Aspects of Massive MIMO

Marcus Karlsson

Division of Communication Systems
Department of Electrical Engineering (ISY)
Linköping University, 581 83 Linköping, Sweden
www.commsys.isy.liu.se

Linköping 2016
Abstract

Next generation cellular wireless technology faces tough demands: increasing the throughput and reliability without consuming more resources, be it spectrum or energy. Massive MIMO (Multiple-Input Multiple-Output) has proven, both in theory and practice, that it is up for the challenge. Massive MIMO can offer uniformly good service to many users using low-end hardware, simultaneously, without increasing the radiated power compared to contemporary system. In Massive MIMO, the base stations are equipped with hundreds of antennas. This abundance of antennas brings many new, interesting aspects compared to single-user MIMO and multi-user MIMO. Some issues of older technologies are nonexistent in massive MIMO, while new issues in need of solutions arise. This thesis considers two aspects, and how these aspects differ in a massive MIMO context: physical layer security and transmission of system information. First, it is shown that a jammer with a large number of antennas can outperform a traditional, single-antenna jammer in degrading the legitimate link. The excess of antennas gives the jammer opportunity to find and exploit structure in signals to improve its jamming capability. Second, for transmission of system information, the vast number of antennas prove useful even when the base station does not have any channel state information, because of the increased availability of space-time coding. We show how transmission without channel state information can be done in massive MIMO by using a fixed precoding matrix to reduce the pilot overhead and simultaneously apply space-time block coding to use the excess of antennas for spatial diversity.
Sammanfattning

Det ställs hårda krav på nästa generations cellulära trådlösa system: att simultant öka datataken på kommunikationen och dess tillförlitlighet utan att konsumera mer resurser, oavsett om det spektrum eller energi. Massiv mimo (eng: Multiple-Input Multiple-Output) har visat, både i teori och praktik, att tekniken är redo att tackla utmaningen. Massiv mimo kan betjäna många användare samtidigt, med god service, utan att öka den utstrålade effekten jämfört med nuvarande system. Massiv mimo, där basstationerna är utrustade med hundratals antenner, skiljer sig från dagens system vilket gör att många nya problem dyker upp och nya infallsvinklar på befintliga problem krävs. Denna avhandling analyserar två problem, och hur dessa förändras i ett massiv mimo sammanhang: säkerhet för fysiska lagret och överföring av systeminformation. Särskilt visas att en störsändare med ett stort antal antenner kan överträffa en traditionell störsändare med en enda antenn. Antalet antenner ger störsändaren möjlighet att hitta strukturer i signaler och utnyttja detta för att förbättra störningens effekt. Det stora antalet antenner visar sig vara användbart även för överföring av systeminformation, där basstationen inte har någon kanalkännedom. Antennerna ger möjligheten att tillämpa spatial kodning (eng: space-time block coding). Vi visar hur överföringen utan kanalkännedom kan göras i massiv mimo genom att använda en fix förkodningsmatris för att reducera antalet pilotsymboler. Samtidigt kodar vi spatiellt över antennerna för att tillhandahålla spatiell diversitet.
Mängden information ökar kraftigt i världen, och så även vårt behov av att ta del av den. Befolkningen växer och vi är i konstant behov av energisnåla alternativ till alla dagens lösningar. Massiv MIMO (eng: Multiple-Input Multiple-Output) är ett nytt sätt att kommunicera trådlöst, främst för mobil kommunikation, som utnyttjar resurser på ett bättre sätt än nuvarande system. Med hjälp av ett stort antal antenner kan massiv MIMO skicka individuella dataströmmar till en mängd olika användare, samtidigt och i samma frekvensband. Detta gör massiv MIMO till en attraktiv kandidat till nästa generations trådlösa mobilnät. Eftersom massiv MIMO är en ny teknik, dyker det upp nya problemställningar som inte tidigare funnits. De senaste åren har tekniken tagit stora steg framåt, men det är fortfarande saker som måste lösas, om massiv MIMO ska bli den trådlösa teknik som används i framtiden. Denna avhandling belyser två aspekter som måste lösas innan massiv MIMO kan användas i ett cellulärt system. Den första är hur denna teknik kan användas som störsändare, för att hindra annan kommunikation. Det andra som undersöks är transmission av systeminformation, som är nödvändig för att användarna i cellen ska fungera och kunna ta in den information som skickas.
Acknowledgments

I am grateful to many people who have, in one way or another, helped me with my thesis, research and anything else during my years of study. Both of my supervisors, Dr. Erik G. Larsson and Dr. Emil Björnson have helped me in countless ways during these years. I am always amazed by their wisdom and ever-thankful for their guidance. I am also humbled by the knowledge of all the colleagues at Communication Systems in Linköping. Discussions with you always teach me something, and leaves me more hungry for knowledge. I would also like to thank our colleagues at Ericsson Research in Linköping for valuable insights and discussions during our meetings.

On a personal level, I’d like to thank my family and friends. You may not help me actively in my research, but the support I get from you makes tough times a lot easier. You help me in more ways than you can imagine.

Marcus Karlsson
Linköping, Fall 2016
Contents

1 Introduction
   1.1 Massive MIMO ........................................... 1
   1.2 Contributions of the Thesis ............................ 3

2 Basic Concepts
   2.1 System Model ........................................... 5
      2.1.1 The Channel ....................................... 6
      2.1.2 The Noisy Channel ................................. 8
      2.1.3 Reciprocity ....................................... 8
      2.1.4 Channel Uses ..................................... 9
      2.1.5 The Coherence Interval ......................... 9
      2.1.6 Multiple-Input Multiple-Output .......... 10
   2.2 Channel Capacity .................................... 11
      2.2.1 Outage Capacity .................................. 13
      2.3 Diversity .......................................... 13
   2.4 Benefits of Massive MIMO ......................... 17
      2.5 Physical Layer Security ......................... 18
      2.6 System Information ............................... 19

3 Future Work ............................................ 21

Bibliography ............................................. 23

Included Papers ......................................... 27

A Jamming with Massive MIMO Technology ........... 29
   1 Introduction ........................................ 31
   2 System Model ....................................... 33
      2.1 The Primary Link ................................ 33
      2.2 The Jammer ....................................... 35
Chapter 1

Introduction

Wireless communication today is an integral part of everyday life for millions of people. To not have your phone or laptop, not being able to check schedules or answer emails, is perceived as a nightmare. The demand for accessing and spreading information, in particular over a wireless connection will surely continue to rise for years to come. Somehow we need to be able to meet this demand, without spending more resources. Most wireless resources, including time, frequency and energy, are already scarce and as more people get connected we do not have the option to simply increase the allocated resources. The frequency spectrum is finite, time is scarce and in an energy-starving world, increasing energy consumption to meet increased demand is not a viable option. Wireless research is all about trying to simultaneously fulfill the conflicting goals of faster and more reliable communication without spending more resources.

