Energy and Spectral Efficiency Analysis for Downlink Massive MIMO Systems

Mahlet Akalu

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, 2021

Adama, Ethiopia

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APPROVAL PAGE OF M.Sc. THESIS

We, the advisors of the thesis entitled "Energy and Spectral Efficiency Analysis for Downlink Massive MIMO Systems" and developed by Mahlet Akalu; hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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Co-Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Mahlet Akalu have read and evaluated the thesis entitled "Energy and Spectral Efficiency Analysis for Downlink Massive MIMO Systems" and examined the candidate during open defence. This is, therefore, to certify that the thesis 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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DECLARATION

I hereby declare that this Master Thesis entitled "Energy and Spectral Efficiency Analysis for Downlink Massive MIMO Systems" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certification in any other university. All sources of material used for this thesis have been duly acknowledged through citation.

__________________ ________________ ____________

Name of student Signature Date

RECOMMENDATION

We, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled “Energy and Spectral Efficiency Analysis for Downlink Massive MIMO Systems” prepared under our guidance by Mahlet Akalu submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electronics and Communication Engineering(Communication Engineering). Therefore, we recommend the submission of revised version of the thesis to the department following the applicable procedures.

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Major Advisor	Signature	Date
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Co-Advisor	Signature	Date

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LIST OF ABBREVIATIONS

ADC	Analog -to- Digital converter
AQN	Additive Quantization Noise
AWGN	Additive Whit Gaussian Noise
BS	Base Station
CSI	Channel State Information
DAC	Digital-to-Analog converter
DB	Digital Beamforming
EE	Energy Efficiency
FDD	Frequency Division Duplex
FSPL	Free Space Path Loss
HB	Hybrid Beamforming
IEEE	Institute of Electrical and Electronics Engineers
LO	Local Oscillator
LOS	Line Of Sight
MATLAB	Matrix Laboratory
MIMO	Multiple Input and Multiple Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
MRT	Maximum Ratio Transmission
MU MIMO	Multi User Multiple Input and Multiple Output
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
SE	Spectral Efficiency

SIC	Successive Interference Cancellation
SINR	Signal-to-Interference-Plus-Noise-Ratio
SISO	Single Input Single Output
SNR	Signal-to-Noise Ratio
TDD	Time Division Duplex
UE	User Equipment
ZF	Zero Forcing

ABSTRACT

Massive multiple-input multiple-output (MIMO) refers to the use of a huge number of antennas at the base station to transmit and receive signals that fully utilize spatial resources, improving wireless network energy efficiency and spectral efficiency. There are many radio frequency chain components corresponding to each antenna which results in higher power consumption in massive MIMO system. From these radio frequency chains components, digital-to-analog converters (DACs) are one of the most power consuming in downlink massive MIMO. The power consumption of DAC can be minimized by reducing its resolution. Massive MIMO systems combined with beamforming play an important role in 5G wireless communication systems. Digital beamforming having dedicated (Radio Frequency) RF chain for each antenna is complex and costly while hybrid beamforming with reduced number of RF chain is less complex and achieve better energy efficiency by lowering the power consumption. In this thesis low resolution DACs are used, considering threshold capacity to lower power consumption and enhance energy efficiency of the system. Modulation is also the other technique used to enhance the capacity and spectral efficiency of the system when DAC capacity is below the threshold. Low resolution DAC and Modulation techniques applied for hybrid and digital beamforming and their performances analyzed. The simulation results show that using low resolution DACs enhance energy efficiency compared to without DAC resolution. For hybrid beamforming, better energy efficiency is achieved compared to digital beamforming using low resolution DAC. Digital beamforming achieve better spectral efficiency through modulation compared to hybrid beamforming.The trade-off between energy and spectral efficiency is also analysed considering low resolution DAC.

Key words*: Massive MIMO, Energy Efficiency, Spectral Efficiency, Low resolution digital-to-analog converters (DACs), Modulation, Hybrid beamforming, Digital beamforming*

CHAPTER ONE

1 INTRODUCTION

1.1 Background

Because of the ever-increasing number of users with multimedia communications, demand for wireless services is rising extensively. The design of high data rate and reliable wireless communication systems is also difficult due to the effects of multipath fading, restricted transmitter capacity, and scarce spectrum. To conquer the obstacle, Multiple Input Multiple Output (MIMO) technology is employed, which utilizes multiple antennas for transmission and reception. The degree of freedom in the propagation channel increases as the number of antennas at the transmitter and receiver grows, resulting in an increase in data rate and connection reliability [1].

