## University of California Los Angeles

# Transmission Techniques for Multi-User MIMO Communications

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Electrical Engineering

by

Mirette Mahmoud Sadek Ahm Sadek

© Copyright by  $\label{eq:market} \mbox{Mirette Mahmoud Sadek Ahm Sadek}$  2006

Richard Wese	- l
Jeff Shamma	_ a
Abeer Alwar	– n
Ali H. Sayed, Committee Chai	– .r

The dissertation of Mirette Mahmoud Sadek Ahm Sadek is approved.

University of California, Los Angeles  $2006 \label{eq:california}$ 

To **Sarah**, my daughter and friend.

## TABLE OF CONTENTS

1	Intr	oducti	ion	1
	1.1	Single	User MIMO Systems	2
		1.1.1	Frequency Flat MIMO Channels	2
		1.1.2	Frequency-Selective MIMO Channels	F. 5
		1.1.3	MIMO Performance Gains	7
		1.1.4	Single User Systems with CSIT	8
		1.1.5	Single User Systems without CSIT	13
		1.1.6	Single User Systems with Partial CSIT	19
	1.2	Multi-	User MIMO Systems	24
		1.2.1	System Model	24
		1.2.2	Multi-User Systems with CSIT	25
		1.2.3	Multi-User Systems without CSIT	30
		1.2.4	Multi-User Systems with Partial CSIT	33
	1.3	Thesis	S Contribution	36
2	Mu	lti Use	er Multiple Access Beamforming Techniques	41
	2.1	System	m Model	42
	2.2	Iterati	ive SDMA Schemes	45
		2.2.1	Conditions and Limitations	48
	2.3	Closed	l-form Zero-Forcing Schemes	49
		2.3.1	Conditions and Limitations	51

	2.4	Conclusions	51
3	Lea	kage-Based Multiuser Beamforming	53
	3.1	Introduction	53
	3.2	System Model	55
	3.3	Multi User Beamforming and Leakage	58
		3.3.1 SLNR and SINR Performances	63
	3.4	Multi User Beamforming with Alamouti Coding	64
	3.5	Channel Estimation Errors	71
	3.6	Simulation Results	72
	3.7	Conclusions	75
4	Act	ive Antenna Selection	86
	4.1	Introduction	36
	4.2	System Model	38
	4.3	Maximum Eigenvalue Distribution	94
		4.3.1 Distribution of the Elements of $\boldsymbol{R}$	96
		4.3.2 Distribution of the Eigenvalues of $R$	00
	4.4	Antenna Selection Procedure	)4
	4.5	Simulations	0.0
	4.6	Conclusions	21
5	Cha	annel Feedback and Channel Tracking	<b>!9</b>
	5.1	Introduction	29

$\mathbf{R}$	References 14		
	5.6	Concluding Remarks	139
	5.5	Simulation Results	136
	5.4	Channel Estimation	134
	5.3	State-Space Model	132
	5.2	Channel Modeling	130

## LIST OF FIGURES

1.1	A MIMO wireless system in the single user case	3
1.2	Transmitted data blocks with a guard period in between	6
1.3	Transmit beamforming in a single user MIMO system	9
1.4	Water-filling solution	12
1.5	Capacity (in bits) vs M for $N \to \infty$ and 0 $dB \le P \le 30$ $dB$ in 10	
	dB increments	18
1.6	Capacity (in bits) vs M for $N=1$ and 0 $dB \leq P \leq 30$ $dB$ in 10	
	dB increments [Tel99]	19
1.7	Capacity (in bits) vs N for $M=1$ and 0 $dB \leq P \leq 30$ $dB$ in 10	
	dB increments [Tel99]	20
1.8	Plot of the necessary and sufficient conditions on the optimality	
	of beamforming for capacity maximization in case of the channel	
	covariance feedback	23
1.9	Downlink and uplink channels of a MIMO communication system	
	with a base station and mobile users	25
1.10	Capacity region for a two user system, each having $N_i = 1$ transmit	
	antenna	29
1.11	Capacity region for a two user system, each having $N_i > 1$ transmit	
	antennas	30
1.12	Block diagram for a multi-user technique with no CSIT	32
2.1	Block diagram of a multi-user MIMO downlink system	43
2.2	Desired signal and interference to user i	43

