UNIVERSITI PUTRA MALAYSIA

ENERGY-EFFICIENT BASE STATION TRANSMISSION DESIGN FOR GREEN 5G MASSIVE MIMO AND HYBRID NETWORKS

VAHID KHODAMORADI

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By

VAHID KHODAMORADI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

October 2021

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DEDICATIONS

To my father who never saw this adventure, in loving memory.

To my greatly beloved mother, for every single prayer, smile, advice, and time to take care of me.

To my dear wife for her faithfully and constant source of support and encouragement during the challenges of education and life.

To my brother and sisters for their sincere love of the land and their ever-present support of my personal endeavors towards learning.

To my advisor and mentors, who freely volunteer their time and facilities to the betterment of youth and the natural environment.

To my beloved friends, for every smile, memory, and lesson we shared together.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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VAHID KHODAMORADI

October 2021

Chair : Prof. Ir. Dr. Aduwati Binti Sali, PhD
Faculty: Engineering

Massive multiple-input-multiple-output (MaMIMO) is considered as the promising technology for 5th generation (5G) wireless communication systems since it can considerably improve energy efficiency (EE). Besides, the integration of conventional MaMIMO with other technology, including simultaneous wireless information and power transfer (SWIPT) and Heterogeneous Networks (HetNets), has shown prominent potentials to satisfy the Quality of Service (QoS) of 5G systems. However, existing research studies concentrated on system EE enhancement, leaving opportunities on new roads to be identified. Therefore, further research problems can be determined to propose new research directions for better energy-efficient system design. This thesis addresses state-of-the-art MaMIMO technology and its integration with SWIPT and HetNets. Hence, this work aims to recognize new opportunities to achieve effective energy-efficient system design that can be divided into three parts.

The first part investigates energy-efficient downlink power transmission in multi-cell MaMIMO systems. A new base station (BS) transmit power adaptation model named BSTPA is proposed under zero-forcing beamforming (ZF-BF) scheme and perfect channel state information (CSI). The analytical closed-form expression of the BSTPA is derived in which the BS transmitted power is adapted to channel condition and user-level QoS, including data rate requirement and maximum allowable outage probability to minimize the total BS radiated power. Then, a new corresponding iterative EE optimization algorithm is proposed based on the BSTPA model to further improve the system's EE. The proposed algorithm maximizes the EE by jointly optimizing the minimum data rate requirement, the number of BS antennas and users. The results indicate that the proposed BSTPA model achieves better EE improvement up to 32% compared to the energy-efficient equal power allocation (EE-EPA) algorithm as the conventional scheme, especially for small per-antenna circuit power consumption.

The second part of the thesis focuses on the energy-efficient system design of the downlink MaMIMO enabled SWIPT based on power splitting (PS) and ZF-BF techniques. A new system model is proposed in which each user equipment (UE) utilizes the harvested power for pilot transmission. Closed-form expressions of UE's energy harvesting (EH) and achievable data rate are first derived. Then, the EE maximization problem is formulated to jointly optimize the CE time duration, the PS ratios, and the BS transmit power allocation and antennas number concerning the data rate requirement and the maximum BS power transmission constraints. However, a new low-complex and alternative optimization (LCAO) algorithm is proposed to tackle the non-linear and non-convex characteristics of the original optimization problem with an acceptable computational complexity. The results indicate that the proposed LCAO algorithm outperforms the equal power allocation (EPA) and max-min algorithms up to 15% and 4% better EE improvement.

In the last part, MaMIMO enabled SWIPT system is integrated with HetNets technology. Therefore, a new system model is proposed based on separated SWIPT where only macro UEs (MUEs) exploit the harvested energy from received signal power and cross-tier interference for pilot transmission. The analytical closed-form expressions of MUEs' EH and data rate are derived. An EE maximization problem is then formulated with respect to the required data rate and MBS transmission capacity. Hence, a new iterative EE optimization (IEEO) algorithm is proposed that individually optimize pilot transmission duration, PS coefficients, macro BS (MBS) transmit power and antennas number, respectively. The results demonstrate that IEEO improves EE up to 6.7% and 9.9% compared to EPA and max-min algorithms.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

REKA BENTUK PENGHANTARAN STESEN PANGKALAN CEKAP TENAGA UNTUK MIMO BESAR-BESARAN 5G HIJAU DAN RANGKAIAN HIBRID

Oleh

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Input-berbilang-output-berbilang masif (MaMIMO) dianggap sebagai teknologi yang berpotensi untuk sistem komunikasi tanpa wayar generasi ke-5 (5G) kerana dapat meningkatkan kecekapan tenaga (EE). Selain itu, persepaduan MaMIMO konvensional dengan teknologi lain termasuk maklumat tanpa wayar serentak dan pemindahan kuasa (SWIPT) dan Rangkaian Heterogen (HetNets), telah menunjukkan potensi yang menonjol untuk memenuhi Kualiti Perkhidmatan (QoS) sistem 5G. Walau bagaimanapun, kajian penyelidikan yang ada tertumpu pada peningkatan sistem EE memberi peluang dan laluan baharu untuk dikenal pasti. Oleh itu, masalah penyelidikan selanjutnya dapat ditentukan untuk mencadangkan arah penyelidikan baharu untuk reka bentuk sistem yang lebih cekap tenaga. Tesis ini membahas teknologi MaMIMO yang canggih dan persepaduannya dengan SWIPT dan HetNets. Oleh itu, hasil kerja ini bertujuan untuk melihat peluang baharu untuk mencapai reka bentuk sistem cekap tenaga yang berkesan yang boleh dibahagikan kepada tiga bahagian.