MIMO is a physical layer technology that allows more data to be delivered within the same amount of time and with the same available bandwidth. When compared to a Single-Input Single-Output system, which uses only one antenna at the transmitter and receiver, MIMO systems allow several data streams to be sent in different spatial routes simultaneously, improving data rates. Signal mixing will occur at receivers if many streams are transmitted across wireless channels at the same time. As a result, additional signal processing, either at the receiver or at the transmitter, or both, is required to separate the data stream, which is referred to as MIMO processing [2].

In Multiuser MIMO systems a base station with multiple antennas can employ scheduling techniques to simultaneously serve several spatially separated user equipment's over the same time-frequency resource. These systems offer multiple access and broadcast capabilities where, each user's equipment in an MU-MIMO system can use a single antenna yet achieving equivalent performance gain to point-to-point MIMO systems. In fact, the physical size and cost constraints of UEs limit the performance of point-to-point MIMO systems, as UEs are often low-cost handheld devices that are unable to support multiple antennas.

Massive MIMO systems are one of very essential technology for fifth generation mobile networks since they can improve energy efficiency and spectral efficiency of cellular network. In these systems, hundreds or even thousands of antennas employed at base stations to serve a relatively small number of users at the same time-frequency resource [3]. Massive MIMO systems offer considerable performance improvements, but they also face challenges like expensive hardware, high total power consumption, and large data processing. Each antenna of Massive MIMO is equipped with a RF chain, comprising digital-to-analog converter. The power consumption and hardware complexity DACs increase with the number of quantization bits as the antenna number increases. So using low-resolution DAC is a promising option. Low-resolution DACs can be evaluated using two key metrics: spectral and energy efficiency.

Energy Efficiency is heavily reliant on lowering circuit power consumption, which is consumed by radio frequency chain circuit components. Analog to digital and digital to analog converters, phase shifters, and power amplifiers all contribute to the power amplifier's energy consumption so amplifiers consume the majority of the power at the transmitter [4]. So using low resolution DACs at transmitters minimize power consumption hence increasing the system's energy efficiency. The digital beamforming system can deliver high rate, but the energy consumption becomes excessive when the transceiver system utilize the same number of RF chains as the number of antennas. A hybrid beam forming system uses fewer RF chains and can be implemented used to provide comparable rate efficiency to a digital beam forming system while being more energy efficient [5].

In massive MIMO there are large number of antenna at the BS also large number of RF chain and correspondingly DAC which results a significant challenge like complexity and high power consumption. So for this Hybrid beam forming is the solution as a means of reducing the number of RF chain. In addition to this using low resolution DAC helps in the reduction of power consumption, since that DACs are one of the most power-consuming hardware components in the downlink, whose power consumption increasing exponentially with the resolution and linearly with bandwidth [6].

Due to the greater number of radio frequency chains, an increase in the number of antenna arrays at a base station leads to increased power consumption. Furthermore, the processing activities of digital-to-analog converter, multiplexer, filter, and power amplifier consume more power as the number of RF chains increases in both BS and UE. Moreover, the RF chains need be connected to all antennas at the BS. BSs account for 80% of the total energy consumed in wireless networks, a large amount of that being wasted due to inefficient operation of radio frequency equipment. When the transmission power in large-scale MIMO systems is high, most EE techniques focus on lowering it. Furthermore, regarding cellular networks' energy resources, power allocation algorithms must minimize power consumption while maximizing the data rate that can be achieved [7].

In this thesis low resolution DAC is utilized for enhancing energy efficiency of Downlink massive MIMO and the effect on hybrid and digital beamforming techniques is analysed. Low resolution DAC is used beyond threshold capacity by reducing the numbers of bits so that power consumption of DAC is reduced, also total power consumption minimized and energy efficiency enhanced. Below the threshold capacity, higher order modulation is used to enhance the capacity of the system and to achieve spectrally efficient system The Modulation effect on both hybrid and digital beamforming is also analysed for energy and spectral efficiency.

1.2 Statement of problem

Massive MIMO systems increase the number of antennas at the base station to large extent over typical MIMO systems in order to achieve considerable energy efficiency and capacity advantages. But scaling up the number of antenna at the Base station result in increase of power consumption and system costs for radio frequency circuitry.The most power consuming radio frequency chain component in massive MIMO include DAC. To minimize its power consumption low resolution DAC is used with reduced number of bit. Reducing the power consumption of DAC contribute to the total power consumption reduction significantly. As the result the system energy efficiency can be enhanced since total power is reduced and they have inverse relationship.

