

Foundations in Signal Processing, Communications and Networking

Volume 22

Series editors

Holger Boche, Technische Universität München, München, Germany

Rudolf Mathar, ICT cubes, RWTH Aachen University, Aachen, Germany

Wolfgang Utschick, Technische Universität München, München, Germany

This book series presents monographs about fundamental topics and trends in signal processing, communications and networking in the field of information technology. The main focus of the series is to contribute on mathematical foundations and methodologies for the understanding, modeling and optimization of technical systems driven by information technology. Besides classical topics of signal processing, communications and networking the scope of this series includes many topics which are comparably related to information technology, network theory, and control. All monographs will share a rigorous mathematical approach to the addressed topics and an information technology related context.

More information about this series at <http://www.springer.com/series/7603>

Andreas Gründinger

Statistical Robust
Beamforming for Broadcast
Channels and Applications
in Satellite Communication

 Springer

Andreas Gründinger
Ergolding
Bayern, Germany

ISSN 1863-8538 ISSN 1863-8546 (electronic)
Foundations in Signal Processing, Communications and Networking
ISBN 978-3-030-29577-6 ISBN 978-3-030-29578-3 (eBook)
<https://doi.org/10.1007/978-3-030-29578-3>

© Springer Nature Switzerland AG 2020

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

*To my family—thanks for always being there
for me and for the smiling faces after a walk.*

Preface

Reliable data access within wireless networks gains importance for an increasing number of applications in the age of autonomous vehicles and latency sensitive communication. Transmit beamforming is seen as the key technology of modern communication systems for simultaneous transmission to a growing number of receivers in the same frequency bands. While ideal beamforming spatially separates the received data at the mobile devices, practical transmit limitations and noise-prone estimation of the unknown channel result in inevitable interference and unwanted data losses. The book addresses these issues. It provides robust formulations that take into account the statistical channel properties and, thus, enable reliable data services for mobiles, e.g., phones and even cars, in future terrestrial and satellite communication (SatCom) systems that are sensitive to data losses.

Therefore, this book is for readers with interest in modern physical-layer beamforming and/or robust optimization techniques. The subject overview and classification of the average and probability restrictions and the presentation of closed-form expressions besides novel and known approximations is one strength of the work. Another strength is that the introduced approximations for the ergodic data rate and the probability for data losses provide also structural information about the original problem. These bounds especially also enable testing feasibility for given target data demands, analyzing the infinite transmit power limit, and transforming the downlink beamformer design task into an uplink filter computation and power allocation. The downlink-uplink duality framework covers unequal demands and existing dualities from literature as special cases. By applying the approximations for SatCom, where interference and channel fading are the main limitations, a fully adaptive beamformer optimization for up to a hundred receivers was possible.

Ergolding, Germany
May 2018

Andreas Gründinger

Acknowledgments

Working at the Institute for Methods of Signal Processing toward recent research in multiuser MIMO communication was an inspiring time. I thank all those who accompanied me during these exciting years.

I am deeply grateful to my adviser, Prof. Wolfgang Utschick, for his guidance from being my mentor in the master's program until now, introducing me to so many interesting areas in signal processing, and for the confidence which he always had in me. I also want to express my sincere gratitude to Michael Joham for guiding my steps as a doctoral student, the effort he has put into correcting my first publications, and the shared insights in MIMO systems. This work and the collaborations with the German Aerospace Center and the University of A Coruña would not have been possible without their encouragement and commitment.

I would also like to express my sincere gratitude to Prof. Luis Castedo Ribas for the opportunity to visit A Coruña, accepting to examine the thesis, and serve in the examination committee. This work has benefited from the collaboration with him and the discussions with his doctoral student José Pablo González Coma.

Many thanks to all the colleagues at the institute for coauthoring papers and for the valuable discussions, constructive criticisms, and friendship.

