UNIVERSITI PUTRA MALAYSIA

CHANNEL MODELLING AND ESTIMATION IN MULTIPLE-INPUT MULTIPLE-OUTPUT ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING WIRELESS COMMUNICATION SYSTEMS

MOHAMMED ABDO SAEED HEZAM

FK 2008 63

CHANNEL MODELLING AND ESTIMATION IN MULTIPLE-INPUT MULTIPLE-OUTPUT ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING WIRELESS COMMUNICATION SYSTEMS

MOHAMMED ABDO SAEED HEZAM

DOCTOR OF PHILOSOPHY
UNIVERSITI PUTRA MALAYSIA

2008

CHANNEL MODELLING AND ESTIMATION IN MULTIPLE-INPUT MULTIPLE-OUTPUT ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING WIRELESS COMMUNICATION SYSTEMS

By

MOHAMMED ABDO SAEED HEZAM

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

September 2008

To my loving parents, wife, and kids,

for their understanding, endless love, and support through the years

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Doctor of Philosophy

CHANNEL MODELLING AND ESTIMATION IN MULTIPLE-INPUT MULTIPLE-OUTPUT ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING WIRELESS COMMUNICATION SYSTEMS

By

MOHAMMED ABDO SAEED HEZAM

September 2008

Chairman: Professor Borhanuddin Mohd. Ali, PhD

Faculty: Engineering

In wireless communications, the demands for high data rates, enhanced mobility, improved coverage, and link reliability have enormously increased in recent years and are expected to further increase in the near future. To meet these requirements, new concepts and technologies are needed. Theoretical studies have shown that using multiple antennas at the transmitter and receiver, known as multiple-input multiple-output (MIMO) technology, can dramatically increase the capacity, coverage, and link reliability of a communication system. Orthogonal frequency-division multiplexing (OFDM) is an attractive technique for high data rates transmission over frequency-selective fading channels, due to its capability in combating the intersymbol interference (ISI). The combination of MIMO and OFDM results in a powerful technique that incorporates the advantages of both MIMO and OFDM, and is a strong candidate for fourth generation (4G) wireless communication systems.

In this thesis, two issues related to realizing practical mobile MIMO OFDM communication systems are addressed. The first issue is about MIMO channel

modeling and effect of realistic channels on the theoretical capacity. For this target, a geometrically-based three-dimensional (3-D) scattering MIMO channel model is developed. The correlation expressions are derived and analytically evaluated. The impact of spatial correlation on MIMO channel capacity is investigated under different antenna array configurations, angular energy distributions, and parameters. Analytical and numerical results have shown that the elevation angle has considerable effect on the spatial correlation and consequently on the MIMO channel capacity for the case when the antenna array of the mobile station (MS) is vertically oriented. This has led to a conclusion that 3-D scattering MIMO channel modeling is necessary for accurate prediction of MIMO system performance.

The second issue addressed in this thesis is the channel estimation in MIMO OFDM systems. New time-domain (TD) adaptive estimation methods based on recursive least squares (RLS) and normalized least-mean squares (NLMS) algorithms are proposed. These estimators are then extended to blindly track the time-variations of the channel in the decision-directed (DD) mode. Simulation results have shown that TD adaptive channel estimation and tracking in MIMO OFDM systems is very effective in slow to moderate time-varying fading channels. It was observed that the performance of the DD RLS-based estimator always outperform that of the DD NLMS estimator at low mobility and low SNR. In contrast, it was found that the DD NLMS estimator gives better tracking performance at moderate mobility and higher SNR. However, as the training rate is reduced, comparable performance with both estimators is obtained at high SNR. Finally, it has been shown that channel estimation in TD is more accurate with less complexity compared to its counterpart in frequency-domain (FD).