The other problem, demand for high data rate wireless communication service is increasing rapidly form time to time and the available spectrum is limited, the network operators are facing difficulty in meeting the traffic requirement problems. To cope up with this growing demand the available spectrum has to be used efficiently. Higher order modulation which enhances the capacity and spectral efficiency of the system can be utilized.

1.3 Objectives

1.3.1 General Objective

The main objective is to achieve energy and spectral efficient Downlink Massive MIMO system by minimizing the total power consumption and enhancing the capacity of the system respectively.

1.3.2 Specific Objectives

- To calculate capacity of the system.
- Minimize the power consumption of DAC by reducing its resolution.
- To calculate total power consumed by the radio frequency chain for hybrid and digital beamforming.
- Calculate and analyze energy efficiency of the system with low resolution DAC.
- Calculate and analyze spectral efficiency of the system through modulation.
- Evaluate hybrid and digital beamforming performance in terms of DAC resolution and modulation.

1.4 Significance

In massive MIMO system to achieve energy efficiency the total power consumption have to be minimized. In this thesis one of the most power consuming radio frequency chain components DAC, is considered and its power consumption minimized by reducing its resolution depending on threshold capacity. So that the total power consumption also reduced and energy efficiency achieved. Higher order Modulation is also used if DAC capacity is below the threshold capacity to enhance the capacity of the system and achieve spectral efficiency for downlink massive MIMO systems.

1.5 Scope

This thesis focuses on enhancing energy and spectral efficiency of single cell down link Massive MIMO systems. As there are huge numbers of antennas in massive MIMO systems, there are also many radio frequency chain components which results in more power consumption in these systems. Among the radio frequency chain components DAC is considered since it is one of the most power consuming component and its power consumption minimized by reducing its resolution. So that energy efficiency can be enhanced. Hybrid and Digital beamforming considered to compare their performance using low resolution DAC and higher order modulation.

1.6 Main contribution

The main contribution of this thesis is on power consumption minimization of DACs which are one of the most power consuming radio frequency chain components of Massive MIMO systems. Depending on threshold capacity DACs resolution is reduced, setting the threshold capacity at the cell edge and comparing capacity of DAC with that threshold. If the DAC capacity greater than threshold, resolution is applied by minimizing the number of bits so the number of bits reduced are depending on threshold capacity. Low resolution DACs are used to minimize the power consumption of DAC so that total power consumption also reduced and energy efficiency enhanced. The other case is if DAC capacity lower than the threshold capacity higher order modulation used to enhance the system capacity and achieve spectral as well as energy efficiency. Additionally by combining Massive MIMO with beamforming, low resolution DACs and modulation technique used for analyzing the performance of hybrid and digital beamforming.

1.7 Thesis Organization

The rest of the thesis is organized as follows;

Chapter 2: Review of different literature on Massive MIMO, Digital to analog converters, Hybrid and Digital beamforming and the existing works related to Low resolution DAC for hybrid and digital beamforming.

Chapter 3: System model and mathematical formulation for down link Massive MIMO considering low resolution DAC and power consumption modelling for both hybrid and Digital beamforming.

Chapter 4: Simulation results and discussion for each of the results obtained.

Finally the Thesis ends with conclusion and recommendation for future work.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Massive MIMO overview

Transmitted signals in wireless communication are attenuated by fading which is caused by shadowing and multipath propagation coming from large obstacles between the transmitter and receiver, posing a challenge for reliable communication. Transmission using MIMO antenna is a familiar diversity technique for improving communication reliability. Moreover, multiple streams can be sent out using multiple antennas, resulting in a multiplexing gain that greatly enhances communication capability.

The effort for exploiting spatial multiplexing gain has moved from MIMO to MU-MIMO, in which a multiple antenna base station serves a single antenna multiple user terminals simultaneously. In multiuser MIMO systems spatial multiplexing gain is important since it is difficult for the user to accommodate large antenna numbers at the BS because of user terminals limited physical size and lower cost specification [8].

A Massive MIMO system, introduced by Marzetta is the usage massive antenna arrays for multiuser transmission in a cellular system. In Massive MIMO, base stations are equipped with huge numbers of active antenna elements while each user has a single antenna. Uplink pilot symbols are used in a time division duplex protocol to cope with the overhead caused by channel training, allowing the channel reciprocity to learn both the uplink and downlink channels of the users.

