UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

MIMO CHANNEL MODELLING FOR INDOOR WIRELESS COMMUNICATIONS

BTJ MAHARAJ

2007

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

MIMO CHANNEL MODELLING FOR INDOOR WIRELESS COMMUNICATIONS

By

Bodhaswar Tikanath Jugpershad MAHARAJ

Promotor: Professor Dr L.P. Linde (University of Pretoria, South Africa)

Submitted in partial fulfillment of the requirements for the degree

Philosophiae Doctor (Electronic)

in the

Department of Electrical, Electronic & Computer Engineering

in the

School of Engineering

in the

Faculty of Engineering, Built Environment & Information Technology

UNIVERSITY OF PRETORIA

September 2007

SUMMARY

MIMO CHANNEL MODELLING FOR INDOOR WIRELESS COMMUNICATIONS

by

Bodhaswar Tikanath Jugpershad MAHARAJ

Promotor: Professor Dr L.P. Linde (University of Pretoria, South Africa)

Department of Electrical, Electronic & Computer Engineering

Philosophiae Doctor (Electronic)

This thesis investigates multiple-input-multiple-output (MIMO) channel modelling for a wideband indoor environment. Initially the theoretical basis of geometric modelling for a typical indoor environment is looked at, and a space-time model is formulated. The transmit and receive antenna correlation is then separated and is expressed in terms of antenna element spacing, the scattering parameter, mean angle of arrival and number of antenna elements employed. These parameters are used to analyze their effect on the capacity for this environment. Then the wideband indoor channel operating at center frequencies of 2.4 GHz and 5.2 GHz is investigated. The concept of MIMO frequency scaling is introduced and applied to the data obtained in the measurement campaign undertaken at the University of Pretoria. Issues of frequency scaling of capacity, spatial correlation and the joint RX/TX double direction channel response for this indoor environment are investigated. The maximum entropy (ME) approach to MIMO channel modelling is investigated and a new basis is developed for the determination of the covariance matrix when only the RX/TX covariance is known. Finally, results comparing this model with the established Kronecker model and its application for the joint RX/TX spatial power spectra, using a beamformer, are evaluated. Conclusions are then drawn and future research opportunities are highlighted.

Keywords:

MIMO channel modelling, frequency scaling, capacity, correlation and maximum entropy.

OPSOMMING

MIMO CHANNEL MODELLING FOR INDOOR WIRELESS COMMUNICATIONS
deur
Bodhaswar Tikanath Jugpershad MAHARAJ
Promotor: Professor Dr L.P. Linde (University of Pretoria, South Africa)
Departement Elektriese, Elektroniese & Rekenaar Ingenieurswese
Philosophiae Doctor (Elektronies)

Veelvuldige-inset-veelvuldige-uitset (VIVU) kanaalmodellering vir ’n wyeband binnemuurse omgewing word in hierdie proefskrif ondersoek. Die teoretiese basis van meetkundige modellering vir ’n tipiese binnemuurse omgewing is aanvanklik ondersoek en ’n ruimte-tyd model is geformuleer. Die stuur- en ontvangsantenna korrelasie is toe geskei en in terme van die antenna elementspasiëring, die verstrooiingsparameter, die gemiddelde aankomshoek en die aantal antennas wat gebruik is, uitgedruk. Hierdie parameters word gebruik om hulle effek op die kapasiteit van die kanaal te bepaal. Die gebruik van 2.4 GHz en 5.2 GHz in die wyeband binnemuurse omgewing is ondersoek. Die konsep van VIVU frekwensieskalering is met behulp van metings by die Universiteit van Pretoria getoets en toegepas. Frekwensieskalering van kapasiteit, ruimtelike korrelasie en die gesamentlike ontvang/stuur dubbelrigtingkanaalrespons is in hierdie omgewing ondersoek. Die maksimum entropie benadering vir VIVU kanaalmodellering is ondersoek en ’n nuwe basis vir die bepaling van die kovariansie matriks wanneer slegs die stuur/ontvang kovariansie bekend is, is ontwikkel. Laastens word resultate van hierdie model met die gevestigde Kronecker model vergelyk. Die toepassing van die gesamentlike stuur/ontvang ruimtelike drywingspektra word met behulp van ’n bundelvormer evalueer. Die studie maak gevolgtrekkings en lig moontlike toekomstige navorsingsgeleenthede uit.

Sleutelwoorde:

VIVU kanaalmodellering, frekwensieskalering, kapasiteit, korrelasie en maksimum entropie.