Bahagian pertama menyiasat penghantaran kuasa paut turun yang cekap tenaga dalam sistem MaMIMO berbilang sel. Model penyesuaian kuasa pemancar stesen pangkalan (BS) baharu yang diberi nama BSTPA dicadangkan di bawah skema pembentuk alur daya sifar (ZF-BF) dan maklumat keadaan saluran sempurna (CSI). Ungkapan bentuk tertutup beranalisis dari BSTPA berasal dari kuasa yang dihantar BS disesuaikan dengan keadaan saluran dan QoS tahap pengguna, termasuk keperluan kadar data dan kebarangkalian gangguan maksimum yang dibenarkan untuk meminimumkan jumlah kuasa terpancar BS. Kemudian, algoritma pengoptimuman

EE berulang sepadan yang baharu dicadangkan berdasarkan model BSTPA untuk meningkatkan lagi EE sistem. Algoritma yang dicadangkan memaksimumkan EE dengan bersama-sama mengoptimumkan keperluan kadar data minimum, bilangan antena BS dan pengguna. Hasilnya menunjukkan bahawa model BSTPA yang dicadangkan mencapai peningkatan EE yang lebih baik hingga 32% berbanding dengan algoritma pemuatan kuasa sama tenaga (EE-EPL) yang cekap tenaga sebagai skema konvensional. Ini terutama untuk penggunaan kuasa litar antena yang kecil.

Bahagian kedua tesis ini memfokuskan pada reka bentuk sistem cekap tenaga dari SWIPT yang diaktifkan oleh MaMIMO paut turun berdasarkan teknik pemisahan kuasa (PS) dan ZF-BF. Model sistem baharu dicadangkan di mana setiap peralatan pengguna (UE) menggunakan kuasa yang diperoleh untuk penghantaran perintis. Ungkapan bentuk tertutup daripada pengumpulan tenaga UE (EH) dan kadar data yang dapat dicapai mula-mula diperoleh. Kemudian, masalah pemaksimuman EE dirumuskan untuk bersama-sama mengoptimumkan jangka waktu CE, nisbah PS, serta peruntukan kuasa transmisi BS dan bilangan antena berkenaan keperluan kadar data dan kekangan transmisi kuasa BS maksimum. Walau bagaimanapun, algoritma pengoptimuman alternatif dan kurang kompleks (LCAO) baharu dicadangkan untuk mengatasi ciri-ciri bukan linear dan bukan cembung daripada masalah pengoptimuman asal dengan kekompleksan perkomputan yang boleh diterima. Hasilnya menunjukkan bahawa algoritma LCAO yang dicadangkan mengatasi algoritma peruntukan kuasa yang sama (EPA) dan algoritma maksimum-minimum hingga 15% dan peningkatan EE 4% lebih baik.

Pada bahagian terakhir, sistem SWIPT yang diaktifkan oleh MaMIMO disatukan dengan teknologi HetNets. Oleh itu, model sistem baharu dicadangkan berdasarkan SWIPT yang dipisahkan, di mana hanya UE makro (MUE) mengeksploitasi tenaga yang diperoleh daripada kuasa isyarat yang diterima dan gangguan rentas peringkat untuk penghantaran perintis. Ungkapan bentuk tertutup beranalisis daripada pengumpulan tenaga EH dan kadar data MUE diperoleh. Masalah pemaksimuman EE kemudian dirumuskan berhubung dengan kadar data yang diperlukan dan kapasiti penghantaran MBS. Maka, algoritma pengoptimuman EE berulang (IEEO) baharu dicadangkan, yang secara automatik mengoptimumkan tempoh penghantaran juruterbang, pekali PS, kuasa penghantaran makro BS (MBS) dan nombor antena. Hasilnya menunjukkan bahawa IEEO meningkatkan EE hingga 6.7% dan 9.9% berbanding dengan EPA dan algoritma maksimum-minimum.

ACKNOWLEDGEMENTS

All praises to Allah and His blessing for the completion of this thesis. I thank God for all the opportunities, trials and strength that have been showered on me to finish writing the thesis. I experienced so much during this process, not only from the academic aspect but also from the aspect of personality.

Foremost, I would like to express my sincere gratitude to Prof. Ir. Dr. Aduwati Binti Sali who giving me the chance to work with her and for the continuous support of my Ph.D study and research, for her patience, motivation, enthusiasm, and immense knowledge. Her guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Ph.D study.

Besides my advisor, I would like to thank the rest of my committee members: Prof. Dr. Borhanuddin Bin Mohd Ali and Prof. Ir. Ts. Dr. Raja Syamsul Azmir Bin Raja Abdullah for their encouragement, insightful comments, and hard questions.

