Energy-Efficient phase shifter selection for Millimeter-Wave-based Massive Multiple Input Multiple Output System

Selam Biru

A Thesis Submitted to the Department of Electronics and Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfilment of the Requirement for the Degree of Master"s in Electronics and Communication Engineering

(Communication Engineering)

Office of Graduate Studies

Adama Science and Technology University

June, 2022

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Advisor: Dr. Satyasis Mishra

Co-Advisor: Dr. Ram Sewak Singh

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DECLARATION

I hereby declare that this Master Thesis entitled "**Energy-Efficient phase shifter selection for Millimeter-Wave-based Massive Multiple Input Multiple Output System**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Name: Selam Biru

Signature:________________

This MSc thesis has been submitted for examination with my approval as a thesis advisor.

Name: Dr. Satyasis Mishra

Signature: _______________

RECOMMENDATION

I certify that I have read and revised the dissertation entitled "**Energy-Efficient phase shifter selection for Millimeter-Wave-based Massive Multiple Input Multiple Output System**" prepared under our guidance by **Selam Biru** submitted in partial fulfillment of the requirements for the degree of Master of Science. Therefore, I recommend the submission of the dissertation to the department for further review and defense.

Dr. Satyasis Mishra		
Advisor	Signature	Date
Dr. Ram Sewak Singh		
Co-Advisor	Signature	Date

APPROVAL SHEET

We hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the dissertation entitled "**Energy-Efficient phase shifter selection for Millimeter-Wave-based Massive Multiple Input Multiple Output System**" by **Selam Biru**.

Dr. Satyasis Mishra

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Advisor	Signature	Date

Dr. Ram Sewak Singh

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Co-Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the dissertation open defense by **Selam Biru** have read and evaluated the dissertation entitled "**Energy-Efficient phase shifter selection for Millimeter-Wave-based Massive Multiple Input Multiple Output System**" and examined the candidate during the open defense. This is, therefore, to certify that the dissertation is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electronics and Communication Engineering (Communication Engineering)

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Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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LIST OF ABBREVIATIONS

ADC	Analog -to- Digital converter
Alt-MMSE	Alternating the minimum mean square error
BS	Base Station
BER	Bit error rate
CSI	Channel State Information
CPSs	Constant phase shifters
DAC	Digital-to-Analog converter
DB	Digital Beamforming
DFT	Discrete Fourier Transform
DZF	Digital zero forcing
EE	Energy Efficiency
EELCHP	Energy efficiency low complexity hybrid precoding
FPSS	Fully connected phase shifter selection
FDD	Frequency Division Duplex
FSPL	Free Space Path Loss
5G	Fifth Generation
HB	Hybrid Beamforming
HRPS	High-resolution phase shifters
IoT	Internet of things
IEEE	Institute of Electrical and Electronics Engineers
LOS	Line of Sight
MATLAB	Matrix Laboratory
mMIMO	Massive Multiple Input and Multiple Output
MU-MIMO	Multi user Multiple Input and Multiple Output
mm-Wave	Millimeter-wave
MRT	Maximum ratio transmission
PSs	Phase shifters
PSS	Phase shifter selection

PC-HB	Partially connected hybrid beamforming
RF	Radio Frequency
SE	Spectral Efficiency
SPSS	Subconnected phase shifter selection
SRPS	Sub connected reduced number of phase shifter
TDD	Time Division Duplex
UE	User Equipment
VPSs	Variable phase shifters
ZF	Zero Forcing

LIST OF SYMBOLS

β	Phase shifter
C_{thr}	Threshold capacity
H	Channel vector
N_{PS}	Number of phase shifter
N_S	Number of switch
N_{RF}	Number of RF chain
ρ	Correlation factor
P_c	Common power consumption term
P_{PS}	Power consumption of phase shifter
P_{RF}	Power consumption of RF chain
P_{syn}	Power consumption of frequency synthesizer
P_{tot}	Total power
P_S	Power consumption of switch
P_{var}	Variable term
α	Threshold level
R_{sum}	Achievable sum-rate
η	Efficiency of the power consumption
Z	Noise vector

ABSTRACT

The next-generation wireless communication requires reduced energy consumption, increased data rate, and better signal coverage. The millimeter-wave frequency spectrum above 30 GHz can help fulfill the performance requirements of the next-generation mobile broadband systems. Massive MIMO technology is being developed for 5G wireless communication systems because many users can be served simultaneously with very better throughput. Emerging Beamforming architectures can reduce energy consumption and hardware complexity with the use of fewer radio frequencies (RF) chains. With the flow of time, the need for high-data-rate wireless communication services is rapidly increasing. Thus the key difficulty is that as the number of users grows, the number of phase shifters grows as well, causing the system to consume more power. As a result, the system's Energy Efficiency decreases. My aim is to achieve the highest Energy Efficiency for millimeter-wave communications systems. In this thesis phase shifter selection mechanism like fully connected with phase shifter selection, sub-connected with phase shifter selection, fully connected and sub connected with phase shifter selection with halved and doubled switches will be applied for a millimeter-wave-based massive MIMO system to improve Energy-Efficiency. Finally from the simulation result, sub connected with phase shifter selection (SPSS) with halved switch can outperform energy efficiency. For 120 number of antenna, I will get 0.01739 Energy Efficiency in the sub-connected phase shifter selection with halved number of switch.

Keywords: - Massive MIMO, Energy Efficiency, Spectral Efficiency, millimeter-wave (mm Wave) communication systems, Hybrid Beamforming.

CHAPTER ONE

1. INTRODUCTION

1.1 Background

Due to the growing human interest from time to time, new applications such as video live streaming, online gaming, the internet of things, smart metering, automotive driving, video surveillance, cloud computing, and eHealth services was emerged. So the development of cellular communication systems has been driven by a combination of market demands and technological advances. As more and more devices are using cellular communication the demands for speed, reliability, and coverage are increasing (Aki, 2020).

The new technology called 5G mobile networks, which are 100 times faster than existing 4G networks, are already being implemented. 5G networks will have data rates of up to 10 Gbps, low latency (in milliseconds), and higher reliability. An HD movie, for example, can be downloaded in a matter of seconds. Many Internet of Things enabled products and smart vehicles can benefit from this technology. To meet the ongoing demands of 5G, efficient wireless access technology that can boost throughput without expanding bandwidth or densifying the cell is required.

Multiple-input-multiple-output (MIMO) techniques such as Beamforming, precoding, and combining can significantly improve the reliability of the transmission and increase the achievable data rates in wireless communication systems. As the number of the antenna elements at the transmitter/receiver increases, higher diversity, and multiplexing gains is observed and the channel matrix tends to have favorable conditions (Rusek et al., n.d.).

Massive multiple-input multiple-output (mMIMO) communication systems and the use of millimeter-wave (mm-Wave) bands represent key technologies that are expected to meet the growing demand of data traffic and the explosion of the number of devices that need to communicate over 5G/6G wireless networks (Romano, 2022). In mMIMO, the number of antennas is much larger than in traditional MIMO systems with the purpose of obtaining a high spectral efficiency.

As a result, Multiple-input-multiple-output systems with a huge number of antennas have gotten a lot of attention. At millimeter Wave frequencies, next-generation wireless communication systems, such as 5G, use massive multiple input multiple output beamforming algorithms to increase the signal-to-noise ratio and spatial multiplexing to increase data throughput. Because propagation loss is a big issue when employing millimeter Wave frequencies, 5G networks use massive multiple input multiple outputs (large scale antenna arrays) to overcome path loss. Because wavelengths are so narrow in millimeter Wave frequency bands, we may collect more antenna elements in the given physical dimensions. Antenna elements can be separated into sub-arrays to reduce system cost, and each T-R module can be allocated to an antenna subarray utilizing a new millimeter Wave communications technology called "Hybrid Beamforming".

Hybrid Beamforming designs allow numerous users to share data using multi-user multiple input multiple outputs with multiplexing improvements, and these multi-user multiple input multiple outputs systems have a lot of potential in millimeter Wave communication networks." Because they use analog Beamformers in the radio frequency domain and digital Beamformers in the baseband domain, In comparison to several transmit antenna elements, hybrid transceivers have fewer radio frequency chains. In millimeter Wave massive MIMO communication systems, in a hybrid Beamforming system, path losses, power consumption, and hardware cost are all regulated by Beamforming gains (Dilli, 2021).

The mMIMO system will be a critical ingredient for millimeter wave technology, which is a major part of the 5G wireless cellular networks, the large Beamforming gain from the massive MIMO system will combat the path loss of millimeter-wave transmission. So, the power consumption significantly increases with limited channel state information (CSI) of the transmitting signals from a base station (BS) to active user equipment (UE). Because 5G requires a multi-gigabit/s transmission rate, keeping a low-power, low-complexity, and low-cost system in the mm-wave transmission band is still essential (Rangan et al., 2014).

Due to it’s a lot of unoccupied spectrum, mm-Wave technology is vital for 5G. However, due to the wavelength being inversely related to free space propagation loss, the complication increases. Combining huge MIMO technologies with extremely lossy mm-wave frequencies will only complicate the entire 5G technological environment. The ideal answer for 5G technology is to implement a hybrid beamforming technique. Owing to the technique's guiding antenna arrays while keeping minimal complexity and Radio frequency chain. The hybrid beamforming technique can function as analog/digital with precoding for the Down link millimeter-wave path at the baseband level.

The analog, digital or hybrid beamformers can be performed depending on the structure of the antenna array. Because the antenna array is only connected to the transceiver by a single RF chain, the analog approach cannot give multiplexing gains (Godara & Member, 1997). Additionally, digital with a dedicated Radio Frequency chain per antenna element can utilize all the degrees of freedom of the channel to simultaneously transmit multiple symbols. But, due to the system complexity, cost, and power consumption, digital for large antenna arrays is not suitable for practical applications (Alkhateeb et al., 2014). Hybrid which have been applied where a few number of RF chains are connected to a large number of antennas via a network of phase shifters have been used to provide a tradeoff between performance and cost, (Sohrabi & Yu, 2015b) (Sohrabi & Yu, 2015a).

1.2 Problem statements

When the number of users in a Massive MIMO system grows, the number of antennas and phase shifters also grows, resulting in significant energy efficiency and capacity gains. Increasing the number of antennas and phase shifters at the BS, on the other hand, increases power consumption and system cost. Also when there are a lot of phase shifters on the same base station. They have increasing amplitude variation and phase errors over different phase configurations, as well as inherent power outages and additional noise contribution. As a result of these basic problems, the transmission loss is high, and the system's power consumption is high.

A basic technique to improving the system's energy efficiency is to reduce power consumption. The number of base station antennas in a huge multiple input multiple output system is extremely enormous, and each BS antenna contains radio frequency chains in both the base station, user equipment, and phase shifters, which increases the power consumption. The number of antennas at the base station might be limited, where power reduction strategy manages the RF chain in both BS and UE, and the phase shifters. This limiting of the number of phase shifters is called phase shifter selection techniques. The phase shifter selection technique only allows some active phase shifters.

1.3 Objective of the study

1.3.1 General Objective

The main objective is to achieve the Energy-Efficient phase shifter selection for Millimeter-Wave-based Massive Multiple Input Multiple Output System.

1.3.2 Specific objectives

- Calculation of system capacity and total power consumed by the radio frequency chain for fully connected and sub-connected with phase shifter selection.
- Study and evaluate the performance parameters like signal to noise ratio, Energy Efficiency, and capacity related to the number of antenna and users.
- Calculate and analyze the Energy Efficiency of the system by using phase shifters selection methods.
- Analyze Energy Efficiency as well as power consumption by comparing the results of the simulation.

1.4 Significance

In order to increase the Energy Efficiency of a huge MIMO system, the total power usage must be decreased. The phase shifter selection method is proposed in this thesis to reduce total power consumption and in order to achieve Energy Efficiency.

- This proposed algorithm reduces operation costs
- Minimize power consumption
- Reduces system design complexity

1.5 Scope

The phase shifter selection algorithms offers a benefit in a huge MIMO system. The advantages of phase shifter selection in large MIMO systems include: reduced hardware complexity, improved spectral performance, increased capacity, improved energy efficiency, and so on. The thesis focused on modeling and simulation of Energy-Efficient phase shifter selection for Millimeter-Wave-based Massive Multiple Input Multiple Output System on a downlink system.

There is also a capacity and power consumption mathematical model. in this proposed thesis for calculating energy efficiency. Finally, MATLAB software is used to simulate the developed and modeled suggested system.

1.6 Main Contribution

The main contribution of this thesis's is to improve the Energy Efficiency by minimizing the power consumption of massive multiple input multiple output systems by using phase shifter selection systems by taking different mechanisms.

The following list highlights and summarizes the study's major contributions.

- ✓ A Massive-multiple input multiple output structure is offered using phase shifter selection methods. The method investigate the Energy Efficiency performance through the phase shifter selection system, and finally the massive-MIMO system with phase shifter selections achieves better Energy Efficiency than a conventional MIMO system.
- ✓ In this thesis, I have used the different phase shifter selection method such as fully connected phase shifter only (FP), Sub connected phase shifter only (SP), Fully-connected with PS selection (FPSS), and Sub connected with PS selection (SPSS) and compared those methods.

1.7 Thesis Organization

The thesis has divided into five chapters. Chapter one presents the introduction, statement of the problem, objectives of the study, scope, significance, and main contribution of the thesis. Chapter two includes a Review of different literature on Massive multiple input multiple output, millimeter-wave, Analog, Digital, and Hybrid Beamforming and the existing works related to Energy-Efficient phase shifter selection for Millimeter-Wave-based Massive Multiple Input Multiple Output System. Chapter three describes the System model and mathematical formulation for downlink Massive MIMO considering phase shifters and power consumption modeling. Chapter four presents' simulation results obtained using MATLAB and discussions of those results. Finally, Chapter five is describe about the conclusion and recommendations for future works. In this thesis phase shifter selection method is utilized for enhancing the energy efficiency of Downlink massive MIMO and the effect on Energy-Efficient phase shifter selection for Millimeter-Wave-based Massive Multiple Input Multiple Output System.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Massive MIMO overview

Marzetta created the enormous massive multiple input multiple output design, with the basic idea being to scale up multi-user MIMO systems by adding a high number of antennas at the base station, far exceeding the number of active terminals. As a result, simple linear processing is almost preferable. In the event of multi-user MIMO, at the same time and with the same frequency, the base station feeds all participating users. Both uplink and downlink modes are supported by the huge MIMO system. Because there are so many base station antennas, the channel becomes essentially deterministic, and Frequency dependency and small-scale fading are eliminated. Channel hardening is the term for this. (Mahboob S, Ruby R, 2012) (Arash et al., n.d.).

Massive MIMO systems are an important technology for 5G mobile networks because they can increase the cellular network's energy efficiency and spectral efficiency. Hundreds, or thousands of antennas, are used in base stations in these systems to serve a small number of consumers at the same time- frequent resource (Wang et al., 2018). Massive MIMO is a type of multi-user MIMO system in which there are a lot of BS antennas and a lot of users. Massive MIMO can greatly increase both spectral and transmit-energy efficiency. This can be obtained by allowing the number of antennas and RF chains to grow very large.

One of the promising strategies for enhancing the spectral efficiency of wireless channels is multiple input multiple output (MIMO). Traditional digital beamforming can be used to fully utilize MIMO's capabilities. Many digital beamforming design methodologies have been developed in recent decades. However, these methods are only suitable for a small number of antennas (Daniel et al., 2014). It has been demonstrated that deploying a large number of antennas at the transmitter and/or receiver can considerably improve the spectral and energy efficiency of microwave and millimeter-wave (mmWave) wireless networks (Alkhateeb et al., 2014) (Marzetta, 2010).

In digital beamforming, one radio frequency (RF) chain is needed for each antenna element at the base station and user equipment where an RF chain includes a low-noise amplifier, down-converter, digital to analog converter (DAC), analog to digital converter (ADC) and so on (Venkateswaran & Veen, 2010) (Zhang et al., 2005).

The high cost and power consumption of mixed-signal components, such as high-resolution ADCs and DACs, mean that dedicating a separate RF chain for each antenna is highly wasteful when the number of base station antennas N is very big (Alkhateeb et al., 2014) (L. Chen, 2011) (Han et al., 2015). For these reasons, beamforming using a small number of RF chains has gained a lot of interest recently. One method for achieving this goal is to use hybrid beamforming, which uses beamforming in both the digital and analog domains (HB). Microprocessors can be used to achieve digital beamforming, whilst low-cost phase shifters (PSs) are used to implement analog beamforming (Le et al., 2015).

2.2 Beamforming design and Channel Estimation

The challenges in massive MIMO systems was huge training overhead of channel estimation in the downlink as well as the heavy feedback overhead. Additionally, the user equipment will bear the heavy burden of high computational complexity to estimate the downlink channel, which is not a wise choice for power saving. To deal with it, most of the existing approaches prefer time division duplex mode with the assumption of channel reciprocity thus the channel can be estimated in the uplink and the downlink precoding matrix can be designed according to the uplink channel state information.

2.3 Beamforming Architectures

Massive MIMO is a system in which the base station has several single-antenna users and has large antennas. Typically, the number of base station antennas is one order of magnitude more than the number of users. Since we have a large number of antennas at the base station, we can generate and allocate separate narrow beams to each user. This beam allocation is called spatial filtering. So, each user can use the same time and frequency resources simultaneously, but illuminated with separate antenna beams. By applying appropriate phase shifts to each element of the antenna array, the pattern of the antenna is steered in the desired direction, which is called beamforming. The main aim of beamforming is to create a directional path between the base station and the user via separate array beams. These spatial beam diversities increase the spectral efficiency, energy efficiency, and security of the link. In an analog Beamformer, the received signals are combined coherently at RF while in a digital Beamformer, the coherent combination of the received signal from each element occurs after digitizing the RF signals.

2.3.1 Beamforming

Beamforming is defined as the ability of the base station to alter the antenna's emission pattern (Molisch et al., 2017). Beamforming assists the base station in determining the best way to deliver data to the customer while simultaneously reducing interference from neighboring users. (Yang et al., 2018).

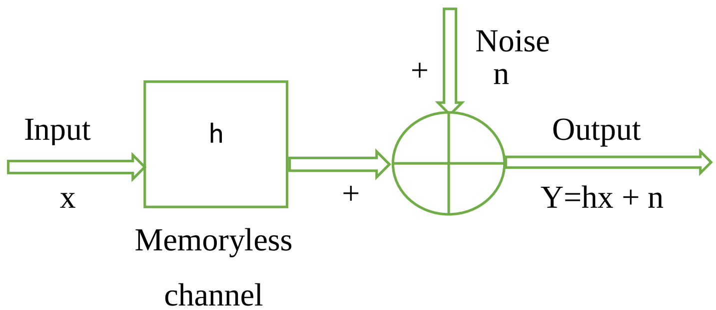


Figure 2.1 Hybrid beamforming

Beamforming is a signal processing procedure used with multiple arrays of the antenna at the transmitter side or/and receiver side in order to send or detect multiple signals from multiple desired terminal simultaneously. Beamforming helps huge multiple input multiple output systems increase spectrum efficiency, and it helps millimeter wave systems to increase data rate. The base station in massive MIMO systems can provide data to the user over several paths, and beamforming coordinates packet movement and arrival time to allow numerous users to contribute data at the same time. Because millimeter waves are unable to pass through obstacles and do not travel over long distances due to their shorter wavelength, beamforming is used to direct concentrated beams toward users. As a result, beamforming allows a user to get a strong signal without being interrupted by other users (Chataut & Akl, 2020).

Analog beamforming, digital beamforming, and hybrid beamforming approaches can be categorized depending on signal processing. In comparison to digital beamforming, analog beamforming offers low complexity, low-cost phase shifters for huge MIMO systems at the penalty of limited performance because it only supports a single data stream. Digital beamforming is advantageous for gathering user signals because it provides more precise and rapid foundation results (Alkhateeb et al., 2014) However, it has a high level of complexity, higher power consumption, and an expensive design. For huge MIMO systems, hybrid beamforming has been created to combine the benefits of analog and digital beamforming.

