AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
Electronics and Electrical Communication Engineering

Massive MIMO Systems for 5G Wireless Networks

A Thesis submitted in partial fulfillment of the requirements of
Master of Science degree in Electrical Engineering
Electronics and Electrical Communication Engineering

by

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Bachelor of Science in Electrical Engineering
(Electronics and Electrical Communication Engineering)
Thebes Higher Institute of Engineering , 2013

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Cairo, 2018

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Statement

This thesis is submitted as a partial fulfillment of Master of Science degree in Electrical Engineering, Electronics and Electrical Communication Department, Faculty of Engineering, Ain shams University, Cairo, Egypt.

The author carried out the work included in this thesis, and no part of it has been submitted for a degree or a qualification at any other scientific entity.

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Thesis Summary

This thesis proposes two novel pilot allocation schemes in order to mitigate the pilot contamination effect and to enhance the system performance with low complexity techniques of pilot allocation. The thesis is divided into seven chapters as listed below:

Chapter 1 provides our motivations towards the fifth generation (5G) wireless networks along with Massive Multiple-Input Multiple-Output (MIMO) technique in order to keep up with the dramatic exponential growth of data traffic. Additionally, a brief introduction exhibits a point-to-point MIMO system, multi-user MIMO system, and massive MIMO system. At the end of the chapter, we provide our contributions in this thesis.

Chapter 2 presents an overview of massive MIMO systems; We move from point-to-point MIMO systems to massive MIMO systems passing through multi-user MIMO systems in more details. In addition, the main operations required to work on massive MIMO systems are discussed. Furthermore, we describe the main advantages of massive MIMO systems and their challenges needed to be tackled to make massive MIMO systems a reality such as the pilot contamination effect.

Chapter 3 explains one of the main challenges for the massive MIMO systems which is the pilot contamination effect that limits the performance of massive MIMO systems. This effect appears in the channel estimation phase when all users in a specific cell transmit orthogonal pilot sequences to its BS, but due to the limitation of channel coherence interval these pilot sequences are reused in the adjacent cells. Hence, the estimated channel state information at the BS in this cell is contaminated by users that use the same pilot sequences in other cells that cause the pilot contamination effect. The techniques used in literature in the last few years to mitigate the pilot contamination effect can be divided into two categories according to the pilot allocation. The first category assigns the pilot sequences to the users randomly, while the other category optimizes the pilot allocation based on a per-user basis.

Chapter 4 describes the system model of the massive MIMO network and the assumptions we use throughout this thesis including cellular network description, channel estimation, and data transmission.

Chapter 5 provides the two proposed-novel pilot allocation schemes to mitigate the pilot contamination effect discussed in Chapter 3 and to enhance the system performance using low complexity techniques. We illustrate how our proposed schemes outperform some of the conventional scheme mentioned in Chapter 3, and how these novel schemes overcome the resource limitations problems. In addition, we analyze the performance of the proposed massive MIMO schemes with non-cooperative base stations. First, the achievable spectral efficiency adopting both the maximum-ratio combining (MRC) and zero-forcing (ZF) schemes are obtained. Then, the obtained spectral efficiency of these proposed schemes is formulated as an optimization problem to maximize the overall spectral efficiency over the ratio of center zone radius to the cell radius and the number of scheduled users per cell. After that, this optimization problem is mathematically solved in order to find the optimal solutions. In addition, the upper bound for ergodic capacity is analytically derived in order to illustrate that the proposed schemes are more close to the upper bound than the conventional schemes in the literature.

Chapter 6 investigates the performance of the proposed schemes to mitigate the pilot contamination effect in massive MIMO systems against the conventional schemes. Firstly, the optimization problem is solved using the exhaustive search and the simulation results of the optimized spectral efficiency for the proposed schemes are compared against the conventional schemes. It turns out that the spectral efficiency of the proposed schemes always outweigh the spectral efficiency of the conventional schemes along the number of BS antennas. This is a consequence of wisely allocating the pilot sequences among the users due to dividing the cell coverage into center and edge zones and sectorizing the edge zone.

Chapter 7 provides overall conclusions for our work. This chapter also provides the possible future research directions.

Abstract

The wireless data traffic has grown exponentially due to the dramatic increase of connected devices and the proliferation of new applications requiring high data rate. According to Martin Cooper law, the demand for wireless data traffic will be doubled every eighteen months. Hence, fifth generation (5G) wireless communication networks are required along with new technologies in which many users can be simultaneously served with very high throughput.

One of the promising technologies that can allow 5G cellular networks to meet these demands is the massive Multi-Input Multi-Output (MIMO) technique, where each base station (BS) is equipped with a large number of antennas to serve a multiple number of single-antenna user equipments (UEs), simultaneously in the same time and frequency resource. Massive MIMO systems can substantially enhance the spectral efficiency in order of magnitude compared to the conventional MIMO systems.

Within the cell, the BS is only required to know the channel state information (CSI) in order to do multi-user precoding in the downlink and data detection in the uplink. The uplink CSI is estimated at the BS based on the uplink orthogonal pilot sequences. Because the number of pilot sequences is limited by the channel coherence interval, the pilot sequences are mutually orthogonal in the same cell but necessarily reused in some adjacent cells. Therefore, the estimated CSI at the BS in a given cell is contaminated by the users that use the same pilot sequences in other cells. This effect is called pilot contamination that limits the performance of massive MIMO systems.