Furthermore, I would like to thank the Deutsche Forschungsgemeinschaft (DFG) for supporting the research to this work under funds Jo 724/1-1, Jo 724/1-2, and Jo 724/2-1 and Qualcomm for the European Innovation Fellowship Award in 2012.

My warmest thanks go to my family, my wife, and our beloved kids for their understanding and patience.

Introduction

Modern communication systems use physical-layer beamforming for serving a continuously growing number of mobile receivers. The aim is to exploit multipath propagation in wireless communication for simultaneous and interference-free data transmission from one multi-antenna transmitter to multiple receivers. Practical limitations for the dynamic range of the amplifiers and erroneous transmitter channel state information (CSI), e.g., due to the varying environment and noise-prone channel estimations, make interference-free transmission inefficient.

To ensure reliable data transmission, beamformers are designed either to achieve the receivers' quality of service (QoS) demands or to maximize their data rate relative to the demands. For imperfect CSI, a careful choice of the performance metric is crucial. Otherwise, transmission can be subject to frequent data loss (outages). For fast-changing channel conditions, demands in data rate shall naturally be satisfied on average, while the probability for the outage event shall be limited for slower changes.

The goal of this work is to provide conservative and efficient solutions for the so obtained statistically robust optimizations and applications to downlink satellite communication (SatCom). The bases are the theory of interference functions, convex conic programming, and Lagrangian duality. Two imperfect CSI models are distinguished the additive Gaussian error model and scalar multiplicative errors.

Multiplicative channel errors essentially enhance the noise power. This enables beamformer solutions that are tractable for SatCom with a hundred of terminals and spotbeams. For additive channel errors, the average rate maximization is analyzed by a minimization of the maximum mean square error between the transmit and receive signals. The solutions benefit from the provided uplink-downlink duality for general conic power limitations. The duality framework is sufficiently general to analyze the effects of practical power restrictions for SatCom. Outage robust beamforming also relies on conservative approximations for the probability constraints. Such formulations either restrict the channel error to reside

in a predefined uncertainty set or are based on concentration inequalities. Two new formulations are analyzed in this context. The resulting solutions outperform some relevant results from the literature. Applications in mobile SatCom employed a further approximation to separate the outages due to rain fading and multipath scattering from each other.

Zusammenfassung

Moderne Funkkommunikationssysteme verwenden Beamforming im Physical-Layer, um eine steigende Zahl mobiler Endgeräte zu bedienen. Ziel ist es, die räumliche Mehrwegeausbreitung in der drahtlosen Funkkommunikation zur gleichzeitigen und interferenzfreien Übertragung an mehrere Empfänger zu nutzen. Interferenzfreie Übertragung ist in realen Systemen jedoch häufig ineffizient. Grund hierfür ist die beschränkte Linearität von Leistungsverstärkern und fehlerhafte Kanalkenntnis am Sender als Folge der sich ändernden Umgebung und unzureichender Kanalschätzung.

Zur zuverlässigen Datenübertragung werden deshalb Beamforming-Verfahren eingesetzt, die entweder den Serviceanforderungen der Empfänger genügen oder die Datenraten relativ zu diesen Anforderungen maximieren. Entscheidend ist auch die Wahl der Metrik, um regelmäßig auftretende Datenverluste (Outages) zu beschränken. Für schnell veränderliche Übertragungskanäle sind die Anforderungen an die Datenraten im Mittel zu erfüllen, während für langsam veränderliche Kanäle die Wahrscheinlichkeit des Outage-Ereignisses begrenzt wird.

Ziel der Arbeit sind konservative Abschätzungen und effiziente Lösungen für die resultierenden Optimierungsprobleme und deren Anwendung in der Satellitenkommunikation. Mathematische Grundlagen für die entwickelten Algorithmen sind die Theorie der Interferenz Funktionen, konisch konvexe Optimierung und Lagrange Dualität. Zudem werden zwei Kanalmodelle unterschieden: das Standardmodell mit additivem Gauß'schen Fehler und ein Modell mit skalaren multiplikativen Fehlern.

