. The capacity increase can be made as a combination of making the wireless infrastructure denser and keeping the current density and making the infrastructure more efficient. In this work the focus will be on the latter i.e how to introduce a very competent access point that can increase the system performance substantially.

The first goal has been to envision the possible environments in which smart antennas would be deployed. Further, with these environments in mind, to create knowledge how smart antennas can be used. Previously, the links in smart antennas systems have received a lot of attention and one issue in this work is to find performance limits on the system level and to find critical issues for the deployment of an infrastructure based on smart antennas.

Issues that are of interest is what happens in a wireless system, when introducing packet-based communication, or what possibilities the assumption that global channel information is available will introduce. Another issue is the possibility to use several antennas, on each mobile terminal and the possible capacity increase offered.

The results are mainly presented in some form of measures of performance that are valid under the assumptions made, but they can also be used as performance limits for systems with less generous assumptions.

1.3 Methodology

Through this thesis many research methods has been used:

The basis for Chapter 2 is scenario analysis. This method starts with identifying a number of trends, that are present today or may be present in the future. From different assumptions about these trends and how they develop, a number of scenarios may be built. These scenarios will for sure never come true, but provide a framework to which the actual evolution can be compared. From the scenarios different working assumptions and research areas may be identified.

In the following chapters, more quantitative methodologies are used. The focus here is to gain knowledge of how different phenomena in wireless communication systems work and how to utilize them for efficient communication. Towards this end, the environment may be modeled and/or measured and the analysis may been analytical or numerical. In cases where the environment is to complex to investigate analytically, simulations have been used.
In Chapters 5 and 6, a wireless communication system with several mobile terminals is investigated in order to find performance limits and advice algorithms and strategies how to communicate efficiently in such a system. In these investigations the system is to a high extent built by models of reality and simulations are used to obtain results.

In Chapters 7 and 8, the communication between one access point and one mobile terminal is investigated. This investigation is based on measurement data, which is analyzed numerically.

1.4 Highlights

Examples of results presented in the following are:

- Strategic scenario analysis
  - Provided a framework in terms of three scenarios for future research
  - Identified working assumptions such as ubiquitous computing and inhomogeneous wireless infrastructures.
  - Identified research areas such as unlicensed public operations and infrastructure deployment strategy.

- Wireless systems with smart antennas
  - Outage results for packet switched uplink beamforming with idealized beamformers, compared to traditional beamforming methods.
  - Outage and throughput results for a cellular wireless system with joint optimal downlink beamforming, power control and access point assignment, showing possibility for a seven-fold increase in throughput over traditional beamforming.
  - Suggestion and evaluation of heuristic algorithm for admission control in joint optimal downlink beamforming, power control and access point assignment. Results show 20% increase in throughput as compared to random admission.

- Dual array link capacity
  - The MIMO channel is characterized from data, measured in an indoor office environment.
1.5 Outline and Contribution

It is shown that a typical indoor office environment has sufficiently rich scattering to be able to utilize the advantages with dual arrays.

It is shown that an intra-element distance in the region of the transmission wavelength will give a capacity very close to the statistical maximum.

1.5 Outline and Contribution

This thesis is mainly organized in two parts consisting of the chapters presented below:

Chapter 1 Introduction gives the background and scope for this work. Further, the chapter presents an outline and lists the contributions.

Chapter 2 Future Generation Wireless Communication includes the work performed by the 4GW group and it provides a background to the area and a motivation for this work. The chapter outlines a methodology to perform research where future scenarios and research areas are pointed out. The material is published in the following articles, that are joint work by the authors without ordering. Publication [LFG+98] defines the methods used.


Chapter 3 Smart Antennas defines the general research problems for introducing smart antennas in wireless systems and the focii of this thesis. This chapter also reviews related work.

Part I Smart Antennas in Wireless Systems contains the following chapters

Chapter 4 Data Models Provides the general definitions of the data and signal models used in the following chapters in this part.

Chapter 5 Uplink Beamforming with Packet Switching The uplink packet transmission throughput of a system with a smart antenna configuration at the access point is analyzed. A slotted ALOHA protocol is utilized and the throughput is calculated analytically, assuming idealized antennas. The results are compared to simulations, where diversity combining and interference rejection schemes are investigated as well. The numerical examples agree well with the derived expressions and show that a substantial increase of the system throughput is possible with low mean packet delay. Published in [SO99] Rickard Stridh and Björn Ottersten, "Packet Data Throughput for Wireless Systems with Smart Antennas", IEEE Vehicular Technology Conference 1999 Fall, Amsterdam, Netherlands.

Chapter 6 Downlink Beamforming - System View The use of admission control and joint optimal downlink beamforming, power control, and access point allocation, in a multi-cell wireless communication system is investigated. The access points of the system employ smart antennas and single antennas are used at the terminals. The possibility to send messages to multiple terminals at the same frequency in the same time slot is exploited. In order to assign resources, optimal beamforming requires a feasible set of mobiles, i.e. that there exists a possibility of offering all admitted users the required Signal-to-Interference-and-Noise Ratio. Therefore, an algorithm for deciding which mobile terminals to admit to a system is proposed and evaluated. Using the proposed admission algorithm, joint optimal downlink beamforming is evaluated and the throughput increase as compared to decentralized beamforming algo-
1.5 Outline and Contribution

Algorithms is assessed from a system point of view. Results show that the proposed algorithm can provide a substantial increase in system performance compared to random removal of users. This work is reported in


Part II Channel Capacity and Modeling Issues for Dual Arrays contains the following chapters

Chapter 7 The MIMO Channel introduces the MIMO channel and the measurements in the ISM band at 5.8 GHz, used in the following chapters. Our investigation shows that the envelope of the channel coefficients for this obstructed-line-of-sight (OLOS) indoor scenarios is approximately Rayleigh distributed.

Chapter 8 MIMO Channel Capacity An analysis of the indoor Multiple-Input-Multiple-Output (MIMO) measurements is performed and the possible increase in capacity, utilizing multiple transmitters and receivers is examined. The investigation shows that in the measured indoor environment, the scattering is sufficiently rich to provide substantial link capacity increases. Furthermore, the effect of intra-element spacing on the channel capacity is studied. This work is reported in


[SO00] Rickard Stridh and Björn Ottersten, "Spatial Characterization of Indoor Radio Channel Measurements at 5 GHz", First IEEE Sensor Array and Multichannel Signal
1 Introduction

Processing Workshop 2000, Cambridge, Massachusetts, USA.


Chapter 9 Conclusions from the investigations and possible future research paths.
Chapter 2

Future Generation Wireless Communication

2.1 Introduction

The development in wireless communication has been divided into generations, where each generation has introduced technology or services not available in the previous generation. The first generation was analog and provided speech services. The second generation was digital and provided not only speech but also a Short Message Service (SMS) and later also technology for accessing the Internet through a mobile device, e.g. Wireless Access Protocol (WAP) and General Packet Radio Service (GPRS). Currently, what is called the third generation (3G) is on its way. This time the main paradigm shift is the introduction of possibilities to use the system for both speech and Internet services, including a higher data rate than 2G services. During the years to come, 3G will develop in a way similar to how GSM has developed with new technologies and new services and finally there will be time for another paradigm shift towards a new generation wireless systems.

The issue of future generation or fourth generation wireless systems has gain a lot of attention lately in e.g. [BFG+01, FPR+01, Per00]. This chapter will describe an initiative, started in 1997, which have had the intention to track the development towards future generation wireless infrastructures and to identify research areas relevant for such a development.
2.2 Personal Computing and Communication

The Personal Computing and Communication (PCC) program was started in 1997, within the Swedish Foundation for Strategic Research (SSF). PCC was initially a cooperation between the Royal Institute of Technology, Chalmers University of Technology and Lund University, and has then been extended to include several Swedish universities.

The overall goal for PCC is to organize a graduate school in the PCC area, educating Ph.Ds for the Swedish industry. The activities are summarized in the PCC vision *Mobile Multimedia to all at today's prices for fixed telephony* [Mol98]. Another goal is to create a nation-wide network in the area of PCC research.

PCC is divided into several projects within such different areas as computer science, hardware electronics, coding and modulation, and wireless infrastructures. The work presented in this thesis has been performed within the project 4th Generation Wireless Infrastructures (4GW).

2.3 4th Generation Wireless Infrastructures - 4GW

Whereas the development of telecommunication equipment and services moves at a fast pace, infrastructure deployment is a slow and costly process demanding a long-range strategic perspective in decision making. As a consequence, R & D efforts in this area are concerned with problems on a time horizon of ten years or more. Studying the feasibility and viability of various future infrastructure architectures and potential road-maps of their deployment has been the focus of the 4th Generation Wireless Infrastructures research.

In an attempt to realize the PCC vision *Mobile Multimedia to all at today's prices for fixed telephony*, a difficult problem arises. In contrast, the process of solving engineering and business problems in current or imminent wireless systems, where system concepts, requirements and markets are reasonably well known, very little is known about these things over a ten year horizon. The approach used in the work to tackle this problem, is to use various scenario techniques. Plausible scenarios, describing the telecommunication scene in year 2010 are used to determine potential...
technical and other bottlenecks in this area.

A continuation of the 4GW scenario project has been published in [KBL+02].

Herein the scenario techniques will be used to paint a more general picture of the telecommunication society 2010 taking technical, economical and social aspects into account. Similar techniques has been used by e.g. Ericsson to predict the telecommunication market in 2005 [Eri96].

2.4 Research Approach

The 4GW work is focused around the working assumptions (WAs) that provide the common platform for interrelating, comparing and selecting research problems in the different work packages (WPs). The task of the WPs is to derive and analyze key problems in the current set of WAs. The focus is on studying the feasibility of solving these problems as well as determining performance limits set due to these bottlenecks. The result will be used to modify the WAs by changing the tradeoffs between various bottleneck areas. The WAs have to be consistent with a set of background assumptions (BAs) describing relevant parts of a techno-socio-economical (TSE) scenario for telecommunications in the time around year 2010. Such scenarios address issues like: user behavior and lifestyle, evolution of fixed telecommunications markets and systems, evolving mobile terminal artifacts and their functionality and design, services requirements with the focus set marketability and lead user groups and projected availability of appropriate technology.

Scenarios have been used as a tool to initiate the research process within the 4GW project. During the last decade, scenarios have been widely spread as a tool for promoting strategic thoughts within organizations. Scenarios have two essential purposes in the project:

- to change the way we think (and thus to synchronize the thinking within the group)
- to envision the future

They are interesting as envisions of thinkable futures; they give the possibility to test ideas and draw conclusions of many different developments. By nature such activities are speculations, although they are systematically built, based on what is known today. By identifying trends and extrapolating them into the future, a basis for strategic discussion can be made.
2.5 Identified Trends

In the scenario work the following are examples of trends in society that has been considered in addition to technology factors [FGL+98a].

The globalization of products, services and companies

Companies establish presence in many countries. The same brand names may be used around the world but products and services are adapted to fit the local culture and requirements. This trend is enabled by increasing world trade and by efficient means of communication that makes it possible to manage companies spread around the globe.

Communicating appliances

An increasing amount of consumer devices will have built in communication capabilities. Thus more tasks can be automated and device management becomes easier.

Services independent of infrastructure

The infrastructures and the services provided over them are becoming more and more separated into different layers. This makes it possible to use the same service via several different infrastructures. Due to standardized interfaces it becomes possible to have different companies providing the infrastructure and the service.

Information trading and information overflow

More and more information becomes available which paradoxically increases the value of refined i.e. meaningful information since it is harder to find. This opens up a market for information brokers that are specialized in finding information that is useful to their clients.

Increasing importance of education

Education increases as a success factor both for the individual and for companies that require highly educated employees in order to be competitive.
2.6 Scenario Summary

Diversification of standardization

As more and more products are sold globally and more and more devices are expected to interact, standardized interfaces become increasingly important. In some areas the leading manufacturer sets de-facto standards. In other areas there is no single company dominating the market forcing companies to cooperate.

2.6 Scenario Summary

Scenarios are the outputs that reveal the essence of the future world from a certain perspective. By using different perspectives, three different scenarios, as outlined below, have been designed. The scenarios are built by using a couple of identified trends developing in a certain direction. The scenarios are described from three different perspectives:

- First, the development in society and technology is outlined
- Second, the impact on the tele/datacommunications world is examined
- Third the life of an ordinary citizen is envisioned.

Below follows short descriptions of the scenarios and how the evolution may continue until 2010.

2.6.1 Anything Goes!

The diversity of telecommunications equipment has increased dramatically, as well as the possibilities of manufacturing cheap, co-existing products. The manufacturing companies have become dominant in the telecommunication world. They advocate open de-facto standards, and use software solutions to create flexible, multi-standard equipment. Because of dramatic price reductions, both residential and business environments have Wireless Local Area Networks (WLAN) solutions. They are operated by a multitude of operators, and the end-users have great freedom of choice in selecting where to purchase wireless services. Competition between operator and equipment provider is fierce and new wireless products and services appear at a high rate. Services and equipment are affordable for almost every-one in the industrialized world, which tends to narrow the social gaps in society.
2.6.2 Big Brother Protects you from Little Brothers

As more and more personal information is available in the information infrastructure, the personal integrity issue become a major concern of the ordinary user. There is a widespread call for regulation and government intervention to ensure information integrity and secure networks. All citizens and companies wishing to deal with almost any aspect of computing and communication will need some kind of regulatory approval. In the private sphere most of the public information services use broadcasting. The impact of this scenario is that the complexity of products and services increase and thus the cost. Service, transport and equipment providers are reduced to a few large actors (brands) that, in the public eye, can be trusted. The development rate and the number of wireless systems is limited and so is the number of operators.

2.6.3 Pocket Computing

Pocket computing pictures the world where the technological development is fast, but due to economical and educational differences, the society is divided between those who can follow the development and those who cannot. Thus some parts of the population have access to a multitude of advanced services, and other parts are using more simple services adapted to their needs. Service providers dominate the scene by providing the wide range of different services (that may include specialized hardware) tailored to various user groups. The mobile multimedia services mainly focused on the high-end consumer and business need. Global solutions are available but too expensive to be affordable by the low-end user. Cultural and educational differences between nations and different standards in society have also led to political instability and unrest.

2.6.4 Scenarios in Trend Space

To compare scenarios and to find empty spaces between scenarios it is possible to plot the scenarios in a grid where the trends span the dimensions. An example is shown in Figure 2.1. In the figure the scenarios are related to the current situation in terms of social factors and standardization factors. In order to find new scenario outcomes the empty space marked by a question mark may be investigated. This space may be plotted for all trends identified.

Further results on the scenario process may be found in [LFG+98] [FGL+98b] [FGL+99].
2.7 Working Assumptions

From the scenarios a couple of interesting areas, important for the future, have been identified as 4GW Working Assumptions.

Tele-presence

Tele-presence is used to create virtual meetings between individuals and provides full stimulation of all senses required to provide the illusion of actually being somewhere else – an illusion that cannot be distinguished from the "real thing". The bandwidth required for tele-presence is, with efficient data compression and fast sensory feedback, less than 100 Mbit/s. The data stream is mostly dominated by 180-degree stereo, hi-resolution, full motion video. The multiple party meeting process is
one of the major communication patterns foreseen for this application. Meeting processes will be mainly real-time.

**Ubiquitous information**

Information anywhere, anytime with virtually seamless connection to a wide range of information services is a key feature of the information infrastructure. Information access of large volumes of data, pictures, video etc is nearly instantaneous in small portable terminals. Compared to real-time meeting process, this application is less delay sensitive. Users can tolerate longer delays since the information is not real-time critical. Possibly high data rates are required for high volume data transfer applications such as video retrieval. The traffic pattern is highly asymmetric with 50/1 ratios or more favoring the system-to-terminal links. Seamless virtual connections (creating the feeling of always being connected) is important for the users.

**Inter-machine communication**

Inter-machine communication is an important application/service, ranging from simple maintenance routines (e.g. refrigerator telling repair shop that it’s broken) to sophisticated massive data exchange (e.g. camera and PC/TV exchanging video/picture information). All cars, household and office equipment down to less than 20 US$ could have wireless interface as standard feature.

**Security**

Security is an indispensable feature of the infrastructure. Data integrity and protection against unauthorized access are key features providing reliable services for banking, electronic payment and handling of personal information. Schemes that reliably prevent unauthorized tracking of users and other intrusions in the private sphere are in operation.

**One-stop-shopping**

Services are provided in a one-stop fashion ("turn-key") directly to the consumer at the point of sales. Services are immediately available when leaving the store. The store (information provider) takes full responsibility for the service as well as for the hardware/software provided, if any.
2.7 Working Assumptions

Non-homogeneous infrastructure

Non-homogeneous infrastructure consisting of several switching fabrics and a multitude of physical media. All elements of significance are digital. The fixed backbone structure is dominated by connection-less packet switching (IP-style). Also, the new air interfaces in wireless systems use packet switching technology. The wireless infrastructure uses a multitude of air interfaces, inherited from the wireless systems of the late 90s and early year of the new millennium. Among the newer, packet oriented micro and millimeter wave wireless systems for the high data rates in the 5 and 60 GHz bands have emerged with data rates up to 100 Mbit/s for hand-portable use. An overlaid architecture provides seamless, transparent internetworking using all kinds of air interfaces.

Public & private access mixed.

Public wireless access quality and bandwidth varies, where higher data rates are confined to dense urban areas, office environments (private/public systems) and homes (private systems). Operators/service providers provide partial coverage for non-real-time wideband (10 Mbit/s) information access in most public places ("info-kiosk", info-stations), in public transportation. Rural area information access bandwidth is limited to 1 Mbit/s but provides reasonable coverage along all main highways and villages.