Massive MIMO systems are multiuser-MIMO systems where a Base Station having hundred or more antennas simultaneously serves much smaller number of users using the same time and frequency resource. Due to their characteristics, Massive MIMO systems can increase the capability of wireless communication systems by a factor of ten or more, while also raising energy efficiency by a factor of 100. Because of the large number of antennas used, these systems are able to maximize performance. On the other hand, the deployment of large number of antennas causes interference, which can be reduced by using beamforming antennas instead of conventional antennas. Beamforming is a signal processing technique that employs multiple antenna arrays at the transmitter and/or receiver to simultaneously send or detect multiple signals from multiple desired terminals at the same time to increase system capacity and performance. It can be realised by arranging the components in an organised array, with beams steered in particular direction being introduced while the others are ignored [9].

2.1.1 Massive MIMO Working principle

In Massive MIMO, Time Division Duplexing operation is preferable in which uplink and downlink transmissions use different time slots but the same frequency spectrum. There is reciprocity in the uplink and downlink channels. Three operations exists during a given coherence interval which are channel estimation with the uplink and downlink training, uplink data transmission, and downlink data transmission [8]. Time Division Duplexing Massive MIMO protocol is shown in Figure 2.1.

2.1.2 Channel Estimation

Base Station needs Channel State Information to detect and precode signals sent by users in the uplink and downlink, respectively. Channel State Information is gained through the uplink training. Each user is given an orthogonal pilot sequence, and sends this pilot sequence to the Base Station. The Base Station is aware of all users' pilot sequences and then estimates the channels based the received pilot signals. Moreover, every user needs partial knowledge of Channel State Information for detecting the signals transmitted from the BS coherently. Through downlink training this information can be obtained. Since the BS beamforms the signals to the users using linear precoding techniques, the user only acquires the effective channel gain to notice its desired signals. As a result, the Base station spends a little time to beamform pilots in the downlink for Channel State Information acquisition at the users.

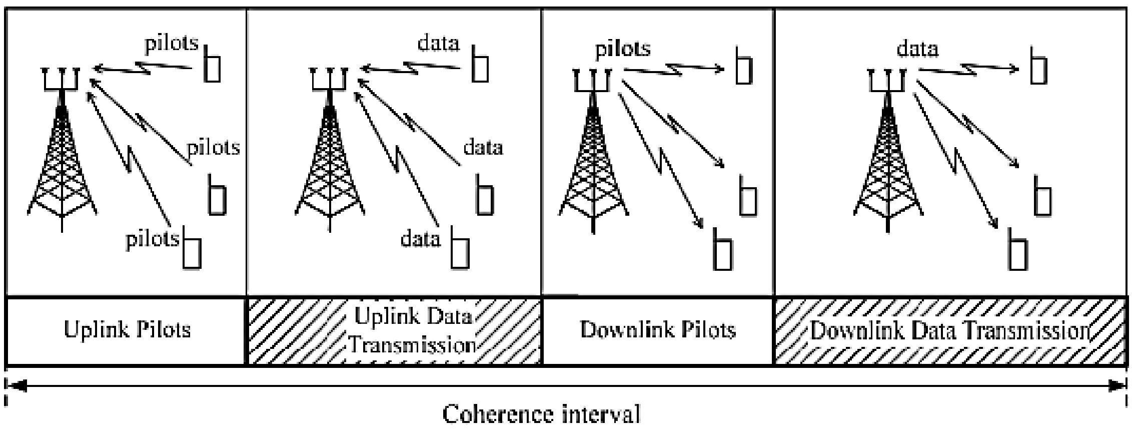

Figure 2.1 Transmission protocol of time division duplexing Massive MIMO [8]

2.1.3 Uplink Data Transmission

A portion of the given coherence interval is utilize for the uplink data transmission. In the uplink, all users transmit their data to the Base Station at the same time frequency resource. The Base Station then uses the channel estimates along with linear combining techniques to detect signals transmitted from all k users.

2.1.4 Downlink Data Transmission

The Base Station transmits signals to users in downlink at the same time frequency resource. More specifically, the Base Station uses estimates of its channel together with the symbols assigned for the K users to generate M precoded signals which are then fed to M antennas.