2.3	Histogram of the number of iterations required for convergence.	
	The system configuration is: $N = 12, M_i = 2, K = 2 \dots \dots$	49
3.1	Block diagram of a multi-user beamforming wireless communica-	
	tions system	56
3.2	A block diagram depicting the leakage from user 1 on other users.	60
3.3	Block diagram of the multi-user beamforming system with OSTBC.	65
3.4	Uncoded BER results for user 1 assuming $N=10$ transmit anten-	
	nas and $K=3$ users, each equipped with $M_i=2$ receive antennas.	
	The dimension condition (3.7) is satisfied with a good margin	76
3.5	Outage comparison for $N=10$ transmit antennas and $K=3$	
	users, each equipped with $M_i = 2$ receive antennas and $1/\sigma^2 = -6dB$ .	77
3.6	Outage comparison for $N=10$ transmit antennas and $K=3$	
	users, each equipped with $M_i = 2$ receive antennas and $1/\sigma^2 = 12dB$ .	78
3.7	$\it Uncoded\ BER\ results\ for\ user\ 1\ assuming\ N=9\ transmit\ antennas$	
	and $K=3$ users, each equipped with $M_i=3$ receive antennas. The	
	dimension condition (3.7) is satisfied with a small margin	79
3.8	Outage comparison for $N=9$ transmit antennas and $K=3$ users,	
	each equipped with $M_i=3$ receive antennas and $1/\sigma^2=-6dB$	80
3.9	Outage comparison for $N=9$ transmit antennas and $K=3$ users,	
	each equipped with $M_i = 3$ receive antennas and $1/\sigma^2 = 12 dB$	81
3.10	$\it Uncoded\ BER\ results\ for\ user\ 1\ assuming\ N=5\ transmit\ antennas$	
	and $K=3$ users, each equipped with $M_i=3$ receive antennas. The	
	dimension condition (3.7) is not satisfied	82

3.11	Outage comparison for $N=5$ transmit antennas and $K=3$ users,	
	each equipped with $M_i=3$ receive antennas and $1/\sigma^2=-6dB$	83
3.12	Outage comparison for $N=5$ transmit antennas and $K=3$ users,	
	each equipped with $M_i=3$ receive antennas and $1/\sigma^2=12dB$	84
3.13	Uncoded BER results averaged over 5000 channels realizations for	
	user 1 assuming $N=9$ transmit antennas and $K=3$ users, each	
	equipped with $M_i = 3$ receive antennas. The channels are assumed	
	uncertain with $1/\sigma_c^2 = 10 dB$	85
4.1	Block diagram of the multi-user beamforming system	91
4.2	Probability density function of $\lambda_{max}$ obtained by simulation and	
	by using (4.51) for $m = 3$ , $s = 4$ , $t = 5$ and $\sigma^2 = 0.3$	104
4.3	Probability density function of $\lambda_{max}$ obtained by simulation and	
	by using (4.51) for $m = 2$ , $s = 4$ , $t = 6$ and $\sigma_i^2 = 0.2$	105
4.4	The derived pdf of $\lambda_{max}$ for $m=2,\ t=6,\ \sigma^2=0.2,\ and\ three$	
	values of $s = \{4, 6, 8\}.$	106
4.5	The derived pdf of $\lambda_{max}$ for $m=2,\ s=4,\ \sigma^2=0.2,\ and\ three$	
	values of $t = \{4, 6, 8\}$	107
4.6	Mean value of $\lambda_{max}$ versus $M_i$ for fixed values of $N$ , $t$ , and $\sigma^2 = 0.2$ .	108
4.7	Mean value of $\lambda_{max}$ versus t for fixed values of N, $M_i$ , and $\sigma^2 = 0.2$ .	109
4.8	SINR outage probability for all the users	111
4.9	Distribution of the number active receive antennas for each user	
	after applying the proposed scheme. $10 \log_{10} 1/\sigma^2 = 0$ for all users.	112

4.10	Distribution of the number active receive antennas for each user	
	after applying the proposed scheme. $10\log_{10}1/\sigma^2=0$ and using	
	the full number of receive antennas for all users	113
4.11	SINR outage probability for all the users	117
4.12	Distribution of the number active receive antennas for each user	
	after applying the proposed scheme. $10\log_{10}1/\sigma^2=0$ for all users.	118
4.13	Distribution of the number active receive antennas for each user	
	after applying the proposed scheme. $10\log_{10}1/\sigma^2=0$ and using	
	the full number of receive antennas for all users	119
4.14	SINR outage probability for all the users	125
4.15	Distribution of the number active receive antennas for each user	
	after applying the proposed scheme. $10\log_{10}1/\sigma^2=0$ for all users.	126
4.16	Distribution of the number active receive antennas for each user	
	after applying the proposed scheme. $10\log_{10}1/\sigma^2=0$ and using	
	the full number of receive antennas for all users	127
4.17	Outage vs. SINR for 2 users each having 2 receive antennas for	
	a system with 12 transmit antennas. The SINR thresholds are	
	$\{30,30\}\ dB.$	128
5.1	The proposed beamforming architecture with feedback	131
5.2	The training pattern used in the simulations	136
5.3	BER versus SNR for a $4 \times 1$ system with $f_d = 60$ Hz, $\rho = 0.8$ ,	
	$N_D = 512, N_{T1} = 6, \text{ and } N_{T2} = 1. \dots \dots \dots \dots \dots$	138
5.4	BER versus SNR for a $4 \times 1$ system with $f_d = 60$ Hz, $\rho = 0.4$ ,	
	$N_D = 512, N_{T1} = 6, \text{ and } N_{T2} = 1. \dots \dots \dots \dots \dots$	139