1.1 Massive MIMO

Massive MIMO (Multiple-Input Multiple-Output) is a promising technology for next generation wireless communication network that can provide unprecedented gains in spectral efficiency, the number of information bits per time-frequency resource. There is no need for complex detection methods like dirty paper coding, which is computationally heavy, as linear processing performs well. Simple hardware can be used in both the base station (BS) and the terminals. The terminals in the cell can be served with uniformly good service.

All these things are made possible at the same time by the use of a large number of BS antennas. The multitude of antennas makes it possible to beamform different signals to different users, so the signals add up constructively at the desired user and destructively everywhere else. This means the BS can multiplex spatially, serving different users in parallel, using the same time-frequency resource. The
beamforming also provides an array gain, as the transmitted energy is focused on the terminal. Linear processing performs very well because of the phenomenon known as favourable propagation.

Massive MIMO also exploits the channel reciprocity, a property of time-division duplex (TDD) systems where uplink and downlink occupy the same frequency band but are non-overlapping in time. This enables the BS to learn both the uplink and the downlink channel from uplink pilots. The terminals do not need to estimate the channel, or even have channel information—as long as the statistics of the channel are known—because of channel hardening. In short, the multitude of antennas at the base station brings benefits that make massive MIMO scalable.

Since the initial paper [1], a sea of papers have been published, analyzing, for example, spectral efficiency [2, 3] and non-conventional ways to benefit from the many antennas [4–7]. Focus has been on showing that the theory behind massive MIMO is solid, and that the gains are impressive even at a finite number of antennas and with non-ideal hardware [8, 9], making it viable in practice.

There exist several testbeds, both from the industry and academia [10–12], showing that the beautiful closed-form rate expressions obtained in theory are actually achievable in reality. The proof of concept phase has past, but there are still holes to fill, before massive MIMO becomes the next generation cellular technology.

Emerging testbeds allow massive MIMO to evolve further, and as it evolves, its availability increases. Eventually, the technology might be used for, e.g., jamming or eavesdropping instead of to convey information. To know how to counteract jamming or eavesdropping, analyzing the potential and strategies of jammers and eavesdroppers become important. Most of the literature has discussed and analyzed how jammers and eavesdroppers behave differently when faced with a massive MIMO BS [13] or what the BS can do to mitigate jamming [14].

Much of the research involving massive MIMO have been done on the physical layer, to understand what precoders to use in what settings, and how different settings affect the rate of information flow. However, transmission without channel state information (CSI) at the BS has received relatively little attention. In order for the terminals/users to be able to connect to the network, they have to receive system information, which is transmitted continuously by the BS, in order to inform the users about the cell operation. This information has to be conveyed without CSI at the base station and thus, transmission without CSI is imperative for massive MIMO to work. Opponents of massive MIMO have said that transmission without CSI is the issue that will inhibit the realization of a cellular massive MIMO system [15]. Recently, several articles have tried to tackle this problem, with the use of space-time block codes [16–20].
1.2 Contributions of the Thesis

The research problems considered are of two different topics: jamming and system information transmission. We analyze what can happen when an adversary gets a hold of the massive MIMO technology, and what damage this can cause. This is a first step towards knowing how we can make massive MIMO secure on the physical layer. Second, the transmission of system information in massive MIMO and the issues around it are discussed, and a solution is proposed.

Both papers below, including the simulations, are written by the first author. The co-authors (supervisors) have with an abundance of comments, ideas and proofreading made the papers more understandable, more rigorous and better in every way. None of the papers below would have the same quality without the help of both supervisors.

**Paper A: Jamming a Point-to-Point Link Using Massive MIMO Technology**

Authored by: Marcus Karlsson, Emil Björnson and Erik G. Larsson

Submitted to: IEEE Transactions on Information Forensics and Security

In this paper, we consider a massive MIMO jammer, a malicious transmitter that aims to stop communication of a point-to-point link with two single-antenna users operating in time-division duplex mode. The jammer could be a hijacked base station or custom build massive MIMO array. We present an algorithm for jamming where the jammer has very limited knowledge of the point-to-point link, in particular no knowledge of the transmitted signals. To estimate the frame timing, the jammer analyzes the structure of the sample covariance matrix. After this, the jammer exploits the channel reciprocity to estimate the channel to one of the users in order beamform noise to reduce the rate of legitimate communication between the two users.

**Paper B: In-band Transmission of System Information in Massive MIMO**

Authored by: Marcus Karlsson, Emil Björnson and Erik G. Larsson

Submitted to: TBD.

The transmission of system information in massive MIMO is analyzed. In particular the use of orthogonal space-time block codes (OSTBCs) to facilitate reliable communication in the downlink without channel state information at the base station. The OSTBCs are precoded with a dimension reducing matrix to reduce the pilot overhead. We discuss the effects of different choices of this precoding matrix when the channels to the different base station antennas are correlated. We further analyze the performance of four OSTBCs in settings with different number of time/frequency diversity branches, and compare the massive system MIMO base station to a system with a single-antenna at the base station.
1 Introduction
Chapter 2

Basic Concepts

In this section some basic concepts regarding wireless communication are presented. Most things are stated without formal proofs as this is textbook material. However, we do provide “hand-waving” explanations and why the assumptions are plausible. Basically, this chapter takes a look at some of the most common models and tools, and why they are used. It is aimed mostly for readers with limited prior knowledge of wireless communication. For more rigorous treatment and introduction to the subject, see for example [21–23].

2.1 System Model

A signal \( x(t) \) is transmitted over a wireless channel. On its way from the transmitter to the receiver, the signal is reflected, scattered and diffracted many times as it bounces from object to object. These objects can be trees, cars, mountains, people, or any other things that the signal happens to hit on its way to the receiver. When the receiver then measures the signal, it sees a linear combination of many time-delayed and attenuated versions of \( x(t) \). This phenomenon is called multipath propagation due to the signal traveling a number of different paths to reach the receiver. Taking both attenuation and time delay into consideration, we can write the received signal as

\[
y(t) = \sum_i a_i x(t - \tau_i),
\]

if we assume the channel is used for a short enough time\(^1\) to be considered time invariant. In (1), \( a_i \) and \( \tau_i \) are the attenuation and the propagation delay of path \( i \), respectively. We do not explicitly give an upper limit on the summation in (1), but it can be seen as “practically infinite”.

