MULTI-USER WIRELESS COMMUNICATION SYSTEMS WITH RATE CONSTRAINTS

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Abstract

In this thesis, we will make a comprehensive study on multi-user wireless communication systems where every user in the system must transmit a certain amount of information within each frame. This hard-fairness scenario is applicable to delay-sensitive services such as voice and video. We will discuss both the theoretical and practical aspects of multi-user wireless systems under such hard rate constraints. The main contributions of this thesis are listed below.

In the first contribution, the closed-form expressions are derived for the average unconstrained minimum transmitted sum power (MTSP) of multi-user single-input single-output (SISO) systems over multiple access channels (MACs) and broadcast channels (BCs). It is shown that significant performance gain, which is referred to as multi-user gain (MUG) in this thesis, can be achieved by allowing multi-user concurrent transmission. The MUG in SISO systems mainly comes from the near-far diversity among users and a large portion of MUG can be achieved with a small number of simultaneous users. The practical implementation aspect of multi-user SISO systems is also considered. We adopt interleave-division multiple-access (IDMA) as a platform and propose several power allocation methods to enhance the system performance. Both evolution and simulation results show that considerable MUG that is predicted in theory can indeed be achieved in practical environments.

In the second contribution, we extend the results for the SISO scenario to the multiple-input multiple-output (MIMO) scenario. We avoid the complicated computation in finding the exact unconstrained MTSP of multi-user MIMO systems for each channel realization by adopting bounding techniques and derive the closed-form expression for the corresponding asymptotical average unconstrained MTSPs. We point out that, besides the near-far diversity, MUG in MIMO systems also comes from direction diversity that is provided by multiple antennas at the base station (BS), and the number of antennas at the BS has a more significant effect on the system capacity than that at the user side. In the meanwhile, we propose a low-cost but asymptotically optimal technique, i.e., the maximum eigenmode beamforming (MEB) technique, to realize the aforementioned MUG in multi-user MIMO systems with practical coding.

In the third contribution, we consider the capacity analysis of cellular systems with various BS cooperation strategies. Based on the results in the first two contributions, some lower and upper bounds are derived for cellular systems with
full BS cooperation (FBSC) and partial signal utilization (PSU). We show that, similar to the single-cell case considered in the second contribution, the number of antennas at each BS still has a more significant effect on the capacity of cellular systems.

In the final contribution, we analyze the performance of multiple access systems with equal power allocation (EPA), i.e., controlling the received signal power of all users to the same level. The EPA scheme has much lower complexity than the general unequal power allocation (UPA) ones that have computational cost increasing rapidly with the number of users and must be implemented online for each channel realization. We study the feasibility and optimality of EPA and the corresponding system throughput (note that the throughput of a multiple access system with EPA is interference limited). We show that, although EPA is indeed sub-optimal in ideally coded systems, it can be optimal when practical coding is concerned, and the corresponding system throughput can be increased at the cost of some degree of distortion (e.g., a non-zero bit-error rate (BER) or frame-error rate (FER)). As for MIMO systems, we show that, provided that the MEB approach with EPA (i.e., MEB-EPA) is sufficiently good to achieve near-optimal performance when the number of users in concurrent transmission is large and the system sum rate is less than a certain threshold that increases approximately linearly with the number of receive antennas. Hence the throughput supportable by MEB-EPA can be very high provided that the receive antenna number is sufficiently large. Additionally, we also study the impact of imperfect channel state information (CSI) at the transmitter side (CSIT) on the performance of systems with EPA. We show that the EPA scheme is more robust to CSIT error than other alternatives such as TDMA, i.e., the former requires less additional power than the latter in combating the CSIT error to guarantee the same system performance as that without CSIT error.

