

Multiple Antenna Doppler-Compensation for OFDM Systems

Dissertation
zur Erlangung des akademischen Grades
Doktor der Ingenieurwissenschaften (Dr.-Ing.)
vorgelegt dem Fachbereich 1 (Physik/Elektrotechnik)
der Universität Bremen

von

Dipl.-Ing. Peter Klenner

Tag des öffentlichen Kolloquiums: 01.April 2011

Gutachter der Dissertation:

Prof. Dr.-Ing. K.D. Kammeyer

Prof. Dr.-Ing. J. Lindner

Weitere Prüfer:

Prof. Dr.-Ing. M. Schneider

Prof. Dr.-Ing. S. Paul



Bremen, April 2011

Forschungsberichte aus dem Arbeitsbereich Nachrichtentechnik
der Universität Bremen

Band 21

Peter Klenner

**Multiple Antenna Doppler-Compensation
for OFDM Systems**

D 46 (Diss. Universität Bremen)

Shaker Verlag
Aachen 2011

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Bremen, Univ., Diss., 2011

Copyright Shaker Verlag 2011

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-0108-2

ISSN 1437-000X

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

Internet: www.shaker.de • e-mail: info@shaker.de

Preface

This work is the result of my activity as a research assistant in the Arbeitsbereich Nachrichtentechnik of the Institute for Telecommunications and Radiofrequency Technology at the University Bremen. I am grateful for the extensive support which I have received during that time.

I am particularly indebted to Mr. Prof. Dr.-Ing. K.-D. Kammeyer for facilitating and supporting my doctorate and for his unfailing interest in my work. I would also like to thank Mr. Prof. Dr.-Ing. J. Lindner of the University Ulm for providing his expertise and for his interest in this work. In their capacity as reviewers, I am much obliged to Mr. Prof. Dr.-Ing. M. Schneider and Mr. Prof. Dr.-Ing. S. Paul.

I have been very fortunate to have worked among a great group of colleagues and friends at the Arbeitsbereich Nachrichtentechnik. Succeeding to finish my work is very much owed to this friendly and competent environment. My express thanks for technical as well as less technical advice in no other than alphabetical order go to Mr. Dipl.-Ing. C. Bockelmann, Mr. Dipl.-Ing. R. Böhnke, Mr. Dipl.-Ing. S. Goetze, Mr. Dipl.-Ing. H. Paul, and Mr. Dipl.-Ing. M. Petermann. For their careful proofreading I would like to offer my thanks to Mr. Dipl.-Ing. C. Bockelmann, Mr. Dipl.-Ing. H. Paul, and Mr. Dipl.-Ing. M. Petermann. Likewise, I want to thank the Deutsche Forschungsgemeinschaft (DFG) for financially supporting large parts of this work.

My heartfelt thanks are due to my parents for always helping and guiding and supporting me. And the last word – with a tiny apology to the uninitiated – goes to my love: В заключение я благодарю мою невесту Наталью, которая снова и снова поощрила меня в течение последних месяцев, чтобы я не терял мужества!

Bremen, April 2011

Peter Klenner

Contents

1	Introduction	1
1.1	Thesis Origin And Main Focus	1
1.2	Thesis Structure	2
1.3	Conventions and Nomenclature	4
2	Fundamentals of Wireless OFDM Systems	7
2.1	Overview	7
2.2	Wireless Transmission	9
2.2.1	Basic System Model	9
2.2.2	Forward Error Correction	10
2.2.3	Linear Digital Modulation	12
2.2.4	OFDM	14
2.2.5	Pilot-Symbol Assisted Modulation (PSAM)	18
2.2.6	Differential Modulation, Noncoherent Reception	21
2.3	Modelling Wave Propagation	22
2.3.1	Omnidirectional Reception	24
2.3.2	The Uniform Linear Antenna Array	29
2.3.3	Mutual Coupling	32
2.3.4	Simulation of Wideband Channels	33
2.4	Intercarrier Interference	33
2.4.1	ICI induced by Imperfect Synchronization	34
2.4.2	ICI induced by Doppler Spread	37
2.5	Performance of MIMO-OFDM	40
2.5.1	Maximum-Likelihood Receiver	41
2.5.2	Linear Detection	44
2.5.2.1	Figures of Merit	44
2.5.2.2	MMSE-Detection	45
2.5.2.3	Zero-Forcing	47
2.5.2.4	Matched Filtering	49

2.5.2.5	Maximum Ratio Combining	50
2.5.3	Differential Demodulation	50
2.5.4	The Correlation Coefficient	52
2.5.5	Capacity Results	53
2.6	Standards and the State of the Art	54
2.6.1	Standards	55
2.6.2	The State of the Art	55
2.7	System Parameters	57
2.8	Summary	58
3	Antenna Structures for Doppler Spread Compensation	61
3.1	Overview	61
3.2	Basic Receive Diversity	62
3.2.1	SIMO (MRC)	63
3.2.2	MIMO (BLAST, Alamouti)	66
3.3	Beamforming	67
3.3.1	Ideal Sectorization	67
3.3.2	Delay&Sum-Beamforming	70
3.3.2.1	SIMO (MF, MRC)	73
3.3.2.2	MIMO (BLAST, Alamouti)	76
3.3.3	MMSE-Beamforming	77
3.3.3.1	SIMO (MF, MRC)	80
3.3.3.2	MIMO (BLAST, Alamouti)	81
3.4	Spatial Interpolation	82
3.4.1	SIMO (MF, MRC)	85
3.4.2	MIMO (BLAST, Alamouti)	86
3.5	The Design of the Antenna Structures	87
3.6	Summary	89
4	Parameter Estimation	91
4.1	Overview	91
4.2	Synchronization	92
4.2.1	Frequency-Nonselective Time-Variant Channel	92
4.2.2	Frequency-Selective Time-Variant Channel	100
4.3	Channel Estimation	105
4.3.1	CE for a Single Transmit Antenna	105
4.3.2	CE for Multiple Transmit Antennas	110
4.4	Data Detection	113
4.5	Estimating Correlations	115
4.6	Summary	117

5 Single-Input-Multiple-Output (SIMO)	119
5.1 Overview	119
5.2 Basic Receive Diversity	120
5.3 Beamforming	124
5.3.1 D&S-Beamforming	126
5.3.2 MMSE-Beamforming	130
5.4 Spatial Interpolation	134
5.5 Summary	137
6 Multiple-Input-Multiple-Output (MIMO)	139
6.1 Overview	139
6.2 BLAST	140
6.2.1 Basic Receive Diversity	140
6.2.2 D&S-Beamforming	141
6.2.3 MMSE-Beamforming	144
6.2.4 Spatial Interpolation	148
6.3 Alamouti's Space Time Block Code	149
6.3.1 Basic Receive Diversity	149
6.3.2 D&S-Beamforming	151
6.3.3 MMSE-Beamforming	154
6.3.4 Spatial Interpolation	156
6.4 Summary	158
7 Summary	161
Appendix	165
A.1 Antenna-wise Correlation	165
A.1.1 Beamforming	166
A.1.2 Spatial Interpolation	167
A.2 Frequency Domain Correlation	169
A.2.1 Omnidirectional Antennas, Basic Receive Diversity	169
A.2.2 Beamforming	170
A.2.3 Spatial Interpolation	171
A.3 Definition of SNR and E_b/N_0	173
A.4 Mean Frequency Offset for Beamforming	174
A.5 Doppler Spread induced Intercarrier Interference	175
A.5.1 Mathematical Description for SISO	175
A.5.2 ICI-Distribution	178

Symbols and abbreviations	181
Literature	189
Index	201