\(^1\)We will define this more precisely in Section 2.1.5.
Generally, $x(t)$ is a passband signal, that is, its spectrum is nonzero only in a band centered around some carrier frequency $f_c$. However, what $f_c$ is depends on the application, and what frequency bands are available for operation. Also, most processing of signals is done in the baseband ($f_c = 0$) so a more useful, equivalent model, is the discrete-time complex baseband model,

$$y[n] = \sum_{l=0}^{L-1} h[l] x[n - l],$$

where $y[n]$ and $x[n]$ are the sampled (complex) baseband versions of $y(t)$ and $x(t)$, respectively. The new variable, $h$ models the chain from transmitted sample $x[n]$ to received sample $y[n]$. This includes pulse amplitude modulation, up-conversion, multi-path propagation and receive filtering. $h[l]$ is called the $l$:th channel tap and the channel as a whole is called an $L$-tap channel. Each channel tap represents the channel gain at a particular time delay.

One way of thinking about how to go from a real signal in the passband, to a complex baseband signal is to look at the spectrum of the real passband signal $x(t)$. As $x(t)$ is real, its spectrum is symmetric around zero as in Figure 1a. This means we can find out everything we need to know about $x(t)$ by only considering the spectrum for frequencies larger than zero. Moving this spectrum down to the baseband means that the baseband signal, in general, is complex, as the spectrum is not necessarily symmetric, see Figure 1b.

Moving the positive spectrum down to the baseband also halves the bandwidth of the signal, making the bandwidth of the real passband signal twice that of its complex baseband equivalent. This might give the impression that one can break the Nyquist criterion, which says with at least $2B$ is necessary to fully represent a signal with bandwidth $B$ Hz. Sure, one can get away with sampling the complex equivalent with $B$ Hz, but now these are complex samples (two real samples each sampling time), effectively giving the same dimensionality.

### 2.1.1 The Channel

The channel coefficient $h[l]$ is basically the aggregation of all the attenuation and time delays effecting the transmitted signal during one symbol time $T_s$. The different delays $\tau_i$ are lumped together, and the effects of all paths (signals) arriving at the transmitter during one symbol time constitutes one channel tap. But objects in the world are not stationary, so the channel changes continuously. When objects in the path, or either of the transmitter or receiver move, the multipath propagation pattern will change. This means that $a_i$ and $\tau_i$ change. If objects move a small distance, in the order of a few wavelengths, the delay of each path, $\tau_i$, may change significantly while $a_i$ remains almost constant.
2.1. System Model

(a) The spectrum of the real passband signal $x(t)$.

(b) The spectrum of the complex baseband equivalent of $x(t)$.

Figure 1: The complex baseband representation of a signal can be obtained by shifting the spectrum of the real signal, and scale appropriately. Both signals are equivalent as they carry the same information, only the latter description is a bit more compact and independent of $f_c$. The bandwidth of the complex baseband representation is further half of its real passband equivalent.
The changes in delays will have a large impact on the received signal as the delayed versions of the signal may shift from adding up constructively, to adding up destructively, resulting in a very small (in magnitude) channel coefficient $h[l]$. This sudden change in the channel is called small-scale fading, as tiny changes in the propagation paths may cause significant changes in the channel coefficient. When the scattering is rich, i.e. there are many objects surrounding the receiver, the central limit theorem kicks in, so that each tap of the channel impulse response is well modeled as a complex Gaussian variable, a common assumption in the literature.

The different attenuations of each path, $a_i$, change more slowly, as objects may have to move tens of meters before a significant change is observed. This type of fading is called large-scale fading, as large object have to move, or the receiver/transmitter has to move a considerable distance before it changes. Because of the slow change, the large-scale fading is easier to track and estimate than the quickly varying small-scale fading, resulting that the large-scale fading is assumed to be known in most models. The large-scale fading is commonly denoted with $\beta$ in the literature, and is the variance of the channel coefficient $h[l]$.

### 2.1.2 The Noisy Channel

Normally, when measuring signals, some kind of noise is present. That is, we measure a noisy signal:

$$y(t) = \sum a_i x(t - \tau_i) + w(t), \quad (3)$$

where $w(t)$ is a noise process. Translating this to the discrete-time model, we have

$$y[n] = \sum_{l=0}^{L-1} h[l] x[n - l] + w[n]. \quad (4)$$

Normally, $w(t)$ is taken to be white Gaussian noise with zero mean. There are multiple reasons for this, the two most prominent being that $w(t)$ is often composed of many different (almost) independent terms and that Gaussian noise is tractable when doing analysis. Because $w(t)$ is white, Gaussian and has zero mean, the samples $w[n]$ are jointly (complex) Gaussian with zero mean.

### 2.1.3 Reciprocity

Channel reciprocity is something that appears in TDD systems. In TDD systems, two transceivers take turns transmitting and receiving during different time slots, using the same frequency band. Because they use the same frequency, the channel is reciprocal (the same backwards and forwards). This is a very useful property, as
the channel only has to be estimated in one direction. If the two transceivers use different frequency bands, the electromagnetic waves will behave differently since, e.g., absorption and diffraction depends on the carrier frequency. Hence, reciprocity is not found in frequency-division duplex systems.

Even though the wireless channel is reciprocal, the hardware might not be. This means that the effective channel may not be reciprocal. However, issue can be solved by calibrating the hardware appropriately.

### 2.1.4 Channel Uses

From the sampling theorem, we know that in order to recreate a signal \( x(t) \) with bandwidth \( B \) from its samples, we have to sample with sampling frequency \( f_s \geq 2B \). If we do not want to oversample, we can get away with the Nyquist rate \( f_s = 2B \). This means a signal with bandwidth \( B \) and duration \( T \) can be represented by \( 2BT \) real valued samples. Conversely, in a time-frequency space of \( B \times T \), it is possible to squeeze in \( 2BT \) real valued samples. The same thing can be done with complex samples/signals, resulting in \( BT \) complex samples. We say that the time-frequency space \( B \times T \) enables \( BT \) (complex) channel uses [24].