In summary, this thesis presents a comprehensive study on multi-user wireless communication systems with rate constraints. Both analytical and simulation results show that non-orthogonal CDMA-type multi-user concurrent transmission (e.g., IDMA) is advantageous over the orthogonal ones (such as TDMA) in terms of MUG, complexity and robustness.
# Contents

Abbreviations vii

List of Symbols ix

1 Introduction 1

1.1 Background ................................. 1
    1.1.1 Brief History of Wireless Communication 1
    1.1.2 Multiple Access Techniques ................. 1
    1.1.3 Service Classification .................... 2

1.2 Motivation and Research Contributions ........ 3

1.3 List of Publications ........................ 4

2 Single-Input Single-Output Systems 7

2.1 System Model ................................ 7

2.2 Theoretical Analysis ......................... 8
    2.2.1 Minimum Transmitted Sum Power (MTSP) .... 8
    2.2.2 Average Unconstrained MTSP ............... 13
    2.2.3 Asymptotic Average Unconstrained MTSP .... 16
    2.2.4 Asymptotic Behavior Analysis ............. 18
    2.2.5 Multi User Gain (MUG) ................... 19
    2.2.6 Normalized MUG .......................... 21
    2.2.7 Unequal Rate Constraint .................. 22
    2.2.8 SISO BC ................................ 24
    2.2.9 A Brief Summary ......................... 25

2.3 Practical Implementation ....................... 26
    2.3.1 System Structures ....................... 27
    2.3.2 Performance Evaluation ................... 30
    2.3.3 Power Allocation ........................ 34

2.4 Appendix ................................ 50
    2.4.1 Proof of Theorem 2.2 ..................... 50
    2.4.2 Duality between SISO MACs and BCs ....... 52

3 Extension to Multiple-Input Multiple-Output Systems 54

3.1 System Model ............................... 54

3.2 Maximum Eigenmode Beamforming ............... 55
3.3 Asymptotic Optimality of MEB ........................................... 60
  3.3.1 A Lower Bound .................................................. 60
  3.3.2 Asymptotic Average Unconstrained MTSP .................... 61
  3.3.3 Examples .......................................................... 62
3.4 Asymptotic MIMO Behavior .............................................. 63
  3.4.1 Outline of MIMO Properties ....................................... 63
  3.4.2 MUG and Normalized MUG ......................................... 64
  3.4.3 The Impacts of \( M \) and \( N \) ........................................ 67
  3.4.4 Direction Diversity ................................................ 69
3.5 MEB with Unequal Rate Constraints ................................... 70
3.6 MIMO BC ............................................................... 71
  3.6.1 Duality-aided MEB Strategy ....................................... 72
  3.6.2 Direct MEB Strategy ................................................ 73
3.7 Practical Implementation ................................................ 74
  3.7.1 System Structure .................................................... 74
  3.7.2 Performance Evolution .............................................. 79
  3.7.3 Power Allocation .................................................... 81
  3.7.4 Numerical Results ................................................... 82
3.8 Appendix ...................................................................... 84
  3.8.1 MTSP for \( K = 1 \) ...................................................... 84
  3.8.2 Some Derivations for MIMO BC ................................... 85
  3.8.3 Detection and SNR Evolution of MEB using (3.53) .......... 89
4 Extension to Cellular Systems ................................. 92
  4.1 System Model ............................................................ 92
  4.2 Full BS Cooperation .................................................... 94
    4.2.1 Theoretical Analysis ............................................... 94
    4.2.2 Numerical Examples ............................................... 96
  4.3 Partial Signal Utilization (PSU) ..................................... 98
    4.3.1 PSU with Finite Concurrent User Density .................... 101
    4.3.2 Asymptotic Performance of PSU ................................. 103
5 Equal Power Allocation ............................................... 109
  5.1 SISO MAC with Full CSIT ............................................ 110
    5.1.1 Ideal Coding ....................................................... 110
    5.1.2 Practical Coding .................................................. 113
  5.2 SISO MAC with Imperfect CSIT .................................... 125
    5.2.1 TDMA ............................................................ 125
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Topics</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2.2</td>
<td>IDMA</td>
<td>125</td>
</tr>
<tr>
<td>5.3</td>
<td>MIMO MAC with Full CSIT</td>
<td>126</td>
</tr>
<tr>
<td>5.3.1</td>
<td>TDMA</td>
<td>127</td>
</tr>
<tr>
<td>5.3.2</td>
<td>MEB-EPA with Ideal Coding</td>
<td>127</td>
</tr>
<tr>
<td>5.3.3</td>
<td>MEB-EPA with Practical Coding</td>
<td>131</td>
</tr>
<tr>
<td>5.4</td>
<td>MIMO MAC with Imperfect CSIT</td>
<td>136</td>
</tr>
<tr>
<td>5.4.1</td>
<td>TDMA</td>
<td>137</td>
</tr>
<tr>
<td>5.4.2</td>
<td>MEB-EPA</td>
<td>137</td>
</tr>
<tr>
<td>5.4.3</td>
<td>Numerical Results</td>
<td>138</td>
</tr>
<tr>
<td>5.5</td>
<td>Appendix</td>
<td>140</td>
</tr>
<tr>
<td>5.5.1</td>
<td>Proof of Proposition 5.1</td>
<td>140</td>
</tr>
<tr>
<td>5.5.2</td>
<td>Proof of Proposition 5.2</td>
<td>140</td>
</tr>
<tr>
<td>5.5.3</td>
<td>Proof of Theorem 5.2</td>
<td>141</td>
</tr>
<tr>
<td>5.5.4</td>
<td>Proof of Theorem 5.3</td>
<td>142</td>
</tr>
<tr>
<td>5.5.5</td>
<td>Proof of Proposition 5.5</td>
<td>146</td>
</tr>
<tr>
<td>6</td>
<td>Conclusions and Future Work</td>
<td>148</td>
</tr>
<tr>
<td>6.1</td>
<td>Conclusions</td>
<td>148</td>
</tr>
<tr>
<td>6.2</td>
<td>Future work</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>Bibliography</td>
<td>152</td>
</tr>
</tbody>
</table>
Abbreviations