2.1.5 Downlink Operation

In Massive MIMO downlink operation, base station having many numbers of antennas transmit different data stream to the user terminals typically have single antenna each as shown in figure2.2 the key goal here is to make sure each user receives only the data stream intended for him, with little interference from the other data streams. Massive MIMO employs spatial-division multiplexing, which ensures that the various data streams share the same frequencies and times. An array of independently-controlled antennas is a critical component in accomplishing wireless spatial multiplexing. The array must know the frequency response of the propagation channels between each of its elements and each of the users in order to perform multiplexing. Using this channel state information in precoding block the data streams are mapped into the signals that drive each of the antennas. The beams can be focused more selectively to the consumers by increasing the number of antennas

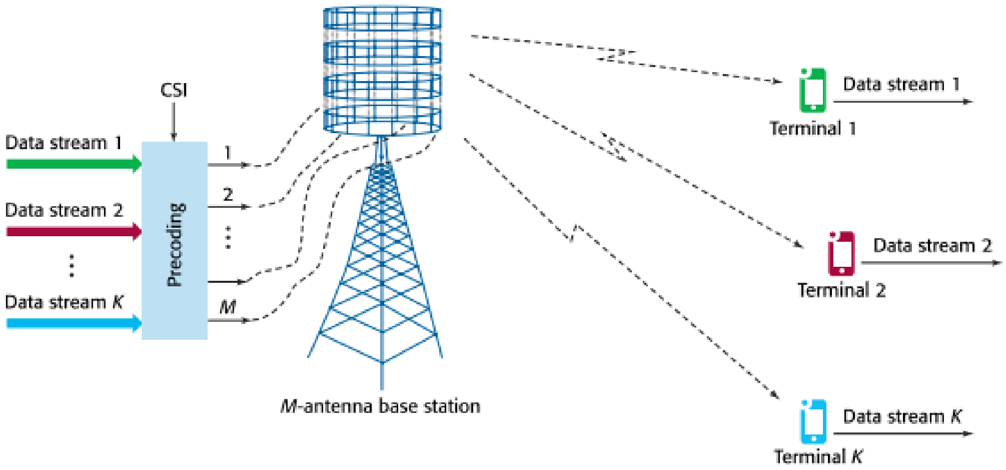

Figure 2.2 Downlink operation [10]

2.1.6 Uplink Operation

The Massive MIMO system's uplink operation, illustrated in figure2.3 is the reverse of downlink operation in which the users transmit data streams to the base station antenna array over the same frequencies and at the same time. The antenna array receives the total of the data streams as modified by their various propagation channels, decoding procedure to obtain actual signals and utilizing the Channel State Information already known well at the base station. As a result, the received signals are decomposed to form the individual data streams.

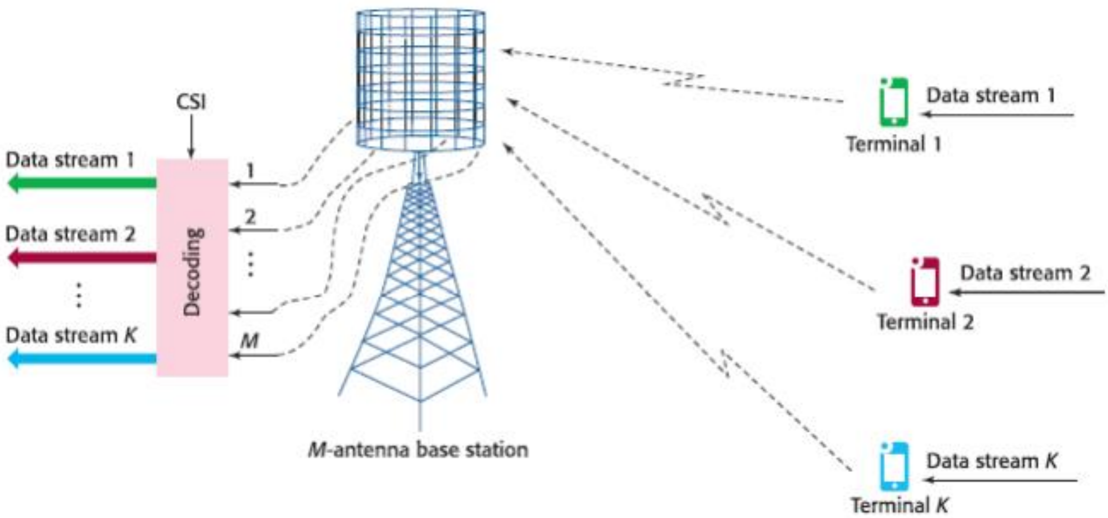

Figure 2.3 Uplink Operation [10]

2.1.7 Massive MIMO Features

• **Linear processing**

Signal processing at the user terminal ends must handle large dimensional channel matrices due to the large number of BS antennas and users. As a result, it is preferable to use simple signal processing. Linear processing which is linear precoding scheme for downlink and linear combing schemes for uplink are almost optimal in Massive MIMO [8].