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PERMODELAN SALURAN DAN TAKSIRAN DALAM TEKNOLOGI MASUKAN BERBILANG KELUARAN BERBILANG DAN PEMULTIPLEKSAN PEMBAHAGI FREKUENSI ORTHOGONAL DALAM SISTEM KOMUNIKASI TANPA WAYAR

Oleh

MOHAMMED ABDO SAEED HEZAM

September 2008

Pengerusi: Profesor Borhanuddin Mohd. Ali, PhD

Fakulti: Kejuruteraan

Dalam komunikasi tanpa wayar, tuntutan untuk data kelajuan tinggi, pergerakan yang meningkat, liputan yang ditambahbaik, dan kebolehpercayaan pautan sudah bertambah pada tahun kebelakangan ini dan dijangka akan kian bertambah dalam masa terdekat. Konsep baru dan teknologi terkini diperlukan untuk memenuhi keperluan ini. Kajian teoretikal menunjukkan bahawa penggunaan beberapa antena di pemancar dan penerima, yang dikenali sebagai teknologi masukan berbilang keluaran berbilang(MIMO), boleh secara dramatik menambah keupayaan muatan, liputan, dan kebolehpercayaan pautan suatu sistem komunikasi. Pemultipleksan pembahagi frekuensi orthogonal (OFDM) adalah suatu teknik menarik untuk pengiriman data kelajuan tinggi diatas saluran memudar yang frekuensi bersifat memilih, kerana kemampuannya dalam menangani masalah gangguan antara simbol(ISI). Gabungan MIMO dan OFDM, menghasilkan teknik terbaik yang mengambil kelebihan kedua-dua MIMO dan OFDM dan merupakan calon terulung untuk sistem komunikasi tanpa wayar generasi ke empat (4G).

Di dalam tesis ini, dua isu yang berkaitan dalam merealisasikan sistem komunikasi praktikal MIMO OFDM bergerak dibincang. Persoalan pertama adalah mengenai permodelan saluran MIMO dan kesan saluran realistik terhadap kemampuan muatan teoritikal. Untuk sasaran ini, model saluran MIMO berselerak berdasar geometrik tiga dimensi (3-D) adalah dibina. Ungkapan hubungkait diterbitan dan dinilai secara analitik. Kesan hubungkait ke atas ruang muatan saluran MIMO bardasarkan konfigurasi tatasusunan antena yang pelbagai, taburan kuasa sudut dan parameter yang berbeza dikaji. Keputusan analitik dan numeric telah menunjukkan bahawa sudut peninggian mempunyai pengaruh ke atas hubungkait ruang dan seterusnya ke atas muatan saluran MIMO dalam kes tatasusunan antena stesen mobil (MS) diorientasikan secara vertikal. Ini mencetuskan kesimpulan bahawa permodelan saluran MIMO berselerak 3-D diperlukan untuk membuat ramalan yang tepat ke atas kecekapan sistem MIMO.

Isu kedua yang dibincang di dalam tesis ini adalah mengenai taksiran saluran dalam sistem MIMO OFDM. Kaedah taksiran penyesuaian baru domain masa (TD) berdasarkan re-kursif paling kecil kuasa dua (RLS) dan algoritma normal paling kecil purata kuasa dua (NLMS) dicadangkan. Taksiran ini dipanjangkan untuk mengesan variasi saluran dalam mod arahan-keputusan (DD). Hasil simulasi menunjukkan bahawa taksiran saluran adaptif domain masa dan pengesanan dalam sistem MIMO OFDM adalah berkesan dalam saluran pudar masa berubah perlahan ke pertengahan. Adalah diperhatikan bahawa hasil taksiran DD RLS sentiasa lebih baik daripada taksiran DD NLMS sewaktu pergerakan yang rendah dan pada nisbah isyarat ke bisingan (SNR) rendah. Sebaliknya kontra didapati bahawa taksiran DD NLMS memberikan pretasi pengesanan yang adalah lebih baik daripada DD RLS pada tahap

pergerakan pertengahan dan SNR yang lebih tinggi. Walau bagaimanapun bila kadar latihan turun, keputusan yang sama antara kedua cara taksiran diperolehi pada tahap SNR yang tinggi. Akhir sekali, telah ditunjukkan bahawa penaksiran dalam domain masa adalah lebih tepat dengan kadar kompleks yang kurang berbanding dengan domain-frekuensi (FD).