APP  A Posteriori Probability
AWGN  Additive White Gaussian Noise
BC  Broadcast Channel
BER  Bit Error Rate
BPSK  Binary Phase Shift Keying
BS  Base Station
CCI  Cross-Cell Interference
CDF  Cumulative Distribution Function
CDMA  Code-Division Multiple-Access
CSI  Channel State Information
CSIT  CSI at the Transmitter Side
CSIR  CSI at the Receiver Side
DOA  Direction of Arrival
EPA  Equal Power Allocation
ESE  Elementary Signal Estimator
FBSC  Full BS Cooperation
FDMA  Frequency-Division Multiple-Access
FEC  Forward Error Correction
FER  Frame Error Rate
ICI  Intra-Cell Interference
IDMA  Interleave-Division Multiple-Access
i.i.d.  Independent and Identically Distributed
IPM  Interior Point Method
i.u.d.  Independent and Uniformly Distributed
LDPC  Low-Density Parity-Check
LLR  Log-Likelihood Ratio
LPM  Linear Programming Method
MAC  Multiple-Access Channel
MAP  Maximum A Posteriori
MEB  Maximum Eigenmode Beamforming
MIMO  Multiple-Input Multiple-Output
MISO  Multiple-Input Single-Output
MMSE  Minimum Mean Square Error
MRC  Maximum Ratio Combining
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTSP</td>
<td>Minimum Transmitted Sum Power</td>
</tr>
<tr>
<td>MUD</td>
<td>Multi-User Detection</td>
</tr>
<tr>
<td>MUG</td>
<td>Multi-User Gain</td>
</tr>
<tr>
<td>NBSC</td>
<td>Non-BS Cooperation</td>
</tr>
<tr>
<td>OC</td>
<td>Optimal Combining</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency-Division Multiple-Access</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>PSU</td>
<td>Partial Signal Utilization</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Services</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase-Shift Keying</td>
</tr>
<tr>
<td>SIC</td>
<td>Successive Interference Cancelation</td>
</tr>
<tr>
<td>SISO</td>
<td>Single-Input Single-Output</td>
</tr>
<tr>
<td>SIMO</td>
<td>Single-Input Multiple-Output</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SUD</td>
<td>Single-User Detection</td>
</tr>
<tr>
<td>SVD</td>
<td>Singular Value Decomposition</td>
</tr>
<tr>
<td>TCM</td>
<td>Trellis Coded Modulation</td>
</tr>
<tr>
<td>TCMA</td>
<td>Trellis-Coded Multiple-Access</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time-Division Multiple-Access</td>
</tr>
<tr>
<td>TSM</td>
<td>Two-Step Method</td>
</tr>
<tr>
<td>UPA</td>
<td>Unequal Power Allocation</td>
</tr>
</tbody>
</table>
List of Symbols