Ad-hoc, unlicensed operation

Ad-hoc, unlicensed operation dominates and many actors will provide parts of the infrastructure. Ad-hoc networking (spontaneous deployment, self-planning) in unlicensed bands (5 and 60 GHz) plays an important role (the dominant role in the "pocket computing" and the "anything goes" scenarios) and compete fiercely with the existing traditional public operator which experience dwindling market shares. Techniques for efficient multi-operator (private/public) sharing of unlicensed spectrum have been developed. Ad-hoc structures, where the equipment of the users (companies or even individuals) provide part of the infrastructure, are adaptive to possible new communication patterns. Control of the new emerging ad-hoc networks (incl. routing, mobility etc.) is fully distributed and highly reliable.
Multimode access points in public systems

Access points with multiple access air interfaces are used to accommodate a wide range of terminals. Large operator systems use advanced access ports with adaptive antennas that self-configure with non-critical installation procedures (self-configuration) to reduce cost. Access ports (wireless gateways) in ad-hoc access systems are simple single mode/single air interface devices. The cost of access port hardware in these systems is negligible in comparison with the cost of planning and physical installation.

Terminals

Terminals exhibit a large range of user rates, from less than 10kbit/s (e.g. simple appliances) to 100 Mbit/s (tele-presence terminals). Battery life for personal terminals will last at least for some weeks. Battery capacity/weight/volume ratios are up one order of magnitude compared with today's. Terminals in the 5 and 60 GHz range use advanced adaptive antennas. Terminals are either multi-mode, multi-function terminals (as in the "anything goes" scenario), or single-purpose, cheap terminals designed solely for a specific service ("pocket computing") or function specific (e.g. receive only).

2.8 Some Key Research Issues in 4GW

From these WAs the following key research issues have been identified.

One-stop shopping - terminal & service adaptability: Since the user wants his services available on the spot, he is not willing to manually configuring his hardware devices and network services. This has to be done by the terminal devices themselves. The mobility and automatic adaptation to various standards and infrastructures that provide different bandwidths at different delays opens up a wide area of research. There are questions on how to most efficiently adapt to new conditions (networks, bandwidth etc.), when to switch between systems and which layer should be responsible for different functions. Security issues in these environments represent major challenges.
Unlicensed public operation
Can multiple operators compete efficiently (to the benefit of the consumer) without fixed frequency allocations? Are there technical solutions to this effect?

Support for new and more complex services
Tele-presence applications provide a major challenge in wireless systems. Multicasting will play an important role in this and other meeting support-type services. Local, physical multicasting has also the potential to make vast improvements in spectrum efficiency.

Infrastructure deployment strategies - the business models
The high bandwidths projected in several of the WA:s will require a dense and potentially costly infrastructure. What are the actors on the infrastructure market? Is the business volume 2010 sufficient to support an infrastructure that fulfills the PCC vision requirements? Will there be an evolutionary path along which money can be made for the involved players?.

Self-configuring ad-hoc networks
One interesting possibility to bring costs down (as implied by the " Anything goes" scenario) is that the users play the role of an "wireless operator" in his local surroundings. He may install his own low cost base stations where he needs them and where space and network connections are available. This calls for techniques that automate configuration, detection of other devices, creation of ad-hoc networks and management of the radio spectrum should be allocated. Adaptive antennas and efficient modulation techniques play important roles in this process.

2.9 Summary
We have introduced a scenario-based structure for the future of wireless infrastructure. Based on these WAs and research issues the work package Smart Antennas in the Fourth Generation Wireless Infrastructures has focused on providing an air interface offering the high capacity and flexibility needed, based on smart antenna technology.
Chapter 3

Smart Antennas

3.1 Introduction

One always present issue, in the mobile communication evolution, is the shortage of frequency spectrum. In the quest for more frequency bands, the carrier frequencies used, have increased from 0.5-1 GHz in the 1st generation systems to 1-2 GHz with 2nd and 3rd generations and currently systems (e.g. HiperLAN2) are standardized towards 5 GHz and research is ongoing towards such high frequencies as 60 GHz [Fla00].

It is also necessary to utilize the existing bandwidth in a much more efficient way. One very important means of doing this, is to utilize the fact that different receivers and transmitters in a system in general have different locations and thus different spatial signatures. Thus the introduction of array antennas that utilize this additional dimension can potentially increase the capacity in a network considerably which was shown early in e.g. [SBEM90, AMVW91]. These arrays of antennas in combination with signal processing and resource management are called Smart Antennas.

Using smart antennas at one or both of the access point and the terminal is a powerful means of separating the different users due to their different spatial signature and thus to increase the throughput in a wireless network. Historically most research has been focused on the access point antenna arrays, but recent investigations have studied the use of antennas arrays at both access point and the terminal sides, i.e. dual arrays.

A cellular wireless communication system consists of access points or
base stations, surrounded by their cells, that are the geographical areas covered by each access point, shown in Figure 3.1. The access point provides the connection to the fixed network and the backbone structure. Several access points may be connected in order to optimize the use of different resources in the cellular system. In the cell area a number of mobile stations or terminals appear. The terminal is in current systems mainly connected to one access point. In the transition between cells, though, the terminals have contact with several access points. In future systems it is possible for a terminal to communicate through several access points.

The connections between the access points and the terminals are called links, and it is of interest in the system that all the links are as independent of each other as possibly, to be able to have multiple users in the systems, i.e. to achieve multiple access. Therefore each link is allocated a special resource. This task is called radio resource management.
3.1 Introduction

and may be static or dynamic and may further, be performed locally or globally. Examples of available resources are

- **Frequency** - the total frequency band is often divided into frequency channels - Frequency Division Multiple Access (FDMA)
- **Time** - Division of the available spectrum into time slots - Time Division Multiple Access (TDMA)
- **Code** - Direct sequence spreading or frequency hopping - Code Division Multiple Access (CDMA)
- **Space** - Use the fact that different users has different spatial signature - Spatial Division Multiple Access (SDMA)
- **Power** - Adapt the transmitted power in order to get message through, avoiding disturbing other links as much as possible - Power Control

All systems currently used, and planned for in the near future, are given a certain frequency band, subsystems within the system are allocated a portion of that frequency band. The allocation of frequency channels in a system may be either static, i.e. each cell is assigned certain frequencies when the system is deployed, or dynamic, i.e. the frequencies are assigned adaptively to the interference situation, upon demand. Within that frequency band either TDMA (GSM), CDMA (UMTS) or a combination of these may be used. Power control may be applied in combination with all the other resources mentioned above.

The resource mainly dealt with in this thesis is the spatial dimension, which may be exploited in combination with all other resources mentioned above. Three aspects will be treated in some detail.

**The channel.** A mathematical description which depends on the physical surrounding in the system through the wave propagation. The channel for smart antennas is much more complex than the channel for scalar channel.

**Receiver and transmitter strategies.** How to, with different amounts of channel knowledge, find and use receiver and transmitter weights in order to maximize the link or network capacity.

**System aspects/performance.** Adding several users into a cellular structure bring in traffic issues and access schemes, which normally are not included in the optimizations of receiver and transmitter weights.
3.2 The Wireless Channel

The wireless channel differs from the wired in many senses. The most important, is that the signal can propagate in many different paths, thus arriving at the receiver from different directions at different time instants. The number of paths depends on the environment. The sum of the signals from the different paths may fluctuate considerably as the different rays sometimes null each other and sometimes adds constructively [Pro95]. This phenomenon is called fading. Rayleigh fading is rapidly time varying due to phase differences in the signals, while slow fading occurs due to shadowing. As the propagation characteristics change with the frequency, the fading will also change if the frequency differences within the signal is large. When the signals arriving at the transmitter have different delays, a delay spread is created, i.e. the same signal is arriving at several time instants, limiting the possible bandwidth of the system and creating the need for a more complex receiver. In this work mainly narrow-band channels are considered.

3.2.1 Spatial Channel Models

Introducing smart antennas implicates the use of a new dimension in the channel models i.e. the spatial dimension and the channel changes from being a scalar to be vector valued. Further, as all users have different positions the access point array will observe different spatial signatures and it may thus be possible to spatially separate different users. Several methods have been proposed to describe the spatial dimension.

A widely used method is to describe the incoming signal with a Direction-of-Arrival (DOA). Further, it may be described as a point source or a scattered source. Taking the environment of a wireless systems into account, the local scattering model has proven useful in situations where the array is elevated, limiting near-field scatterers, and the terminal is in the far field and non-line-of-sight. In the model it is assumed that the terminal is surrounded by a large number of scatterers, causing the signal to arrive at the access point with an angular spread. This method has been brought into the area of array processing in e.g. [ZO95, TO96] and is investigated in [Zet97].

Spatial channel model overviews may be found in e.g. [ECS+98] and [FMB98].
3.2.2 Multiple-Input-Multiple-Output Channels

The introduction of Wireless Local Area Networks (WLAN) motivates the use of multiple antennas on both access point and terminal sides. The terminal in such a WLAN could be a laptop computer or a handheld computer, both giving opportunity to carry multiple antennas. It is also possible to equip smaller handsets with several antennas, with e.g. different polarization [BNB99, Bec01]. Further the movement to higher frequency bands, and thus shorter wavelength allow multiple antennas and receivers on smaller devices.

To assess a communication channel the Channel Capacity was introduced in [Sha48]. The capacity is a measure of the maximum possible rate that can be transported over a channel, with arbitrarily low bit error probability. The channel capacity can be achieved, with perfect channel knowledge at the receiver and coding of infinite delay.

The use of arrays on both ends of the channel introduces the Multiple-Input-Multiple-Output (MIMO) channel. The capacity for MIMO for Additive-White-Gaussian-Noise (AWGN) channels with and without fading was first derived in [Tel95]. This paper showed, in theory, substantial capacity increase, provided that the channel paths where independent and that the channel could be estimated. Further the issue of waterfilling over spatial channels, based on channel knowledge at the transmitter was introduced. Comparable results has been published in [FG98]. An important condition for the MIMO channel to support this increase is that the environment provides sufficient multi-path propagation resulting in a high rank channel. These issues are covered in Part II of this thesis.

The MIMO channel is even more difficult to estimate than the channel with only one array. Thus space-time coding provides an alternative, not requiring channel knowledge at the transmitter. Space-time coding was introduced in [GFK96] and [TSC98]. A scheme with possible use in MIMO channels is the Alamuti scheme [Ala98]. This scheme is based on transmit diversity and the scheme used in UMTS is to a high extent flavored by the Alamuti scheme [3GP00].

To be able to design dual array systems in wireless communication, the chosen channel model is important. The issue of MIMO channel modeling is fairly new and the models are more complex compared to the SIMO/MISO models. The above capacity work is mainly based on rather simple channel models e.g. assumptions of independently fading channel elements. It is thus of interest to investigate real measured channels with
the objectives to develop good models and to find out what capacity the channel offers.

However, models based on measurement data are quite rare. In [KSMP00], a model is presented based on the measurements for indoor pico-cell scenarios. In [YBO+01, YBO+02], statistical models based on 5.2 GHz measurements are presented for the typical NLOS indoor scenarios [MBKF00].

In [WFGV98] measurements on the Bell Labs Layered Space Time (BLAST) system working in laboratory environment at 1.9 GHz was presented showing very high spectrum efficiency. The theory behind the BLAST systems has been presented in [Fos96].

Channel measurement are very important in the evaluation of channel models. One example of MIMO channel measurements is found in the SATURN project with measurement equipment described in [BMK00] and initial results showing high scattering properties even in LOS channels, are presented in [MBKF00].

3.3 Receiver and Transmitter Strategies

Generally, the use of antenna arrays adds two advantages:

- The ability to fight Rayleigh fading, based on the assumption that the correlation of the fading between different antenna elements is low.

- The possibility to focus the beam, in transmit and/or in receiver mode, decreasing the noise and interference received from other users and the interference transmitted to other users. This may be done by generally focusing the power in the direction of the desired signal or by adding the constraint of nulling the interference if it is spatially non-white. The latter case is called interference rejection and it is the generally desired case in wireless systems today (with exception for single-rate CDMA, where the interference may be considered to be spatially white). As noise and interference is reduced by this method, the range of one access point is increased.

Early contributions in the area of antenna arrays for mobile communication are [AMVW91] and [SBEM90]. The issue of smart antennas has been overviewed in e.g. [God97a, God97b]. The special area of beamforming is summarized in [VB88].
3.3 Receiver and Transmitter Strategies

3.3.1 Sensor Array Processing

To be able to utilize the spatial dimension of the wireless channel, knowledge about the channel is important. Either parametric methods are used to estimate an angle, or statistic methods are used to estimate channel statistics, we need sensor array processing. Sensor array signal processing was originally used in radar and sonar technology where the use of antenna arrays started earlier than in wireless communication.

The main problem considered in sensor array processing is the Direction-of-Arrival (DOA) estimation, i.e. estimating the direction to the desired emitter. Several methods have been presented in the area. Examples of non-parametric DOA estimators are the conventional beamformer and the Capon beamformer. Parametric methods include stochastic and deterministic Maximum Likelihood as well as subspace methods as Pisarenko and MUSIC. An overview of the field of sensor array processing is given in [KV96].

In order to estimate the channel between the transmitter and receiver two methods may be used. A known training sequence in the transmitted signal can be utilized by the receiver to estimate the channel. As wireless communication signals are very structured, though, it is also possible to blindly estimated the channel from the knowledge of the signal structure, not requiring a training sequence. In this work it is assumed that some method for channel estimation exists and that some channel knowledge is present.

3.3.2 Beamforming

With knowledge of the channel to the desired user, the signals transmitted or received on the different antennas elements may be combined to give required gain on the desired signal.

Uplink Beamforming

In uplink beamforming it possible to estimate the channel via the received signal and thus to have a good channel estimate [God97a, God97b, VB88]. The basic method is beamforming, where the weights in the receiver are matched to the estimated channel vector. Zero-forcing methods may be used in order to take care of interfering signals, though with high sensitivity of estimation errors and risk of worsening the noise situation. A optimal solution is found by maximizing the SINR, giving the Minimum Mean Square Error solution.
Downlink Beamforming

In downlink beamforming, knowledge of the channel has to be present in advance of transmitting and thus it is sometimes impossible to know the exact channel realization. Statistics of the channel vector is possible to estimate from the uplink, though, and downlink methods may thus be formulated based on channel statistics. Especially in FDD systems the system capacity is less in the downlink compared to the uplink.

Downlink beamforming work may be found in [Zet97] [AFFM98] [GF97] [BO01], all touching the problem of using uplink channel statistics for the downlink beamforming in FDD cases. Methods examined are matched arrays, directions based transformations and linear transformations. Further it is possible to let the terminal estimate the downlink channel and then feeding the estimate back to the access point. Generally the second order channel statistics are used, expressed as a covariance matrix of the channel vectors.

The basic method for downlink beamforming is to point the main beam in the direction of the desired receiver i.e. conventional beamforming. This means that the power is maximized to the desired user without concern about the other users.

The next step is to avoid transmitting too much power to other users. This may be done by minimizing the summed inverse of SINR for each user [Zet97], and this minimization may be solve as a generalized eigenvalue problem, with methods described in [GvL96]. This method is decentralized and the minimization may be performed at each access point.

The focus of joint optimal beamforming and power control is to minimize the transmit power, provided that all links fulfill the QoS requirement, here stated as a requirement on the SINR at each mobile terminal. In [Ben99] semi-definite optimization methods [Stu98] are used to solve a relaxed expression of the minimization problem. In [RFLT98, VM99] iterative solutions are designed and optimality is proved. In [SB02] the problem is divided into a feasibility step and a power minimization step. The joint optimal beamforming and power control problem must be solved globally and thus all channels or all channel statistics must be known in the optimization. Joint optimal beamforming and power control on the downlink is evaluated for a cellular system in Chapter 6.

In [Ben00] the joint optimal beamforming and power control framework is extended to optimally include assignment of access point for each terminal.

The above problem requires an admission control algorithm in order
to be able to find a feasible solution. Several admission control algorithms are available, e.g. in combination with power control [Zan92].

An alternative in downlink beamforming has been presented in [VTL02], where the concept of opportunistic beamforming is introduced. This concept is based on random creation of spatial channels with beamforming and then transmission to the terminal that happens to get a good channel. Opportunistic beamforming requires very limited channel feedback, but also sufficient amount of users and a proper scheduling algorithm.

3.4 System Aspects

Introducing smart antennas into a wireless network adds the impact of traffic behavior, impact of multiple access methods and power strategies. To model a complete system it may be very complex to use the exact receiver and transmitter strategies mentioned above. One option is then to use idealized models to model the smart antennas. Ideal antenna models have been used in [CR98] and [PER98], and the issue of access methods has been investigated in [WC93].

Different measures are of interest when analyzing a system and frequently used measures are outage, i.e. probability of no connection, and bit error rate. Using packet switched communications, measures as throughput and packet delay are valid.

Different beamforming strategies are optimized with respect to different parameters. It is, though, hard to optimize with respect to all parameters in a system and thus it is of interest to investigate and compare the different methods mentioned above with traffic models and access schemes.

As the wireless channel fluctuates, not only with time but also with position, the concept of multi-user diversity may be introduced. This concept is well suited for packet based transmission and assumes that there in every time slot are channels that are good and channels that are bad. With channel information a scheduling algorithm may schedule the communications to the good channels. Examples of scheduling algorithms are found in [SDSK98]. It is also possible to introduce fluctuations in the channels in which to schedule over. In [HL01] fluctuations in the user Quality-of-Service demands are introduced, while in [VTL02] fluctuations are introduced with beamforming.
3.4.1 Uplink vs. Downlink

As mentioned in Section 2.7 the traffic in future wireless systems is believed to be asymmetric, i.e. the traffic to the terminal (downlink traffic) is much higher than the traffic from the terminal to the access point, see Figure 3.2. This implicates that the downlink is the critical link and where most effort has to be made to increase the capacity.

Wireless systems may be divided into Frequency Division Duplex (FDD) and Time Division Duplex (TDD). In an FDD system, the uplink and downlink use different frequency channels and while in a TDD system the uplink and downlink use the same frequency channel, but different time slots. One property following with TDD is the tougher requirement on synchronization in the network. Example of FDD systems are GSM and WCDMA, and of TDD is HiperLAN2.

Use of antenna arrays, at the access point, offers a lot of advantages such as possibility of suppression of interference, but also drawbacks. For example, to be able to form efficient beams in the cell, the channel has to be known. The channel is more complex and so are the algorithms to estimate it. Generally, the estimate of the channel has to be present at the access point to be able to send and receive the desired signals. The obvious method is to estimate the uplink channel, blindly or from
a training sequence, and then to use that estimate when receiving the uplink signal. From the uplink signal it is then possible to estimate the downlink channel. Assuming Time Division Duplex (TDD), i.e. the uplink and downlink are using the same frequency, but different timeslots, and further that the channel variations (due to fading) are slow, it is possible to use the uplink estimate for the downlink beamforming.

