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Simultaneous Wireless Information and Power Transfer for Energy Efficient Massive MIMO

Muhammad Shahzaib Munir

Master of Electrical and Computer Engineering

Thesis Supervisor:

Assoc.Prof. Dr.Oguz Bayat

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Simultaneous Wireless Information and Power Transfer for Energy Efficient Massive MIMO

by

Muhammad Shahzaib Munir

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Department of Engineering and Architecture

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Master of Electrical and Computer Engineering

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Asssoc. Prof. DR. Oguz Bayat

Supervisor

Examining Committee Members (first name belongs to the chairperson of the jury and the second name belongs to supervisor)

Assoc. Prof. Oguz Bayat	(Committee Member)	
Assistant Prof. Çağatay Aydin	(Committee Member)	
Assistant Prof. Adil Deniz Duru	(Committee Member)	

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Assistant Prof. Çağatay Aydin

Head of Department

Approval by Institution 16 / 01 / 2018

Assoc. Prof. Oguz Bayat

Director

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Muhammad Shahzaib Munir

DEDICATION

I would like to dedicate this thesis to my loving parents DR. Muhammad Munir and Sabahat Munir and sincere gratitude towards my siblings Nimra, Fatima, Anas and Absham and my friend Awais Khan …………….

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ABSTRACT

Simultaneous Wireless Information and Power Transfer in Energy Efficient Massive MIMO

Munir, Muhammad Shahzaib,

M.S Electrical and Computer Engineering, Department of Engineering and Architecture,

Altinbas University,

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The forecast on the telecommunication industry has been severely affected with the increase in number of connected devices and mobile subscribers. Moreover, the challenging concern to the energy consumption of the wireless communication system is also the outcome of this boom. The roll out of additional base stations and data rates per subscriber has turned to chase the system's energy strains. The global mobile data and energy consumption are getting in concern for future wireless communication. Over the past decades, wireless devices have gained immense power in terms of providing multimedia services to the users. Massive MIMO is promising a numerous amount of assistance in terms of achieving the required data rate with more space to incorporate the system with energy efficient designs. The idea of Internet of things(IOT) is kickstarting the frequent growth of connected devices in future. Transferring energy to power these devices wirelessly is getting more popular these days to diminish the burden of battery with limited capacity. The media services, image and video processing are limiting the processing, battery life and storage of smart devices. For more than one century radio

frequency signals have been used to carry information and the energy in it has remained unutilized for a very long time. This has turned to give birth to the concept of harvesting energy from the radio signals which can bring the green radio communication on the table.

Simultaneous wireless information and power transfer (SWIPT) is becoming a future paradigm to deal with the energy issues of future technologies enabling the system to transfer both data and energy simultaneously. The amount of energy then can be harvested by the receiver designed purposefully to utilize this energy and bring it to power the sensor networks to increase the overall energy efficiency. SWIPT techniques are getting fairly in demand for future technologies like sensor networks, wearable devices, IOT, 5G and beyond technologies etc.

In this work we have develop an inauguration of massive MIMO system and incorporated it with the harvesting technology based on SWIPT. A space switching(SS) based massive MIMO SWIPT model is proposed in the system to investigate the energy performance. We have developed optimal and low complexity algorithms to maximize the overall EE of the massive MIMO system and analyzed the system assuming the perfect knowledge of channel state information(CSI) for all the scenarios. The balancing tradeoff between the optimizing constraints will be analyzed and evaluated to attain the optimal performance.

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Acronyms / Abbreviations

4G	Fourth generation
5G	Fifth generation
ADCs	Analog-to-digital converters
AWGN	Additive white Gaussian noise
AS	Antenna Switching
BS	Base Station
CSIT	Channel information at transmitter
DACs	Digital-to-analog converters
D2D	Device-to-device
DM	Dinklebach Method
DL	Downlink
EE	Energy Efficiency
EH	Energy Harvester
ID	Information Decoder
IOT	Internet of things
LTE-A	Long-Term Evolution-Advanced
mmWave	Millimeter Wave

M2M	Machine-2-Machine
MIMO	Multiple-Input-Multiple-Output
MF	Matched-filter
MRT	Maximum Ratio Transmission
MOO	Multi-Objective Optimization
PS	Power Splitting
QoS	Quality of Service
RF	Radio frequency
RZF	Regularized Zero-Forcing
SLNR	Signal-To-Leakage-Plus-Noise Ratio
SISO	Single Input Single Output
SS	Space Switching
SWIPT	Simultaneous Wireless Information and Power Transfer
TS	Time Switching
UE	User Equipment
UL	Uplink
WPT	Wireless Power Transfer
WET	Wireless Energy Transfer
ZF	Zero-Forcing

Symbols

ς	Efficiency of power amplifier
$\tilde{\beta}$	Eigen channel assignment
Ɲ	Number of active receive antenna set
p	Power allocation
η	Efficiency

1. INTRODUCTION

1.1 Introduction

As the previous most topical fourth-generation(4G) technology for cellular mobile communication systems, termed as Long-Term Evolution-Advanced (LTE-A), supporting 20 MHz of flexible bandwidth configuration and allowing peak target data rates of 1 GBps in the downlink and 500 Mbps in uplink to be achieved respectively. This has turned to pursue not only higher data rates but also a significant increase in spectral and energy efficiencies to meet the requirements of exponentially increasing traffic and data demands. Industry exertions and hoards to define, advance and deploy the systems and stipulations for the Fifth- Generation (5G) mobile system and services are well underway beckoning the dawn of the 5G Era. The design of future 5G cellular network will undergo some fundamental changes with the progression of modern research paradigms.

Recently the five disruptive emerging technologies that have been introduced to 5G system's design, is identified in (F. Boccardi, 2014) which includes device-centric architectures, millimeter wave(mmWave) communications, smarter devices, machine-2-machine(M2M) communications and massive-multiple-input-multiple-output (MIMO). These are classified according to Henderson-Clarke model (Afuah, 2003), shown in Fig [1.1]. Previously cellular system designs have relied on cell-structured architectures and role of devices in radio access networks were almost passive. The future trend is now evolving the cell-structured architecture into a device-centric architecture where any device can be able to communicate with the set of available heterogeneous nodes in the network to exchange multiple information flows. On the other hand, global bandwidth shortage has turned its attention to mmWave communication due to its unexploited bandwidth and huge spectrum available for cellular operators.

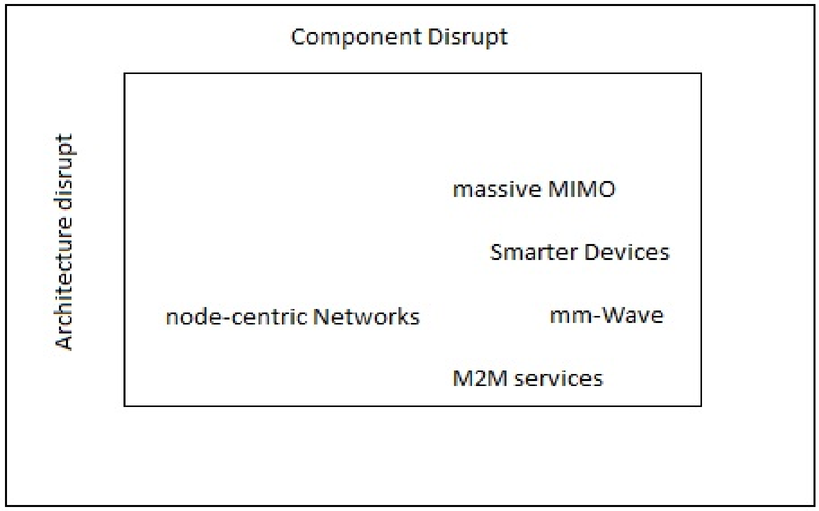

Fig. 1.1 Five disruptive technologies for 5G design

However, mmWave have issues fighting with blockages and have higher power consumption when it comes to analog-to-digital converters(ADCs) and digital-to-analog converters(DACs), mixed-signal components. Consequently, we see mmWave as a potentially promising technology for 5G communication, but it needs some radical changes both on component and architecture level which could lead us to a new user experience and unbeatable data rates. Smarter devices have been proposed that can be incorporated with 5G cellular networks, namely device-to-device(D2D) communication, local caching, and advanced interference rejection to evolve the future wireless communication. D2D communication can handle local communication more efficiently and have reduced latency. Local caching, a paradigm of cloud computing further enables content to be stored locally and thus easily accessible. In addition to D2D communication and a large volume of memory and with the idea of devices accommodating several antennas consequent the opportunity for active interference rejection concept. Future generation networks have the provision of machine-to-machine(M2M) communication where a large number of devices are connected to the network and requirements such as high link reliability, low latency, and real-time operation have to be met.

In the near future, we can expect to see high-end electronic devices integrated with communication modules which may reform our everyday lives. There will be more internet and wireless devices embedded with our everyday objects which will enable us to communicate with them and our surroundings will no longer be passive. This idea of connecting everything with the internet is termed as the internet of things(IoT) (Zorzi, 2010). The ever-growing data traffic and especially with the concept of IoT we can expect to see a drastic increase in a number of wirelessly connected devices. This trend shows that future 5G networks should handle up to unlimited-fold of current data traffic demand. There will be more demand for wireless data traffic in future, the number of connected devices is expected to reach 50 Billion by 2020 (UMTS, 2011) while the mobile data traffic to increase at a rate of 49 Exabytes per month by 2021 (Cisco, 2017), as shown in Fig. [1.2]. So, the future 5G and beyond technologies are expected to meet this demand. For wireless data traffic, one cannot neglect the importance of spectral efficiency which is directly proportional to throughput and has an inverse proportion with bandwidth. So, the new technologies should have higher spectral efficiencies to meet the requirements of modern wireless applications. It is defined numerically as the ratio

$$Spectral\ efficiency\ = \frac{Throughput}{Bandwidth}$$

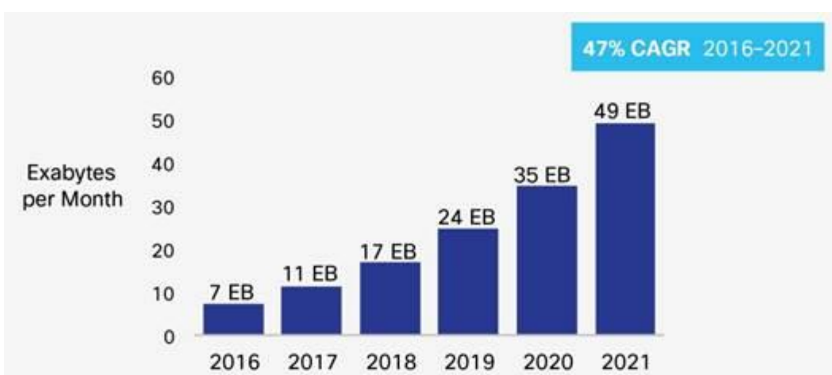

Fig. 1.2 Mobile Data Traffic Demand

Massive Multiple Input-Multiple Output (massive MIMO) technology, where a Base Station(BS) equipped with arrays of antennas will be deployed to serve multiple users at a time have tendency to meet the required spectral efficiencies. Massive MIMO is the fundamental ingredient technology for 5G and future wireless systems. In addition to spectral efficiency and throughput to get attainable data rates and with the increase in number of antennas at BS stations, energy consumption has become a main concern in wireless communication systems to exploit this technology. Bit-per- joule Energy Efficiency(EE) is the key parameter used to manipulate the consumption of energy in wireless communication systems and is defined as

$$Energy\ Eficiency(\frac{\text{bits}}{\text{Joules}}) = \frac{Throughput(\text{bits/sec})}{Power\ Consumption(\text{Joules/sec})}$$

The number of antennas in massive mimo is expected to be scaled up to tens and hundreds in number and the day by day increase in number of user equipment(UE) connected to the BS antennas are causing a major concern gradually. Therefore, one of the most demanding challenges to implement this massive array of antennas is the challenge to provide them with steady and adequate power supplies. Batteries are still referred as the most commonly and widely used source to power wireless electronic devices. The number of sensors and antennas included in a sensor network of wireless communication system is very large and the density of these devices is also high which makes the traditional solutions of replacing and recharging of batteries to prolong life time of these devices impractical. Moreover, the renewable energy sources, such as wind and solar cannot accommodate the energy requirements of massive mimo based devices due to its complexity and dependencies on location and environment (Ahmed, 2013).

The feature which allows the terminal to recharge batteries from external resources is projecting the global scientists and researchers to look into the energy harvesting technologies for the future energy efficient wireless applications. Wireless power transfer(WPT) is a new paradigm of energy harvesting technology in which energy is harvested from electromagnetic radiations or from the sources intentionally transmitted for energy harvesting purposes. The tendency of Radio frequency(RF) based WPT to provide stable and sufficient power to sensor networks over a wireless channel is tremendous. For more than one century RF signals have been used as carrier of information transfer in wireless communication which makes the possibility of transferring energy over the air with the information simultaneously giving birth to a new paradigm termed as simultaneous wireless information and power transfer(SWIPT) (Ng, 2014) (Goldsmith, March 2006). In the future, with beckoning of IOT and massive MIMO technologies, SWIPT technologies can have great tendencies in order to supply energy and exchange information with ultra-low power sensors, that is supportive to future wireless systems and cellular activities.

1.2 Motivation and Background

The latest trend in wireless communication is Green radio communication, whose designs and operations help the system, minimize the energy consumption. One of the main network design objective for green radio communication is to diminish the amount of energy consumption while keeping the satisfactory quality of service (QoS). Almost half of a mobile service provider's annual operating expenditure is spent on powering the equipment of network (Zorzi M. , 2010). The amount of electrical power consumed by each BS, in cellular networks is roughly up to 2.7KWH (UMTS, 2011). The consumption of energy per annum is very high with densely deployed BSs over the world. Such high energy consumption is responsible for high CO_2 emission. So, this high emission has put a major concern to value the environmental consideration while designing the network for green radio communication.

The telecommunication industry is held responsible for the 2% of worldwide total carbon dioxide emission (Cisco, 2017). Massive MIMO is supposed to be the part of future 5G paradigms to deal with the spectral and energy demands. Integrating energy harvesting technologies into modern communication inventions for better energy efficiency is regarded as one of the main metric for realistic implementations of future energy efficient large-scale communication systems. However, the energy configuration of massive MIMO technologies still present a significant number of open questions. Several studies have investigated and exposed the optimal resource allocation of conventional renewable energy resources, such as solar, wind etc. However, these renewable energy resources are known for their unpredictable nature and can be critical to implement for harvesting purposes specially when QOS is of principal concern. Moreover, they are prone to environmental changes which make them inconvenient to merge with future wireless systems. It is worth nothing to say about the RF-based energy harvesting that most of its applications are supportive to power the low-end applications (e.g., sensor networks), but it can somehow be implemented for circumstances with more considerable power consumptions if dedicated wireless power transmission is implemented. WPT technology, where the terminals charge their batteries from electromagnetic radiation is confidently the energy harvesting technology that overcomes the above limitations. In WPT, green energy can be harvested either from ambient signals opportunistically, or from a dedicated source in a fully controlled manner; in the latter case, green energy transfer can take place from more powerful nodes (e.g. base stations) that exploit conventional forms of renewable energy (T. Yoo, 2006).