I dedicate this work to

- The glory of our creator for giving me the intellect, energy and opportunity
- The Jugpershad Jewnath Family - they ventured, struggled and succeed in humility

ACKNOWLEDGEMENTS

I would like to thank

- Professor Louis P. Linde for his support and encouragement
- Professor Jon W. Wallace for his technical guidance, insight and collaborative support
- The National Research Foundation (NRF), Thuthuka Program
- Professor Michael A. Jensen, Brigham Young University, USA
- My wife Pravina, and children Avikar and Akshay TJ

CONTENTS

CHAPTER ONE - INTRODUCTION **1**
1.1 Background and Motivation 1
1.2 Author's Contributions and Outputs 3
1.2.1 Research Contribution 3
1.2.2 Journal Publications 4
1.2.3 Conference Proceedings 4
1.2.4 Invited Paper 5
1.2.5 Additional Contributions 5
1.3 Outline of Thesis 6

CHAPTER TWO - CHANNEL MODELLING: AN OVERVIEW **8**
2.1 MIMO Communication System Model 8
2.2 MIMO System Capacity 10
2.2.1 Water-Filling Capacity 13
2.2.2 Uninformed Transmitter Capacity 14
2.2.3 Diversity and Spatial Multiplexing 14
2.3 Multipath Characterization 15
2.3.1 Beamforming 15
2.3.2 Bartlett Beamformer 16
2.3.3 Capon Beamformer 17
2.3.4 Double-Directional Channel Model 18
2.3.5 Ray Tracing 19
2.3.6 Geometric Models 20
2.4 Conclusion 24

CHAPTER THREE - GEOMETRIC MODELLING **25**
3.1 Introduction 25

3.2 Model Description 26
3.3 Model Analysis 28
3.4 Results 33
3.5 Conclusion 38

CHAPTER FOUR - WIDEBAND MIMO MEASUREMENT SYSTEM **39**
4.1 Introduction 39
4.2 System Overview 40
4.3 System Components 42
    4.3.1 Transmitter Subsystem 42
    4.3.2 Receiver Subsystem 43
    4.3.3 Synchronization Module 45
    4.3.4 Monopole Antennas 48
4.4 System Deployment 50
    4.4.1 Wideband Probing 50
    4.4.2 Calibration Procedure 55
    4.4.3 Measurement Environment 57
    4.4.4 Data Collection 59
4.5 Conclusion 61

CHAPTER FIVE - DATA ANALYSIS AND MODEL ASSESSMENT **62**
5.1 Capacity Modelling 65
    5.1.1 Introduction 65
    5.1.2 Model Description 65
    5.1.3 Results 67
5.2 Modelling Spatial Correlation 74
    5.2.1 Introduction 74
    5.2.2 Model Description 74
    5.2.3 Results 76
5.3 Double Directional Channel Modelling 81
    5.3.1 Introduction 81
    5.3.2 Model Description 82
    5.3.3 Results 83
5.4 Conclusion 89

5.4.1 Capacity Modelling 89
5.4.2 Spatial Correlation 89
5.4.3 Double Directional Channel 89

CHAPTER SIX - MAXIMUM ENTROPY MODELLING **91**
6.1 Introduction 91
6.2 Model Description 92
6.3 Data Processing 95
6.4 Results 96
6.5 Conclusion 104

CHAPTER SEVEN - CONCLUSION **105**
7.1 Summary 105
7.2 Future Recommendations 107

REFERENCES 108

LIST OF ABBREVIATIONS

2D	2-Dimensional
A/D	Analogue-to-Digital
AOA	Angle of Arrival
AOD	Angle of Departure
b/s/Hz	Bits per second per Hertz
ccdf	Complementary Cumulative Distribution Function
CIR	Channel Impulse Response
CIRC	Circular Array
COTS	Conventional Off-the-Shelf Components
CSI	Channel State Information
DDCIR	Double Directional Channel Impulse Response
DOA	Direction of Arrival
DOD	Direction of Departure
EVD	Eigenvalue Value Decomposition
EVT1/2	Event 1 or 2
FC	Full Covariance
I/O	Input-Output
IF	Intermediate Frequency
ISM	Industrial Scientific and Medical Bands
KM	Kronecker Model
LIN	Linear Array
LNA	Low Noise Amplifier
LO	Local Oscillator

LOS	Line-Of-Sight
ME	Maximum Entropy
MIMO	Multiple-Input-Multiple-Output
MIO	Multifunction Input-Output
MSE	Mean Square Error
NLOS	Non Line of Sight
PC	Personal Computer
PDF	Probability Distribution Function
RF	Radio Frequency
RX	Receiver
SIMO	Single-Input-Multiple-Output
SISO	Single-Input-Single-Output
SNR	Signal-to-Noise-Ratio
SP8T	Single-Pole-8-Throw
SVD	Singular Value Decomposition
SW	Switch
SYNC	Synchronization Unit
TOA	Time of Arrival
TTL	Transistor-Transistor Logic
TX	Transistor
UCA	Uniform Circular Array
ULA	Uniform Linear Array
UP	University of Pretoria
UPS	Uninterruptible Power Supply
UWB	Ultra-wideband
VIVU	Veelvuldige-Inset-Veelvuldige-Uitset
WB	Wideband

LIST OF FIGURES

2.1 Block diagram of a generic MIMO wireless system 9
2.2 Ergodic capacity for a SISO channel vs SNR 11
2.3 Comparison of Shannon capacity for SISO and ergodic capacity for Rayleigh fading MIMO Channels. 13
2.4 Uniform circular 8 element antenna array layout 17