Systems used today, like GSM and UMTS, are using Frequency Division Duplex (FDD), meaning that uplink and downlink signals are sent on different frequencies. This means that even if the uplink channel may be estimated, the knowledge about the downlink channel is limited as the signal fades differently on different carrier frequencies. Further, even if the joint beamforming and power control problem is solved for the uplink [Ben99], the terminal has to use the optimal power when transmitting and the access point has to use the optimal weights when receiving and thus the optimal solution has to be communicated to the terminal before it starts transmitting.

There is a traffic difference between uplink and downlink. In the downlink, the system (access point) has knowledge of the current traffic and thus possibility to schedule the transmission to multiple users, whereas on the uplink the user terminal does not have knowledge of other users’ traffic. On the downlink scheduling can thus be performed, using algorithms assessed in e.g. [SDSK98], while a simpler scheme such as the slotted ALOHA random access scheme may be used on the uplink.

### 3.4.2 Packet Switching Aspects

The transition during the 90s, from wireless voice to wireless data has changed the method of carrying information from circuit switched networks to combined circuit and packet switched networks. Currently work is going on to only use packet switched networks under the Internet Protocol (IP). This influences the lower level in the Open Systems Interconnection (OSI) model. In a circuit switched network the quality of service measurement from layer one was to give a certain Signal-to-Interference-and-Noise-ratio (SINR), during the whole time the link was active. Using packet switching, the new dimension time or latency is interesting as it increases the degrees of freedom making it possible to support more traffic in the network. The issue of uplink communications in a packet switched system with smart antennas was investigated in [SO99].
3.5 Summary

In this chapter the concept of smart antennas has been introduced. In the following some of the problems and challenges of smart antennas will be addressed, e.g. packet switched communication, downlink beamforming strategies and dual arrays.
Part I

Smart Antennas in Wireless Systems
Chapter 4

Data Models

4.1 Introduction

In order to investigate the impact of smart antennas on a wireless system, the whole system has to be taken into account. Certain assumptions influence the link between the transmitter and the receiver, such as propagation and noise. Other assumptions influence the system such as traffic models and network planning. Here follows a description of models and assumptions used in the following chapters. Each of the following chapters are self contained and the reader can proceed directly to them.

4.2 Signal Model

In the signal model, we will consider discrete-time, base-band and complex valued signals. Consider the following scenario: A transmitter wants to transmit the $n_T \times 1$ message $s(t)$ through the $n_R \times n_T$ channel $H$ to a receiver. The signals assumed herein are narrowband and the channels are narrowband without time dispersion. The system has $n_T$ transmitters and $n_R$ receivers. At the transmitters the $n_T \times n_T$ weight $W_T$ is applied and at the receivers the $n_R \times n_R$ weight $W_R$ is applied. The total transmitted signal is then written

$$x(t) = W_T s(t)$$

(4.1)

The received signal $r(t)$ is denoted

$$r(t) = W_R^* H W_T s(t) + W_R^* n(t)$$

(4.2)
where \( n(t) \) is the \( n_R \times 1 \) noise vector at the receiver side. Generally \( s(t) \) contains the information to be transmitted. The channel matrix \( \mathbf{H} \), contains the effects that the channel has on the transmitted signal. In order to design a system with this signal model three issues are of interest

- What system of communicating piers do we have?
- What does the channel \( \mathbf{H} \) look like and what spatial characteristics does it have?
- How should the weight matrices \( \mathbf{W}_T \) and \( \mathbf{W}_R \) be chosen for different systems?

The model above describes the three different cases touched on in this thesis. First, in the general case where both the receiver and the transmitter are equipped with antenna arrays, i.e. dual arrays, the Multiple-Input-Multiple-Output (MIMO) channel matrix \( \mathbf{H} \) represents the channel between the receiver and the transmitter, and the transmitter and receiver weights are adapted to the total channel. This case is investigated in Part II.

Second, the uplink case is treated. In this case Single-Input-Multiple-Output channels are considered, i.e. one transmitted signal is received by an array. In the downlink case Multiple-Input-Single-Output channels are considered. In these two cases we assume that each access point communicates with several mobile terminals.

### 4.2.1 Uplink Communication

In the uplink we will consider an array at the access point and a single antenna at the terminal. Several terminals will be active simultaneously. It is assumed that we have \( d \) sources, i.e. \( n_T \) above is denoted \( d \). The number of antenna elements at the access point is then denoted \( n_R \).

The transmitted signal vector \( s(t) \) contains the scalar signals \( s_i(t) \) from terminals \( i, i = 1\ldots d \). The only transmitter weights used are the scalar power weights, used in each terminal. Each of the \( n_T \) signals transmitted, is assumed to pass the \( n_R \times 1 \) frequency flat fading vector channel \( \mathbf{v}_i^n \) i.e. the channel matrix \( \mathbf{H} = [\mathbf{v}_1^n \mathbf{v}_2^n \cdots \mathbf{v}_d^n] \). The vectors \( \mathbf{v}_i^n \) are random zero-mean complex valued vectors denoting the spatial channel from terminal \( i \), with correlation matrix

\[
\mathbf{R}^n_i = E[\mathbf{v}_i^n(\mathbf{v}_i^n)^*]
\]  
(4.3)
4.2 Signal Model

The signal vector $x^u$ at the antenna array is

$$x^u(t) = \sum_{i=1}^{d} v^u_i s_i(t) + n(t)$$

(4.4)

where $n(t)$ is the noise vector at the receiver. The noise is assumed to be spatially and temporally white. At the access point, receiver weights $w_i$ are applied to find the desired signals and $W_R = [w_1 \ldots w_{n_R}]$. When receiving the signal $s_k(t)$ the received signal is

$$r^u_k(t) = w^*_k x^u(t) = w^*_k \sum_{i=1}^{d} v^u_i s_i(t) + w^*_k n(t)$$

(4.5)

The received signal may be written

$$r^u_k(t) = w^*_k v^u_k s_k(t) + \sum_{i=1, i \neq k}^{d} w^*_k v^u_i s_i(t) + w^*_k n(t) = c_S + c_I + c_N$$

(4.6)

where $c_S$ is the desired signal, $c_I$ is the unwanted interference from other users and $c_N$ is the noise.

A common performance criterion is the Signal-to-Interference-and-Noise ratio (SINR). The SINR for the uplink is defined

$$\text{SINR}^u = \frac{E[|c_S|^2]}{E[|c_I|^2] + E[|c_N|^2]}.$$  (4.7)

4.2.2 Downlink Communication

In the downlink case, the access point wants to transmit the scalar signals $s_i$, to the terminal $i$, $i = 1 \ldots d$. There are $K$ access points serving these mobile terminals and it is possible for each access point to serve several mobile terminals. The $i$th mobile terminal is assigned to access point $\kappa(i)$ and the set $\mathcal{I}(j) = \{i; \kappa(i) = j\}$ contains all mobile terminals assigned to the $j$th access point. The total transmitted signal becomes

$$x_j(t) = \sum_{i \in \mathcal{I}(j)} w_i s_i(t)$$

(4.8)

Here the transmitter weights for terminal $i$, $w_i$ contain both the spatial weighting and the power scaling.
The received signal at the \(i\)th terminal is modeled as

\[
r^d_i(t) = \sum_{j=1}^{K} (v^d_{i,j})^* x_j(t) + n_i(t) \tag{4.9}
\]

where the random complex valued vector \(v^d_{i,j}\) is the spatial downlink channel to terminal \(i\) from access point \(j\), with correlation matrix

\[
R^d_{i,j} = E[(v^d_{i,j})(v^d_{i,j})^*]. \tag{4.10}
\]

In the same manner as in the uplink case it is possible to divide the signal into desired signal plus unwanted interference from other users and noise. Thus a \(\text{SINR}^d\) may be defined as a performance measure in the same manner as above, see Chapter 6.

### 4.3 Spatial Channel Models

In the signal model presented above, the channel matrix \(H\) contains the channel and propagation characteristics. The propagation model chosen for the design of wireless networks is of great importance when using smart antennas. Several channel models are proposed in the literature e.g. [TO96] [Zet97] [FMB98] [ECS+98].

One important distinction for spatial channel models is the difference between point source models and models assuming scattering. The structure of the models is highly dependent on the environment. For communication between antennas that are higher than the surrounding buildings and nature, i.e. a Line-of-Sight channel, the point source model is acceptable. In wireless communication, at least the terminal is often in an area surrounded by scattering objects, such as buildings, cars and walls, which will scatter the incoming signal. This motivates the scattering models that will be introduced below. In the uplink and downlink communications case, a local scattering model parameterized by the Direction-of Arrival and the spread angle is used, while for the case of dual array communications over a MIMO channel, a rich scattering indoor environment is assumed.

#### 4.3.1 Scalar Channel Factors

Independent of the spatial characteristics, scalar factors such as propagation loss, apply on the channel. In free space a model is used where
the radio signal decreases proportional to $\frac{1}{r^p}$, where $r$ is the distance between transmitter and receiver and the propagation coefficient, $\alpha_p = 2$. Close to the surface of the earth and in cities, the propagation environment is more complicated and there $\alpha_p$, is in general between 3.5 and 4 [AZ98]. Due to scattering, the received signal fades. The fast fading is assumed to be frequency flat and Rayleigh distributed. The mean over the link gain is assumed shadow fading and the gain is assumed to have a lognormal distribution with variance, $\sigma^2_{\text{shadow}}$ [AZ98].

### 4.3.2 Local Scattering Channel Model

One model to describe the propagation between a terminal and an access point in an urban environment is the local scattering model. The local scattering model may be interpreted in two ways. Either the source is spatially distributed, or a point source is surrounded by discrete reflectors, reflecting the transmitting signal to the receiver array, as shown in Figure 4.1. This model has been introduced into array processing in [ZO95] and [TO96].

Returning to the signal model in e.g. (4.4), we want to find out the distribution of the channel vectors for the local scattering model. Assuming $s(t)$ to be the only transmitted signal, the received vector $x(t) = [x_1(t) \ldots x_n(t)]^T$ will become

$$x(t) = s(t) \sum_{n=1}^{L} \gamma_n(t)a(\hat{\theta}_n(t)) + n(t) = s(t)v(t, \theta, \sigma_\theta) + n(t) \quad (4.11)$$

where $L$ is the (large) number of rays in the sum signal, $\gamma_n(t)$ is the random complex gain and $\hat{\theta}_n(t)$ is the random angular deviation from $\theta$. The vector $a(\theta)$ is the array response and it is dependent of the antenna array geometry chosen. The covariance matrix for the zero-mean channel vector $v(t, \theta, \sigma_\theta)$ is defined as $R_v = E[v(t, \theta, \sigma_\theta)v^*(t, \theta, \sigma_\theta)]$. This covariance matrix is derived for a Uniform Circular Array (UCA) and small angular deviations in Appendix 4.A.

### 4.4 Receiver and Transmitter Strategies

#### 4.4.1 Antenna Models

Herein we assume two kinds of antennas models, the uniform circular array antenna and the idealized antenna.
A Uniform Circular Array (UCA) with $m$ antenna elements is shown in Figure 4.2. The antenna elements are assumed to be omni-directional. The array radius is calculated to achieve an antenna element spacing just below $\frac{\lambda}{2}$ between the elements [AFFM98].

The array response, $a(\theta)$ for the UCA, with an incoming far field beam from angle $\theta$, is defined

$$a(\theta) = \left[ e^{j \frac{2\pi n}{m} \cos(-\theta)} \ldots e^{j \frac{2\pi (n-1)}{m} \cos\left(\frac{2\pi}{m} - \theta\right)} \right]^T$$

(4.12)

Throughout this part, several ways of using the UCA will be examined, i.e. ways to combine the incoming signals and side information such as channel knowledge.

**Idealized Antenna Model**

A simple approximation of a smart antenna is the idealized sector antenna, defined with unit gain in the desired direction sector and a lower
gain in other directions. A basic idealized sector antenna is used to find maximum throughput in a cell and the implications for the Medium Access Control (MAC) layer in [CR98]. A more sophisticated model, taking sidelobes and fading into account is used in [PER98] for circuit switched networks (AMPS). Further definitions of the idealized antenna are found in Chapter 5.

4.4.2 Uplink Receiver Strategies

For the uplink case it is assumed that perfect channel information is present. This is possible since the channel may be estimated during reception.
### 4.4.3 Downlink Transmitter Strategies

It is not realistic to assume exact channel knowledge at the transmitter since the channel estimated has to be based on measurement on the uplink. There are methods proposed on how to transform the uplink channel statistics into downlink channel statistics [BO01]. In practice this can be achieved by assuming that the uplink and downlink distributions are the same and by estimating the parameters $\theta$ and $\sigma_{\text{spread}}$ of the channel distribution and then to using this knowledge when transmitting.

For the downlink case it is thus assumed that the transmitter has knowledge of the channel statistics i.e. the second order statistics (4.10) of all link channels.

### 4.5 System Aspects

#### 4.5.1 Traffic Models

The Poisson model is widely used to describe arrivals in telephone systems, where it may be assumed that the populations is infinite [Kör92]. Related is the Bernoulli model for finite populations. The latter may be used when mean delay is a output parameter [Kör92].

Bringing the spatial domain into a system analysis calls for a spatial traffic model. The system analyzed in the two following chapters consists of terminals, uniformly distributed over the area.

#### 4.5.2 Cellular Model

A very important issue in cellular systems is how close to the receiver interfering signals are transmitted. For the case with only one terminal in each cell, the reuse distance, i.e. the distance between cells using the same resource such as time slot or frequency, is important. As seen in Figure 3.1, a hexagonal structure may be used to represent the cellular net. Partitioning the available resources into $K$ subsets, where $K \in \{1, 3, 4, 7, 9, \ldots\}$, it is possible to get six co-channel sets. The center to center distance between these cell is

$$D = \sqrt{3KR} \quad (4.13)$$

where $R$ is the cell radius [Zan92].

In current systems, the cells are further divided into sectors, covered by a sector access point. Herein, we use one omni-directional access point
4.5 System Aspects

per cell and the access points are positioned in the cell centers. Only reuse one is considered.

In practice, of course, the hexagonal cellular model, are not used since it is impossible to partition the landscape into hexagonal areas. Even if possible that would not give the best assignment of access point-terminal pair anyway, due to propagation effects. Thus the real cell is defined from, what access point a terminal is connected to i.e. depending on the access point assignment algorithm. A widely used algorithm is to assign the terminal to the access point, from which it receives the strongest signal. This method is used herein as comparison to the method for joint optimal beamforming, power control and base station assignment [Ben00], investigated.

4.5.3 Systems Simulations Issues

When simulating a cellular system, many models have to be taken into account. In the case of taking signals from surrounding cells into account a proper traffic process must be present on in these surrounding cells too. Herein this issue is taken care of by using a wrapped system, i.e. all cells are surrounded by all other cells. Thus the whole simulated area corresponds to a torus shape. First the cellular structure is created and then a number of mobiles are positioned on the grid. The number of terminals is taken from an assumed arrival distribution, mentioned above. The mobiles are positioned uniformly in space over the grid.

All scalar effects of the channel are included in a gain matrix, $G$. The effects of spatial processing is then added to the gain matrix and the Signal-to-Interference-and-Noise Ratio is evaluated in order to find the probability of outage, i.e the probability that a mobile terminal does not have a received SINR below the target SINR for the desired service.
Appendix 4.A Approximation for Gaussian Distributed Scattering

4.A.1 Derivation of Covariance Matrix for a UCA with Gaussian Distributed Scattering

In order to efficiently simulate vector channels with the Uniform Circular Array (UCA), the covariance matrix for the channel is needed.

The incoming signal is assumed narrowband and to consist of several rays, which comes from scatterers in the surrounding of the terminal. Then it has proven valid [Zet97] [TO96] [Ben99], to model the angles of the incoming rays as having Gaussian distribution with average angle $\theta$ and angular spread $\sigma$.

With the channel vector $\mathbf{v}(t, \theta, \sigma_\theta)$, the received signal may be modeled as

$$\mathbf{x}(t) = \mathbf{s}(t)\mathbf{v}(t, \theta, \sigma_\theta) + \mathbf{n}(t) \quad (4.14)$$

where $\mathbf{n}(t)$ is white Gaussian noise.

The covariance matrix of $\mathbf{v}(t, \theta, \sigma_\theta)$ is defined

$$\mathbf{R}_\mathbf{v} = E[\mathbf{v}(t, \theta, \sigma_\theta)\mathbf{v}^*(t, \theta, \sigma_\theta)] \quad (4.15)$$

The array response, $\mathbf{a}(\theta)$ for a UCA is defined

$$\mathbf{a}(\theta) = \begin{bmatrix} e^{j\frac{2\pi}{\lambda} \cos(-\theta)} & \cdots & e^{j\frac{2\pi}{\lambda} \cos(\frac{m-1}{m} 2\pi - \theta)} \end{bmatrix}^T \quad (4.16)$$

Denoting the spreading angle $\bar{\theta}$, the covariance matrix may be written

$$\int_{-\infty}^{\infty} p(\bar{\theta}, \sigma_\theta) \mathbf{a}(\theta + \bar{\theta})\mathbf{a}^*(\theta + \bar{\theta}) d\bar{\theta} \quad (4.17)$$

where $p(\bar{\theta}, \sigma_\theta)$ is the density function for the angular spread.

