

# CHARACTERIZATION OF MIMO CHANNEL CAPACITY IN URBAN MICROCELLULAR ENVIRONMENT

**Abdulla A. Abouda**



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# CHARACTERIZATION OF MIMO CHANNEL CAPACITY IN URBAN MICROCELLULAR ENVIRONMENT

**Abdulla A. Abouda**

Dissertation for the degree of Doctor of Science in Technology to be presented with due permission for public examination and debate in Auditorium S1 at Helsinki University of Technology (Espoo, Finland) on the 24<sup>th</sup> of April 2007 at 12 o'clock noon.

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Department of Electrical and Communications Engineering  
Communications Laboratory**

**Teknillinen korkeakoulu  
Sähkö- ja tietoliikennetekniikan osasto  
Tietoliikennelaboratorio**

Distributor:  
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Communications Laboratory  
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FIN-02015 HUT  
Tel. +358-9-451 2366  
Fax +358-9-451 2345

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ISBN 978-951-22-8717-8 (paper)  
ISBN 978-951-22-8718-5 (electronic)  
ISSN 0356-5087  
URL: <http://lib.hut.fi/Diss/2007/isbn9789512287185>

Otamedia Oy  
Espoo 2007



ABSTRACT OF DOCTORAL DISSERTATION		HELSINKI UNIVERSITY OF TECHNOLOGY P.O. BOX 1000, FI-02015 TKK <a href="http://www.tkk.fi">http://www.tkk.fi</a>	
Author Abdulla A. Abouda			
Name of the dissertation Characterization of MIMO Channel Capacity in Urban Microcellular Environment			
Manuscript submitted 19 <sup>th</sup> of December 2006		Manuscript revised 7 <sup>th</sup> of March 2007	
Date of the defence 24 <sup>th</sup> of April 2007			
<input type="checkbox"/> Monograph		<input checked="" type="checkbox"/> Article dissertation (summary + original articles)	
Department	Electrical and Communications Engineering		
Laboratory	Communications		
Field of research	Communications Engineering		
Opponent(s)	Professor Markku Juntti		
Supervisor	Professor Sven-Gustav Häggman		
Instructor	Doctor Hassan M. El-Sallabi		
<p>Abstract</p> <p>The research work in this thesis consists of several investigations of multiple-input multiple-output (MIMO) wireless channel capacity in urban microcellular environment. The investigations can be categorized into three groups, 1)- model-based investigations, 2)-measurement-based investigations, and 3)- theoretical investigations. Utilizing three dimensional (3D) channel models the influence of environment physical parameters and antenna array configuration on MIMO channel capacity are investigated. In terms of environment influence, parameters such as street width, wall relative permittivity and multipath richness are considered. In terms of antenna array configuration, the effect of array geometry and uniform linear array (ULA) azimuthal orientation are considered. It is shown that the effect of these parameters on MIMO channel capacity is significant.</p> <p>Based on field measurements, the effect of spatial smoothing on the accuracy of a widely used stochastic narrowband MIMO radio channel model, namely, the Kronecker model, and the impact of temporal signal to noise ratio (SNR) variations on MIMO channel capacity are investigated. Results from non-line of sight (NLOS) and line of sight (LOS) propagation scenarios are analyzed. While under NLOS conditions spatial smoothing significantly enhances the applicability of the Kronecker structure, under LOS conditions spatial smoothing does not help to improve the accuracy of the Kronecker model. It is also noticed that while the temporal SNR variation has significant impact on the capacity of MIMO wireless channel in a NLOS propagation scenario, the influence is smaller under LOS conditions.</p> <p>Theoretical investigation of antenna mutual coupling (MC) on the capacity of MIMO wireless channels is presented with particular emphasis on the case of high SNR scenario. It is shown that the effect of MC on MIMO channel capacity can be positive or negative depending on the spatial correlation properties of the propagation environment and the characteristics of the two ends MC matrices.</p> <p>The impact of phase noise (PN) on the accuracy of measured MIMO channel capacity is studied by considering its effect on both the spatial multiplexing gain and the power gain. It is shown that in the case of a low rank physical channel matrix the PN impact is more pronounced on the spatial multiplexing gain than on the power gain. Based on that an eigenvalue filtering (EVF) technique is proposed to improve the accuracy of the measured MIMO channel capacity.</p>			
Keywords MIMO systems, Channel capacity, Mutual coupling, Phase noise, Array geometry, Kronecker model			
ISBN (printed)	978-951-22-8717-8	ISSN (printed)	0356-5087
ISBN (pdf)	978-951-22-8718-5	ISSN (pdf)	
Language	English	Number of pages	127
Publisher	Helsinki University of Technology, Communications Laboratory		
Print distribution	Helsinki University of Technology, Communications Laboratory		
<input checked="" type="checkbox"/> The dissertation can be read at <a href="http://lib.hut.fi/Diss/2007/isbn9789512287185">http://lib.hut.fi/Diss/2007/isbn9789512287185</a>			

# Preface

*In the name of Allah, the beneficent, the merciful. Praise be to Allah, the lord of the worlds.* The work in this thesis is part of my research results in the period between August 2004 and September 2006 at the Communications Laboratory of Helsinki University of Technology, under the supervision of Prof. S.G Häggman and instruction of Dr. H.M. El-Sallabi. For both of them I am very grateful. I will never forget the stimulating discussions with Dr. El-Sallabi that have lighten my way to the real research work. For him I will be indebted for a long time. I would like also to express my gratitude to all people in the Communications Laboratory for offering a nice research environment. Special thanks to Viktor Nässi for his computer support.

I would like to use this chance to thank the pre-examiners of this thesis, Prof. Persefoni Kyritsi from Aalborg University, Denmark, and Prof. Ali Abdi from New Jersey Institute of Technology, USA, for the time they spent reading my thesis and their constructive comments. Thanks to Prof. Markku Juntti from Oulu University, Finland, for accepting the opponency task.

All my dear friends in Finland are acknowledged from the deepest point in my heart for making life easy and enjoyable. Special thanks to Dr. M. Elmusrati and Dr. I. Gadoura for their unforgettable help during my early difficult days in Finland. Special thanks also to N. Tarhuni for his daily company, Matlab support and endless fruitful discussions. The group of weekly Qourn gathering, Ahmed, Ali, Faisal, Kaled, Nagy, Naser, Nour and Dr. Amer, deserves more than thanks for offering a faithful atmosphere, may Allah bless them all. All people in Al-Iman mosque are acknowledged for providing a friendly islamic environment.

All my brothers, sisters, relatives and friends in Libya are acknowledged for their care, continuous support and endless encourage. Great thanks to the great lady in my life, my mother Ghazala for her kindness and ultimate encourage and support. To her all my achievements are dedicated. Whatever I do for here is just a drop of water in a big sea. My lovely wife Asma and dear sons Ahmed and Ali played an essential role in this achievement and deserve more than thanks. During difficult days when life become very difficult they always made it to look completely different.

Finally I would like to remember my dear friend Ahmed Mouati and express my deep gratitude to his soul for his care and real friendship, may Allah bless him.

Abdulla A. Abouda

Espoo, March 21, 2007

# List of abbreviations

*The following abbreviations are used in the summary part of this thesis.*

AOA	angle of arrival
AOD	angle of departure
AWGN	additive white Gaussian noise
BER	bit error rate
BS	base station
CCDF	complementary cumulative distribution function
CSI	channel state information
EDOF	effective degree of freedom
EVF	eigenvalue filter
HP	horizontally polarized
iid	independent identical distributed
ISI	inter symbol interference
KS	Kolmogorov Smirnov
LOS	line of sight
MC	mutual coupling
MIMO	multiple-input multiple-output
ML	maximum likelihood
MMSE	minimum mean square error
MS	mobile station
MSI	multi stream interference
nD	n dimensional
NLOS	non-line of sight
OFDM	orthogonal frequency division multiplexing
PN	phase noise
RF	radio frequency
SISO	single-input single-output
SIMO	single-input multiple-output
SM	spatial multiplexing
SNR	signal to noise ratio
SUC	successive cancelation
TDMS	time-division multiplexed switching
TOA	time of arrival
UCA	uniform circular array
UCuA	uniform cubic array

ULA	uniform linear array
URA	uniform rectangular array
VP	vertically polarized
xG	$x^{th}$ generation
ZF	zero forcing

# List of symbols

The following symbols are used in the summary part of this thesis.