\( \alpha_k \) The fraction of user \( k \)' active sub-frame length over the whole frame length in an adaptive TDMA scheme

\( C_K \) The maximum throughput of a \( K \) user SISO MAC achieved by EPA

\( d_{k,\text{max}} \) The maximum singular value of \( H_k \)

\( e_{\text{DEC}}(\cdot) \) The extrinsic information generated by decoders

\( e_{\text{ESE}}(\cdot) \) The extrinsic information generated by the ESE part

\( \mathbb{E}(\cdot) \) The expectation operation

\( \varepsilon \) The outage probability of each user

\( f(\cdot) \) The PDF of \( \{|h_k|^2\} \) (or \( \{\|H_k\|\} \))

\( F(\cdot) \) The CDF of \( \{|h_k|^2\} \) (or \( \{\|H_k\|\} \))

\( f^{k:K}(\cdot) \) The PDF of the \( k \)-th smallest variable among \( \{|h_k|^2, k = 1, 2, \cdots, K\} \) (or \( \{\|H_k\|^2, k = 1, 2, \cdots, K\} \))

\( F^{k:K}(\cdot) \) The CDF of the \( k \)-th smallest variable among \( \{|h_k|^2, k = 1, 2, \cdots, K\} \) (or \( \{\|H_k\|^2, k = 1, 2, \cdots, K\} \))

\( \Psi(K, R) \) The normalized MUG achievable in a \( K \)-user SISO system with sum rate \( R \)

\( \Psi_{N \times M}(K, R) \) The normalized MUG achievable in a \( K \)-user \( N \times M \) MIMO system with sum \( R \)

\( \Psi_{N \times M}^{\text{MEB}}(K, R) \) The normalized MUG achievable by MEB in a \( K \)-user \( N \times M \) MIMO system with sum \( R \)

\( g(\cdot) \) The average BER (or FER) function for a given input SNR value

\( G_0 \) The outage threshold for each user

\( G(K, R) \) The MUG achievable in a \( K \)-user SISO system with sum rate \( R \)

\( G_{N \times M}(K, R) \) The MUG achievable in a \( K \)-user \( N \times M \) MIMO system with sum rate \( R \)

\( G_{N \times M}^{\text{MEB}}(K, R) \) The MUG achievable by MEB in a \( K \)-user \( N \times M \) MIMO system with sum rate \( R \)

\( \gamma_k^{(l)} \) A lower bound for \( SNR_k \) after the \( l \)-th iteration of detection

