Order Statistics in Wireless Communications

Diversity, Adaptation, and Scheduling in MIMO and OFDM Systems

Covering fundamental principles through to practical applications, this self-contained guide describes indispensable mathematical tools for the analysis and design of advanced wireless transmission and reception techniques in MIMO and OFDM systems. The analysis-oriented approach develops a thorough understanding of core concepts, and discussion of various example schemes shows how to apply these concepts in practice. The book focuses on techniques of advanced diversity combining, channel adaptive transmission, and multiuser scheduling, the foundations of future wireless systems for the delivery of highly spectrum-efficient wireless multimedia services. Bringing together conventional and novel results from a wide variety of sources, it will teach you to accurately quantify trade-offs between performance and complexity for different design options so that you can determine the most suitable design choice based on specific practical implementation constraints.

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To
Our Families

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Preface

Order statistics is an important sub-discipline of statistical theory and finds applications in a vast variety of fields, with life science as the most notable example [1]. Over the years, order statistics has made an increasing number of appearances in design and analysis wireless communication systems, primarily because of the simple but effective engineering principle – "pick the best". For example, the diversity combining technique is an effective solution to improve the performance of wireless communication systems operating over fading channels by generating differently faded replicas of the same information-bearing signal. Selection combining (SC) [2, 3], which selects the replica with the best quality for further processing, is an attractive practical combining scheme and has been researched extensively in the literature. The performance analysis of the SC scheme entails the distribution functions of the largest random variables among multiple ones, which is available in conventional order statistics literature.

More recently, order statistics has also found application in the analysis and design of many emerging wireless transmission and reception techniques, such as advanced diversity combining techniques, channel adaptive transmission techniques, and multiuser scheduling techniques. These techniques are becoming the essential building blocks of future wireless systems for the delivery of multimedia services with high spectrum efficiency [4]. In particular, order statistics results have allowed for the accurate quantification of the trade-off of performance versus complexity among different design options, which will greatly facilitate the applications of these technologies in future wireless systems. At the same time, these applications to wireless system analysis provide new incentives for the further development of order statistic theory. In fact, the study of advanced diversity combining techniques has led to some new order statistics results [5, 6], in terms of the joint distribution functions of linear functions of ordered random variables.

The primary goal of this book is to provide a comprehensive and coherent treatment of the general subject of order statistics in wireless communications. By collecting the relevant results in the literature in a unified fashion, the book will serve as a useful resource for students and researchers to further exploit the potential of order statistics in the analysis and design of advanced wireless transmission technologies. It is our sincere hope that the book will build a solid foundation for readers to further explore the potential of order statistics in advanced wireless communication research. We also believe that the new wireless

communication research problems will in turn stimulate the future evolution of order statistics theory, which will benefit the solution of research problems in other research fields.

Diversity, adaptation, and scheduling are becoming three essential concepts in wireless communications [4]. Diversity combining can effectively mitigate the deleterious fading effect through the generation and exploration of differently faded replicas of the same information signal. Channel adaptation can acheive highly spectral and power-efficient transmission over fading channels by matching the transceiver parameters properly with the prevailing fading channel condition. Multiuser scheduling can explore the multiuser diversity gain inherent in multiuser systems for overall capacity benefit. These fundamental design principles manifest themselves in various transmission and reception technologies for both narrowband and wideband systems with single-antenna or multiple-antenna scenarios. In particular, both multiuser multiple-input–multiple-output (MIMO) systems and orthogonal frequency division multiple access (OFDMA) systems can apply user scheduling techniques to improve the overall system throughput.

Another goal of this book is to provide an in-depth analysis-oriented exposition of diversity combining, link adaptation, and user scheduling techniques. The uniqueness of our approach lies in the fact that for each design option of different techniques, we obtain the exact analytical expression of important performance metrics. Such analytical results build on accurate understanding of scheme design, careful statistical reasoning, and proper application of order statistics. Combined with the associated complexity quantification, the book will help foster a deep understanding of the underlying design principles and tradeoffs of different techniques. The readers will also benefit from the analytical methodologies, which may help them solve their specific research problem.

This book is intended for senior graduate students, researchers, and practising engineers in the field of wireless and mobile communications. Refs [4,7] may serve as suitable background references for this book. The material of this book has been used in a term-long graduate-level course on advanced wireless communications at the University of Victoria, Canada, and an intensive three-week short course at the Tsinghua University, China. It has proven to be an ideal venue for students to enhance their analytical skills as well as to expand their knowledge of advanced wireless transmission technologies.

The authors would like to acknowledge their current and past students, postdocs, and collaborators for their contributions in the works that have been included in this book. Specifically, the authors would like to thank Prof. Seyeong Choi, Prof. David Gesbert, Prof. Young-chai Ko, Prof. Geir Oien, Prof. Khalid A. Qaraqe, Dr. Peng Lu, Dr. Sung-Sik Nam, Dr. Ki-Hong Park, Dr. Lin Yang, Mr. Seung-Sik Eom, Mr. Noureddine Hamdi, Mr. Bengt Holter, and Mr. Le Yang. The authors want to thank Dr. Phil Meyler at Cambridge University Press whose remarkable talent identified the potential of this project. Finally, the valuable support from Ms. Sarah Finlay and Ms. Sabine Koch at Cambridge University Press during the preparation of the book is much appreciated.