I thank my friends, fellow labmates, colleagues and professors in the Research Centre of Excellence for Wireless and Photonics Network (WiPNET), Universiti Putra Malaysia, for the stimulating learning environment and all the beautiful years we spent and learned in it together.

I also want to extend my thanks to all Staffs in the Faculty of Engineering and School of Graduate Studies, Universiti Putra Malaysia, for their help and support in the administrative works.

I would like to thanks my mother, sisters and brother; deserve endless gratitude and special mention, and thanks for their inseparable support and prayers. They plant in me the love of science and learning for the benefit of people. Thank you for every step of moral and financial support, you are always there for me.

Last but not the least, I would like to thank my wonderful wife, whose constant love and support keep me motivated and confident. My accomplishments and success are because she believed in me.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by Members of Supervisory Committee

This is to confirm that:
- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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LIST OF ABBREVIATIONS

3GPP	The third generation partnership project
5G	The fifth generation
AS	Antenna switching
AWGN	Additive white Gaussian noise
B5G	The beyond fifth generation
BS	Base station
BSTPA	Base station transmitted power adaptation
CE	Channel estimation
CSI	Channel state information
DoF	Degree of freedom
EE	Energy efficiency
EE-EPA	Energy-efficient equal power allocation
EH	Energy harvesting
EPA	Equal power allocation
Gbps	Gigabits per second
HetNets	Heterogeneous networks
ICI	Inter-cell interference
ICT	Information and communication technology
ID	Information decoding
IEEO	Iterative energy efficiency optimization
i.i.d	Independent and identically distributed
IoT	Internet of things
LCAO	Low-complex alternative optimization
LTE	Long-term evolution
MaMIMO	Massive Multi-input multi-output
MBS	Macro base station
MISO	Multiple-input single-output

MMSE	Minimum mean square error
MRT	Maximum ratio transmission
MUE	Macro user equipment
PS	Power splitting
QoS	Quality of service
PA	Power amplifier
RF	Radio frequency
SBS	Small base station
SC	small-cell
SE	Spectral efficiency
SINR	Signal to interference plus noise ratio
SS	Spatial switching
SUE	Small user equipment
SWIPT	Simultaneous wireless information and power transfer
TDD	Time division duplex
TS	Time switching
UE	User equipment
WPT	Wireless power transfer
ZF-BF	Zero-forcing beamforming

CHAPTER 1

INTRODUCTION

This chapter first presents an overview on the *Green* 5-*th* generation (5G) wireless communication networks followed by the related problems occurring in these wireless systems. Then a brief objectives and methodology is introduced to answer how support the aforementioned problems and achieving the research objectives. Finally, the research contributions are listed followed by thesis organization at the end of this chapter.

1.1 Background

The concept of *green communication* is a rapidly growing approach in a wide spectrum of communication technology and industrial fields. The main idea is to concentrate on reducing pollution and minimizing risk to the environment in all stage of product and processes. Besides, the energy consumption is a critical concern for network providers as the information and communication technology (ICT) industry is globally consuming up to 10% of the total energy consumption [1]. The ICT energy consumption is potentially increasing due to the fast increase in wireless and network services and extra bandwidth needed for the next generation of communication systems. However, this ICT energy consumption comes at the price of a sizable carbon footprint that is estimated to 5% of the global CO2 emissions [2]. This CO2 emission is increasing as rapidly as network services. Moreover, it is anticipated that Mobile data traffic will grow seven-fold from 2017 to 2022 [3] which means that more than 70% of the ICT industry will be wireless by 2022.

According to the reports, Base Station (BS) consumes up to 80% of the total power in cellular networks [2]. Therefore, the ICT total energy consumption motivates the academia and industry to consider green cellular networks as an essential step that can reduce the impact of wireless communications on the environment. It becomes more critical that there are intense activities aim at globally decreasing the carbon footprint and total energy consumption of cellular networks by 20% in 2020 [4]. Eventually, the aim of green communication is optimizing the networks energy efficiency (EE) so that guarantee the users' quality of service (QoS) demands.

With the rise of instantaneous communication, it is expected to push almost everything integrated into the internet across the globe. The number of devices that connect to the internet is anticipated to reach 100 billions by 2030 [5], including both human and machine communications. For this reason, the ICT industry is moving toward 5G and beyond (B5G) of communication networks. 5G systems are expected to provide a peak data rate up to 20 $Gbits/sec$, an average achievable data rate more than 100 $Mbits/sec$, and connectivity of a considerable number of devices to the internet. The aim is improving this aggressive spectrum reuse and high spectral efficiency to significantly boost the capacity of wireless networks. To this end, massive Multi-Input-Multi-Output (MaMIMO) systems, simultaneous wireless information and power transfer (SWIPT) and Heterogeneous Networks (HetNets) are three key technologies having great potentials to be candidates of satisfying the targets of 5G systems [6–8]. On the other hands, these three technologies are expected to achieve high EE, but they are energy wasteful as their power consumption increase exponentially [9–11]. For this reason, energy consumption has become a primary concern in the design and operation of 5G wireless communication systems. Indeed, the EE has become one of the critical pillars of 5G systems that emerged as a new prominent figure of eligibility due to economic, operational, and environmental concerns.