Multiplikative Kanalfehler steigern hauptsächlich die Rauschleistung. Dies ermöglicht duale Fixpunktverfahren zur Berechnung des Beamforming für über hundert Antennen und Empfänger in der Satellitenkommunikation. Für additive Kanalfehler wird die Maximierung der mittleren Datenraten durch eine Minimierung des maximalen mittleren quadratischen Fehlers zwischen den Send- und Empfangssignalen approximiert. Lösungen dieses Problems profitieren von der eingeführten Uplink-Downlink Dualität mit konischen Nebenbedingungen. Damit werden die Effekte praxisnaher Leistungsbeschränkungen auf das Sendeverhalten analysiert. Bei Outage begrenzten Verfahren sind ebenfalls konservative Näherungen für die Wahrscheinlichkeitsnebenbedingungen erforderlich. Solche

Näherungen beschränken entweder Kanalfehler auf einen definierten Bereich oder basieren auf stochastischen Ungleichungen. Die Arbeit analysiert in diesem Zusammenhang zwei neue Formulierungen. Die daraus resultierenden Lösungen übertreffen dabei relevante Verfahren aus der Literatur. Bei Anwendungen für mobile Satellitenkommunikation werden neben den Kanalfehlern durch die Mehrwegeausbreitung noch Schwankungen in der Atmosphäre mit berücksichtigt.

Contents

1	Multi-User Downlink Communication	1
1.1	Gaussian Vector Broadcast Channel Model	5
1.2	Quality-of-Service Optimization and Rate Balancing	6
1.3	Solutions for Perfect Transmitter Channel Knowledge	9
1.4	Beamformer Design with Multiple Power Constraints	17
1.5	Outline of the Chapters and the Contributions	20
2	Models for Incomplete Channel Knowledge	29
2.1	Additive Error Models	30
2.2	Multiplicative Error Models	34
2.3	Multiplicative Approximations for Additive Fading	36
3	Precoder Design for Ergodic Rates with Multiplicative Fading	39
3.1	Closed-Form Rate Expressions	41
3.2	Lower and Upper Rate Bounds	42
3.3	Quality-of-Service Feasibility Region	52
3.4	Post-Processing Power Allocation	55
3.5	Sequential Approximation Strategy	58
3.6	Branch and Bound Method	65
3.7	Numerical Optimization Results for Ergodic Rates	67
4	Mean Square Error Transceiver Design for Additive Fading	77
4.1	Mean Square Error Based Rate Bounds	79
4.2	Closed-Form Mean Square Error Expressions	80
4.3	Quality-of-Service Optimization	83
4.4	Quality-of-Service Feasibility Region	96
4.5	Average Mean Square Error Balancing	98
4.6	Ergodic Rate Balancing Approximations	110
4.7	Numerical Results for Mean Square Error Optimizations	112

- 5 Outage Constrained Beamformer Design** 127
 - 5.1 Chance-Constrained Optimization 128
 - 5.2 Multiplicative Fading Example 133
 - 5.3 Outage Probability Computation for Additive Fading 136
 - 5.4 Power Allocation and Feasibility for Fixed Beamforming 137
 - 5.5 Robust Uncertainty Reformulations 143
 - 5.6 Tractable Bounds with Concentration Inequalities 149
 - 5.7 Numerical Results for Chance-Constrained Optimization 155
- 6 Applications in Satellite Communication** 171
 - 6.1 Satellite Channel Characteristic 172
 - 6.2 Balancing Optimization for Satellite Communication 177
 - 6.3 Ergodic Rate and Mean Square Error Optimization 178
 - 6.4 Results for Rate and Mean Square Error Balancing 179
 - 6.5 Outage Constrained Rate Optimization 186
 - 6.6 Results for Outage Constrained Rate Balancing 190
- 7 Summary, Conclusions, and Open Research** 199
 - 7.1 Research Results for Robust Beamforming 199
 - 7.2 Other Research on Robust Beamforming 202
- A Additional Information** 205
 - A.1 Basic Properties of the Rate Based Optimizations 205
 - A.2 Interference Functions and Property Preserving Transforms 206
 - A.3 Ergodic Rate Bounds for Multiplicative Fading 210
 - A.4 Feasible QoS Region with Ergodic Rate Bounds 212
 - A.5 On Uniqueness of the QoS Optimal Power Allocation 213
 - A.6 Duality for Second Order Cone Programs 214
 - A.7 Properties of the Dual Uplink MSE Optimizations 220
 - A.8 Some Distribution and Quantile Functions 222
- References** 227
- Index** 243

