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978-0-521-19925-4 - Order Statistics in Wireless Communications: Diversity, Adaptation and Scheduling in MIMO and OFDM Systems

Hong-Chuan Yang, Mohamed-Slim Alouini

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## 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.

**Hong-Chuan Yang** is an Associate Professor in the Electrical and Computer Engineering Department at the University of Victoria, Canada. He has developed several mathematical tools for accurate performance evaluation of advanced wireless transmission technologies in fading environments, and his current research focuses on channel modeling, diversity techniques, system performance evaluation, cross-layer design, and energy-efficient communications.

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in MIMO and OFDM Systems

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CAMBRIDGE UNIVERSITY PRESS  
Cambridge, New York, Melbourne, Madrid, Cape Town,  
Singapore, São Paulo, Delhi, Tokyo, Mexico City  
  
Cambridge University Press  
The Edinburgh Building, Cambridge CB2 8RU, UK  
  
Published in the United States of America by Cambridge University Press, New York

[www.cambridge.org](http://www.cambridge.org)  
Information on this title: [www.cambridge.org/9780521199254](http://www.cambridge.org/9780521199254)

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First published 2011

Printed in the United Kingdom at the University Press, Cambridge

*A catalogue record for this publication is available from the British Library*

ISBN 978-0-521-19925-4 Hardback

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**To  
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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 achieve 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 trade-offs 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, post-docs, 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. Nouredine 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 $\mathbf{A}$                                |
| $\text{BER}_n^{-1}(\cdot)$   | the inverse BER operation                                                 |
| $\langle \text{BER} \rangle$ | overall bit error rate of adaptive transmission system                    |
| $\overline{\text{BER}}_n$    | 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 $\gamma$                              |
| $I_0(\cdot)$                 | 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 $\gamma$                                    |
| $p_{X,Y}(\cdot)$             | 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 $\gamma$                                  |
| $P_b(E)$                     | bit error rate                                                            |
| $\overline{P}_b$             | average bit error rate                                                    |
| $P_E(\gamma)$                | instantaneous error probability for given SNR $\gamma$                    |
| $\overline{P}_E$             | average error rate                                                        |
| $PL(d)$ dB                   | path loss at distance $d$ in dB                                           |
| $P_{\text{out}}$             | outage probability                                                        |
| $\text{Pr}[\cdot]$           | 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 $s$                                                  |
| $\text{tr}\{\cdot\}$         | 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 $\alpha$        |
| $\gamma_{l:L}$         | $l$ th largest one among total $L$ SNR values  |
| $\bar{\gamma}$         | average received SNR                           |
| $\tilde{\gamma}$       | normalized SNR by its average                  |
| $\Gamma_i$             | 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                      |
| $\Omega$               | 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              |
| OBS      | 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                                   |