2.3.2 General Beamforming classification

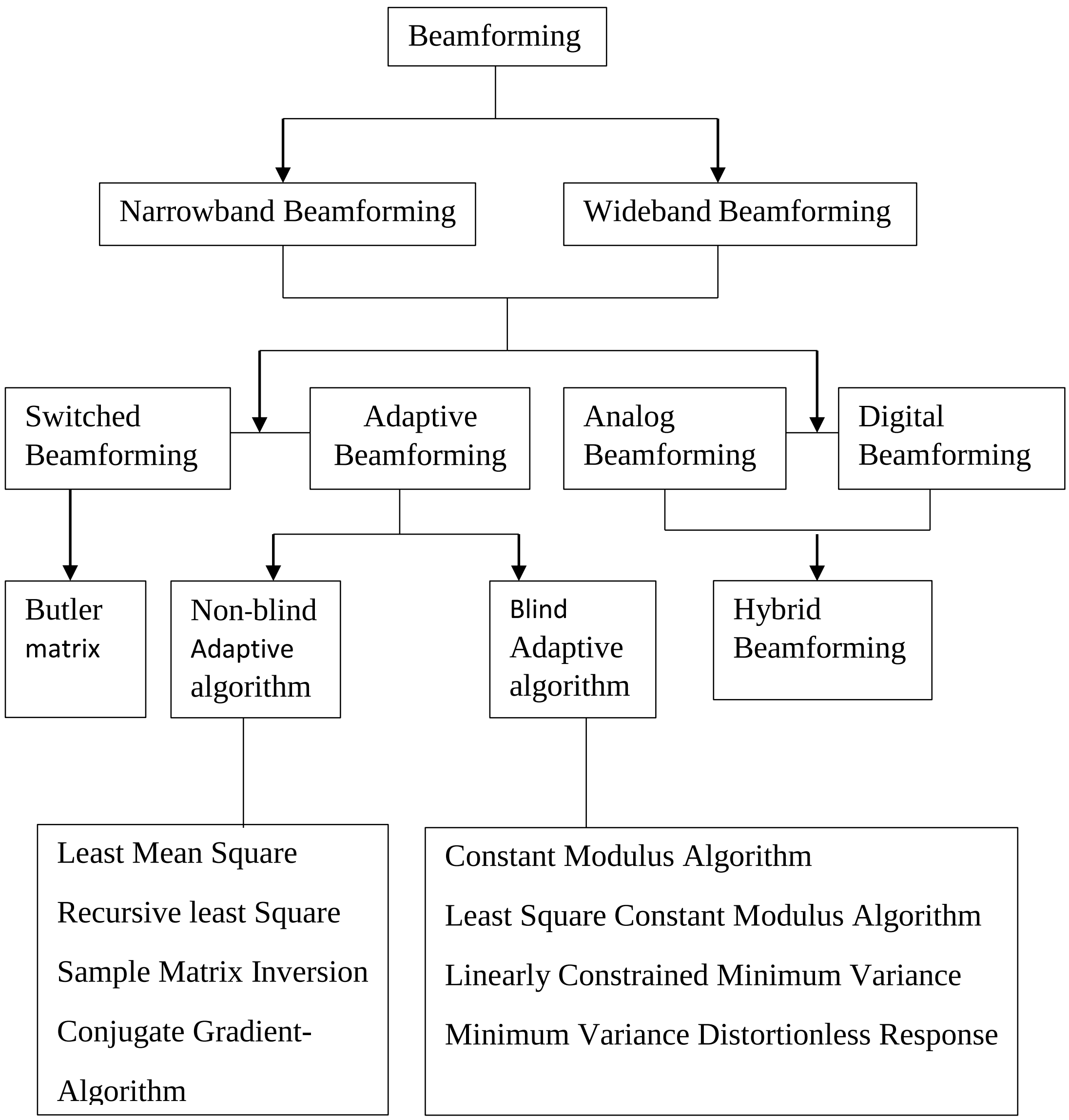
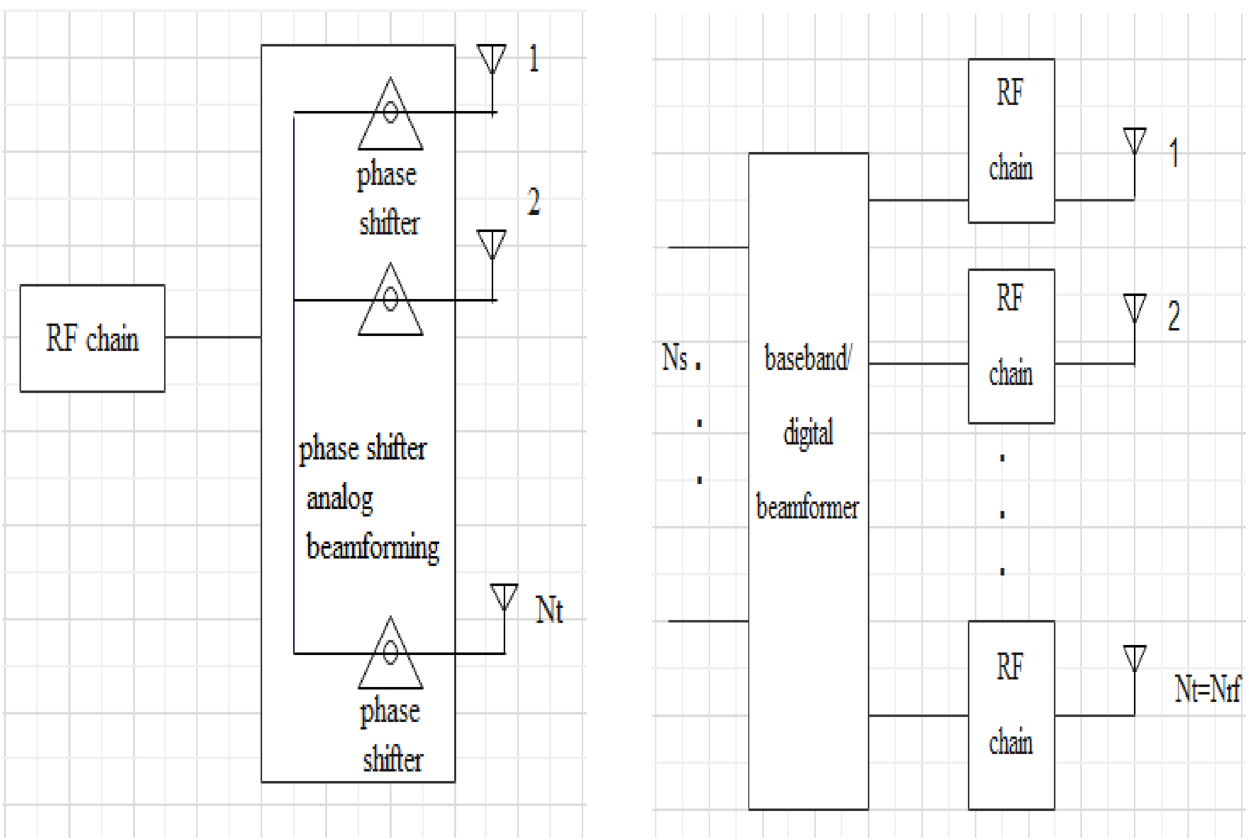


Figure 2.2 General Beamforming classification (Dilli, 2021)

2.3.3 Analogue Beamforming

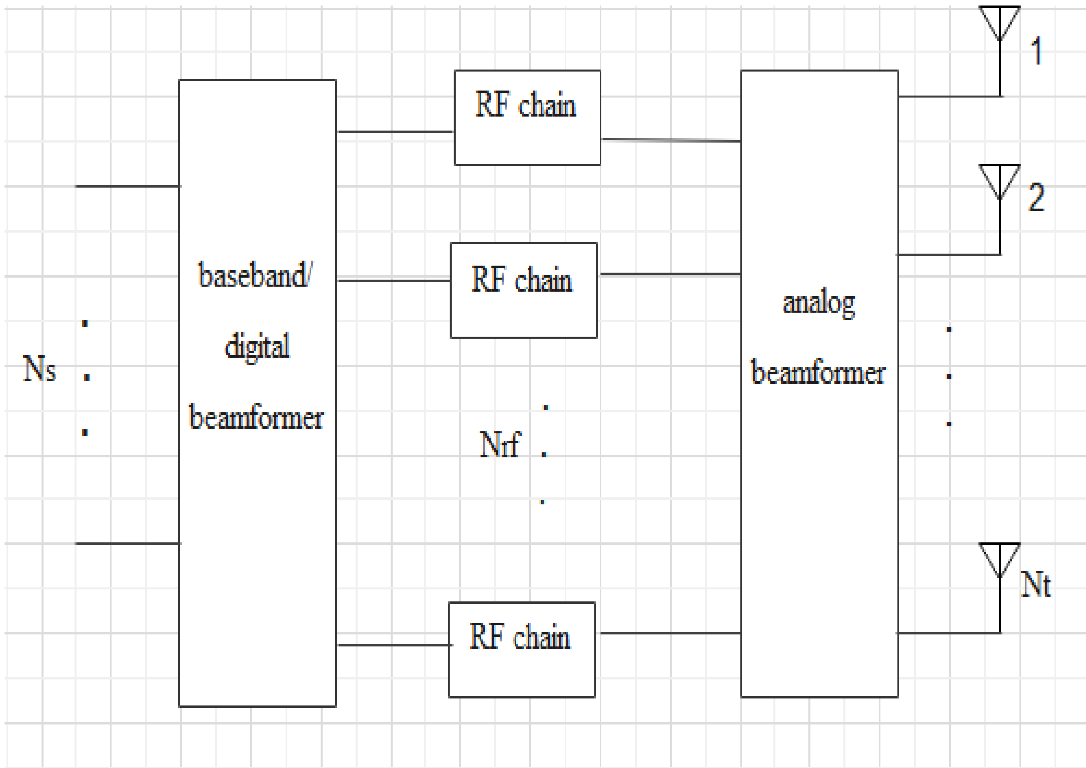
Analog beamforming's main purpose is to broadcast the same signal from numerous antennas with various phases using phase-shifters. To process transmit and receive arrays, radio frequency components with phase shifting and possibly gain modification capabilities are used. The primary principle behind analog beamforming is to regulate the phase of each transmitted signal using inexpensive phase shifters. As a result, analog beamforming is less expensive than digital beamforming to implement. However, because phase shifter amplitudes are not variable, its performance is inferior to that of digital beamforming. In such a system, a single RF chain with many analog phase shifters is employed to convey a single data stream (Engda et al., n.d.).

The hardware structure for analog beamforming is easier to build. Because only the phases of the transmit signals may be modified, not their amplitudes, this beamforming has low antenna gain and suffers severe performance loss. By combining analog and digital beamforming to gain the benefits of both, known as hybrid beamforming, which is commonly employed in massive MIMO systems, better performance can be achieved (Molisch et al., 2017). Analog beamforming increases the effects of the Radio frequency chain by reducing the number of ADCs or DACs, which enhance power amplifier outputs or changing mixer architecture for cost savings.



(a) Analog Beamformer

(b) Digital Beamformer



(b) Hybrid Beamformer

Figure 2.3 Beamforming architectures

In the Analog Beamformer architecture, one RF chain is connected to all antenna elements by an analog Beamformer network, as seen in Figure 2.3 (a). In this architecture, the antenna phase shifts are controlled with external hardware called phase shifters.

2.3.4 Digital Beamforming

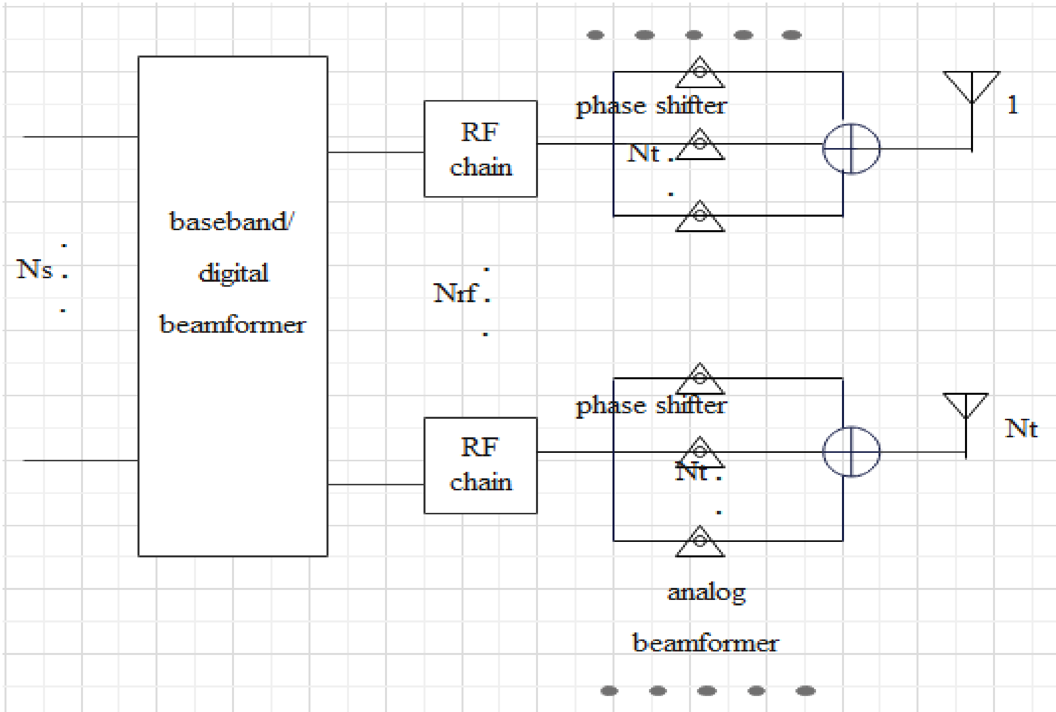
A single radio frequency chain is required for each antenna element to provide good performance, but it has a high power consumption and a complex architecture. Down-converter, low-noise amplifier, digital to analog converter, analog to digital converter, and other components make up the RF chain. As a result, the cost and power consumption of mixed-signal components, such as high-resolution DACs and ADCs, are higher for a large number of BS antennas. As a result, beamforming using a limited number of RF links is becoming more important (In, 2011). By deploying beamforming in both digital and analog methods, hybrid beamforming is the ideal mechanism for achieving this goal. Beamforming in digital beamforming is done at the baseband frequency, but beamforming in analog beamforming is done with low-cost phase shifters.

In the Digital Beamformer structure, each antenna element is connected to a Radio Frequency chain. In other words, the number of RF chain and antenna elements is equal, as shown in Figure 2.3 (b). Each RF chain consists of an Analog to Digital Converter (ADC), Digital to Analog (DAC), up converter, amplifiers, filters, and switches. In the digital beamforming process, all the beamforming algorithms and phase shifts are implemented in the baseband after digital sampling. This architecture benefits from flexibility in pattern and high performance, where multiple beams can be generated simultaneously, but it is costly and power-consuming. Furthermore, calculating the channel state information for digital beamformers at massive MIMO suffers from overhead.

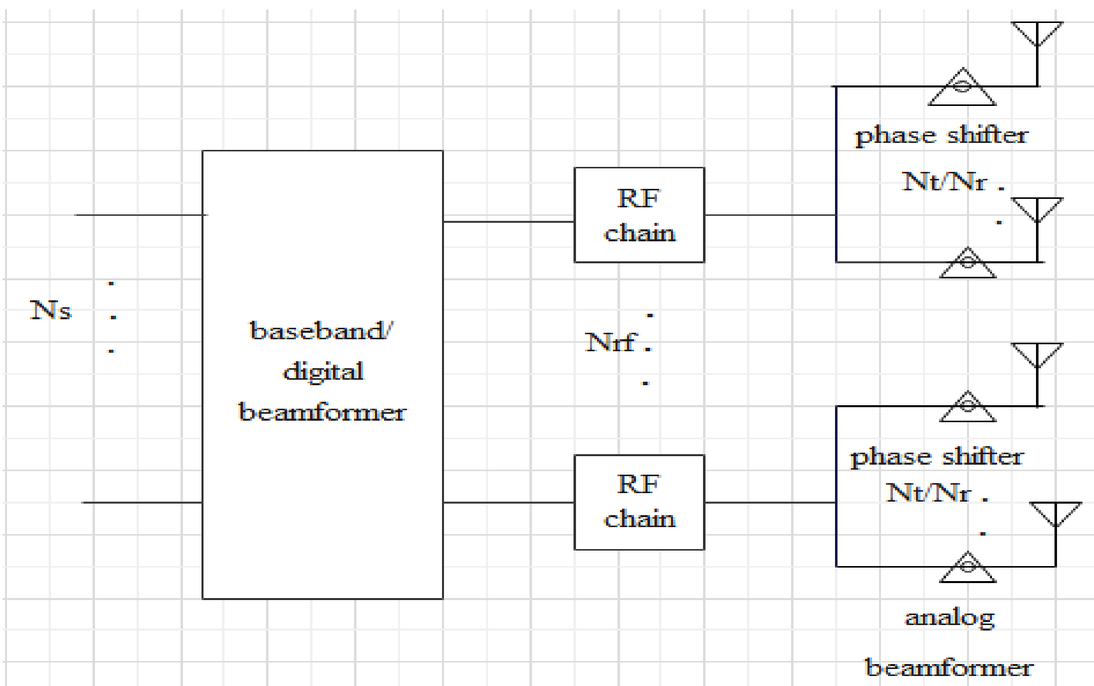
2.3.5 Hybrid Beamforming

Is a type of Beamforming that avoids the drawbacks of either digital or analog Beamforming by combining their benefits. When compared to analog-only designs, using different simultaneous beam transmissions and reduces the training overhead (Jasim et al., 2017). In hybrid Beamforming, the number of RF chains is significantly lower than the number of antennas while maintaining spatial multiplexing gain, making it simpler than digital systems. By separating the multiple input multiple output optimization process between the analog and digital domains, they provide greater flexibility than typical analog Beamformer. The hybrid technique's advantage is that a digital precoder can compensate for the analog precoder's lack of precision (Ahmed et al., 2018).

Hybrid Beamformer phased array technology exploits the low cost and EE of combined-signal RF components to implement cost-effective MIMO transceivers. This approach has received significant interest in exploring new architectures for the RF chain. The well-known types of hybrid beamformers are i) fully connected and ii) partially-connected Hybrid beamforming. In the fully connected case, all the array elements are connected to an RF chain, as shown in Figure 2.4 (a). Whereas, in the partially connected case, each sub-array of antennas is connected to an RF chain as shown in Figure 2.4 (b). The partially connected structure benefits from the reduced cost and complexity compared to the fully connected architecture.



(a) Fully-connected Hybrid Beamformer



(b) Partially-connected Hybrid Beamformer

Figure 2.4 Hybrid Beamformer architectures

Table 2.1 Comparison of Precoding Techniques

Features	Beamforming types		
	Analog beamforming	Digital beamforming	Hybrid beamforming
Number of streams	Single stream	Multi-stream	Multi-stream
Number of users	Single-user	Multi-user	Multi-user
Signal control capability	Phase control only	Phase & amplitude control	Phase & amplitude control
Degree of freedom	Least	Highest	Intermediate
Implementation	Phase shifters	ADC/DAC, mixer	Phase shifters, ADC/DAC, and mixer
Hardware requirement	Least	Highest	Intermediate
Energy consumption	Least	Highest	Intermediate
Cost	Least	Highest	Intermediate
Complexity	Least	Highest	Intermediate
Performance	Least	Optimal	Near-optimal
Suitability for mmWave massive MIMO	Unsuitable	Impractical	Is realistic

2.4 Phase Shifters

The main purpose of Phase shifter is controlling the relative phase of each element in a phase array antenna. We use the phase shifters formula to determine the relationship between two waveforms and their resulting phase angle. In a phased array, the power from the transmitter is fed to the radiating element via devices called phase shifter. RF phase shifters are used to change the transmission phase angle of an input signal. Phase shifters are a major useful block in RF transmission circuits. In radio communication, phase shifters are used for electronic beam steering of the transmitted RF waves. Due to the increase in RF application area, there is a high demand for phase shifters that have high performance with very less cost and also very less power consumption.

In hybrid beamformers with a fully-connected structure, phase shifter selection has been established as an effective way for providing a trade-off between energy and spectrum efficiency. Each phase shifter is equipped with an ON/OFF switch in this technique, and phase shifters that do not contribute significantly to spectral efficiency are identified and turned off. This concept was subsequently extended for low-complexity, energy-efficient hybrid beamformers with a sub-connected topology to reduce the number of phase shifters (Payami, Masouro, et al., 2018).

Fully-connected and sub-connected phase shifter networks are the two most common varieties. Each RF chain is connected to all of the antennas in the fully connected configuration. It can use the entire array gain, but because of the large number of phase shifters it requires, it has a significant power consumption. Each RF chain is connected to a subset of antennas in the sub-connected design, resulting in a simpler circuit but worse spectral efficiency than the fully-connected configuration (Payami, Ghoraishi, et al., 2018).