The Nikola Tesla’s idea of wireless energy transfer(WET) has been long gone before it started gathering attention in recent years (Tesla, 1914). The exploration of new possibilities in WET techniques are due to the breakthrough innovation in the field of electromagnetic theory and wireless technologies. The concept of modern electrical power transport is the byproduct of the contribution of the scientists and inventors towards the tremendous development of public interest in WET technologies over the years. The popularity of mobile electronic devices has paparazzied the need of WPT and WET technologies re-emerged in the late 20th century. SWIPT has extended the ideology of WET and WPT for wireless applications with the fundamental changes in receiver design to transmit both power and information simultaneously. The RF signals have tendency to carry both information and power at the same time which can be utilized by the receiver designed on the criteria of SWIPT to harvest energy and decode information. The amount of energy harvested can help the system to maintain an optimal energy efficiency leading the system to an energy efficient design.

1.3 Need of Energy efficient systems

I believe energy disaggregation will be the key to modern future technologies and has a broader implication for building smart grids and automated communication equipment. The huge amount of service expectation from 5G networks along with the contribution of current mobile communication towards the global carbon footprint has put the energy consumption concern on the table. The contribution of mobile communication towards the global carbon footprint stake has put energy consumption a critical concern, when 5G networks are designed to meet such huge service expectations. Trends in (Cisco, 2017) suggest that the mobile ICT sector would emit more than 300 million tons of greenhouse gases per annum by 2020. Observe from Figure 1.2 shows that most of these emissions come from mobile access and mobile devices, i.e., from powering the wireless communications between the base stations (BSs) and the user equipment's (UEs). Therefore, for a sustainable evolution into future 5G networks, it is critical for future wireless technologies to not only address the multifold increase in service expectations, but also to operate at compact power consumption levels. The focus of this thesis is on energy-efficient massive MIMO technology, which can offer high EE levels as compared to the current LTE and LTE-A technologies.

1.4 Aims and Challenges

The increase in number of connected devices and mobile subscribers has not only affected the forecast on telecommunication market but also has put a challenging concern to energy consumption of wireless communication systems. The roll out of additional base stations and data rates per subscriber has turned to chase the system's energy strains. This explosive growth of service equipment and wireless network's energy consumption has significantly increased the world-wide CO_2 emission. With the influx of new technologies, practical implementation of energy efficient system has become more stimulating. The most challenging apprehension in energy efficient communication is the inadequate number of energy resources. The renewable energy resources are difficult merge with the future wireless systems due to its dependency on environment changes. The limitations of energy efficiency in wireless communication can only be overcome by designing the green wireless systems to achieve the energy efficiencies without compromising the QoS of the wireless network services.

The aims in my thesis is to investigate the analysis of SWIPT in massive mimo to build energy efficient communication systems. Massive mimo is the proposed future paradigm for 5G and beyond technologies and powering the large number of antennas at BS will undergo a lot of energy consumption. WET and WPT are the most appropriate energy harvesting technologies which can maximize the energy efficiency in massive mimo based communication systems. With SWIPT for massive MIMO, the energy can be harvested from external environment to maximize EE with the transfer of energy and information simultaneously. In my thesis, the scheme with the division of the exploration of massive mimo along with the investigation of SWIPT is shown in Fig [1.3].

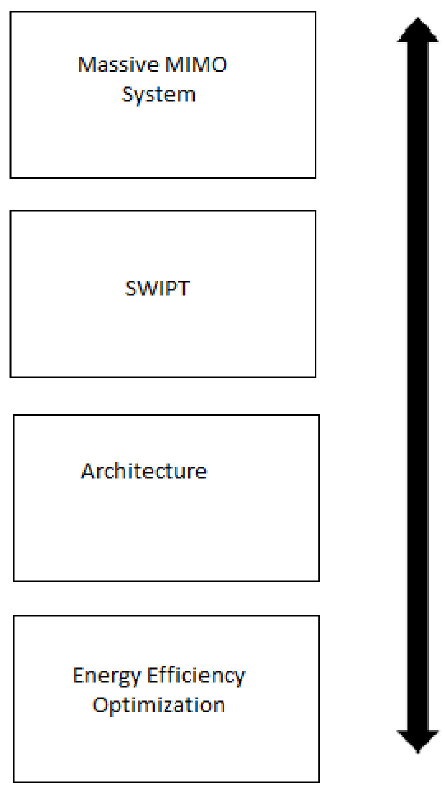

Fig. 1.3 Scheme model for research

One of the main challenge in massive mimo is to minimize the power consumption as possible at base stations. SWIPT for massive mimo is an appealing solution which can minimize the amount of power utilized with concerning architecture to be designed, to acquire the maximal results by harvesting energy from BS's RF signals. The architecture and circuit designs for SWIPT to cooperate with the massive mimo can be challenging as well.

1.5 Methodology and Research Approach

The approach and methodology used in this master's thesis can be seen as a flow diagram, visualized in Fig. [1.4] and will be further described in this section. This thesis project first consisted of a phase where expertise about massive MIMO and low-complexity hardware solutions, for per antenna functionality, was built up. In order to do this, several scientific papers were studied. To be able to investigate the aims of this master's thesis, a massive MIMO model was needed. The model was developed from scratch and necessary functions were implemented in MATLAB, partly using built-in MATLAB functions. This resulted in a simulation environment used to perform the investigations needed to reach the goals of this thesis. During this process a good understanding of the simulation framework, system model and communications theory behind it was built up.

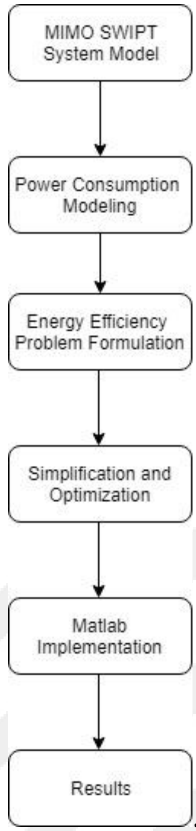

Figure 1.4 Flow diagram of the methodology

1.6 Thesis contribution

In terms of spectral efficiencies, deploying large number of antennas at BS can have tremendous outcomings for 5G and future wireless technologies. WPT technologies are getting enormous admiration these days to overcome the energy issues in wireless and sensor networks. SWIPT is said to be the anticipated solution for energy issues in wireless communication. Designing energy efficient communication systems and communication antennas based on SWIPT harvesting technology can be challenging. In this explosion, energy efficient SWIPT model for massive MIMO is analyzed to maximize the EE of the overall communication system. The contribution of this thesis can be listed as follows.

- Energy-Efficient SWIPT model: The thesis will be able to demonstrate the system model based on SWIPT based energy harvesting technologies for massive MIMO. We will follow the basic power consumption modelling for massive MIMO and follow the same model to analyze the proposed SS based SWIPT model for massive MIMO. This system will enable the communication system to harvest maximum amount of energy in order of maximize overall energy efficiencies. This can help build future green radio communication systems.

- EE optimization: We will analyze the optimization techniques to maximize the EE of the proposed SWIPT model for massive MIMO.

1.7 Thesis structure

The thesis structure is organized as follows.

Chapter 2 provides the basic Massive MIMO concept including its background material along with the linear and non-linear precoding schemes for channel estimation. Moreover, the basic power consumption modelling in massive MIMO has been discussed briefly to develop the EE problem formulation.

Chapter 3 provides the SS based SWIPT model for massive MIMO and the system has been analyzed following the power consumption modelling of massive MIMO. The metrices of EE in massive MIMO is formulated using the above power consumption modelling.

Chapter 4 provides an energy efficiency problem formulation to analyze massive MIMO under SS based SWIPT harvesting technology. Different optimizing techniques have been followed to simply the problem and maximize the possible EE for the proposed system.

Chapter 5 provides the numerical analysis of the proposed system to implement the system on Matlab and the results have been shown in form of graphs and discussions

Chapter 6 provides the final conclusion and drawbacks in the research work done. Moreover, the future scope of the study has been discussed.

2. MASSIVE MIMO CONCEPT

2.1 Background of MIMO

The concept of modern wireless communication technology that uses multiple antennas technologies at one or both ends of radio link was introduced in 1990s (Julia Andrusenko, 2015). MIMO has been considered as one of the main key enabling antenna technology for 4G wireless communication technologies, which was exploited in 3GPP standards of LTE release 8 in 2008 (Brydon). With multiple antennas, the system performance can be improved without increasing the required spectrum. Mimo system have grown a substantial reputation and the technology has been incorporated into wireless standards, such as IEEE 802.11n, IEEE 802.11ac, WiMAX, HSPA+, LTE and LTE advanced,802.16m (E. Dahlman, 2008). In wireless communications, mimo systems are providing higher data rates under certain channel conditions and providing a consistent communication under the channel fading schemes. The beamforming of multiple antennas has more network coverage which results in higher received signal power. The previous studies have shown more advantages of using multi-user mimo(MU-MIMO) over single-user mimo(SU-MIMO). Both two cases of mimo can be seen in Fig. [2.1] as both utilizes multiple antennas with different performance bids.

2.1.1 Single-User MIMO

In SU-MIMO transmitter and receiver are equipped with multiple antennas but only one device at a time is served via point to point wireless link. It is a basic mimo technology proposed initially for system performance later replaced by MU-MIMO for better results in wireless communication.

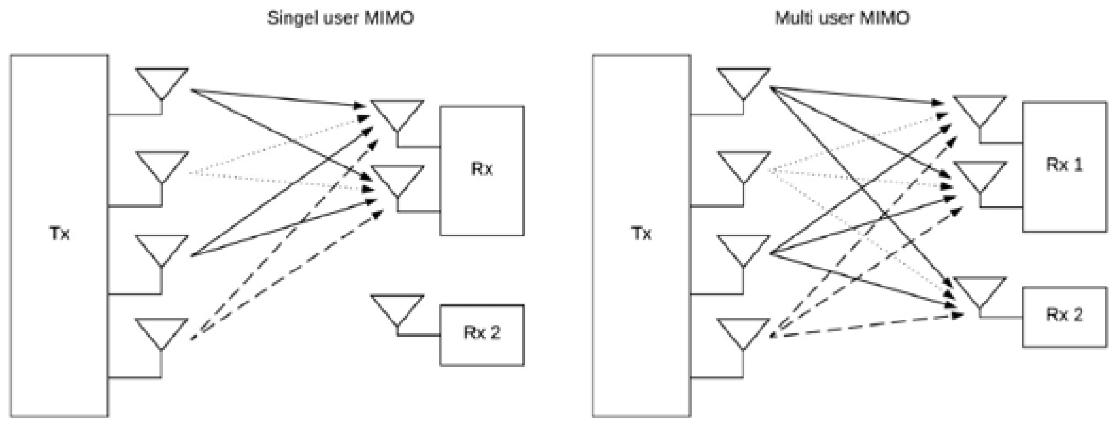

Fig. 2.1 Single-User MIMO Vs Multi-User MIMO

2.1.2 Multiple-User MIMO

MU-MIMO exploits the spatial multiplexing gain where a multiple antenna base station serves several users with multiple wireless links simultaneously. As a result, MU-MIMO overcomes the most of prorogation limitations and performance gains issues in terms of data rates. LTE allows a base station to generate two beams optimized for two receivers. A mobile receiver can decode its own beam with a low level of interference from the other beam. Such interference can be further reduced by smart scheduling in choosing the user pairs that are well separated in space channels. MU-MIMO has been incorporated with LTE-A to support up to four users simultaneously to increase the capacity, while each receiver can be able to receive multiple data streams. To minimize the mutual interference, the manipulation of signals is done on the transmitter side. A base station multi-user mimo can also receive signals from multiple users simultaneously which makes it a more promising technique as compared to the point-to-point single user mimo. The good summaries on work done on multi-user MIMO found in (T. Yoo, 2006) (Julia Andrusenko, 2015), showed that using multiple antennas at BSs and users and serving each other with multiple wireless streams simultaneously has much higher sum rates. The promising results of multi-user MIMO in wireless applications has extended the research in (D. Gesbert, 2010) to multi cell mimo cooperation. Fig. [2.2] illustrates the

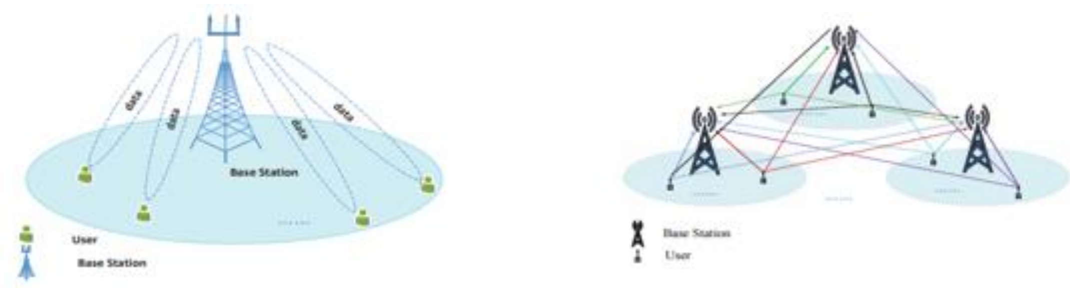

Fig. 2.2 A multi-user MIMO system and a multi-cell multi-user MIMO system

operation of a basic multi user mimo and multi cell multi user-mimo systems deployed over a wireless communication environment.

2.2 Massive MIMO: A multi user technology

Massive Mimo is the scaled-up version of MU-MIMO technology and is a future paradigm of 5G, deploying hundreds or thousands of antennas at BS to serve tens or hundreds of users simultaneously with the same time-frequency resource. Beamforming techniques are used by the signals to interact with each user terminal, improving throughput and reducing the inter-user interference without requiring extra spectrum for communication. At downlink(DL), the idea of multi-antenna BS serving many single-antenna users simultaneously, for higher data rates, link reliability and higher energy efficiencies is the basic building unit of massive mimo (E. G. Larsson, 2014) (Tse, 2003) (P. J. Smith, 2003). In future massive mimo will play a very important key role in designing energy-efficient networks with high spectral efficiencies. Fig [2.3] shows the illustration of a single cell massive mimo deployment scenario where BS equipped with M number of antennas serving K terminals of UEs simultaneously where the number of antennas at BS is much larger than the terminals at UE i.e. M>>K. In general, we consider UE with single-antenna to simplify the analysis although it is possible for a UE to have multiple antennas.