$m$	number of independent streams of data symbols
$n$	number of eigenvalues passing the EVF
$N_r$	number of receive antennas
$N_t$	number of transmit antennas
$\mathbf{b}$	transmitted data vector
$\hat{\mathbf{b}}$	received data vector
$\mathbf{x}$	transmitted signal vector
$\hat{\mathbf{x}}$	estimation of transmitted signal vector
$\mathbf{y}$	received signal vector
$\mathbf{n}$	receiver noise vector
$\mathbf{G}_{phy}$	physical channel matrix
$\mathbf{G}_{meas}$	measured channel matrix
$\mathbf{G}$	channel matrix
$\mathbf{H}$	normalized channel matrix
$\mathbf{H}_{meas}$	normalized measured channel matrix
$\mathbf{H}_{kron}$	channel matrix obtained using the Kronecker model
$\mathbf{H}_w$	spatially white channel matrix
$\alpha$	normalization factor
$\sigma_x^2$	total transmitted signal power
$\sigma_n^2$	noise power at each receive antenna
$\sigma_\varphi^2$	phase noise variance
$\rho$	signal to noise ratio
$\ \cdot\ _F$	Frobenius norm
$Tr(\cdot)$	trace of matrix
$\mathbf{I}_N$	identity matrix of size $N$
$\lambda$	wavelength
$\lambda_i$	$i^{th}$ eigenvalue
$\hat{\lambda}_i$	$i^{th}$ filtered eigenvalue
$\lambda_{th}$	threshold value
$\otimes$	Kronecker product
$E\{\}$	expectation operation
$vec(\cdot)$	stacks the columns of the matrix argument into a single column
$(\cdot)^T$	transpose operation
$(\cdot)^H$	Hermitian transposition operation



$\log_2(\cdot)$	base-2 logarithm
$\mathbf{G}_{MMSE}$	MMSE matrix filter
$r$	rank of the channel correlation matrix
$c$	channel capacity
$c_{EVF}$	channel capacity obtained after filtering the eigenvalues
$\bar{c}$	ergodic capacity
$c_{out,q}$	outage capacity
$W$	bandwidth
$\mathbf{C}_r$	receiver mutual coupling matrix
$\mathbf{C}_t$	transmitter mutual coupling matrix
$\mathbf{R}_x$	transmitted signal covariance matrix
$\mathbf{R}$	channel correlation matrix
$\hat{\mathbf{R}}$	measured channel correlation matrix
$\mathbf{R}_{rx}$	receiver correlation matrix
$\mathbf{R}_{tx}$	transmitter correlation matrix
$\mathbf{R}_H$	full channel correlation matrix
$\mathbf{R}_{H_{Kron}}$	full channel correlation matrix obtained using the Kronecker model
$\mathbf{h}$	column vectorization of the normalized channel matrix

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## List of thesis publications

The work in this thesis is based on the following publications.

- [P1] **Abdulla A. Abouda**, H.M. El-Sallabi, Lasse Vuokko and S.G. Häggman, "Impact of Temporal SNR Variation on MIMO Channel Capacity in Urban Microcells," in *Proc. of the 9<sup>th</sup> International Symposium on Wireless Personal Multimedia Communications WPMC 2006*, pp. 341–344, Sep. 2006, San Diego, CA, USA.
- [P2] **Abdulla A. Abouda**, H.M. El-Sallabi and S.G. Häggman, "Reducing Impact of Phase Noise on Accuracy of Measured MIMO Channel Capacity," to appear in *IEEE Antennas and Wireless Propagation Letters AWPL*.
- [P3] **Abdulla A. Abouda**, H.M. El-Sallabi, Lasse Vuokko and S.G. Häggman, "Spatial Smoothing Effect on Kronecker MIMO Channel Model in Urban Microcells," *Journal of Electromagnetic Waves and Applications JEMWA*, vol. 21, no. 5, pp. 681–696, 2007.
- [P4] **Abdulla A. Abouda**, N.G. Tarhuni and H.M. El-Sallabi, "Model-Based Investigation on MIMO Channel Capacity in Main Street of Urban Microcells," in *Proc. of IEEE International Symposium on Antennas and Propagation, AP-S 2005*, vol. 2A, pp. 313–316, Jul. 2005, Washington, DC, USA.
- [P5] **Abdulla A. Abouda**, H.M. El-Sallabi and S.G. Häggman, "Effect of Antenna Array Geometry and ULA Azimuthal Orientation on MIMO Channel Properties in Urban Microcells," *Progress In Electromagnetic Research PIER 64*, pp. 257–278, 2006.
- [P6] **Abdulla A. Abouda** and S.G. Häggman, "Effect of Mutual Coupling on Capacity of MIMO Wireless Channels in High SNR Scenario," *Progress In Electromagnetic Research PIER 65*, pp. 27–40, 2006.
- [P7] **Abdulla A. Abouda**, H.M. El-Sallabi and S.G. Häggman, "Effect of Mutual Coupling on BER Performance of Alamouti Scheme," in *Proc. of IEEE International Symposium on Antennas and Propagation, AP-S 2006*, pp. 4797–4800, Jul. 2006, New Mexico, USA.

As a general guideline, the author of this thesis has had the main responsibility of each publication. The idea of [P4] was originally proposed by N.G. Tarhuni. Discussions with Dr. H.M. El-Sallabi have considerably improved the work of this thesis. Prof. S.G. Häggman and Dr. H.M. El-Sallabi supervised this thesis work.

# Chapter 1

## Introduction

### 1.1 Background and motivation

Currently we are witnessing the deployment of third generation (3G) mobile communication systems which are expected to outperform second generation (2G) systems in terms of supported data rates. Despite the fact that the 3G systems can offer up to 2 Mb/s data rates, they may not be sufficient to meet the requirements for future high data rate applications. New multimedia applications such as video streaming and wireless teleconferencing require higher data rate communications. New activities in various organizations have already started researching for fourth generation (4G) mobile wireless communication systems in order to cope with these increasing demands in data rates [1]-[5]. It is expected that the 4G systems will support data rates up to 100 Mb/s for mobile applications [5]. However, in order to fulfill their promise, the 4G systems have to utilize the available resources wisely and achieve up to 10 b/s/Hz spectral efficiency [5]. Multiple-input multiple-output (MIMO) wireless systems, characterized by multiple antenna elements at the transmitter and receiver, have shown astonishing increase in spectral efficiency and significant improvement in link reliability in rich multipath environments [6]-[10]. One possible choice for the 4G systems is to utilize the MIMO technology in order to achieve high spectral efficiency and consequently provide reliable high data rates.

While coding and signal processing are key elements to the successful implementation of MIMO systems, the propagation channel, the antenna design and the accuracy of measurement data represent major design parameters that ultimately impact MIMO system performance. Understanding the effects of these parameters on MIMO systems performance is essential for the successful design and deploy-

ment of MIMO systems and this is the motivation behind this thesis work.

## 1.2 Research problems and objectives

The promising advantages of MIMO systems over traditional single antenna systems depend largely on the correlation properties between antenna elements [11]-[14]. Low correlation values reveal high MIMO system performance in terms of data rates and link reliability and high correlation values indicate the opposite. There are several factors affecting the correlation properties. Among these factors are the environment physical parameters [15]-[17], the antenna array configuration [18]-[21] and the antenna element properties [22]-[38]. These parameters play a key role in determining the MIMO system performance. One of the objectives of this thesis work is to conduct a thorough investigation of the effect of propagation environment characteristics, antenna array configuration and antenna element properties on MIMO system performance.

Successful design and deployment of MIMO wireless communication systems require detailed channel characterization. In order to carry out this characterization, two approaches are widely common, field measurements, e.g. [39]-[49], and model-based, e.g. [50]-[55]. The field measurements are costly, time consuming, the results are site dependent and they are also subject to measurement errors such as phase noise (PN) in the local oscillators [56]-[61]. Significant measurement errors result in unsuccessful design and deployment of MIMO systems. Investigating the impact of PN on measured MIMO channels and developing a technique to reduce this impact is another objective of this thesis work.

Due to the difficulties in field measurement many researchers have turned to model-based characterization. The advantage of model-based analysis is the flexibility of testing the influence of different parameters that can not be controlled in field measurements in addition to the possibility of interpreting the obtained results more accurately. The stochastic Kronecker MIMO radio channel model is one of the widely used channel models in MIMO literature [62]-[65]. However, the results predicted with this channel model have shown different degree of accuracy when compared to field measurement results. Another objective of this thesis work is to explore the validity of the stochastic Kronecker MIMO radio channel model based on data measured in an outdoor microcellular environment.

## 1.3 Contributions

This thesis work contributes to the field of MIMO systems with the followings.

- Based on measured data the impact of temporal signal to noise ratio (SNR) variations on MIMO channel capacity is investigated [P1].
- An eigenvalue filtering (EVF) technique to improve the accuracy of measured MIMO channel capacity in presence of PN is proposed [P2].
- Spatial smoothing is introduced to improve the accuracy of the stochastic Kronecker MIMO radio channel model [P3].
- The influence of environment physical parameters on MIMO channel capacity in main street of urban microcells is investigated [P4].
- The effect of four antenna array geometries and the azimuthal orientation of uniform linear array (ULA) on MIMO channel properties in typical propagation scenarios are investigated [P5].
- Conditions where mutual coupling has positive and negative impact on MIMO system performance are identified [P6][P7].

## 1.4 Outline

The rest of this thesis work is organized as follows. Chapter 2 provides background material on MIMO wireless communication systems and presents a summary of [P1]. Chapter 3 presents an overview of MIMO channel measurement and modeling and a summary of [P2],[P3] and [P4]. Chapter 4 presents an overview of the role of antenna parameters in MIMO system performance and a summary of [P5],[P6] and [P7]. Conclusions and highlight for future work are given in Chapter 5.

## Chapter 2

# MIMO system background

This chapter presents some background material related to MIMO communication systems that could be useful to understand the research results of this thesis work. However, due to the fact that a large volume of material has been published in the literature about MIMO systems, only subsets of issues such as system model and channel capacity under spatial multiplexing scheme are emphasized in this chapter.