\( \Gamma \) The SNR threshold for each user in a practically coded system

\( h_k \) The channel coefficient of user \( k \) in a SISO system

\( H_k \) The channel matrix from user \( k \) to the BS(s) in an MIMO or cellular system
I^{(l)}  The total interference-plus-noise after the l-th iteration of detection
\[ I(k, k') \]  The indicator function for two users k and k'
K  The number of users in a single-cell system in Chapters 2, 3 and 5 (or the average number of users per cell in a cellular system in Chapter 4)
l  The iteration index
L  The maximum iteration number
M  The number of antennas at each BS
n(j)  The complex AWGN noise sample at time j at the bast station of a single-cell SISO MAC
\[ n(j) \]  The complex AWGN noise vector at time j at the receiver of a single-cell MIMO MAC in Chapter 3, 5 (or a uplink cellular system in Chapter 4)
n_k(j)  The complex AWGN noise sample at time j at the receiver of user k in a single-cell SISO BC
\[ n_k(j) \]  The complex AWGN noise vector at time j at the receiver of user k in an MIMO BC
N  The number of antennas at each mobile unit
N_0  The single-side power density of the complex AWGN noise \[ n(j), n_k(j) \] or each entry of \[ n(j) \] and \[ n_k(j) \]
N_c  The number of cells in a cellular system
p_k  The transmitted power of user k
\[ p_k^{ins} \]  The instantaneous transmitted power of user k
\[ P(K, R) \]  The average unconstrained MTSP of a K-user SISO system with sum rate R
\[ P^{EPA}(K, R) \]  The average MTSP achievable by EPA in a K-user SISO system with sum rate R
\[ P_{N \times M}(K, R) \]  The average unconstrained MTSP of a K-user \( N \times M \) MIMO system with sum rate R (or the average unconstrained MTSP per cell of an \( N \times M \) cellular system with user density \( K \) and sum rate per cell R)
\[ P^{LB}_{N \times M}(K, R) \]  A lower bound for \( P_{N \times M}(K, R) \)
\[ P^{MEB}_{N \times M}(K, R) \]  The average MTSP of MEB in a K-user \( N \times M \) MIMO system with sum rate R (or the average MTSP per cell of MEB in an \( N \times M \) cellular system with user density \( K \) and average sum rate per cell R)
\[ Pr(\cdot) \]  The probability operation
\( \pi_k \) The interleaver used by user \( k \)
\( q \) The equal received power level of all users in a single-cell MAC
\( q_k \) The received power of user \( k \)
\( q_{k}^{ins} \) The instantaneous received power of user \( k \)
\( r_k \) The instantaneous rate of active user \( k \) in an adaptive TDMA scheme
\( R \) The sum rate of a single-cell system in Chapters 2, 3 and 5 (or the average sum rate per cell in a cellular system in Chapter 4)
\( R_0 \) The equal rate constraint of each user
\( R_k \) The rate constraint of user \( k \) in each frame
\( \rho \) The channel uncertainty coefficient
\( S \) Spreading length
\( SNR_k \) The signal-to-noise ratio of user \( k \)
\( \sigma \) The standard derivation of the real/imaginary part of \( n(j) \), \( n_k(j) \) or each entry of \( \mathbf{n}(j) \) and \( \mathbf{n}_k(j) \)
\( \mathbf{u}_{k,\text{max}} \) The maximum left-singular vector of \( \mathbf{H}_k \)
\( v(\cdot) \) The average variance function for a given input SNR value
\( \mathbf{v}_{k,\text{max}} \) The maximum right-singular vector of \( \mathbf{H}_k \)
\( \text{Var}(\cdot) \) The variance operation
\( x_k(j) \) The coded signal of user \( k \) with unit power at time \( j \) in a SISO system
\( \mathbf{x}_k(j) \) The coded signal of user \( k \) with unit power at time \( j \) in an MIMO system
\( \xi_k(j) \) The noise-plus-interference component in \( \mathbf{y}(j) \) with respect to \( x_k(j) \)
\( \xi_k(j) \) The noise-plus-interference component in \( \mathbf{y}(j) \) with respect to \( \mathbf{x}_k(j) \)
\( \xi_{k,k'}(j) \) The noise-plus-interference component in \( \mathbf{y}_k(j) \) with respect to \( x_{k'}(j) \)
\( \xi_{k,k'}(j) \) The noise-plus-interference component in \( \mathbf{y}_k(j) \) with respect to \( \mathbf{x}_{k'}(j) \)
\( \mathbf{y}(j) \) The received signal at time \( j \) in a SISO MAC
\( \mathbf{y}_k(j) \) The signal received by user \( k \) at time \( j \) in a SISO BC
\( \mathbf{y}(j) \) The received signal at time \( j \) in an MIMO MAC
\( \mathbf{y}_k(j) \) The signal received by user \( k \) at time \( j \) in an MIMO BC
List of Figures