Acronyms

The following acronyms and abbreviations are used throughout this work:

ACS	Alternating convex search
BB	Branch and bound
BC	Broadcast channel
CDF	Cumulative distribution function
CSI	Channel state information
dB	Decibel
DPC	Dirty paper coding
EVD	Eigenvalue decomposition
FDD	Frequency division duplex
FSL	Free space loss
GEO	Geostationary earth orbit
GP	Geometric program
IFC	Interference channel
i.i.d.	Identically and independent distributed
KKT	Karush–Kuhn–Tucker
LMI	Linear matrix inequality
LoS	Line of sight
LP	Linear program
LPM	Lorentz positive map
MAC	Multiple access channel
MF	Matched filter
MIMO	Multiple-input multiple-output
ML	Maximum likelihood
MMSE	Minimum mean square error
MRT	Maximum ratio transmission
MSE	Mean square error
PCLI	Probabilistically constrained linear inequality
PDF	Probability density function
PG	Projected gradient

PtP	Point-to-point
QCP	Quadratically constrained program
QF	Quantile function
QoS	Quality of service
RB	Rate balancing
RF	Radio frequency
RZF	Regularized zero-forcing
SatCom	Satellite communication
SCS	Sequential convex search
SDC	Semidefinite cone
SDP	Semidefinite program
SDR	Semidefinite relaxation
SINR	Signal-to-interference-plus-noise ratio
SIR	Signal-to-interference ratio
SMSE	Sum mean square error
SNR	Signal-to-noise ratio
SOC	Second-order cone
SOCP	Second-order cone program
SQ	Scalar quantization
TDD	Time division duplex
THP	Tomlinson–Harashima precoding
VQ	Vector quantization
WSMSE	Weighted sum mean square error
ZF	Zero-forcing

Nomenclature

The basic symbols and operators used throughout this work are listed below. Generally, boldface lower case is used for column vectors and upper case for matrices. Other symbols, functions, or operations are defined at the required position within the text.

$ \cdot $	Absolute value
$\ \cdot\ _2$	Euclidean norm, i.e., L^2 norm
$\ \cdot\ _F$	Frobenius norm
\otimes	Kronecker product
$(\cdot)^*$	Complex conjugate
$(\cdot)^T$	Transpose
$(\cdot)^H$	Complex conjugate transpose
$(\cdot)^{-1}, (\cdot)^\dagger$	Inverse, pseudo-inverse
$(\cdot)_{\setminus\{k\}}$	All columns except for the k -th one
$\text{Re}(\cdot)$	Real part
$\text{Im}(\cdot)$	Imaginary part
$\text{tr}(\cdot)$	Trace
$\text{diag}(\cdot)$	Diagonal matrix with scalars as diagonal entries
$\text{bdiag}(\cdot)$	Block diagonal matrix with matrices as diagonal entries
$\text{vec}(\cdot)$	Column-stacking operation
$\text{det}(\cdot)$	Determinant operation
$\text{rank}\{\cdot\}$	Rank of a vector or matrix
$\text{range}\{\cdot\}$	Range space of a linear map
$\text{null}\{\cdot\}$	Kernel or nullspace of a linear map
j	Imaginary number, i.e., $\sqrt{-1}$
e	Euler's number, i.e., $e \approx 2.71828$
γ	Euler–Mascheroni constant, i.e., $\gamma \approx 0.57722$