ACKNOWLEDGEMENTS

In the name of ALLAH, the Most Merciful and the Most Beneficent

Alhamdulillah, the Almighty and the Praise-worthy, for his help and support during the course of life and moment of truth.

First of all, I would like to express my sincerely gratitude and deepest thanks to my advisor, Professor Dr. Borhanuddin Mohd. Ali, for his constant support, invaluable guidance, and encouragement through the years of my graduate studies at UPM. What I have learned from him will provide me with lifetime benefits.

I would like to extend my thanks and appreciation to the other members in my supervisory committee, Associate Professor Dr. Sabira Khatun and Professor Dr. Mahamod Ismail, for their valuable advice, time, participating enthusiastically in the discussions and comments during the course of this thesis work.

I would like to express my thanks and sincere appreciation to Assistant Professor Dr. Nor Kamariah, for her support, valuable discussions and comments. In addition, I am grateful to all the members of the broadband and wireless groups for their co-operation and making my research enjoyable.

I would like to express my deepest gratitude and thanks to my parents for their endless love, support, and encouragement to get the PhD.

Finally, I would like to express my gratefulness and thanks to my wife for her love, support, enriching companionship, and taking care of our kids during my studies.

I certify that an Examination Committee has met on 2 September 2008 to conduct the final examination of Mohammed Abdo Saeed Hezam on his Doctor of Philosophy thesis entitled "Channel Modelling and Estimation in Multiple-input Multiple-output Orthogonal Frequency Division Multiplexing Wireless Communication Systems" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the Doctor of Philosophy.

Members of the Examination Committee are as follows:

Abdul Rahman Ramli, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Sudhanshu Shekhar Jamuar, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Raja Syamsul Azmir Raja Abdullah, PhD
Assistant Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

David Gesbert, PhD
Professor
Department of Mobile Communications
Institute Eurecom, France
(External Examiner)

_____
HASANAH MOHD GHAZALI, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 27 November 2008

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee are as follows:

Borhanuddin Mohd. Ali, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Sabira Khatun, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mahamod Ismail, PhD
Professor
Faculty of Engineering
Universiti Kebangsaan Malaysia
(Member)

_____
HASANAH MOHD GHAZALI, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 19 December 2008

DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

_____

MOHAMMED ABDO SAEED HEZAM

Date: 14/01/2008

TABLE OF CONTENTS

		Page
DEDICATION		ii
ABSTRACT		iii
ABSTRAK		v
ACKNOWLEDGEMENTS		viii
APPROVAL		ix
DECLARATION		xi
LIST OF TABLES		xvi
LIST OF FIGURES		xvii
LIST OF ABBREVIATIONS/ NOTATIONS		xxii
CHAPTER		
1	**INTRODUCTION**	**1**
	1.1 MIMO Channel Modelling	3
	1.2 Channel Estimation in OFDM-based Communication Systems	3
	1.3 Why Adaptive Channel Estimation?	6
	1.4 Motivations and Problem Statement	7
	1.5 Aim and Objectives	9
	1.6 Brief Methodology	10
	1.7 Contributions of the Thesis	11
	1.8 Organization of the Thesis	12
2	**LITERATURE REVIEW**	**15**
	2.1 Wireless Propagation Characteristics	15
	2.2 Modelling Key Parameters	17
	2.2.1 Free Space Path Loss	17
	2.2.2 Multipath Propagation Effects	18
	2.2.3 Doppler Shift	19
	2.2.4 Shadowing	20
	2.3 Orthogonal Frequency Division Multiplexing	22
	2.3.1 OFDM Block Diagram	22
	2.3.2 Guard Interval and Cyclic Prefix	23
	2.3.3 The OFDM System Model	25
	2.3.4 OFDM Signal Model	25
	2.3.5 OFDM Signal Demodulation	27
	2.3.6 OFDM Applications	29
	2.4 MIMO Technology	30
	2.4.1 MIMO Signal Model	31
	2.4.2 The Eigen-analysis Method	32
	2.4.3 Capacity of Deterministic MIMO Channels	33
	2.4.4 Capacity of Random MIMO Channels	36