Massive mimo is not very feasible with frequency division duplexing(FDD) mode due to huge feedback overhead and substantial antenna size at BS. Moreover, the channel acquisition scales linearly with the increase in number of antennas. Generally, the solution is to operate massive mimo in TDD mode where the downlink channel can be estimated effectively at BS to exploit channel reciprocity. A single-cell massive MIMO transmitter can cut its radiated power by a factor proportional to the square root of the number of deployed antennas with deficient channel information at a fixed rate (H. Q. Ngo, 2013) . The additional channel properties, arising with the exploitation of large number of antennas at transmitter are result of random matrix theory assumptions (R. Couillet, 2011). This propagation scenario of deploying several antennas at BS is called favorable propagation where the radio links of the UE and BS terminals become orthogonal to each other (T. L. Marzetta, 2010).

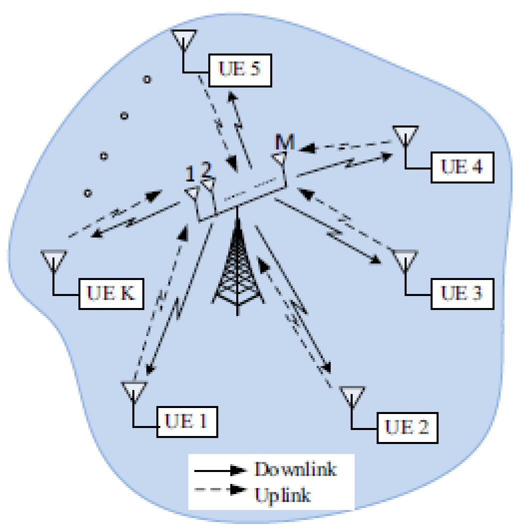

Fig. [2.3] A single-cell MIMO demonstration

Furthermore, there are lot of complications involved in hardware implementation of conventional MIMO systems whereas massive MIMO can be instigated with low-complexity hardware which makes it an informal and effective deployment as compared to current MIMO systems. We can use the extra degree of freedom designing hardware supported waveforms for massive MIMO provided by the excess of antennas at BS. The work in (Brydon) extends the result that the conventional MIMO systems with only few number of antennas fed by expensive and high-power amplifiers can be replaced by array of hundreds of antennas fed by low cost and low power amplifiers which makes massive MIMO not only striking for its higher energy efficiencies but can also yield cost-effective hardware implementations. The operators can thus able to reduce per bit cost and outspread their business around the world with the real-world reimbursements of massive MIMO.

The summary of some of the silent features of massive MIMO are:

1) A massive MIMO system will increase the spatial efficiencies multiple times and provide with high QOS with the massive deployment of antennas at BS serving multiple terminals simultaneously.
2) This massive deployment of antennas will provide with the extra degree of freedom in term of channel capacities. The following cases can show how these capacities can be utilized.
    - Single antenna serving a single terminal.
    - Multiple number of antennas serving a single terminal for QOS.
    - Hundreds or thousands of antennas serving multiple terminals simultaneously.
3) Massive Mimo technology is scalable up to multiple times as increasing in number of antennas in TDD will not affect the channel estimation. Moreover, the resources needed for channel estimation can be allocated easily in TDD operation over FDD. So maximal results can be obtained by incorporating massive MIMO into TDD as the channel estimation of FDD is highly dependent on number of antennas.
4) Massive MIMO systems can overcome the ever-growing wireless spectrum shortage.
5) Massive MIMO systems can be assembled with low-cost and low-powered components.
6) As the number of antennas at BS and number of users are large so the optimal results of massive MIMO can be obtained by using linear processing schemes.
7) Massive MIMO relies on large number of radio links and beamforming so the air interface latency exaggerated by fading can be reduced.

8) With OFDM, the sub carrier in massive MIMO simplifies the signaling and limit it dependencies on multiple access layer with substantially large channel gains.
9) Energy efficient hardware designs for antennas and other circuitries can easily be incorporated with massive MIMO systems.
10) Massive MIMO offers an effective solution that can be used to overcome signals from intentional jammers and increase the robustness against the intentional man-made interference as well.
11) All the complexity required will be on BS side.
12) Overall the deployment of Massive Mimo over a wireless communication system can result in higher data rates, spectral and energy efficiencies with appropriate link reliability.

The breakthrough contribution of massive MIMO is provided in (T. L. Marzetta, 2010) where the whole idea is proposed. The industry and academia has projected this technology to be a great potential to meet the requirements of the next-generation wireless system. On the other hand, there are still some lack of conviction considering the practical aspects and scenarios of massive MIMO.

2.3 System Model

For system model assumptions, we consider a multi user massive MIMO system as shown in Fig [2.4] in which a BS is made up with M transmitting antennas serving K active user antennas where the number of K can be smaller than the number of M transmitting antennas to keep up with the concept of massive MIMO. We assume the system to have perfect CSI and the resource for K user have a same time-frequency domain. Depending on system protocols TDD or FDD schemes can be used for channel estimation. Consider a MIMO transmission, the received signal at a K user antenna at downlink can be expressed as

$$Y = \boldsymbol{H}x + n \tag{2.1}$$

Where $\boldsymbol{H} \in \mathrm{C}^{K\times M}$ is the channel matrix formed between K and M antennas respectively and $Y \in \mathrm{C}^{K\times 1}$ is the vector to represent the received signal. Moreover, $x \in \mathrm{C}^{M\times 1}$ represents the transmitting symbols by M transmitting antennas equipped at BS and $n \in C^{K\times 1}$ describes the standard additive white gaussian noise(AWGN) with zero mean and a unit variance.

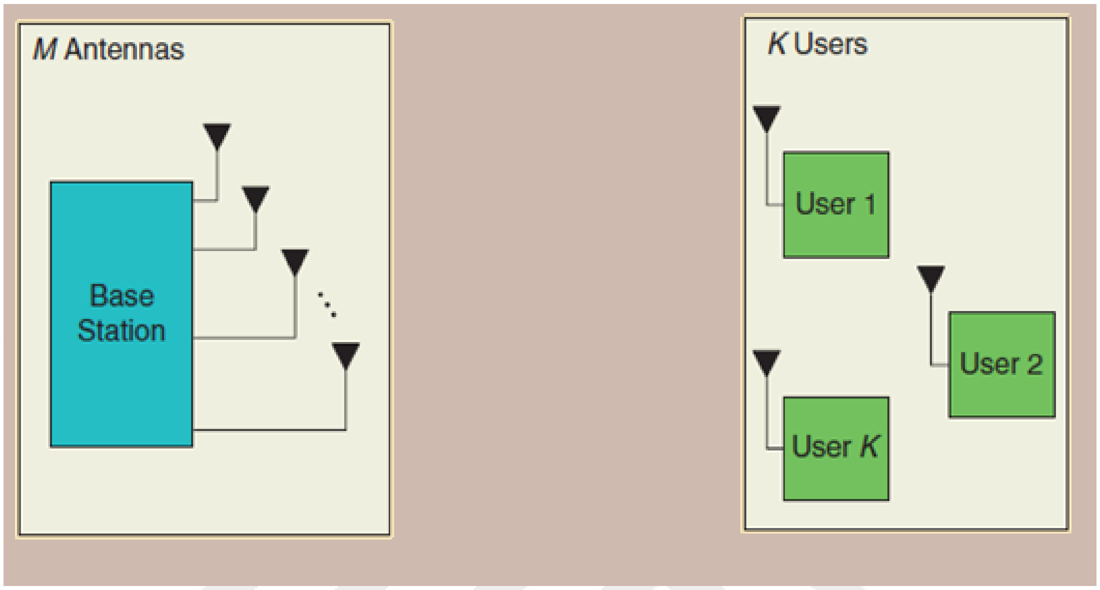

Fig. 2.4 SWIPT System Model for Massive MIMO

2.3.1 Uplink Transmission

When a K user request to connect a BS by transmitting signal the transmission link built in this scenario is termed as Uplink or reverse link Transmission. As for massive MIMO the Shannon capacity for uplink C_{UL} under favorable propagation can be expressed as

$$C_{UL} = \sum_{k=1}^{K} log_2 \left(1 + p_{u,k} M \beta_k\right) \qquad (2.2)$$

Where $p_{u,k}$ is uplink SNR for the kth antenna and large-scale fading is represented with β_k for the kth antenna of UE.

2.3.2 Downlink Transmission

Whereas the downlink transmission or forward link transmission is the scenario when a BS equipped with M transmitting antennas transmit signal to connect with the K antennas of UE and the corresponding Shannon capacity C_{DL} with $p_{d,k}$ uplink SNR for the kth user antenna can be represented as

$$C_{DL} = \max_{(a_k \geq 0, \Sigma a_k \leq 1)} \sum_{k=1}^{K} log_2 \left(1 + p_{d,k} M a_k \beta_k\right) \quad (2.3)$$

where, a_k is the optimization vector to obtain the corresponding Shannon capacity at downlink.

2.3.3 Shannon – Hartley Equation

Shannon-Hartley gives an equation relating the maximum capacity of the channel having a certain bandwidth and some amount of noise, according to the theorem proposed the maximum capacity for AWGN channel can be given as follows

$$C = B \log_2(1 + \frac{S}{N})$$

In this formula C is the maximum capacity that can be achieved by a channel in bit/second, B denotes the bandwidth of that channel in Hertz and S is the amount of signal in Watts. The signal to noise ratio in dB is represented as $\frac{S}{N}$ and N here denotes the noise power.

If a binary digit is sent across a AWGN channel with a transmission rate R, that would be equal to the channel capacity (R=C). The Shannon equation becomes

$$\frac{C}{B} = \log_2(1 + \frac{E_b}{N_0}\frac{C}{B})$$

where E_b demonstrate the average energy per bit and N_0 is the noise power spectral density.

Rearranging,

$$\frac{E_b}{N_0} = \frac{B}{C}(2^{\frac{C}{B}} + 1)$$

Letting $\frac{C}{B} = \eta$ the equation becomes

$$\frac{E_b}{N_0} = \frac{2^{\eta} - 1}{\eta}$$

The things that limit the capacity of MIMO is the number of transmitting and receiving antennas along with the coherence interval. Considering large number of antennas and a multi-cell environment, the factor of inter-cell interference also affects the channel capacity, so the number of pilots for each user should be allocated accordingly to get maximum capacity. With large number of antennas with massive MIMO any number of users can be scheduled.

2.4 Overview of Precoding schemes for Massive MIMO

In MU-MIMO precoding and detection schemes are used to limit the effect of inter user interference so that signal-to-noise-ratio(SNR) at each user can be increased. In general, to separate the independent data streams, precoding schemes are employed at uplink and detection schemes at downlink respectively. Precoding schemes are significantly the essential part of signal processing in MU MIMO systems. In this section, we will briefly describe some common precoding scheme used in multi-user MIMO systems. Precoding of MIMO is further categorized into linear and non-linear precoding schemes as shown in Fig. [2.5]. In massive MIMO non-linear precoding will undergo higher signal processing complexity whereas maximum achievable rates

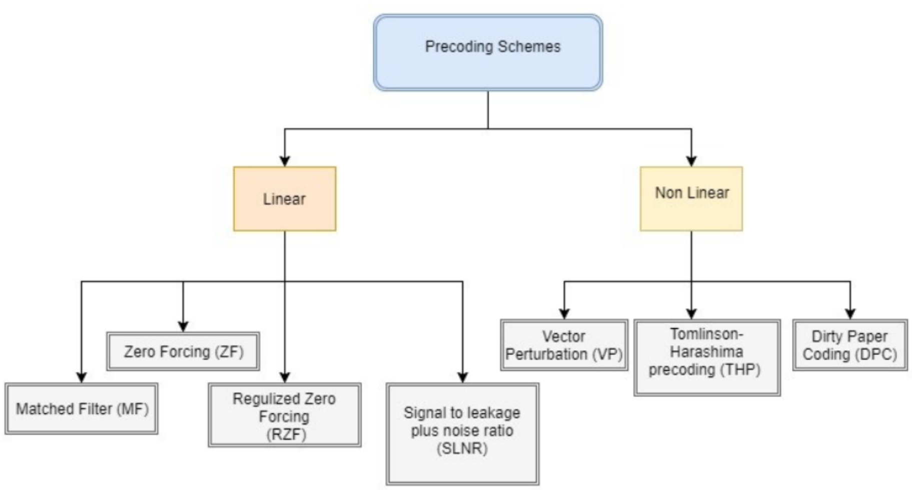

Fig. 2.5 Types of Precoding Schemes

can be attained. The signal processing involved in linear precoding techniques are modest and have turned out to be near optimal with the increase in number of antennas in MU massive MIMO systems.

2.4.1 Non-linear precoding

As described earlier these precoding techniques involves higher complexity but can be employed for higher achievable rates. Dirty paper coding(DPC) techniques can enhance the maximum achievable sum rate in downlink channels of MU-MIMO system. DPC was proposed in (Costa, 1983) to reduce channel interference, However the complexity involved in it is much higher and grows exponentially with the number of users (U. Erez, 2005). Vector perturbation(VP) is another non-linear precoding that inspect the user data for noise cancellation before transmission. This technique can also help improving the performance of linear precoders but comes at a cost of significant signal processing complexity (B. M. Hochwald, 2005). The non-linear that is more practical since and involves less complexity as compared to DPC and VP is the Tomlinson-Harashima precoding (THP) (C. Windpassinger, 2004). The results obtained with this precoding are not satisfying and power loss involved in it damages the transmission energy efficiencies.

2.4.2 Linear precoding

The most common linear precoding used in MU-MIMO systems are detailed as matched-filter (MF), zero-forcing (ZF), regularized zero-forcing (RZF), signal-to-leakage-plus-noise ratio (SLNR).

2.4.2.1 MF Precoding

MF is the simplest and most inexpensive linear precoding technique used to increase the received power to maximize SNR at each user. It is also known as maximum ratio transmission(MRT) (Lo, 1999). Let **F** be the general precoding matrix then F_{MF}, data vector for MF precoding can be defined as

$$F_{MF} = H^H \tag{2.4}$$

where, H is the channel matrix and normalizes the average power of MR precoder. The performance of this precoder is not very satisfying in mitigating the interference at each user (D. Tse, 2005).

2.4.2.2 ZF Precoding

The ZF precoder is computationally expensive but far superior as compared to the MF precoder. It fully eliminates the intra-cell interference to enhance the pre-detection noise at receivers prior to transmission (Meyer, 2000). The expression for ZF precoding data matrix can be given as follows

$$F_{ZF} = H^H (H H^H)^{-1} \tag{2.5}$$

where, H is the estimated channel matrix and F_{ZF} is the ZF precoder to increase SNR at each user.