### 2.1 System model

In this thesis we consider a single user narrowband MIMO wireless communication system employing  $N_t$  transmit antennas and  $N_r$  receive antennas, schematically shown in Figure 2.1. Considering the narrowband case is justified when the channel response is constant over the system bandwidth (flat fading) or when the transmitted wideband signal is divided into narrowband frequency bins and processed independently as the case in orthogonal frequency division multiplexing (OFDM) [66]. This highlights the effect of the spatial dimension, a unique factor of MIMO communication systems and ignores the complexity of the wide-band channel response. Despite the fact that the numerical results presented in this thesis are for square MIMO system, i.e.  $N_r = N_t$ , in principle the discussion is extendable to other MIMO system sizes. However, it is well known that under spatial multiplexing scheme in order to decode the received signal in the receiver side the number of receive antennas should be large than or equal to the number of transmit antennas, i.e.  $N_r \geq N_t$ . The system model in Figure 2.1 can be divided into two main parts, 1)- the signal processing part and 2)- the channel part which represents the end-to-end response. The channel part combines the physical channel  $\mathbf{G}_{phy} \in \mathbb{C}^{N_r \times N_t}$ , the



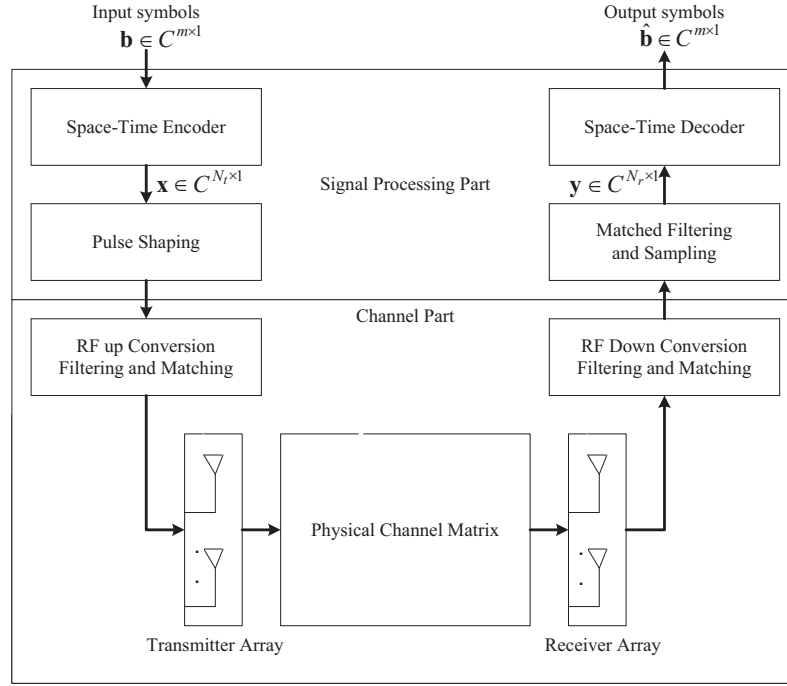


Figure 2.1: A block diagram of a generic MIMO wireless communication system.

two end antenna arrays and the radio frequency (RF) components. Each element  $g_{i,j}$  in the channel matrix represents the complex channel coefficient connecting the  $j$ th transmit antenna to the  $i$ th receive antenna.

Assume  $m$  independent streams of data symbols, denoted  $\mathbf{b} \in \mathbb{C}^{m \times 1}$ , are entering the system at each time instant. These input symbols are first encoded into a discrete time transmitted signal vector  $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$  with total transmitted signal power  $\sigma_x^2$ . Depending on the employed signaling scheme, the encoding can be over the  $N_t$  transmit antennas and/or over time. The encoded symbols are pulse shaped and converted into continuous time baseband waveforms. The continuous time baseband waveforms are up-converted and then fed to the transmit antennas. The transmitted signal propagates through the physical channel matrix. At the receiver side, a received continuous time signal captured by the receiver array is down converted to produce a continuous time baseband received signal. The continuous time baseband signal is matched filtered and sampled to get the discrete-time received signal vector  $\mathbf{y} \in \mathbb{C}^{N_r \times 1}$ . The space-time decoder decodes the received symbols to produce estimates of the transmitted streams of symbols  $\hat{\mathbf{b}} \in \mathbb{C}^{m \times 1}$ .

For linear channel elements, the MIMO channel input-output relationship can be

written as

$$\mathbf{y} = \mathbf{G}\mathbf{x} + \mathbf{n} \quad (2.1)$$

where  $\mathbf{G} \in C^{N_r \times N_t}$  is the channel matrix and  $\mathbf{n} \in C^{N_r \times 1}$  is the receiver noise vector with covariance matrix  $\mathbf{R}_n = E\{\mathbf{n}\mathbf{n}^H\} = \sigma_n^2 \mathbf{I}_{N_r}$  where  $\sigma_n^2$  is the noise power at each receive antenna and  $E\{\cdot\}$  denotes expectation operation.

From (2.1) it can be seen that the transmitted signal vector  $\mathbf{x}$  is projected onto the channel matrix  $\mathbf{G}$  and therefore, the number of independent data streams  $m$  that can be supported must be at most equal to the rank of the channel matrix. In other words, the properties of the channel matrix such as the distribution of its singular values, determine the performance potential for the MIMO system. Factors such as propagation environment characteristics, antenna array configuration and antenna elements properties influence these properties. Therefore, poor design of system components or incorrect assumptions about the channel lead to drastic reduction in system performance relative to the desired performance.

### 2.1.1 Channel matrix normalization

Since the MIMO system performance depends on both the channel correlation properties and the average receive SNR, it is important and convenient to properly normalize the channel matrix for correct interpretation of the results. For a given channel matrix  $\mathbf{G}$ , its normalized version  $\mathbf{H}$  can be obtained as follows

$$\mathbf{H} = \frac{1}{\alpha} \mathbf{G} \quad (2.2)$$

where  $\alpha$  is a normalization factor given by

$$\alpha = \sqrt{\frac{1}{N_r N_t} \|\mathbf{G}\|_F^2} \quad (2.3)$$

where  $\|\cdot\|_F$  denotes the Frobenius norm of the matrix argument. With normalized channel matrix, the average receive SNR can be defined in terms of the total transmitted signal power  $\sigma_x^2$  and noise power at each receive antenna  $\sigma_n^2$  as

$$\rho = \frac{\sigma_x^2}{\sigma_n^2} \quad (2.4)$$

It is worthy to notice that there are different normalization techniques used in MIMO literature [67]. The above normalization technique keeps the total power in each channel realization fixed but does not remove the power imbalance between

the elements of the channel matrix. In [68] it is shown that the power imbalance results in significant MIMO system performance degradation even at low correlation propagation environment. Compensating the power imbalance requires a normalization technique that operates on each sub-channel [67]. In this thesis the issue of power imbalance is not considered.

### 2.1.2 Signaling schemes

In contrast to single antenna wireless communication systems, MIMO systems can benefit from different gain mechanisms which make them very attractive for reliable high data rate communications. These mechanisms include spatial multiplexing gain and power gain which includes both the diversity gain and the two ends array gains [69]. However, there is a fundamental tradeoff between the different types of gains and they are not simultaneously achievable [70]. The contribution of each mechanism depends largely on the employed signaling scheme [70][71]. In order to benefit from the new resources, a proper space-time signaling scheme should be used. The available space-time techniques in literature are designed either to maximize the spectral efficiency, as in [72][73], or to achieve the highest reliability, as in [74][75]. Both groups of signaling schemes are operating at the extreme points of the diversity-multiplexing tradeoff curve developed in [70]. In this thesis work we consider the spatial multiplexing (SM) scheme where different signals are transmitted from different transmit antennas simultaneously. The SM scheme operates at one end of the diversity-multiplexing tradeoff curve where the SM gain is maximized and the diversity gain is minimized. The reason for considering this scheme is due to the fact that it achieves the highest MIMO system performance in terms of channel capacity. With SM and no coding in the time dimension the functionality of the space-time encoder in Figure 2.1 reduces to that of a serial to parallel converter.

### 2.1.3 MIMO receivers for SM

The employed receiver structure depends on whether the transmitter employing encoding in time or not. When there is no encoding in time, different receiver structures range from optimal maximum likelihood (ML) to more practical linear receiver such zero forcing (ZF), minimum mean square error (MMSE) and successive cancelation (SUC) can be used for MIMO systems. When the transmitter employs SM with horizontal or diagonal encoding other receiver structures are used. Since the SM scheme adopted in this thesis does not employ encoding in time, the

structures of the ML and MMSE receivers are briefly discussed.

### ML receiver

The ML receiver performs vector decoding and is the optimal receiver. Assuming equally likely transmitted symbols, the ML receiver chooses the vector  $\hat{\mathbf{x}}_i$  that fulfills

$$\hat{\mathbf{x}}_i = \arg \min_{\mathbf{x}_i} \|\mathbf{y} - \mathbf{H}\mathbf{x}_i\|_F^2 \quad (2.5)$$

The optimization is performed through an exhaustive search over all candidate vector symbols.