2.4.1 Full Duplex Technology

To avoid interference, wireless transmission and reception are usually not done at the same frequency bands. To get orthogonal non-interfering signals, any bidirectional system must use the time or frequency domain to segregate the uplink and downlink channels. as seen in Figure 2.5, full duplex refers to simultaneous transmission and reception across the same frequency band and at the same time. Full-duplex signal transmission will be used in 5G networks to potentially increase network capacity and benefit higher layers (e.g., MAC layer) (Chataut & Akl, 2020).

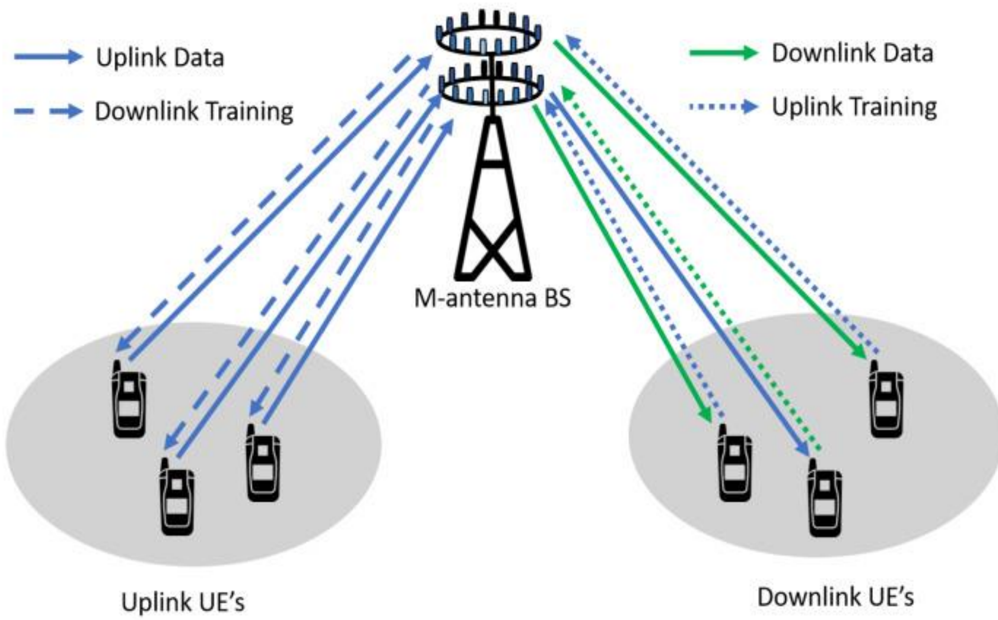


Figure 2.5 Full duplex technology (Chataut & Akl, 2020).

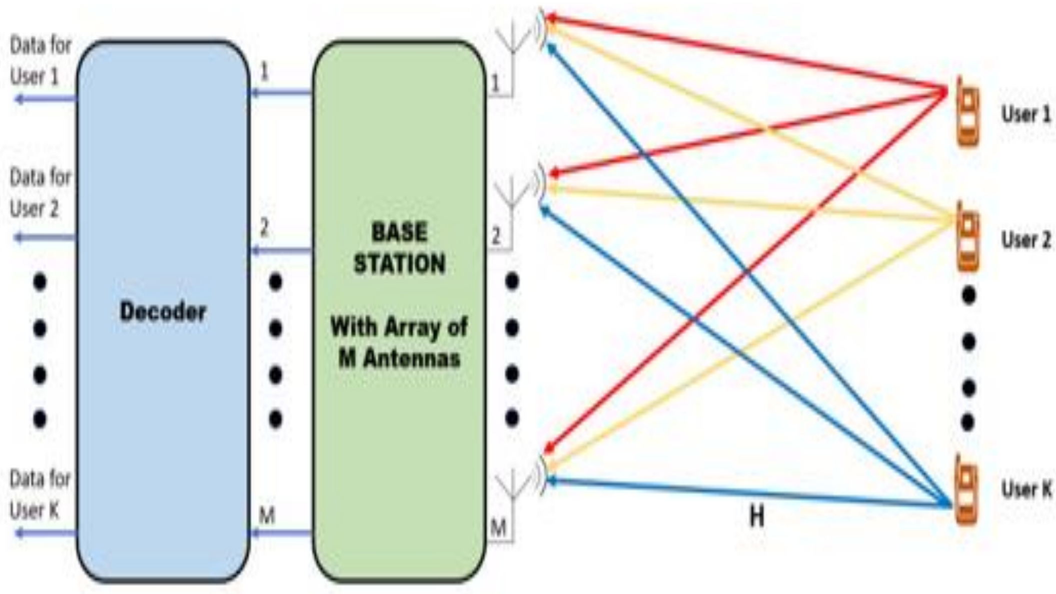
2.4.2 Uplink Transmission

The uplink channel is used to transmit data and the pilot signal from the user terminal to the base station, as shown in figure 2.6 a. Let us consider a massive MIMO uplink system equipped with M antennas at the base station and at the same time communicating with N (M ≫ N) single-antenna users. If the signal transmitted by the user or the deterministic pilot signal to estimate the channel is $\chi \in \mathbb{C}^N$, the signal received at the base station during uplink is given as:

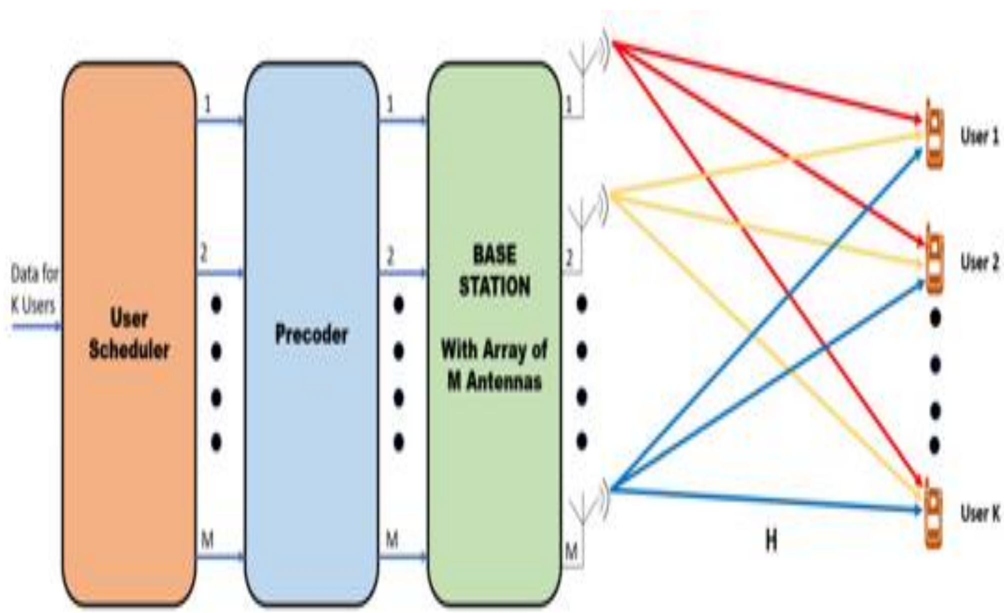
$$y = H_X + n_{uplink}$$

Where $y \in \mathbb{C}^M$, is the signal received at the base station, H is the channel vector between the user terminal and the base station, and elements of $H \in \mathbb{C}^{N\times M}$, are independent and identically distributed with zero mean and unit variance, that is, H~CN(0,1). The additional term $n_{uplink} \in \mathbb{C}^M$ is the addition of interference from several transmissions and the receiver noise. The interference added is independent of the user signal *x*, but it can be dependent on the channel H.

$$n_{uplink} = n_{uplink} - \text{interference} + n_{noise}$$



(a) Uplink



(b) Downlink

Figure 2.6 Massive MIMO uplink and downlink operation (Chataut & Akl, 2020).

2.4.3 Downlink Transmission

The downlink channel is mostly used to send data or estimate the channel between the user and the base station. The channel is estimated by the base station using training pilots. Figure 2.6 b depicts a downlink transmission with multiple user devices and a base station. Consider a downlink massive MIMO system in which the base station has M antennas and is simultaneously serving N users with a single antenna. Multiple users receive independent information from the base station at the same time. The signal received by the user, yk$\in\mathbb{C}^{M\times 1}$at the K_{th} user is:-

$$y_k = h_k x_k + n_{downlink}$$

Where h_k is a channel vector between the K_{th} user and the base station, whose elements are independent and identically distributed with zero mean and unit variance (0,1). $\mathbb{C}^{M}$ is the signal transmitted by the base station to user k, and $n_{downlink}$ is the additional noise, which is made up of the receiver noise n_{noise} ~CN(0,$\delta^2 I$) and downlink interference. $n_{downlink}$ is the amount of

Interference created by sending to multiple users at the same time, and is expressed as:

$$n_{downlink} = n_{downlink} - \text{interference} + n_{noise}$$

2.4.4 Energy Efficiency

Energy efficiency is defined as the ratio of spectral efficiency to transmit power, and massive MIMO can provide substantial energy efficiency gains by achieving higher spectral efficiency with low power consumption. However, the increasing number of the antenna does always increase the spectral efficiency, because the power consumption also increases along with the number of antennas and more users (Chataut & Akl, 2020).

2.5 Advantages of Massive MIMO

- **High spectral efficiency and high communication reliability:** Massive MIMO obtains all gains from conventional multi-user multiple input multiple outputs, meaning that, with *M*-antenna base station and *K* single-antenna users, we can achieve a diversity of order *M* and a multiplexing gain of min (*M*, *K*). By increasing both *M* and *K*, we can inherit a huge SE and very high communication reliability.
- **High energy efficiency:** In the uplink Massive multiple input multiple outputs, coherent combining can improve a very high array gain which allows for a substantial reduction in the transmit power of each user. In the downlink, the BS can focus the energy in the spatial directions where the terminals are located. Because of that with massive antenna arrays, the radiated power can be reduced by an order of magnitude, or more, and therefore, we

can achieve high Energy Efficiency. For a fixed number of users, by doubling the number of base station antennas, while reducing the transmit power by two, we can maintain the original spectral efficiency, and hence, the radiated energy efficiency is doubled.

- **Simple signal processing:** For most propagation environments, the use of an excessive number of BS antennas over the number of users yields favorable propagation where the channel vectors between the users and the BS are paired wisely (nearly) orthogonal. Under favorable propagation, the effect of inter-user interference and noise can be eliminated with simple linear signal processing (liner precoding in the downlink and linear decoding in the uplink). As a result, simple linear processing schemes are nearly optimal. Another the key property of Massive MIMO is channel hardening. Under some conditions, when the number of BS antennas is large, the channel becomes (nearly) deterministic, and hence, the effect of small-scale fading is averaged out. The system scheduling, power control, etc., can be done over the large-scale fading time scale instead of over the small-scale fading time scale. This simplifies signal processing significantly.

2.6 Challenges of massive MIMO system

Massive MIMO technology is more than just an extension of MIMO technology, and there are still many issues and challenges to overcome in order to make it a reality. Massive MIMO systems face a number of fundamental challenges (Lu et al., 2014).

- **Unfavorable Propagation**

Massive MIMO is thought to work in favorable propagation conditions. However, in actuality, a number of circumstances make the channel's propagation undesirable. The propagation environment, for example, when the number of users is substantially more than the number of scatters, or when the scatters between the BS and the channels of various users are normal. The interference of the BS antennae across a large area is one possible solution to this problem.

- **Pilot Contamination**

Cellular networks, in reality, are made up of a huge number of cells. Due to a scarcity of frequency spectrum, multiple cells share frequency resources. As a result of the limited channel coherence period, assigning orthogonal pilots to all users is challenging. Normally, these orthogonal sequences between the various cells are reused. As a result, the pilot sequences communicated to other cells can alter the channel estimation process in a specific cell, as shown in figure 2.7. The phenomenon known as "pilot contamination" can degrade system performance. Pilot contamination is one of the primary challenges that limits the efficiency of large MIMO systems. Even as the number of BS antennas grows, this effect cannot be decreased.

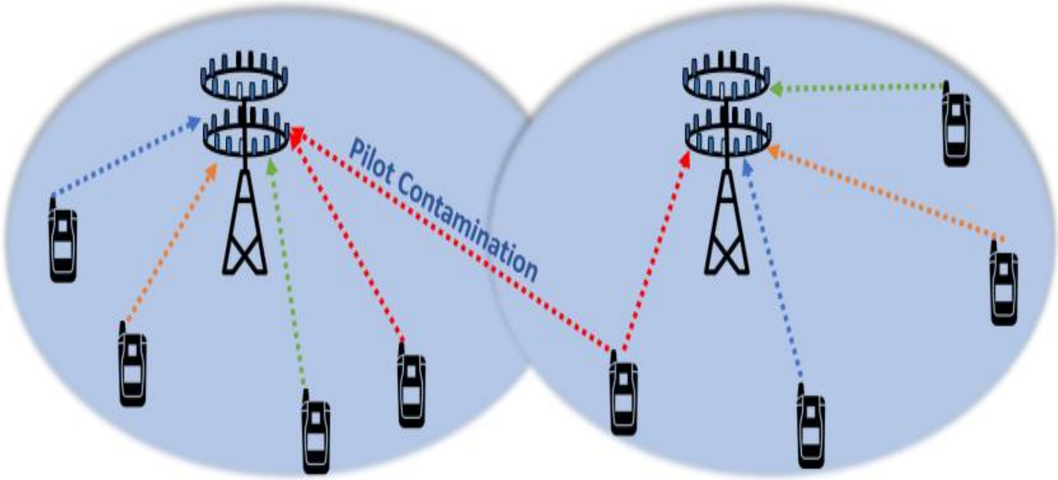


Figure 2.7 Massive MIMO pilot contamination effect (Chataut & Akl, 2020).

- **Channel Estimation**

Massive MIMO uses Channel State Information for signal detection and decoding (CSI). CSI defines the cumulative influence of fading, scattering, and other factors on the condition of the communication link from the transmitter to the receiver. Massive MIMO performance grows linearly with the number of sending or receiving antennas, whichever is less, if the CSI is perfect (Ali et al., 2017). CSI must be estimated both downlink and uplink in a system using Frequency Division Duplexing (FDD). The BS uses orthogonal pilot signals sent by the user terminal to estimate channel during the uplink. During the downlink, the base station sends pilot signals to the user, who acknowledges the downlink transmission's estimated channel information. The downlink channel estimate approach in FDD becomes exceedingly difficult and infeasible to apply in real-world applications for a huge MIMO system with numerous antennas. In wireless communication, Figure 2.8 a depicts the FDD and Time Division Duplexing (TDD) modes, while Figure 2.8 b depicts the typical pilot transmission and CSI feedback mechanism in FDD and TDD mode. In FDD systems, TDD provides a solution to the problem of downlink transmission. In TDD, the base station can estimate the downlink channel using uplink channel information by utilizing the channel reciprocity property. During uplink, the user sends orthogonal pilot signals to the base station, and the base station estimates the CSI to the user terminal based on these pilot signals (Lu et al., 2014). The base station will then beamform downlink data towards the user terminal using the estimated CSI. The pilot contamination problem occurs and is a significant challenge during massive MIMO channel estimation due to the restricted number of orthogonal pilots that can be reused from one cell to another. Increased hardware and processing complexity owing to the increased number of antennas are other problems. As a result, for vast MIMO systems, a channel estimation technique with low complexity and overhead is highly desirable (Wu et al., 2016).

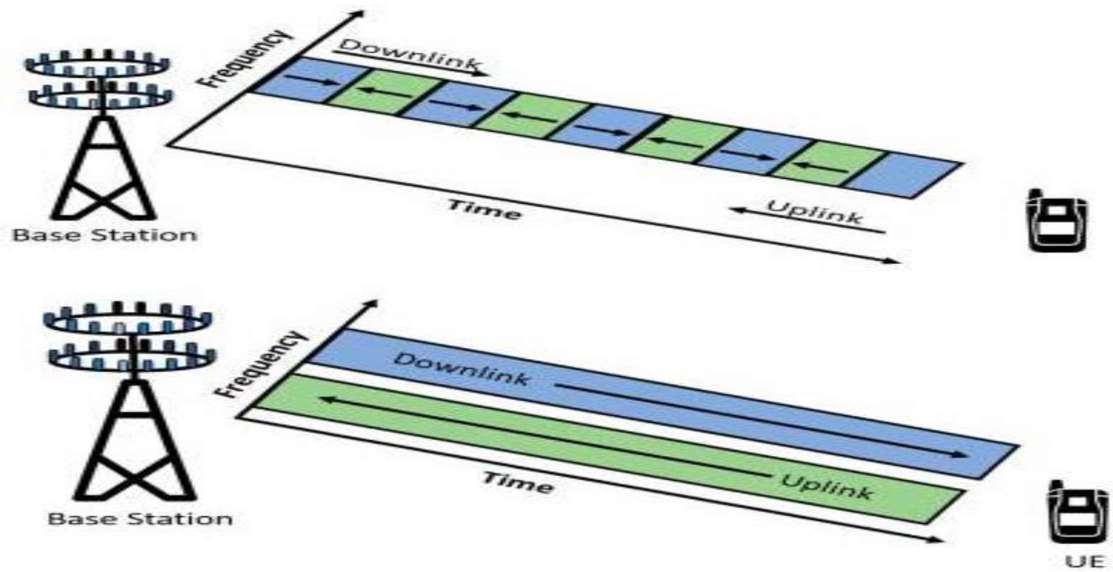


Figure 2.8 Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) mode (Chataut & Akl, 2020).

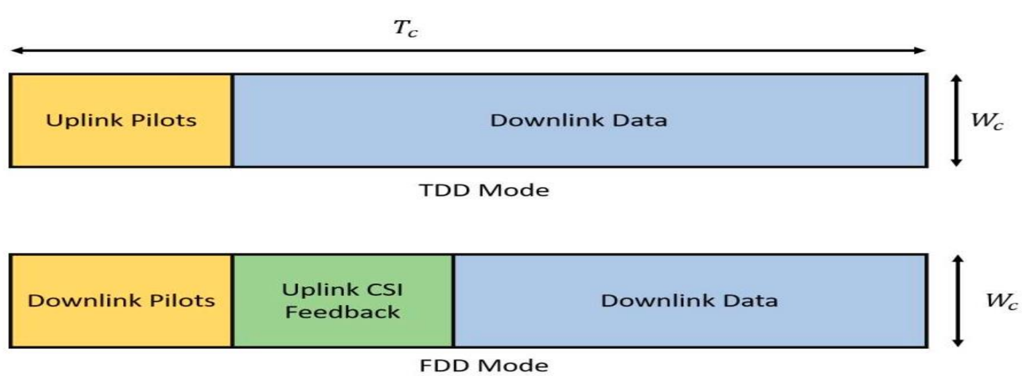


Figure 2.9 Typical pilot transmission and CSI feedback mechanism in FDD and TDD mode (Chataut & Akl, 2020).

- **High power consumption**

Massive MIMO consumes more power due to the huge number of antennas and also the large number of radiofrequency chains corresponding to each antenna. As the radio frequency chain grows in size, each component requires more power.

2.7 Millimeter Waves

Cellular connectivity typically uses a frequency below 6 GHz, while services such as medical imaging, microwave remote sensing, amateur radio, terahertz computing, and radio astronomy use frequencies above that. The RF band has been congested due to the tremendous rise in data transmission. As a result, a user's bandwidth is limited, resulting in a slower and less reliable connection. Using frequencies above 6 GHz for wireless communication is one solution to this problem. Above 6 GHz has never been used for wireless communication, however millimeter wave broadcasting has been the subject of extensive investigation. Millimeter waves have a frequency range of 30 GHz to 300 GHz, and their length varies from 1 to 10 mm, compared to the radio waves utilized in today's mobile communication system, which are measured in tens of centimeters.

In the last several years, many elements of millimeter waves have been reported (Rangan et al., 2014). (Huang et al., 2020). The promise and challenges of millimeter-wave technology are discussed by the authors of (Dan Wu et al., 2015). In this paper, the future of the 5G network using millimeter wave technology is discussed (Chakraborty et al., 2018). Millimeter waves have ten times the bandwidth of the entire 4G cellular spectrum. These high-frequency waves have been used in some satellite applications, but not for mobile broadband. Millimeters are not appropriate for long-range applications because of their lower wavelength. Figure 2.9 shows the overall system of hybrid precoder in mmWave MIMO systems.