The MaMIMO system, also known as large-scale MIMO or very large MIMO, refers to a wireless system that BSs are equipped with more than 100 small antennas (a very large antenna array). It can simultaneously serve tens of user equipment (UE) with the same time-frequency resources [12]. A fundamental property of MaMIMO is that in the most propagation environments, the transmission channels become increasingly favorable. In these desirable propagation channels, the linear processing is almost optimal because the effect of inter-user interference and uncorrelated noise with simple downlink pre-coders and uplink de-coders can be disappeared. Hence, due to the large array and highly efficient spatial multiplexing gain, a large spectral efficiency (SE) and EE will be obtained [13, 14]. As well as, the published result in [15] proves that with a simple power control algorithm, MaMIMO becomes a scalable technology that can uniformly serve all the UEs with high QoS. By equipping the BS with a very large antenna array, the effect of small-scale fading can be averaged out which makes pair-wisely orthogonal channel vectors among BS and UEs [16]. For these reasons, MaMIMO can be a promising candidate for developing 5G wireless communication systems.

Meanwhile, data traffic' tremendous growth has limited the energy consumption of the cellular networks that can no longer be economical and cost-effective for low power devices such as the Internet of things (IoT) and wireless sensor nodes. Therefore, a more consistent battery recharge or battery replacement is essential to extend the network lifetime, resulting in maintenance cost mounting. Lately, SWIPT technology has been introduced as a steady and continuous energy supply for the wirelessly energy-constrained systems, which appears to be the novel research boundary of combining wireless communication and wireless power transmission [11, 17, 18]. Nevertheless, SWIPT points to the scenario in which a transmitter broadcasts electromagnetic-waves to its intended recipient capable of utilizing the power of the electromagnetic-waves for information decoding (ID) and energy harvesting (EH) at the same time. For this reason, SWIPT can be a promising technology candidate for wireless communication networks since wireless UEs with a limited battery capacity will simultaneously receive information and recharge their battery without the need for external power sources [18].

In the recent years, HetNets have been considered a wide solution that have great potentials to improve the coverage and capacity of wireless networks performance as we already moved to the green 5G cellular networks [19–21]. In such HetNets, various classes of low-cost and low-power BSs, known as small BSs (SBS), are deployed within the traditional macro BS (MBS) to ensure the seamless connectivity. HetNets are consisting of different SBSs such as micro, pico, and femto cells with different power transmission and coverage area. HetNets can bring the UEs and BSs closer to each other results in increasing UEs' throughput while reducing the transmitted signal power. In fact, enhancing networks coverage with small cell deployment has brought about considerable improvement in the SE and EE of the cellular networks that make HetNets as a promising candidate to satisfy the targets of green communications in 5G wireless networks.

To this end, wireless communication networks increasingly move to the architecture with high-density and heterogeneity deployment to overcome the ever-increasing traffic demand that is expected in the near future. The combination of MaMIMO enabled SWIPT system with HetNets can introduce the new green wireless communication era for 5G because HetNets can significantly decrease the wireless power-loss. Hence, the MaMINO enabled SWIPT with HetNets enables wireless mobile terminals to harvest power from their ambient strong radio-frequency (RF) signals broadcasted or beamformed by BSs and thus allowed their functionality without power outage risk [22].

To summarize, EE has become a critical concern for green 5G communication systems due to increasing demands for wireless technology and data rate. Therefore, it is essential to meet all UEs' QoS requirements while minimizing the power consumption of the network. In fact, EE is the primary topic in the development of 5G wireless communications that attached to the green communication concept [23]. Due to the high potential of MaMIMO, SWIPT and HetNets, the combination of them is expected in the development of next-generation of wireless communication networks. In such hybrid systems, multiple SCs coexist with a MBS that equipped with MaMIMO technology. For this reason, these two technologies are inherently complementary. On one hand, the MBS with massive MIMO offers a large number of degree of freedom (DoF) in the spatial domain, that can avoid cross-tier interference. However, as the number of macro user equipment (MUE) grows, the throughput of the MaMIMO system is limited by channel estimation overhead and pilot contamination [12]. On the other hand, the integration of SWIPT with MaMIMO can remarkably improve the system's performance and EE due to the ability of MaMIMO in providing narrow and sharp beam for UEs. Due to these great benefits, MaMIMO, SWIPT and HetNet has potentially the advantage of energy saving that significantly has drawn attention recently [24–27].

1.2 Problem Statements

In the following, the main problems of this study have been addressed and listed as

(i) In the concept of green wireless communication networks, the evolution of BS power transmission to boost the EE becomes more challenging in multi-cell MaMIMO systems since UEs sufferers from inter-cell interference (ICI) and the intertwined factors that impact the downlink transmitted power and EE of BS [2]. Most of the existing works do not take into account different user's QoS requirements. These models also depend on a fixed transmit power, which cannot reflect the actual EE levels concerning QoS requirements.

(ii) To the author's best knowledge, no study yet investigated the EE improvement by adapting the downlink BS power transmission to channel condition and different QoS requirements (including data rate requirement and maximum allowable outage probability). The earlier studies do not present a comprehensive overview of the impact of optimized system design parameters and user-level QoS on downlink power transmission and overall system EE [2, 7]. Therefore, to evaluate EE improvement, an optimization algorithm is needed based on the BS transmitted power adaptation model and QoS constraints.