### MMSE receiver

The decoding complexity of the ML receiver can be reduced by using a linear filter to separate the transmitted data streams and then independently decode each stream. In single antenna systems the MMSE receiver is used to mitigate the inter-symbol interference (ISI) and noise enhancement. In MIMO context it is used to balance between the multi-stream interference (MSI) and noise enhancement. The output of the MMSE receiver is given by

$$\mathbf{z} = \mathbf{G}_{MMSE}\mathbf{y} \quad (2.6)$$

where the matrix filter  $\mathbf{G}_{MMSE}$  is given by

$$\mathbf{G}_{MMSE} = (\mathbf{H}^H\mathbf{H} + \frac{N_t}{\rho}\mathbf{I}_{N_t})^{-1}\mathbf{H} \quad (2.7)$$

where  $(\cdot)^H$  and  $\mathbf{I}_N$  denote Hermitian transposition and identity matrix of size  $N \times N$ , respectively. Estimation of the transmitted signal vector  $\mathbf{x}$  is obtained by decoding the outputs of the MMSE filter independently.

## 2.2 MIMO channel capacity

Capacity is a fundamental limit on the spectral efficiency that a communication channel can support reliably. In contrast to the capacity of the scalar additive white Gaussian noise (AWGN) channel that was first derived in [76], MIMO channels exhibit fading and encompass a spatial dimension. Throughout this thesis work, the MIMO channel capacity is used as a fundamental performance measure because it captures both the SNR and the multipath spatial characteristics.

For a given channel realization, the channel capacity is given by [7][10]

$$c = \max_{\text{Tr}(\mathbf{R}_x) = \sigma_x^2} \log_2 \det \left( I_{N_r} + \frac{1}{\sigma_n^2} \mathbf{H} \mathbf{R}_x \mathbf{H}^H \right) \quad \text{b/s/Hz} \quad (2.8)$$

where  $\text{Tr}(\cdot)$  denotes the trace of the matrix, and  $\mathbf{R}_x = E\{\mathbf{x}\mathbf{x}^H\}$  is the transmitted signal covariance matrix. The channel capacity  $c$  is the maximum data rate per unit bandwidth that can be transmitted with arbitrarily low probability of error. For a given bandwidth  $W$  the achievable data rate is  $Wc$  b/s.

### 2.2.1 Uniform power allocation

The MIMO channel capacity depends largely on the availability of the channel state information (CSI) at the two communication ends. When the transmitter does not have knowledge about the CSI it divides the total transmitted signal power  $\sigma_x^2$  equally between the transmit antennas. This implies that the covariance matrix of the transmitted signal vector is given by  $\mathbf{R}_x = E\{\mathbf{x}\mathbf{x}^H\} = \frac{\sigma_x^2}{N_t} \mathbf{I}_{N_t}$ . Under this scenario the channel capacity in (2.8) can be written as

$$\begin{aligned} c &= \log_2 \det \left( I_{N_r} + \frac{\sigma_x^2}{\sigma_n^2 N_t} \mathbf{R} \right) \\ &= \sum_{i=1}^r \log_2 \left( 1 + \frac{\rho}{N_t} \lambda_i(\mathbf{R}) \right) \end{aligned} \quad (2.9)$$

where  $\mathbf{R} = \mathbf{H}\mathbf{H}^H$  is the channel correlation matrix,  $r$  and  $\lambda_i(\mathbf{R})$  are the rank and  $i$ th eigenvalue of the channel correlation matrix, respectively. In absence of CSI in the transmitter side the total transmitted power is divided equally between the transmit antennas. Some of these channels might be in deep fade and the power injected in those channels is wasted. CSI knowledge at the transmitter side can increase the channel capacity significantly by allocating different power to the different channels through a waterpouring technique [69].

The channel capacity in (2.9) reveals useful information about the MIMO system performance. It tells us that there are  $r$  spatial parallel channels each has SNR  $\frac{\rho}{N_t}$  and power gain of  $\lambda_i(\mathbf{R})$ . Relative to single antenna transmission systems, the number of spatial parallel channels is usually referred to as the spatial multiplexing gain and the power increase in each spatial channel is usually considered as the power gain. These are the two mechanisms providing gain in MIMO wireless systems. This is valuable information for MIMO system performance prediction.

### 2.2.2 Statistical analysis

Due to the randomness of the channel matrices the achievable channel capacity is also random and requires statistical characterization of the information rate. Ergodic capacity and outage capacity are commonly used statistics for this purpose [77][78]. The ergodic capacity is always associated with fast fading channels where one transmission spans a number of coherence periods. The ergodic capacity represents the ensemble average of the information rate over the distribution of the elements of the normalized channel matrix

$$\bar{c} = E\left\{\log_2 \det\left(I_{N_r} + \frac{\rho}{N_t} \mathbf{H}\mathbf{H}^H\right)\right\} \quad (2.10)$$

On the other hand, the outage capacity is always associated with slow fading channels where the channel remain constant over a number of transmissions. The outage capacity quantifies the level of performance that is guaranteed with a certain level of reliability. For a  $q\%$  outage capacity  $c_{out,q}$  is the information rate that is guaranteed for  $(100 - q)\%$  of the channel realizations, i.e.

$$P\left(\log_2 \det\left(I_{N_r} + \frac{\rho}{N_t} \mathbf{H}\mathbf{H}^H\right) \leq c_{out,q}\right) = q\% \quad (2.11)$$

### 2.2.3 Capacity of $\mathbf{H}_w$ channels

Consider a spatially white MIMO channel matrix  $\mathbf{H}_w$  where the entries of this channel matrix are independent identical distributed (iid) each modeled as a zero mean complex Gaussian. This channel is suitable for modeling a rich multipath propagation environment in non-line of sight (NLOS) propagation scenario [54]. Figure 2.2 shows the ergodic capacity of  $\mathbf{H}_w$  channel at different SNR and for different square MIMO systems where the number of transmit and receive antennas are equal to  $N$ . The case of single-input single-output (SISO) channel is also shown for sake of comparison. The gain in channel capacity relative to the SISO case can be clearly seen. At 35 dB SNR the SISO channel can support up to 10 b/s/Hz, however, with MIMO technology about  $N$  times this capacity can be achieved.

### 2.2.4 Impact of correlation

The spatially white channel results from a rich scattering environment with sufficient antenna spacing at transmitter and receiver. In practice, however, these assumptions may not be true due to several reasons. For instance, real propagation environments may not have sufficient scattering and compact design of mobile

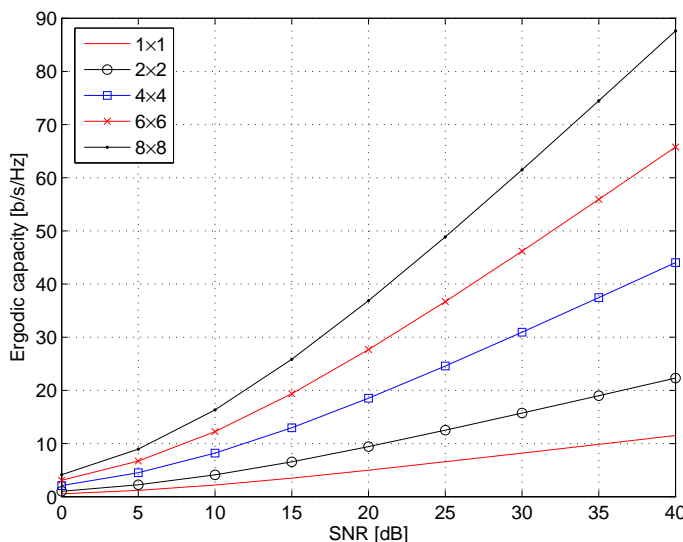


Figure 2.2: Ergodic capacity of  $\mathbf{H}_w$  channel at different SNR and for different MIMO size.

handset limits the available antenna spacing. These practical issues result in correlated signals and consequently degrade MIMO systems performance. Incorporating these issues into realistic propagation channel models is the main objective of several MIMO system studies that aim to measure or model MIMO channels.

### 2.2.5 Impact of temporal SNR variation [P1]

The impact of SNR variation on MIMO system performance is not largely addressed in literature. However, results of channel capacity variations of measured indoor MIMO wireless channel were presented in [79]. It is shown that the SNR variation has a greater impact on the channel capacity than the channel correlation properties. In [80] an analysis of the effect of pedestrian movement on channel capacity of a single room environment was presented. Significant capacity increase due to pedestrian movement is predicted. In [81] it is shown that the channel capacity is mostly function of the pathloss.

In [P1] the impact of SNR variation over time on capacity of MIMO wireless channels in urban microcells is considered based on data measured in an outdoor microcellular environment. The measurement campaign was carried out at downtown of Helsinki at 5.3 GHz carrier frequency. The measurement campaign represents an urban microcellular environment where a transmitter equipped with 16 elements dual-polarized planar antenna was located in the main street below the

rooftops level at height of 10 m. A pseudo noise code with 60 MHz chip frequency was transmitted with power limited to 37 dBm. A receiver equipped with 15 directive and dual-polarized semispherical antenna at height of 1.6 m was moved in different streets to create different propagation scenarios. The receiver velocity was approximately 0.2 m/s and the channel transfer matrix was sampled at 14 Hz rate, meaning that between measurement of consecutive complex channel matrices the receiver was moved a distance of 0.014 m. The results presented in [P1] are based on data taken from two propagation scenarios of the measurement campaign, NLOS and line of sight (LOS). In the LOS scenario the receiver terminal was moved in the main street where the transmitter terminal is located. In the NLOS scenario the receiver terminal was moved in a street perpendicular to the main street with no line of sight component.