2.4.2.3 RZF precoding

Regularized zero forcing is the performance enhancement precoder for ZF precoding technique which helps ZF in maximizing the SINR and mitigating the inter-user interference at each user. It just regularizes the precoding matrix to a factor ϑ. The precoding matrix for RZF is thus defined as

$$F_{RZF} = H^H (HH^H + \vartheta I_N)^{-1} \tag{2.6}$$

where H is the channel matrix and the optimal regularization factor for a single-cell scenario is given by ϑ opt $=N\sigma^2$ (A. B. Gershman, 2010). RZF precoding is predictably set to satisfy the minimum mean square error (MMSE) criterion.

2.4.2.4 SLNR precoding

There is no difference between the general form of SLNR and RZF precoder, however RZF precoding technique is supposed to minimize the MMSE of the transmitted and received symbol vectors, as in SLR precoding technique the SLNR precoder aims to maximize the signal-to-leakage-plus-noise-ratio (M. Sadek, 2007) (H. Tataria, 2015). The expression for SLNR precoder is same as of RZF precoder and is given by

$$F_{SLNR} = H^H(HH^H + \vartheta I_N)^{-1} \tag{2.7}$$

2.5 Limiting factors of massive MIMO

Despite the terrific benefits of Massive MIMO, the deployment of large scale antennas at BS reveals a series of challenges prior to its real-world execution. In particular, we will address some of the limiting factors of massive MIMO in 5G and beyond technologies in this subsection. Described below is the concise presentation of the practical limitations of massive MIMO.

2.5.1 Pilot contamination

In massive MIMO considering the realistic multi-cell scenarios the throughput and EE performances of the system are affected by a phenomenon called pilot contamination in which the channel estimate attained in a given cell will be contaminated by pilot sequences transmitted by the UEs in other cells. Real time cellular networks consist of many cells where many of these cells have to share the same time-frequency resources due to limited frequency spectrum. Orthogonal pilot sequences are difficult to assign for all users in all cells in multicellular system due to which terminals are expected to use non-orthogonal pilots which causes performance imperfections at BS. Even increasing the number of antennas at BS does not vanish the effect of Pilot contamination is thus a major limitation of MIMO. The visual representation of pilot contamination in a multicell cellular system is shown in Fig. [2.6].

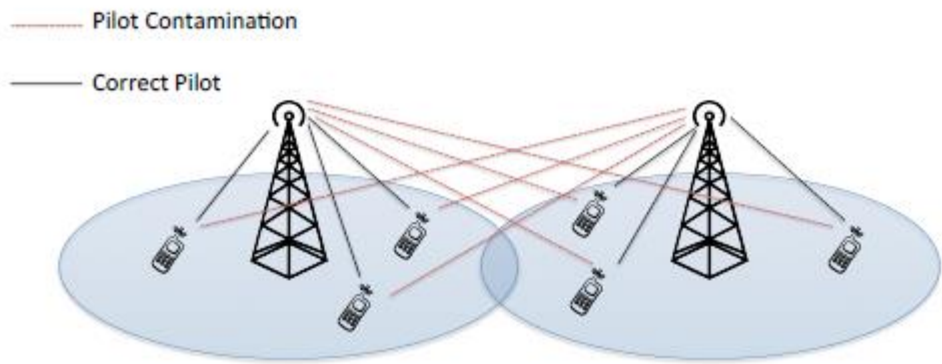

Fig. 2.6 Visual Representation of Pilot Contamination

Recent work has adopted different approaches to mitigate the effect of pilot contamination. Protocol-based techniques (T. L. Marzetta, 2010), (Y. Li, 2012) (K. Appaiah, 2010) (F. Fernandes, 2013) blind transmissions (H. Q. Ngo E. G., 2012) and pilot contamination precoding schemes are proposed in (C. Windpassinger. R. F. H. Fischer, 2004) (Gershman, 2010) (M. Schubert, 2004). Moreover, there is still ongoing research on this topic.

2.5.2 Unfavorable Propagation Condition

Many theoretical studies on massive MIMO literature is based on the phenomena called favorable propagation which is closely related to deployment of large number of antennas at BS and user channels become orthogonal with it (see section 2.3). However, in practice there may be unfavorable propagation environment which does not allow channels to incorporate with the system. For example, when the number of scatterers is small as compared to number of users in a propagation environment which means different users in BS have to share common scatterers which will make the channel unfavorable for estimation. Distributing the antennas at large scale can overcome this problem. But still "Does massive MIMO really rely on favorable propagation?" still need a lot of investigation to employ a proper channel estimation in real propagation environments.

2.5.3 Hardware Complexity and Design Constraints

A huge effort from academia and industry is required to design system constraints in massive MIMIO to maintain its compatibility with the hardware. As the current LTE standards usually allow up to 8 antenna ports at BS (Gesbert, 2007). In massive MIMO, to accommodate large number of antennas at BS, new design and standards are required to integrate the current system with efficient deployment. So, the BS in massive MIMO will undergo with a lot of hardware complexity. In addition to that, with massive MIMO, the costly transceivers, amplifiers, DAC and ADC converters should have to be replaced with inexpensive and low powered amplifiers and transceivers to regulate massive array of antennas at BS. Since the hardware design of massive MIMO is very complex so it is very important to design it as inexpensive as possible, thus related hardware designs should have to be considered.

High hardware complexity often leads to low efficiency in terms of cost and energy. Antennas are usually cheap and easy to deploy, but RF chains can be relatively expensive. Due to large array gains, massive MIMO is energy efficient in terms of radiated transmit-power. However, energy consumption in hardware can be quite high. Analog and RF components are expected to dominate massive MIMO energy consumption. Many studies have been conducted to simplify the hardware complexity of massive MIMO to make this technology into practice. In my thesis SWIPT based harvesting system will be incorporated with massive MIMO to limit energy consumption in hardware at both ends of the communication system.

2.5.4 Power consumption challenges

With the evolution of massive MIMO, BS can be able to support large number of antennas serving multiple number of users simultaneously. This will lead the system to hardware complexity and power consumption challenges at BS. Although massive MIMO is proposed to be an energy efficient technology as it provides opportunities to improve EE and provide large degrees of freedom for obtaining reasonable spectral efficiency, while at the same time possessing the total power consumption at a low level when using low powered hardware. So, the main challenge is to design EE models for massive MIMO, so it can able to bring the new dimensions to green communication. Current academia is working on improving energy performances of massive

MIMO in wireless communication systems. This thesis will focus on energy harvesting based EE optimizing technologies for green wireless communication.

2.6 Power Consumption modeling in massive MIMO

In massive MIMO, while considering a wireless network system the major possession of power consumption is at BS with downlink communication, UEs power consumption is totally dependent on the strength of transmitted power from antennas at BS. As massive MIMO involves deployment of large number of antennas which will help in strong beamforming and strength of transmitted signal will be very high, SWIPT will help optimizing the energy by harvesting the maximum energy at receiver end. We will adopt a realistic power consumption model for our energy efficiency investigation. Studies in (G. Auer, 2010) shows the power consumption model of different types of BSs in LTE. We will consider the power consumption model used in prior work (K. N. R. Surya Vara Prasad, 2017) for energy efficiency analysis in massive MIMO. The sum power consumption of the massive MIMO transmission can be modeled as

$$P = P_T + P_{cir} + P_{syn} \tag{2.8}$$

Where P_T is the total transmission power, P_{cir} is the circuit power consumed which is linearly dependent with the number of antennas M at BS. It also accounts for the power consumed in mixers, filters, frequency synthesizers, DACs and ADCs and P_{syn} refers to the remaining system power consumption. Moreover, P_{syn} is the amount of power consumed by remaining system dependent components. As the transmission power involves the power consumed by the power amplifiers as well.

Therefore,

$$\mathrm{P_T} = \frac{P_T}{\eta},$$

where, η is the drain efficiency of the power amplifier. Moreover, considering the lossy factors $\sigma_{feed}, \sigma_{cool}, \sigma_{DC}$ and σ_{MS} in the antenna feeder, DC power supply, cooling system and main supply the total power consumption expression can be written as

$$P = \frac{\frac{P_T}{\eta\ (1-\sigma feed)} + P_{cir} + P_{syn}}{(1-\sigma DC)(1-\sigma cool)(1-\sigma MS)} \quad (2.9)$$

Let Ϛ denotes the reciprocal of drain efficiency of amplifiers and other lossy factors, the whole transmission power will join up as $ϚP_T$. Thus, the total power consumption of MIMO system can be represented as

$$P = ϚP_T + P_{cir} + P_{syn} \quad (2.10)$$

whereas, the expression forP_{cir} can be given as

$$P_{cir} = M\left(P_{DAC+ADC} + P_{filter} + P_{mixer}\right) + P_{syn}$$

As massive MIMO technology uses large number of antennas so power consumption at BS is highly dependent on number of RF transmission chains N_{TRX}. So, the range of power can be distributed as follows

$$P_{in} = \begin{cases} N_{TRX}.\left(P_0 + \Delta_p P_{out}, \quad 0 < P_{out} \leq P_{max}\right) \\ N_{TRX}.P_{sleep}, \quad P_{out} = 0 \end{cases}$$

where P_{max} is the maximum RF output power and P_{sleep} represents the power consumption at sleep mode, P_0 is the power consumption at zero RF output power and Δ_p is the slope of the load dependent power consumption. We will consider the above power consumption model for our system investigation.

2.7 Energy-Efficient Massive MIMO

To guarantee sustainable evolution, EE have become an important design criterion for future 5G and beyond technologies. Massive MIMO is a key enabler technology to achieve high spectral efficiencies by increasing number of antennas at large scale. The energy efficiency of massive MIMO can be maximized by cutting off the power consumption without compensating the spectral efficiencies. Based on different analogies, a number of research directions have been trailed for the design of Energy-Efficient massive MIMO systems. We can observe from (Ericsson, 2014), by achieving near-optimal throughput performance, EE of a massive MIMO system can be maximized. Available literature has devised few methods to design low complexity algorithms for BS like user scheduling, precoding schemes and multiuser detection, so as to cut the power expenditure in the system. Moreover, power consumption in the system can also be minimized by efficient resource utilization and relaxing hardware requirements by methods such as, antenna selection, power amplifier dimensioning and economical transceiver designs (K. N. R. Surya Vara Prasad E. H., 2017).

Focusing on energy optimization, radio resources can be tuned into efficient energy designs to maximize the exploitation of reliable information transmitted per watt, by efficiently using the power distributed over the network. Many novel approaches have been proposed to increase EE in wireless communication systems. In this regard prior work in (Ali Yazdan, 2017) have shown some significant proceedings in optimizing EE in massive MIMO. Depending on number of RF chains, there is a tradeoff exists between spectral efficiencies and power consumption which means decreasing RF chains help decrease the power consumption compensating the spectral efficiencies of system as well. Studies in (Ali Yazdan, 2017), (O. El Ayach, 2014) proposed the hybrid digital/analog precoding for massive MIMO with marginal loss in spectral efficiencies, while power consumption is always lowered. Hybrid precoding can be useful in rural areas where smaller numbers of users are found. Besides this more studies in (Ali Yazdan, 2017) have shown two more promising techniques to lower the power consumption so that maximum EE in massive MIMO can be achieved. One of them is varying the ADC resolutions to respect front haul bandwidth constraints in C-RAN based energy efficient architecture for massive MIMO and other involve energy harvesting with WPT which we are going to discuss in detail in upcoming chapters.

3. SWIPT FOR MASSIVE MIMO

3.1 Problem statement

Most of the previous studies focus on obtaining CSIT in a communication system whereas the energy efficiency of the system is neglected. This lack of consideration may lead the system to higher power consumption and poor energy efficiency. The ideal performance of the system cannot only be achieved only by the perfect channel information at transmitter (i.e. CSIT) of the system. The exponential increase in number of connected devices is causing a major concern in power consumption of future wireless applications. The high-end applications, video streaming, gaming, high-speed streaming and downloading are affecting the battery performance of the devices. The main power source for wireless network such as sensor networks are batteries having limited operation time. It is usually very inconvenient and expensive to replace or recharge batteries every time and it can be risky in toxic environment sometimes. The modern technology is adapting energy harvesting technologies to get rid of battery issues. The most promising energy harvesting technologies are WPT and WET, where the energy maybe harvested from ambient electromagnetic resources. Typically, the lower power applications are more supportive towards the RF-based energy harvesting technology. In this regard, SWIPT is making its way to incorporate with the modern communication systems. The idyllic recitals of SWIPT performance in massive MIMO systems has been proposed in (Zhang, 2016).

For MIMO systems the previous literature (Zeng, 2015) has shown that the system using TDD for acquiring CSIT for the uplink and downlink channel reciprocity have more advantages over the system using FDD. In order for a MIMO SWIPT using TDD, the studies have shown many optimal transmission schemes. To obtain the efficient and reliable results, the limited feedback scheme is proposed to be the realistic approach to obtain CSIT, which enables transmitter to perform these optimal transmission schemes. In traditional communication system, the limited feedback system’s receiver first estimates the downlink channels sent from transmitter and then receiver based on transmitter channel information send a feedback back to transmitter (Love, 2008). For

SWIPT system both the information and energy transmission should be assessed to analyze the impact of feedback on receiver. Moreover, the cost of energy and time consumed by sending feedbacks can also be reduced by short feedback sequence. The main aim of the thesis is to analyze the system performance of SWIPT incorporated with massive MIMO for energy optimization. The main advantage of massive MIMO is its feasibility to incorporate with WET technologies easily, and is thus provides a natural solution to energy efficient wireless communication. The massive number of antennas at BS is providing an extreme degree of freedom to incorporate massive MIMO with SWIPT based energy harvesting technologies. We will propose a SWIPT model for a multi-user massive MIMO system and analyze the energy efficiency and overall performance of the system.

3.2 Existing solutions and performance of SWIPT

A non-trivial tradeoff for maximizing information rate versus power transfer by optimizing the input distribution of the performance analysis of SWIPT for single antenna or SISO has been shown in (L. R. Varshney, 2008) by Varshey. He proposed a Capacity-Energy function for fundamental tradeoff between Information and energy transfer. However, the above results can only be obtained under certain power constraints, no non-trivial tradeoff exists for average power constraints. Further in (P. Grover, 2010) the work of Varshey is extended to frequency-selective function for optimizing the maximal information vs. energy transfer which turns the average power constraints to have a non-trivial tradeoff.

The optimal performance of SWIPT with practical implementation of MIMO broadcasting in terms of energy efficiencies has been proposed in (Zhang, 2016). A three-node system model is proposed which consists of a transmitter and two different receivers responsible for information decoding and energy collection from RF based energy signals respectively (ID and EH). ID and EH can also be embedded with same user terminal. When both the receivers are integrated with in one user terminal, the energy harvester module is responsible to collect energy beams from RF energy signals which could help achieving high energy transfer efficiency and ID receiver module will usually participate in CSIT estimation. The paper also includes two effective structure for receiver, time switching (TS) and, power splitting(PS), in terms of one terminal receiver. The energy receiver and the information receiver work in two orthogonal time slots in time switching whereas in power splitting, the received signal splits into two different power level signal streams, one sent to ID and other to EH respectively. Since the transmission schemes for information transfer and power transfer are different from each other, the Rate-Energy region has been proposed in this paper so that the performance of both receivers can be sustained.