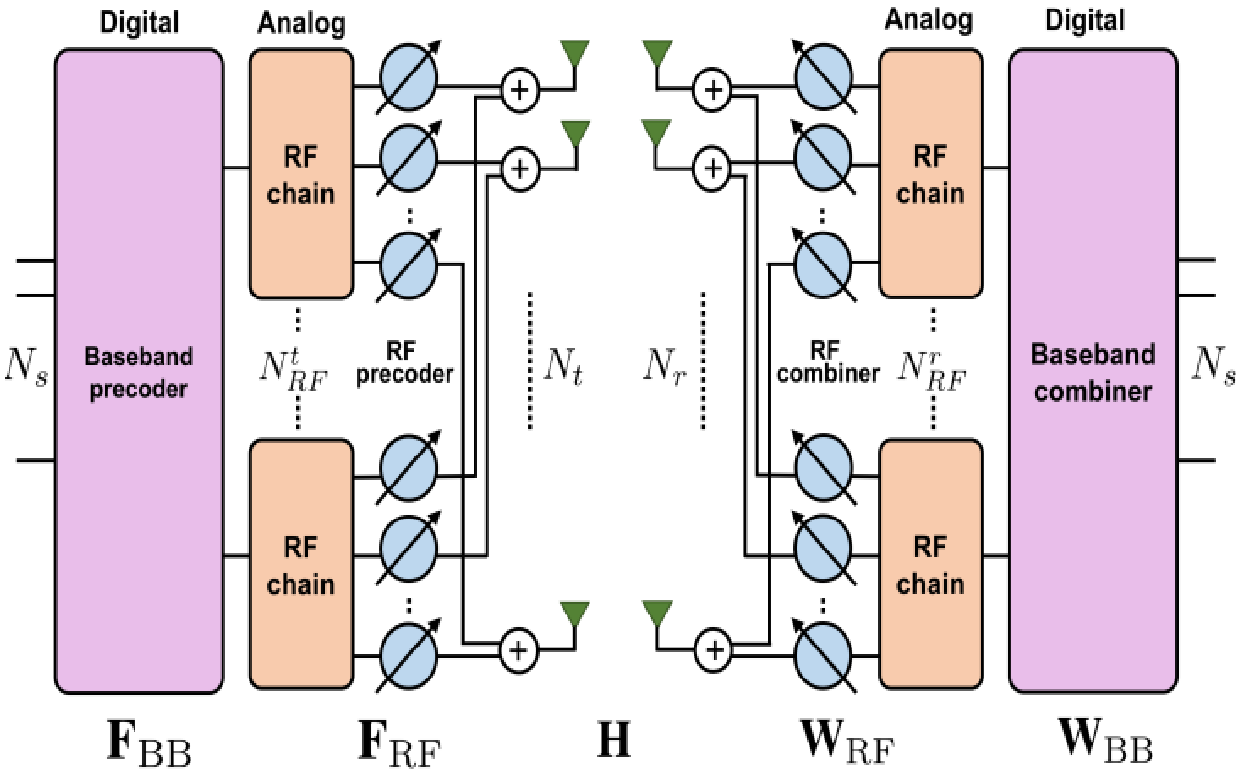


Figure 2.10 Hybrid precoder in mmWave MIMO system (Ayach et al., 2014) (Yu et al., n.d.)

However, in order to fully exploit the gains provided by mMIMO, each antenna requires its own dedicated radio frequency chain. mMIMO systems are challenging to implement due to space constraints. However, the mmWave frequency range makes it possible because the antenna size is dramatically decreased at such high frequencies. Many antennas also result in an equal number of RF chains, which are both costly and energy-intensive. The user equipment and the base station use phased array beamforming technology to solve this problem.

Beam-forming is a method of controlling an array of antennas so that radio waves are transmitted in a certain direction. Beamforming antenna arrays not only transmit power or signals in all directions, but also discern the direction of interest and send and receive larger signal beams in that direction (Alraddady et al., 2022).

2.8 Related work

The authors of (Chen & Qi, 2018) suggested Beam Design with Quantized Phase Shifters for Millimeter-Wave Massive MIMO. In this paper, beam design for millimeter-wave (mmWave) massive MIMO systems are studied regarding quantized phase shifters and different number of

RF chains. It considers the beam design with quantized phase shifters and different number of RF chains for mmWave massive MIMO systems. Given the objective beam, this paper formulates the beam design problem as a hybrid optimization problem and then converted it into several discrete optimization sub-problems. It proposes a partial random search (PRS) based beam design algorithm and an FS-based beam design algorithm.

In literature (Lin, 2017), the author of this paper suggested and analyzed On the Quantization of Phase Shifters for Hybrid Precoding Systems. This paper reflects the quantization of phase shifters for the radio frequency precoder in a hybrid precoding scheme. This paper identified two likely implementation structures are identified that use two-phase shifters for each Coefficient of the analog radio frequency precoder. Whereas the analysis of this paper is done by assuming high-resolution quantization. This can be enhanced by applying each coefficient of the optimal unrestricted precoder using two-phase shifters and the digital precoder only used for scales each sub-stream appropriately. These suggested structures enhance the full multiplexing improvement when the phase shifters are not quantized, although these structures behave separately in the presence of quantization. This paper assesses the mean square quantization errors of the two structures. However, the performance is more sensitive to quantization errors. Quantization of the phases can cause a substantial decrease in the system execution.

Hybrid Beamforming for Large Antenna Arrays with Phase Shifter Selection is given in (Payami et al., 2016). In This paper, an asymptotically optimal hybrid beamforming solution for large antenna arrays by exploiting the properties of the singular vectors of the channel matrix was suggested. It is proposed that the performance of the hybrid beamformers using phase shifters with more than 2- bits resolution is comparable with analog phase shifting. A novel phase shifter selection scheme that reduces the power consumption at the phase shifter network is proposed when the wireless channel is modeled by Rayleigh fading. By using this selection scheme, the SE can be increased as the power consumption in the phase shifter network reduces. But, to integrate HB into practical systems, the impact of these parameters should be investigated.

In literature (Bogale et al., 2016), the author suggested and analyzed On the Number of RF Chains and Phase Shifters, and Scheduling Design with Hybrid Analog-Digital Beamforming. Hybrid beamforming for downlink multiuser massive multiple-input multiple-output (MIMO) systems with frequency selective channels. The proposed HB design employs sets of digitally controlled phase (fixed phase) paired phase shifters (PSs) and switches. For this system, first determine the required number of radio frequency (RF) chains and PSs such that the proposed HB achieves the same performance as that of the digital beamforming (DB) which utilizes N (number of transmitter antennas) RF chains. But the main drawback of this paper is it is limited to only the best-selected users in each sub-carrier.

The authors (Gadiel & Lee, 2019), have proposed Energy-Efficient Hybrid Beamforming with Variable and Constant Phase Shifters. In this paper, the authors propose a novel partially connected hybrid beamforming (PC-HBF) architecture, which employs variable phase shifters (VPSs) and constant phase shifters (CPSs) for analog beamforming to harness the potential of these two types of phase shifters. In the proposed architecture, the system sum-rate optimization to determine the analog precoders can be formulated as a combinatorial problem. However, its exact solution is intractable, and in massive multiple-input multiple-output systems, exhaustive search to solve the corresponding combinatorial problem is practically infeasible. . A greedy algorithm is used in this paper to overcome the challenges faced by providing a near-optimal solution with reduced complexity. The paper shows by optimally combining variable phase shifters and constant phase shifters. To resolve this problem, it employs a greedy algorithm that provides a near-optimal solution with reduced complexity

The authors of (Ribeiro et al., 2018) have provided Hybrid Combining Based on Constant Phase Shifters and Active/Inactive Switches. This paper proposes a new hybrid analog and digital combining architecture for millimeter-wave (mmWave) multi-user multiple-input multiple-output (MU-MIMO) systems. The proposed structure employs antenna subset selection per radio frequency (RF) chain based on active/inactive switches and uses constant phase shifters (CPS) to control the phases of signals in the RF circuit. In this scheme, for each RF chain, a subset of receive antennas that contribute more to the desired signal power than the interference power is chosen for signal combining in the analog domain, whereas other receive antennas are excluded from signal combining, thereby enhancing sum-rates. Simultaneously, the proposed structure reduces power consumption in the RF circuit by exclusively activating switches that correspond to the antennas selected for each RF chain.

In literature (Deng et al., 2019), the author of this paper Proposed MmWave Multiuser MIMO Precoding with Fixed Subarrays and Quantized Phase Shifters. This paper considers Millimeter wave (mmWave) wireless communication promises high data-rates when combined with multiuser multipleinput multiple-output (MU-MIMO) technology. A practical deployment of these technologies, however, faces numerous challenges, including the design of energy-efficient a nalog hardware. To address these challenges, this paper consider a hybrid base station architecture that consists of a set of fixed subarrays with quantized phase shifters (FS-QPS). This system investigates the multiuser beamforming gains with different phase quantization levels and subarray geometries.

The authors (Venkateswaran & Veen, 2010), proposed Analog Beamforming in MIMO Communications With Phase Shifter Networks and Online Channel Estimation. This paper considers the design of the analog and digital Beamforming coefficients, for the case of narrowband signals. The aim of this paper is to cancel interfering signals in the analog domain, accordingly minimizing the required analog to digital conversion resolution. For a given resolution, this paper shows the proposal to reduce the mean squared error between the required user and its receiver estimate through proposing the optimal analog Beamformer. For this case, a design method to sequentially approximate the desired overall Beamformer by a linear combination of implementable analog Beamformers. Finally, this paper design an optimal APN beamforming matrix, By reducing the interference at the input of the ADCs, as a result reduced resolution is possible, which results to reduced power consumption by using mean-square error (MSE) at the output of the digital Beamformer and the ADC power consumption.

From the above literature, researchers have done for improving energy efficiency by minimization of power consumption in a massive MIMO system, by using different techniques and algorithms. Unlike those papers this thesis focuses on the phase shifter selection method and comparison of fully connected with phase shifter selection (FPSS) and sub-connected with phase shifter selection (SPSS), to improve energy efficiency.

The overall review is explained in table form in table 2.2 below

Table 2.2 Literature review

S/n	Author	Title	Algorithm	Gaps
1	Kangjian Chen	Beam Design with Quantized Phase Shifters for mm Wave MIMO	Partial random search (PRS)	It does not consider beam training using designed beam with a quantized phase shifter
2	Lin, Y. P.	On the Quantization of Phase Shifters for Hybrid Precoding Systems	Mean square quantization errors (MSQE)	The performance is more sensitive to quantization errors
3	Junquan Deng	MmWave Multiuser MIMO Precoding with Fixed Subarrays and Quantized Phase Shifters	fixed subarrays with quantized phase shifters (FS-QPS)	It is limited for fixed subarrays
4	Payami et al.	Hybrid Beamforming for Large Antenna Arrays with Phase Shifter Selection	Zero-forcing (ZF)	But, to integrate HB into practical systems, the impact of these parameters should not be investigated.
5	Tadilo Endeshaw Bogale	On the Number of RF Chains and Phase Shifters, and Scheduling Design with Hybrid Analog-Digital Beamforming	User scheduling algorithm	It is limited only to the best-selected users in each sub carrier
6	Godwin Mruma Gadiel	Energy-Efficient Hybrid Beamforming with Variable and Constant Phase Shifters	PC-HBF with exhaustive search &greedy algorithm	It only considers analog beam forming
7	Vlachos et al.,	Hybrid Combining Based on Constant Phase Shifters and Active/Inactive Switches	Gram- Schmidt-based algorithm	Using constant PS will lead to signal distortion (fading problem)

CHAPTER THREE

3. METHODOLOGY

3.1 Introduction

This chapter is mostly concerned with the methods used in this thesis. The materials, data gathering, and analysis methods, system mathematical modeling, and design of energy-efficient phase shifter selection for Millimeter-Wave-based Massive Multiple Input Multiple Output System are all explained. Moreover, millimeter-wave 5G technologies, with an emphasis on millimeter wave, Massive MIMO, and radiofrequency chain components, particularly based on phase shifters selection, were reviewed from various journals, IEEE papers, and books.

3.2 Materials

Microsoft Office 2013 and MathType 6.0 equation editor is utilized. MATLAB is a computer programming language that includes technical toolboxes and Simulink. The thesis documentation is written in Microsoft Office. MathType 6.0 is a Microsoft Office word and PowerPoint presentation tool for composing mathematical formulas and equations.

3.3 Methods

The following techniques are developed to achieve the desired objectives based on this literature and having the explanation of the problem: -

1) Different mathematical formulations and system modeling
   - Using several phase shifter selection techniques, and a mathematical model for calculating energy efficiency, power consumption, and capacity has been developed
   - A mathematical model for total power consumption and system capacity according to phase shifter selection mechanism
2) Use a flow chart for the phase shifter selection method
3) Determine the simulation's input parameters
4) Use MATLAB R2015a to run the simulation
   - Simulation for Energy Efficiency analysis with related to several users, base station antenna, threshold phase shifter

- Simulation for energy efficiency analysis using different phase shifter selection mechanism

The procedure used throughout this thesis study can be summarized in Figure 3.1, which shows the workflow.

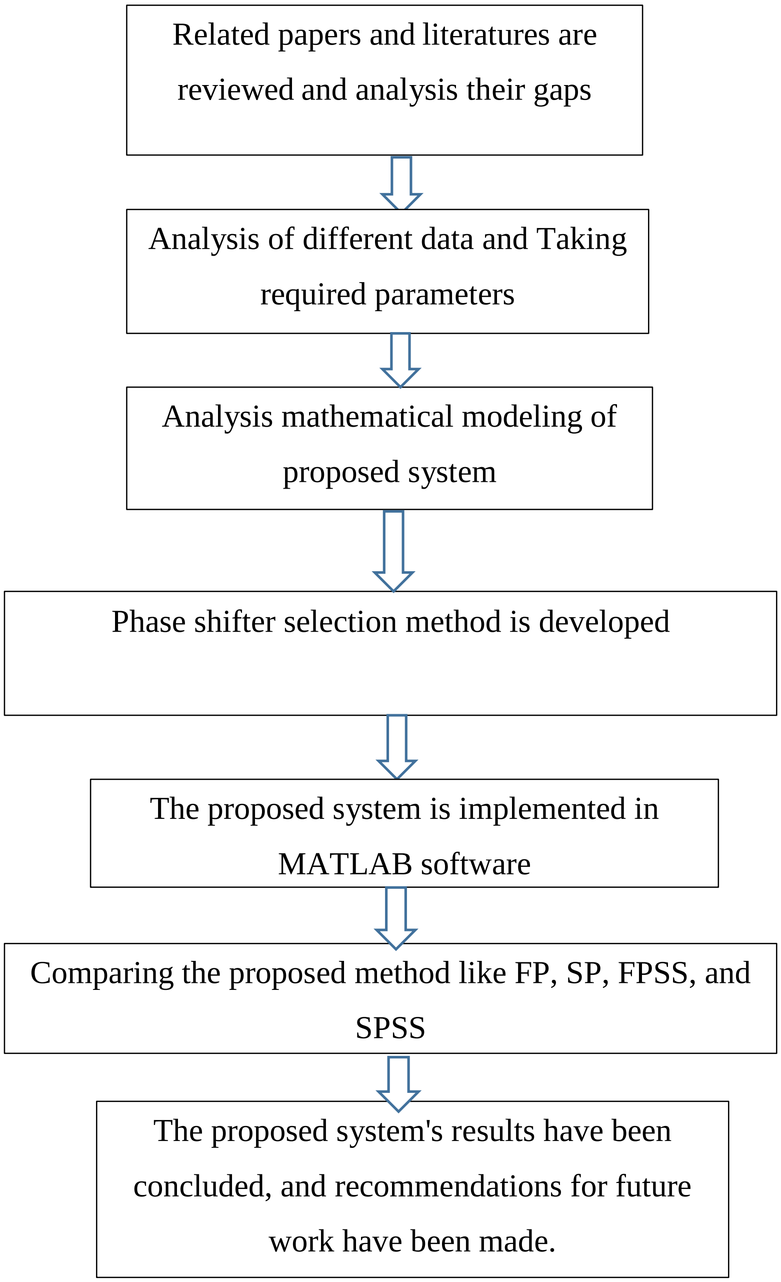
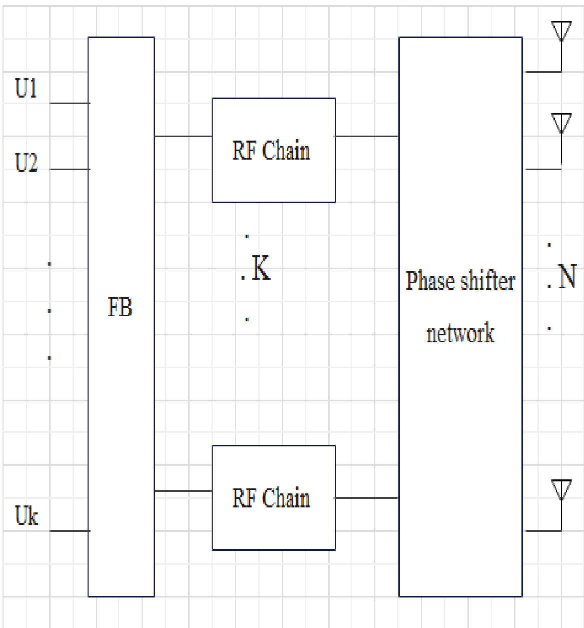
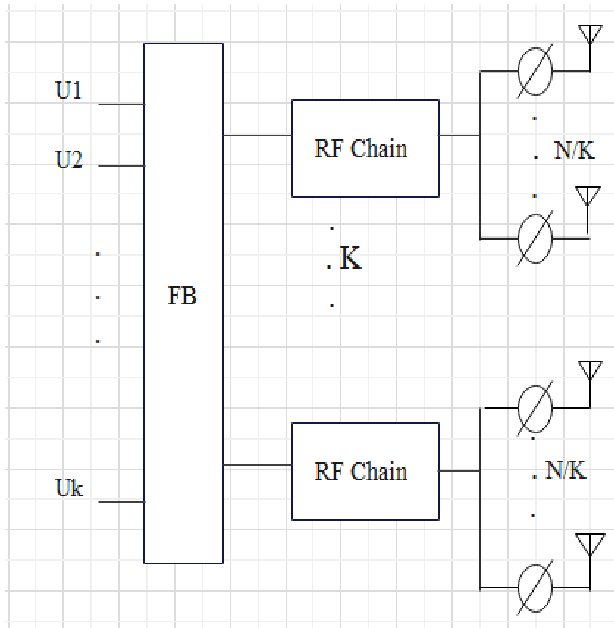


Figure 3. 1 The workflow of the thesis

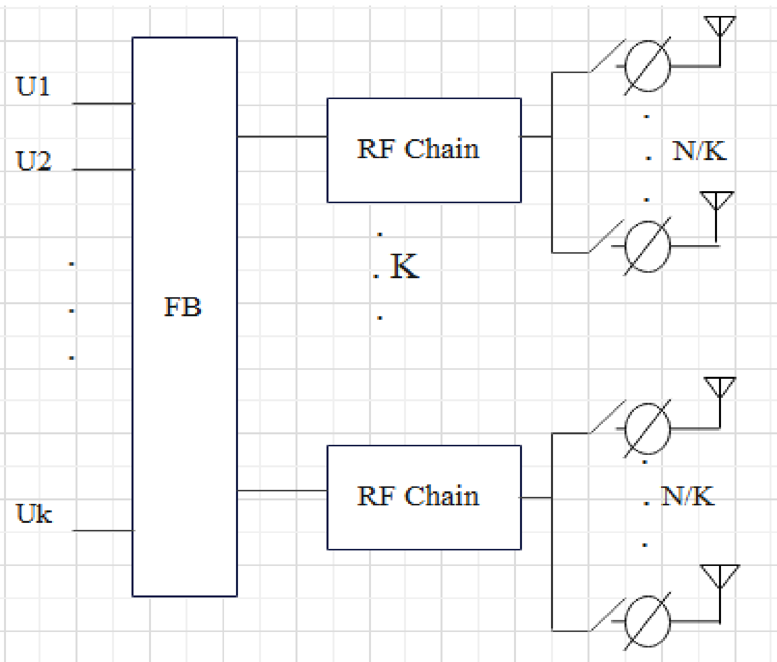
3.4 The Proposed Block Diagram of phase shifter Selection



(a) Fully connected



(b) Sub-connected



(c) Sub-connected with PSS

Figure 3. 2 The Proposed Block Diagram of phase shifter Selection

Fully-connected PS-only (FP): Where the antennas and RF chains are connected through a network of phase shifters. Its power consumption can be very high due to the massive number of phase shifters it requires

Fully connected with PS selection (FPSS): The aim of PS selection is to identify and turn off the phase shifters. In This case, equipping each PS in FP with an ON/OFF switch to protect the phase shifters when they are turned off.