Using the following expression for a small angle $\beta$

$$\cos(\alpha + \beta) = \cos(\alpha) \cos(\beta) + \sin(\alpha) \sin(\beta)$$
$$\approx \cos(\alpha) \cdot 1 + \beta \sin(\alpha) \quad (4.18)$$

the array response in $k$th element in $\mathbf{a}(\theta + \bar{\theta})$ may be approximated as

$$e^{j\frac{2\pi}{\lambda} \cos(\frac{m-1}{m} 2\pi - \theta)} = e^{j\frac{2\pi}{\lambda} [\cos(\frac{m-1}{m} 2\pi - \theta) 1 + \sin(\frac{m-1}{m} 2\pi - \theta) \bar{\theta}] \quad (4.19)$$
4.A Approximation for Gaussian Distributed Scattering

yielding the $k\ell$th element in the matrix $\mathbf{a}(\theta + \tilde{\theta})\mathbf{a}^*(\theta + \tilde{\theta})$

$$|\mathbf{a}(\theta + \tilde{\theta})\mathbf{a}^*(\theta + \tilde{\theta})|_{k\ell} =
\begin{align*}
e^{j\frac{2\pi}{\sqrt{m}}\left[\cos\left(\frac{k-1}{2\pi}2\pi\theta\right)1+\sin\left(\frac{l-1}{2\pi}2\pi\theta\right)\tilde{\theta}\right]} 
&\cdot e^{-j\frac{2\pi}{\sqrt{m}}\left[\cos\left(\frac{k-1}{2\pi}2\pi\theta\right)1+\sin\left(\frac{l-1}{2\pi}2\pi\theta\right)\tilde{\theta}\right]} =
\end{align*}
$$

\begin{align*}
e^{j\frac{2\pi}{\sqrt{m}}\left[-2\sin\left(\frac{k-1}{2\sqrt{m}}2\pi\theta\right)\sin\left(\frac{L-1}{2\sqrt{m}}2\pi\theta\right) + 2\tilde{\theta}\sin\left(\frac{k-1}{2\sqrt{m}}2\pi\theta\right)\cos\left(\frac{L-1}{2\sqrt{m}}2\pi\theta\right)\right]}
\end{align*}

(4.20)

This gives the $k\ell$th element in the covariance matrix to be

$$R_{k\ell} = \int_{-\infty}^{\infty} p(\tilde{\theta}, \sigma_{\tilde{\theta}}) e^{j\frac{2\pi}{\sqrt{m}}\left[-2\sin\left(\frac{k-1}{2\sqrt{m}}2\pi\theta\right)\sin\left(\frac{L-1}{2\sqrt{m}}2\pi\theta\right) + 2\tilde{\theta}\sin\left(\frac{k-1}{2\sqrt{m}}2\pi\theta\right)\cos\left(\frac{L-1}{2\sqrt{m}}2\pi\theta\right)\right]} d\tilde{\theta} \quad (4.21)$$

Using $p(\tilde{\theta}, \sigma_{\tilde{\theta}})$ for a Gaussian distribution, the integral may be solved e.g. by using the moment generating function for $N(0, \sigma)$, giving the final expression

$$R_{k\ell} = e^{\frac{j2\pi}{\sqrt{m}}\sin\left(\frac{k-1}{\sqrt{m}}\pi\right)\sin\left(\frac{L-1}{\sqrt{m}}\pi\theta\right)\sigma_{\tilde{\theta}}^2} \cdot e^\frac{2}{\sqrt{m}}\left[\frac{2\pi}{\sqrt{m}}\sin\left(\frac{k-1}{\sqrt{m}}\pi\right)\cos\left(\frac{L-1}{\sqrt{m}}\pi\theta\right)\right]^2 \quad (4.22)$$
Chapter 5

Uplink Beamforming with Packet Switching

5.1 Introduction

The purpose of this chapter is to investigate what throughput may be achievable on the uplink for a packet-switched system with antenna arrays at the base station. An idealized sector/multi-beam antenna model is investigated analytically and compared to models utilizing spatial processing in simulations. One objective is to find the differences between using diversity combining and interference rejection and how the choice between these affects the system performance. Performance is characterized in terms of cell throughput and packet delay.

Several channel and antenna models can be found in the literature. A basic idealized sector antenna is used to find maximum throughput in a cell and the implications for the Medium Access Control (MAC) layer in [CR98]. A more sophisticated model, taking sidelobes and fading into account is used in [PER98] for circuit switched networks (AMPS). However, the results differ from those in [PER98]. In [PER98], the distribution of the envelopes (instead of powers) is used in the outage probabilities which is incorrect.

The traffic and protocol issues for spatial processing are investigated in [WC93]. In [Zet97] statistical models for spatial channels are presented and beamformers are proposed. These models may provide a means to utilize the spatial diversity of the channel. Models for traffic and multiple
This chapter is comprised of three parts. First an analysis of packet-switching in one cell is carried out and an expression for the throughput is derived. This result is then compared to simulations. The simulations are then expanded to include a statistical channel model as well as different beamformers and more advanced traffic issues.

5.2 System and Analysis

5.2.1 Traffic Model

The system analyzed consists of the uplink of one cell with uniformly distributed mobile stations. Interference from other cells is neglected as sufficient frequency planning is assumed. The mobile terminals generate packets from independent Poisson distributions with infinite terminal population. Packet switching is used with random multiple access according to the Slotted-ALOHA scheme [PL95]. It is well known that the Slotted ALOHA scheme has a maximum throughput of 37%, where 100% corresponds to when all transmitted packets are successfully received. The system is assumed to be interference limited and thus the noise power is small.

When receiving a packet, the success for this packet depends on the Carrier-to-Interference-Ratio (CIR). Thus several packets may be successfully received at the receiver in each slot, so called capture.

5.2.2 Channel and Receiver models

Two kinds of channels are assumed. First, a planar wavefront model is used for ideal beamformers. The channel to the \(i\)th terminal is then defined as an Angle-of-Arrival \(\theta\) and a Rayleigh faded envelope \(x_i \sim \mathcal{CN}(1, \sigma_x)\), where \(\sigma_x\) is the standard deviation.

Second, a low rank (flat fading) statistical channel model is used to model flat fading due to local independent scattering at the terminal [Zet97], see Chapter 4. The angular distribution of the received signal is assumed Gaussian for relatively small angular spread. The received signal from each transmitter is made up of several rays due to local scattering. The channel from terminal \(i \in [1, d]\), where \(d\) is the number of terminals active, is modeled as \(v_i \sim \mathcal{N}(0, \mathbf{R}(\theta_i, \sigma_{spread}))\), where \(\mathbf{R}(\theta, \sigma_{spread})\) is the correlation matrix depending on the nominal angle-of-arrival of the
signal and standard deviation of the spread angle. Thus the multi channel receive vector is

\[ x_i(t) = v_i s_i(t) + n_i(t) \]  \hspace{1cm} (5.1)

where \( s_i(t) \) is the transmitted signal and \( n_i(t) \) is the receiver noise. The vectors \( x_i, v_i \) and \( n_i \) are of dimension \( m \times 1 \), where \( m \) is the number of antenna elements in the array.

### 5.2.3 Beamforming

An ideal beamformer is used for the planar wavefront channel model. The beamformer, used in [PER98] under the name flat-top beamformer, consists of a perfect sector lobe of width \( \Delta \theta \) with gain 1 and a sidelobe level with gain \( 0 \leq A \leq 1 \). The main beam is always pointing in the direction, \( \theta \), of the desired terminal. The idealized weight to the \( j^{th} \) terminal when the \( i^{th} \) terminal is desired is then

\[ w_{ij} = \begin{cases} 1 & j^{th} \text{ terminal in } i^{th} \text{ mainlobe} \\ \sqrt{A} & j^{th} \text{ terminal in } i^{th} \text{ sidelobe} \end{cases} \]  \hspace{1cm} (5.2)

and thus the total received signal, \( r_i \), becomes

\[ r_i = \sum_{j=1}^{d} w_{ij} x_j \]  \hspace{1cm} (5.3)

In figure 5.1, a flat-top beamformer with beamwidth of 25° is compared to a simple beamformer with eight antenna elements for a local scattering channel. In the following \( A = 0.1 = -10 \text{ dB} \) and beamwidths of 10°, 30° and 60° will be used. An omni-directional antenna will be used for reference.

For the statistical channel, a Uniform Circular Array (UCA) is used at the base station. With the UCA the signal is resolved using diversity (Maximum Ratio Combining) and Interference Rejection (Zero Forcing and Minimum Mean Square Error). Herein it is assumed that the channels to the sources are known and that the autocorrelation and crosscorrelation are estimated perfectly at the receiver.

\[ R_{xx} = VR_{ss} V^H + \sigma^2 I \]  \hspace{1cm} (5.4)

\[ R_{xs} = VR_{ss} = V \]  \hspace{1cm} (5.5)
Figure 5.1: Comparison of idealized antenna with beamwidth = 25° and sidelobe level -10 dB and MRC with 8 elements and a local scattering channel with $\sigma_{\text{spread}} = 3^\circ$. 
where the signal correlation matrix $R_{ss}$ is assumed to be the identity matrix and $V = [v_1, v_2, \ldots, v_d]$.

For Maximum Ratio Combining, Zero Forcing and MMSE, solutions the following weight vectors are used, respectively

\[
W_{\text{MRC}} = V^H \\
W_{\text{ZF}} = V^\dagger \\
W_{\text{MMSE}} = R_{xx}^{-1}V. 
\]

5.2.4 Outage Calculations

The $i$th total received signal, $r_i$, after beamforming is then modeled as:

\[ r_i = \sum_{j=1}^{d} w_i^* x_j, \]

where $w_i$ is a column in $W = [w_1, w_2, \ldots, w_d]$.

The Carrier-to-Interference Ratio, CIR, is defined as the desired signal power $C^{(i)}$ from terminal $i$ divided by the interference power $I^{(i)}$ from all other terminals when terminal $i$ is the desired user

\[ \text{CIR} = C^{(i)}/I^{(i)} \]

Outage occurs when the CIR is less than a target CIR $\gamma_0$, given by the application and coding environment.

After the beamforming, the total received signal and interference power is

\[ P^{(i)} = E[r_i r_i^*] = C^{(i)} + I^{(i)}. \]

To calculate the probability of outage [Stui96] [PER98] with idealized antennas, let the main beam always be pointed at the desired user. Then the interfering users within the cell can be divided into two groups: The $n_1$ interferers inside the main lobe and the $n_2$ interferers in the sidelobe. Further assuming perfect power control (before beamforming) implies that all users in one group will have the same received mean power. The carrier power is denoted $C$ and the interference power is denoted $I = \sum J_{kl}$, where $k = 1$ (in main lobe), 2 (in sidelobe), and $l$ runs through
the \( n_k \) interferers in the lobe specified by \( k \). The outage probability is then

\[
P(CIR < \gamma_0|n_1, n_2) = P\left(\frac{C}{I} < \gamma_0 \right) = \int_{-\infty}^{\infty} \int_{0}^{\gamma_0 \beta} p_C(\alpha)p_I(\beta)d\alpha d\beta
\]  

(5.12)

which may be calculated as shown in Appendix 5.A.

For the simple case where either \( n_1 \) or \( n_2 \) is zero, we have [Stü96]

\[
P(CIR < \gamma_0|n_k) = 1 - \frac{1}{(1 + \frac{n_k}{m_c \gamma_0})^{n_k}}
\]  

(5.13)

where \( n_k \) is the number of interferers either inside or outside the main beam. The total probability of outage is then [PER98]

\[
P(CIR < \gamma_0) = \sum_{n_1} \sum_{n_2} P(CIR < \gamma_0|n_1, n_2)P(n_1, n_2)
\]  

(5.14)

where \( P(n_1, n_2) \) is the probability of \( n_1 \) interferers in the main lobe and \( n_2 \) interferers in the sidelobe.

Note that the calculations above differ from those in [PER98]. In [PER98], the distribution of the envelopes (instead of powers) is used in the outage probabilities which is incorrect.

### 5.2.5 Throughput

For this Slotted-ALOHA system the throughput \( S \) is calculated as the offered load (packets/slot/cell) \( G \) multiplied with the probability of success given that load, \((1 - P(CIR < \gamma_0))\),

\[
S = G \cdot (1 - P(CIR < \gamma_0)).
\]  

(5.15)

### 5.2.6 Simulations

A finite population is used in the simulations [WC93]. Unsuccessful packets will be retransmitted and the terminals are assumed to have a one packet buffer i.e. as long as the last packet has not succeeded, a new packet can not be sent from a terminal.
5.3 Results

5.3.1 Theoretic Model and Idealized beamformers

Calculations and simulations have been performed for different sidelobe levels, lobewidths and cell loads. Figure 5.2 shows results on throughput, calculated with the analytical model presented above and a sidelobe level of -10 dB. Figure 5.3 shows the corresponding results for the simulated

Figure 5.2: Calculated throughput for Ideal Antenna with side lobe level -10 dB.

The local scattering channel is created from 10 rays with an angle spread of $\sigma_{\text{spread}}$. A typical value in an outdoor environment is $\sigma_{\text{spread}} = 3^\circ$ [Zet97]. This value is used independent of the range to the terminal. It is assumed herein that the target CIR for successful reception is 15 dB. The radius of the UCA is derived from the number of elements in the array, to give an inter-element distance of half a wavelength.

It is assumed that there is sufficient capacity at the access point to process all the incoming packet transmission, i.e., the limiting factor is the probability of outage.
system and it shows that the analytical model can be used to calculate the throughput in a packet system with a flat-top beamformer. In these results no retransmission of rejected packets is performed. These results show that the throughput in a packet system may be increased substantially compared to the omni-directional antenna system. However the main increase comes with the introduction of the sector antenna and narrowing the beam further will only give slightly improved performance. It is shown that the possible throughput may be increase from 37 % to 48 % with sector antennas.

### 5.3.2 Combining Methods

Simulations on statistical channels have been performed for different number of antenna elements in the UCA for both maximum ratio combining and interference rejection. Figure 5.4 shows the throughput possible using Maximum Ratio Combining, compared to an omni-directional antenna.

The results show a substantial increase of throughput when using in-
5.3 Results

Figure 5.4: Simulated throughput for maximum ratio combining for different number of antenna elements. Target CIR for successful reception is 15 dB.

Interference rejection as opposed to maximum ratio combining. In this interference limited system assumed, the zero forcing and the interference rejection solutions achieve the same results. The interference rejection throughput is shown in figure 5.5. Using combining methods does not reach a throughput ceiling as the idealized antennas did. Instead it is shown that for the assumed system maximum ratio combining may increase the throughput to be more than 60 % and when using interference rejection combining it is possible to increase the throughput several times.

5.3.3 Latency and Delay Issues

In a packet network a variety of services are offered with different requirements of quality of service. One crucial parameter is the packet delay. Figure 5.6 shows the throughput plotted as a function of mean delay. Note that it is possible to achieve the maximum throughput while
Figure 5.5: Simulated throughput for the minimum mean square estimator solution for different number of antenna elements. Target CIR for successful reception is 15 dB.

maintaining a low mean delay.

5.4 Summary

A analytic expression for the throughput in a slotted ALOHA packet network using idealized smart antennas has been developed and supported by simulations. A planar wavefront propagation model with an ideal beamformer is assumed as well as a local scattering channel model providing a spatial extension of the flat fading channel. Diversity combining (Maximum Ratio Combining) and interference rejection are compared when the channel realizations are known. System performance is characterized in terms of packet throughput and delay. We show that the system throughput for a packet network utilizing adaptive array antennas may be increased substantially while maintaining a low packet delay.
Figure 5.6: Packet throughput as function of the mean delay for Interference rejection combining (MMSE). For 12 and 16 elements the curves end as the delay is limited to about three and one slots, respectively. Target CIR for successful reception is 15 dB.

Interference rejection can potentially provide a significant improvement over diversity combining alone.
Appendix 5.A Derivation of Outage Probability for the Idealized Beamformer

The outage probability is given by

\begin{equation}
P(CIR < \gamma_0 | n_1, n_2) = P\left( \frac{C}{T} < \gamma_0 \right) = \\
\int_{-\infty}^{\infty} \int_{0}^{n_2}\ p_C(\alpha)p_I(\beta)d\alpha d\beta
\end{equation}

(5.16)

Assume that the signal envelopes of the power $C$ and $I_{kl}$ are Rayleigh fading and thus that the powers have exponential distributions. Define $I_k$ as the sum of all the interferers power in lobe $k$. This is a sum of exponentially distributed variables and thus it is Gamma distributed

\begin{align}
p_C(\alpha) &= \frac{1}{m_C} e^{-\frac{\alpha}{m_C}} \\
p_I(\beta_k) &= \frac{1}{m_{I_k}} \left( \frac{\beta_k^{m_{I_k}} - 1}{m_{I_k}} \right) e^{-\frac{\beta_k}{m_{I_k}}}.
\end{align}

(5.17) (5.18)

where $m_C = E[C]$ and $m_{I_k} = E[I_{kl}]$. To find the distribution for $I = I_1 + I_2$, Laplace methods may be used as $p_I = p_{I_1} * p_{I_2}$ and thus $Lp_I = Lp_{I_1} Lp_{I_2}$, where $Lp_{I_k} = \left( \frac{1}{m_{I_k}} \right)^{n_k}$. This yields

\begin{equation}
Lp_I = \frac{1}{m_{I_1} m_{I_2}} \left( \frac{1}{s + \frac{1}{m_{I_1}}} \right)^{n_1} \left( \frac{1}{s + \frac{1}{m_{I_2}}} \right)^{n_2}
\end{equation}

(5.19)

\begin{align}
&= \frac{1}{m_{I_1} m_{I_2}} \\
&= \left[ \frac{A_1}{(s + \frac{1}{m_{I_1}})^1} + \frac{A_2}{(s + \frac{1}{m_{I_1}})^2} + \cdots + \frac{A_{n_1}}{(s + \frac{1}{m_{I_1}})^{n_1}} + \right. \\
&\left. \frac{B_1}{(s + \frac{1}{m_{I_2}})^1} + \frac{B_2}{(s + \frac{1}{m_{I_2}})^2} + \cdots + \frac{B_{n_2}}{(s + \frac{1}{m_{I_2}})^{n_2}} \right]
\end{align}

where $A_j$ and $B_j$ are coefficients from the partial fraction decomposition and may be found via solving a linear equation system. This expression
can be inverse transformed as

\[ p_I (\beta) = \frac{1}{m_{I_1}^n m_{I_2}^n} \left[ \sum_{j=1}^{n_1} \frac{A_j \beta^{j-1}}{(j-1)!} e^{-\frac{\beta}{m_{I_1}}} + \sum_{j=1}^{n_2} \frac{B_j \beta^{j-1}}{(j-1)!} e^{-\frac{\beta}{m_{I_2}}} \right] \]  