2.1 The power regions of a two-user system with different multiple access schemes over an (a). AWGN SISO MAC and (b). fading SISO MAC. .................................................. 13

2.2 The average unconstrained MTSP and the corresponding asymptotic MTSP for a SISO system over a single-cell fading MAC. $N_0 = 1$. The outage probability is $\varepsilon = 10^{-2}$. .................................................. 17

2.3 The achievable MUG for SISO multiple access systems with different number of users $K$ over a single-cell fading channel. The outage probability is set at $\varepsilon = 10^{-2}$. .................................................. 21

2.4 The normalized MUG achieved by a finite number of users in SISO multiple access systems over a single-cell fading channel. The outage probability is set at $\varepsilon = 10^{-2}$. .................................................. 22

2.5 System structure of a $K$-user system over a SISO MAC. ....... 27

2.6 System structure of a $K$-user system over a SISO BC. ............. 30

2.7 Examples of $v(\cdot)$ function for some ideal codes and practical codes. The practical codes under consideration are constructed using a rate-1/2 convolutional code with generator $(23, 35)_8$ followed by length-$S$ spreading ($S = 1, 2$ and $4$, respectively). The numbers marked beside the curves are coding rates. ........................................... 33

2.8 Illustration of the feasible region (the shaded area) of a five-user IDMA system over an AWGN SISO MAC with $\sigma^2 = 1$. The SNR threshold $\Gamma$ is selected to ensure $BER_k \leq 10^{-4}, \forall k$. ................. 36

2.9 Performance comparison between (a). LPM-I and LPM-II and (b). LPM-II and IPM. $L = 30$ and the system sum rate is fixed at $R = 4$ bits/symbol. The spreading lengths are $S = 1, 2$ and $4$ for $K = 4$, $8$ and $16$, respectively. ................................. 44

2.10 The required average transmitted power versus the number of users $K$ for an IDMA system over fading SISO MACs. $\varepsilon = 10^{-2}$, and the system sum rates in (a) and (b) are $4$ and $8$ bits/symbol respectively. 47