Figure 2.3 shows the measured channel capacity in terms of the complementary cumulative distribution function (CCDF) under fixed and varying SNR for  $4 \times 4$  MIMO system of the two propagation scenarios. The temporal SNR was calculated in both propagation scenarios as

$$\rho = \frac{\sigma_x^2}{\sigma_n^2 N_r N_t} \| \mathbf{G}_{meas} \|_F^2 \quad (2.12)$$

where  $\mathbf{G}_{meas}$  is the measured channel matrix and the term  $\frac{\sigma_x^2}{\sigma_n^2}$  was chosen in order to set the average temporal SNR to 20 dB. While the temporal SNR variation has significant impact on the measured capacity in the NLOS propagation scenario, the influence is smaller under LOS conditions. One interesting observation is that the slope of the CCDF of the channel capacity under fixed and temporally varying SNR. Fixing the SNR changes the slope of the channel capacity significantly under NLOS conditions. However, the change is not significant under LOS conditions. The slope of the channel capacity reveals useful information about the propagation scenario when the temporal SNR variation is considered. A steeper slope reflects the existence of strong multipath component that can maintain high and stable SNR. A smaller slope reflects large fluctuations of the available multipath components. The effective degree of freedom (EDOF), introduced in [11], represents the number of effective SISO channels equivalent to the MIMO channel at a fixed SNR. The results presented in [P1] reflects the EDOF of the measured channels under varying SNR.



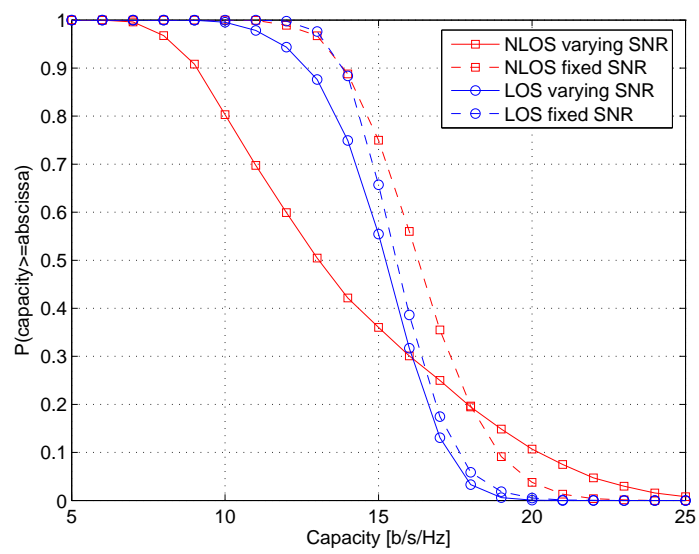


Figure 2.3: CCDF of measured channel capacity with SNR fixed to 20 dB and temporally varying SNR.

## Chapter 3

# MIMO channel measurement and modeling

Assessing the performance of MIMO systems in realistic environments requires a detailed description of the multipath channel. Since a matrix of transfer functions should be accurately represented, this description has to go beyond traditional models or measurement campaigns. In some cases channel measurements are used to fully characterize these channels. However, cost, accessibility to the measured data and accuracy are the main disadvantages of this approach. Because of that many researchers have turned to develop channel models that capture the key behavior observed in the experimental data. This chapter presents an overview of MIMO channel measurement and modeling and summarizes the relevant research results of this thesis work.

### 3.1 Transfer matrix measurement

The most straightforward approach to characterize MIMO wireless channels is to deploy a system that directly measures the  $N_r \times N_t$  channel matrix. In this case, all components in the channel part in Figure 2.1 are embedded in the measured channel and the measurements will only be applicable for the analysis of systems employing the same array configurations and antenna elements. Results based on a variety of measurement campaigns have appeared in literature, e.g. [39]-[45]. The reported results are usually in terms of channel capacity, signal correlation structure, rank of channel matrix, path loss and delay spread. The measurement campaigns can be classified based on the architecture of the measurement equipment into two main groups.

1. Measurement-based on true array system. This type of measurement equipment uses a true array system where all antennas operate simultaneously. The main advantages of such systems are the closeness to real world MIMO channels and ability of measuring channels that vary in time. However, the cost of the parallel transmit and receive electronics is the main drawback of this type of measurement equipments.
2. Measurement-based on switched array or virtual array. Switched array designs use a single transmitter and single receiver to measure the transfer function with high speed switches sequentially connecting all array elements to the electronics [46][47]. Switching times for such systems are generally very low (few  $\mu\text{s}$  to 100 ms), indicating that the measurement over all antenna pairs can be conducted before the channel changes appreciably for most environments of practical interest. Virtual array instruments use precision displacement (or rotation) of a single antenna element to prescribed locations [48][49]. A complete channel matrix measurement often takes several seconds or minutes, requiring a long mean stationary time of the measured channel. Therefore, virtual arrays are most suitable for fixed indoor measurement campaigns when activity is low. Measurement impairments such as thermal additive noise [56] and PN in the local oscillators [57][58] are other drawbacks of such systems.

### 3.1.1 Reducing the impact of phase noise on accuracy of measured MIMO channel capacity [P2]

Time-division multiplexed switching (TDMS) of a single radio frequency chain systematically between the elements of transmit/receive antenna array is a widely used practical implementation technique of MIMO wireless channel measurement sounders [82]. Despite being a cost effective implementation technique, channel matrices measured with this kind of channel sounders are subject to significant measurement errors. In addition to the thermal additive white Gaussian noise, addressed in [56], PN in the local oscillators may result in significant channel measurement errors [57][58]. Due to the random noise present in the solid state devices the PN is modeled as a Gaussian wide sense stationary process [59]. It was shown that this PN can result in deceptive channel capacity increase up to 100% [57]. In related studies the impact of PN on direction of arrival estimation was investigated in [60] for single-input multiple-output (SIMO) systems. In context of single antenna transmission schemes, the impact of measurement impairments was studied

in [61].

In [P2] we investigate the impact of PN on the accuracy of measured MIMO channel capacity by analyzing the channel capacity error. The impact of PN on the two MIMO channel gain mechanisms is considered. We show that the impact of PN is more pronounced on the spatial multiplexing gain than on the power gain and based on that we propose an eigenvalue filtering (EVF) technique to improve the accuracy of the measured channel capacity. We show that in presence of PN more accurate channel capacity estimation can be obtained by filtering the eigenvalues of the measured channel matrix. The eigenvalues with power gain less than predefined threshold are filtered out and are not used for the channel capacity calculations as follows

$$c_{EVF} = \sum_{i=1}^n \log\left(1 + \frac{\rho}{N_t} \hat{\lambda}_i\right) \quad (3.1)$$

where  $\hat{\lambda}_i$  is the  $i$ -th filtered eigenvalue of the measured channel correlation matrix that can be obtained as

$$\hat{\lambda}_i = \begin{cases} \lambda_i(\hat{\mathbf{R}}), & \forall \lambda_i(\hat{\mathbf{R}}) \geq \lambda_{th} \\ 0, & \forall \lambda_i(\hat{\mathbf{R}}) < \lambda_{th} \end{cases} \quad (3.2)$$

where  $\hat{\mathbf{R}} = \mathbf{H}_{meas} \mathbf{H}_{meas}^H$  is the measured channel correlation matrix,  $n$  is the number of the eigenvalues of the measured channel correlation matrix passing the EVF and  $\lambda_{th}$  is the threshold value. One possible choice for the filter threshold is to sacrifice a fraction of the power in the channel matrix for the sake of more accurate channel capacity estimation. Figure 3.1 shows the percentage of relative ergodic capacity error of  $8 \times 8$  MIMO system with and without EVF. Channel matrices with different ranks subject to PN with standard deviation  $\sigma_\varphi = 3.5^\circ$  are shown. In the case of full rank physical channel matrix the presence of PN has no impact on the estimated channel capacity regardless of the SNR level. On the other hand, with the rank one physical channel matrix the presence of PN results in about 150% deceptive channel capacity increase at 40 dB SNR. With the rank four physical channel matrix the error in the ergodic channel capacity is about 25% at the same SNR. EVF at  $\lambda_{th} = 0.01 \|\mathbf{H}\|_F^2$  results in significant reduction in the channel capacity error. In the case of full rank channel matrix EVF results in slight underestimation of the channel capacity. However, this underestimation is less than 10% at SNR less than 40 dB.