(5.20)

Inserting (5.20) in (5.16) gives the expression for the outage probability

\[ P(\text{CIR} < \gamma_0 | n_1, n_2) = \int_{-\infty}^{\infty} \int_{0}^{\gamma_0 \beta} p_C(\alpha) p_I(\beta) d\alpha d\beta \]

\[ = \int_{-\infty}^{\infty} p_I(\beta) \left[ \int_{0}^{\gamma_0 \beta} \frac{1}{m_C} e^{-\frac{\alpha}{m_C}} d\alpha \right] d\beta \]

\[ = 1 - \int_{-\infty}^{\infty} p_I(\beta) e^{-\frac{\beta}{m_C}} d\beta \]

\[ = 1 - \frac{1}{m_{I_1}^n m_{I_2}^n} \left[ \sum_{j=1}^{n_1} \frac{A_j}{(j-1)!} \int_{0}^{\infty} \beta^{j-1} e^{-\left(\frac{\beta}{m_{I_1}} + \frac{\gamma_0}{m_C}\right)} \right] + \sum_{j=1}^{n_2} \frac{B_j}{(j-1)!} \int_{0}^{\infty} \beta^{j-1} e^{-\left(\frac{\beta}{m_{I_2}} + \frac{\gamma_0}{m_C}\right)} \right] \]

\[ = 1 - \frac{1}{m_{I_1}^n m_{I_2}^n} \left[ \sum_{j=1}^{n_1} \left( \frac{A_j}{m_{I_1} + \frac{\gamma_0}{m_C}} \right) + \sum_{j=1}^{n_2} \frac{B_j}{m_{I_2} + \frac{\gamma_0}{m_C}} \right] \]

For the case where either \( n_1 \) or \( n_2 \) is zero the we have [Stü96]

\[ P(\text{CIR} < \gamma_0 | n_k) = 1 - \frac{1}{(1 + \frac{m_k}{m_C} \gamma_0)^{n_k}} \]  

(5.22)

where \( n_k \) is the number of interferers either inside or outside the main
beam. The total probability of outage is given by [PER98]

\[ P(\text{CIR} < \gamma_0) = \sum_{n_1} \sum_{n_2} P(\text{CIR} < \gamma_0 | n_1, n_2) P(n_1, n_2) \]  

(5.23)

where \( P(n_1, n_2) \) is the probability of \( n_1 \) interferers in the main lobe and \( n_2 \) interferers in the sidelobe.
Chapter 6

Downlink Beamforming - a System View

6.1 Introduction

This chapter considers the downlink of a system using the multiple access scheme denoted Space Division Multiple Access (SDMA). Downlink communication is treated since data traffic is expected to be asymmetric leading to a capacity bottleneck in the communication from the access points to the terminals.

The issue of downlink beamforming has been investigated in e.g. [GP94, GP96, Zet99, BO01]. The problem of optimal downlink beamforming is formulated in [FN95] and the criteria used for optimality is minimizing the total transmitted power, given that all users have acceptable Quality of Service (QoS). Of course other optimality criteria exist. The optimization problem above, can be solved using the algorithms in [RFLT98, Ben99, SB02]. The algorithm has been extended to perform joint optimal power control, beamforming and access point assignment in [Ben01]. In [SBO01], the solutions in [Ben99, Ben01] for joint optimal power control and beamforming with and without access point assignment are assessed from a system perspective. The area of power control in combination with admission control by stepwise removing mobile terminals, is investigated in [Zan92].

As stated above, several algorithms for solving the optimal downlink beamforming problem have been presented. All algorithms, however,
require the existence of a feasible solution. As it is always of interest to fit as many users as possible into the system, there is a risk that too many mobile terminals want to communicate at the same time and therefore, no solution of the optimization problem may not exist. The optimization problem has to be reduced, i.e., some mobiles are refused access to the system. This introduces the problem of admission control, i.e., how to admit or remove mobiles in the system. In this work we suggest a heuristic algorithm that will reach a good feasible set of mobiles to optimize over. The algorithm aims at removing or not admitting, the specific mobile that is most critical to the system, in terms of the possibility to achieve the Quality-of-Service requirement, here defined as the target Signal-to-Interference-and-Noise Ratio (SINR) for all remaining mobile terminals. Note that not admitting or removing a mobile terminal could mean to let the terminal wait for the next time slot in a scheduling context.

In addition, system assessment of joint optimal beamforming, power control, and access point assignment, is performed in the context of cellular networks taking into account traffic and radio resource management issues. Results are given as system throughput as a function of the traffic load in the system. The results are also compared to earlier presented beamforming techniques.

The resource allocation algorithm herein will require global knowledge of channel statistics and may be used in the search for the fundamental performance limits of a wireless system. However, for systems of limited size, in slowly changing environments (e.g., indoor systems), it may be possible to implement centralized beamforming based on knowledge of global channel statistics.

The chapter is organized as follows: First the system and signal assumptions are reviewed, followed by the algorithms used for beamforming, power control, and access point assignment. Then the optimization theory in general and the admission algorithm in specific are given. Finally, the simulation results and a summary conclude the chapter.

6.2 System Assumptions

6.2.1 System Model

A cellular system, with several terminals sharing the same frequency channel is investigated. Each access point communicates with several terminals. We assume a controlled environment where all mobile terminals request a channel resource of a certain quality, which may be different
6.2 System Assumptions

Figure 6.1: Links for which the channel statistics is assumed known. Each line (solid and dotted) represent the covariance matrix of the channel between transmitter and receiver. Solid lines show the links from one access point to all terminals, as example for different users. When connecting, the terminals are allocated to an appropriate access point.

It is assumed that the access points are equipped with array antennas of type Uniform Circular Array, with \( n_t \) omni-directional elements and that the channel is a low rank (flat fading) narrowband random channel.
modeled with local independent scattering at the terminal. It is further assumed that the second-order statistics of the vector channels between all transmitters and receivers are known. In a Frequency Division Duplex system, the uplink and the downlink channels will typically fade independently which means that the instantaneous downlink channel can in general not be accurately estimated from uplink measurements. However, it may still be reasonable to estimate the second-order statistics of the fast fading of the downlink channel based on uplink measurements averaged over the fast fading. Several methods have been proposed to compensate for the carrier offset between the uplink and downlink channels, see for example [BO01], and will not be described further here. In Figure 6.1 it is shown how many channels that have to be estimated and the channels from one access point to all mobile terminals are highlighted.

The user requirement on QoS is assumed to be fulfilled if the Signal-to-Interference-and-Noise Ratio (SINR) at the user terminal $i$ exceeds a specified SINR requirement $\gamma_i$.

### 6.2.2 Signal Model

Assume that there are $d$ mobile terminals requesting downlink communication in the system. There are $K$ access points serving these mobile terminals and it is possible for each access point to serve several mobile terminals. The $i$th mobile terminal is assigned to access point $\kappa(i)$ and the set $\mathcal{I}(j) = \{i; \kappa(i) = j\}$ contains all mobile terminals assigned to the $j$th access point. In the system, all users utilize the same time and frequency resources.

The $n_t \times 1$ signal $x_j(t)$, transmitted from access point $j$ has the form

$$x_j(t) = \sum_{i \in \mathcal{I}(j)} w_i s_i(t), \quad (6.1)$$

where $w_i$ is the $n_t \times 1$ transmit weight vector for terminal $i$. The signal received at terminal $i$ is modeled as

$$r_i(t) = \sum_{j=1}^{K} (v_{i,j})^T x_j(t) + n_i(t). \quad (6.2)$$

The $n_t \times 1$ baseband vector channel from access point $j$ to terminal $i$, $v_{i,j}$ is assumed to be zero mean and circular symmetric with

$$E[v_{i,j}] = 0 \quad (6.3)$$

$$E[v_{i,j}v_{i,j}^T] = \mathbf{0} \quad (6.4)$$
6.3 Beamforming

and the $n_t \times n_t$ channel covariance matrix is denoted

$$\mathbf{R}_{i,j} = E[\mathbf{v}_i \mathbf{v}_j^*].$$

(6.5)

The user requirement on QoS is assumed to be fulfilled if the Signal-to-Interference-and-Noise Ratio (SINR) at the user terminal $i$ exceeds the SINR requirement $\gamma_i$ for every terminal $i$. 

$$\frac{\mathbf{w}_i^* \mathbf{R}_{i,i} \mathbf{w}_i}{\sum_{n=1 \atop n \neq i}^d \mathbf{w}_n^* \mathbf{R}_{i,n} \mathbf{w}_n + \sigma_i^2} \geq \gamma_i, \quad i = 1 \ldots d,$$

(6.6)

where the scalar $\sigma_i^2$ is the noise power received at receiver $i$.

6.3 Beamforming

In this section several algorithms for downlink beamforming are presented. First the suboptimal methods used as reference are given, followed by the optimal ones.

6.3.1 Suboptimal Beamforming Methods

The performance of the joint optimal beamforming and power control algorithm will be compared to some alternative beamforming methods. These are briefly described below.

Conventional beamforming

Conventional beamforming is optimal, with respect to Signal-to-Noise Ratio (SNR) in absence of interference and with spatially white noise. The weight vectors, when transmitting to terminal $i$, are given by

$$\mathbf{w}_i = \arg \max_{\mathbf{w}} \frac{\mathbf{w}^* \mathbf{R}_{i,i} \mathbf{w}}{\mathbf{w}^* \mathbf{w}},$$

(6.7)

where the maximum is then obtained by using a scaled version of the principal eigenvector of $\mathbf{R}_{i,i}(i)$. This method needs knowledge only about the second-order statistics of the channel to the mobile terminal, to which transmission is desired and the weight calculation may be distributed to the access point.
Generalized eigenvalue-based beamforming

The generalized eigenvalue-based beamformer is a decentralized beamforming strategy that gives the maximum signal power at the desired terminal and keeps the total transmitted power to all other terminals, communicating with this access point, below a certain value [Zet99] [GF98]. The beamformer is given by

$$w_i = \arg \max_w \frac{w^* R_{i,s(i)} w}{w^* (\sum_{n=1}^d R_{n,s} + \alpha I) w}$$  \hspace{1cm} (6.8)

where $\alpha I$ may be interpreted as an approximation of channels unknown to the access point or as a robustification to channel uncertainties [Zet99, Ben99]. The problem can be solved as a generalized eigenvalue problem [GvL96]. This method requires knowledge about the second-order statistics to all mobile terminals included in the summation in the denominator of (6.8). In the channel covariance matrices to all mobile terminals are assumed known and the weight calculation may be distributed to the access point.

An extension to (6.8) has been suggested [Zet97, Zet99, GF98] in order to balance the beamformer with respect to the different gains a mobile has to different access points.

$$w_i = \arg \max_w \frac{w^* R_{i,s(i)} w}{w^* (\sum_{n=1}^d R_{n,s} + \alpha I) w}$$  \hspace{1cm} (6.9)

This method needs knowledge of the second-order channel statistics to the desired user, the other users, and those between all other users and the access points they are assigned to.

The parameter $\alpha_i$ used above was chosen according to [BO99].

$$\alpha_i = \frac{0.1}{n_T} \text{Tr} \left[ \sum_{n=1}^d R_n \right]$$  \hspace{1cm} (6.10)

Another possible choice of the parameter $\alpha_i$, as suggested in [GMP+99], is to choose it 20–25 dB below the signal strength expressed as $\text{Tr}[R_i]$. 
6.3.2 Power Control

Power control decoupled from beamforming may be performed using the following criteria [Zan92]. The requirement in (6.6) may be rewritten as

\[
\text{SINR}_i = \frac{P_i G_{i,k(i)}}{\sum_{n=1}^{d} P_n G_{i,k(n)} + \sigma_i} \geq \gamma_i, \quad i = 1 \ldots d
\]  

(6.11)

where \( G_{i,j} \) represents the link gain from access point \( j \) to user \( i \) and \( P_i \) represents the transmit power for terminal \( i \). Applied with beamforming, the normalized beamforming part is included in the gain. It is possible to get the optimal power vector by solving (6.11) for equality. This system of inequalities provides a SINR-balanced system i.e. all terminals will have the same target SINR, and thus if one mobile has a SINR below the target SINR then all mobiles will have SINR below the target, which is not desirable. A method that avoids this problem is to remove terminals until all remaining terminals reach the target SINR. A heuristic method for choosing mobiles in order to remove as few mobiles as possible is suggested in [Zan92]. In this investigation, iteratively removing a random mobile terminal is used in order to compare the decentralized beamforming algorithms with the joint optimal algorithms. An admission control algorithm based on the joint optimal algorithms will be presented below.

6.3.3 Joint Optimal Beamforming and Power Control

Optimal beamforming is defined as transmitting with the set of beamformers, for all access points, that minimize the total transmitted power in the system, while providing sufficient received Signal-to-Interference-and-Noise Ratio (SINR) at each terminal. The problem may be formulated

\[
\min \sum_{n=1}^{d} \|w_n\|^2
\]

(6.12)

s.t. \( \frac{w_n^* R_{i,k(i)} w_i}{\sum_{n=1}^{d} w_n^* R_{i,k(n)} w_n + \sigma_i^2} \geq \gamma_i, \quad i = 1 \ldots d. \)

where \( \sigma_i^2 \) is the noise variance at terminal \( i \) and \( \gamma_i \) is the target SINR for user \( i \).
This algorithm requires knowledge of the second-order statistics of the channels between all access points and all mobile terminals and the optimization is done centralized.

Efficient algorithms for solving (6.12) are described in [BO01, VM99, RFLT98, SB02]. When too many users are present in the system, the optimization problem cannot be solved and no transmit weight vectors are obtained. To fully use joint optimal beamforming and power control in a practical system, an admission or scheduling algorithm must be added.

6.3.4 Joint Optimal Beamforming, Power Control and Access Point Assignment

Above, the assignment of mobile terminals to access points was assumed to be given. This can be done in a decentralized way, where for example the mobile terminal is assigned to the access point to which it has the best link gain. However, the optimal beamforming algorithm can be extended to determine not only the transmit weights, but also the optimal access point assignment of the mobile terminals, which, in general, does not correspond the best link gain assignment. First, view the antenna arrays of all the access points as a single joint access point and determine the optimal beamforming vectors from this combined access point to all the terminals. The covariance matrix of the channel from the joint access point to terminal \( i \) is defined as

\[
R_i = \begin{bmatrix}
R_{i,1} & 0 & \cdots & 0 \\
0 & R_{i,2} & \cdots & 0 \\
\vdots & \vdots & \ddots & 0 \\
0 & \cdots & 0 & R_{i,d}
\end{bmatrix}
\]  (6.13)

The optimal weight vector from the joint access point to the \( i \)th terminal, may then be written \( w_i = [w_{i,1}, w_{i,2}, \ldots, w_{i,d}] \), where \( w_{i,j} \) is the weight vector from access point \( j \) to terminal \( i \). It can be shown that for the optimal solution, \( w_{i,j} = 0 \) for all \( j \neq k \) where \( k \) corresponds to the optimal access point assignment for terminal \( i \). i.e only one access point will be used for each terminal, see [Ben01]. In other words all mobile terminals are assigned to a single access point.
6.4 Semidefinite Optimization

Semidefinite optimization [BV00, WSV00] has shown to be a powerful tool for solving a large variety of problems. Here follows a short review of optimization over convex semidefinite cones, highlighting the results which are required when introducing the heuristic admission algorithm used herein.

6.4.1 Introduction to Optimization over Semidefinite Convex Cones

Optimization techniques for convex functions and constraints has been a very active area of research for the last two decades. A number of, so-called, interior point or path following methods have appeared that can solve not only linear optimization problems but almost all convex optimization problems, in polynomial time. One class of convex problems that is of great interest in signal processing and control theory is the class of semidefinite problems. A general formulation of a semidefinite problem is

\[
\begin{align*}
\min_{X_k} & \sum_{k=1}^{K} \text{Tr}[C_k X_k] \\
\text{s.t.} & \sum_{k=1}^{K} \text{Tr}[A_{k,l} X_k] = b_l, \quad l = 1, \ldots, L \\
X_k & = X_k^* \succeq 0, \quad k = 1, \ldots, K,
\end{align*}
\]  

(6.14)

where \( X \succeq 0 \) denotes a matrix \( X \) that is positive semidefinite. Note that even if this is a highly non-linear constraint, it is still convex since the set of positive semidefinite matrices form a convex cone. In practice, several program packages are available to efficiently find the solution of (6.14), for example the SeDuMi toolbox [Stu99].

Introducing the Lagrange multipliers \( \lambda_l \), the Lagrange dual of (6.14) is defined as

\[
\begin{align*}
\max_{\lambda_l} \min_{X_k \succeq 0} & \sum_{k=1}^{K} \text{Tr}[C_k X_k] - \sum_{l=1}^{L} \lambda_l \left( \sum_{k=1}^{K} \text{Tr}[A_{k,l} X_k] - b_l \right).
\end{align*}
\]  

(6.15)
It can be shown to be equivalent to

$$\max \sum_{l=1}^{L} \lambda_l b_l$$

s.t. $C_k - \sum_{l=1}^{L} \lambda_l A_{k,l} \succeq 0$, $k = 1, \ldots, K$

(6.16)

We say that an optimization problem is feasible when there is at least one point that satisfies all constraints. We will use the following lemma, which relates the feasibility of the primal problem (6.14) to properties of the dual problem (6.16).

**Lemma.** Farkas' lemma. The primal problem (6.14) is strongly infeasible if and only if there exists a dual improving feasible direction, i.e. a point $\lambda_0$ and a direction $\lambda^+$ such that the set of vectors $[\lambda_1, \ldots, \lambda_L]^T = \lambda_0 + t\lambda^+$ are feasible solutions of (6.16) for all $t > 0$ and the cost function of (6.16) goes to infinity when $t$ grows.