Besides time switching and power splitting two more schemes for receiver has been discussed latterly in (Ioannis Krikidis, 2014). One of them is antenna switching (AS) which include the dynamical switching of each antenna element between decoding/rectifying for SWIPT, dividing the receiving antennas into two group, one for information decoding and other harvesting energy respectively. The other one is spatial switching (SS), the technique in which communication link is transformed into eigen channels that can either decode information or harvest energy. The output of each eigen channel contains a switch that drives the channel output to ether conventional decoding or to rectifying circuit. The performance analysis all the four schemes is discussed with numerical illustration in (Ioannis Krikidis, 2014). The results have shown the performance benefits of PS scheme over the AS scheme as outperforms it for a high transmitting power, while TS scheme has poor performance due to required time division. Moreover, the complete explanation of these schemes can also be found in this paper.

Previous studies in (Xu, 2014) (Zeng, 2015) have investigated some of the CSIT estimation schemes for wireless energy transfer systems which can equally applicable to SWIPT MIMO systems as well. A novel design framework has been proposed in (Zeng, 2015) to obtain channel reciprocity and maximizes the net harvested energy at energy receivers but the channel reciprocity is held only for system using TDD. Later in (Xu, 2014) feed-back based channel learning method is proposed for MIMO wireless energy transfer which is applicable for both TDD and FDD operation. It is generally very difficult for energy receiver to perform in channel estimation due to hardware limitations of energy receivers, as CSIT estimation involves complicated signal processing. The analytic results of feed-back based channel estimation are more appealing as compared to other existing similar work. However, the system performance can also be increased by increasing feedback bits, but this can somewhat affect the energy efficiency. One-bit feedback can be used where energy efficiency is of main concern. Ideal performance of the studies on feedback based schemes can be seen in (Xu, 2014).

SWIPT for a MISO system is considered in (Chen, 2014) which maximizes the energy efficiency of the system by harvesting energy at receiver during information and energy transfer simultaneously. To increase efficiencies of both power and information transfer the author proposed a quantized feedback scheme but simply ignores the fact that feedback consumes more energy and time. However, the perfect accuracy of CSIT of the system can be obtained using feedback design. Our aim in this thesis is to obtain maximum energy efficiency for the system without compromising on the perfect CSIT and system performance. The system performance for CSIT estimation is limited with FDD operation but feedback schemes can be used to increase the performance, whereas for maximal system performance and high energy efficiency can be obtained operating the system in TDD. Therefore, we will analyze SWIPT for massive MIMO for energy efficiency in TDD.

3.3 System Model

In my thesis, a TDD triggered downlink MU massive MIMO system has been considered as shown in Fig [2.4] from chapter 2 and the corresponding SWIPT for massive MIMO is modeled in fig [3.1]. To transmit information and energy signals simultaneously, the system's BS is furnished with M multifunctional transmitting antennas. Let K be the number of users equipped with a single antenna in which ID and EH component is embedded with the same user terminal and to keep up with the concept of massive MIMO, the K user antennas are smaller in number as compared to the number of transmitting antennas i.e. M>>K. The single K user represents a single receiver antenna with an information decoding and energy harvesting component. Most of the previous work on SWIPT MIMO consider PS or TS receiver techniques for optimizing the system performance. Hence in this thesis, we will adopt SS-based MIMO SWIPT for energy maximization of the overall system. Therefore, the ID component and the EH component will follow SS based receiving scheme. The EH component can gain energy from energy bearing RF signals and plays an important role to supply energy to ID component. In the context of SS-based receiver, the corresponding eigen-channels formed by the decomposition of MIMO channel using singular value decomposition(SVD) is being used either to send information or transfer energy at a time (D. W. K. Ng, 2014).

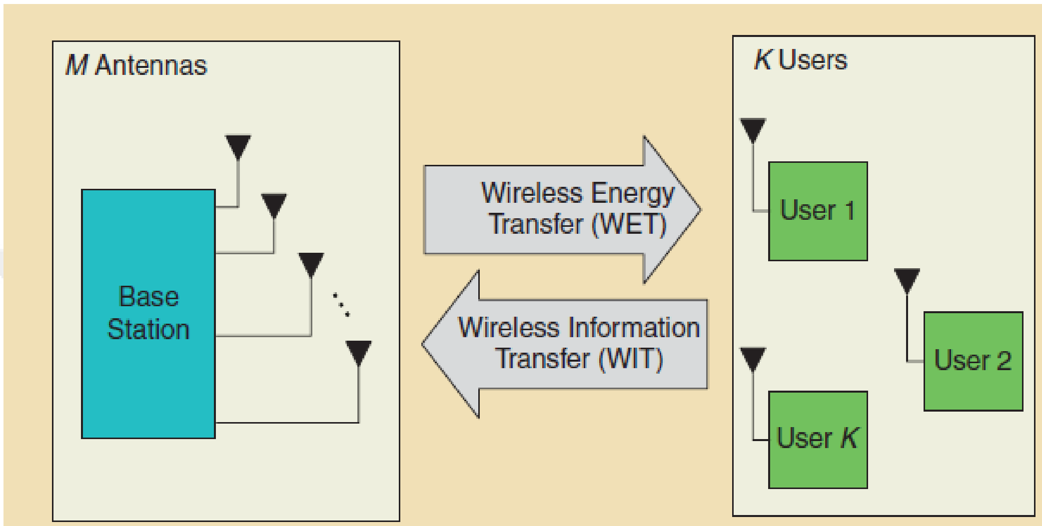

Fig. 3.1 SWIPT Model for massive MIMO

Considering the source is connected to a constant power supply, while the destination is capable of transferring and harvesting the maximum amount of energy simultaneously, Fig [3.2] illustrates the schematic example of massive MIMO SWIPT with SS based receiver. The original work on SS based SWIPT in (S. Timotheou, 2015) focuses on minimizing the transmit power, however this may not be energy efficient as overall power consumption of the system heavily depends on circuit power at both ends. Therefore, this thesis investigates the EE maximization of SWIPT for SS based massive MIMO with practical power consumption model. Moreover, the number of active user antennas, transmitting power and energy harvested are taken in to consideration to analyze the energy efficiency of the system.

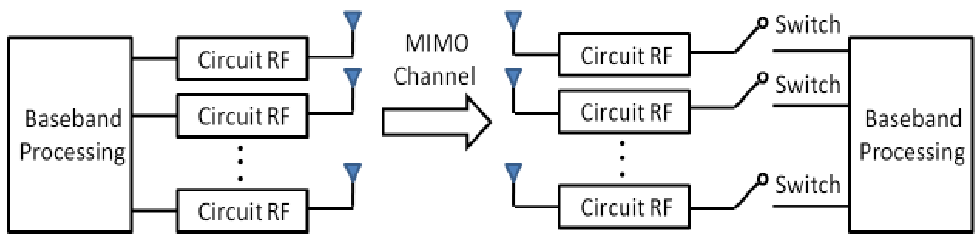

Fig. 1. Schematic example of a point-to-point MIMO system with SS-based receiver.

Fig. 3.2 SS based receiver for point to point MIMO

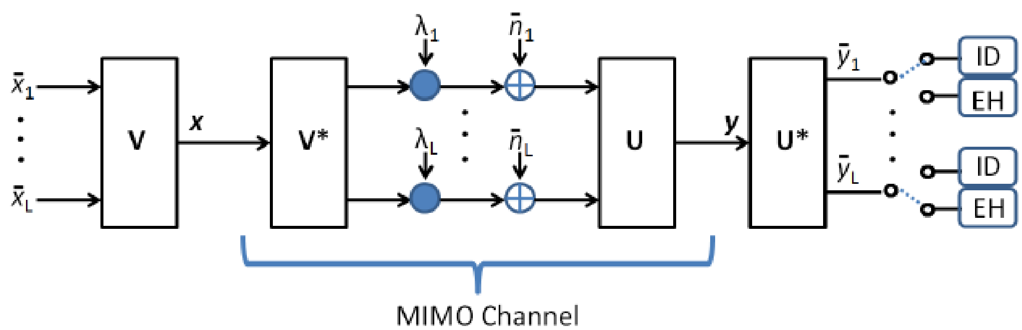

Fig. 2. Schematic example of the SVD of the MIMO channel into L parallel AWGN channels.

Fig. 3.3 SVD of massive MIMO for L SISO channels

Higher sum rates and maximum harvested energy can be achieved by employing large number of receiver antennas, but this comes with a cost of high transmitting power, so we can tradeoff between net harvested energy and transmit power to obtain high energy efficiency. Maximum EE can be obtained by the suitable selection of active receiver antennas by activating the corresponding RF chain, switches either to transfer information to ID or energy to EH. As a result of this trade-off, utilizing all the available antennas with SS receiver will help obtaining the desired harvested power. With the number of active receive antennas K, the selected active antenna is represented by Ɲ = {1,2,3…. K}. The channel matrix representing source to destination can be represented as $\mathbf{H} \in C^{K \times M}$. An uncorrelated flat-fading MIMO Rayleigh channel model is considered in this thesis and with the active receive antenna set χ the corresponding channel from BS to UE can be represented as $\mathbf{H}_{\mathrm{N}} \in C^{K\times M}$, where K = |Ɲ|. Considering the additive white Gaussian noise(AWGN) vector with zero mean and unit variance be $x \in C^{M\times 1}$ and the transmit signal vector be $n \in C^{K\times 1}$ respectively.

The received signal is expressed as

$$Y = \mathbf{H}_{\mathrm{N}} x + n \tag{3.1}$$

The mutual information(MI) in the MIMO SWIPT system with the SS-based receivers is illustrated in (M. Sadek A. T., 2007). Let Q be the transmit covariance matrix, therefore with the selected receive antenna set Ɲ, the transmit covariance matrix is illustrated as $\mathbf{Q}_{\mathrm{N}} = E[x\, x^{H}]$ The MI of the above system can be formulated as

$$I(\mathrm{x};\ \mathrm{y}) = \log\det\left(\boldsymbol{I}_K + \mathbf{H}_{\mathrm{N}}\, \mathbf{Q}_{\mathrm{N}} \mathbf{H}_{\mathrm{N}}{}^{\boldsymbol{H}}\right) \tag{3.2}$$

Fig [3.3] provides the illustration of SVD-based transformation of MIMO channel matrix $\mathbf{H}_{\mathrm{N}}$ with active receive antenna set Ɲ. This is the actual MIMO channel decomposition for possible conveying of information and energy. This transformation of channel matrix can be represented in terms of by $\mathbf{U} \in C^{K\times K}$ and by $\mathbf{V} \in C^{M\times M}$ unitary matrices and a diagonal matrix containing the singular values of channel matrix $\mathbf{H}_{\mathrm{N}}$, λ_i(Ɲ) respectively and is expressed as

$$\mathbf{H}_{\mathrm{N}} = \mathbf{U\Sigma V^{H}}$$

With the selected antenna set Ɲ, the MIMO channels are further decomposed into L parallel SISO channels and can be expressed rendering to (A. Shojaeifard, 2015) as follows for i-th parallel SISO channel

$$\tilde{y}_i = \lambda_i(\mathrm{N})\tilde{x}_i + \tilde{n}_i$$

where $\tilde{n}_i$ is the AWGN for the i-th SISO channel. Therefore, the output of each eigen channel is either connected to the ID component or the EH component. Consider using a binary variable β_i

to indicate either the i-th eigen channel is used for data transmission (β_i =1) or energy transfer (β_i = 0). Therefore, for L parallel SISO channels, the sum-rate for the selected antenna set Ɲ can be expressed as

$$C = \sum_{i=1}^{L} log_2(1+ \beta_i\, p_i\, \lambda_i\, (Ɲ)) \tag{3.3}$$

where p_i is the allocated power for data transmission of i-th eigen channel. Similarly, on the other hand the harvested energy at receiver component can be formulated as

$$E = \sum_{i=1}^{L} \eta(1- \beta_i)\, p_i\, \lambda_i\, (Ɲ) \tag{3.4}$$

where η represents the conversion loss from the energy transducer from harvested to electrical energy.

3.3.1 Power consumption modeling for proposed system

The basic power model for MIMO system has been discussed already in chapter 2, we casted the same model with our proposed system for our power consumption analysis. The power model should hold the power consumption of the entire system from transmitter to receiver for MIMO SWIPT. Recalling the Eq. [2.10] for power consumption in a MIMO system.

$$P = ϛP_T + P_{cir} + P_{syn}$$

Where ϛ, P_T, P_{cir} and P_{syn} are reciprocal of drain efficiency of power amplifiers and losses, transmit power, circuit power and the remaining component power respectively. For SS-based MIMO SWIPT, the power model should consider the whole chain to account the power consumption of the entire system which also include the RF harvested energy besides the transmit and circuit power. It can be argued later that P_{syn} of the system is very small so it can be neglected as it may not significantly affect the EE of the system. Similar approach has been adapted in [60] for SS-based MIMO SWIPT where harvested energy is considered in the system. In particular, the total power consumption can be formulated as follows

$$P = \varsigma P_T + P_{cir} - E \tag{3.5}$$

where E (defined in) is the harvested energy by active receivers. The minus sign indicates that the amount of energy harvested can be subtracted from the total power consumption to maximize the energy efficiency. For L eigen channels the total transmission power can be summed up as $P_T = \sum_{i=1}^{L} pi$. The circuit power of the system depends on the number of RF chains formed by the active links between transmitting(M) and receive(K) antennas. Therefore, the circuit power can be split into static and dynamic parts based on number of active link formed by both ends.

$$P_{cir} = P_{sta} + P_{dyn}M + P_{dyn}K$$

Where P_{sta} and $P_{dyn}M$ are the static and dynamic circuit power at transmitter whereas $P_{dyn}K$ denotes the dynamic circuit power at receiver and is proportional to active receive antennas.

3.3.2 Energy efficiency of the proposed model

With the above power consumption model, we can formulate the energy efficiency of the proposed system. The EE can be defined as the number of bits per unit energy, hence the EE of SS-based MIMO SWIPT with active number of antenna set Ɲ can be expressed as

$$\Psi_{EE} \triangleq \frac{C}{P} = \frac{\sum_{i=1}^{L} log2(1+ \beta i \ \mathrm{p}i \ \lambda i(Ɲ))}{\varsigma P_T + P_{sta} + P_{dyn}M + P_{dyn}K - \sum_{i=1}^{L} \eta(1-\beta i) \ \mathrm{p}i \ \lambda i(Ɲ)} \tag{3.6}$$

where C is the sum rate of L SISO eigen-channels formed by the active RF links. The objective of this thesis is to maximize EE of SWIPT in massive MIMO system without affecting the sum rate of the system. We can now proceed to optimization problem formulation with this equation.