2.5 Review of MIMO Channel Modelling 37
2.5.1 Physically-based MIMO Channel Models 39
2.5.2 Analytical MIMO Channel Models 49
2.6 Previous Works on 3-D Channel Modelling 58
2.7 Overview of Channel Estimation 61
2.7.1 Channel Estimation in OFDM-based Systems 61
2.7.2 Channel Estimation in MIMO OFDM Systems 66
2.7.3 Pilot Patterns 67
2.7.4 Classical Channel Estimation Methods 68
2.7.5 The MSE Criterion 73
2.7.6 Tracking Time-varying Channels 73
2.7.7 Adaptive Channel Estimation 74
2.7.8 Time- vs. Frequency-domain Channel Estimation 75
2.8 Summary and Conclusions 76

3 **MIMO CHANNEL MODELING IN THREE-DIMENSIONAL SCATTERING ENVIRONMENT 78**
3.1 Introduction 78
3.2 Concept of 3-D Scattering Models 79
3.3 Generalized Model for MIMO Channel in 3-D Scattering Environment 82
3.4 Antenna Array Response Vector 86
3.5 Spatial Angles Distributions at the MS 88
3.5.1 Azimuthal Angle Distribution 88
3.5.2 Elevation Angle Distribution 89
3.6 Azimuthal Angle Distribution at the BS 89
3.7 Derivations of the Correlation Functions 90
3.7.1 The Joint Spatial-temporal Correlation Function 91
3.7.2 Spatial Cross-correlation Function 92
3.7.3 Temporal Correlation Function 93
3.8 ULA Correlation Function 94
3.9 UCA Correlation Function 96
3.10 MIMO System Model 98
3.11 Capacity of MIMO Fading Channels 99
3.12 Correlated MIMO Channel Model 100
3.13 Capacity of Correlated MIMO Channels 101
3.14 Optimal Power Allocation 102
3.15 Conclusions 104
4 **ANALYTICAL AND SIMULATION RESULTS AND DISCUSSION 106**
4.1 Introduction 106
4.2 Signal Cross-correlation in 3-D Scattering MIMO Channels 106
4.2.1 Horizontally Separated Antenna Elements 107
4.2.2 Vertically Separated Antenna Elements 108
4.2.3 Effect of Antenna Array Orientation on Spatial Fading Correlation 110
4.2.4 Signal Temporal Autocorrelation in 3-D Scattering MIMO Channels 111
4.3 Effects of Spatial Fading Correlation on MIMO Channel Capacity 112

4.4 Effect of Number of Antennas on MIMO Channel Capacity 113
4.5 Impact of the Propagation Environment on MIMO Channel Capacity 114
4.5.1 MIMO Channel Capacity with Uniform Angular Energy Distribution 115
4.5.2 MIMO Channel Capacity with Laplacian Angular Energy Distribution 118
4.6 Capacity Optimization Using Water-filling Algorithm 120
4.7 Effect of Antenna Spacing on MIMO Channel Capacity 122
4.8 Conclusions 123

5 **ADAPTIVE CHANNEL ESTIMATION AND TRACKING IN MIMO OFDM SYSTEMS 126**
5.1 Introduction 126
5.2 MIMO OFDM System 127
5.3 Wireless Channel Statistics 132
5.4 Significance of the Proposed Channel Estimators 133
5.5 Training Schemes Design 133
5.6 MIMO Channel Estimation and Tracking 134
5.6.1 Mathematical Formulation of the RLS Estimator 136
5.6.2 MIMO Channel Tracking Based on the First-order Markov Model 140
5.7 LMS Algorithm 141
5.7.1 LMS-based Channel Estimation in MIMO OFDM Systems 142
5.7.2 Normalized LMS Algorithm 143
5.8 Linear MIMO Equalization and Detection 143
5.9 Computational Complexity Comparisons 145
5.10 Conclusions 145