3.1 Geometric Model for a 2x2 MIMO channel 27
3.2 ccdf versus capacity for varying antenna elements, $n_T = n_R$ 34
3.3 ccdf versus capacity for varying antenna spacing, d=d_{mn} 35
3.4 ccdf versus capacity for varying scattering parameter, k 35
3.5 ccdf versus capacity for varying RX antenna orientation, β 37
3.6 ccdf versus capacity for varying SNR(ρ) in dB 37

4.1 High level diagram of the wideband MIMO channel sounder 41
4.2 High level block diagram of the TX subsystem 42
4.3 Transmit RF module 43
4.4 High level block diagram of the RX subsystem 44
4.5 Block Diagram of the RX subsystem connections 44
4.6 Simplified schematic of the SYNC unit 46
4.7 Top view of SYNC Unit 47
4.8 Reset/Trigger switch allowing simultaneous reset of two SYNC units 49
4.9 Front view of SYNC Unit 50
4.10 Rubidium frequency standard 50
4.11 A 2.4 GHz Monopole antenna 51
4.12 2.4 GHz Linear eight element array 51
4.13 2.4 GHz Circular eight element array 52
4.14 A 5.2 GHz Monopole antenna 52
4.15 5.2 GHz Linear eight element array 53

4.16 5.2 GHz Circular eight element array 53
4.17 Grid plate layout for fixing monopole antenna array 54
4.18 Example of multitone signal plotted versus time and frequency 56
4.19 Procedures for system calibration: (a) original measurement setup, (b) single-channel calibration, and (c) direct matrix calibration 57
4.20 System constructed and deployed at the University of Pretoria (UP) 58
4.21 Measurement scenario in CEFIM at UP 59
4.22 Switching sequence for measurements at each location 60
4.23 Channel matrix representation 60

5.1 Capacity PDF for the MIMO system at 2.4 GHz with different array configurations 62
5.2 Capacity PDF for the MIMO system at 5.2 GHz with different array configurations 63
5.3 Eigenvalue CDFs for linear arrays at 2.4 GHz and 5.2 GHz 64
5.4 Eigenvalue CDFs for circular arrays at 2.4 GHz and 5.2 GHz 64
5.5 Capacity versus excitation bandwidth at location 7 for ULA 69
5.6 Capacity versus excitation bandwidth at location 9 for ULA 69
5.7 Average capacity at each of the measurement locations using ULA 70
5.8 Capacity versus excitation bandwidth at location 8 for circular array 71
5.9 Capacity versus excitation bandwidth at location 9 for circular array 71
5.10 Average capacity at each of the measurement locations in CEFIM 73
5.11 Frequency scaling relationship of capacities in WB indoor environment 73
5.12 Calculated relative correlation coefficients with curve fit for RX location 4 . . . 77
5.13 Calculated relative correlation coefficients with curve fit for RX location 7 . . . 77
5.14 Calculated relative correlation coefficients with curve fit for TX location 4 . . . 78
5.15 Calculated relative correlation coefficients with curve fit for TX location 8 . . . 78
5.16 Relationship of RX decorrelation with respect to frequency scaling 80
5.17 Relationship of TX decorrelation with respect to frequency scaling 80
5.18 Spatial spectra for Location 4 employing the Bartlett Beamformer 84
5.19 Spatial spectra for Location 4 employing the Capon Beamformer 84
5.20 Spectral contour for Location 4 employing the Bartlett Beamformer 86
5.21 Spectral contour for Location 4 employing the Capon Beamformer 86

5.22 Spatial spectra for Location 7 employing the Bartlett Beamformer 87
5.23 Spatial spectra for Location 7 employing the Capon Beamformer 87
5.24 Spatial spectra for Location 11 employing the Bartlett Beamformer 88
5.25 Spatial spectra for Location 11 employing the Capon Beamformer 88

6.1 Dominant singular eigenvalues for Location 3 at 2.4 GHz carrier frequency . . 98
6.2 Dominant singular eigenvalues for Location 7 at 2.4 GHz carrier frequency . . 98
6.3 Dominant singular eigenvalues for Location 3 at 5.2 GHz carrier frequency . . 99
6.4 Dominant singular eigenvalues for Location 7 at 5.2 GHz carrier frequency . . 99
6.5 Spatial power spectra for FC and ME at 2.4 GHz at Location 3 100
6.6 Spatial power spectra for FC and ME at 2.4 GHz at Location 7 101
6.7 Spatial power spectra for FC and ME at 5.2 GHz at Location 3 102
6.8 Spatial power spectra for FC and ME at 5.2 GHz at location 7 103

List of Tables

4.1 Parameters of the example multitone signal 55

5.1 TX/RX Pairwise Average Correlation of Capacity for ULA 68
5.2 TX Pairwise Average Correlation of Capacity for UCA 72
5.3 RX Pairwise Average Correlation of Capacity for UCA 72
5.4 Decorrelation Parameter (b) and Error wrt Wavelength (λ) at RX 79
5.5 Decorrelation Parameter (b) and Error wrt Wavelength (λ) at TX 79
5.6 Correlation coefficient of 2.4 GHz and 5.2 GHz spectra 85

6.1 Correlation coefficient of spatial power spectra at 2.4 GHz 97
6.2 Correlation coefficient of spatial power spectra at 5.2 GHz 97