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Notation

General notation

$\mathbf{A}^H$	Hermitian transpose of matrix $\mathbf{A}$
$\mathrm{BER}_n^{-1}(\cdot)$	the inverse BER operation
$< BER >$	overall bit error rate of adaptive transmission system
$\overline{BER}_n$	average error rate of modulation mode n
$\mathbf{E}[\cdot]$	statistical expectation
$E_1(\cdot)$	exponential integral function of first order
$F_\gamma(\cdot)$	cumulative distribution function of γ
$I_0(\cdot)$	modified Bessel function of zero order
$J_0(\cdot)$	Bessel function of zero order
$\mathcal{L}_s{}^{-1}(\cdot)$	inverse Laplace transform with respect to s
$\mathcal{M}_\gamma(\cdot)$	moment generating function of γ
$p_{X,Y}(\cdot)$	joint probability density function of X and Y
$p_{X\|Y=y}(x)$	conditional probability density function of X given Y is equal to y
$p_\gamma(\cdot)$	probability density function of γ
$P_b(E)$	bit error rate
$\overline{P}_b$	average bit error rate
$P_E(\gamma)$	instantaneous error probability for given SNR γ
$\overline{P}_E$	average error rate
$PL(d)$ dB	path loss at distance d in dB
P_{out}	outage probability
$\Pr[\cdot]$	probability of an event
$P_s(E)$	symbol error rate
$\overline{P}_s$	average symbol error rate
$Q(\cdot)$	Gaussian Q-function
$Q_1(\cdot,\cdot)$	Marcum Q-function
$\Re\{\cdot\}$	real part of a complex number
s^*	complex conjugate of s
$tr\{\cdot\}$	trace of a matrix
$\mathcal{U}(\cdot)$	unit step function
$\mathbf{x}$	vector $\mathbf{x}$ (bold face lowercase letter)
$\|\mathbf{x}\|^2$	norm square of vector $\mathbf{x}$

$\mathbf{X}$	matrix $\mathbf{X}$ (bold face capital letter)
$\dot{\alpha}$	time derivative of the process α
$\gamma_{l:L}$	lth largest one among total L SNR values
$\overline{\gamma}$	average received SNR
$\tilde{\gamma}$	normalized SNR by its average
Γ_i	sum of the first i largest ordered SNRs
$\Gamma_{i:j}$	sum of the i largest SNRs among j ones
$\Gamma(\cdot)$	Gamma function
$\Gamma(\cdot,\cdot)$	incomplete Gamma function
Ω	short-term average channel power gain

Abbreviations

AAP	average access probability
AAR	average access rate
AAT	average access time
ABA-CBBI	adaptive beam activation based on CBBI
AFL	average feedback load
AMDC	joint adaptive modulation and diversity combining
ASE	average spectrum efficiency
ASK	amplitude shift keying
AT-GSC	absolute threshold GSC
AWGN	additive white Gaussian noise
AWT	average waiting time
BBI	best beam index
BBSI	best beam SINR and index
BER	bit error rate
BS	base station
CBBI	conditional best beam index feedback
CDF	cumulative distribution function
CLT	central limit theorem
CSI	channel state information
DPC	dirty paper coding
EDF	exceedance distribution function
EGC	equal gain combining
GEV	generalized extreme-value
GSC	generalized selection combining
GSEC	generalized switch and examine combining
GSECps	GSEC with post-examine selection
GSMuS	generalized selection multiuser scheduling
GWC-ZFBF	greedy weight clique ZFBF
i.i.d.	independent and identically distributed

i.n.d.	independent and non-identical distributed
ISI	intersymbol interference
LCR	level crossing rate
LOS	line of sight
MEC-GSC	minimum estimation and combining GSC
MGF	moment generation function
MIMO	multiple-input–multiple-output
MISO	multiple-input–single-output
MRC	maximum ratio combining
MSE	mean square error
MS-GSC	minimum selection GSC
NT-GSC	normalized threshold GSC
OC	optimum combining
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OOBS	on–off based scheduling
OT-MRC	output threshold MRC
OT-GSC	output threshold GSC
PDF	probability density function
PMF	probability mass function
PSD	power spectral density
PSK	phase shift keying
QAM	quadrature amplitude modulation
QBBSI	BBSI schemes with quantized SINR feedback
QPSK	quadrature phase-shift keying
RMS	root mean square
RUB	random unitary beamforming
SBS	switched-based scheduling
SC	selection combining
SEC	switch and examine combining
SECps	switch and examine combining with post-examining selection
SHO	soft handover
SINR	signal to interference plus noise ratio
SNR	signal-to-noise ratio
SSC	switch and stay combining
STBC	space-time block code
SUP-ZFBF	successive projection ZFBF
TDD	time division duplexing
TDMA	time division multiple access
T-GSC	GSC with threshold test per branch
UWB	ultra wideband
WCDMA	wideband code division multiple access
ZFBF	zero-forcing beamforming