6 **CHANNEL ESTIMATION AND TRACKING IN MIMO OFDM SYSTEMS: SIMULATION RESULTS AND DISCUSSIONS 147**
6.1 Introduction 147
6.2 Simulation Parameters and Settings 148
6.3 RLS-based Channel Estimation in MIMO OFDM systems 149
6.3.1 Initiation Conditions 150
6.3.2 Channel Estimation in Time-domain 150
6.3.3 Channel Estimation in Frequency-domain 154
6.4 Indoor MIMO OFDM Mobile Communication Systems 156
6.4.1 Channel Estimation and Tracking Based on DD EW-RLS Scheme 156
6.4.2 Channel Estimation and Tracking Based on DD NLMS Scheme 162
6.5 Outdoor MIMO OFDM Mobile Communication Systems 164
6.5.1 Channel Estimation and Tracking Based on DD EW-RLS Scheme 165
6.5.2 Channel Estimation and Tracking Based on DD NLMS Scheme 171

6.6 LS-based Channel Estimation 175
6.7 Conclusions 177

7 **CONCLUSIONS AND FUTURE WORK** **180**
7.1 Conclusions 180
7.1.1 MIMO Channel Modelling 180
7.1.2 Adaptive Channel Estimation in MIMO OFDM Systems 181
7.2 Future Work 183

BIBLIOGRAPHY **185**
APPENDICES **200**
BIODATA OF STUDENT **209**
LIST OF PUBLICATIONS **210**

LIST OF TABLES

Table		Page
2.1	A comparison between the MIMO channel modelling methods	57
6.1	Indoor OFDM system and channel parameters	149
6.2	Indoor multipath channel profile	149
6.3	The initial conditions of the RLS algorithm parameters	150
6.4	Optimum values of the forgetting factor λ in indoor environment	156
6.5	Outdoor multipath channel profile	164
6.6	Outdoor OFDM system and channel parameters	165
6.7	Optimum values of the forgetting factor λ in outdoor environment	165

LIST OF FIGURES

Figure		Page
1.1	Evolution of wireless communication systems toward 4G in terms of mobility and data rates.	7
1.2	Structure of the thesis.	14
2.1	(a) Small-fading effects over a shorter distance of several meters. (b) Attenuation and lognormal fading effect on a signal over several kilometers.	16
2.2	The mechanisms of multipath transmission.	18
2.3	Schematic diagram showing a wave impinging on a mobile.	20
2.4	Effect of moving the receiver on the received signal.	21
2.5	FFT-based OFDM system block diagram.	23
2.6	(a) Addition of a guard interval to an OFDM symbol; (b) OFDM symbol cyclic extension.	24
2.7	Wireless MIMO channel with M_t transmit and M_r receive antennas.	32
2.8	Illustration of the one-ring model.	42
2.9	Illustration of the two-ring model.	44
2.10	Propagation scenario for the distributed scattering model.	45
2.11	Model parameters for a single cluster in the extended S-V model.	48
2.12	An illustration of exponential decay of mean cluster power and ray power within clusters.	48
2.13	(a) Block-type pilot arrangement. (b) Comb-type pilot arrangement.	67
3.1	A multipath signal component in three-dimensions.	80
3.2	Geometry of MIMO channel model with 3-D scattering.	83
3.3	Plane waves impinging on a uniform linear array.	86
3.4	Scattered waves in the direction of the mobile receiving antenna.	87
3.5	Plane waves impinging on a uniform circular array.	88

3.6 Propagation model for a MIMO fading channel where signals from a mobile arrive within $\pm\Delta$ of angle ω_0 at a receiver equipped with a ULA. 95