Sub-connected PS-only (SP): Where each RF chain is connected to a subset of antennas.

Sub-connected with PS selection (SPSS): We equip each PS with a dedicated switch. In this method, the number of the required phase shifters and switches is equal to N. More details on them are written in sub-topic 3.6 below.

3.5 System model and Mathematical Formulation

Consider a scenario in which the BS has N Omni-directional antennas and serves K << N single-antenna consumers in a single-cell multiuser massive MIMO downlink system. The system bandwidth and feasible sum rate, respectively, are denoted by B and R sum. The EE is therefore defined as

$$E = \frac{BR_{sum}}{P_{tot}} \quad \ldots\ldots 1$$

Where P_{tot} denotes total power that is essential to attain R_{sum}. We model P_{tot} as, P_{tot} = P_c + P_{var} (Garcia-rodriguez et al., 2016), where P_c is common power consumption term and P_{var} is the variable term for the Beamforming structures. Specifically, $P_c = \frac{\rho}{\eta} + P_{syn}$

Where η is the power amplifier's efficiency and P_{syn} is the frequency synthesizer's power consumption, respectively. P_{var} on the other hand, is determined by the RF circuitry ($P_{var} = N_{RF}P_{RF} + N_{PS}P_{PS} + N_S P_S$ where, N_{RF}, N_{PS}, N_S, P_{RF}, P_{ps} and P_S represent the number and power consumption of the RF chains, phase shifters, and switches, respectively.

For massive MIMO systems, Zero-forcing (ZF) is known to be an asymptotically optimal precoder that maximizes the SE when H follows uncorrelated i.i.d. Rayleigh fading. In this case, the achievable sum-rate is $R_{sum}^{ZF} = K\log_2(1 + \rho(N - K))$ (Payami et al., 2016). The system requires N RF chains and the EE of the fully digital system becomes

When H follows uncorrelated i.i.d. Rayleigh fading, Zero-forcing (ZF) is known to be an asymptotically optimal precoder that optimizes the $R_{sum}^{ZF} = K\log_2(1 + \rho(N - K))$ is the sum-rate that can be achieved in this scenario (Payami et al., 2016). The system necessitates N RF chains, and the completely digital system's EE can be:-

$$E^{ZF} = BK\log_2 \frac{1 + p \quad N - K}{P_C + NP_{RF}} \text{ .... } 2$$

Formulation of Energy Efficiency

The ratio of total transferred bits or capacity to total power usage is known as energy efficiency. It is assessed as

$$EE = \frac{Capacity}{p_{tot}} \text{ .... } 3$$

Where,

$$C = B * \log_2[1 + SINR] \text{ .... } 4$$

$$SINR = \frac{P_{tx}}{1 + N_o * B} \text{ .... } 5$$

The interference is suppressed, the SNR can be defined as follows using beamforming:-

$$SNR = \frac{P_{tx}}{N_o * B} \text{ .... } 6$$

Let B is the system bandwidth, P_{tx} is transmitting power, and N_o is noise power spectral density.

3.6 Energy Efficiency of Hybrid Precoder with Phase Shifter Selection

In Figure 3.2 our contributions in terms of constructing the EE model and developing closed-form EE approximations for the HB structures. And also propose the asymptotic closed-form expression of sum-rate when the PS selection technique is applied to a multiuser scenario with fully connected HB (Payami et al., 2016).

3.6.1 Traditional fully-connected PS-only (FP)

The block diagram of a fully connected PS-only HB structure with a network of phase shifters connecting the antennas and RF chains is shown in Figure 3.2 (a).

When the transmit power P is fixed, EE is maximized at the maximum sum rate. As a result, the EE will be maximized using the same set of Beamforming matrices. There are N_{PS}=$N_{RF}N = KN$ phase shifters in Figure 3.2 (a), and the EE of this structure is

$$E^{FP} \approx \frac{BK\log_2\left(1+\pi\rho\left(N-K\right)/4\right)}{P_c + KP_{RF} + KNP_{ps}} \quad \text{.......7}$$

Despite the fact that the numerator in equation (7) represents the proposed Beamformer's asymptotic SE, in the non-asymptotic zone, it gives a good approximation of performance. (Payami et al., 2016).

3.6.2 Fully connected with PS selection (FPSS)

The aim of phase shifter selection is to identify and turn off the phase shifters that have a negligible impact on SE. This method was first proposed in (Payami et al., 2016) for point-to-point HB with a fully connected structure, and it was then adapted to a multiuser scenario with a sub-connected hybrid precoder in (Payami et al., 2016).

This arrangement is achieved by providing an ON/OFF switch to each PS in Figure 3.2 (a) to protect the phase shifters when they are switched off. To keep phase shifters safe when they're turned off The RF Beamformer is configured similarly to the prior method.

$$f^{FPSS}_{RF,n,k} = \begin{cases} 0 & \text{if } \sqrt{N}\left|\mathbf{v}_{n,k}\right| \le \alpha \\ \exp\left(j\angle\mathbf{v}_{n,k}\right) & \text{if } \alpha < \sqrt{N}\left|\mathbf{v}_{n,k}\right| \end{cases} \quad \text{.......8}$$

Where α is the threshold level to turn off the phase shifters. For uncorrelated i.i.d. Rayleigh fading channels, (8) result in switching off approximately $\beta\% = 1 - \exp(-\alpha^2)$ of the phase shifters (Payami et al., 2016).

When the RF Beamformer and the baseband precoder in Figure 3.2 (a) are set according to (4) and $f_B^{FPSS} = (HF_{RF}^{FPSS})^{-1}$, the total sum-rate R_{sum}^{FPSS}, for $N \to \infty$ and uncorrelated i.i.d. Rayleigh fading is expressed as $R_{sum}^{FPSS} = K\log_2(1 + \Upsilon)$ where

$$\gamma = \frac{\rho\ N-K\left(\frac{\sqrt{\pi}}{2}+\alpha e^{-\alpha^2}-\frac{\sqrt{\pi}}{2}\mathrm{erf}(a)\right)^2}{1-\beta/100} \qquad \text{..9}$$

There are N_S = KN switches that are constantly active in this structure, as well as (1 − β/100) NK phase shifters that are in use. For the purpose of simplicity, we'll suppose that is carefully chosen so that (1/100) NK is an integer. As a result, the floor function can be disabled. When PS selection is used, the EE in Figure 3.2 (a) becomes

$$E^{FPSS} \approx \frac{BK\log_2\left(1+\frac{\rho(N-K)\left(\frac{\sqrt{\pi}}{2}+\alpha e^{-\alpha^2}-\frac{\sqrt{\pi}}{2}\mathrm{erf}(a)\right)^2}{(1-\beta/100)}\right)}{P_c+KP_{RF}+(1-\beta/100)KNP_{PS}+KNP_S} \qquad \text{.......................10}$$

Relation to SNR

Correlation is strongly related to SNR which is a more commonly used measure in signal processing, Consider a signal x ant two noise signals n_1 and n_2 all having zero mean and all being uncorrelated with each other, let S = E[x^2] and Ni = [n_i^2] be the energy of the signal and the noise signals respectively. Then the correlation between a(x+n_1) and b(x+n_2) is

$$\rho = \frac{S}{\sqrt{S+N_1 \quad S+N_2}}$$

3.6.3 Sub-connected PS-only (SP)

Although the fully-connected structure of Figure 3.2 (a) can nearly achieve the performance of digital Beamformers, it requires complex circuitry and a large number of phase shifters. Furthermore, because to the huge number of phase shifters, the power consumption of fully-connected structures can be rather significant. Due to the enormous number of RF routes, such architectures suffer from significant levels of crosstalk distortion. As a result, in reality, the HB of Figure 3.2 (b) with sub-connected structure, in which each RF chain is connected to a subset of antennas, is favored. The sum-rate R_{sum}^{sp} and closed-form formulations of an asymptotically optimal PS-only HB for sub-connected structure were obtained in (Payami et al., 2016). It provides hardware simplicity at the expense of SE. N phase shifters and K RF chains are all that are required in Figure 3.2 (b). As a result, in Figure 3.2 (b), the EE of the sub-connected structure is approximated by

$$E^{SP} \approx \frac{BK\log_2\left(1+\frac{\pi\rho(N-K)}{4K}\right)}{P_c+KP_{RF}+NP_{PS}} \qquad \text{.........11}$$

Compared to (7) for the fully-connected PS-only HB structure, the sum rate (the numerator of (11)) has a factor of 1/K inside the logarithm which represents a smaller array gain. However, the power consumption (denominator) is reduced by (K−1) NP_{PS} (linear scale), indicating a possible improvement in the EE.

3.6.4 Sub connected with PS selection (SPSS)

We provide each PS with a dedicated switch in order to apply PS selection to the sub connected structure of Figure 3.2 (b). as illustrated in Figure 3.2 (c) The number of phase shifters and switches required in this method is equal to N. In comparison to Figure 3.2 (b), the number of active phase shifters is reduced to N (1 − β/100). The EE is approximated in this situation by

$$E^{SPSS} \approx \frac{BK\log_2\left(1+\frac{\rho(N-K)\left(\frac{\sqrt{\pi}}{2}+\alpha e^{-\alpha^2}-\frac{\sqrt{\pi}}{2}\operatorname{erf}(a)\right)^2}{K(1-\beta/100)}\right)}{P_c+KP_{RF}+(1-\beta/100)NP_{PS}+NP_S} \qquad \text{.........12}$$

3.7 Flow chart description

The flowchart below demonstrates how, depending on a threshold capacity, the phase shifter selection approach minimizes EE. To determine the threshold capacity, the model's first path loss was estimated for the given open space in order to obtain the minimal received power detected at the cell boundary. The appropriate minimum SNR value is then computed using the formulas below using the minimum received power. The loss in signal power as a signal passes across free space is known as free space path loss.

$$FSPL=\frac{P_t}{P_r}=\left(\frac{4\pi d}{\lambda}\right)^2 \qquad \text{.........13}$$

Where d is the distance between the transmitter and the receiver (km), f is the frequency (MHz), p_t and p_r is the transmit power and is the received power, and R is the distance between the transmitter and the receiver. The minimum received power is determined as follows:

$$pr_{min} = P_t\left(\frac{\lambda}{4\pi d}\right)^2 \text{.........} 14$$

Then,

$$SNR = \frac{pr_{min}}{N_o * B} \text{.........} 15$$

Then threshold capacity is calculated as,

$$C_{thr} = BLog_2\left(1 + \frac{P_t\lambda^2}{4\pi D_{max}}\right) \text{.........} 16$$

Where D_{max} can be expressed

$$D_{max} = SNR_{min} \text{.........} 17$$

Finally, EE can be,

$$EE = \frac{C_{thr}}{P_{tot}} \text{.........} 18$$

After obtaining the threshold capacity we calculate our EE_{thr} Then after calculating EE_{thr} we use the phase shifter selection method to reduce the system's power usage, in this case the optimal number of phase shifter is a number at which capacity reaches minimum level. So we don't fix the optimum number because in a different weather condition the range and capacity will change, so in every iteration the value is change. Then again we find the new total power and EE, then compare EE and EE_{thr}. If the $EE \leq EE_{thr}$ it results in wastage of capacity so the number of bits has to be reduced by using the phase shifter selection method. But if the EE>= EE_{thr} we stop here.

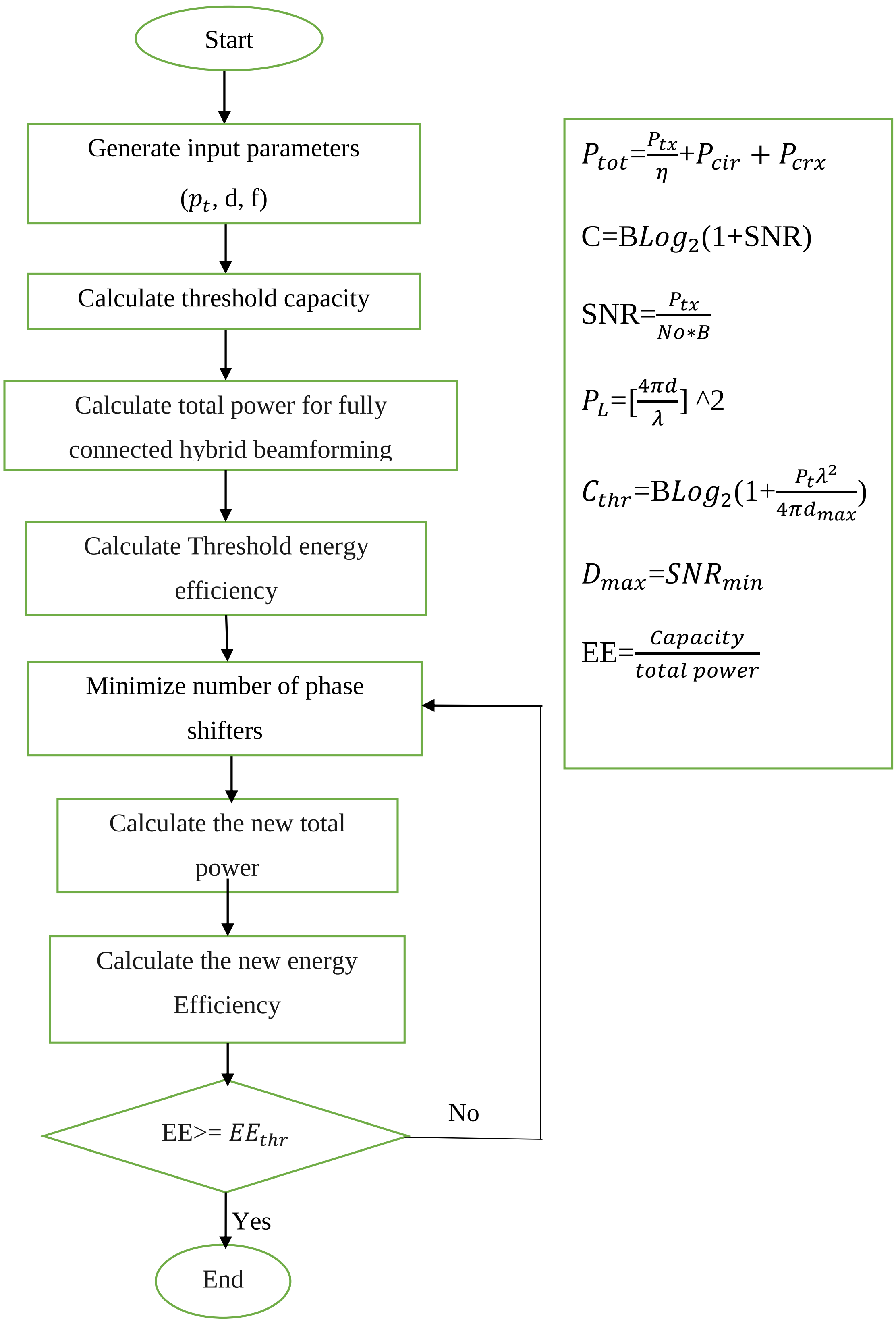


Figure 3.3 Flow chart of the overall system

Table 3.1 Simulation input parameters

Input Parameters	**Value**
Number of users	25
Number of transmit antenna	128
number of RF chain	15
Bandwidth	2×10^6 Hz
Power consumption of frequency synthesizer	0.05
common power consumption	0.2
Noise signal	9×10^{-8}
sampling rate	28×10^9
Transmit power	3 Watts
Power due to mixer	0.0003 %
Power amplifier coefficient	0.48 %
Signal to Noise Ratio	20db
Power due to filter	0.03 Watts
Power due to mixer	0.0003 %
phase shifter power consumption	10 Mw
Correlation coefficient	0.5
Power consumption of switch	1mW
Power consumption of RF chain	50mW

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1 Introduction

In this section, the simulation results of the proposed system on the MATLAB software when compared to the prior works on the literature to verify the general objective as well as specific objectives of the thesis, and different phase shifter selection mechanisms are also compared. The simulation results shown in this chapter are all for the same given value With the transmit antenna M=128, a number of users K=25, N_{RF}=15 and SNR=20dB of the system parameters.

4.2 Plotting of beam size and distance at 10m and 100m

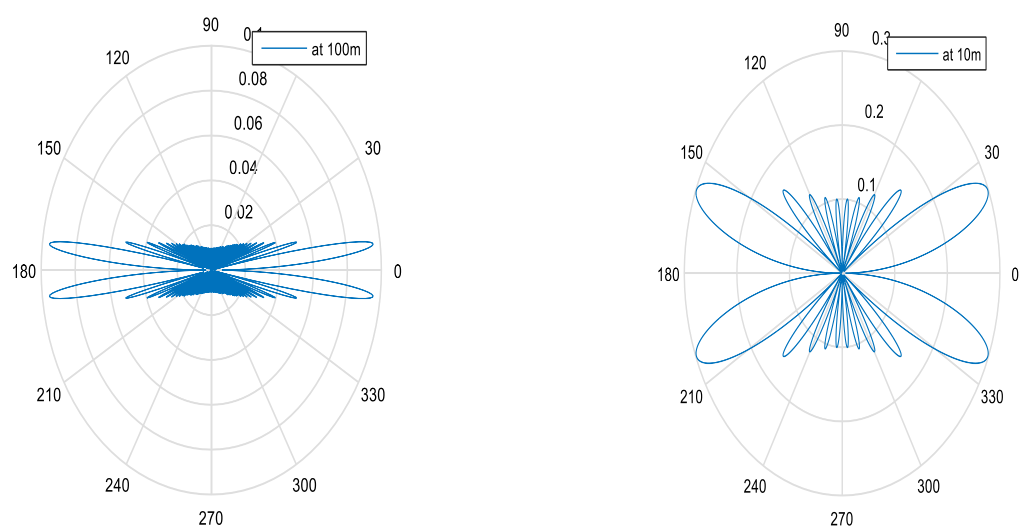


Figure 4.1 Beam size with side lobe

Massive MIMO generate much more beams, those beams are sharper and narrower and they will have directivity. In the Figure 4.1, the array size at the distance of 10m and 100m. In a smaller array size, a smaller number of transmission elements can generate beams with bigger beam width. So they are good in cases where we want to cover wide spaces with a minimum cost however in bigger array sizes, as we add more transmission elements the beam gets narrower/sharper which means we can generate more beams in the same element, but the beam also gets more directional. In massive MIMO units, it will have a much better channel quality indicator because of less indifference and also because of the Beamforming gain provided, because each beam will be directive and if they give you more gain it will be better in coverage and quality.