(iii) In the downlink of MaMIMO enabled SWIPT systems, a striking limitation of most prior studies is situated in ignoring the BS circuit power consumption or considering it as a fixed model. This could be a practically misleading outcome as the system energy consumption changes with different system design parameters such as the number of active users, the number of BS antennas, achievable data rate, user's QoS constraints, and the type of filters at transmitter/receiver. Additionally, the optimal parameters were proven only through simulation [28, 29]. Although these optimal parameters are useful but cannot provide a complete insight into how jointly QoS constraints and different system design parameters influence the system's power consumption and EE.

(iv) In energy-constrained wireless communication networks, most of the works have intended to design the energy-efficient MIMO enabled SWIPT systems with HetNets. These studies have widely investigated the integration of SWIPT systems with HetNets under both TS and PS schemes for various MIMO scenarios. Nevertheless, MaMIMO technology has been ignored, and SWIPT systems can not exploit the ambient electromagnetic energy signal based on the deployed large antenna array at BSs. Besides, these works are mainly interested in deploying wireless energy harvesting at the SUEs or deployed EH nodes at SBSs, leading to failure in utilizing a large-scale antennas array at MBSs to reduce radiated and total power consumption. Furthermore, the impact of cross-tier interference on MUEs energy harvesting and information decoding where the MBS employs MaMIMO technology has not been investigated [30, 31]. More precisely, due to the channel estimation's imperfection, the amount of EH used in the pilot transmission will directly affect the MBS transmitted power and system EE performance. So far, the optimality of the MaMIMO enabled SWIPT system with HetNet is mainly conditional on EH's input power level and all types of received signal power, including cross-tier interference. Hence, an energy-efficient system design is very challenging.

1.3 Research Objectives

The main objectives of this study concerning the aforementioned problems can be listed as follow:

(i) To formulate a mathematical model that identifies different system design parameters which adapt the BS transmitted power to channel condition and user-level QoS requirements in multi-cell MaMIMO systems.

(ii) To propose an EE maximization algorithm based on the formulated BS transmitted power adaptation model to enhance the system's EE while guaranteeing QoS constraints.

(iii) To propose a new EE maximization framework using sequential fractional programming approach in the downlink of MaMIMO enabled SWIPT systems based on the closed-form expressions of the harvested energy and achievable data rate. The proposed algorithm jointly optimizes the channel estimation time, power-splitting coefficients, BS transmit power vector and number of antennas.

(iv) To propose a new EE maximization framework using decomposition approach with respect to the closed-form expressions of the harvested energy and achievable rate in MaMINO enabled SWIPT systems with HetNets. The proposed algorithm jointly optimizes the pilot transfer duration, power-splitting coefficients, BS transmit power vector and number of antennas.

1.4 Research Scope and Study Module

This thesis presents a critical analysis on the state-of-the-art to recognize new opportunities for green 5G wireless communication network design with the support of MaMIMO technology. The aim is to develop a crucial outlook on how EE maximization can be attempted in classical MaMIMO and its integration with SWIPT and HetNets technologies in the case of green 5G architecture. To accomplish this, different stages in the design of MaMIMO systems, varying from BSs computational operations to the hardware architecture, are investigated for EE maximization opportunities. The analysis starts with EE maximization for classical MaMIMO networks. It continues to "hybrid systems," where MaMIMO

