

MULTI-USER WIRELESS COMMUNICATION SYSTEMS WITH RATE CONSTRAINTS

WANG PENG

Department of Electronic Engineering

Supervisor: Prof. Li Ping

DOCTOR OF PHILOSOPHY
CITY UNIVERSITY OF HONG KONG
JANUARY 2010

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

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

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

MTSP	Minimum Transmitted Sum Power
MUD	Multi-User Detection
MUG	Multi-User Gain
NBSC	Non-BS Cooperation
OC	Optimal Combining
OFDMA	Orthogonal Frequency-Division Multiple-Access
PDF	Probability Density Function
PSU	Partial Signal Utilization
QAM	Quadrature Amplitude Modulation
QoS	Quality of Services
QPSK	Quadrature Phase-Shift Keying
SIC	Successive Interference Cancellation
SISO	Single-Input Single-Output
SIMO	Single-Input Multiple-Output
SNR	Signal-to-Noise Ratio
SUD	Single-User Detection
SVD	Singular Value Decomposition
TCM	Trellis Coded Modulation
TCMA	Trellis-Coded Multiple-Access
TDMA	Time-Division Multiple-Access
TSM	Two-Step Method
UPA	Unequal Power Allocation

List of Symbols

α_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
$d_{k,\max}$	The maximum singular value of $\mathbf{H}_k$
$e_{\text{DEC}}(\cdot)$	The extrinsic information generated by decoders
$e_{\text{ESE}}(\cdot)$	The extrinsic information generated by the ESE part
$\mathbb{E}(\cdot)$	The expectation operation
ε	The outage probability of each user
$f(\cdot)$	The PDF of $\{ h_k ^2\}$ (or $\{\ \mathbf{H}_k\ \}$)
$F(\cdot)$	The CDF of $\{ h_k ^2\}$ (or $\{\ \mathbf{H}_k\ \}$)
$f^{k:K}(\cdot)$	The PDF of the k -th smallest variable among $\{ h_k ^2, k = 1, 2, \dots, K\}$ (or $\{\ \mathbf{H}_k\ ^2, k = 1, 2, \dots, K\}$)
$F^{k:K}(\cdot)$	The CDF of the k -th smallest variable among $\{ h_k ^2, k = 1, 2, \dots, K\}$ (or $\{\ \mathbf{H}_k\ ^2, k = 1, 2, \dots, K\}$)
$\Psi(K, R)$	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
$\Psi_{N \times M}^{MEB}(K, R)$	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
$G_{N \times M}^{MEB}(K, R)$	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
Γ	The SNR threshold for each user in a practically coded system
h_k	The channel coefficient of user k in a SISO system
$\mathbf{H}_k$	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 base station of a single-cell SISO MAC
$\mathbf{n}(j)$	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
$\mathbf{n}_k(j)$	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 $\mathbf{n}(j)$ and $\mathbf{n}_k(j)$
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)
$P_{N \times M}^{LB}(K, R)$	A lower bound for $P_{N \times M}(K, R)$
$P_{N \times M}^{MEB}(K, R)$	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

π_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
ρ	The channel uncertainty coefficient
S	Spreading length
SNR_k	The signal-to-noise ratio of user k
σ	The standard derivation of the real/imaginary part of $n(j)$, $n_k(j)$ or each entry of $\mathbf{n}(j)$ and $\mathbf{n}_k(j)$
$\mathbf{u}_{k,\max}$	The maximum left-singular vector of $\mathbf{H}_k$
$v(\cdot)$	The average variance function for a given input SNR value
$\mathbf{v}_{k,\max}$	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 $y(j)$ with respect to $x_k(j)$
$\boldsymbol{\xi}_k(j)$	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 $y_k(j)$ with respect to $x_{k'}(j)$
$\boldsymbol{\xi}_{k,k'}(j)$	The noise-plus-interference component in $\mathbf{y}_k(j)$ with respect to $\mathbf{x}_{k'}(j)$
$y(j)$	The received signal at time j in a SISO MAC
$y_k(j)$	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 Γ 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 2×2 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 4×4 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 throughput 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