4.3 Energy efficiency, capacity, and total power consumption analysis for different numbers of users at a fixed number of antenna

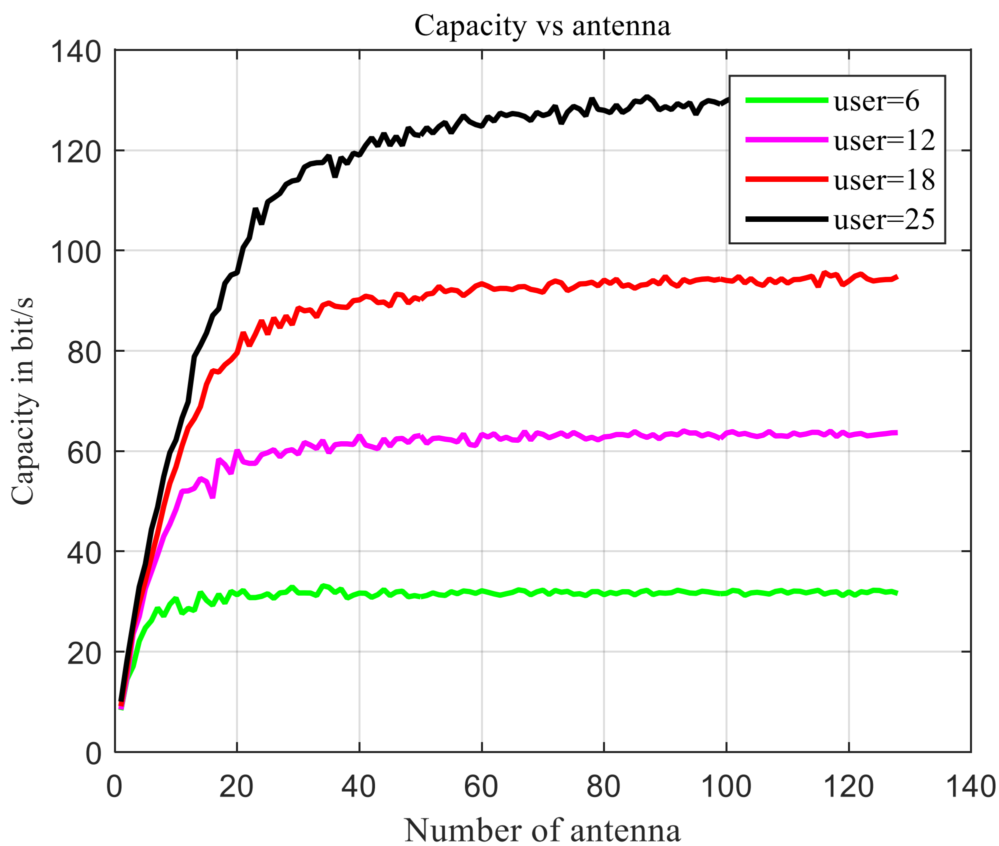


Figure 4.2 Capacity versus the number of antenna at 6, 12, 18, and 25 users

Generally, Capacity is proportional to min (Nt, K) where Nt is the number of transmitting antennas and K is the number of the user. I have seen that if the Nt > K, the total capacity with a given area/ throughput/ increases. But according to the relation min (Nt, K) capacity should be proportional to K, if Nt > K. So, From the simulation result in Figure 4.2, capacity in bit/sec and number of antenna for the different user is obtained, and here, from the simulation result when the number of a user has increased the capacity was also increasing for a certain user. But when the number of a user is increased for an increasing number of antennae the capacity is declining. This declination in bit/second will result in poor efficiency of the system.

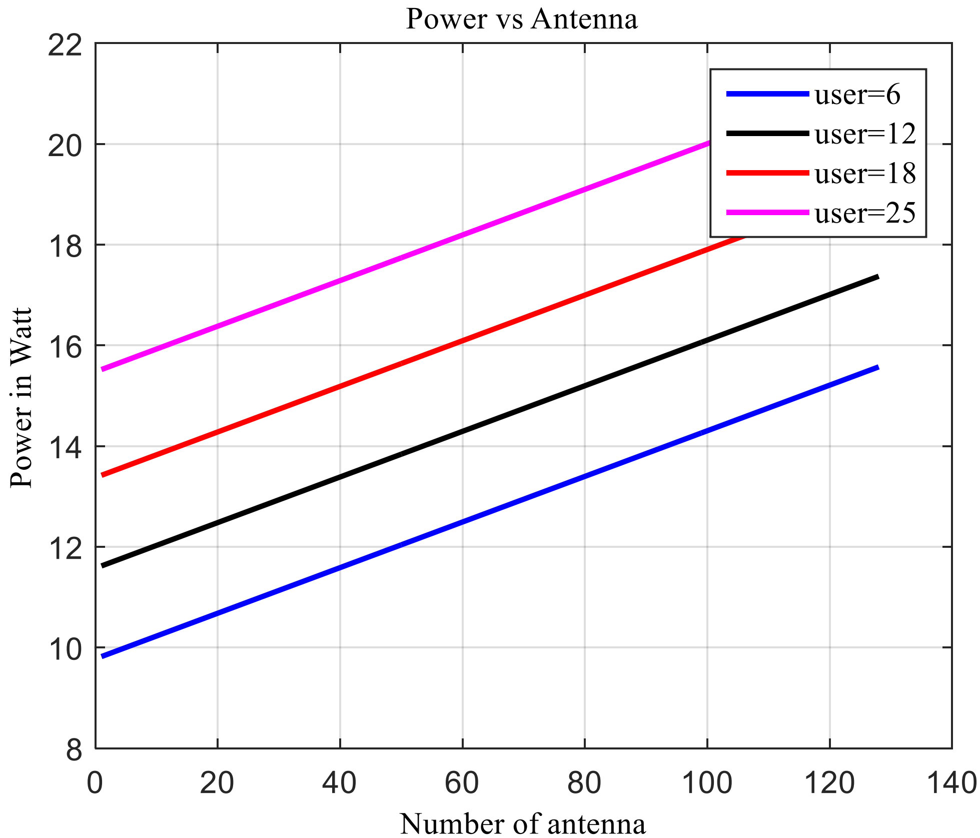


Figure 4.3 Power versus the number of antenna at 6, 12, 18, and 25 users

Figure 4.3 shows the simulation result of power and number of antenna for a different number of users. The result shows that power increase linearly when the number of antenna increases and when the number of users increased for the given number of base station antenna increment, total power usage also increases. See the numerical data in table 4.1

For 6,12,18,25 users when as the number of antennas grows, so does the power usage. Figure 4.3 depicts the implications of increasing the number of antennas on overall power consumption in this situation. Furthermore, as the fixed number of users grows, the overall power consumption grows with keeping the increment of the number of transmit antenna, as shown in table 4.1. When it comes to energy efficiency, an increase in total power consumption has a significant impact on the trend of energy efficiency.

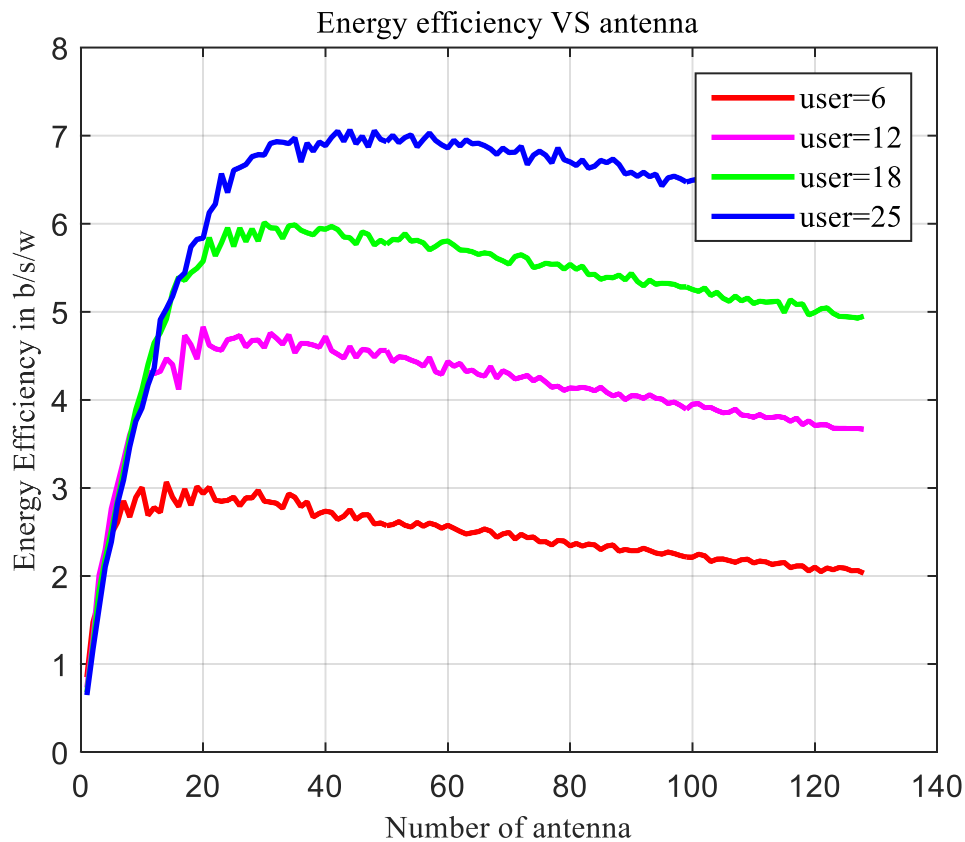


Figure 4.4 Energy Efficiency versus the number of antenna at 6, 12, 18, and 25 users

Here, The simulation result in Figure 4.4 shows the relation between Energy Efficiency, and the total number of transmit antennas for four different numbers of users. It can be seen that the Energy Efficiency increases when the number of transmit antenna increases linearly and finally it becomes constant it can be seen in table 4.2. And EE versus number of antenna at different users are illustrated in table 4.1

Table 4.1 EE and number of antenna for different users

	EE (b/s/w)			
No/ of antenna	**User=6**	**User=12**	**User=18**	**User=25**
40	2.752	4.58	6.018	6.912
60	2.48	4.375	5.814	6.903
90	2.335	4.114	5.432	6.663
120	2.094	3.712	5.015	6.18

However, as the transmit antenna value grows larger, these Energy Efficiency values become saturated. This is because, as shown in Figure 4.4, capacity increases logarithmically with the number of antennas, and capacity increases as the number of user's increases.

This is because the amount of users increases the system's capacity. Temporarily, the Energy Efficiency of each value of users grows and then drops. This tendency can be explained by the fact that when the number of transmit antennas grows, the increased power consumption caused by RF chains has a greater influence on Energy Efficiency than capacity increases, which lowering the Energy Efficiency value.

Table 4.2 Capacity, EE, and total power comparisons for different numbers of users and antenna

Number of antenna (128)			
Number of users	**Total power (watt)**	**Capacity (bit/s)**	**Energy efficiency (b/s/w)**
6	15.573	31.62	2.03
12	17.373	63.67	3.66
18	19.173	94.85	4.95

4.4 Analysis of Energy Efficiency and capacity for a given number of users at different transmit antenna

4.4.1 Analysis of Energy Efficiency with a given number of users at different numbers of transmit antenna

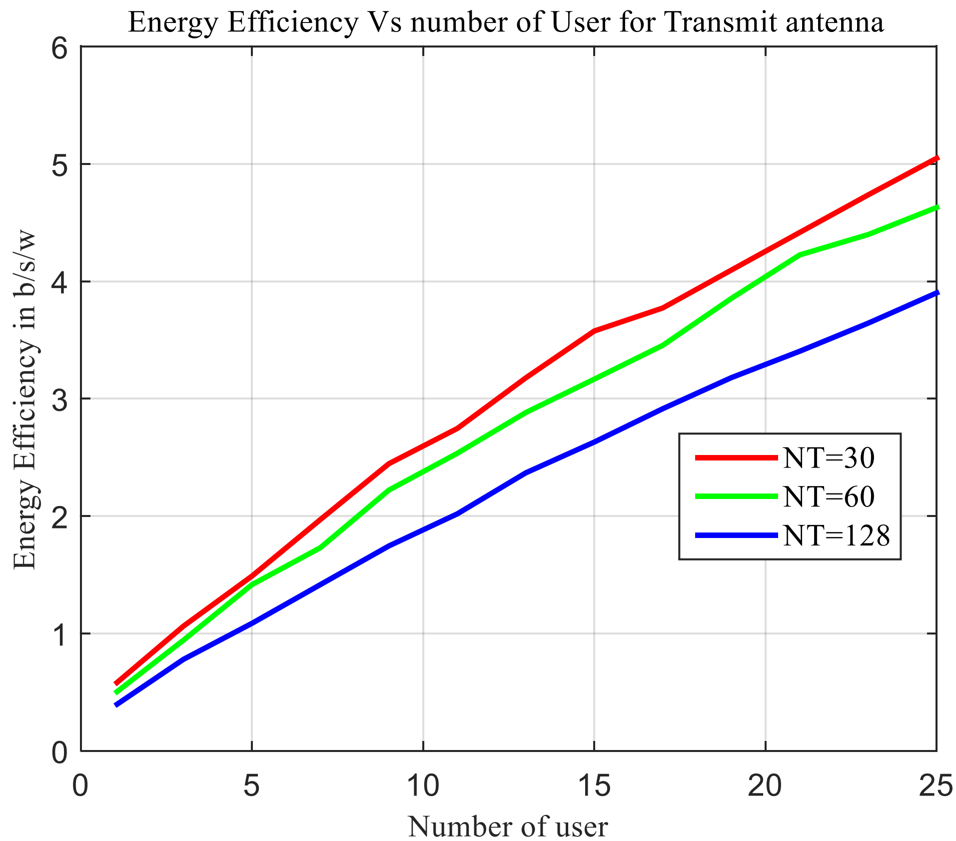


Figure 4.5 Energy Efficiency versus the number of users at a transmit power of NT=30, 60, and 128

Figure 4.5 shows the Energy Efficiency with respect to the number of users for various transmit antenna values (30, 60, 128). The number of users in the wireless communication system has a significant impact on the system capacity and increasing the number of users causes inter-user interference, therefore, the number of users causes the system capacity to decrease.

From the result in Figure 4.5 as the number of user increases EE also increase because the system's capacity can be raised as the number of users grows with related to number of transmit antennas shown in table 4.2. This is because as the transmit antenna's value rises, so does the total power usage also increase. As power use grew, Energy Efficiency declined.

4.4.2 Analysis of capacity with a given number of users at different numbers of transmit antenna

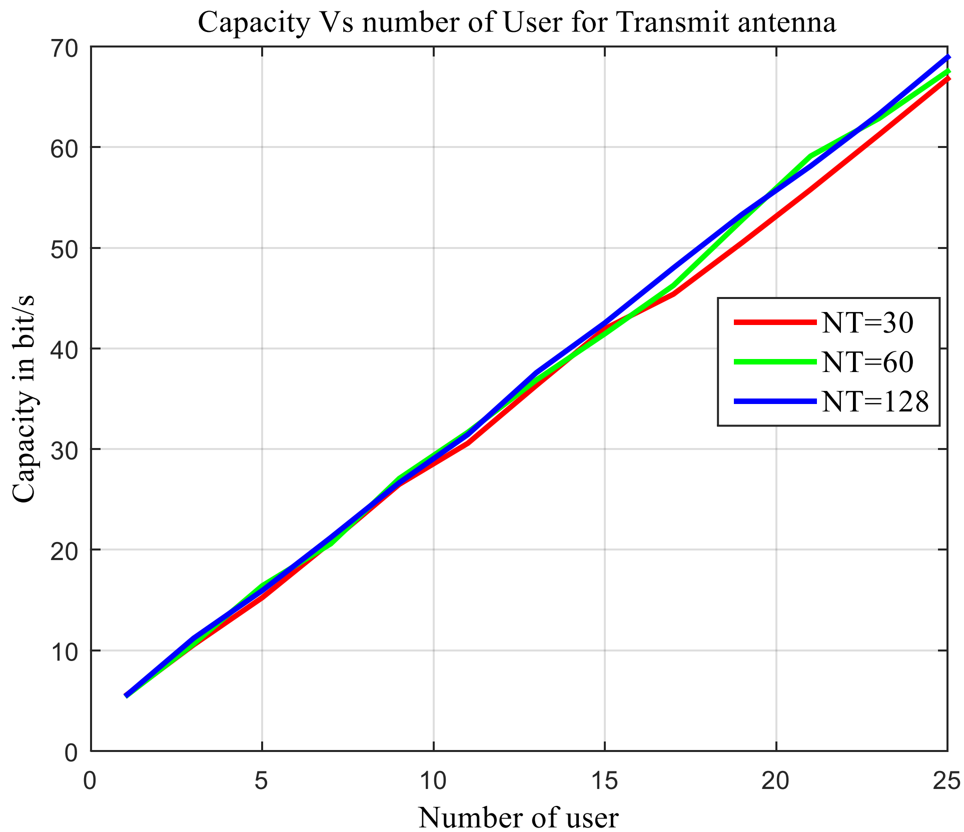


Figure 4.6 Capacity versus the number of users at a transmit power of NT=30, 60, and 128

From the simulation result, seen in Figure 4.6, for a given constant value of transmit antenna, capacity is a function of the number of users (30, 60, and 128). As the number of fixed antennas increases, so does the power consumption and the optimal number of users that optimize capacity increases as can be shown in table 4.3 for various transmit antenna values at the base station. When comparing different transmit antenna values, the antenna with a bigger value has a higher capacity than those with a smaller value. Finally, as the number of users grows, the system capacity grows together with the increment of the various transmit antenna specific values.

Table 4.3 Numerical analysis of EE and capacity for a given number of users at different transmit antenna

Number of users (25)			
Number of antenna	**Capacity in (bit/s)**	**Power in (watt)**	**Energy efficiency (b/s/w)**
30	66.80	13.23	5.05
60	67.54	14.59	4.63
128	68.95	17.67	3.32

4.5 Analysis of Energy Efficiency and SNR for different numbers of users

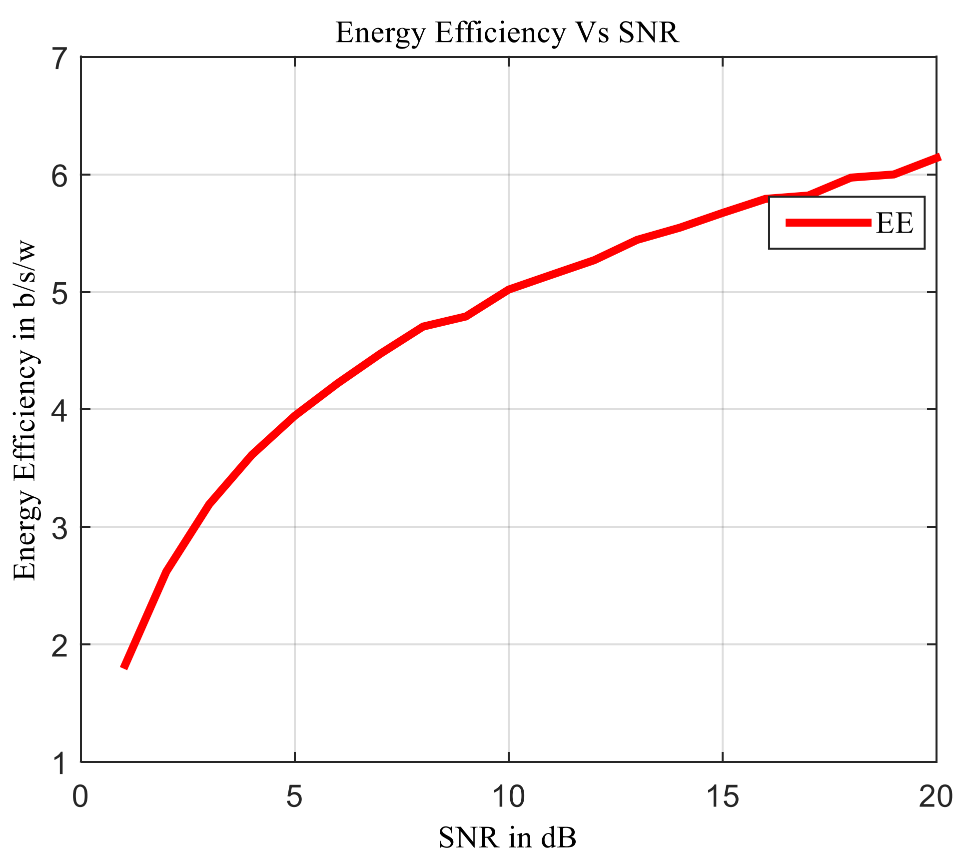


Figure 4. 7 Energy Efficiency versus signal to noise ratio

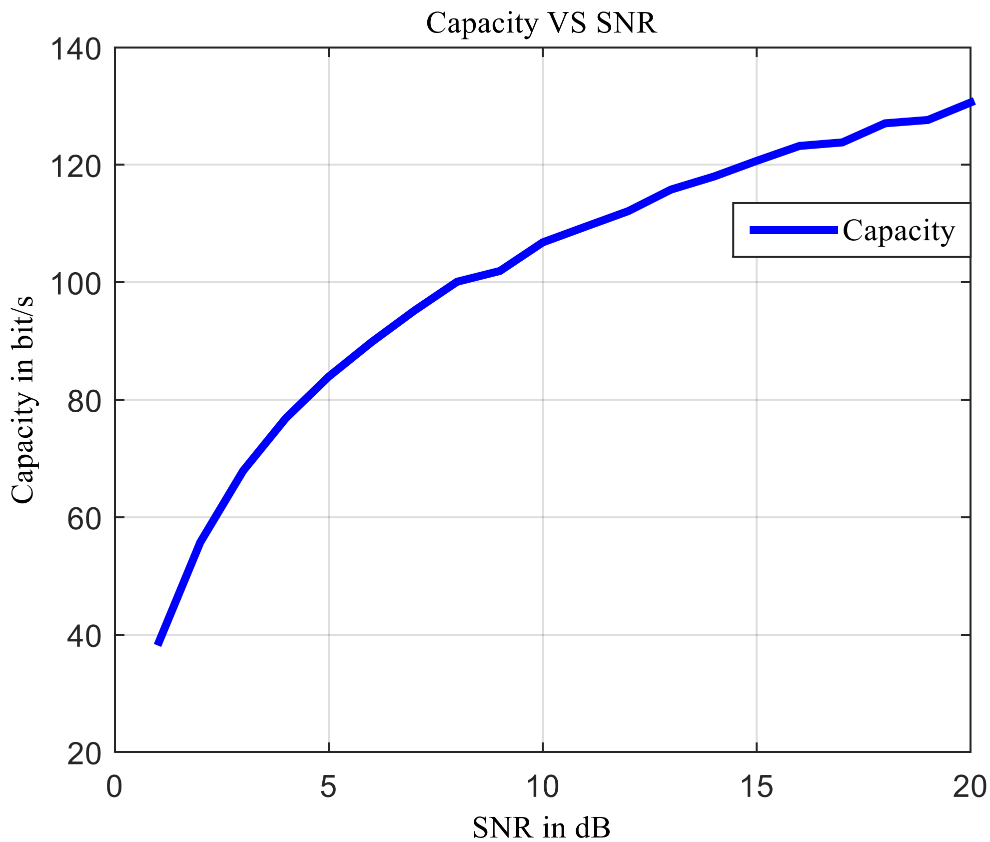


Figure 4.8 Capacity versus signal to noise ratio

From Figure 4.7 and Figure 4.8 the relationship between EE and SNR, as well as capacity and SNR, has been established. And as a simulation result shown in table 4.1, the total power consumption is 21.2731w when SNR is 20dB. Figures 4.7 and 4.8 show the influence of SNR on capacity and Energy Efficiency in a Massive MIMO system with a fixed number of users of 25 and a fixed number of transmit antenna of 128. The capacity grows logarithmically as SNR increases, and the Energy Efficiency increases logarithmically as well. As a result of this, the capacity in terms of (SNR) and the SNR's dependence on the fixed value of power consumption enhances the system's Energy Efficiency.