3.7 Propagation model for a MIMO fading channel where signals from a mobile arrive within $\pm\Delta$ of angle ω_0 at a receiver equipped with a UCA. 96

3.8 Schematic of the water-filling algorithm. 102

4.1 Cross-correlation between signals received at two elements of Horizontally separated $(\varepsilon = 0^\circ)$ antenna elements, $\eta = 0^\circ$. 107

4.2 Cross-correlation between signals received at two elements of Vertically separated $(\varepsilon = 90^\circ)$ antenna array, $\eta = 0^\circ$. 109

4.3 Cross-correlation between two paths of a 2×2 MIMO channel with vertically placed MS antennas ($\varepsilon = 90^\circ$) and $\alpha = 20^\circ$. 109

4.4 Cross-correlation versus antenna spacing for various values of ε, and when $\alpha = 20^\circ$ and $\eta = 0^\circ$. 110

4.5 Autocorrelation of the real part of a fading as a function of the normalized delay. 111

4.6 Effect of the fading correlation on a 4×4 MIMO Channel Capacity. 112

4.7 Influence of the number of antennas $(M_t = M_r)$ on the ergodic capacity as a function of the angular spread. 113

4.8 Capacity of a 4×4 correlated MIMO fading channel for uniform AOA distribution and different angle spread Δ. $R = 0.5\lambda$. 115

4.9 Effect of the angle spread, Δ, on the ergodic capacity of a 4×4 correlated MIMO fading channel. 116

4.10 Effect of antenna spacing on the ergodic capacity of a 4×4 correlated MIMO channel as a function of the angular spread. SNR=20 dB. 117

4.11 Effect of antenna spacing on the 10% outage capacity of a 4×4 correlated MIMO channel as a function of the angular spread. SNR=20 dB. 117

4.12 Capacity of a 4×4 correlated MIMO fading channel for Laplacian AOA distribution and different values of the decaying factor a. $R = 0.5\lambda$. 118

4.13 Influence of the antenna spacing R on the capacity of a 4×4

correlated MIMO fading channel, with Laplacian angular energy distribution and $a = 10$. 119

4.14 Capacity of a 4×4 correlated MIMO fading channel with equal and optimized power allocation, and uniform angular energy distribution. 121

4.15 Capacity of a 4×4 correlated MIMO fading channel with equal and optimized power allocation, and Laplacian angular energy distribution. 122

4.16 Effect of antenna spacing on the ergodic capacity of a 4×4 correlated MIMO fading channel, with uniform angular energy distribution and ULA at the MS. 123