### 2.1.5 The Coherence Interval

We mentioned earlier in Section 2.1 that if we look at the system for a short enough time, the output can be described by (1). Sufficiently short time here refers to a time frame for which the propagation channel can be considered constant (or at least predictable). The coherence time, \( T_c \), is a measure of how fast the channel changes. The magnitude of \( T_c \) varies vastly between different channels: for wires, \( T_c \) is practically infinite, while for a wireless channel \( T_c \) can be in the order of milliseconds. The point is, even a time varying channel/system can be considered time invariant if looked at for a sufficiently short time.

The coherence time is limited by how quickly the propagation channel changes. Even though the construction of buildings or cutting down trees change propagation environment, much smaller things than this can change the channel drastically. For the channel to change significantly, it is enough to let either the transmitter or the receiver move a fraction of the wavelength (which for a 1 GHz carrier is about 30 cm).

An analogue to the coherence time in the frequency domain is the coherence bandwidth, \( B_c \), which is the bandwidth over which the channel frequency response is essentially constant. The coherence bandwidth of a channel is related to the delay spread, \( T_d \), of the channel. The delay spread is the difference in propagation time
between the longest and the shortest path, i.e.

\[ T_d = \max_{i \neq i'} |\tau_i - \tau_{i'}|. \]

As \( T_d \) essentially tells us how long the channel impulse response is. The frequency response of the channel, is constant over a frequency band inversely proportional to the delay spread. As a ball park estimate, the coherence bandwidth is

\[ B_c \sim \frac{1}{T_d}. \]

A channel’s impulse response and frequency response can hence be considered constant during \( \tau_c = T_c B_c \) channel uses. \( \tau_c \) is called the coherence interval, and is the time-frequency product over which a channel can accurately be modeled as a linear and time invariant system. The signal \( x(t) \) have to fit into this coherence interval, meaning, it cannot contain more than \( \tau_c \) symbols.

If the bandwidth of the transmitted signal is larger than \( B_c \), or, equivalently, if the delay spread is longer than one symbol time \( T_s \), the channel is said to be frequency selective, resulting in an \( L \)-tap channel, with approximately

\[ L = \frac{T_d}{T_s} \]

channel taps. If \( L = 1 \) we have a frequency flat channel.

### 2.1.6 Multiple-Input Multiple-Output

Previously in Section 2.1 we have only considered a single-antenna receiver as well as a single-antenna transmitter. The model (4) can be generalized to a system involving multiple receiver and transmitting antennas (not necessarily co-located): a mimo channel. Here we consider a frequency flat channel, that is \( L = 1 \).\(^2\)

Let us consider a transmitter with \( N_t \) antennas and a receiver with \( N_r \) antennas. If we consider a transmitter-receiver antenna pair, say transmit antenna \( m \in \{1, \ldots, N_t\} \) and receive antenna \( k \in \{1, \ldots, N_r\} \), we have the same situation as in the Single-Input Single-Output (siso) case covered earlier in (4). The received signal if only antenna \( m \) transmits (all other antennas are silent) can be written

\[ y_k = h_{k,m} x_m + w_k, \]

\(^2\)The frequency selective model can also be extended in a similar manner, it is just slightly messier, and does not give any additional insights.
2.2 Channel Capacity

where $h_{km}$ represents the channel gain from transmit antenna $m$ to receiving antenna $k$. When the entire array transmits, the received signal at antenna $k$ will be the sum of all signals transmitted from the $N_t$ transmit antennas:

$$y_k = \sum_{m=1}^{N_t} h_{km} x_m + w_k.$$ 

All $N_r$ of the simultaneously received samples can conveniently be written as

$$y = Hx + w,$$

where

$$y = [y_1, \ldots, y_{N_r}]^T,$$

$$x = [x_1, \ldots, x_{N_t}]^T$$

and

$$w = [w_1, \ldots, w_{N_r}]^T.$$ 

$H$ is a matrix with element $(k, m)$ equal to $h_{km}$.

## 2.2 Channel Capacity

A wise man once said that speaking about capacity is something one should not do, unless it is absolutely necessary and you know exactly what you want to say. In this section, we will state the capacity for some insightful channels, necessary to comprehend common performance metrics used in the literature. More details of the claims made here can be found in, e.g., [22, 25–27].

Capacity is formally the tight upper bound on the rate at which information can transmitted, error free, over a channel. It is measured in bits per channel use (bpcu). In many cases, the capacity of a channel is unknown, so lower bounds or achievable rates are computed instead. In all cases below, the noise is assumed to be independent of the transmitted signal.

The simplest (non trivial) channel is the additive white Gaussian noise channel (AWGN channel):

$$y = \sqrt{\rho} x + w,$$

where the noise $w \sim \mathcal{CN}(0, 1)$. Assuming $\mathbb{E} [|x|^2] \leq 1$, the capacity of this channel is equal to

$$C_{\text{AWGN}} = \log_2 (1 + \rho),$$

and $\rho$ is called the signal-to-noise-ratio (SNR). The SNR is defined as the ratio between the average received signal energy and the noise energy (per channel use).
In general, the channel will be more complicated than an AWGN channel, as we will have fading, MIMO and non-Gaussian noise. Therefore, consider a MIMO channel (cf. (5)):

\[ \mathbf{y} = \sqrt{\rho} \mathbf{H} \mathbf{x} + \mathbf{w}. \]  

(6)

Let \( \mathbb{E}[\mathbf{x} \mathbf{x}^H] = \mathbf{C}_x \succeq 0 \) denote the covariance matrix of the transmitted symbol vector. We also impose the power constraint \( \text{tr}(\mathbf{C}_x) \leq 1 \), on the transmitted signal. Assuming perfect channel state information (CSI) at the receiver and an identity covariance matrix for the noise, the \textit{ergodic} capacity is given by

\[
C_{\text{MIMO}} = \max_{\mathbf{C}_x \succeq 0, \text{tr}(\mathbf{C}_x) \leq 1} \mathbb{E} \left[ \log_2 \det(\mathbf{I}_{N_t} + \rho \mathbf{H} \mathbf{C}_x \mathbf{H}^H) \right].
\]

If the transmitter chooses to transmit i.i.d. symbols, giving \( \mathbf{C}_x = \frac{1}{N_t} \mathbf{I}_{N_t} \), which is the reasonable choice if the transmitter does not have CSI (statistical or instantaneous) we get the achievable rate

\[
C_{\text{MIMO}} \geq \mathbb{E} \left[ \log_2 \det(\mathbf{I}_{N_t} + \frac{\rho}{N_t} \mathbf{H} \mathbf{H}^H) \right].
\]

Ergodic rates requires coding over a large number of channel realizations.