4.6 Analysis of threshold number of phase shifter and SNR for different values of correlation coefficient by considering threshold value

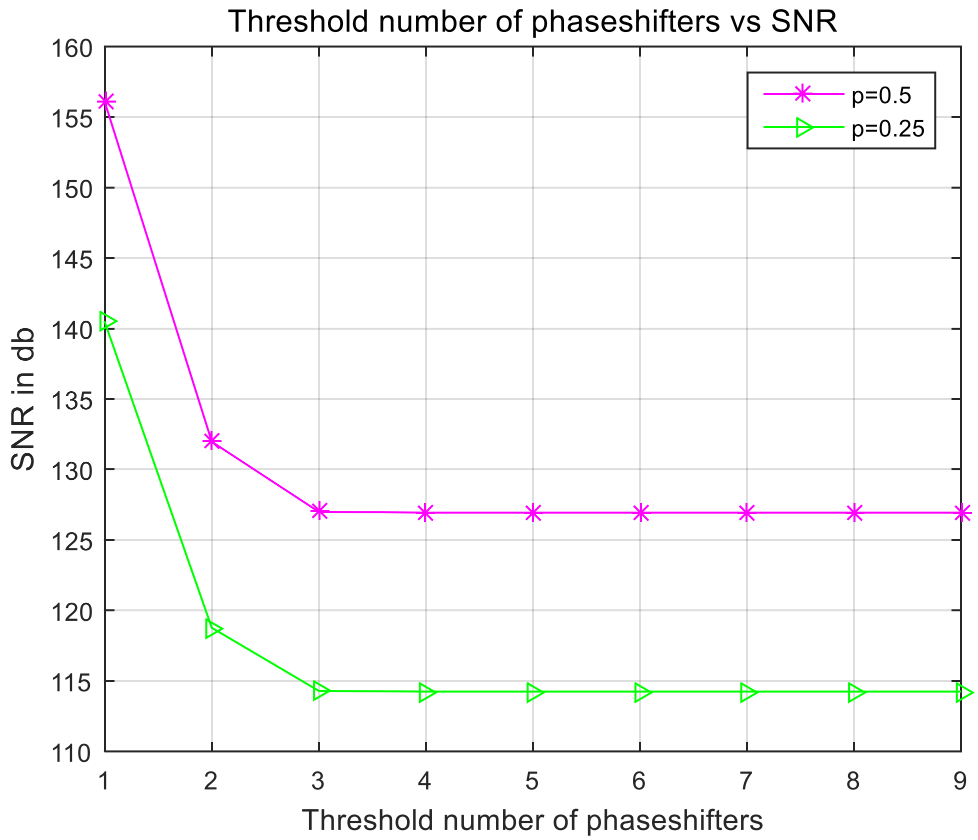


Figure 4.9 Signal-to-noise ratio versus threshold phase shifters

As observed in Figure 4.9, threshold phase shifter and SNR for different value of correlation coefficient was analyzed. As we know from a theoretical perspective threshold phase shifter and SNR are inversely related until a certain point and finally, it shows uniform or constant values. So from the result, it shows that when SNR decreases at the same time threshold phase shifter also increases. For instance, let us take threshold values a= 2 and 3, the corresponding SNR values are 119 and 115 respectively which decrease for increasing values of threshold phase shifters and after the threshold value is 3 it results in constant value for each variable correlation coefficients.

4.7 Analysis of power of RF chain and Energy Efficiency for different numbers of user

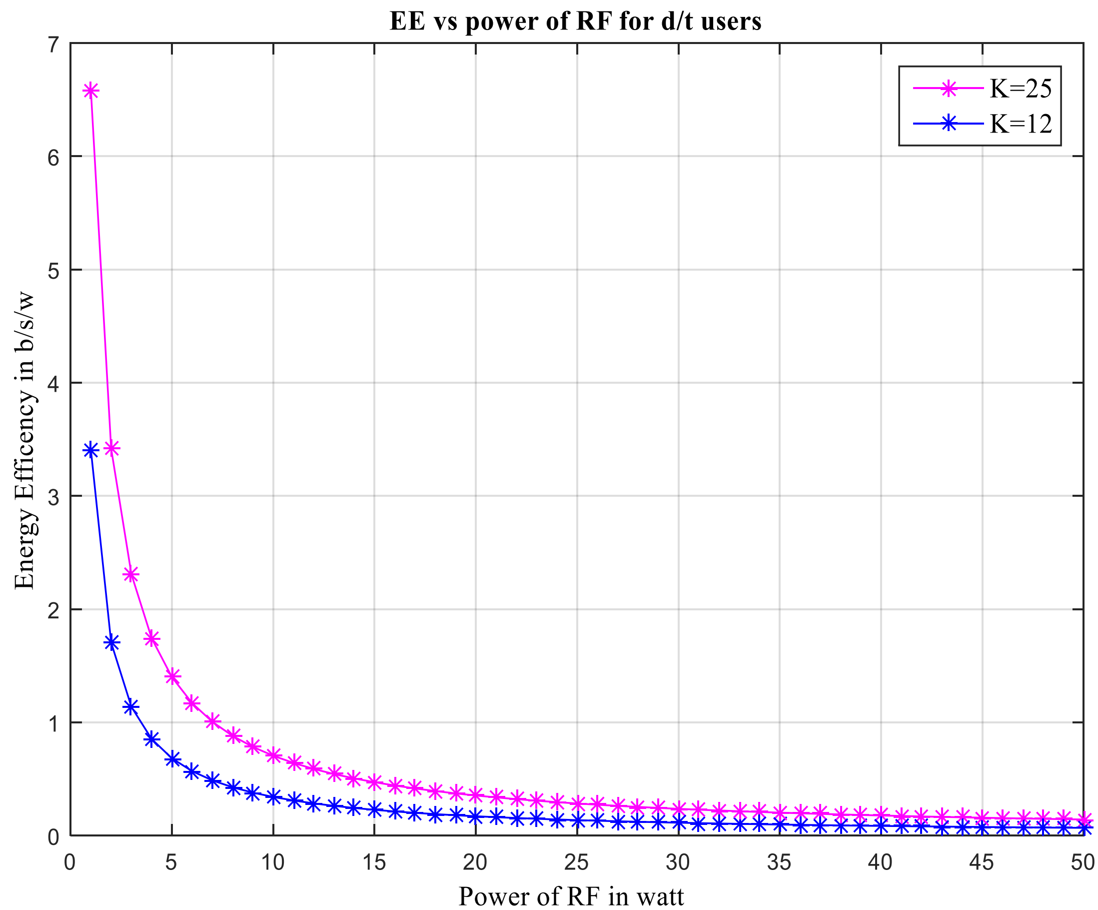


Figure 4.10 Energy Efficiency versus the power of radiofrequency chain for K=12, and 25

Figure 4.10, shows Energy Efficiency and power of the radio frequency chain are inversely related for different users under a constant total number of transmit antennas. That means at a certain number of users under a constant number of transmit antenna, when total power consumption is large the Energy Efficiency is low. As a result of the simulation, the EE tabulation result and power values for different users are listed in table 4.4

Table 4.4 EE and power of RF simulation values for different numbers of users

Number of transmit antenna (128)			
K=12		**K=25**	
Power of RF	**EE (b/s/w)**	**Power of RF (watt)**	**EE (b/s/w)**
2	1.704	2	3.418
4	0.8526	4	1.742
8	0.4264	8	0.8797
18	0.1895	18	0.3931

4.8Analysis of power of RF chain and Energy Efficiency for SP and FP

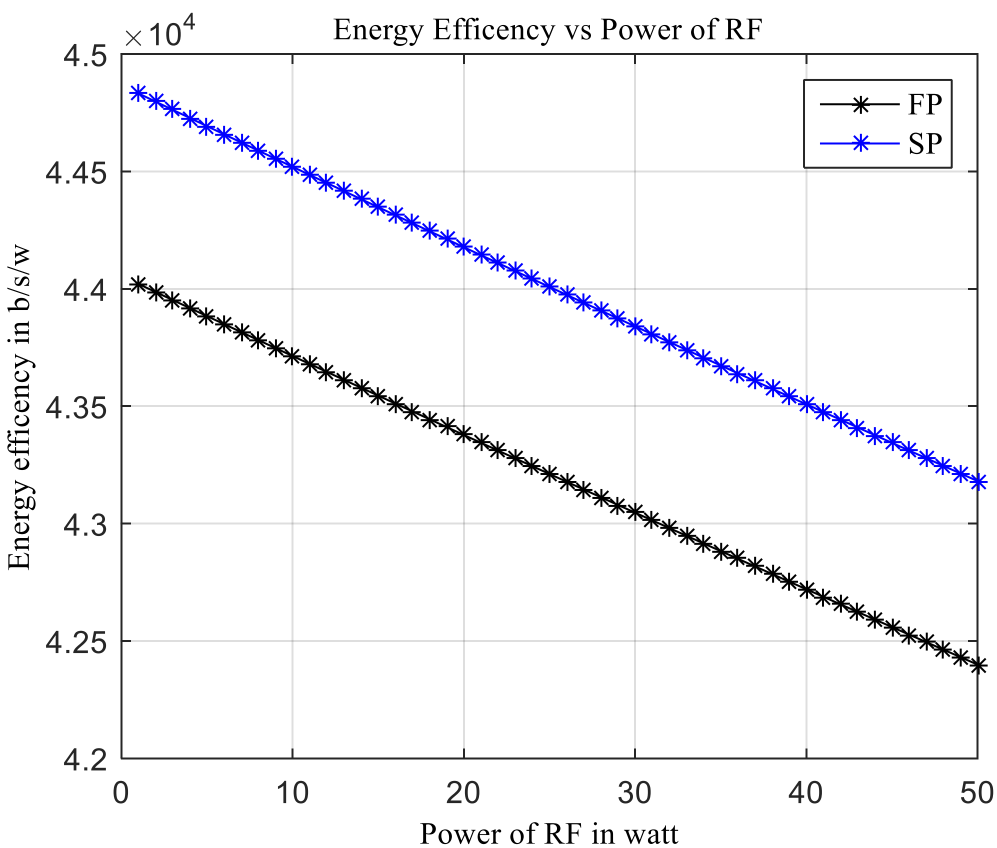


Figure 4.11 Energy Efficency for FP and SP for different power of RF chain

Figure 4.11 shows the relationship between Energy Efficiency and power of RF chain for fully connected and sub connected phase shifter without phase shifter selection. Then, the simulation result shows that Energy Efficiency decreases when the number of power of RF chain increases. Finally, when applying the two algorithms to get better Energy Efficiency, the Energy Efficiency of sub connected phase shifter only give better result than fully connected phase shifter only.

4.9 Analysis of power of RF chain and EE for fully connected PSS and a single PS and RF chain

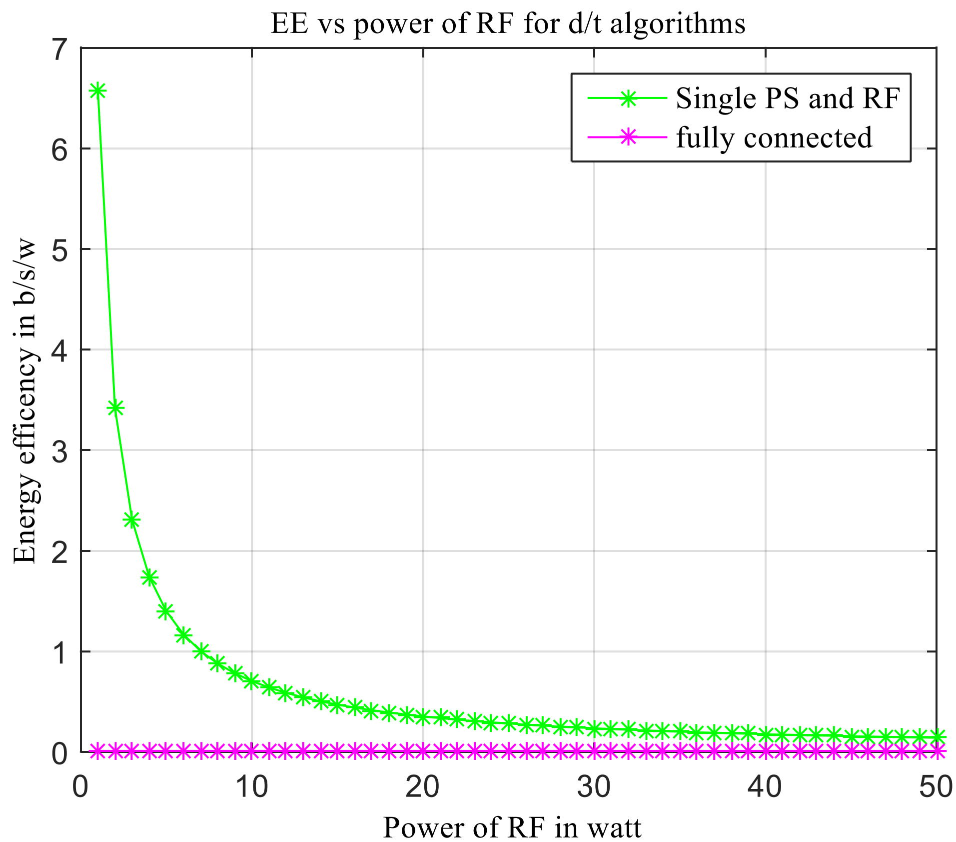


Figure 4.12 Energy Efficiency vs the power of RF chain for fully connected hybrid beamforming and for a single-phase shifter and a single radio frequency chain

Figure 4.12 shows the relationship between Energy Efficiency versus the power of RF chain for fully connected hybrid Beamforming and for a single-phase shifter and a single radio frequency chain. From a result, the EE of a single Ps and RF phase shifter gives a better result than fully connected. That means in the case of fully connected, Energy Efficiency shows the constant value which is approximately zero even if the power of RF chain is increasing.

4.10 Analysis of threshold number of phase shifters and Energy Efficiency for FPSS, and SPSS

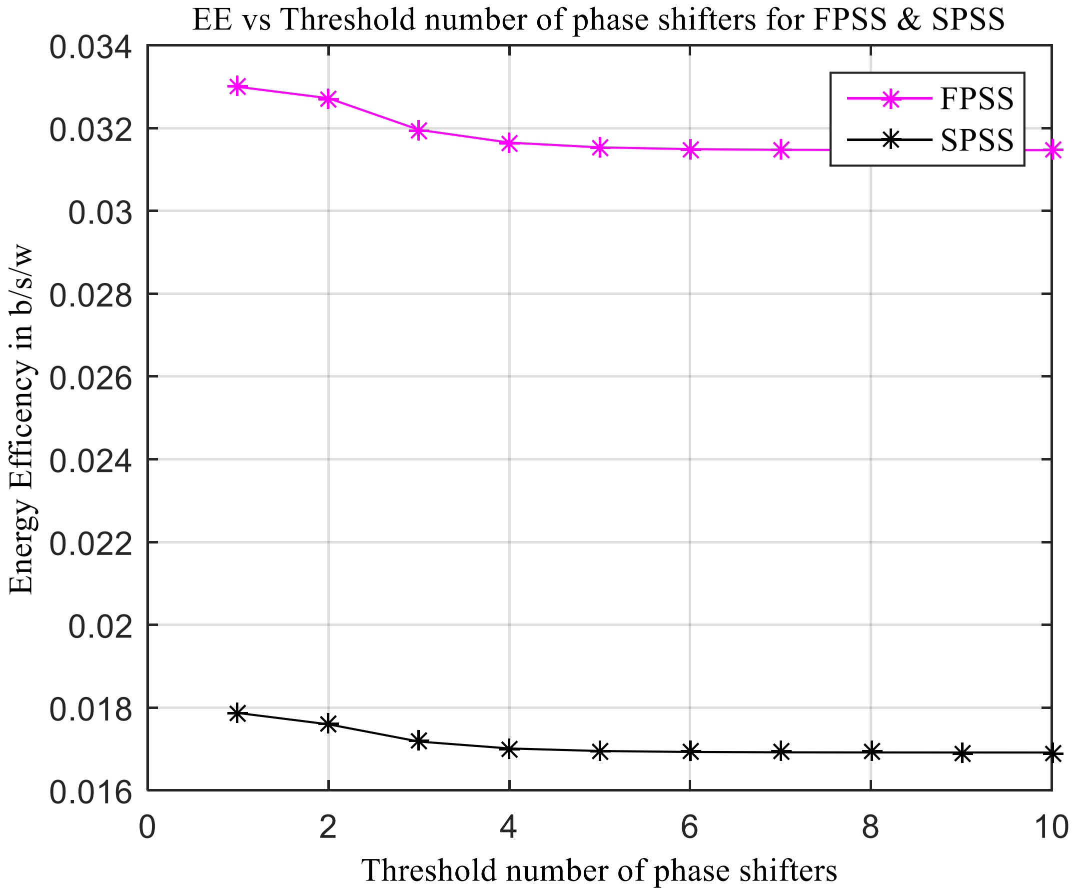


Figure 4.13 Energy Efficiency versus threshold number of a phase shifter for FPSS, and SPSS

As shown in Figure 4.13 it analysis the EE and the threshold number of phase shifters for FPSS and SPSS. The result shows that the system is more efficient for SPSS than FPSS when a threshold number of phase shifters can perform the switching process of the phases towards user position and this effectiveness of SPSS from EE perspective is analyzed numerically in table 4.5 below.