For unknown rank measured channel matrix, filtering out 1% of the power of the

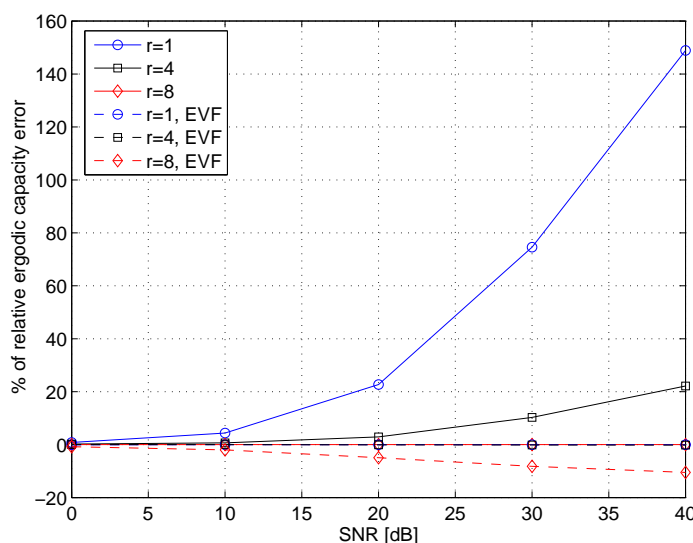


Figure 3.1: Percentage of relative ergodic capacity error of  $8 \times 8$  MIMO system with and without EVF.

channel matrix is shown to be a good choice in terms of channel capacity accuracy.

## 3.2 Transfer matrix modeling

The simplest channel models directly compute the channel matrix  $\mathbf{H}$  based upon a statistical description. For example, in a NLOS propagation scenario, it is commonly assumed that the channel between one transmit and one receive antenna will have a magnitude and phase that follow Rayleigh and uniform distributions, respectively [54]. This combination indicates that the individual complex elements of  $\mathbf{H}$  are circular symmetric complex Gaussian random variables. In this case, the distribution is completely specified by the full channel correlation matrix  $\mathbf{R}_H = E\{\mathbf{h}\mathbf{h}^H\}$ , where  $\mathbf{h} = \text{vec}(\mathbf{H})$  and  $\text{vec}(\cdot)$  stacks the columns of the matrix argument into a single column vector. In case of no correlation between the signals on different antennas, the full channel correlation matrix  $\mathbf{R}_H$  is an identity matrix, i.e.  $\mathbf{R}_H = \mathbf{I}$ , which leads to independent matrix entries. This is the case when orthogonal channels are assumed. However, if the correlation structure is to be included, a correlation matrix must be constructed directly from measured data [62]-[65] or from a correlation model [13][83]. If the fading statistics at the transmit and receive sides are assumed to be independent, a separable correlation structure, referred to as the Kronecker product model [42] [62]-[65], can be created. The Kronecker structure is in the form  $\mathbf{R}_{H_{\text{Kron}}} = \mathbf{R}_{tx} \otimes \mathbf{R}_{rx}$  where  $\mathbf{R}_{tx}$  and  $\mathbf{R}_{rx}$  are correlation

matrices for signals on the transmit and receive arrays, respectively, and  $\otimes$  denotes the Kronecker product. Utilizing the Kronecker model, a channel matrix  $\mathbf{H}_{kron}$  can be generated according to

$$\mathbf{H}_{kron} = \mathbf{R}_{rx}^{1/2} \mathbf{H}_w (\mathbf{R}_{tx}^{1/2})^T \quad (3.3)$$

This approach is very simple to implement, and therefore facilitates assessment of space-time codes using Monte Carlo simulation approaches. Some studies have shown that this model is highly effective in matching measured results for systems with up to four antenna elements [62]-[65]. However, recent work has demonstrated key deficiencies in this Kronecker product model [84]. In fact, one study has demonstrated that the Kronecker structure leads to high errors not only in the computed capacity but also in the correlation matrix representation [85]. Another study has confirmed this error in the capacity as well as error in the joint statistics of the resulting transfer matrix [86]. Nevertheless, the simplicity of this model makes it an attractive starting point in the analysis of any MIMO system performance [87][88]. Therefore, improved modified versions were proposed in [89][90].

### 3.2.1 Effect of spatial smoothing on Kronecker MIMO channel model [P3]

In [P3] the effect of spatial smoothing on the performance of the stochastic Kronecker MIMO radio channel model is extensively investigated based on the measured data described in section 2.2.5. The channel matrices obtained using the Kronecker model and its spatially smoothed version are compared to those obtained from the measured data in terms of the distribution of the channel coefficients and the distribution of the eigenvalues of the channel correlation matrix. The comparison is performed by utilizing the Kolmogorov-Smirnov (KS) goodness test [91]. The KS is a common test that has been widely used in studying the goodness of fit of a variety of fading distributions to channel measurements [92]. The achievable channel capacity and the symbol error rate performance over the measured and modeled channels are also compared. Furthermore, the validity of the Kronecker structure in modeling the full channel correlation matrix is also assessed. It is shown that while under NLOS conditions spatial smoothing improves the accuracy of the large eigenvalues and significantly enhances the applicability of the Kronecker structure, the Kronecker model still renders more accurate small eigenvalues. In the LOS scenario both the Kronecker model and its smoothed version fail to render the eigenvalues of the measured channel correlation matrix but spa-

tial smoothing slightly improves the applicability of the Kronecker structure.

### 3.3 Multipath characterization

Another approach for modeling MIMO wireless channels is to directly describe the properties of the physical channel multipath components. In this approach the obtained multipath channels are independent of the properties of the associated antenna system which facilitates studying the impact of antenna properties. Models capturing multipath behavior range from deterministic site-specific ray-tracing to simpler statistical descriptions.

1. **Deterministic ray-tracing.** Deterministic ray-tracing modeling begins by creating a two dimensional (2D) or three dimensional (3D) geometrical model of the propagation environment. Then the response of the model to electromagnetic excitation is computed through computational techniques. Such models can also provide statistical channel information by applying Monte Carlo analysis on many random transmit/receiver locations and/or model geometries. Ray-tracing techniques based on geometrical optics, often supplemented by diffraction theory to enhance accuracy in shadow regions, have emerged as the most popular techniques for analyzing site-specific scenarios due to their ability to analyze very large structures with reasonable computational resources [93]-[98]. Several investigations of MIMO systems performance have been conducted based on ray-tracing techniques, e.g. [99]-[101]. Ray-tracing techniques have demonstrated reasonable accuracy in predicting large-scale path loss variation. However, preliminary comparisons of ray-tracing predications with measurements indicate that the simulations tend to underestimate MIMO channel capacity [102]. This likely due to over simplification of the geometrical scenario representation than failure of the electromagnetic simulation approach. Other recent work [103] has shown promising agreement between measured and simulated results of angle of arrival (AOA) estimation in microcells.
2. **Geometric scattering models.** The high computational cost of rigorous ray-tracing simulations in addition to the fact that this type of technique is very site specific are the main drawbacks of ray-tracing techniques. Due to that more approximate models have appeared where more simplified geometries and scattering mechanisms are assumed [104]-[108]. Scatterers are modeled as discrete objects located around the receiver and/or transmitter. These ob-

jects can represent site-specific obstacles, or their locations and scattering properties (e.g. cross-section) which can be defined in terms of their statistical distribution. These models also allow for dynamic channel evolution by computing the response as the transmitter or receiver moves through the environment.

3. Statistical scattering models. Statistical cluster models directly specify distributions on the multipath angle of departure (AOD), AOA, time of arrival (TOA) and amplitude by grouping multipath components into clusters that decay exponentially with increasing delay time [51][109][110]. A single cluster might correspond to a single scattering object. In more advanced models, the birth and death of clusters due to movement of the subscriber can be taken into account [111]. Statistical descriptions of the multipath arrival parameters have been obtained through measurements [112]-[115] and ray-tracing [116]. In [117][118] cluster and discrete scattering models are combined to include both distant and local scattering.

### 3.3.1 Influence of environment physical parameters on MIMO channel capacity [P4]

3D spatial variant multi-ray radio wave propagation models for main street and perpendicular streets in an urban street grid were developed in [52] and [53], respectively. The propagation channel models are different from ray tracing models in a sense that there is no searching for coupling paths between base station (BS) and mobile station (MS). All the ray characteristics, such as AOA, AOD and path length, are given in closed form mathematical expressions by using the set membership criteria. The advantage of getting the ray characteristics in explicit mathematical expressions is a significant reduction in computation time which is the main limitation of the available simulation tools. These propagation channel models are utilized in this thesis work to investigate the influence of environment physical parameters and antenna array configuration on MIMO system performance in typical deployment scenarios [119]. The reason for considering model based approach to carry out these studies is the complexity of measurement and theoretical approaches.

In [15] a geometrical interpretation of the MIMO channel capacity was presented. In [16] the influence of two street corners, regular and chaflane, on MIMO channel capacity was considered. In [17] the reduction on measured channel capacity is linked to the dominant wave propagation mechanism. Propagation characteristics



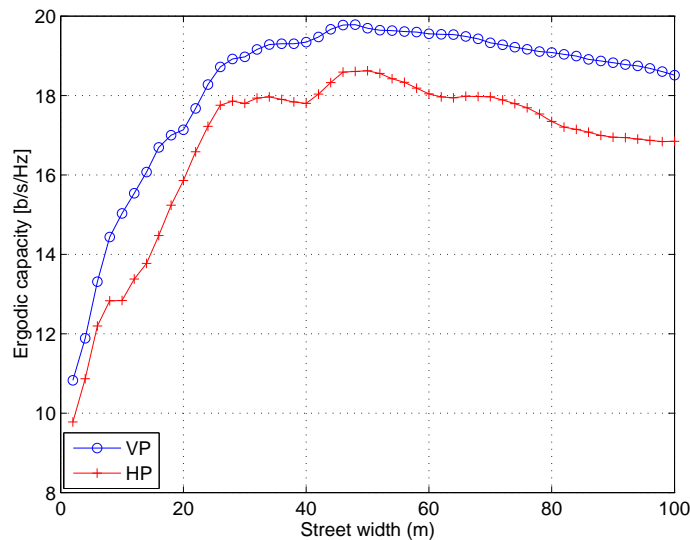


Figure 3.2: Influence of street width on capacity of  $4 \times 4$  MIMO system at 20 dB SNR.

of vertical and horizontal polarizations based on measured data were presented in [121]. It is shown that under LOS conditions the horizontally polarized signal falls off faster than the vertically polarized signal.