If the noise is correlated, with covariance matrix \( \mathbf{C}_w \), the capacity is given by \cite{26} \(3\)

\[
C_{\text{MIMO}} = \max_{\mathbf{C}_x \succeq 0, \text{tr}(\mathbf{C}_x) \leq 1} \mathbb{E} \left[ \log_2 \det(\mathbf{I}_{N_t} + \rho \mathbf{C}_w^{-1} \mathbf{H} \mathbf{C}_x \mathbf{H}^H) \right].
\]

Again, this can only be achieved if transmitter and receiver have perfect CSI. A useful lower bound, used in Paper A, is obtained by assuming no CSI at the transmitter, so \( \mathbf{C}_x = \frac{1}{N_t} \mathbf{I}_{N_t} \):

\[
C_{\text{MIMO}} \geq \mathbb{E} \left[ \log_2 \det(\mathbf{I}_{N_t} + \frac{\rho}{N_t} \mathbf{C}_w^{-1} \mathbf{H} \mathbf{H}^H) \right].
\]

This bound is valid for any noise with covariance \( \mathbf{C}_w \), but a further lower bound is obtained if we let \( \mathbf{w} \sim \mathcal{CN}(0, \mathbf{C}_w) \), since Gaussian is the worst case uncorrelated noise \cite{28, Theorem 1}.

\(3\)This follows from the channel capacity for uncorrelated noise by multiplying the received signal with \( \mathbf{C}_w^{-1/2} \) (whitening the noise), and consider the effective channel \( \mathbf{C}_w^{-1/2} \mathbf{H} \), provided that the inverse exists.
2.2.1 Outage Capacity

The ergodic capacity measures in Section 2.2 are only valid if we consider long codewords and code over many channel realizations (coherence intervals). If this is not an option, for example if transmission only takes place during a single coherence interval, another measure is needed. Strictly speaking, the capacity of the fading channel is zero, as there is no rate that can be guaranteed to hold for any channel realization. Instead, in slow fading channels, one usually talk about outage capacity/rates.

A communication link is said to be in outage if it fails to support the rate \( R \) given to it. Outage-free communication can only be guaranteed if the rate \( R \) is smaller than the capacity of the channel. As the capacity of a fading channel depends on the channel realization, error-free communication cannot be guaranteed when looking at a single channel realization. The outage probability of a siso fading channel (see (6) with one transmit and receive antenna) is defined as

\[
p_{\text{out}}(R) = \mathbb{P}(R > \log_2 (1 + |h|^2 \rho)),
\]

where the effective snr \( |h|^2 \rho \) will depend on the channel realization \( h \). For any rate \( R \), there will always be a nonzero probability that \( |h|^2 \) is too small to support the rate.

If we can tolerate an outage probability of \( \epsilon > 0 \), the outage capacity is defined as the largest rate \( R \) such that the outage probability is smaller than \( \epsilon \), i.e.,

\[
C_\epsilon \triangleq \sup \{ R : p_{\text{out}}(R) < \epsilon \}.
\]

2.3 Diversity

Consider the received signal \( y \) when a single-antenna transmitter transmits the signal \( x \) over the channel \( h \) to a single-antenna receiver, corrupted by AWGN with unit variance:

\[
y_1 = h_1 x + w_1.
\]  

(7)

If we assume that the receiver knows \( h_1 \), this is equivalent to

\[
y_1' = \frac{h_1^*}{|h_1|} y_1 = |h_1| x + w_1',
\]

where \( w_1' \) has the same distribution as \( w_1 \). I.e. an AWGN channel with snr \( |h_1|^2 \). The snr will depend on the realization of the channel \( h_1 \), and if \( |h_1| \) is (very) small, the channel is said to be in a deep fade.
Now consider a receiver with two antennas, that collects two samples of the same signal, but with different (independent) channel and noise realizations. In addition to the received signal on antenna one, \((7)\), the receiver obtains
\[
y_2 = h_2 x + w_2.
\]
Processing both of these received samples in a similar way as above, and adding them up gives
\[
y = h_1^* y_1 + h_2^* y_2 = (|h_1|^2 + |h_2|^2) x + h_1^* w_1 + h_2^* w_2.
\]
The SNR is now proportional to \(|h_1|^2 + |h_2|^2\), which always is larger than \(|h_1|^2\), so one benefit from using more antennas is clear: the effective SNR when decoding the symbol is increased. However, this benefit is only secondary, the major thing is that the SNR now is a sum of two independent (non-negative) random variables. The benefit of this is that the probability of a deep fade is significantly reduced (and thereby the probability of erroneous detection). This increased resistance to deep fades is termed diversity.\(^4\)

When the transmitter is equipped with several antennas, \(N_t > 1\), transmit diversity can be achieved. Transmit diversity is, however, a bit more tricky to achieve than receive diversity. Consider a single sample at the receiver (now with \(N_r = 1\)), with the same signal transmitted from two antennas:
\[
y = h_1 x + h_2 x + w = (h_1 + h_2) x + w.
\]
The SNR is then proportional to
\[
|h_1 + h_2|^2
\]
which may be small, even if neither \(|h_1|\) nor \(|h_2|\) is small. We see that we cannot simply achieve transmit diversity, without CSI at the transmitter this way.

In Figure 2 we compare the SNR of cumulative distribution of \(|h_1|^2\), \(|h_1 + h_2|^2\) and \(|h_1|^2 + |h_2|^2\). We see that in the case when we have diversity, the probability of deep fades is significantly smaller than in the other two. In this example, we consider the case with \(h_i \sim \mathcal{CN}(0, 1)\) for \(i = 1, 2\) and \(h_1\) and \(h_2\) are independent.

On the other hand, if we let the transmission span two channel uses, and we transmit with antenna 1 during the first, and antenna 2 during the second, the received signals are
\[
y_1 = h_1 x + w_1
\]
\(^4\)Many authors define diversity (or more precisely the diversity order) more strictly, as the slope of the bit-error curve against SNR, in log-log scale.
2.3. Diversity

Figure 2: The effective SNR for transmission and reception with 1 or 2 antennas.

and

\[ y_2 = h_2 x + w_2, \]

which is the same as if we would have one transmit antenna and two receiver antennas. However, in this case we spent two channel uses transmitting the same symbol, effectively cutting the rate in half compared to the example with receive diversity.