4.11 Analysis of threshold number of phase shifters and EE for FPSS

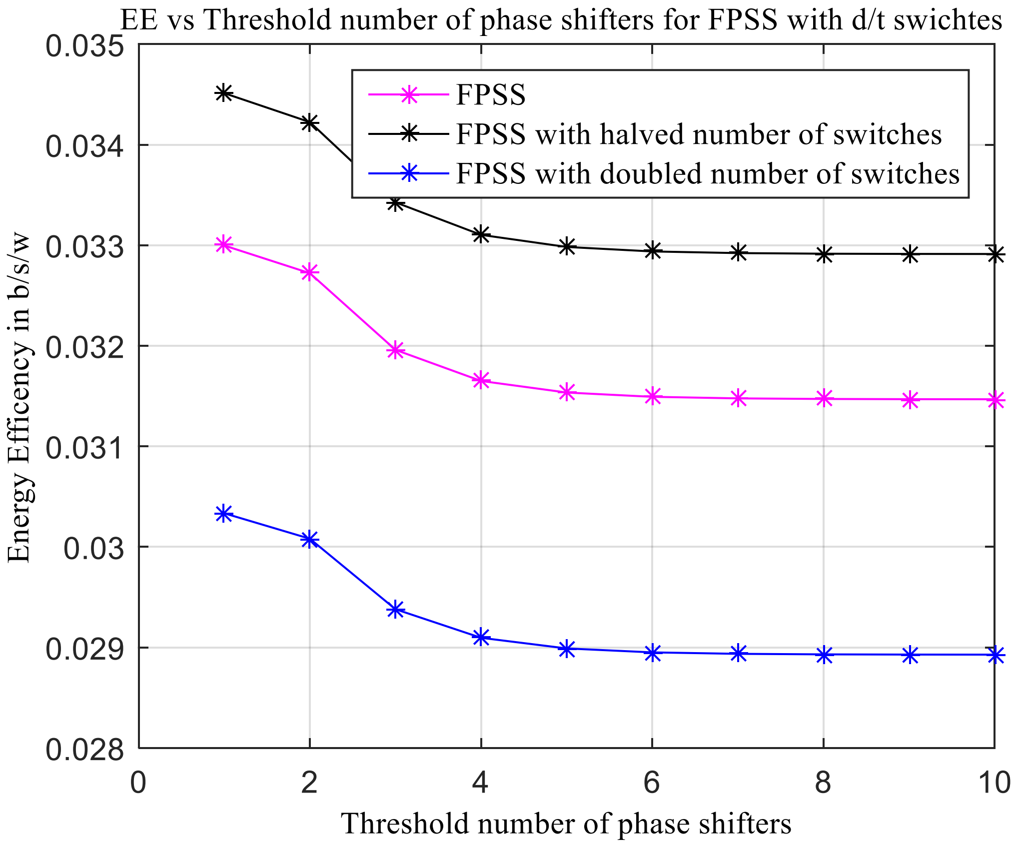


Figure 4.14 Energy Efficiency versus threshold number of a phase shifter for various numbers of switch

Figure 4.14 shows the comparison between EE and the threshold number of phase shifters for FPSS and FPSS with a different number of switches. The result shows that the EE of FPSS with halved number of Switches can over-perform FPSS with doubled number of switch as well as FPSS with halved number of Switches due to a small number of switch can have a high ability to minimizing power consumption. For more detailed explanations see the numerical result in table 4.5 below in each case.

Table 4.5 EE and the threshold number of a phase shifter for different phase shifter selections with constant and variable switches

	EE (b/s/w)				
	With constant switches		With variable switches		
Threshold number of phase shifter	**FPSS**	**SPSS**	**FPSS**	**FPSS with ½ switches**	**FPSS with doubled Switches**
2	0.0327	0.0176	0.03272	0.03422	0.03008
5	0.03154	0.01695	0.03154	0.03298	0.02899
10	0.03147	0.01692	0.03147	0.03291	0.02893

4.12 Analysis of the number of antennas and EE for FPSS, and FPSS with different switches

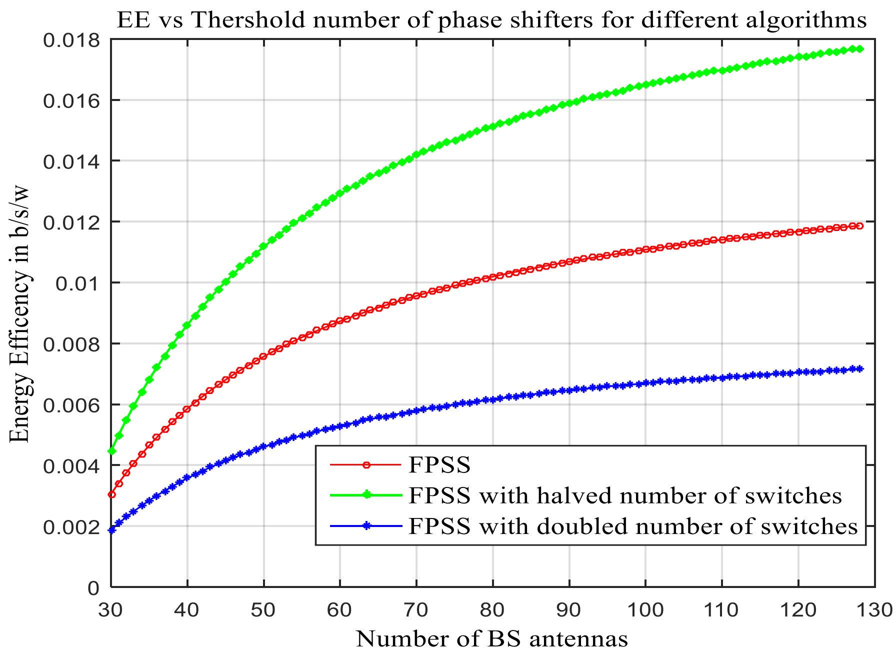


Figure 4.15 Energy Efficency versus the number of antenna for FPSS, and FPSS at different switches

As shown in the Figure 4.15 the Energy Efficiency and the base station antenna for FPSS such as constant switches and FPSS at different switches were illustrated and the result shows that Energy Efficiency is better in the case of FPSS with half switches due to these switches can reduce power consumption. As we have seen in table 4.6, the numerical values show that for a specific number of antennas FPSS with half switches shows better Energy Efficiency.

Table 4.6 Numerical results for a number of antennas and EE at normal FPSS and FPSS with different switches

	EE (b/s/w)		
No/ of antennas	**FPSS**	**FPSS with ½ switches**	**FPSS with doubled switches**
40	0.005855	0.00861	0.00357
60	0.008726	0.01291	0.005293
90	0.01068	0.01588	0.006457
120	0.01168	0.01739	0.007004

4.13 Analysis of Energy Efficiency and number of base station antenna for FPSS and SPSS

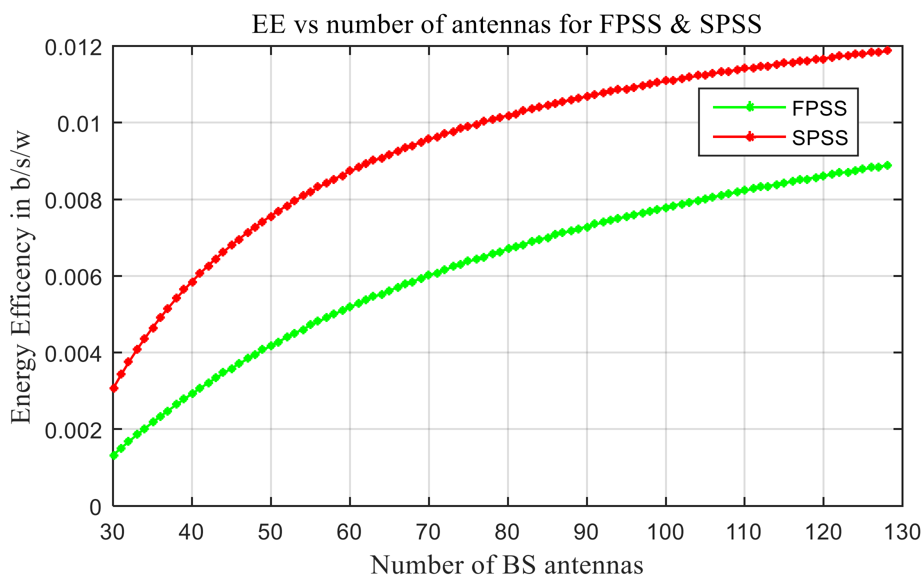


Figure 4.16 Energy Efficency for FPSS and SPSS with number of BS antennas

Figure 4.16 shows that the relationship between Energy Efficiency and number of base station antennas on the application of fully connected with phase shifter selection and sub connected with phase shifter selection. From the simulation result, sub connected with phase shifter selection gives better Energy Efficiency when the number of base station antennas are increasing. From the result, the Energy Efficiency of SPSS is better than the Energy Efficiency of others, and this comparison was verified through numerical analysis in table 4.7 below.

Table 4.7 Numerical comparisons of EE vs number of BS antenna for FPSS and SPSS

EE (b/s/w)		
ANTENNAS	**FPSS**	**SPSS**
40	0.002926	0.006062
60	0.005185	0.008726
90	0.007288	0.01068
120	0.00861	0.01168

4.14 Analysis of number of BS antennas and EE for FPSS, and SPSS

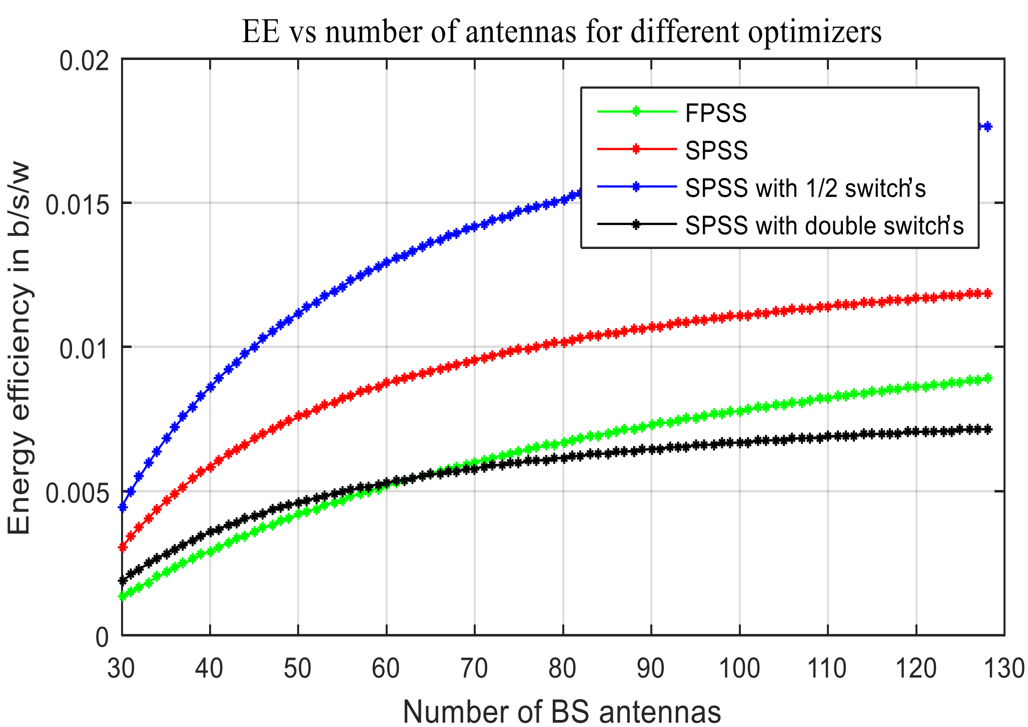


Figure 4.17 Energy Efficiency and number of base station antenna for FPSS, and SPSS

In this Figure 4.17, the number of base station antennas and Energy Efficiency for FPSS, and SPSS with different numbers of switch are illustrated and compared. From the result, the Energy Efficiency of SPSS with half switches is better than the Energy Efficiency of others, and this comparison was verified through numerical analysis in table 4.8 below.

Table 4.8 Numerical comparisons of EE vs number of BS antenna for FPSS and SPSS

	EE (b/s/w)			
	With constant switches		**With variable switches**	
Number Of Antenna	**FPSS**	**SPSS**	**SPSS with ½ switches**	**SPSS with doubled Switches**
40	0.002926	0.005855	0.00861	0.00357
60	0.005293	0.008726	0.01291	0.005293
90	0.007288	0.01068	0.01588	0.006457
120	0.00861	0.01168	0.01739	0.007044

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Massive MIMO employs a high number of antennas to achieve its goals, and it improve the wireless communication system's capacity, reliability, and data rate. When the number of users means human interest increases the number of base station antenna and phase shifters increases with the number of users in this case the system uses more power. In this thesis, I demonstrated that Energy-Efficient phase shifter selection for Millimeter-Wave-based Massive Multiple Input Multiple Output System considerably improve Energy Efficiency. The benefits in Energy Efficiency are particularly obvious in fully-connected phase shifter selection mechanism. To see detailed information on the Energy Efficiency, see the simulation results in chapter four. First of all the result shows theoretical details. For instance, Energy Efficiency is inversely related to total power consumption and capacity in bit/sec and the number of antennas for the different users is obtained. From the result, it could be concluded that when the number of a user has increased the capacity was also increasing for a certain user as explained in table 4.1.

Another is also as we know from a theoretical perspective threshold phase shifter and SNR are inversely related until a certain point and finally, it shows uniform or constant values. So from the result in figure 4.9, this scenario was also investigated when SNR decreases at the same time threshold phase shifter also increases. And from the result in table 4.3, as observed that energy efficiency and power of the radiofrequency chain are inversely related for different users under a predetermined number of transmit antennas. That means for a specific number of users under a constant number of transmit antenna, when total power consumption is large the energy efficiency is low. Based on these theoretical aspects which are verified through MATLAB simulation results, the second step is applying certain algorithms in order to minimize power consumption as well as improve energy efficiency. For this purpose in this paper, I applied different algorithms like FPSS, SPSS, FPSS with single switches, FPSS with double switches, SPSS with single switches, and SPSS with double switches were analyzed. For 120 number of antenna, I will get 0.01739 Energy Efficiency in the sub-connected phase shifter selection with halved number of switch.

Finally from the simulation result, sub-connected phase shifter selection with halved number of switch can outperform energy efficiency over other algorithms which is also illustrated in table 5.1.

Table 5.1 Numerical analysis of entire results

	EE			
	With constant switches		**With variable switches**	
Number Of Antenna	**FPSS**	**SPSS**	**SPSS with ½ switches**	**SPSS with doubled Switches**
40	0.002926	0.005855	0.00861	0.00357
60	0.005293	0.008726	0.01291	0.005293
90	0.007288	0.01068	0.01588	0.006457
120	0.00861	0.01168	0.01739	0.007044

5.2 Recommendation

In this thesis, Energy-Efficient phase shifter selection for Millimeter-Wave-based Massive Multiple Input Multiple Output System was considered. Finally, I improve the Energy Efficiency by minimizing the power consumption, by using the phase shifter selection method and comparing fully connected with phase shifter selection and sub connected with phase shifter selection mechanisms.

In the future if any researchers will want to do with phase shifter selection method, apply:-

- Reduced number of phase shifter selection mechanisms by considering the probability of errors.
- And finally using other algorithms to improve the Energy Efficiency and system cost

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APPENDIX

Code for comparison of Energy Efficiency versus power of RF chain, Single PS and RF, and fully connected.

```
clear all;
clc;
close all;
B=2000000;
K=25
beta=0.9:0.01:1
K2=12
N=128;
p=0.5;
Pc=0.2;
Prf=1:50;
Pps=10;
Ps=1;
Pps2=28;
EE=(K*log(2)*(1+p*(N-K)))./(Pc+N.*Prf+Pps)%
EE2=(K2*log(2)*(1+p*(N-K)))./(Pc+N.*Prf)%

plot(Prf,EE,'m-*'); hold on;
plot(Prf,EE2,'b->'); hold on;
legend('K=25','K=12')
hold on
grid
figure
Pps3=20
EE3=(K*log(2)*(1+3.14*p*(N-K)))/(4)./(Pc+K.*Prf+K*N.*Pps3)%
%EE4=(K*log(2)*(1+3.14*p*(N-K)))/(4)./(Pc+K.*Prf+K*N.*Pps3)%
%EE2=(K2*log(2)*(1+p*(N-K)))./(Pc+N.*Prf)%
```

```
%EE=(B.*K*log(2)*(1+0.5*(N-K)/4)/(Pc+N*Prf))
plot(Prf,EE,'g-o'); hold on
plot(Prf,EE3,'m-o'); hold on
xlabel(' Power of RF')
ylabel('Energy efficency')
legend('Single PS and RF','fully connected')
grid
a=1:10
beta=1-2.71.^(-(a.^2))
Prf=50
Ps2=Ps/2;
Ps3=2*Ps

rr=(Pc+K*Prf+K*N*Pps+K*N*Ps)

rr2=(Pc+K*Prf+K*N*Pps+K*N*Ps2)
rr3=(Pc+K*Prf+K*N*Pps+K*N*Ps3)

rr_spss=(Pc+K*Prf+N*Pps+N*Ps)

figure

EEzz=((K*log(2)*(1+p*(N-K)*(sqrt(3.14/2+2.71.^(-a)-sqrt(3.14/2).*erfc(a))))./(1-beta/100))/rr
EEzz2=((K*log(2)*(1+p*(N-K)*(sqrt(3.14/2+2.71.^(-a)-sqrt(3.14/2).*erfc(a))))./(1-
beta/100))/rr2
EEzz3=((K*log(2)*(1+p*(N-K)*(sqrt(3.14/2+2.71.^(-a)-sqrt(3.14/2).*erfc(a))))./(1-
beta/100))/rr3
plot(a,EEzz,'m-o');hold on;
plot(a,EEzz2,'k-*');hold on;
plot(a,EEzz3,'b->')
xlabel('Threshold number of phase shifters')
```

```
ylabel('EE')
legend('FPSS','FPSS with halved number of switches','FPSS with doubled number of switches')
grid
```

Code for comparison of Energy Efficiency versus Threshold number of phase shifters

```
figure

EEzz_spss=((K*log(2)*(1+p*(N-K)*(sqrt(3.14/2+2.71.^(-a)-sqrt(3.14/2).*erfc(a))))./K.*(1-
beta/100))/rr_spss
plot(a,EEzz,'m-o');hold on;
plot(a,EEzz_spss,'k-*');hold on;
xlabel('Threshold number of phase shifters')
ylabel('EE')
legend('FPSS','SPSS')
grid
```

Code for EE versus N for comparison of FPSS, FPSS with halved Ps, and FPSS with doubled Ps

```
figure
a=4;
beta=1-2.71.^(-(a.^2))
Ps=20
Ps2=Ps./2;
Ps3=2.*Ps
k=20
N=30:128
rr=(Pc+K.*Prf+K*N*Pps+K.*N*Ps)

rr2=(Pc+K*Prf+K.*N*Pps+K.*N*Ps2)
rr3=(Pc+K*Prf+K.*N*Pps+K.*N*Ps3)

rr_spss=(Pc+K*Prf+N*Pps+N*Ps)
rr=(Pc+K.*Prf+K.*N*Pps+K.*N*Ps)
```

```
EE_FPSS=((K*log(2)*(1+p*(N-K)*(sqrt(3.14/2+2.71.^(-a)-sqrt(3.14/2).*erfc(a))))./(1-
beta/100))./rr
EE_FPSS_with_halved_Ps=((K*log(2)*(1+p*(N-K)*(sqrt(3.14/2+2.71.^(-a)-
sqrt(3.14/2).*erfc(a))))./(1-beta/100))./rr2;
EE_FPSS_with_doubled_Ps=((K*log(2)*(1+p*(N-K)*(sqrt(3.14/2+2.71.^(-a)-
sqrt(3.14/2).*erfc(a))))./(1-beta/100))./rr3
plot(N,EE_FPSS,'m-o');hold on;
plot(N,EE_FPSS_with_halved_Ps,'k-*');hold on;
plot(N,EE_FPSS_with_doubled_Ps,'g->');hold on;


xlabel('Number of BS antennas')
ylabel('EE')
legend('FPSS','SPSS with halved number of switches', 'SPSS with doubled number of switches')
grid
```

Code for EE versus number of BS antenna for comparison of FPSS and SPSS

```
figure
EEzz_spss_with_N=((K*log(2)*(1+p*(N-K)*(sqrt(3.14/2+2.71.^(-a)-
sqrt(3.14/2).*erfc(a))))./K.*(1-beta/100))./rr_spss
plot(N,EE_FPSS,'k-*');hold on;
plot(N,EEzz_spss_with_N,'g->');hold on;


xlabel('Number of BS antennas')
ylabel('EE')
legend('FPSS','SPSS')
grid
```

Code for threshold phaseshifters versus SNR

```
clear all;

clc;
```

```
close all;
a=9:-1:1
p=0.5;
N=128;
e=2.718;
K=25;
p2=0.45;
b=(1-exp(-a))



a=[9     8     7     6     5     4     3     2     1]


SNR=p*(N-K)*(3.14/2+a.*e.^(-a.^2)-sqrt(3.14/2)*erfc(a)).^2'
SNR2=p2*(N-K)*(3.14/2+a.*e.^(-a.^2)-sqrt(3.14/2)*erfc(a)).^2'
a=9:-1:1
plot(sort(a,'descend'),sort(SNR),'m-*'); hold on
plot(sort(a,'descend'),sort(SNR2),'g->'); hold on
xlabel('threshold phaseshifters')
ylabel('SNR')
legend('p=0.5','p=0.25')
grid
```