5.5	BER versus SNR for a $4 \times 1$ system with $f_d = 60$ Hz, $\rho = 0.8$ ,	
	$N_D$ =512, $N_{T1}$ = 8, and $N_{T2}$ = 1. See Figure 5.1 for an explana-	
	tion of the parameter D	140
5.6	BER versus SNR for a $4 \times 1$ system with $f_d = 60$ Hz, $\rho = 0.4$ ,	
	$N_D$ =512, $N_{T1}$ = 8, and $N_{T2}$ = 1. See Figure 5.1 for an explana-	
	tion of the parameter D	141

#### ACKNOWLEDGMENTS

First and foremost, my deepest gratitude goes to my parents who made me who I am today and who should definitely share the credit for every success I achieve in life. Without their guidance and support, nothing of this would have been possible. I would also like to thank my sister Yomna and her family for their support.

I would like to express my gratitude and appreciation for my advisor, Prof. Ali H. Sayed. Throughout the last five years, I have learned a lot from him. He taught me how to approach research and how to question everything and to never take anything for a fact. His relentless quest for perfection was really inspiring. I only wish that, in the future as a professor and supervisor myself, I can be as supportive and as inspiring to my students as he was to me and to many others. Thanks to him, I feel like I will be walking out of UCLA with more than a Ph.D.

Special thanks are due to my colleague and mentor Alireza Tarighat. We have collaborated on several problems and I learned a lot from his expertise. Working with him was both fruitful and fun. He taught me how to keep an eye on the big picture even when I was overwhelmed by the details.

I would also like to thank my dear friends May Gadallah and Gehan El Shafei. For the past five years they have been like family to me. Their support, help, and love are really appreciated and the good times we had together are unforgettable. Life would have been totally different without them. Many thanks are also due to my very dear friend Mouna Mana. During the past year, she has been like a sister to me. She has been the best companion in UCLA and outside of it, and the good memories we share are invaluable. All of my dear friends have added taste to my life, a very good taste.

I cannot possibly go without thanking my colleagues Waleed Younis and Nabil Yousef in whose steps I followed.

The biggest thanks of all goes to my beloved daughter Sarah. For the past five years, she was my daughter, my friend and my partner. Even at this young age, she has always been responsible and supportive. She endured patiently with me and always showed her appreciation for my work. We went through a lot together and this Ph.D. is certainly hers as much as it is mine. Thank you my sweet heart.

Chapter 3 is a version of [STSb], chapter 4 is a version of [STSa], and chapter 5 is a version of [MS04]. I would like to acknowledge the contribution of Dr. Alireza Tarighat and Prof. Dr. Ali H. Sayed to these chapters.

Finally I would like to acknowledge that my Ph.D work was partially supported by the National Science Foundation under grants NSF ECS-9820765, NSF CCF-0208573, and NSF ECS-0401188. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not reflect the views of the National Science Foundation.

#### $V_{\rm ITA}$

1973	Born, Cairo, EGYPT.
1997	B.S. Electronics and Communication Engineering, Ain Shams University, Cairo, EGYPT.
1997–2001	Teaching and research assistant, Electronics and Communication Engineering Dept., Ain Shams University, Cairo, EGYPT.
2001	M.S. Electronics and Communication Engineering, Ain Shams University, Cairo, EGYPT.
2001–2005	Teaching Assistant, Electrical Engineering Department, UCLA.
2001–2005	Research Assistant, Electrical Engineering Department, UCLA.

#### **PUBLICATIONS**

M. Sadek, A. Tarighat, and A. H. Sayed, "Exploiting spatio-temporal correlation for rate-efficient transmit beamforming," *Proc. Asilomar Conference on Signals, Systems and Computers*, Monterey, CA, Nov. 2004, pp. 2027–2031.

A. Tarighat, M. Sadek, and A. H. Sayed, "A multi user beamforming scheme for