The take home here is that diversity can greatly decrease the probability of being in a deep fade. We can achieve diversity both from multiple transmit antennas or multiple receiver antennas, although to achieve transmit diversity without transmitter CSI is impossible, unless we are willing to sacrifice something.

The goal of a space-time block code (STBC) is to provide transmit diversity, without transmitter CSI, but with sacrificing as little rate as possible. Consider a transmitter with two antennas transmitting \([x_1, x_2]^T\) the first channel use and \([-x_2^*, x_1^*]^T\) the second channel use. The received signals in two consecutive channel uses are then

\[ y_1 = h_1 x_1 + h_2 x_2 + w_1, \]

and

\[ y_2 = -h_1 x_2^* + h_2 x_1^* + w_2, \]

which in matrix notation can be written as

\[ [y_1, y_2] = [h_1, h_2] \begin{bmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{bmatrix} + [w_1, w_2]. \]
This can be written as

\[
\begin{bmatrix}
y_1 \\
y_2 \\
y
\end{bmatrix} =
\begin{bmatrix}
h_1 & h_2 \\
h_2^* & -h_1^* \\
H
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
\end{bmatrix} +
\begin{bmatrix}
w_1 \\
w_2 \\
\end{bmatrix}.
\]

The receiver, having full knowledge of \(H\), can now form

\[
\tilde{y} = \frac{1}{\|h\|} Hy,
\]
resulting in

\[
\tilde{y}_1 = \|h\| x_1 + \tilde{w}_1
\]
and

\[
\tilde{y}_2 = \|h\| x_2 + \tilde{w}_2.
\]

The two noise terms, \(\tilde{w}_1\) and \(\tilde{w}_2\), are mutually uncorrelated zero mean Gaussian random variables with unit variance. Each of these received samples has the same \(\text{SNR}\), \(\|h\|^2\) and we achieve diversity of order two since

\[
\|h\|^2 = |h_1|^2 + |h_2|^2.
\]

What is more interesting, we transmit two symbols over two channel uses, so we achieve transmit diversity without losing any rate: a quite remarkable feat!

This transmit strategy for two transmit antennas was presented by Alamouti in the late 90’s [29]. Inspired by Alamouti’s fantastic transmit strategy—providing full diversity, rate, and simple decoding—the theory of (orthogonal) space-time block coding, generalizing Alamouti’s code, developed with the use of orthogonal designs [30].

As the theory of \textsc{stbc} developed, it became apparent that, in many ways the Alamouti code is not generalizable. For example, Liang showed in [31] that there are no orthogonal space-time block code with rate 1 for any number of transmit antennas larger than two. In fact, he showed that the maximum rate decreases with increasing number of transmit antennas, and that the rate approaches \(1/2\) as \(N_t\) grows large.

Another key property of a \textsc{stbc} is the delay, the number of channel uses needed to transmit the symbols of the codeword. A tight lower bound on the minimum delay for maximum rate \textsc{ostbcs} was derived in [32]. The paper showed that the minimum delay grows, quite fast, with increasing number of antennas.

So, sadly, there is no simple way to determine what space-time code to use, without considering the specific scenario. This becomes a trade-off between diversity on the one hand, and rate and delay on the other.
2.4 Benefits of Massive MIMO

Some of the most important benefits of massive MIMO can be seen by studying a small example. Consider $N_t = 2$ transmit antennas, and a receiving BS with a large number antennas, $N_r$. Two different complex symbols, $x_1$ and $x_2$ are transmitted with normalized transmit power $\rho$ ($\mathbb{E} \left[ |x_1|^2 \right] = \mathbb{E} \left[ |x_2|^2 \right] = 1$) and received at the BS:

$$y = \sqrt{\rho} H x + w.$$ 

The channel vectors $h_1, h_2$ are independent with $h_1, h_2 \sim \mathcal{CN}(0, I_{N_s})$ and the normalized noise $w \sim \mathcal{CN}(0, I_{N_s})$.

Consider detection of $x_1$ at the BS. With perfect CSI, the BS can form

$$\tilde{y} = \frac{1}{N_r} H^H y.$$ 

The first element in the vector $\tilde{y}$ is

$$\frac{1}{N_r} (h_1^H h_1 x_1 + h_1^H h_2 x_2 + h_1^H w).$$

When $N_r$ is large, due to the law of large numbers, the scaled inner products

$$\frac{h_1^H h_1}{N_r}, \quad \frac{h_1^H h_2}{N_r}, \quad \frac{h_1^H w}{N_r}$$

are well approximated by their expected values. Because the coefficient of the effective scalar channel is close to deterministic when $N_r$ is large, we say that the channel hardens. If $h_1^H h_2 = 0$ we have favorable propagation and if

$$\lim_{N_s \to \infty} \frac{h_1^H h_2}{N_r} = 0$$

we have asymptotic favorable propagation. If we have both channel hardening and favorable propagation, (8) is an AWGN channel with (almost) deterministic channel gain. In addition, we have the array gain

$$\begin{align*}
\mathbb{E} \left[ \frac{1}{\|h_1\|} h_1^H h_1 \right]^2 &= \mathbb{E} \left[ \frac{1}{\|h_1\|} h_1^H h_1 \right]^2 = N_r, \\
\mathbb{E} \left[ \frac{1}{\|h_1\|} h_1^H h_2 \right]^2 &= \mathbb{E} \left[ \frac{1}{\|h_1\|} h_1^H w \right]^2.
\end{align*}$$
2.5 Physical Layer Security

Wireless communication is inherently vulnerable to attacks because the medium (air) is open. Anyone with the proper equipment can transmit signals into the air, and it is very difficult to stop. Even though there are regulations granting access to a frequency band only to a certain user, this is very difficult to enforce. As a consequence, physical layer security is an important topic in wireless communication. Physical layer security involves studying how to transmit and form signals over the wireless medium in order to guarantee secrecy and robustness. It is not to be confused with encryption, which is a way to protect a message from being read by a third party.

In physical layer security, one usually considers three parties: a transmitter-receiver pair—called Alice and Bob—and an adversary. The communication link between Alice and Bob is termed the legitimate link. The adversary may behave differently depending on its agenda and we classify it as an eavesdropper (and call it Eve) if the goal is to extract information sent over the legitimate link, and as a jammer if it aims to destroy the legitimate communication between Alice and Bob.