**Proof** A proof is given in [LSZ97].

### 6.4.2 Solution of the Beamforming Problem

The optimization problem (6.12) can be solved using so-called Lagrange relaxation [VB96] techniques. Define the matrix $W_i = w_i w_i^*$. This the relaxation corresponds to letting $w_i w_i^*$, in general, have a rank greater than one and (6.12) may be rewritten

$$\min \sum_{i=1}^{d} \operatorname{Tr}[W_i]$$

s.t. $\operatorname{Tr}[R_{i,i(n)} W_i]$

$$- \gamma_i \sum_{\substack{n=1 \ldots d \sslash n \neq i}} \operatorname{Tr}[R_{i,i(n)} W_n] \geq \gamma_i \sigma_i^2, \quad i = 1 \ldots d$$

$W_i = W_i^* \succeq 0$,

where $W_i \succeq 0$ denotes that $W_i$ is positive semidefinite.

Using the fact that optimality is reached at equality in the constraints, it is straightforward to write (6.17) in the form (6.14) and solve numerically. In general, such a relaxation technique can only provide a lower
6.4 Semidefinite Optimization

bound on the original problem but for this specific problem formulation, it can be shown [Ben99, Ben01] that if (6.17) is feasible, then it has at least one optimal solution where \( \text{rank}[W_i] = 1 \) for all \( i = 1 \ldots d \), i.e. \( W_i = w_i w_i^T \), where the \( w_i \) solve (6.12). This formulation of the optimal beamforming problem may be extended to include additional constraints or robustness to channel uncertainties.

6.4.3 Terminal Admission

If no feasible solution exists to the optimization problem, the constraints have to be relaxed, either by relaxing the constraints, e.g. by decreasing the target SINR, or by removing a specific constraint. In this work we treat the case of removing one or several constraints and the goal is to remove as few constraints as possible. This is equivalent to removing as few mobiles as possible and thus keeping a high throughput. In order to find the mobile terminal, i.e. the constraint, that is most critical to the system feasibility we examine the dual problem. The dual of (6.17) is given by

\[
\max_{\lambda_1, \ldots, \lambda_d} \sum_{i=1}^{d} \lambda_i \gamma_i \sigma_i^2 \\
\text{s.t. } I - \lambda_i R_{i,\kappa(i)} + \sum_{n=1, n \neq i}^{d} \lambda_n \gamma_n R_{n,\kappa(i)} \succeq 0, \quad i = 1 \ldots d.
\]

This is equivalent to the virtual uplink problem described in [RFLT98, SB02], if \( \lambda_i \gamma_i \) is interpreted as the virtual uplink power.

According to the Lemma above, if the primal does not have a solution, the dual must have an improving feasible direction \( \lambda^+ = [\lambda_1^+, \ldots, \lambda_d^+]^T \). From the definition it follows directly that this improving direction fulfills

\[
\lambda_i^+ \succeq 0 \\
\sum_{n=1, n \neq i}^{d} \lambda_n^+ \gamma_n R_{n,\kappa(i)} - \lambda_i^+ R_{i,\kappa(i)} \succeq 0, \quad i = 1 \ldots d,
\]
which is equivalent to
\[
\rho_i \geq 0 \quad \frac{\rho_i u^* R_{i,n}(i) u}{u^* (\sum_{n=1}^{d} \rho_n R_{n,n}(i)) u} < \gamma_i, \quad i = 1 \ldots d, \tag{6.20}
\]
for all \( u = [u_1 \ldots u_d]^T \) and with \( \rho_i \) defined as \( \rho_i = \lambda_i^+ \gamma_i \). To summarize, the constraints in (6.20) have a solution if and only if our original problem (6.12) does not have a feasible solution. Removing mobile \( m \) corresponds to removing constraint \( i = m \) and thus removing the term \( \rho_m R_{m,n}(i) \) in the denominator of the remaining constraints. We suggest to remove the mobile corresponding to the largest \( \rho_i \). This will decrease the denominator of all the other constraints in (6.20) and thus make it more difficult to find a feasible point of (6.20). Also, a large value of \( \rho_i \) indicates that constraint \( i \) of (6.20) was easy to fulfill.

This proposed algorithm is clearly suboptimal but offers good heuristics. An optimal algorithm would be very complex.

### 6.4.4 Implementation Aspects

When the beamforming problem is solved with the interior point software packet SeDuMi [Stu99] or some other convex optimization package using self-dual embedding techniques, the algorithm provides a certificate of the infeasibility in the form of the dual improving feasible direction (Farkas-dual) [LSZ97]. In order to find the mobile terminal that is most critical for the problem feasibility, a good heuristic is thus to find the largest element of the dual improving feasible direction. The terminal with the SINR constraint corresponding to this dual variable can be considered one of the most limiting for system feasibility. If two terminals are located closely together such that no feasible solution can be found, both will typically get a large Farkas-dual variable but it is often sufficient to remove one of them to reach a feasible situation. Thus, we suggest to repeatedly remove the most critical terminal, one at a time, until a feasible solution can be found. Below, we show that this heuristic method can give a significant increase in system capacity compared to random removals. Since the Farkas-dual solution is not unique in most cases, the exact result will depend on the specific algorithm.
6.5 Results

The following resource management techniques are assessed below:

- Traditional beamforming with power control, decoupled from the beamforming.
- Generalized eigenvalue based beamforming [Zet99] with power control, decoupled from the beamformer.
- Joint optimal beamforming and power control
- Joint optimal beamforming, power control and access point assignment.

In the first three cases, the user is assigned to communicate with the access point from which it has the highest gain, called maximum gain allocation, while in the fourth case the allocation is included in the optimization algorithm. In the two latter cases, the admission control is included in the beamforming algorithm and in all four cases a random admission control algorithm is used to allow comparison.

6.5.1 Simulation Setup

A multi-cellular system with uniform circular arrays at all access points, corresponding to the assumptions above is simulated. Mobile terminals arrive to the system according to a Poisson process and they are uniformly distributed over the area. In order to take signals from surrounding cells into account a wrapped system is used, i.e. all cells are surrounded by all other cells. Thus the whole simulated area corresponds to a torus shape consisting of nine to sixteen cells.

To simulate the channel vectors, a local scattering model is used [TO96]. Thus the channel statistics for the channel from access point $j$ to terminal $i$ is parameterized by the nominal azimuth angle $\theta_{i,j}$ and the standard deviation $\sigma_{i,j}$ of the angular spread. The total covariance matrix including the propagation properties in the gain matrix, is given by

$$R_{i,j} = G_{i,j} R(\theta_{i,j}, \sigma_{i,j}),$$  \hspace{1cm} (6.21)

where $R(\theta_{i,j}, \sigma_{i,j})$ is the channel covariance matrix. Here the gain matrix $G_{i,j}$ contains the influence of path loss and shadow fading, while the
influence of beamforming and power control is included in the weight vectors given by the beamforming algorithms and power control algorithms. The covariance matrices between all access points and terminals are assumed known. The noise in the system is assumed very low, as the main issue investigated here is the interference from other transmitters. The parameters used in the system simulations are shown in Appendix 6.A.

For the classical beamforming and the generalized eigenvalue method, the weight vectors are created according to (6.7) and (6.8). Based on the gain matrix and the beamformer antenna diagrams, power control is applied. The joint beamforming and power control algorithm provide power controlled weights directly. In the simulations it is assumed that all users request the same target SINR i.e. \( \gamma_i = \gamma_0 \) for \( i = 1 \ldots d \).

For the cases with joint beamforming and power control the optimization problem is solved as described above and if the solution is infeasible the most critical terminal or one random terminal is removed and the new optimization problem is solved. The procedure is iterated until a feasible solution is reached. The positive semidefinite optimization problems are solved with the optimization program package SeDuMi [Stu99].

In SeDuMi numerical errors are detected, if the solution is very close to being infeasible and very unstable. These solutions usually require very large transmit power and are thus not of practical interest. In this case one terminal is randomly removed from the system to reach a stable solution. This means that the results may be somewhat below the possible maximum.

6.5.2 Outage and Throughput

The results are given in different measures. In the first part where no admission control is used the results are given as outage probability i.e. \( P(\text{SINR} < \gamma_0) \).

Assuming that the channel is constant during a short packet duration, the throughput (packets/cell/slot) \( S \) is calculated as the offered load (packets/cell/slot) \( G \), multiplied with the probability of success given that load, \( (1 - P(\text{SINR} < \gamma_0)) \) i.e.

\[
S = G \cdot (1 - P(\text{SINR} < \gamma_0)). \quad (6.22)
\]

When admission control is used the results are given as probability of blocking, i.e. probability of not being admitted to the system and for a given outage probability. The outage probability is controlled by using a fade margin, which is described below. The throughput is calculated
6.5 Results

Figure 6.2: Probability of outage for different downlink beamforming methods. Required SINR is 7 dB.

as Load × (Probability of no blocking), and excludes the retransmission that would be possible in a packet switched system.

6.5.3 Performance without Admission Control

This section shows the differences between different downlink beamforming schemes, including the optimal scheme and between different QoS requirements in terms of required SINR, when neither admission control nor fade margin are used.

When no admission control algorithm is used and the optimal beamforming algorithm does not have a solution, all users experience outage. The corresponding phenomena will occur with the reference methods with decoupled power control when the load is too high. This makes it possible to compare the cases, though the results may be somewhat pessimistic. To fully use joint optimal beamforming and power control in a real system, an admission control scheme must as shown below. All
results described here are valid for a reuse one SDMA system, resulting in a high interference level from not only users in the same cell but also in all surrounding cells.

Joint optimal beamforming and power control allows five times higher load than conventional beamforming combined with optimal power control at an outage level of 10% as seen in Figure 6.2. The corresponding figure over the generalized eigenvalue method is twice the load.

When allowing higher outage rate, a possible throughput of 0.75 is possible as shown in Figure 6.3. That is more than twice the maximum throughput for the traditional beamformer.

Outage is shown in Figure 6.4 for different Quality-of-Service levels parameterized as SINR requirement $\gamma_0$. For typical speech services requiring about 7 dB a doubling of the load is possible compared to services requiring higher rates like 15 dB. These values are valid for an outage level of 10%.

As mentioned above, these results are very pessimistic and in the
6.5 Results

Figure 6.4: Probability of outage for different QoS levels with joint optimal downlink beamforming and power control

following admission control will be used and thus the results will be given as blocking rate and allowed outage rate will be a design parameter as shown below.

6.5.4 Fade Margin

Assuming that only second-order statistics are known to the system and not the actual channel realizations, will introduce fading in the system and even though a mobile terminal is admitted to the system, the probability of outage is large. In order to keep this probability low a fade margin is used. The fade margin is added to the target SINR in (6.12), i.e. $\gamma_i + \gamma_f$ is used instead of $\gamma_i$.

The results for optimal beamforming with the heuristic admission algorithm for a setup with the average load four mobiles terminals per cell, are presented in Figure 6.5. It is shown that for $\gamma_0 = 7$ dB, the probability of outage is 60% with no fade margin ($\gamma_f = 0$ dB) and that a
fade margin $\gamma_f = 10$ dB, will keep the probability of outage below 10%. These results is theoretically supported in [BO96], where the approximate expression for the average $\text{SINR}_{\text{mean}}$ is given as

$$P[\text{SINR}_{\text{mean}} < \gamma] = 1 - e^{\gamma / \text{SINR}_{\text{channel}}}.$$  \hspace{1cm} (6.23)

where $\text{SINR}_{\text{mean}}$ is the value used in the optimization algorithms, that uses the second-order statistics of the channels and $\text{SINR}_{\text{channel}}$ is the actual result from the simulations, calculated from channel realizations.

The increase of the fade margin certainly will influence the system performance and the number of admitted mobile terminals for different fade margins, $\gamma_f$ is given in Figure 6.6. In the simulations below, a fade margin $\gamma_f = 10$ dB is used and in addition to the throughput and blocking rates given, the outage probability in the system is slightly below 10%.
6.5 Results

6.5.5 Performance with Random Admission Control

Introducing random admission control in the simulations show that the use of joint optimal beamforming and power control allows five times higher load than conventional beamforming combined with optimal power control at a blocking rate of 10% as seen in Figure 6.7. The corresponding figure over the generalized eigenvalue method is twice the load. Adding optimal access point allocation will increase the possible load with an additional 25%, still assuming an allowed blocking rate of 10%, as shown in Figure 6.8. Comparing the two algorithms for eigenvalue-based beamforming with random admission control indicates a 10% improvement when using the normalization defined in (6.9), as shown in Figure 6.9.

Figure 6.6: Number of mobile terminals in the system for different fade margins. The target SINR in the simulations is 7 dB
Figure 6.7: Blocking rate for different beamforming methods with random admission and maximum gain access point assignment. Required SINR is 7 dB and outage probability is 10%.

6.5.6 Performance with Heuristics Admission Control and Access Point Assignment

Applying the proposed heuristic admission control algorithm to the system gives a substantial increase of the throughput. The blocking rate is shown in Figure 6.8. Note that the proposed heuristic removal algorithm has substantially lower blocking rates than the random removal algorithm used as a reference. In Figure 6.10 it is shown that the throughput, using the random removal algorithm reaches a ceiling, while the heuristic algorithms manages to remove the critical users and thus reaches substantially higher throughput levels. Note that the classical beamforming curve with random removal and maximum gain assignment is given as a dotted line.

Adding optimal access point allocation, jointly to the optimal beamforming and power control, further decreases the blocking rate and thus
6.5 Results

Figure 6.8: Blocking rate for optimal beamforming with different admission and access point assignment schemes. Required SINR is 7 dB and outage probability is 10%.

increases the throughput as shown in Figure 6.10.

At an allowed blocking rate of 10%, it is possible to double the possible load, when using optimal access point allocation and heuristic admission, compared to the case with maximum gain access point allocation and random admission.

Finally in Figure 6.8 and Figure 6.10, note that there are crossovers between the curve for random admission and optimal assignment and the curve for optimal assignment and maximum gain assignment. This may be interpreted as for lower loads (here below 1.8 mobiles/cell) it is more important to assign each mobile to the right access point while for higher loads it is more important to admit the right mobiles to the system.
### Figure 6.9: Blocking rate for generalized eigenvalue-based beamforming, with and without normalization. Required SINR is 7 dB and outage probability is 10%.

#### 6.5.7 An Example of a CDMA-like System

The results presented above are focused on a relatively complex system, possible to implement in the future. In order to illustrate how the impact would be on a current system such as the 3G/WCDMA system, we change the system to use only two antenna elements at the access point and use very low target SINR, to simulate a possible processing gain of up to 20 dB.

First as a reference to the above, a system with eight antenna elements at the access points is simulated for different target SINR, representing different processing gains in CDMA. For this example the simulated load is 16 mobile terminals per cell. The results are shown in Figure 6.11.

In the following results for two antennas elements per access point the simulated load is four mobile terminals per cell and only one snapshot is investigated. All other assumptions are constant.

The results are shown in Figures 6.12 and 6.13. In these simulation...
a fade margin of 10 dB is used to keep the outage probability below 10% as shown in Figure 6.12. In Figure 6.13 the number of admitted terminals for each assumed SINR target is given. The case where $\gamma_0 = 7$ dB ($\gamma_f = 10$ dB and 2 antenna elements) may be compared to the $\gamma_f = 10$ ($\gamma_0 = 7$ dB and 8 antenna elements) case in Figure 6.6. Going from eight to two antennas would in this case degrade the performance, in terms of number of admitted terminals, five times.

Decreasing the target SINR by 20 dB, assuming a CDMA processing gain of 100 would in this case increase the number of admitted terminals about eight times.

In Figure 6.14 the number of admitted terminals using conventional beamforming is shown. As expected the advantage of optimal beamform-
Figure 6.11: The number of mobile terminal admitted to a system, with joint optimal downlink beamforming, power control and access point assignment and heuristic admission control, as function of the target SINR. The system load is 16 users per cell. Eight antennas elements are used at the access points and the fade margin is 10 dB.

6.5.8 An Example on Optimal Access Point Assignment

In Figure 6.15, an example of the allocation is shown. The scenario is a wrapped system with relatively heavy load (4.5 terminals per access point) and 16 access points. This example is simulated without fade margin and the outage rate as well as the blocking rate is high. As the simulated system is wrapped, access points on border may be shown
6.5 Results

For this particular system the same number of terminals are admitted with maximum gain allocation and optimal allocation. However in four cases the terminals are allocated to different access points with the two algorithms, which indicated that less power may be used when transmitting to the same terminals. Note that shadow fading is still included, which means that the distances in the figure is not equivalent to the best gain.

6.5.9 Admission Control Fairness

It is of interest to investigate if it is a certain subgroup of mobile terminals that are rejected from the system in each snapshot. Mainly two subgroups may be identified in the simulations; the ones that are very close to

Figure 6.12: Cumulative distribution function for the SINR at the mobile terminals for different target SINR. Two antennas elements are used at the access points and the fade margin is 10 dB.
Figure 6.13: The number of mobile terminal admitted to a system with joint optimal downlink beamforming, power control and access point assignment and heuristic admission control, as function of the target SINR. Two antennas elements are used at the access points and the fade margin is 10 dB.

another terminal in the grid and thus experience large interference, and the ones that are very far from the closest access point and thus need high transmit power, causing high interference. Again, the scenario is a wrapped system with 16 access points.

From simulations it is seen that the second category is in a slight dominance and it may be concluded that the system is unfair to the mobile terminals far away from the closest access point, which was expected as we optimize the system performance. Shown in Figures 6.16 and 6.17 is a simulated example of a system with heuristic admission control, which is run several times under high load. In Figure 6.16, the admitted mobile terminals are shown. The admitted mobile terminals are slightly
Figure 6.14: The number of mobile terminal admitted to a system, using classical beamforming, as function of the target SINR. Two antennas elements are used at the access points and the fade margin is 10 dB.

less dense far from the access points i.e. at the cell borders. The corresponding plot for the rejected terminals is shown in Figure 6.17. There it is shown that although the rejected terminals are slightly denser at the cell borders, terminals all over the grid are rejected. Thus it may be concluded that the admission control algorithm is not unreasonably unfair.

### 6.6 Summary

In this chapter we have demonstrated the use of optimal beamforming, power control and access point allocation in a wireless communication system. The system assessment of optimal beamforming has been performed under the assumption that knowledge of the global channel statistics is
Figure 6.15: The allocation map for optimal allocation versus maximum gain allocation. Terminals that have two connectors experience different allocation with different methods.