5.1 Baseband MIMO OFDM system model. 127

5.2 Illustration of adaptive filter modeling of unknown channel. 135

6.1 Structure of time-orthogonal training sequences for 2×2 MIMO OFDM system. 151

6.2 MSE of channel estimates with time-orthogonal training sequences (Scheme I). 151

6.3 The BER performance vs. SNR, with time-orthogonal transmitted training sequences (Scheme I). 152

6.4 MSE of channel estimates with simultaneously transmitted training sequences (scheme II). 153

6.5 The BER performance vs. SNR, with simultaneously transmitted training sequences (scheme II). 153

6.6 MSE of channel estimates of the EW-RLS estimator in FD. 155

6.7 The BER performance vs. SNR, with EW-RLS channel estimation in FD. 155

6.8 MSE of channel estimates of the DD EW-RLS estimator with 10% training data. 158

6.9 MSE of channel estimates of the DD EW-RLS estimator with 4% training data. 158

6.10 The BER performance vs. SNR, with DD EW-RLS channel tracking and 10% training data. 159

6.11 The BER performance vs. SNR, with DD EW-RLS channel tracking and 4% training data. 159

6.12 The BER performance vs. SNR, with EW-RLS channel estimation (no tracking) and 10% training data. 161

6.13 The BER performance vs. SNR, with EW-RLS channel estimation (no tracking) and 4% training data. 161

6.14 The BER performance vs. SNR, with DD NLMS channel tracking and 10% training data. 163

6.15 The BER performance vs. SNR, with DD NLMS channel tracking and 4% training data. 163

6.16 MSE of channel estimates of the DD EW-RLS estimator with 10% training data. 166

6.17 MSE of channel estimate of the DD EW-RLS estimator with 4% training data. 167

6.18 MSE of channel estimates of DD EW-RLS estimator with 2% training data. 167

6.19 The BER performance vs. SNR with DD EW-RLS channel tracking and 10% training data. 169

6.20 The BER performance vs. SNR with DD EW-RLS channel tracking and 4% training data. 169

6.21 The BER performance vs. SNR with DD EW-RLS channel tracking and 2% training data. 170

6.22 RLS-based time domain channel tracking of $\mathbf{h}_{11}$. 171

6.23 The BER performance vs. SNR with DD-NLMS channel tracking and 10% training data. 172

6.24 The BER performance vs. SNR with DD NLMS channel tracking and 4% training data. 173

6.25 The BER performance vs. SNR, with DD NLMS channel tracking and 2% training data. 173

6.26 LMS-based time domain channel tracking of $\mathbf{h}_{11}$. 174

6.27 MSE of channel estimates of the LS estimator with no data transmitted during the training mode. 175

6.28 MSE of channel estimates of the LS estimator with pilots transmitted in every OFDM symbol. 176

6.29 The BER performance vs. SNR, with LS channel estimation and pilots

transmitted in every OFDM symbol. 176

A.1 Signal impinging on a uniform linear antenna array in a three-dimensional signal scattering. 200

A.2 Decomposition of the impinging wave into its perpendicular components. 200

LIST OF ABBREVIATIONS/ NOTATIONS

Abbreviations

1-D	One-dimensional
1G	First Generation
2-D	Two-dimensional
2G	Second Generation
3-D	Three-dimensional
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
AA	Azimuthal Angle
A/D	Analog-to-Digital Converter
ACF	Autocorrelation Function
ADSL	Asymmetric Digital Subscriber Line
AoA	Angle-of-Arrival
AoD	Angle-of-Departure
APS	Angular Power Spectrum
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLAST	Bell Labs Layered Space-Time
BPSK	Binary Phase Shift Keying
BS	Base Station
BW	Bandwidth
CFR	Channel Frequency Response
CIR	Channel Impulse Response

CLA	Circular Linear Array
COST	European forum for CO-operative Scientific Research
CP	Cyclic Prefix
CSI	Channel State Information
D/A	Digital-to-Analog
DAB	Digital Audio Broadcast
dB	deciBel
DD	Decision-Directed
DDCE	Decision-Directed Channel Estimation
DFT	Discrete Fourier Transform
DMT	Discrete Multi-Tone
DoA	Direction-of-Arrival
DoD	Direction-of-Departure
DPSK	Differential PSK
DSL	Digital subscriber Line
DVB	Digital Video Broadcast
DVB-H	Digital Video Broadcasting – Hand-held
DVB-T	Digital Video Broadcast - Terrestrial
EA	Elevation Angle
ETSI	European Telecommunication Standardization Institute
EVD	Eigenvalue Decomposition
EW-RLS	Exponentially Weighted Recursive Least Squares
FD	Frequency Domain
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform

FIR	Finite Impulse Response
GBSB	Geometrically Based Single-Bounce
GBSBEM	Geometrically Based Single-Bounce Elliptical Model
GI	Guard Interval
GSCM	Geometry-based Stochastic Channel Model
HDSL	High-bit-rate DSL
HIPERLAN/2	High Performance Local Area Network type 2
HIPERMAN	High Performance Metropolitan Area Network
i.i.d.	independent identically distributed
IBO	Input Back-Off
ICI	Intercarrier Interference
IDFT	Inverse Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IQ	In-phase and Quadrature-phase
ISI	Intersymbol Interference
LAN	Local Area Network
LMMSE	Linear Minimum Mean Square Error
LMS	Least Mean Squares
LoS	Line-of-Sight
LS	Least Squares
MCM	Multi-Carrier Modulation
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
ML	Maximum Likelihood