Eavesdroppers do not aim to destroy or disturb the legitimate communication between Alice and Bob, but want to know what information is transmitted. In most cases it is even preferred if Eve avoids being noticed, as to not arouse any suspicion. Eavesdroppers are further divided into two categories: passive and active. Passive eavesdroppers only listens, and do not transmit any kind of signal. They rely on simply being close enough to the transmitter to pick up parts of the legitimate signal. An active eavesdropper are allowed to transmit signals to aid its mission. An active eavesdropper is often more potent than its passive counterpart. The downside of an active eavesdropper is that they are easier to detect than passive ones.

A jammer does not care about the information content of the transmitted signal, but is dedicated to make sure that the information can not be conveyed between transmitter and receiver. In contrast to eavesdroppers, there are no passive jammers (a jammer that does not transmit anything is useless). The jammer, a malicious transmitter deliberately tries to deny the receiver from decoding the message. The jammer transmits noise (not necessarily Gaussian) in order to confuse the receiver and make the noise level so high that the legitimate signal cannot be decoded.

There are many applications and examples of both jamming and eavesdropping, especially from the military, where secrecy is of great importance. However, jamming can also be found on a more personal level. Jamming can, for example, be used by burglars to nullify alarms or sensors, in order to break in to private homes unnoticed. Maybe more distressing is when first responders, like firefighers or police radio are jammed, in order to gain an advantage in riots [33] or jamming of infrastructure relying on gps [34]. Nowadays, when privacy is a hot topic, a more timely worry
might be eavesdropping, when a third party listens to transmissions and tries to find out what message was sent.

2.6 System Information

Whenever a cell phone is turned on, it immediately starts looking for a cell to connect to. This procedure is called cell search, and is done continuously for a turned on cell phone, in order to keep the connection to the cell, or find a new cell. During the cell search, the terminal both synchronizes to the cell and finds the physical identity of the cell.

After the cell search is finished, the terminal still needs some extra information to function in the cell, it needs system information. This information is continuously broadcast by the BS, to let the terminals know about the cell operation. In LTE, the system information includes information about uplink and downlink bandwidths and other things needed to operate in the cell. This information needs to be conveyed to the terminals, before they can connect to the network.

System information needs to be conveyed before the BS has any CSI, and hence, many of the benefits with massive MIMO (Section 2.4) are lost during this phase. However, transmitting this information is necessary in order for the network to function. But because the benefits are lost, this part of the transmission is at a big disadvantage, compared to when the BS has CSI. For massive MIMO to improve coverage over contemporary systems, both the coherent coverage—when CSI is available at the BS—and blind coverage—when the BS does not have CSI, have to be improved. Coverage is only as big as the smallest area covered by both CSI and no-CI transmission, as depicted in Figure 3.

Another consequence of the gap between transmission with and without CSI, is that as little information as possible should be transmitted without CSI. Transmission without CSI is much more costly, so very few bits will be transferred during this phase, perhaps as few as one hundred.
Figure 3: Blind coverage is the area covered by the no-csi transmission, and coherent coverage is the area covered by the BS when CSI is available. The coverage area is only as big as the area covered by the weakest signal.
Chapter 3

Future Work

There are still issues relating jamming and system information yet to be fully understood. I plan to continue working on problems related to both physical layer security and transmission without CSI.

For physical layer security, I want to see how far we can take the massive MIMO jammer in Paper A, and how effective it will be in other scenarios. I would like to prove the claim that the jammer will still work well, even with less information about the legitimate transmission. I also want to analyze how massive MIMO can be used to mitigate various kinds of jamming.

Transmission of system information is something that is critical for massive MIMO to work, and if an in-band solution is to be implemented, the different methods need to be compared. For transmission without CSI, I plan to analyze the difference of the proposed solutions in the literature to give a clear answer what solution is the preferred choice in practice.
3 Future Work
Bibliography

[1] T. L. Marzetta, “Noncooperative cellular wireless with unlimited numbers of base station antennas,” *IEEE Transactions on Wireless Communications*, vol. 9, no. 11, pp. 3590–3600, Nov. 2010.

[2] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, “Energy and Spectral Efficiency of Very Large Multiuser MIMO Systems,” *IEEE Transactions on Communications*, vol. 61, no. 4, pp. 1436–1449, Apr. 2013.

[3] E. Björnson, L. Sanguinetti, J. Hoydis, and M. Debbah, “Designing multi-user MIMO for energy efficiency: When is massive MIMO the answer?” in *2014 IEEE Wireless Communications and Networking Conference (WCNC)*, Apr. 2014, pp. 242–247.

[4] S. K. Mohammed and E. G. Larsson, “Per-Antenna Constant Envelope Precoding for Large Multi-User MIMO Systems,” *IEEE Transactions on Communications*, vol. 61, no. 3, pp. 1059–1071, Mar. 2013.

[5] E. G. Larsson, “Joint beamforming and broadcasting in massive MIMO,” in *2015 IEEE 16th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Jun. 2015, pp. 266–270.

[6] E. Björnson, E. de Carvalho, E. G. Larsson, and P. Popovski, “Random access protocol for massive MIMO: Strongest-user collision resolution (SUCR),” in *2016 IEEE International Conference on Communications (ICC)*, May 2016, pp. 1–6.

[7] C. Mollen, J. Choi, E. G. Larsson, and R. W. Heath, “Uplink Performance of Wideband Massive MIMO with One-Bit ADCs,” *IEEE Transactions on Wireless Communications*, vol. PP, no. 99, pp. 1–1, 2016.

[8] J. Hoydis, S. ten Brink, and M. Debbah, “Massive MIMO in the UL/DL of Cellular Networks: How Many Antennas Do We Need?” *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 2, pp. 160–171, Feb. 2013.
[9] E. Björnson, J. Hoydis, M. Kountouris, and M. Debbah, “Massive MIMO systems with non-ideal hardware: Energy efficiency, estimation, and capacity limits,” *IEEE Transactions on Information Theory*, vol. 60, no. 11, pp. 7112–7139, 2014.

[10] C. Shepard, H. Yu, N. Anand, E. Li, T. Marzetta, R. Yang, and L. Zhong, “Argos: Practical many-antenna base stations,” in *Proceedings of the 18th Annual International Conference on Mobile Computing and Networking*, ser. Mobicom ’12. New York, NY, USA: ACM, 2012, pp. 53–64.

[11] J. Vieira, S. Malkowsky, K. Nieman, Z. Miers, N. Kundargi, L. Liu, I. Wong, V. Öwall, O. Edfors, and F. Tufvesson, “A Flexible 100-antenna Testbed for Massive MIMO,” in *2014 IEEE Globecom Workshops (GC Wkshps)*, Dec. 2014, pp. 287–293.