0	Zero or all-zero vector/matrix of appropriate dimension
1	One or all-ones vector/matrix of appropriate dimension
\mathbf{e}_i	Canonical unit-norm vector with one at the i -th position
I	Identity matrix (operation)
$\exp(\cdot)$	Exponential function
$\ln(\cdot)$	Natural logarithm
$\log_2(\cdot)$	Binary logarithm
$E_1(\cdot)$	Exponential integral function $E_1(x) = \int_x^\infty \frac{\exp(-t)}{t} dt$
$\Gamma(\cdot)$	Gamma function, i.e., $\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt$
$E[\cdot]$	Expectation operation
$\Pr(\cdot)$	Probability operation
$f_z(\cdot)$	Probability density function of a random variable z
$F_z(\cdot)$	Cumulative distribution function of z , i.e., $F_z(x) = \Pr(z \leq x)$
min	Minimize (also minimum of a set of two or more scalars)
max	Maximize (also maximum of a set of two or more scalars)
arg min	Minimizing decision variables of the problem
arg max	Maximizing decision variables of the problem
s.t.	Subject to the constraints
\mathbb{R}, \mathbb{R}_+	Real and nonnegative numbers (with scalar inequalities $>, \geq, <, \leq$)
\mathbb{C}	Complex numbers
\mathbb{R}_+^N	Vectors with nonnegative entries, $\mathbb{R}_+ = \{\mathbf{x} \in \mathbb{R}^N : x_i \geq 0, i = 1, \dots, N\}$
\mathcal{L}^N	Lorentz cone, second-order cone, $\mathcal{L}^N = \{(y, \mathbf{x}) \in \mathbb{R}_+ \times \mathbb{C}^N : \ \mathbf{x}\ _2 \leq y\}$
\mathcal{H}^N	Hermitian matrices, $\mathcal{H}^N = \{\mathbf{A} \in \mathbb{C}^{N \times N} : \mathbf{A} = \mathbf{A}^H\}$
\mathcal{H}_+^N	Positive semidefinite matrices, $\mathcal{H}_+^N = \{\mathbf{A} \in \mathbb{C}^{N \times N} : \mathbf{x}^H \mathbf{A} \mathbf{x} \geq 0, \mathbf{x} \in \mathbb{C}^N\}$
$\mathbf{x} \geq \mathbf{y}$ ($\mathbf{x} > \mathbf{y}$)	Elementwise (strict) inequality, $x_i \geq y_i$ ($x_i > y_i$), $i = 1, \dots, N$
$\mathbf{x} \leq \mathbf{y}$ ($\mathbf{x} < \mathbf{y}$)	Elementwise (strict) inequality, $x_i \leq y_i$ ($x_i < y_i$), $i = 1, \dots, N$
$\mathbf{X} \succeq \mathbf{Y}$ ($\mathbf{X} \succ \mathbf{Y}$)	$\mathbf{X} - \mathbf{Y}$ is positive semidefinite (definite)
$\mathbf{X} \preceq \mathbf{Y}$ ($\mathbf{X} \prec \mathbf{Y}$)	$\mathbf{Y} - \mathbf{X}$ is positive semidefinite (definite)
\mathcal{N}	Real Gaussian distribution
$\mathcal{N}_{\mathbb{C}}$	Circularly symmetric complex Gaussian distribution
\mathcal{U}	Uniform distribution
\mathcal{X}_n^2	(Non-)central chi-squared distribution of degree n
\mathcal{E}	Exponential distribution

The notations $\mathbf{x} \geq \mathbf{0}$ and $\mathbf{x} \in \mathbb{R}_+^N$ as well as $\mathbf{X} \geq \mathbf{0}$ and $\mathbf{X} \in \mathcal{H}_+^N$ are equivalent and define a nonnegative vector $\mathbf{x} \in \mathbb{R}^N$ and a semidefinite matrix $\mathbf{X} \in \mathcal{H}^N$, respectively.