MMAC	Multimedia Mobile Access Communications
MMSE	Minimum Mean Square Error
MS	Mobile Station
MSE	Mean-Square Error
MSI	Multistream Interference
NLMS	Normalized least Mean square
NLoS	Non-Line-of-Sight
OFDM	Orthogonal Frequency Division Multiplexing
OOB	Out-of-Band
P/S	Parallel-to-Serial
PAN	Personal Area Network
PAPR	Peak-to-average power Ratio
PAS	Power Azimuth Spectra
PDF	Probability Density Function
PDP	Power-Delay Profile
PN	Pseudo-Noise
PSD	Power Spectral Density
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature PSK
RF	Radio Frequency
RLS	Recursive Least Squares
RT	Ray-Tracing
Rx	Receiver
S/P	Serial-to-Parallel

SATURN	Smart card And Terminal User Requirements and Needs
SCM	Spatial Channel Model
SIMO	Single-Input Multiple-Output
SISO	Single-Input Single-Output
SNR	Signal-to-Noise Ratio
STBC	Space-Time Block Coding
STTC	Space-Time Trellis Coding
S-V	Saleh-Valenzuela
SVD	Singular Value Decomposition
TD	Time-Domain
ToA	Time-of-Arrival
Tx	Transmitter
ULA	Uniform Linear Array
URA	Uniform Rectangular Array
VHDSL	Very High Speed DSL
WiBro	Wireless Broadband
WiMAX	Worldwide Interoperability for Microwave Access
WINNER	Wireless World Initiative New Radio
WLAN	Wireless Local Area Network
WSS	Wide-Sense Stationary
ZF	Zero-Forcing
ZMCSCG	Zero-Mean Circularly-Symmetric Complex Gaussian

Notations and Symbols

Symbols with bold face represent either vectors or matrices as it is stated. The symbols with regular font are used for scalar quantities.

$(.)^T$	complex transpose
$\mathbf{a}^*$	complex conjugate of vector $\mathbf{a}$
$(.)^H$	complex transpose and conjugate (Hermitian)
$*$	convolution product
$\otimes$	Kronecker product
$\odot$	element-wise Schur-Hadamard multiplication operator
$(.)^+$	Moore-Penrose inverse
$\|\|.\|\|$	Euclidean norm
$\mathbf{A}^{-1}$	inverse of matrix $\mathbf{A}$
$\mathbf{A}^{-T}$	inverse transpose of matrix $\mathbf{A}$
$\mathbf{I}_N$	$N \times N$ identity matrix
det ($\mathbf{A}$)	determinant of matrix $\mathbf{A}$
Re {a}	real part of complex scalar a
Im {a}	imaginary part of complex scalar a
Rank($\mathbf{A}$)	rank of matrix $\mathbf{A}$
diag (.)	diagonal matrix of the argument vector
vec{$\mathbf{H}$}	stacks columns of the matrix $\mathbf{H}$ on top of each other
unvec{.}	inverse of *vec*{.} operation
tr(.)	trace of the argument matrix
$E\{.\}$	expectation operator

$\delta(.)$	dirac delta function
min	minimum
max	maximum
arg max	maximizing argument
lim	limit
e	exponential function
$\hat{a}$	estimate of a
$I(\mathbf{x};\mathbf{y})$	mutual information between vector $\mathbf{x}$ and vector $\mathbf{y}$
$p(\mathbf{x})$	probability distribution function of the vector $\mathbf{x}$
$H(\mathbf{w})$	differential entropy of the vector $\mathbf{w}$
$\mathbf{R}_{\mathbf{xx}}$	covariance matrix of the vector $\mathbf{x}$
$\lvert\mathbf{a}\rvert$	magnitude of the complex vector $\mathbf{a}$
$J_0(.)$	*0*th order Bessel function of the first kind