[12] P. Harris, S. Zang, A. Nix, M. Beach, S. Armour, and A. Doufexi, “A Distributed Massive MIMO Testbed to Assess Real-World Performance and Feasibility,” in *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*, May 2015, pp. 1–2.

[13] D. Kapetanovic, G. Zheng, and F. Rusek, “Physical layer security for massive MIMO: An overview on passive eavesdropping and active attacks,” *IEEE Communications Magazine*, vol. 53, no. 6, pp. 21–27, Jun. 2015.

[14] J. Wang, J. Lee, F. Wang, and T. Q. S. Quek, “Jamming-aided secure communication in massive MIMO rician channels,” *IEEE Transactions on Wireless Communications*, vol. 14, no. 12, pp. 6854–6868, Dec. 2015.

[15] E. Björnson, E. G. Larsson, T. L. Marzetta, and others, “Massive MIMO: Ten myths and one critical question,” *IEEE Communications Magazine*, vol. 54, no. 2, pp. 114–123, 2016.

[16] X. Meng, X. G. Xia, and X. Gao, “Constant-envelope omni-directional transmission with diversity in massive MIMO systems,” in *2014 IEEE Global Communications Conference*, Dec. 2014, pp. 3784–3789.

[17] M. Karlsson and E. G. Larsson, “Massive MIMO as a cyber-weapon,” in *2014 48th Asilomar Conference on Signals, Systems and Computers*, Nov. 2014, pp. 661–665.

[18] M. Karlsson, E. Björnson, and E. G. Larsson, “Broadcasting in massive MIMO using OSTBC with reduced dimension,” in *2015 International Symposium on Wireless Communication Systems (ISWCS)*, Aug. 2015, pp. 386–390.
[19] X. Meng, X. Gao, and X. G. Xia, “Omnidirectional Precoding Based Transmission in Massive MIMO Systems,” *IEEE Transactions on Communications*, vol. 64, no. 1, pp. 174–186, Jan. 2016.

[20] X. Meng, X.-G. Xia, and X. Gao, “Omnidirectional Space-Time Block Coding for Common Information Broadcasting in Massive MIMO Systems,” *arXiv:1610.07771 [cs, math]*, Oct. 2016.

[21] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge: Cambridge University Press, 2005.

[22] T. L. Marzetta, E. G. Larsson, H. Yang, and H. Q. Ngo, *Fundamentals of Massive MIMO*. Cambridge: Cambridge University Press, 2016.

[23] E. G. Larsson and P. Stoica, *Space-Time Block Coding for Wireless Communications*. Cambridge: Cambridge University Press, 2003.

[24] D. Slepian, “On bandwidth,” *Proceedings of the IEEE*, vol. 64, no. 3, pp. 292–300, Mar. 1976.

[25] E. Telatar, “Capacity of Multi-antenna Gaussian Channels,” *Eur. Trans. Telecomm.*, vol. 10, no. 6, pp. 585–595, Nov. 1999.

[26] A. Goldsmith, S. A. Jafar, N. Jindal, and S. Vishwanath, “Capacity limits of MIMO channels,” *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 5, pp. 684–702, Jun. 2003.

[27] T. M. Cover and J. A. Thomas, *Elements of Information Theory (Wiley Series in Telecommunications and Signal Processing)*. Wiley-Interscience, 2006.

[28] B. Hassibi and B. M. Hochwald, “How much training is needed in multiple-antenna wireless links?” *IEEE Transactions on Information Theory*, vol. 49, no. 4, pp. 951–963, Apr. 2003.

[29] S. M. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[30] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, “Space-time block codes from orthogonal designs,” *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, Jul. 1999.

[31] X.-B. Liang, “Orthogonal designs with maximal rates,” *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2468–2503, Oct. 2003.
[32] S. S. Adams, N. Karst, and J. Pollack, “The Minimum Decoding Delay of Maximum Rate Complex Orthogonal Space Time Block Codes,” *IEEE Transactions on Information Theory*, vol. 53, no. 8, pp. 2677–2684, Aug. 2007.

[33] Regeringen och Regeringskansliet, “Göteborg 2001 (SOU 2002:122),” http://www.regeringen.se/rattdokument/statens-offentliga-utredningar/2002/01/sou-2002122/, Jan. 2002.

[34] J. A. Volpe, “Vulnerability assessment of the transportation infrastructure relying on GPS,” *ResearchGate*, Jan. 2001.
Included Papers
Papers

The articles associated with this thesis have been removed for copyright reasons. For more details about these see:

http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-132718
Other Recently Published Theses From

The Division of Communication Systems
Department of Electrical Engineering (ISY)
Linköping University, Sweden

Christopher Mollén, *On Massive MIMO Base Stations with Low-End Hardware*, Linköping Studies in Science and Technology. Licentiate Thesis, No. 1756, 2016.

Antonios Pitarokoilis, *Phase Noise and Wideband Transmission in Massive MIMO*, Linköping Studies in Science and Technology. Dissertations, No. 1756, 2016.

Anu Kalidas M. Pillai, *Signal Reconstruction Algorithms for Time-Interleaved ADCs*, Linköping Studies in Science and Technology. Dissertations, No. 1672, 2015.

Ngô Quốc Hiển, *Massive MIMO: Fundamentals and System Designs*, Linköping Studies in Science and Technology. Dissertations, No. 1642, 2015.

Mirsad Čirkić, *Efficient MIMO Detection Methods*, Linköping Studies in Science and Technology. Dissertations, No. 1570, 2014.

Reza Moosavi, *Improving the Efficiency of Control Signaling in Wireless Multiple Access Systems*, Linköping Studies in Science and Technology. Dissertations, No. 1556, 2014.

Johannes Lindblom, *The MISO Interference Channel as a Model for Non-Orthogonal Spectrum Sharing*, Linköping Studies in Science and Technology. Dissertations, No. 1555, 2014.

Antonios Pitarokoilis, *On the Performance of Massive MIMO Systems with Single Carrier Transmission and Phase Noise*, Linköping Studies in Science and Technology. Licentiate Thesis, No. 1618, 2013.

Tumula V. K. Chaitanya, *HARQ Systems: Resource Allocation, Feedback Error Protection, and Bits-to-Symbol Mappings*, Linköping Studies in Science and Technology. Dissertations, No. 1555, 2013.