In [P4] we consider the influence of environment physical parameters on MIMO channel capacity in main street of urban microcells. Parameters such as main street width, wall relative permittivity, multipath richness in addition to antenna height and inter-element spacing are considered. The investigation is conducted for vertically polarized (VP) and horizontally polarized (HP) signals. The definition of VP and HP is relative to the ground plane. The investigations are conducted under the assumption of fixed average SNR. We show that the influence of environment physical parameters on MIMO channel capacity is significant. For instance Figure 3.2 shows the influence of street width on capacity of  $4 \times 4$  MIMO system at 20 dB SNR for VP and HP signals. It can be seen that while narrow streets (2-5 m) result in low angular spread and consequently low channel capacity, the highest channel capacity is obtained at street width ranges from 40 m to 60 m. However, very wide street ( $>60$  m) results in long propagation path length and at almost right angle reflection at wall surface which causes a high loss and consequently low capacity. In general it is observed that higher channel capacity is obtained with VP signal than with the HP signal. This is due to the fact that the VP signal suffers lower loss of multipath components from side walls reflections compared to the HP signal. This result confirms the measurement-based conclusion drawn in [121].

## Chapter 4

# Role of antenna in MIMO system performance

Usually antenna properties are either excluded or ideal isotropic antenna elements are assumed for modeling and studying the performance of MIMO systems. However, it is important to emphasize that the channel matrix depends not only on the propagation environment but also on the properties of the antenna elements and the array configuration. Some of antenna issues are reviewed and a summary of the research results of this thesis work is presented in this chapter.

### 4.1 Array configuration

It is very difficult to answer definitively what the antenna topology that maximizes MIMO system performance is. However, some general observations are possible. Previous research results have focused largely on evaluating MIMO system performance under the assumption of ULA geometry at both ends with a specific array orientation. Despite the implementation advantages of other array geometries, they have not been extensively investigated. Recently, in [18] the impact of five antenna array geometries on performance of MIMO wireless system is studied using the clustered channel model [51] in an indoor scenario. It is shown in [18] that in low spatial correlation environment the ULA geometry outperforms the other considered array geometries in terms of channel capacity and bit error rate (BER) performance. In [19] a compact MIMO antenna array is proposed by combining polarization diversity and space diversity into one arrangement consisting of a cube. It is shown that even for very small inter-element spacing considerable capacity is obtained due to polarization diversity. Adaptive system that selectively connect a

subset of available antennas to the electronic modules are explored in [120].

The assumption of a specific array orientation at both of the transmitter and the receiver ends requires the arrays at the two ends to be fixed to a specific direction. In reality, this is a valid assumption for fixed wireless communication systems. However, in mobile communications the BS has a fixed array orientation but the MS is unlikely to be fixed to a specific direction. The effect of ULA azimuthal orientation on MIMO system performance has been studied in [20] and [21]. In [20] based on data measured in an office corridor it is shown that under LOS conditions the channel capacity varies significantly depending on the receiver array orientation. However, due to cost and complexity of field measurements only a few array orientation angles at the receiver side were considered. In [21] it is shown that the maximum channel capacity is obtained when the ULA at the two communication ends are 'broadside' oriented to each other. Their investigation was carried out based on a stochastic channel model [64].

#### 4.1.1 Effect of antenna array geometry and ULA azimuthal orientation on MIMO channel properties [P5]

In [P5] we present a thorough investigation of the influence of antenna array configuration on MIMO channel properties in typical propagation scenarios. The effect of antenna array geometries and azimuthal orientation of ULA are considered. Figure 4.1 shows the considered antenna array geometries, namely, ULA, uniform circular array (UCA), uniform rectangular array (URA) and uniform cubic array (UCuA). These geometries represent three types of antenna arrays, one dimensional ULA, two dimensional UCA and URA and three dimensional UCuA. All these geometries have the same number of antenna elements and fixed inter-element spacing. Orientation angle varying from 0 to  $\pi$  at the two communication ends is considered for the ULA. For the other geometries fixed array orientation is assumed. It is shown that the antenna array geometry has a significant impact on MIMO channel properties. Under different propagation scenarios the ULA shows superiority to the other considered geometries in terms of the mean channel capacity and number of spatial parallel channels.

Figure 4.2 shows the effect of different antenna array geometries on the eigenvalues of  $8 \times 8$  MIMO channel at 10% outage probability in NLOS and LOS propagation scenarios. It can be seen that in both propagation scenarios the ULA can offer better and more parallel channels than the other considered array geometries. However, this superiority depends largely on the ULA azimuthal orientation. Figure 4.3 shows the effect of ULA azimuthal orientation on the ergodic capacity of

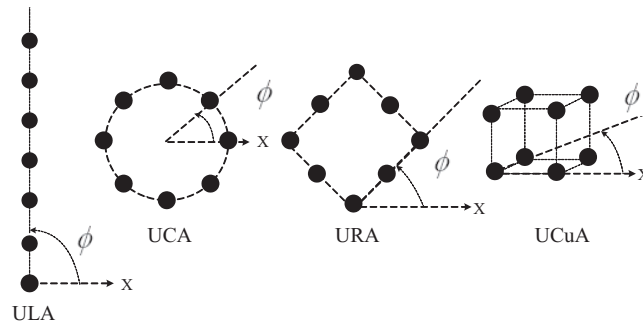
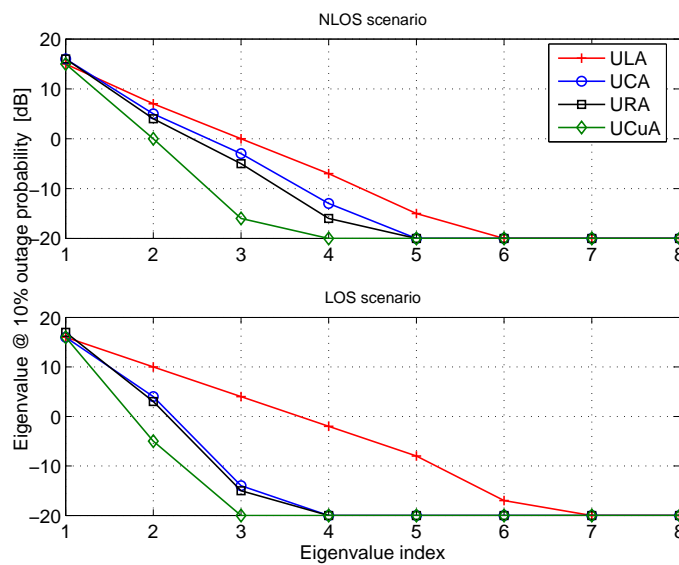


Figure 4.1: Considered antenna array geometries.

Figure 4.2: Effect of array geometry on the eigenvalues of  $8 \times 8$  MIMO channel in NLOS and LOS propagation scenarios.

$8 \times 8$  MIMO channel at 20 dB SNR in NLOS and LOS propagation scenarios. It can be clearly seen that the channel capacity varies significantly under different ULA azimuthal orientation. The maximum channel capacity is obtained when the ULA at both ends are transversal to the main wave propagation direction. It is concluded that the MIMO channel properties highly depend on the number of antenna elements facing the wave propagation direction and the distance between these elements. The obtained results suggest that in order to maximize the channel capacity the ULA at the BS side should be transversal to the main wave propagation direction.

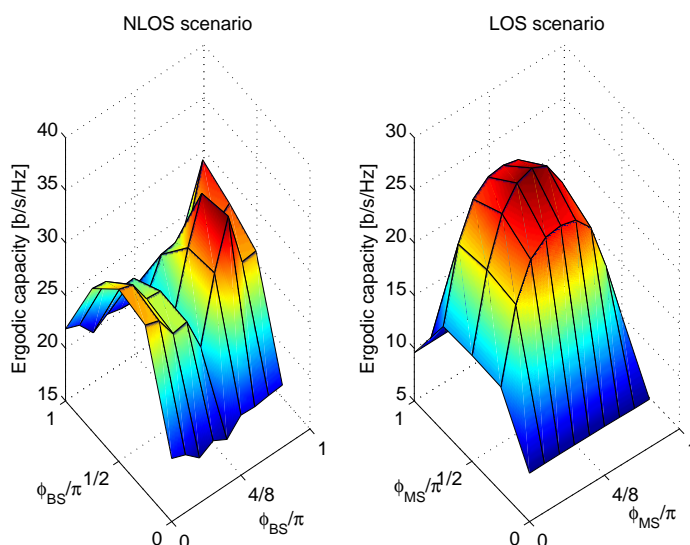


Figure 4.3: Effect of ULA azimuthal orientation on ergodic capacity of  $8 \times 8$  MIMO channel in NLOS and LOS propagation scenarios at 20 dB SNR.