List of Figures

Fig. 1.1	Annual publications on “robust beamforming” at IEEEExplore	3
Fig. 3.1	Constraint function for ergodic rates and its bounds	59
Fig. 3.2	Convergence behaviour of the sequential convex search	62
Fig. 3.3	Minimum transmit power for the QoS optimization with ergodic rates.....	69
Fig. 3.4	Results of the RB optimization with ergodic rates	71
Fig. 3.5	Maximum ergodic RB result for increased system dimensions	72
Fig. 3.6	QoS and RB results with the sequential convex approximation strategy	73
Fig. 3.7	Histogram of the iterations until convergence	74
Fig. 3.8	Average ergodic RB results with multiplicative Rician fading	75
Fig. 4.1	Inner bounds for the MSE feasibility region with imperfect CSI	99
Fig. 4.2	Difference between MSE, SINR, and rate balancing for distinct targets.....	101
Fig. 4.3	Average MSE balancing result with per-antenna power constraints	115
Fig. 4.4	Inactive power constraints for the alternating convex search results.....	116
Fig. 4.5	Weighted sum MSE balancing results with per-antenna constraints	117
Fig. 4.6	Empirical CDFs of the number of iterations until convergence	118
Fig. 4.7	Performance and CDF of the outer iterations until convergence ...	119
Fig. 4.8	Sum MSE minimization results for various power constraints	120
Fig. 4.9	Largest per-antenna power for the optimization with a sum constraint	121
Fig. 4.10	Number iterations for the sum MSE minimization.....	122
Fig. 4.11	Approximate ergodic RB results with per-antenna constraints	124
Fig. 5.1	Effects of post-processing on the minimal transmit power	156

Fig. 5.2	Outage probability after chance-constrained QoS optimization	157
Fig. 5.3	Minimal transmit power after chance-constrained QoS optimization	159
Fig. 5.4	Minimal transmit power of the QoS optimization with $K = 3, 4$	161
Fig. 5.5	Outage probability after QoS optimization with $K = 2, 3, 4$	162
Fig. 5.6	Performance of the chance constrained RB optimization.....	164
Fig. 5.7	Performance of the RB optimization with $K = 3, 4$	166
Fig. 5.8	Outage probability at the RB solution	167
Fig. 5.9	Performance of the MSE approximations for outage constrained RB.....	169
Fig. 6.1	Exemplary spotbeam structure for covering Europe	173
Fig. 6.2	Angular model for multi-spotbeam satellite communication	174
Fig. 6.3	Ergodic rate balancing performance for satellite communication ..	180
Fig. 6.4	Average MSE balancing results for S-band satellite communication.....	182
Fig. 6.5	Influence of various power limitations on satellite communication.....	184
Fig. 6.6	Dynamic per-antenna power range for sum constrained optimizations	185
Fig. 6.7	Outage restricted satellite communication with rain and Rician fading	191
Fig. 6.8	Outage constrained satellite communication with 7 spotbeams	192
Fig. 6.9	Optimized division of the outage probability for rain and Rician fading	193
Fig. 6.10	Optimized division with equal and distinct outage probabilities ...	194
Fig. 6.11	Solution probability division between rain and Rician fading	195
Fig. 6.12	Achieved outage bounds for conservative beamforming	196
Fig. 6.13	Achieved outage bounds under varying fading conditions	196

List of Tables

Table 1.1	SINR uplink–downlink duality results for the vector broadcast channel.....	18
Table 3.1	Effective noise variance and offset for bounds on the ergodic rate	44
Table 4.1	Targets for MSE balancing with per-receiver constraints	114
Table 5.1	Rate targets for chance-constrained QoS and RB optimization	163
Table 5.2	Percentage of rank-one solutions for the SDR approximation	168
Table 6.1	Link budget parameters of the (mobile) terminal SatCom system	174