4. ENERGY EFFICIENCY OPTIMIZATION

4.1 Energy Efficiency Optimization Problem

As discussed earlier, EE is one of the most desired feature of modern communication system. An energy aware massive MIMO can result in saving energy consumption of the future cellular communication. In this chapter, we try to obtain the maximum harvested energy and non-zero sum-rate of the SS based SWIPT massive. Moreover, we will also discuss the tradeoff between the transmission power and harvested energy to obtain the optimized EE. The proposed system in chapter 2 can maximize the EE of the massive MIMO system by acquiring the two important constraints, the sum rate and the harvested energy. In Eq. [3.5] the transmission power P_T can be extended according to the L parallel SISO channels as $P_T = \varsigma \sum_{i=1}^{L} \mathrm{p}i$. Thus, the corresponding EE of the system can be further formulated as

$$\Psi\mathrm{EE} \triangleq \frac{\mathrm{C}}{P} = \frac{\sum_{i=1}^{L} \log 2(1+ \beta i \ \mathrm{pi} \ \lambda i(\mathrm{N}))}{\varsigma \sum_{i=1}^{L} \mathrm{pi} + P_{sta} + P_{dyn} M + P_{dyn} K - \sum_{i=1}^{L} \eta (1-\beta i) \mathrm{pi} \lambda i(\mathrm{N})} \tag{4.1}$$

Based on this equation we can mathematically formulate the corresponding optimization problem as

$$\max_{\beta\mathrm{i},\mathrm{pi},\mathrm{N}} \frac{\sum_{\mathrm{i}=1}^{\mathrm{L}} \log 2(1+ \beta\mathrm{i} \ \mathrm{pi} \ \lambda\mathrm{i}(\mathrm{N}))}{\varsigma \sum_{\mathrm{i}=1}^{\mathrm{L}} \mathrm{pi} + \mathrm{P_{sta}} + \mathrm{P_{dyn}M} + \mathrm{P_{dyn}K} - \sum_{\mathrm{i}=1}^{\mathrm{L}} \eta(1-\beta\mathrm{i})\mathrm{pi}\lambda\mathrm{i}(\mathrm{N})} \tag{4.2}$$

s.t

$$\sum_{\mathrm{i}=1}^{\mathrm{L}} log_2\big(1 + \beta\mathrm{i} \ \mathrm{pi} \ \lambda\mathrm{i}(\mathrm{N})\big) \geq \mathrm{C_{min}} \tag{4.3}$$

$$\sum_{\mathrm{i}=1}^{\mathrm{L}} \eta(1 - \beta\mathrm{i})\mathrm{pi}\,\lambda\mathrm{i}(\mathrm{N}) \geq \mathrm{E_{min}} \tag{4.4}$$

$$\sum_{\mathrm{I}=1}^{\mathrm{L}} \mathrm{pi} \leq \mathrm{P_{max}} \tag{4.5}$$

$$\text{Pi} \geq 0, \beta\text{i} \in \{0,1\}, \forall \text{i} \in \text{L} \tag{4.6}$$

Where C_{min}, P_{max} and E_{min} are the optimizing constraints for minimum sum-rate, maximum transmit power and minimum harvested energy respectively. Moreover (4.5) and (4.6) are the allocated power and SS parameter constraints for the EE optimization problem.

With the above constrains we can observe the optimizing problem to be a mixed linear non-integer as it involves a nonlinear function, a binary and a continuous variable respectively. The problem (4.2)- (4.6) is non-convex with active receive antenna set $\mathcal{N}$,power allocated pi and eigen channel assignment βi. Solving $\mathcal{N}$ with βi and pi is not straightforward as the number of active antenna set $\mathcal{N}$ relates to channel matrix and has a comprehensive effect on EE optimization problem. Moreover, it is possible to solve an optimizing problem with one variable first and then over with the remaining variables (S. Boyd, 2004). Therefore, at first, we will optimize the EE problem over the power allocated and the eigen channel assignment variables pi and βi respectively and then we can determine the number of active antenna set $\mathcal{N}$ to improve the achievable EE further.

4.2 Optimizing Eigen channel assignment and Power allocation

In this section, we fixed the number of active receive antenna set $\mathcal{N}$ to omit its constraint and for the problem simplification. Solving a non-convex problem involves a high amount of complexity. So, we try to simply the problem with most widely used approximation method, OFDMA resource allocation (C. Xiong, 2011). Considering this context, we can formulate the approximation for eigen channel assignment and power allocation as

$$\max_{\widetilde{\beta}_i, \text{pi},} \frac{\sum_{i=1}^{L} \widetilde{\beta}_i \log 2\left(1+ \frac{\text{pi}\,\lambda\text{i}}{\widetilde{\beta}_i}\right)}{\varsigma \sum_{i=1}^{L} \text{pi} + P_{sta} + P_{dyn}M + P_{dyn}K - \sum_{i=1}^{L} \eta(1-\widetilde{\beta}_i)\text{pi}\lambda\text{i}} \tag{4.7}$$

s.t $$\sum_{i=1}^{L} \widetilde{\beta}_i log_2\left(1+\frac{\text{pi}\,\lambda\text{i}}{\widetilde{\beta}_i}\right) \geq C_{min} \quad (4.8)$$

$$\sum_{i=1}^{L} \eta\left(1-\widetilde{\beta}_i\right)\text{pi}\,\lambda\text{i} \geq E_{min} \quad (4.9)$$

$$\sum_{I=1}^{L} \text{pi} \leq P_{max} \quad (4.10)$$

$$\text{Pi} \geq 0, \widetilde{\beta}_i \in \{0,1\}, \forall \text{i} \in \text{L} \quad (4.11)$$

we can clearly see that for i-th eigen channel as $\widetilde{\beta}_i \rightarrow 0$, $\widetilde{\beta}_i log_2\left(1+\frac{\text{pi}\,\lambda i}{\widetilde{\beta}_i}\right)$ also tends to zero and when $\widetilde{\beta}_i$ is nearly equal to 1, $\widetilde{\beta}_i log_2\left(1+\frac{\text{pi}\,\lambda i}{\widetilde{\beta}_i}\right)$ tends back to original form i.e., $log_2(1+\beta\text{i pi}\,\lambda\text{i})$. So, for eigen channel assignment to either transmit data or energy is almost entirely assigned with the approximation constraint $\widetilde{\beta}_i$ instead of βi. On the other hand, the optimization problem from (4.7) -(4.11) may result in fractional solution to avoid this we can round of the eigen channel assignment approximation to either 0 or 1 which enables us to solve the problem in precise.

4.2.1 Dinkelbach Method for maximal achievable EE

Dinkelbach Method is one of the efficient method to solve problem that involves non-linear fractional programming (Dinkelbach, 1967). The solution to the optimization problem (4.7) – (4.11) may contain the non-linear fractional constraints. Therefore, we can apply DM method to achieve the maximum EE for our SS-based MIMO SWIPT system. In this regard, the fractional form of the problem is transformed into a numerator- denominator subtraction. Consider U_N and U_D be the numerator and denominator respectively and γ^* is equivalent to the achievable EE Ψ_{EE}. The proposition based on (Jie Tang, 2017) can be obtained as follows

$$\gamma^* = \text{maximum achievable EE } \Psi_{EE} \qquad (*)$$

$$\max_{p,\tilde{\beta}} U_N(p,\tilde{\beta}) - \gamma^* U_D(p,\tilde{\beta}) = U_N(p^*,\tilde{\beta}^*) - \gamma^* U_D(p^*,\tilde{\beta}^*) = 0$$

We developed an algorithm based on DM method for resource allocation of problem (4.2)- (4.6) to change it from fractional form to an equivalent subtractive form

For $U_N(p,\tilde{\beta}) \geq 0$and $U_D(p,\tilde{\beta}) \geq 0$

$$U_N(p,\tilde{\beta}) = \sum_{i=1}^{L} log_2\,(1 + \beta i \text{ p}i\ \lambda i)$$

$$U_D(p,\tilde{\beta}) = \varsigma \sum_{i=1}^{L} \text{p}i + P_{sta} + P_{dyn}M + P_{dyn}K - \sum_{i=1}^{L} \eta\,(1 - \beta i)\ \text{p}i\ \lambda i)$$

$$\Gamma^* = \frac{U_N\,(p^*,\tilde{\beta}^*)}{U_D\,(p^*,\tilde{\beta}^*)}$$

$$\mathrm{P} = [p_0, p_1 \ldots\ldots p_L] \quad \tilde{\beta} = [\tilde{\beta}_0, \tilde{\beta}_1 \ldots\ldots \tilde{\beta}_L]$$

From the above preposition we can future demonstrate our optimization problem (4.7) – (4.11) by iterative resource allocation based on DM method as

$$\max_{p,\tilde{\beta}} \sum_{i=1}^{L} \tilde{\beta}_i \log_2\left(1 + \frac{\text{pi}\,\lambda\text{i}}{\tilde{\beta}_i}\right) - \gamma^*(\varsigma \sum_{i=1}^{L} \text{pi} + P_{sta} + P_{dyn}M + P_{dyn}K - \sum_{i=1}^{L} \eta\,(1\ \tilde{\beta}_i)\ \text{pi}\ \lambda\text{i})$$

(4.12)

$$\text{s.t} \ \sum_{i=1}^{L} \widetilde{\beta}_i \log_2\left(1 + \frac{pi\,\lambda i}{\widetilde{\beta}_i}\right) \geq C_{min} \tag{4.13}$$

$$\sum_{i=1}^{L} \eta\left(1 - \widetilde{\beta}_i\right)pi\,\lambda i) \geq E_{min} \tag{4.14}$$

$$Pi \leq P_{max} \tag{4.15}$$

$$Pi \geq 0,\ \widetilde{\beta}_i \in \{0,1\}, \forall i \in L \tag{4.16}$$

The convex problem-solving approach based on Dinkelbach method is stable for the above obtained optimization problem, but the complexity of this problem depends on the number of optimization variable. With larger active receive antenna set the solution of problem can be complex.

4.2.2 Multi-Objective Optimization Low-Complexity Approach

The above proposed resource allocation solution based on Dinklecack method is efficient, but it can involve many complex iterations if the number of antennas are very large, which means the number of eigen chains formed will also be large and the complexity of the problem will increase as well. A low complexity algorithm based on Multi-Objective Optimization (MOO) can limit the complexity of the iterative problem formed in previous subsection. Moreover, the approximation for eigen channel assignment and power allocation can also be avoided with this technique. Assuming the each eigen channel for ID and EH component is allocated, we determine the power allocation to maximize the EE of the whole system. We consider a uniform power allocation as one of the optimization constraint always dominate the other, to acquire the best eigen-channels the power allocation is compromised. This uniform allocation of power for SS based MIMO SWIPT may not be efficient to obtain the EE but is easy to implement in practice due to lower complexity. Considering the both data and energy transmission along with the power allocation algorithm we prose the solution based on MOO literature in (Veldhuizen, 2007), which can be defined as follows in general.

$$\min_{x} Y(x) = \left(y_1(x), y_1(x) \ldots \ldots . y_k(x)\right)$$

s.t $a_i(x) \leq 0$, i=1,2,3……., m,

$b_j(x) = 0$, j= 1,2,3……, n,

whereas $Y(x), a_i(x), b_j(x)$ are the objective functions and the MOO problem can optimize the constraints up to k functions. Moreover, all the objective function involve in a problem can be formulated as a single scalar objective function with this approach.

$$\min_{\alpha_l, x} \sum_{l=1}^{k} \alpha_l Y_l(x)$$

s.t $\sum_{l=1}^{k} \alpha_l = 1, \alpha_l > 0, l = 1,2,3 \ldots \ldots, k,$

$a_i(x) \leq 0$, i=1,2,3……., m,

The efficient solution for the original MOO problem can be obtained by minimizing this single objective function (Veldhuizen, 2007). In our proposed system we consider power transfer and sum rate as our objective functions to formulate a MOO problem, so we can transform them into a single objective function. In (Q. Sun, 2014) the transmission rate by the harvested energy is modeled to combine both objective functions as

$$C_{EH} = \theta \ \sum_{i=1}^{l} \eta p i \lambda i,$$

where θ represents the efficiency of harvested energy to data transmission. We can now further proceed with our MOO problem to determine power allocation with the above equation as

$$\max_{pi>0} \{\sum_{i=1}^{L} \log_2 (1 + pi\lambda i), \theta \sum_{i=1}^{L} \eta p i \lambda i\} \tag{4.17}$$

$$\text{s.t} \qquad \sum_{I=1}^{L} pi \leq P_{max} \tag{4.18}$$

Now we transform this above MOO problem to a single objective function as

$$\max_{pi>0} \ \sum_{i=1}^{L} \alpha_1 \log_2 (1 + pi\lambda i) + \alpha_2 \theta \sum_{i=1}^{L} \eta p i \lambda i \tag{4.19}$$

$$\text{s.t} \quad \sum_{I=1}^{L} pi \leq P_{max} \tag{4.20}$$

4.3 Active Receive antenna selection

In this section, we further explore the achievable EE by optimizing the active receive antenna set Ɲ. High throughput can be obtained by raising the number of active receive antennas as it will achieve higher sum-rate, but it may not be optimal for EE of the system. Undoubtedly increasing the number of active receive antenna can help harvesting more energy but with the cost of higher power consumption at BS for transmitting. So, we optimize the active receive antennas to get the best tradeoff between the power allocation and harvested energy without affecting the sum-rate. For each possible receive antenna set Ɲ, we analyze the EE of SS based MIMO SWIPT based on the proposed eigen channel assignment and power allocation. Based on the above optimization for the constraints p and $\tilde{\beta}$, Ɲ active receive antenna set can be optimized as

$$Ɲ^{opt} = \arg \max_{Ɲ\in\{1,2....K\}} \Psi \text{EE}\ (Ɲ) \tag{4.21}$$

The optimal solution will calculate all the possible antenna set by antenna selection process to maximize the EE of the system. With the given number of active receive antennas we select the set of receive antennas that maximizes the EE of the system. This is further used for either ID or EH receiver of the receive antenna. So, with operating ID and EH component of selected active receive antennas and with fixed transmit power P, the optimization problem for EE based on MOO can be formulated as (Appendix A for proof)

$$\max_{Ɲ:\,|Ɲ| = K,\ \mathbf{Q}_Ɲ > 0} \{\frac{\log\det\left(I_K + \mathbf{H}_Ɲ\mathbf{Q}_Ɲ\mathbf{H}_Ɲ^H \right)}{\varsigma tr\mathbf{Q}_Ɲ + P_{sta} + P_{dyn}M + P_{dyn}K}, \frac{\theta\eta tr\left(\mathbf{H}_Ɲ\mathbf{Q}_Ɲ\mathbf{H}_Ɲ^H \right)}{\varsigma tr\mathbf{Q}_Ɲ + P_{sta} + P_{dyn}M + P_{dyn}K}\}$$

$$\text{s.t}\quad tr\mathbf{Q}_Ɲ = P$$

Where $\frac{\log\det\left(I_K + \mathbf{H}_Ɲ\mathbf{Q}_Ɲ\mathbf{H}_Ɲ^H \right)}{\varsigma tr\mathbf{Q}_Ɲ + P_{sta} + P_{dyn}M + P_{dyn}K}$ and $\frac{\theta\eta tr\left(\mathbf{H}_Ɲ\mathbf{Q}_Ɲ\mathbf{H}_Ɲ^H \right)}{\varsigma tr\mathbf{Q}_Ɲ + P_{sta} + P_{dyn}M + P_{dyn}K}$ represents the EE for ID and EH components respectively and the above equation can be transformed on the basis of equal transmitting power allocation at each antenna as

$$\max_{Ɲ:\,|Ɲ| = K,\mathrm{P} > 0} \left\{ \frac{\log\det\left(I_K + \frac{P}{K}\mathbf{H}_Ɲ\mathbf{H}_Ɲ^H \right)}{\varsigma \mathrm{P_T} + P_{sta} + P_{dyn}M + P_{dyn}K}, \frac{\theta\eta\frac{P}{K}tr\left(\mathbf{H}_Ɲ\mathbf{H}_Ɲ^H \right)}{\varsigma \mathrm{P_T} + P_{sta} + P_{dyn}M + P_{dyn}K} \right\}$$

$$= \max_{Ɲ:\,|Ɲ| = K} \left\{ \det(\mathbf{H}_Ɲ\mathbf{H}_Ɲ^H), tr(\mathbf{H}_Ɲ\mathbf{H}_Ɲ^H) \right\}$$