In this thesis, we propose two novel pilot allocation schemes in order to mitigate the pilot contamination effect and to enhance the performance of massive MIMO systems

with low complexity of pilot allocation. In these proposed schemes, the cell coverage is partitioned into center and edge zones. Furthermore, the edge zone is sectorized into a number of uniform sectors by the smart antenna technique. The achievable spectral efficiency adopting both the maximum-ratio combining (MRC) and zero-forcing (ZF) schemes are obtained. Then, the obtained spectral efficiency of these proposed schemes are formulated as an optimization problem with an objective of maximizing the overall spectral efficiency over the ratio of center zone radius to the cell radius and the number of scheduled users per cell. After that, this optimization problem is mathematically solved in order to find the optimal solutions. In addition, the upper bound for ergodic capacity is analytically derived in order to illustrate that the proposed schemes are more close to the upper bound than the conventional schemes in the literature.

Finally, the performance of these proposed schemes is investigated through simulations results in which the optimization problem is also solved using the exhaustive search in order to find the optimized spectral efficiency for the proposed schemes. Moreover, the obtained results are compared against the conventional schemes, and the upper bound on the ergodic capacity. It turns out that the spectral efficiency of the proposed schemes always outweigh the spectral efficiency of the conventional schemes along the number of BS antennas and also the performance gap between the upper bound on ergodic capacity and the proposed schemes is less than the performance gap between the upper bound on ergodic capacity and the conventional schemes. This is a consequence of wisely allocating the pilot sequences among the users due to dividing the cell coverage into center and edge zones and sectorizing the edge zone.

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Table of Contents

List of Symbols

$\mathbf{a}_{fu}$	information vector transmitted by the u-th user in the f-th cell
$a_{fu}(t)$	symbol transmitted by the u-th user in the f-th cell in a time slot (t)
B	number of orthogonal pilot sequences
b_j	location of the BS in the j-th cell
$\beta_j(\mathbf{z}_{fu})$	variance of channel attenuation from the j-th BS and the position of u-th user in the f-th cell
C_j	set of center zone user in the j-th cell
σ^2	noise power at the receiver
σ_P^2	noise power at the j-th BS during the channel estimation phase
d_2	distance between the u-th user in the f-th cell and the BS in j-th cell
$\mathbf{e}_{jfu}$	estimation error of the u-th user in the f-th cell
$\mathcal{F}_q$	permutation of U users satisfy that the channel quality of each user is sorted in descending order
$\mathcal{F}_p$	permutation of U pilot sequences satisfy that the inter-cell interference of each pilot sequence is sorted in descending order
F	number of non-cooperative cells in massive MIMO system
$\mathcal{F}$	set of cells in massive MIMO system

f	one of the cell in the network
$\mathbf{H}$	channel matrix between the user and the BS in P2P MIMO system
$\mathbf{h}_u$	uplink channel vector of the u-th user
$\mathbf{h}_u^T$	downlink channel vector of the u-th user
$\mathbf{h}_{jfu}$	channel response between the j-th BS and the u-th user in f-th cell
$\bar{\bar{\mathbf{h}}}_{jfu}$	effective power-controlled uplink channel of the u-th user in f-th cell
$\hat{\bar{\bar{\mathbf{h}}}}_{jfu}$	estimated effective power-controlled uplink channel of the u-th user in the f-th cell
$\mathbf{G}$	linear detection matrix
$\mathbf{g}_u$	the u-th column of the linear detection matrix
ξ_{jlu}	variance of the estimated effective power-controlled channel between an arbitrary user u in cell f and BS j
Γ_C	ratio of center zone radius to the cell radius
G_f	set of users in the f-th cell that use the same pilot sequences of the u-th user in the j-th cell
I_{C_j}	interference term for the center zone users in the j-th cell
I_{E_j}	interference term for the edge zone users in a single sector in the j-th cell
j	cell of interest
$\chi_{j,G_f}^{(\gamma)}$	propagation parameter between the BS in the j-th cell and an arbitrary user in the set G_f in the f-th cell
κ	pathloss exponent
$\mathcal{L}_f$	set of cells indices that use the same pilot sequences as cell f
λ	wavelength

M	number of antennas at the BS
$\mathcal{M}$	set of cells that cover the sectors allocated with the same pilot sequence in a specified area
$\mu_{\bar{\bar{\mathbf{h}}}}$	mean of effective power-controlled channel of the u-th user in the f-th cell
$\mu_{\mathbf{y}}$	mean of the received signal at the j-th BS from the u-th user in the f-th cell
μ_r	mathematical expectation of the random variable r
μ_θ	mathematical expectation of the random variable θ
$\mathbf{n}$	noise vector at the receiver in P2P MIMO system
$\ddot{\mathbf{n}}$	noise vector at the BS during uplink data transmission
$\breve{n}_u$	additive noise at the u-th user
$\mathbf{N}_j$	noise matrix at the j-th BS
$\mathbf{N}_j^P$	noise matrix at the j-th BS during the channel estimation phase
$\mathbf{N}_j^D$	noise matrix at the j-th BS during the data transmission phase
$\mathbf{n}_j^D(t)$	additive noise in a time slot (t)
N	number of sectors in the edge zone
$\ddot{\mathcal{P}}$	power of the uplink transmitted signal
$\breve{\mathcal{P}}$	downlink transmit power at the u-th user
$\mathcal{P}_{fu}$	transmit power of the u-th user in the f-th cell
$\mathbf{\Psi}$	estimation error covarinace matrix
$\mathbf{q}$	precoded signal vector intended to the users
$\mathbf{R}_{\mathbf{xx}}$	covariance matrix of the transmitted signal vector $(\mathbf{x})$