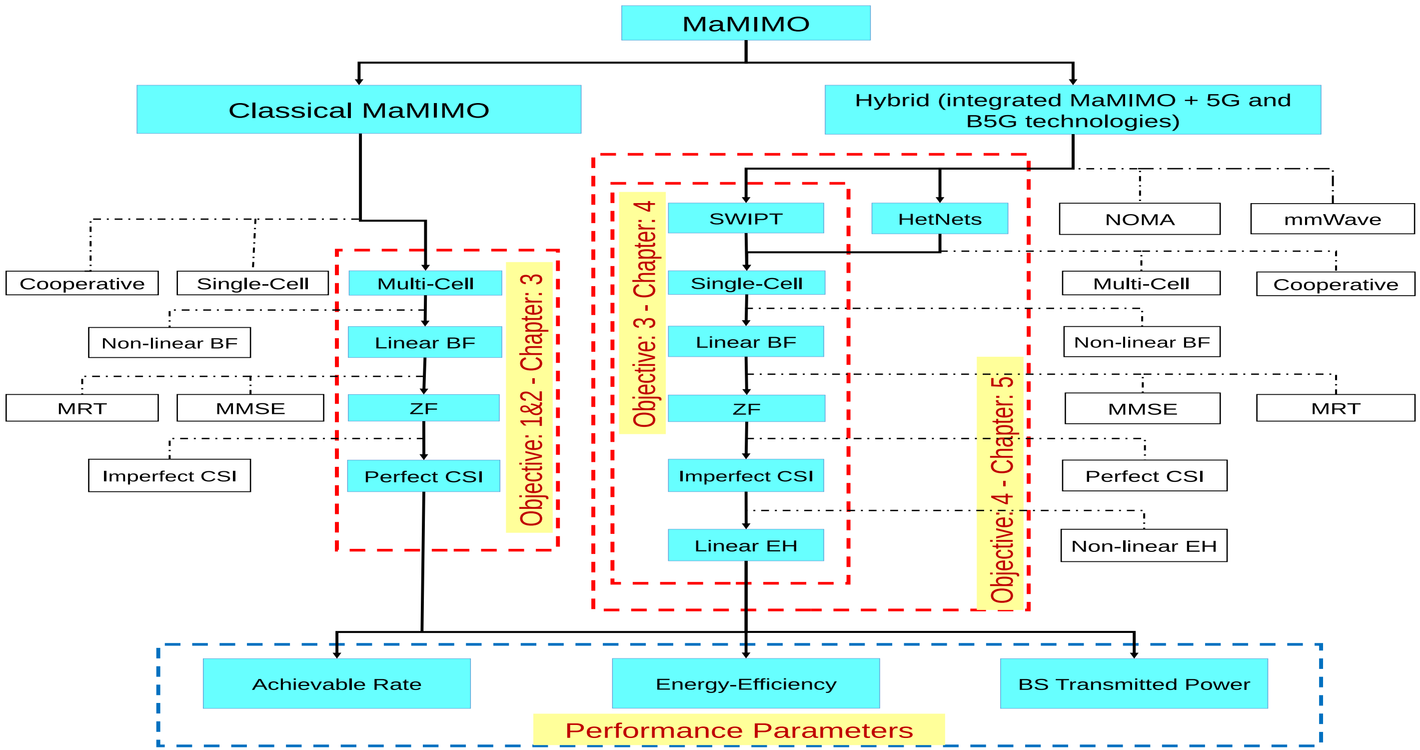

Figure 1.1: Scope of the Study.

operates in conjunction with other 5G technologies candidate, namely SWIPT and HetNets. Each hybrid system has its own set of characteristics that can be adopted to develop a new energy-efficient system design. For this reason, this thesis reviews the current state-of-the-art to determine the key research directions that strive for energy-efficient design in hybrid MaMIMO systems. It should be noted that most of the existing studies have concentrated on some particular directions, which left some new opportunities to be identified. As a result, further research problems can be determined to propose new research directions for future work. Therefore, with the newly identified opportunities and research directions, energy-efficient hybrid MaMIMO systems are believed to be promising candidates for green 5G design.

The current study's scope and the summary of the approaches to accomplish the determined objectives have been shown in figure 1.1. The colored boxes show the direction to reach the objectives mentioned earlier, and the dashed line differentiates the emerging technologies of the proposed system model in each objective. It should be noted that the un-colored boxes denote the other technologies and scenarios that are not covered in this study.

1.5 Brief Methodology

Regarding the problems mentioned earlier, followed by the four objectives, the proposed methodology to achieve the green design goals of this study can be subdivided into three phases illustrated in Figure 1.2. The first step aims to recognize the new roads to more energy-efficient system design in MaMIMO systems as the predominant 5G technology. Therefore, phase one presents the downlink of a multi-cell MaMIMO network with zero-forcing beamforming (ZF-BF), which verified with the literature reviews (demonstrated in Chapter 3). A closed-form expression of the BS transmitted power adaptation model termed BSTPA is derived which adjusts the downlink BS transmission power to channel condition and QoS limitations (w.r.t Objective 1). Also, the impact of system design parameters and QoS on the average EE per BS is investigated to propose a new optimization algorithm that maximizes the EE (w.r.t Objective 2). The proposed system model is then tested for BS transmitted power and average EE per BS where uniform data rate requirement and maximum allowable outage probability are considered as the user-level QoS to obtain the optimal system design parameters.

In the following, this study seeks to identify the new opportunities for better energy-efficient system design in the concept of green 5G wireless communication networks with support of MaMIMO technology and hybrid networks that integrated with important 5G technologies including SWIPT and HetNets. Hence, a hybrid single-cell MaMIMO enabled SWIPT system based on the power splitting (PS) scheme and ZF-BF is considered in the second phase. Imperfect channel state