As the above equation involves the determinant of channel matrix which will lead to a complex computation due to large number of antennas, so we can limit the complexity by taking Frobneius-Norm of the channel matrix. Then for EE maximization the proposed optimization can be performed to obtain the results. The whole solution of the EE optimization problem with graphical demonstrations of results can be seen in (Jie Tang, 2017) for SS based MIMO SWIPT.

4.4 EE maximization

Based on the above calculations, the EE metrices is maximized with respect to the optimizing constraints for power allocation p eigen channel assignment $\tilde{\beta}$ and the number of active receive antenna set ℕ. The transmitted power and the harvested power can be optimized with number of antennas proportional to $\frac{1}{M}$ and $\frac{1}{K}$ respectively. Increasing the number of active receive antennas will maximize the harvested energy but the transmitting power at BS by the M transmitting will increase accordingly. So, we optimize the EE of the system accordingly to tradeoff between these two power constraints. In this regard, the number of active receive antenna set ℕ plays an important role. Therefore, we define our maximum metrices bounded as the following expression.

$$\underbrace{\frac{\tilde{\beta} log_2\left(1+\frac{p\lambda}{\tilde{\beta}}\right)}{\eta(1-\tilde{\beta})p\lambda}}_{\text{Harvested energy}} \leq \max_{\tilde{\beta},p,ℕ\geq 0} EE \leq \underbrace{\frac{\tilde{\beta} log_2\left(1+\frac{p\lambda}{\tilde{\beta}}\right)}{\varsigma p+P_{sta}+P_{dyn}M+P_{dyn}K}}_{\text{Transmitted energy}} \tag{4.22}$$

This reveals that the overall energy efficiency is finite to some extent in massive MIMO, and for $p > 0$, EE is non-zero for K= 1 and for non-zero transmit power but as $N \rightarrow \infty$ the EE tends to become zero as it grows the denominator of EE metrics to infinity. For $p = 0$ we can get some finite growth in EE if the power consumption does not increase with N. For some finite K that is number of active receive antennas N the maximum achievable EE depends on $\widetilde{\beta,}\,\mathrm{p}\ and\ \mathrm{N}$. Whereas p is the dominating optimizing constraint. Further the power consumption which is solely dependent on the circuit architecture can be minimized by using low resolution hardware proposed in (Zhang W. , 2012) (A. Mezghani, 2010).

5. NUMERICAL RESULTS

5.1 Numerical Illustration

The SS based SWIPT for massive MIMO is projected to maximize the EE of the communication system, to examine the effectiveness of the proposed system we illustrate how overall EE of the system is dependent of the transmitted power and circuit power consumption. We introduced a harvested energy absorbed by the SS based receiver, subtracted from the total power consumption in able to maximize system's EE. The overall EE of the system is maximized according to the optimizing constrains $\mathrm{p}, \widetilde{\beta}\ and\ \mathrm{N}$ respectively. The tradeoff between the transmitted power and the harvested power is illustrated graphically to represent how the number of receive antennas is affecting the both constraints. We consider two setups for $\mathrm{p}\ and\ \widetilde{\beta}$ to demonstrate the relation between EE, number and transmitted power and the active receive antenna set N. The splitting between $\mathrm{p}\ and\ \widetilde{\beta}$ is set as $\frac{\mathrm{p}}{\mathrm{p}+\widetilde{\beta}} = \{0,0.01,0.1\}$. The efficiencies including the power amplifier efficiencies is set to 30% (i.e. = $\omega = \frac{1}{\varsigma}$ = 0.3) and the efficient for EH receiver is set to 10% (i.e. $\eta = 0.1$). The maximum transmitted power for both UL and DL is assumed to be equal and set to $\mathrm{p}_{max} = 2.0222\mu J/channel$ and the harvested energy estimated for SS based receiver is set to E=$0.0222\mu J/channel$. For the maximal transmit power p_{max} the SNR of the system can be estimated as 20 dB. We consider a symmetric scenario, so the UL and DL ratio is set to 0.5. The simulation constraints can be seen in table [5.1] for the SS based MIMO SWIPT Matlab implementation to demonstrate the results for the proposed system.

Table 5.1 Simulation parameters

Effective bandwidth	9MHz
Power amplifier efficiency (= $\omega = \frac{1}{\varsigma}$)	0.3 (30%)
Signal-to-Noise Ratio (SNR)	20dB
Uplink to Downlink Ratio(UL/DL)	0.5
Maximum transmit power (p_{max})	2.00227 $\mu J/channel$
Harvested Energy (E)	0/0022 $\mu J/channel$
Efficiency of EH receiver (η)	0.1 (10%)
Number of antennas (K)	500
Active receive antenna set (Ɲ)	107
Splitting for constraints for power allocation and eigen channel assignment ($\frac{\text{p}}{\text{p}+\widetilde{\beta}}$)	{0, 0.01, 0.1}

Fig [5.1] shows the relation of the energy efficiencies with the number of active receive antennas Ɲ with optimized harvested constrains splitting of $\text{p}\ and\ \widetilde{\beta}$. The transmit power for M antennas can be optimized numerically or by power scaling with $\frac{1}{2}$. The RF chains build from the M transmitting antennas and K receiving is dependent on number of active receive antenna set Ɲ. Therefore, the transmit power and harvested energy varies with respect to the RF chains. For $\frac{\text{p}}{\text{p}+\widetilde{\beta}}$ is sufficiently close to small or zero we can use the maximum number of antennas which have not affected any EE can be seen in Fig [5.1]. However, as this factor increases the EE tends to decrease for the both other splitting 0.01 and 0.1 as the transmit power increased and harvested energy is decreased. Moreover, the other performance losses are also considered in the system to see the difference. Whereas Fig. [5.2] illustrates the effect on transmitted energy by the number of RF chains built by active receive antenna set N.

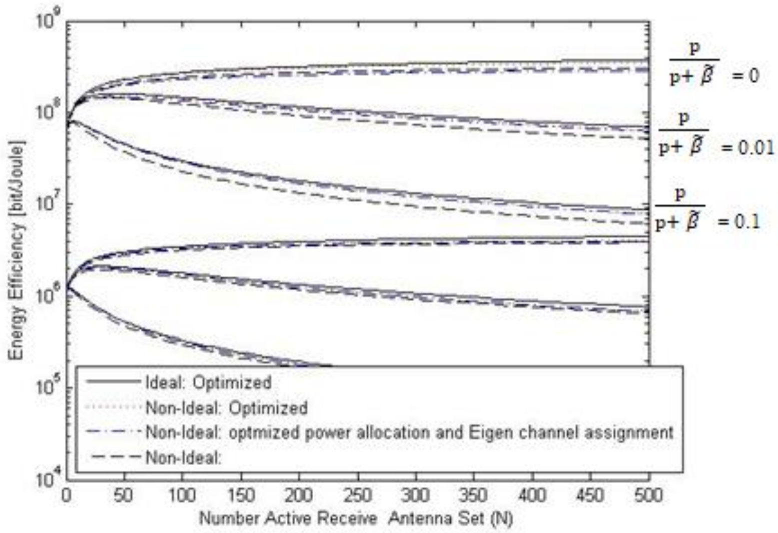

Fig. 5.1 Achievable energy efficiency with ideal and non-ideal optimizing constraints

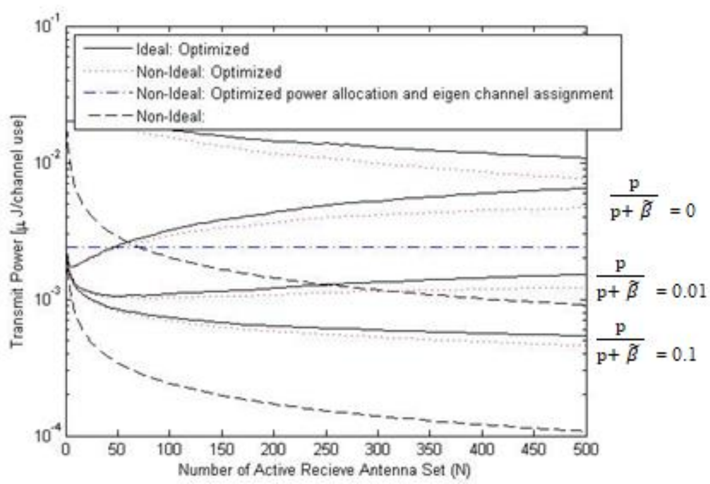

Fig. 5.2 Transmit power for number of active receive antennas

We can see a gradual increase of EE in Fig. [5.1] for $0 \leq K \leq 20$ all the setups of $\frac{\mathrm{p}}{\mathrm{p}+\tilde{\beta}}$ but as the number of antennas increases there is a slight decrease of EE for $\frac{\mathrm{p}}{\mathrm{p}+\tilde{\beta}} = 0.01$ and for $\frac{\mathrm{p}}{\mathrm{p}+\tilde{\beta}} = 0.1$ the graph of EE tends to decrease as the transmit power increase to a larger extent for K >20 and can be seen in Fig. [5.2].

For $0 \leq K \leq 20$

For first 20 antennas range the maximal EE can be obtained as shown in Fig. [5.3] for all the splitting of power allocation and eigen channel assignment proportions.

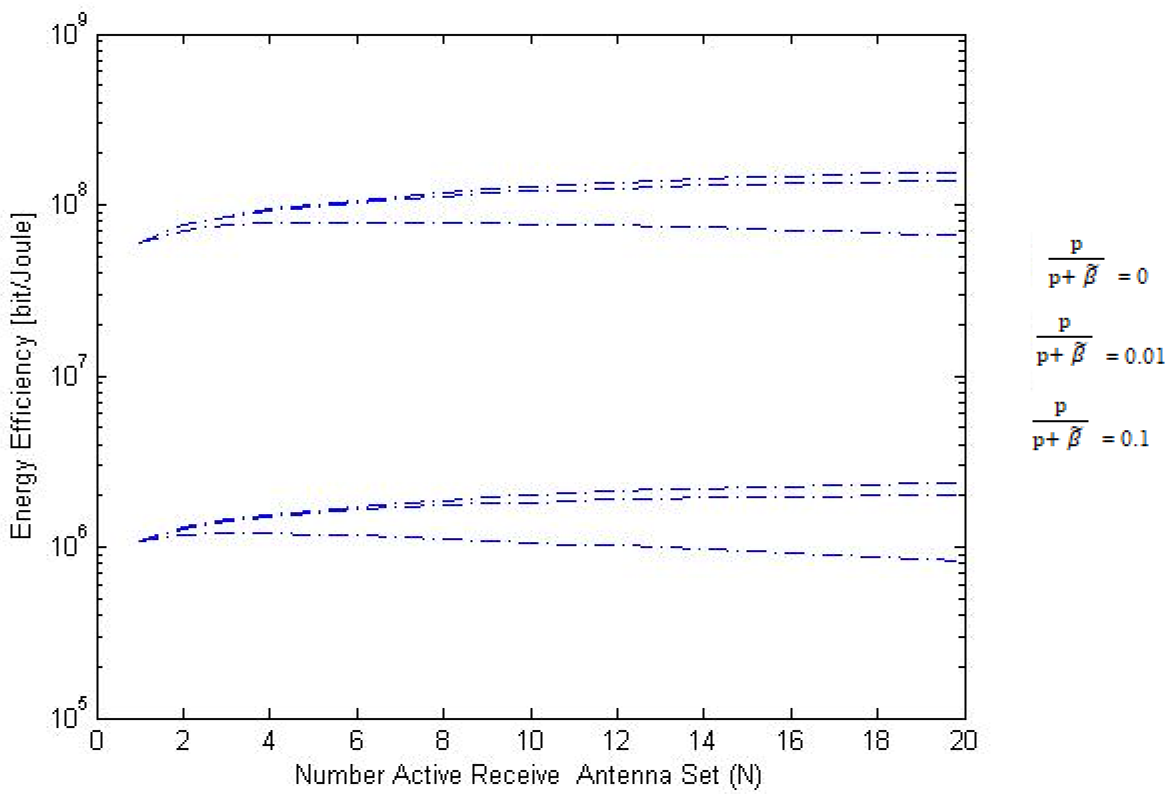

Fig. 5.3 Achievable EE for $0 \leq K \leq 20$

As we can see a clear exponential increase of EE for all $\frac{\mathrm{p}}{\mathrm{p}+\tilde{\beta}} = \{0{,}0.01{,}0.1\}$ respectively and the comparison of all three splitting is shown in Fig. [5.4].

