



Lehrstuhl für Netzwerktheorie
und Signalverarbeitung



Forschungsberichte

Herausgeber: Prof. Dr. techn. Josef A. Nossek

Felix Antreich

**Array Processing and Signal Design for
Timing Synchronization**

Shaker Verlag

Berichte aus dem Lehrstuhl für Netzwerktheorie und
Signalverarbeitung der Technischen Universität München

Felix Antreich

**Array Processing and Signal Design
for Timing Synchronization**

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.: München, Techn. 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 978-3-8440-0373-4

ISSN 1433-1446

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

Array Processing and Signal Design for Timing Synchronization

Felix Antreich

Vollständiger Abdruck der von der Fakultät für Elektrotechnik und Informationstechnik der Technischen Universität München zur Erlangung des akademischen Grades eines
Doktor-Ingenieurs
genehmigten Dissertation.

Vorsitzender: Univ.-Prof. Dr. sc. nat. Christoph-Georg Günther
Prüfer der Dissertation:

1. Univ.-Prof. Dr. techn. Josef A. Nossek
2. Prof. Gonzalo Seco-Granados,
Universitat Autònoma de Barcelona (UAB) / Spanien

Die Dissertation wurde am 20.01.2011 bei der Technischen Universität München eingereicht und durch die Fakultät für Elektrotechnik und Informationstechnik am 04.07.2011 angenommen.

Acknowledgements

I am deeply grateful to my supervisor Prof. Josef A. Nossek for his kind and lasting support, all the valuable discussions, and especially for posing the right questions at the right time. I also would like to thank Prof. Gonzalo Seco-Granados not only for being the second reviewer of the thesis, but also for the sustained and fruitful collaboration we had in the past years, and for hosting several wonderful visits to Universitat Autònoma de Barcelona (UAB). Furthermore, I want to thank Prof. Christoph Günther for serving as the chairman of the dissertation committee and for his constant encouragement of my work at the Institute for Communications and Navigation of the German Aerospace Center (DLR).

I want to express special thanks to Prof. A. Lee Swindlehurst for our productive collaboration, the many valuable discussions, and for hosting my stay at the University of California, Irvine (UCI) in 2010, which was a great experience. Furthermore, I would like to express my gratitude to Jean-Luc Issler for our collaboration, instructive discussions, and for hosting my stay at Centre National d'Etudes Spaciales (CNES) in 2008.

I would like to thank my colleagues Mario Castañeda, Amine Mezghani, Hans Brunner, Leo Gomes Baltar, and Michel Ivrlač of the Institute for Circuit Theory and Signal Processing of the Technische Universität München (TUM) for all their help, important discussions, suggestions, and all the fun we had. I want to express special thanks to Frank Dietrich for the helpful discussions and suggestions.

Additionally, I would like to thank all my colleagues of the Institute for Communications and Navigation of DLR for their support and the collaborative atmosphere. Especially, I am deeply grateful to Oriol Esbri-Rodriguez and Marcos Vinícius Thomas Heckler for their friendship and encouragement throughout all these years.

I owe deep gratitude to my wife Eliane and to my family who have supported me with their love and commitment at all times. Querida Nane, este trabalho é dedicado a você!!

Munich, August 2011

Felix Antreich

Contents

Preface	1
1. Synchronization Array Signal Processing	3
1.1 Motivation	3
1.2 Overview and Contributions	5
1.3 Data Model	6
1.3.1 Structured Model	9
1.3.2 Unstructured Model	10
1.4 Maximum Likelihood (ML) Estimation	11
1.5 Space-Alternating Generalized Expectation Maximization (SAGE)	13
1.5.1 Structured Model	20
1.5.2 Unstructured Model	22
1.6 Extended Invariance Principle (EXIP)	24
1.6.1 Complex Formulation of the DOA Estimation Problem	30
1.6.2 Solution for Uniform Linear Arrays	32
1.6.3 Robustness to Calibration Errors	36
1.6.4 DOA Estimation with Unitary ESPRIT	38
1.7 Simulation Results	39
1.7.1 Decision on LOSS	40
1.7.2 Resolution Capability of the Spatially Structured and Unstructured Model	41
1.7.3 Scenario A	49
1.7.4 Scenario B	53
1.8 Summary and Conclusions	57
2. Signal Design for Timing Synchronization	59
2.1 Motivation	59
2.2 Overview and Contributions	61
2.3 System Model	62
2.4 Statement of the Problem	63
2.4.1 Synchronization Accuracy	64
2.4.2 Time Concentration	65
2.4.3 Smooth Cut-Off	67
2.4.4 Interchip Interference (ICI), Intra and Inter System Multiple Access Interference (MAI)	67

2.4.5	Multi-Objective Optimization Problem	70
2.5	Prolate Spheroidal Wave Functions (PSWF)	73
2.6	Parametric Nonlinear Bi-Objective Optimization Problem	79
2.7	Pareto optimal Set and Final Solutions	83
2.7.1	Time-Bandwidth Product $\varrho = 0.75$ without MAI-R	84
2.7.2	Time-Bandwidth Product $\varrho = 1$ without MAI-R	92
2.7.3	Time-Bandwidth Product $\varrho = 2$ without MAI-R	97
2.7.4	Time-Bandwidth Product $\varrho = 1$ with MAI-R	102
2.8	Summary and Conclusions	107
Appendix		109
A1	Pseudo Random (PR) Sequences and Pulse Shapes	109
A1.1	Rectangular Chip Pulse Shape	109
A1.2	Binary Offset Carrier (BOC) Signals	112
A2	Cramer-Rao Lower Bound (CRLB)	115
A2.1	Structured Model	116
A2.2	Unstructured Model	118
A3	Structure of (1.144)	122
A4	Proof of Theorem 5	123
A5	Matrix Operators	126
A5.1	Hadamard-Schur Product	126
A5.2	Kronecker Product	126
A5.3	Khatri-Rao Product	126
A5.4	Vec operator	126
A6	List of Used Symbols	127
A6.1	List of Used Symbols in Chapter 1	127
A6.2	List of Used Symbols in Chapter 2	131
A7	List of Used Acronyms	133
Bibliography		135