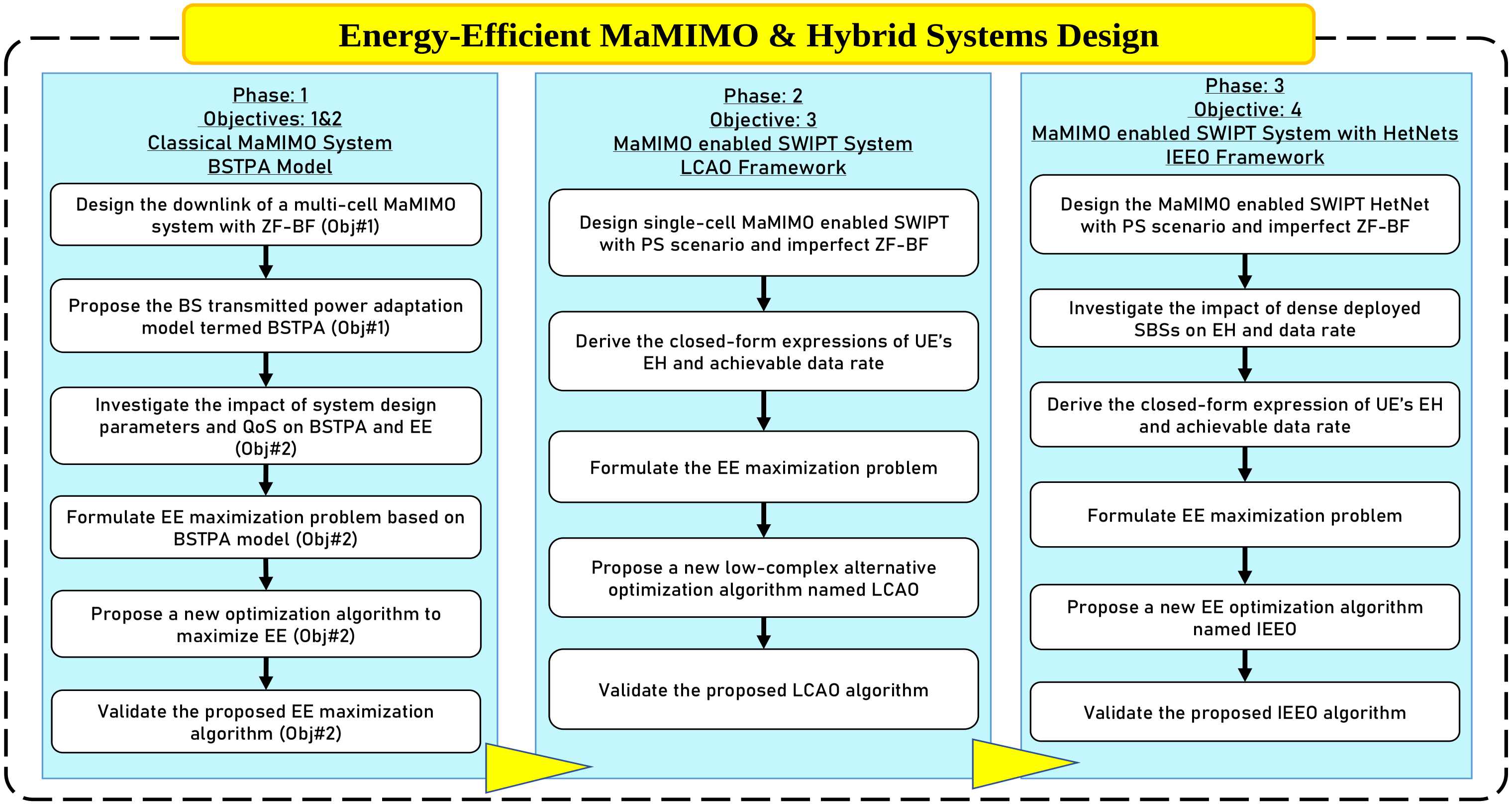

Figure 1.2: Methodology Organization.

information (CSI) is assumed since the perfect CSI is not practical in MaMIMO networks (demonstrated in Chapter 4). In the proposed system model, each UE utilizes a portion of the received signal power for channel estimation and pilot transmission. Then, the asymptotic tight lower-bound of EH and achievable rate of UEs are derived. Based on the derived closed-form expression of EH and data rate, the EE maximization problem is formulated to propose a low-complex alternative optimization algorithm named LCAO that iteratively aims to achieve the different optimal design parameters concerning users QoS and maximum BS transmission capacity (w.r.t Objective 3). The computational complexity of the proposed LCAO algorithms is then analyzed, and the optimality and convergence are validated compared to the exhaustive search. Besides, the performance of the proposed LCAO algorithm is examined with two conventional power allocation strategies.

Finally, phase three extends the work to hybrid MaMIMO enabled SWIPT systems with HetNets as another key 5G technology. The optimal downlink of a new MaMIMO enabling SWIPT system with HetNets is investigated for the third phase (demonstrated in Chapter 5). The impact of cross-tier interference from dense deployed SBSs on the EH and data rate is examined. In the proposed system model, The nearest users, also known as macro user equipment (MUE), exploit a portion of the harvested energy from the received signal powers, including cross-tier interference and employing it for pilot sequence power transmission and further signal processing. Additionally, the far UEs are connected to the dense deployed SBSs for seamless connectivity. A closed-form expression of the MUE's EH and achievable rate are derived. Eventually, a system EE maximization problem is formulated in which a more realistic power consumption model is proposed to exhibit how different system design parameters influence energy-efficient system design while maintaining QoS and maximum MBS power transmission constraints. A new optimization algorithm termed IEEO is designed aims to achieve optimal design parameters while maintaining UEs' QoS requirements (w.r.t Objective 4). Finally, the complexity, optimality and convergence of the proposed IEEO algorithm are analyzed.

1.6 Research Contributions

The Research contributions are listed as follows:

(i) A new method termed BSTPA is proposed that adapts the BS transmitted power to channel conditions and user-level QoS in classical multi-cell MaMIMO networks. For this purpose, an analytical closed-form expression of the BS transmitted power is derived for unique data rate requirement and maximum allowable outage probability as QoS constraints. The aim is to minimize the total BS transmission power to enhance the average EE per BS to achieve the green wireless communication goal.