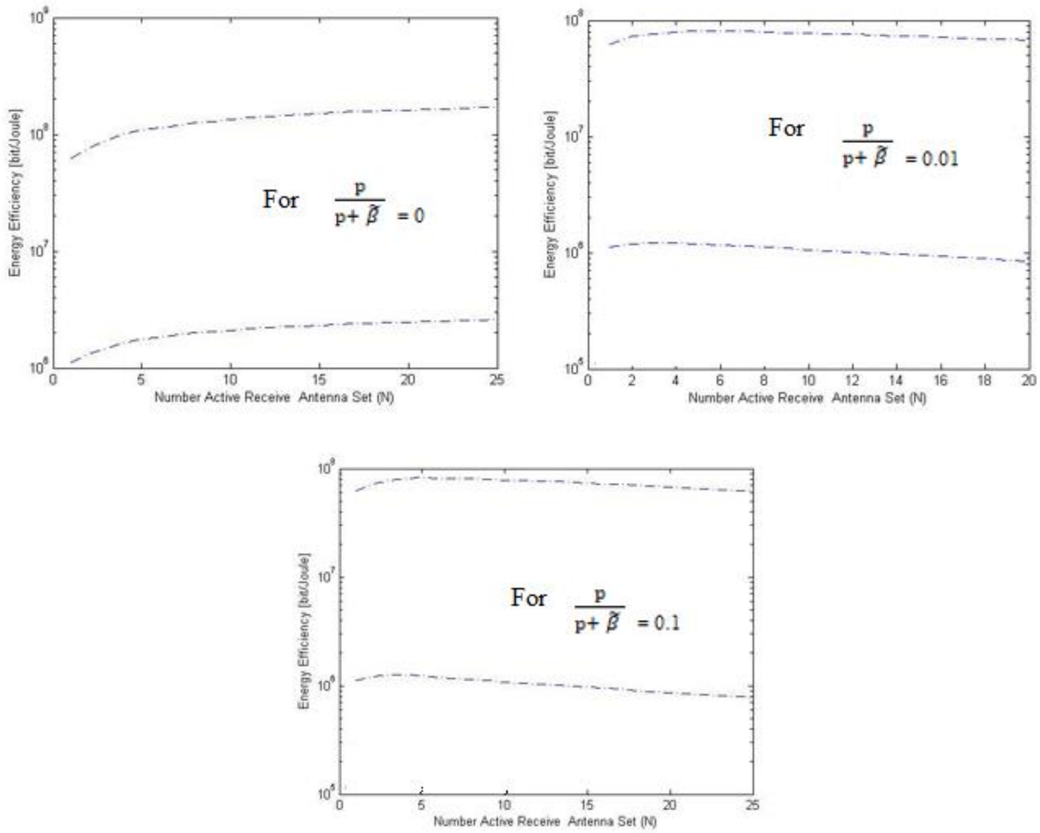

Fig. 5.4 Achievable EE comparison for all three setups for $0 \leq K \leq 20$

<u>For $0 \leq K \leq 500$</u>

Considering the same splitting as used above but this time for antenna range $0 \leq \mathrm{K} \leq 500$ **, we** can see the results from Fig. [5.5] that after 20 antennas the maximal EE is still achievable for $\frac{\mathrm{p}}{\mathrm{p}+\tilde{\beta}} = 0$ but it remains constant for $\frac{\mathrm{p}}{\mathrm{p}+\tilde{\beta}} = 0.01$ and decrease gradually for $\frac{\mathrm{p}}{\mathrm{p}+\tilde{\beta}} = 0.1$ repectively. Moreover, the one on one comparison is also illustrated in Fig. [5.6].

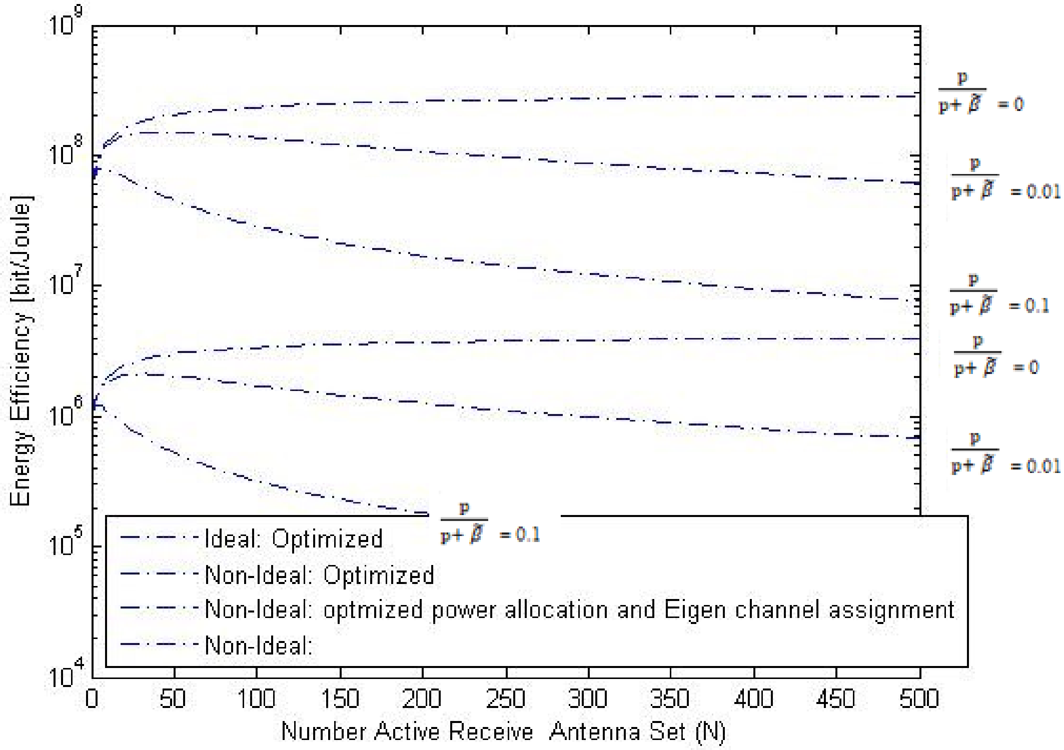

Fig. 5.5 Achievable EE comparison for all three setups for $0 \leq K \leq 500$

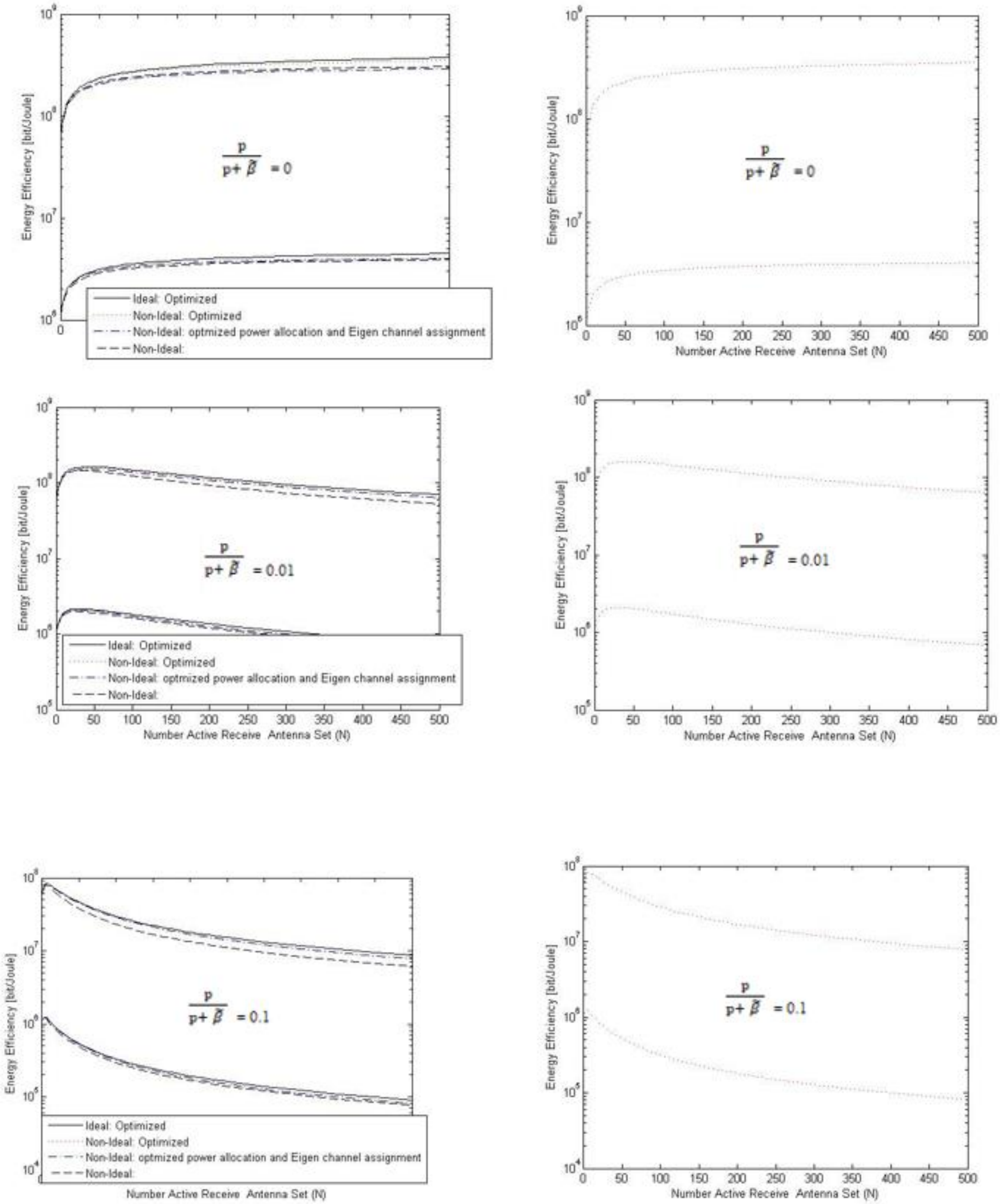

Fig. [5.6] Comparison of achievable EE for all splitting for $0 \leq K \leq 500$

6. CONCLUSION AND FUTURE WORK

6.1 Conclusion

The growing economic and social impact of energy efficiencies on wireless community is causing a major performance and energy concern in future disruptive technologies. As massive MIMO is gaining an immense popularity for future communication systems. The implementation of large array of antennas connected with trafficking UEs may result in poor EE. However massive MIMO is providing a significant degree of freedom to incorporate with energy efficient technologies due to its massive number of transmitting antennas. Therefore, in this thesis a multi user massive MIMO SWIPT using SS based harvesting architecture for receiving and harvesting energy has been proposed. We consider the basic power consumption of massive MIMO system and introduced the harvested energy to analyze the overall energy performance of the system.

With SS based receiver the EE optimization problem has been formulated for the proposed massive MIMO model based on SWIPT harvesting technology. We have considered the basic power consumption model for massive MIMO and maximized the EE of the overall system by considering the number of active receive antennas, power allocation and eigen channel assignment as our optimizing constraints. The resulting problem was very complex to handle so convex programing based Dinkelbach method and MOO low complexity methods have been adapted to simplify the solution of our optimization problem. The active antenna selection is separated to simplify the complexity of problem. Numerical results illustrate that using SS based SWIPT model for massive MIMO can help achieve the maximum EE for future wireless systems. Moreover, these harvesting based technologies can also be used for future disruptive technologies like 5G, IOT etc. However, the antenna system and receiver design for the proposed model can be challenging and to limit the effect of transmit power low complexity hardware can be used to achieve the best possible results in term of energy efficiencies.

6.2 Future Work

As scaling up the number of antennas at BS can come up with great potential for beyond LTE and future wireless systems. For next generation wireless communication, there is an immense need of energy efficient systems. Massive MIMO has a great tendency to incorporate energy efficient designs for its antenna systems. The proposed SWIPT model for massive MIMO in this thesis have shown great outcomes to maximize energy efficiency. However, the model failed to limit the transmit power from the large number of antennas at BS for massive MIMO. In the future work, we are interested in designing EH receiver for SWIPT for massive MIMO to maximize the harvested energy. In future we are expecting to have everything connected with internet which shows that SWIPT harvesting technologies can be a great source for designing energy efficient systems for upcoming technologies like IOT, M2M,5G beyond etc. The characteristics of SWIPT can be better studied if the current system model is updated. So, the practical implementation of SWIPT needs a lot of research and practical system design to provoke green radio communication.

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APPENDIX A

The maximization problem that leads to an optimized equation when both the ID and EH component is active is shown below

$$\max_{\mathbb{N}: |\mathbb{N}| = K,\ \mathbf{Q}_{\mathbb{N}} > 0} \left\{\frac{\log\det\left(I_K + \mathbf{H}_{\mathbb{N}}\mathbf{Q}_{\mathbb{N}}\mathbf{H}_{\mathbb{N}}^H \right)}{\varsigma tr\mathbf{Q}_{\mathbb{N}} + P_{sta} + P_{dyn}M + P_{dyn}K}, \frac{\theta\eta tr\left(\mathbf{H}_{\mathbb{N}}\mathbf{Q}_{\mathbb{N}}\mathbf{H}_{\mathbb{N}}^H \right)}{\varsigma tr\mathbf{Q}_{\mathbb{N}} + P_{sta} + P_{dyn}M + P_{dyn}K}\right\}$$

$$\text{s.t} \quad tr\mathbf{Q}_{\mathbb{N}} = P$$

The nonlinear fractional problem solution obtained from the Dinklebach method became iterative and difficult to simulate as the number of antennas is very large. Moreover, the equation is changed from fractional to linear form.

$$\max_{\mathbb{N}: |\mathbb{N}| = K, \mathbf{Q}_{\mathbb{N}} > 0} \log\det\left(I_K + \mathbf{H}_{\mathbb{N}}\mathbf{Q}_{\mathbb{N}}\mathbf{H}_{\mathbb{N}}^H \right) + \varpi\, \eta tr\left(\mathbf{H}_{\mathbb{N}}\mathbf{Q}_{\mathbb{N}}\mathbf{H}_{\mathbb{N}}^H \right) - \varpi\ \varsigma tr\mathbf{Q}_{\mathbb{N}} + P_{sta} + P_{dyn}M + P_{dyn}K$$

As the transmit power for the specific number of antennas is fixed so $\varpi\ \varsigma tr\mathbf{Q}_{\mathbb{N}} + P_{sta} + P_{dyn}M + P_{dyn}K$ can be seen as a constant and neglected to give the following form

$$\max_{\mathbb{N}: |\mathbb{N}| = K, \mathbf{Q}_{\mathbb{N}} > 0} \gamma_1 \log\det\left(I_K + \mathbf{H}_{\mathbb{N}}\mathbf{Q}_{\mathbb{N}}\mathbf{H}_{\mathbb{N}}^H \right) + \gamma_2\, \eta tr\left(\mathbf{H}_{\mathbb{N}}\mathbf{Q}_{\mathbb{N}}\mathbf{H}_{\mathbb{N}}^H \right)$$

This sum optimization is the solution of MOO optimization problem.