2.11 The required average transmitted power versus the number of users $K$ for an IDMA system over fading SISO BCs. $\varepsilon = 10^{-2}$. The system sum rate is $4$ bits/symbol. ................................. 50
3.1 Comparison between the average MTST for MEB with finite $K$
and the asymptotic average unconstrained MTSP of various MIMO
systems over a single-cell fading channel. $N_0 = 1, \varepsilon = 10^{-2}$. The
antenna settings $N \times M$ are marked on the curves. ............... 62
3.2 The asymptotic MUG versus the sum rate $R$ for various multiple
access systems over a single-cell fading channel. $\varepsilon = 10^{-2}$. The
antenna settings $N \times M$ are marked on the curves. ............... 65
3.3 The normalized MUG achieved by a finite number of users in MIMO
multiple access systems over a single-cell fading channel. $\varepsilon = 10^{-2}$. 66
3.4 The average MTSP versus the sum rate $R$ for various multiple access
systems with different $M$ and $N$ over a single-cell fading channel.
$N_0 = 1, \varepsilon = 10^{-2}$. The antenna settings $N \times M$ are marked on the
curves. ............................................................... 68
3.5 The transmitter and the receiver structures of an MEB-based IDMA
system over an MIMO MAC. ........................................ 75
3.6 Evolution and simulation results for the BER performance of an
MEB-based IDMA system over a $2 \times 2$ MIMO MAC. The outage
probability is set at $\varepsilon = 10^{-2}$. $R = 4$ bits/symbol, $S = 2$. The corresponding MEB limits are also plotted for reference. ........... 82
3.7 Evolution and simulation results for the BER performance of an
MEB-based IDMA systems over a $4 \times 4$ MIMO MAC. The outage
probability is set at $\varepsilon = 10^{-2}$. $R = 4$ bits/symbol, $S = 2$. The BER
performance of the corresponding TDMA-based system and their
theoretical limits are also plotted for reference. ...................... 83
4.1 The power efficiency of the MEB strategy in a cellular system with
FBSC and different densities of simultaneous users $K$. $N = M = 1$.
The outage probability for each user is $\varepsilon = 10^{-2}$. ............... 97
4.2 The capacities of FBSC cellular systems with different $M$ and $N$.
$\varepsilon = 10^{-2}$. The density of average simultaneous users per cell is
assumed to be high enough ($K \rightarrow \infty$). ....................... 98
4.3 The capacities of FBSC cellular systems with different $M$. $N = 1$
and $\varepsilon = 10^{-2}$. The user density is assumed to be high enough
($K \rightarrow \infty$). The edge-length of each cell is normalized to $\sqrt{M}$,
instead of 1. ................................................................. 99
4.4 The system transmission failure probability versus the average sum
rate per cell in a cellular system with NBSC. $N = M = 1, \varepsilon = 10^{-2}$. 102
4.5 The power efficiency of cellular systems with NBSC (solid curves). We set $N = 1$ in Fig. (a) and $M = 1$ in Fig (b), respectively. $\varepsilon = 10^{-2}$. The corresponding maximum achievable throughputs (dashed lines) are also plotted for reference. .................. 106

4.6 The power efficiency of various cellular systems with NBSC (solid curves). $M = 1$, $\varepsilon = 10^{-2}$. The corresponding maximum achievable throughputs (dashed lines) are also plotted for reference. ............. 107

4.7 The power efficiency of various cellular systems with NBSC (solid curves). $\varepsilon = 10^{-2}$. The corresponding maximum achievable throughputs (dashed lines) are also plotted for reference. .................. 108

5.1 The power efficiencies of EPA in (a). AWGN and (b). fading SISO MACs with different $K$. The corresponding throughout upper bounds $\{C_K\}$ (in (a)) and the curves for the optimal scheme with UPA (in (b)) are also plotted for reference. The channel condition in (b) is the same as that used in Fig. 2.2 with $\varepsilon = 10^{-2}$. ............ 112

5.2 An illustration of the SNR evolution process. The cross points of the two curves in the figures are the solutions to equation (5.13). However, only the first cross point in each figure can be achieved by the SNR evolution process with $\gamma_1^{(0)} = \gamma_2^{(0)} = 0$. .................. 114

5.3 Feasible and quasi-optimal probabilities of practically coded MEB-EPA based IDMA systems with different numbers of users over an MIMO MAC. $M = 4$. A rate 1/2 convolutional coding scheme with generator $(23,35)_8$ followed by a length-$S$ repetition coding is used by all users. $S = 1$ and 2 in (a) and (b), respectively. ............ 134

5.4 BER performance comparison between EPA and UPA in a MEB-based multi-user MIMO systems with convolutional coding followed by length-2 spreading over single-cell fading channels. $M = N = 4$ and $\varepsilon = 10^{-2}$. ................................................................. 136

5.5 FER performance of the MEB strategies with UPA and EPA over a single-cell fading channel with imperfect CSIT. $M = N = 4$, $\varepsilon = 10^{-2}$ and $R = 4$ bits/symbol. The corresponding performance of the TDMA scheme is also plotted for reference. ............ 139
List of Tables

2.1 Relative Power Profiles for the Simulations in Fig. 2.9(b) . . . . . . . 45

5.1 Values of Parameters for EPA with Coding Scheme I . . . . . . . . 123
5.2 Values of Parameters for EPA with Coding Scheme II . . . . . . . 123
5.3 Values of Parameters for EPA with Coding Scheme III . . . . . . . 124