When a feasible solution does not exist for the optimization problem, terminals must be removed/block from the system. By studying the dual of the optimization problem, critical constraints can be identified and based on these, a heuristic admission control algorithm is proposed and evaluated. The results show that the proposed algorithms substantially increase the system performance compared to a reference system with random removal of users.

The results may be used as a demonstration what is possible in a system actually providing knowledge of global channel statistics, but also as an upper limit to the throughput in a multi-cell system with smart antennas and suboptimal processing.
Several examples are provided illustrating how the optimal beamforming framework functions from different points of views.
Figure 6.16: Admission control example where admitted mobile terminals, accumulated over several simulation snapshots, are shown as small dots and access point are shown as larger dots. A slight decrease of mobile density may be noted at the borders. Axis scales are given in meters.
Figure 6.17: Admission control example where rejected mobile terminals, accumulated over several simulation snapshots, are shown as small dots and access point are shown as larger dots. It is hard to note any change in mobile density over the area. Axis scales are given in meters.
## Appendix 6.A Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cells</td>
<td>9 and 16</td>
</tr>
<tr>
<td>Reuse factor</td>
<td>1</td>
</tr>
<tr>
<td>Noise level</td>
<td>-120 dB</td>
</tr>
<tr>
<td>Shadow fading standard deviation</td>
<td>8 dB</td>
</tr>
<tr>
<td>Propagation attenuation</td>
<td>$a_{att} = 3.5$</td>
</tr>
<tr>
<td>Number of antenna elements</td>
<td>8</td>
</tr>
<tr>
<td>Angular spread variance</td>
<td>9 degrees$^2$</td>
</tr>
<tr>
<td>Uniform circular array radius</td>
<td>$0.4\lambda$</td>
</tr>
</tbody>
</table>
Part II

Channel Capacity and Modeling Issues for Dual Arrays
Chapter 7

The MIMO Channel

7.1 Introduction

Utilizing dual arrays to communicate over a Multiple-Input-Multiple-Output (MIMO) channel can provide substantial increases in channel capacity [Win87, Tel95, FG98, WFGV98]. An important condition for the MIMO channel to support these increases is that the environment provides sufficient multi-path propagation resulting in a high rank channel. For analysis, design, and simulation of wireless communications with dual arrays, it is of importance to have a statistical description of the spatial properties of the channel. Herein we study the properties of experimental MIMO data collected in an indoor environment. The channel measurements are then analyzed in terms of the capacity for different intra-element spacings in the following chapter.

Multiple antennas at both the terminal and access points are being considered in future 3G and Wireless Local Area Networks (WLAN). The terminal in the latter case may be a laptop computer or a hand-held computer where multiple antennas are conceivable. In a rich scattering environment, good diversity is expected even with limited antenna spacing, especially for WLAN in the higher frequency bands (5-6 GHz). In smaller devices, multiple channels with good diversity may be achieved by using different polarization [BNB99, Bec01].

A communication channel may be assessed by considering the channel capacity, [Sha48]. The capacity is a measure of the maximum possible rate that can be transported over a channel, with arbitrarily low bit error probability. The channel capacity can be achieved, with perfect channel
knowledge at the receiver and coding of infinite delay.

When arrays are used at both the transmit and receive sides, the channel is often termed a MIMO channel as compared to e.g. Single-Input-Single-Output (SISO) channel. The capacity for MIMO channels with and without fading, in the presence of Gaussian noise, was first derived in [Tel95]. Therein, substantial capacity increases, were established provided that the channel matrix elements were independent. In addition, the notion of waterfilling over spatial channels, based on channel knowledge at the transmitter was introduced, see also, [RC96].

The MIMO channel has shown to provide a substantial increase in channel capacity as demonstrated in [WFGV98]. An important condition for the MIMO channel to support this increase is that the environment provides sufficient multi-path propagation resulting in a high rank channel.

The MIMO channel is even more difficult to estimate than the channel with only one array. Thus space-time coding provides a transmission scheme, not requiring channel knowledge at the transmitter. Space-time coding was introduced in [GFK96] and [TSC98]. A scheme with possible use in MIMO channels is the Alamuti scheme [Ala98]. This scheme is based on transmit diversity with two antennas elements and the scheme considered for 3G (WCDMA) is to a high extent flavored by the Alamuti scheme [3GP00].

When designing high performance dual array systems in wireless communication, the choice of channel model is critical. For MIMO channels, the spatial dimension must be taken into account and the models will in this sense be more complex compared to the SIMO/MISO models. The capacity calculations referenced above are mainly based on rather simple channel models e.g. assumptions of independently fading channel matrix elements. It is thus of interest to investigate measured channels with the goal of establishing their capacity and also develop compact models to represent the data.

Within the area of non-parametric unstructured models, contributions are found in [Tel95], while the structured models can be found in [PAKM00]. In [CRFLL00], a model based on the Kronecker structure of the channel covariance matrix has been assumed to analyze the channel capacity and is verified in [YBO+01] for the typical non-line-of-sight (NLOS) indoor scenarios. A wideband MIMO channel model that extends the Kronecker structure to each channel tap can be found in [YBO+02]. Parametric MIMO scattering models have been proposed in [Shi00] and [GBP00] extends the scattering models to explain the so-
The MIMO Channel

7.2 The MIMO Channel

called 'pinhole’ phenomenon that may occur. An analysis of the sensitivity of the channel estimates and interference is carried out in [BFHS00].

In [WFGV98] measurements on the Bell Labs Layered Space Time (BLAST) system working in laboratory environment at 1.9 GHz were presented showing very high spectrum efficiency. The theory behind the BLAST systems has been presented in [Fos96].

MIMO channel capacity for an indoor office environment was presented in [SO00, SKO00]. These results are based on measurements in the 5.8 GHz made at Telia Research AB in Malmö Sweden. The results showed that the indoor environment was rich scattering and thus that substantially increased spectrum efficiency was possible. Further the capacity dependence on the intra-element distance was investigated. This investigation is in parts described below.

Results for macro-cellular systems operating in the 1.9 GHz band, were recently reported in [MWS00]. It was shown that the temporal variations of the capacity are much smaller for a $4 \times 4$ MIMO system as compared to the SISO case due to the additional diversity.

Measurement and analysis have been performed in the SATURN project with measurement equipment described in [BMK00] and initial results showing high scattering properties even in LOS channels, are presented in [MBKF00].

This and the following chapter present the capacity of MIMO channel measurements in a realistic office environment and determines if the scattering is sufficiently "rich" to provide substantial capacity increases. The capacity calculations are based on obstructed-line-of-sight (OLOS) indoor measurements 5.8 GHz from a typical office environment at Telia Research in Malmö, Sweden [KBBP00, SO00]. The OLOS channel is a generalization of the NLOS channel where there still may exist some dominating paths even though the LOS path is obstructed.

7.2 The MIMO Channel

If both the terminal and the access point are deployed with antenna arrays, we will have a Multiple-Input-Multiple-Output (MIMO) Channel, shown in Figure 7.1. Several authors have shown that exploiting the MIMO channel will provide substantially increased spectrum efficiency [Fos96] [Tel95]. A commonly used method, that will be used as comparison in Chapter 8 is to assume a totally unstructured channel model where all the elements in the $n_R \times n_T$ MIMO channel matrix, $H$, are
independent and identically distributed (IID) and that $E[|h_{i,j}|^2] = 1$.

Denote the number of inputs (transmitters) by $n_T$ and the number of outputs (receivers) by $n_R$. The MIMO narrow-band channel response may be modeled by a channel matrix $H = [h_1 \ h_2 \ \cdots \ h_{n_T}]$, where $h_i$ is the $n_R \times 1$ channel vector containing the gain and phase responses from transmit antenna $i, i = 1 \ldots n_T,$ to the receivers. The $n_R \times 1$ received signal $y(t)$ is modeled as

$$y(t) = Hs(t) + n(t) \quad (7.1)$$

where $s(t)$ is the transmitted signal and $n(t)$ is additive white Gaussian noise with variance $\sigma^2$. With total transmitted power $p$, the average power $\frac{p}{n_T}$ is sent from each transmitter. The signal-to-noise-ratio $\rho$, is the received power at each receiver element, divided by the noise power $\sigma^2$.

Herein, we distinguish between two power distribution cases:

- Uniform Input Power Channel (UIPC) and
- Non-Uniform Input Power Channel (NIPC)

where UIPC may be seen as a case where no channel information is present at the transmitter and uniform power distribution is the natural
choice. NIPC allows non-uniform power distribution at the input. Thus channel knowledge at the transmitter may be used for NIPC. For both UIPC and NIPC, there is a constraint on the maximum transmitted power.

7.3 Channel Measurements

7.3.1 Measurement Description

Figure 7.2: (a). The receiving antenna was moved on a track by a step motor. (b). The transmitting antennas was mounted on a trolley.
Figure 7.3: The average frequency correlation function for the wideband measurements.

The measurements were carried out by Telia Research in their offices, located on the third floor at the Scandinavian Center in Malmö, Sweden. The general planning of the floor consists of office rooms, open spaces and corridors. Most spaces are separated by walls, while glass is used in some places. The transmitter was positioned in an office room, while the receiver was in an indoor open area. Several channel measurements were carried out in this scenario. However, other scenarios have not been investigated. The measured channels that were analyzed correspond to a typical OLOS scenario and the distance from transmitter to receiver was 10 – 15 m. Figure 7.7 shows an overview of the measurement site, the transmitter was positioned in room 322 and the receiver at ”Rx” in the open area to the left.

The measurements were conducted at 5.8 GHz carrier frequency. By transmitting a pseudo-random noise (PN) sequence of rate 200 MHz, at the transmitter and correlating with the same synchronous sequence at the receiver, complex impulse responses were measured. The method of
correlating PN-sequences in the receiver gives a sinc-shaped spectrum at
the receiver with a 2 dB-bandwidth of about 60 MHz, of which 40 MHz
is used in the analysis. In the measurements, the signal power level is on
average at least 20 dB above the noise floor.

The data was collected with a synthetic array antenna, using one
receiver and one transmitter, see Figure 7.2, that were synchronized.
Both antennas were of monopole type and the transmit power was 32
dBm. The transmit antenna was moved between seven different positions
separated by 300 mm, i.e., $\Delta_{Tx} \approx 6\lambda$. Of these seven positions three are
used herein. For each of the seven transmitter positions, the receive
antenna was moved linearly between 21 different positions, using a step
motor on a track, moving 13 mm ($\Delta_{Rx} \approx \frac{\lambda}{4}$), between each position. This
corresponds to spatial measurements over in total about five wavelengths.
At each combination of transmit and receive positions 20 samples were
taken. The measurement time for the 20 samples was about 50 ms and

![Figure 7.4: CDF of the envelope of the channel coefficient for OLOS
indoor MIMO scenario and the fitted Rayleigh distribution envelope (nor-
malized).](image_url)
the excess delay window was 300 ns.

Using a synthetic array in a real indoor environment is sensitive to time-variations. All measurements have therefore been performed under controlled conditions, in order to provide a static indoor environment. The outdoor environment is considered static as the building is situated in an open area with no moving objects (foliage or traffic) within the excess delay window. Further, the general indoor channel, even when uncontrolled, has been reported to be highly static [ZBM+01].

Further information about the measurement setup and environment may be found in [KBBP00].

7.3.2 Measurement Data Processing

The wide-band channel measurements are narrow-band filtered and then used in the capacity expression, (defined below in (8.2)) with a given SNR. The filtering is done by applying the Discrete Fourier Transform (DFT) on the data. The average frequency correlation function for the wideband measurements is shown in Figure 7.3. As mentioned above, the

Figure 7.5: Example of a single measured impulse response.
method of correlating PN-sequences in the receiver gives a sinc-shaped spectrum at the receiver. From each of the 20 broadband measurements, the 12 narrow-band channels, corresponding to the 40 MHz spectrum, mentioned above, were taken, in order to keep the spectrum of the used frequencies flat and the measured signal level sufficiently high over the noise floor. This results in a total of 240 narrow-band channels, though possibly correlated, in the frequency band around 5.8 GHz.

The cumulative distribution functions are obtained by calculating the capacity for the 20 snapshots, the 12 frequency bins and also in space over all $n_t \times n_R$ combinations possible for the intra-element distance desired, i.e. we treat the snapshots from different frequency bins and combinations as different channel realizations. This is done under the assumption that the distribution of the channel is locally stationary in time, frequency and space. For instance, the total number of channel realizations for a $2 \times 2$ setup is $20 \times 12 \times (2 \times 20) = 9600$.

The measured MIMO channel matrices used in the capacity expres-
The MIMO Channel

The dimensions are normalized by a common factor such that

\[ E[||H||^2_F] = n_T n_R \]  

(7.2)

where \( E[\cdot] \) denotes the expected value.

### 7.3.3 Signal and Noise Power Levels

In the measured data the signal power level is on average at least 20 dB over the noise floor, assuming that the last 50 ns of the impulse response has negligible signal power and thus may be considered as noise.

One example of a measured impulse response is shown in Figure 7.5. In Figure 7.5 it is clear that the multi-path propagation is significant in this environment.

### 7.3.4 Channel Distribution

The distribution of the elements of the MIMO channel matrix has been investigated by examining the cumulative distribution function (CDF) of both the envelope of the channel coefficient and the phase of channel coefficient.

Figure 7.4 shows the result of the envelope distribution of the channel coefficient with the fitted Rayleigh distribution envelope. There is good agreement between the two CDF curves and the K-factor for these measurements is close to zero [SBE+02]. In Figure 7.6 it is also observed that the phases of the channel coefficient are uniformly distributed over \([-\pi, \pi]\). Hence, we conclude that the elements of the MIMO channel matrix are well modeled as zero-mean complex Gaussian in this OLOS indoor measurement scenario.

### 7.4 Summary

In this chapter we have introduced the MIMO channel and the channel measurements to be used in the following chapter and we have defined the transmission strategies to be used. Further the MIMO channel has been characterized from measurement data.
Figure 7.7: The measurement site at Telia Research. The transmitter was positioned in room 322 and the receiver as marked “Rx” in the open area to the left.
Chapter 8

MIMO Channel Capacity

8.1 Introduction

The purpose of the investigation in this chapter is to examine the capacities of MIMO channels in a realistic office environment and see if the scattering is sufficiently "rich" to decorrelate the relationship between the transmitters and receivers. The capacity calculations are based on obstructed-line-of-sight indoor measurements at 5.8 GHz from a typical office environment at Telia Research i Malmö, Sweden [BKB99, SO00].

8.2 Channel Capacity

The Shannon capacity is a measure of the maximum possible rate, that can be transported over a channel, with arbitrarily low bit error probability. The channel capacity can be achieved, with perfect channel knowledge at the receiver and coding of infinite delay.

The original expression for channel capacity on a single Additive White Gaussian Noise channel is [CT91]

$$C = \log_2(1 + \frac{S}{N}) \text{ bits/s/Hz} \quad (8.1)$$

where $S$ is the signal power and $N$ is the noise power.

The expression for channel capacity on the $n_R \times n_T$ MIMO channel, $H$, defined in previous chapter, with additive white Gaussian noise under
UIPC conditions is \cite{Fos96}

\[ C_{\text{UIPC}}^{\text{MIMO}} = \log_2 \det(I_{n_R} + \frac{\rho}{n_T} HH^*) \text{ bits/s/Hz} \quad (8.2) \]

where (*) denotes the complex conjugate transpose and \( \rho \) is the signal-to-noise-ratio.

### 8.2.1 Frequency Selective Channels

The classical information theoretical channel capacity is defined for a narrowband and thereby frequency flat channel. For a frequency selective channel the capacity may be obtained by averaging over the frequency band

\[ C_{\text{NIPF}}^{\text{MIMO}} = \frac{1}{W} \int_W \log_2 \det(I + \frac{1}{\sigma_n^2} H(f)Q(f)H^*(f)) df \approx \]

\[ \frac{\Delta f}{W} \sum_{i=1}^{q} \log_2 \det(I + \frac{1}{\sigma_n^2} H_i Q_i H_i^*) \text{ bits/s/Hz} \quad (8.3) \]

where \( W \) is the overall bandwidth of the channel. \( H(f), Q(f) \) and \( H_i, Q_i \) are the frequency responses for the channel and power distribution for the continuous and discrete frequency cases, respectively. An approximation is done converting the integral into a Riemann sum, in order to adopt the expression to the sampled system.

The issue of frequency selective channel capacity will only be used in the HiperLAN2 example below.

### 8.2.2 Waterfilling

For the case where a TDD scheme is used or if channel knowledge is fed back to the transmitter, both methods requiring the channel to be stationary, the MIMO channel may be known to the transmitter. If the channel \( H \) is known at the transmitter, it is possible to use transmitter weights to adapt the transmitted signal to the channel and to transform the MIMO-channel into parallel Gaussian sub-channels with a common power constraint. Assuming parallel Gaussian sub-channels, optimal power allocation over these sub-channels by waterfilling \cite{Tel95} \cite{CT91} will achieve the capacity. This corresponds to the non-uniform input power channel (NIPC) case.
8.2 Channel Capacity

The $n_T \times 1$ transmit signal vector sent, is $s(t)$. Then, using transmit weights $W_T$ and receive weights $W_R$, the received $n_R \times 1$ signal will be

$$y(t) = W_R^* H W_T s(t) + W_R^* n(t) \quad (8.4)$$

where $n(t)$ is the $n_R \times 1$ Gaussian noise vector.

One approach is to use a Singular-Value-Decomposition (SVD) [GeL96] to find the transmit and receive weights and thus obtain parallel sub-channels. Denote the SVD by

$$H = USV^* \quad (8.5)$$

where $U$ and $V$ are unitary matrices i.e. $U^* U = I$ and $V^* V = I$. The matrix $S$ is diagonal and has the singular values of $H$ and zeros as diagonal elements. The weight matrices are chosen as

$$W_T = VY \quad (8.6)$$
$$W_R = U \quad (8.7)$$

where $Y = \text{diag}(\sqrt{\epsilon_1}, \ldots, \sqrt{\epsilon_n})$ and $n = \min(n_T, n_R)$.