## 4.2 Mutual coupling

Mutual coupling (MC) phenomenon that appears when the antenna elements are closely spaced is one of the parameters that strongly affect the performance of MIMO systems. However, research results on the effect of MC on MIMO system performance have drawn different conclusions. For instance in [25][26] it is shown that the MC between antenna elements has a negative impact on the capacity of MIMO wireless channels. On the other hand, in [27]-[34] it is shown that the presence of MC between antenna elements is a desirable phenomenon to increase channel capacity through what is known as pattern diversity. However, there is no contradiction between these results since MC may have positive or negative impact on MIMO system performance depending on the correlation properties of the propagation environment and the two ends antenna MC matrices [35]. In other studies [36]-[38] the effect of MC and antenna termination on the capacity of MIMO channels is examined.

### 4.2.1 Effect of MC on MIMO channel capacity in high SNR scenario [P6]

In [P6] we present theoretical results on the effect of antenna MC on MIMO channel capacity with particular emphasis on the case of a high SNR scenario. We show that the effect of MC on MIMO system performance can be positive or negative

depending on the spatial correlation properties of the propagation environment and the characteristics of the transmitter and receiver MC matrices. Two cases are considered

1. Channel capacity variations due to MC effect on correlation properties and target SNR. In this case and under high SNR scenario the following result is obtained

**Proposition 1:** In a high SNR scenario, if normalization is not performed after including the two ends MC effect, an improvement in the channel capacity over the case of ideal isotropic antenna elements is obtained due to coupling effect if and only if the term  $\beta_1 = \prod_{i=1}^N \lambda_i(\mathbf{C}_r \mathbf{C}_r^*) \lambda_i(\mathbf{C}_t \mathbf{C}_t^*) > 1$ .

where  $\mathbf{C}_t$  and  $\mathbf{C}_r$  are the transmitter and receiver mutual coupling matrix, respectively,  $\lambda_i(\mathbf{C}_t \mathbf{C}_t^*)$  and  $\lambda_i(\mathbf{C}_r \mathbf{C}_r^*)$  are the  $i$ -th eigenvalues of the transmitter and receiver MC correlation matrices, respectively.

2. Channel capacity variations due to MC effect on correlation properties at fixed SNR. In order to keep the SNR fixed to a target value and consider only channel capacity variations due the changes in the correlation properties, normalization should be performed after including the coupling effect at the two ends. In this case the effect of MC depends on both the correlation properties of the propagation environment and the MC matrices, therefore, the following result is obtained

**Proposition 2:** In a high SNR scenario, if normalization is performed after including the two ends MC effect, an improvement in the channel capacity over the case of ideal isotropic antenna elements is obtained due to coupling effect if and only if the term  $\beta_2 = \frac{\prod_{i=1}^N \lambda_i(\mathbf{C}_r \mathbf{C}_r^*) \lambda_i(\mathbf{C}_t \mathbf{C}_t^*)}{[\frac{1}{N^2} \sum_{i=1}^N \lambda_i(\mathbf{C}_r \mathbf{H} \mathbf{C}_t \mathbf{C}_t^* \mathbf{H}^* \mathbf{C}_r^*)]^N} > 1$ .

Studying channel capacity variations due to MC effects on correlation properties at a fixed SNR reveals that the presence of MC in highly correlated propagation environment may have a decorrelation effect and consequently positive effect on the channel capacity. On the other hand, the presence of MC in a low correlation propagation environment may have negative impact on the channel capacity due to the extra correlation effect. Figure 4.4 shows the effect of MC on the capacity of  $2 \times 2$  MIMO channel at 20 dB SNR and in different propagation environments. The result presented in terms of the percentage of ergodic capacity difference between the cases with presence and absence of MC relative to the case no coupling is present. In the receiver side an ULA with  $0.5\lambda$  dipole elements is considered where  $\lambda$  is the wavelength. The receiver MC matrices are calculated at different inter-

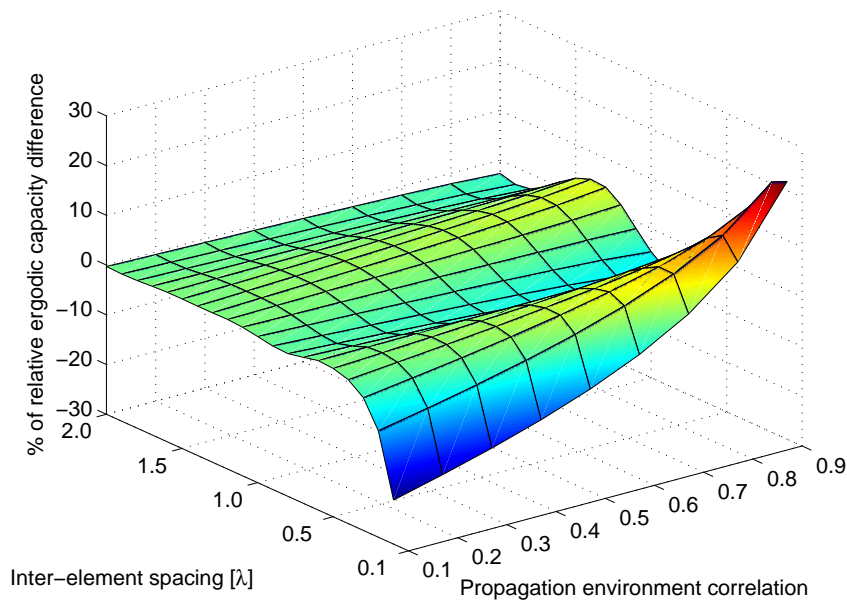


Figure 4.4: Effect of antenna MC on capacity of  $2 \times 2$  MIMO channel at 20 dB SNR.

element spacing numerically [122] under matched load condition. Normalization is performed after considering the MC effect in order to keep the SNR fixed to the target value. It can be clearly seen that the effect of MC at highly correlated propagation environment and at inter-element spacing less than  $0.5\lambda$  results in relative capacity increase.

#### 4.2.2 Effect of MC on BER performance of Alamouti scheme [P7]

In [P7] we present an investigation of the effect of MC on the performance of the Alamouti scheme [75] by studying the BER performance under different propagation scenarios and for different coupling situations. We show that the presence of MC may have positive or negative effect on the BER performance of the Alamouti scheme depending on the correlation properties of the propagation environment and on the two ends MC matrices.

## Chapter 5

# Conclusions and future work

### 5.1 Conclusions

Several investigations of MIMO channel capacity in an urban microcellular environment have been conducted in this thesis work. Based on data measured in an outdoor microcellular environment the impact of temporal SNR variation on MIMO channel capacity and the effect of spatial smoothing on the Kronecker MIMO radio channel model were investigated. Utilizing 3D spatial multi ray channel models the influence of environment physical parameters, antenna array geometry and ULA azimuthal orientation were considered. Using a theoretical approach the effect of MC on MIMO channel capacity and the impact of PN on the accuracy of measured MIMO channel capacity were explored.

In the measurement-based studies it is shown that the impact of temporal SNR variations on MIMO channel capacity is significant only when there is no strong multipath component as in the case of a NLOS scenario. Spatially smoothing the transmitter and receiver correlation matrices enhances the accuracy of the predicted results by the Kronecker model under NLOS scenario. However, under LOS conditions spatial smoothing does not help in improving the accuracy of the Kronecker model. The aim of introducing spatial smoothing to the Kronecker model structure is not to propose a new improved version of the Kronecker model rather than to gain deep understating of its performance in matching results from measured data in urban microcellular environment.

From the model-based investigations it is observed that the influence of environment physical parameters such street width, wall relative permittivity and multipath richness on MIMO channel capacity is significant. Under different propagation scenarios, the effect of antenna array geometry on MIMO channel properties



depends on the number of antenna elements facing the wave propagation direction. The ULA shows superiority to the other considered geometries in terms of channel capacity and number of spatial channels. Although the model-based results are for some specific typical propagation scenarios, the trends observed from the results are valid for other scenarios and could be useful to MIMO system designers.

In terms of antenna MC, it is shown that the MC between antenna elements can have a positive or a negative impact on MIMO systems performance depending on the correlation properties of the propagation environment and the MC matrices of the transmitter and receiver arrays. In a highly correlated propagation scenario, the presence of MC may have a decorrelation effect. Despite the fact that the numerical results for MC study are for half wave length dipole antenna, the theoretical approach is valid for other antenna types.

The error due to PN can result in significant overestimation of the measured channel capacity in a high SNR scenario. We have shown that filtering the eigenvalues of the measured channel correlation matrix can result in significant improvement in the accuracy of the measured channel capacity. The result of this study is supported with simulation results for known cases. Validating the result with measurements could be possible but it is not done in this thesis.

## 5.2 Future work

An over all conclusion that can be drawn from this thesis work is that the performance of MIMO system in outdoor microcellular environment is promising even when practical issues such as the ones considered in this thesis work are taken into consideration. However, in this thesis work the concern was to investigate the impact of some practical issues on MIMO systems performance in a single user scenario and for the narrowband case. Extending the work to consider a wideband MIMO system in a multiuser scenario is the main task for future work.

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## **Thesis publications**

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