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Andreas Gründinger

Statistical Robust Beamforming for Broadcast Channels and Applications in Satellite Communication

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Andreas Gründinger
Ergolding
Bayern, Germany

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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
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Andreas Gründinger

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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 Sende- 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

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.

$\lvert \cdot \rvert$	Absolute value
$\lVert \cdot \rVert_2$	Euclidean norm, i.e., L^2 norm
$\lVert \cdot \rVert_{\mathrm{F}}$	Frobenius norm
$\otimes$	Kronecker product

$(\cdot)^*$	Complex conjugate
$(\cdot)^{\mathrm{T}}$	Transpose
$(\cdot)^{\mathrm{H}}$	Complex conjugate transpose
$(\cdot)^{-1}, (\cdot)^{\dagger}$	Inverse, pseudo-inverse
$(\cdot)_{\setminus\{k\}}$	All columns except for the k-th one

$\mathrm{Re}(\cdot)$	Real part
$\mathrm{Im}(\cdot)$	Imaginary part
$\mathrm{tr}(\cdot)$	Trace
$\mathrm{diag}(\cdot)$	Diagonal matrix with scalars as diagonal entries
$\mathrm{bdiag}(\cdot)$	Block diagonal matrix with matrices as diagonal entries
$\mathrm{vec}(\cdot)$	Column-stacking operation
$\det(\cdot)$	Determinant operation
$\mathrm{rank}\{\cdot\}$	Rank of a vector or matrix
$\mathrm{range}\{\cdot\}$	Range space of a linear map
$\mathrm{null}\{\cdot\}$	Kernel or nullspace of a linear map

j	Imaginary number, i.e., $\sqrt{-1}$
e	Euler's number, i.e., $\mathrm{e} \approx 2.71828$
γ	Euler–Mascheroni constant, i.e., $\gamma \approx 0.57722$

$\mathbf{0}$	Zero or all-zero vector/matrix of appropriate dimension
$\mathbf{1}$	One or all-ones vector/matrix of appropriate dimension
$\mathbf{e}_i$	Canonical unit-norm vector with one at the i-th position
$\mathbf{I}$	Identity matrix (operation)

$\exp(\,\cdot\,)$	Exponential function
$\ln(\,\cdot\,)$	Natural logarithm
$\log_2(\,\cdot\,)$	Binary logarithm
$\mathrm{E}_1(\,\cdot\,)$	Exponential integral function $\mathrm{E}_1(x) = \int_x^\infty \frac{\exp(-t)}{t}\,\mathrm{d}t$
$\Gamma(\,\cdot\,)$	Gamma function, i.e., $\Gamma(x) = \int_0^\infty t^{x-1}\mathrm{e}^{-t}\,\mathrm{d}t$

$\mathrm{E}[\,\cdot\,]$	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, $\mathbb{R}_+ = \{\boldsymbol{x} \in \mathbb{R}^N : x_i \geq 0, i = 1, \ldots, N\}$
$\mathcal{L}^N$	Lorentz cone, second-order cone, $\mathcal{L}^N = \{(y, \boldsymbol{x}) \in \mathbb{R}_+ \times \mathbb{C}^N : \|\boldsymbol{x}\|_2 \leq y\}$
$\mathcal{H}^N$	Hermitian matrices, $\mathcal{H}^N = \{\boldsymbol{A} \in \mathbb{C}^{N\times N} : \boldsymbol{A} = \boldsymbol{A}^{\mathrm{H}}\}$
$\mathcal{H}_+^N$	Positive semidefinite matrices, $\mathcal{H}_+^N = \{\boldsymbol{A} \in \mathbb{C}^{N\times N} : \boldsymbol{x}^{\mathrm{H}}\boldsymbol{A}\boldsymbol{x} \geq 0, \boldsymbol{x} \in \mathbb{C}^N\}$

$\boldsymbol{x} \geq \boldsymbol{y}$ ($\boldsymbol{x} > \boldsymbol{y}$)	Elementwise (strict) inequality, $x_i \geq y_i$ ($x_i > y_i$), $i = 1, \ldots, N$
$\boldsymbol{x} \leq \boldsymbol{y}$ ($\boldsymbol{x} < \boldsymbol{y}$)	Elementwise (strict) inequality, $x_i \leq y_i$ ($x_i < y_i$), $i = 1, \ldots, N$
$\boldsymbol{X} \succeq \boldsymbol{Y}$ ($\boldsymbol{X} \succ \boldsymbol{Y}$)	$\boldsymbol{X} - \boldsymbol{Y}$ is positive semidefinite (definite)
$\boldsymbol{X} \preceq \boldsymbol{Y}$ ($\boldsymbol{X} \prec \boldsymbol{Y}$)	$\boldsymbol{Y} - \boldsymbol{X}$ 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 $\boldsymbol{x} \geq \mathbf{0}$ and $\boldsymbol{x} \in \mathbb{R}_+^N$ as well as $\boldsymbol{X} \succeq \mathbf{0}$ and $\boldsymbol{X} \in \mathcal{H}_+^N$ are equivalent and define a nonnegative vector $\boldsymbol{x} \in \mathbb{R}^N$ and a semidefinite matrix $\boldsymbol{X} \in \mathcal{H}^N$, respectively.

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