Using the methods in [Tel95] for diagonalizing a MIMO channel, we obtain the NIPC capacity by maximizing

$$C_{\text{NIPC}}^{\text{MIMO}} = \sum_{i=1}^n \log_2 \left(1 + \frac{\rho}{\epsilon_i n_T} \sigma_i^2 \right) \quad (8.8)$$

with respect to $\epsilon_i$, where $\sigma_i$ are the singular values of $H$ and $\sum_{i=1}^n \epsilon_i \leq n_T$.

This yields the received vector

$$y(t) = SY s(t) + U^* n(t). \quad (8.9)$$

Since $SY$ is a diagonal matrix and $U$ is unitary, the channel is made up of independent Gaussian sub-channels. Thus the $\epsilon_i$ will distribute the total transmitted power optimally over the sub-channels and classic coding may be used to exploit the capacity, illustrated in Figure 8.1.

In the case of frequency selective channels, waterfilling may be performed jointly over both frequency and space components if the channel behavior is known to the transmitter. This corresponds to a Non-uniform Power Input Frequency Selective Channel (NIPF), which will be used in the HiperLAN2 example below.
Figure 8.1: Example of $4 \times 4$ Multiple-Input-Multiple-Output channel with and without diagonalization into spatial sub-channels. When diagonalization is performed the channel may be consider being made up of parallel independent Gaussian channels and water filling may be performed to achieve the capacity for the Non-uniform-Power-Input-Channel.

8.3 Results

The capacity for the measurement data is computed and compared to the capacity for simulations performed using channel matrix elements, $H_{ij}^{BD}$, that are zero-mean IID complex Gaussian. The simulated channel corresponds to a Rayleigh fading channel under the most favorable conditions that can be expected on average in an uncontrolled environment, i.e., totally uncorrelated matrix elements in the channel matrix. To allow comparison the simulated channel data satisfy (7.2). In all results below
8.3 Results

\[ \Delta_{Tx} = 6\lambda \text{ and } \Delta_{Rx} = \frac{\lambda}{4} \text{ when nothing else is stated.} \]

The measurement noise is critical when attempting to estimate the MIMO channel capacity [AGV01]. Very low measurement noise is required for situations with large K-factors or large array sizes. As described in Section 7.3, the K-factor in the current data is well below one and for array sizes up to \(9 \times 2\) the estimation error is well below .5 bit/s/Hz in the capacity distribution at SNR 20dB.

### 8.3.1 UIPC Channel Capacity

The capacity for different signal-to-noise-ratios, with three receivers and one, two, and three transmitters is shown in Figure 8.2. Note the substantial increase in capacity as the number of transmitters increases from one to three. As a reference the simulated curve for the IID channel is plotted as well, indicating low correlation among the elements in \(H\) under...
these conditions. The following results are given for an SNR fixed at 20 dB.

Figure 8.3: The cumulative distribution function of the UIPC capacity for different numbers of receivers. Two transmitters at an SNR of 20 dB are used. $\Delta_{R_x} = \frac{\lambda}{4}$.

Increasing the number of receive and transmit antennas will also increase the capacity. This increase is indicated in Figure 8.3, which shows the cumulative distribution function for the capacity for different numbers of receivers. The capacity increase is initially large until the channel rank reaches its maximum, 2 (the number of receivers equals the number of transmitters $n_T = 2$). As expected, the increase for $n_R > n_T$ follows a logarithmic curve. This is due to an SNR increase from noise averaging over the channels. Also note that the variations in capacity are much more limited when using more receive antennas due to diversity gain from more sub-channels.

By picking out three of the receivers in the receive array it is possible to see how the intra-cell distance influences the capacity. In Figure 8.4
8.3 Results

![Graph showing cumulative distribution function for UIPC capacity](image)

**Figure 8.4:** The cumulative distribution function of the UIPC channel capacity for different intra-element distances. The SNR is 20 dB and three elements are used in both the transmitter array and the receiver array. $\Delta_{Rx} = \{\frac{\lambda}{4}, \frac{\lambda}{2}, \lambda, 2\lambda\}$.

The cumulative distribution function of the capacity is shown for different intra-element distances. Note that the possible capacity increase is small when increasing the distance between the elements beyond $\Delta = 2\lambda$.

### 8.3.2 NIPC Channel Capacity

The average capacities for UIPC and NIPC as functions of the number of receivers are shown in Figure 8.5. For UIPC, the transmitter has channel knowledge and thus, optimal power allocation is possible. The NIPC capacity is greater than the UIPC capacity, especially for the cases when $n_R \leq n_T = 3$ (channel rank is less than 3). Then the transmit power is directed into the subspace that is visible to the receiver, i.e., related to the $n_R$ non-zero singular values, and power waste is avoided. For the case of $n_R > n_T$ the gain is smaller and the capacity converges to the capacity...
8.3.3 Example: HiperLAN2 Channel Capacity

HiperLAN2 is a European Wireless LAN initiative, designed to operate in the 5 GHz band. The physical layer of HiperLAN2 is based on Orthogonal Frequency Division Multiplexing (OFDM) and is equivalent to the physical layer of IEEE 802.11a. HiperLAN2 uses dynamic TDD as multiple access method while IEEE 802.11a uses CSMA/CA. The channel separation in HiperLAN2 is 20 MHz. The HiperLAN2 physical layer provides several modes, each with different coding rates and modulation. These modes are selected by a link adaptation scheme ranging from 6 Mbits/s to 54 Mbits/s when signal-to-noise ratios varies from 5 dB to 25 dB. The user throughput in HiperLAN2, at signal-to-noise 20 dB is approximately 30 dB Mbits/s [DAK*01], and the Shannon scalar channel

![Graph comparing channel capacity for UIPC and NIPC](image)

**Figure 8.5:** Comparison of the channel capacity for UIPC and NIPC. The measured channel is compared to the simulated IID channel. Three transmit elements are used and the SNR is 20 dB.

of the UIPC as the transmit power is not recovered at the receiver.
8.3 Results

Figure 8.6: The cumulative distribution function of the UIPC and NIPF MIMO channel capacities for a HiperLAN2-type 3 × 3 system. The SNR is 20 dB and $\Delta_{R_x} = \frac{1}{2}$.

capacity at signal-to-noise ratio 20 dB is $20 \text{ MHz} \times \log_2(1 + 20 \text{ dB}) = 133 \text{ Mbits/s}$.

Assuming that the 12 frequency bins used (corresponding to 40 MHz bandwidth at 5.8 GHz) correspond to two HiperLAN2 channels, the MIMO capacity per HiperLAN2 channel has been calculated. The same normalization as above is used. In Figure 8.6 the capacity for a $3 \times 3$, 20 MHz MIMO channel with $\Delta_{R_x} = \frac{1}{2}$, is shown for the UIPC and NIPF channels i.e for no waterfilling and waterfilling over both frequency and space, respectively. Using the NIPF assumption, close to 80% of the channels reach a capacity of 300 Mbits/s.
8.4 Summary

Indoor MIMO channel measurements at 5.8 GHz have been analyzed in terms of channel capacity. Comparisons have been made to a simulated IID MIMO channel (under the same gain normalization) which corresponds to the most favorable situation in an uncontrolled environment. We conclude that for this experimental setup with intra-element distance $6\lambda$ on the transmitter side and $\frac{1}{2}$ to $2\lambda$ on the receiver side, the environment provides adequate multi-path propagation resulting in a high rank channel and a significant capacity increase compared with a low rank channel. For an intra-element distance exceeding about $2\lambda$, the results are indistinguishable from the IID channel case.

In an example the possible capacity for a HiperLAN2-like system was indicated to be more than 280 Mbits/s.
Chapter 9

Summary and Future Work

9.1 Summary

We have considered the future development within wireless communication with focus on the future generation wireless systems using smart antennas.

The possible techno-socio-economical surroundings of such systems where examined in a scenario analysis. With that background smart antenna systems have been investigated for both uplink and downlink transmission. Further, channel assessment in terms of link capacity, for the case of MIMO channels has been performed on measured data in the 5 GHz band.

An analytical expression for the throughput in a slotted ALOHA packet network using idealized smart antennas has been developed and supported by simulations. A planar wavefront propagation model with an ideal beamformer is assumed as well as a local scattering channel model providing a spatial extension of the flat fading channel. Diversity combining (Maximum Ratio Combining) and interference rejection are compared when the channel realizations are known. System performance is characterized in terms of packet throughput and delay. We show that the system throughput for a packet network utilizing adaptive array antennas may be increased substantially while maintaining a low packet delay. Interference rejection can potentially provide a significant
improvement over diversity combining alone.

It is shown that the possible downlink throughput in a cellular system may be substantially increased, using joint optimal beamforming and power control. However, this method requires global channel statistics knowledge and is thus appropriate for limited or isolated systems or future systems with global channel knowledge. Further, it has been shown that the possible throughput may be increased using an heuristic admission scheme, that outperforms random admission. Also the advantages when performing global access point allocation, integrated in the optimal beamforming algorithm, have been demonstrated. Global access point allocation is shown to further improve throughput as compared to assigning each mobile terminal to the access point from which it as the best gain. For a blocking rate of 10% the throughput in terms of admitted mobile terminals per cell may be increased from 0.2 for traditional beamforming, best gain access point allocation and random admission, to 1.5 mobile terminals for optimal beamforming, optimal access point allocation and the proposed heuristic admission control algorithm. An example of a practical system, such as WCDMA has been simulated. Then the advantage of conventional beamforming becomes smaller, though still present.

Indoor MIMO channel measurements at 5.8 GHz have been analyzed in terms of channel capacity. Comparisons have been made to a simulated IID MIMO channel (under the same gain normalization) which corresponds to the most favorable situation in an uncontrolled environment. We conclude that for this experimental setup, the environment provides adequate multi-path propagation resulting in a high rank channel and a significant capacity increase compared with a low rank channel. For an intra-element distance exceeding about two wavelengths the results are indistinguishable from the IID channel case.

9.2 Future Work

The performed work points out possible future work in two directions, smart antenna systems and dual array issues with the ultimate goal of MIMO system investigations.

9.2.1 Smart Antennas in Wireless Systems

As described in this thesis, the data communication part of wireless communication is increasing. Further, this data communication is foreseen
to be asymmetric. This indicates that the downlink capacity is crucial for the system and that the requirement for low delay, may not be crucial. Using the fact that the downlink traffic is well known, or at least predictable, at the access point, it is thereby possible to schedule the downlink packets to increase the downlink throughput further. The issue of scheduling integrated with optimal beamforming and admission control is one very interesting research field for the future.

Further, the downlink methods assessed herein require global channel knowledge. Decentralized beamforming methods with capabilities close to the optimal method, will be of interest in order to implement the optimal schemes in practical systems.

It is possible to apply the admission control algorithm without solving the complete optimal beamforming problem and thus to decrease the complexity of the admission control problem. This possibility and the influences on the scheduling problem should be further investigated.

The use of packet switching offers great advantages. At the same time the channel estimation may become more difficult as the packet communication is not continuous and estimation may have to be done on each packet.

The possibility to use optimal downlink beamforming in future CDMA systems is of interest. The examples in Chapter 6 give a limited insight under very basic assumptions and a deeper investigation of how the extension to wideband signals and the use of real spreading codes may be done and how it influences the performance is needed.

### 9.2.2 Smart Antennas with Dual Arrays

It is shown for a limited environment that the channel capacity increase of a MIMO link is substantial. It is of great interest to see for what environments the results are valid. Further, to be able to simulate and design dual array systems, the area of channel modeling for MIMO channels hopefully contains a lot of additional results.

The MIMO channel capacity results hold for one single terminal-to-access-point link. This means that the spatial dimension used to increase the number of standard rate users in a system with only an access point array, is now used to increase the capacity for a single user. The system perspectives on MIMO channel capacity is of interest for future investigation.
9.2.3 Feasibility

In this thesis the advantages and possibilities of smart antennas are investigated. It is a fact that a single access point with smart antennas is more complex, and therefore maybe more expensive than a traditional access point. Thus it is of great interest to see if the increased capacity, flexibility and coverage of smart antennas outweigh the increased complexity and cost.
Appendix A

Acronyms

Some of the acronyms used in this thesis are explained below

1G  1st Generation Wireless Systems e.g. NMT, AMPS

2G  2nd Generation Wireless Systems e.g. GSM, DAMPS CDMA


4GW  4th Generation Wireless Systems

ALOHA  Random Multiple Access scheme

AP  Access Point

AMPS  American Mobile Phone Standard

AWGN  Additive White Gaussian Noise

CDF  Cumulative Distribution Function

CDMA  Code Division Multiple Access

CIR  Carrier-to-Interference-Ratio
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
</tr>
<tr>
<td>DOA</td>
<td>Direction Of Arrival</td>
</tr>
<tr>
<td>EDGE</td>
<td>Enhanced Data Rates for Global Evolution</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile communication or Groupe Spécial Mobile</td>
</tr>
<tr>
<td>HiperLAN2</td>
<td>HIgh PERformance LAN 2</td>
</tr>
<tr>
<td>IID</td>
<td>Independent and Identically Distributed</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>LOS</td>
<td>Line-Of-Sight</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Protocol</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple-Input-Multiple-Output</td>
</tr>
<tr>
<td>MISO</td>
<td>Multiple-Input-Single-Output</td>
</tr>
<tr>
<td>MMSE</td>
<td>Minimum Mean Square Error</td>
</tr>
<tr>
<td>MRC</td>
<td>Maximum Ratio Combining</td>
</tr>
<tr>
<td>MUSIC</td>
<td>MUltiple SIgnal Classification</td>
</tr>
<tr>
<td>NIPC</td>
<td>Non-uniform Input Power Channel</td>
</tr>
</tbody>
</table>
A  Acronyms

NIPF  Non-uniform Input Power Frequency Selective Channel

NLOS  Non-Line-Of-Sight

QoS  Quality of Service

OSI  Open Systems Interconnections

PCC  Personal Computing and Communication

SATURN  Smart Antenna Technology in Universal bRoadband wireless Networks

SDMA  Space Division Multiple Access

SIMO  Single-Input-Multiple-Output

SISO  Single-Input-Single-Output

SINR  Signal-to-Interference-and-Noise Ratio

SIR  Signal-to-Interference Ratio

SNR  Signal-to-Noise Ratio

SSF  Swedish Foundation for Strategic Research

SVD  Singular Value Decomposition

TDD  Time Division Duplex

TDMA  Time Divisions Multiple Access

UCA  Uniform Circular Array

UIPC  Uniform Input Power Distribution
UMTS  Universal Mobile Telephone System
WCDMA  Wideband Code Divisions Multiple Access
WLAN  Wireless LAN
ZF  Zero Forcing
## Appendix B

### Notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X^T$</td>
<td>the transpose of the matrix $X$</td>
</tr>
<tr>
<td>$X^*$</td>
<td>the Hermitian or the Conjugate transpose of the matrix $X$</td>
</tr>
<tr>
<td>$X^\dagger$</td>
<td>The pseudo-inverse of the matrix $X^*$ i.e. $X^\dagger = (X^<em>X)^{-1}X^</em>$ if $X$ is full rank</td>
</tr>
<tr>
<td>$X_{kl}$</td>
<td>Element in row $k$ and column $l$ of a matrix $X$.</td>
</tr>
<tr>
<td>$\text{Tr}[X]$</td>
<td>is the trace of $X$ i.e. $\text{Tr}[X] = \sum_i X_{ii}$, where $X$ square.</td>
</tr>
<tr>
<td>$|X|_F$</td>
<td>The Frobenius norm of $X$ i.e. $\text{Tr}[XX^*]$</td>
</tr>
<tr>
<td>$X \succeq 0$</td>
<td>The matrix $X$ is positive semidefinite</td>
</tr>
<tr>
<td>$\max$</td>
<td>The maximum of a function</td>
</tr>
<tr>
<td>$\arg \max$</td>
<td>The argument resulting in the maximum of a function</td>
</tr>
<tr>
<td>$P(\cdot)$</td>
<td>The probability function</td>
</tr>
<tr>
<td>$E[\cdot]$</td>
<td>Expected value of a random variable</td>
</tr>
<tr>
<td>$x \sim N(0, \Sigma)$</td>
<td>$x$ is normal distributed with zero mean and covariance matrix $\Sigma$</td>
</tr>
<tr>
<td>$x \sim \text{CN}(0, \Sigma)$</td>
<td>$x$ is complex normal distributed with zero mean and covariance matrix $\Sigma$</td>
</tr>
</tbody>
</table>


134 Bibliography


Index

3G, 9
4GW, 10
access point, 21
access point assignment, 43, 61, 68
Ad-hoc operation, 17
admission control, 61
Anything Goes, 13
asymmetry, 30
beamforming, 27
Big Brother, 14
carrier frequency, 21
CDMA, 23, 82
channel, 23
channel capacity, 107
channel estimation, 30
conventional beamforming, 65
Direction-of-Arrival, 24
downlink, 37
downlink beamforming, 61
dual arrays, 21, 97
education, 12
fade margin, 77
fairness, 85
Farkas’ lemma, 70
FDMA, 23
frequency selective channel, 108
globalization, 12
GSM, 2, 9
HiperLAN2, 114
idealized antenna, 40
infrastructure, 10
Lagrange multiplier, 69
link, 22
local scattering, 39, 73
measurements, 100
MIMO, 25, 97
mobile terminal, 22
multicasting, 19
Non-homogeneous infrastructure, 17
optical telegraph, 1
optimal beamforming, 28, 67
PCC, 10
Pocket Computing, 14
Poisson traffic model, 42
power control, 23, 67
propagation loss, 38
Rayleigh fading, 24
rich scattering, 97
SATURN, 26
scenario, 11, 13
scheduling, 29
SDMA, 23, 61
security, 16
SeDuMi, 72, 74
semidefinite optimization, 69
shadow fading, 24
Smart Antennas, 21
SSF, 10
standardization, 13
synthetic array, 101

TDMA, 23
tele-presence, 15
terminals, 18
trends, 12

ubiquitous information, 16
uniform circular array, 40
uplink, 36

virtual uplink, 71

waterfilling, 108
working assumptions, 11