(ii) The impact of different system design parameters (including the number of UEs served by BS, number of antennas at BS, and data rate requirement) and

QoS limitations on the BS transmitted power and average EE per BS are investigated and analyzed. This analysis provides new insights into the interaction between the propagation environment, system design parameters, and different components of the total BS power consumption model under QoS requirements. Then, a corresponding iterative optimization algorithm to maximize the average EE per BS is proposed to obtain the optimal design parameters. The proposed algorithm aims to achieve the optimal EE value globally and the optimal amount of data rate, the number of BS antennas, and the number of UEs. Furthermore, the computational complexity of the proposed algorithm is examined, and the performance of the proposed optimization algorithm based on the BSTPA model is compared with the energy-efficient equal power allocation (EE-EPA) strategy presented in [32].

(iii) Propose a SWIPT system based on the PS scheme and ZF-BF for the downlink of a massive MIMO network. In the proposed scenario, each UE mainly utilizes the energy harvesting for the channel estimation while the rest is supplied to the user's battery for further signal processing. Then, the closed-form expressions of the users' harvested energy and achievable data rate are derived. Based on the asymptotic rate, an EE maximization problem is formulated while satisfying the UEs' QoS and the BS power transmission restrictions. Since the formulated EE maximization problem is non-convex and non-linear that demands considerable challenges, a low-complex alternative optimization algorithm named LCAO is proposed. The optimal channel estimation time and the PS coefficients at the UEs side in closed-form and the optimal transmit power vector and antenna numbers at the BS side are jointly derived. The proposed LCAO algorithm is illustrated theoretically in details, and its complexity, optimality and convergence are also investigated. Finally, the performance of the LCAO algorithm is compared with equal power allocation (EPA) and max-min fairness strategies as two standard and widely used methods [33].

(iv) A dense deployed HetNet with MaMIMO SWIPT enabling system based on the PS scheme and ZF-BF is proposed. MUEs exploit a portion of the EH with the aid of SBSs' cross-tier interference power for pilot sequence transmission power, and the rest is utilized in signal processing. The average cross-tier interference is introduced and its impact on the EH and the achievable data rate of MUEs is investigated. Moreover, a new system EE maximization algorithm named IEEO is designed while guarantee QoS and BS transmission power capacity constraints followed by jointly achieving the optimal PS coefficients, MBS transmitted power and number of antennas. Finally, the complexity, optimality and convergence of the IEEO algorithm are examined. Finally, the performance of the proposed optimization algorithm is compared with EPA and max-min fairness strategies.

1.7 Thesis Organization

The remainder of this thesis is organized as follows:

Chapter 2 provides a brief overview of 5G wireless communication and enabled technologies, emphasizing the MaMIMO transmission scenario and its integration with SWIPT and HetNets technologies. The energy-efficient MaMIMO design in the concept of green wireless communication criteria is reviewed, and the QoS requirements and design parameters are addressed. Moreover, the motivation of the study and the relevant existing study are presented. Finally, the chapter is concluded, followed by a brief discussion on the outline and the significance of this research.

Chapter 3 presents the downlink of a classical multi-cell MaMIMO network employing ZF-BF, where the large-scale antennas array deployed at the BSs serve multiple single-antenna UEs. The channel model, the received signal model and signal-to-interference-plus-noise-ratio (SINR) are introduced, followed by the proposed BS transmitted power adaptation model named BSTPA. Then, the total power consumption and EE model are included. An EE maximization problem based on the BSTPA model is formulated, and a corresponding optimization algorithm is designed to achieve the maximum EE point with optimal system design parameters. Moreover, the complexity of the proposed optimization algorithm is analyzed. Finally, the simulation and analytical results are presented, confirming the better performance of the proposed BSTPA model in contrast with the EE-EPA method.

Chapter 4 introduces the downlink of a single-cell MaMIMO enabled SWIPT network employing PS scenario and ZF-BF with imperfect CSI. The system and channel models are then described in order to analyzes the average harvested energy and achievable data rate of UEs. Afterwards, the EE and the total BS power consumption models are shown and the EE maximization problem is formulated. Therefore, an iterative optimization algorithm termed LCAO is designed to obtain the optimal channel estimation time, the PS coefficients, the BS transmit power vector and the number of BS antennas. The simulation and numerical results are presented, and the study's findings are compared with two benchmarks (EPA and max-min fairness) to validate the better performance of the proposed LCAO algorithm. Finally, the chapter is concluded in the end.

Chapter 5 proposes the optimal downlink of HetNets with a MaMIMO enabled SWIPT system based on the PS scenario and employed ZF-BF with imperfect CSI. The channel model and assumptions are introduced to analyze the EH and achievable data rate of MUEs. Besides, a new total MBS power consumption model is presented to formulate a system EE maximization problem. Then, an alternative optimization algorithm named IEEO is designed to achieve the pilot transmission time allocation, the optimal PS ratios, the MBS transmit power vector and the number of BS antennas while satisfying MUEs QoS and MBS maximum power transmission capacity constraints. The simulation results are presented to validate the proposed system model performances. Lastly, the optimality of the proposed IEEO algorithm is evaluated theatrically and numerically.

Chapter 6 concludes this study, and some recommendations and directions are introduced for future works.

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