• **Favorable propagation**

In massive MIMO, Base Station is suited with an excessively large number of antennas relative to the number of User terminals. Deploying a huge number of antennas at the Base Station results in favourable propagation, where the wireless channels become nearly deterministic because the BS-UE channel vectors become near-orthogonal to each other. This is due to the fact that when the number of antennas at the BS is increased unboundedly the effects of small-scale fading tend to disappear asymptotically.

•**Antenna array**

Antenna arrays of Massive MIMO Base Station do not have to be physically big in order to limit them from occupying large space.

• **Scalable**

Since the BS acquires the channel through UL pilot when operating in TDD protocol, the time spent on channel estimation does not depend on the number of Base Station antennas. Thus, the number of Base Station antennas can be increased without adding more time to the estimation process. Furthermore, because multiplexing and demultiplexing are not needed at the user ends, signal processing on each terminal is independent of the other users.

2.1.8 Massive MIMO Advantages

Massive MIMO have many advantages compared to the conventional MIMO system. Some of them are listed below [8].

- **High spectral efficiency and communication reliability**

Massive MIMO takeover all gains from multiuser MIMO. Having M number of antenna on the Base station and K users with single antenna, a diversity of order M and multiplexing gain can be achieved. Very high spectral efficiency and communication reliability can be obtained by increasing both the number of antenna and number of users.

- **High energy efficiency**

Base station focuses the energy on directions where user terminals found in the downlink. Therefore, huge antenna arrays will minimize the emitted power by an order of magnitude, allowing us to achieve high energy efficiency. Energy can be concentrated into small regions in space with a large number of antennas this makes increase in energy efficiency possible. Enhancement in spatial resolution and the coherent superposition of wave fronts is mainly the reason for this. The wave fronts are radiated by antennas summed up constructively at users the locations. Interference among users can be suppressed by using suitable precoding scheme.

- **Simple signal processing**

The use of huge number of base station antenna over the number of user results in favorable propagation in many of propagation environments where the channel vector between user and Base Station nearly orthogonal. Under favorable propagation, the effect of interuser interference and noise can be eliminated with simple linear signal processing or linear precoding and linear decoding in the downlink and uplink respectively. As a result, simple linear processing schemes are nearly optimal.

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 this property is channel hardening. The system scheduling, power control and other functions performed can be done over the large-scale fading time scale instead of over the small-scale fading time scale. This simplifies the signal processing significantly.

- **Reduction of latency**

Wireless communication systems performance restricted by fading, where the signal strength minimized drastically. This happens in multi path channels where signals on arrival add up destructively. Fading results in a difficulty to obtain reduced latency wireless links since Mobile Subscriber must wait until the propagation channel has sufficiently altered before receiving any data if it is trapped in a fading dip. Massive MIMO which depends on the use of huge numbers and beamforming avoid fading, so that fading no longer limits latency.

2.1.9 Challenges in Massive MIMO

Despite the huge advantages of Massive MIMO, there are issues that needs to be tackled the main challenges in massive MIMO are listed below;

- **Pilot Contamination**

Practical cellular networks consist of many cells. This many cells share the same time-frequency resources due to the limited availability of frequency spectrum. In multicellular systems, orthogonal pilot sequences for all users in all cells cannot be assigned, due to the limitation of the channel coherence interval. Orthogonal pilot sequences have to be reused from cell to cell. So, the channel estimate obtained in a given cell will be contaminated by pilots transmitted by users in other cells. This is called pilot contamination which reduces the system performance and it’s the major limitation of Massive MIMO [8].

- **Unfavourable propagation**

Massive MIMO normally works under favorable propagation environments. But practically there may be propagation environments where the channels are not favorable. Like in propagation environments where the numbers of the scatters’ is small compared to the numbers of users, or when some common scatters’ share the channels from different users to the BS, the channel is not favorable. Distribute the BS antennas over large area can be One possible solution for this.

- **High power consumption**

In Massive MIMO because of the presence of huge number of antenna and also large number radiofrequency chain corresponding to each antenna there is more power consumption. Every components of the radio frequency chain consume more power as they as large in number.

2.2 Beamforming

Multiple antennas deployment at the transmitter and receiver enhances the system's overall Performance. This performance improvement is made possible by to the use of beamforming, which is realized by utilizing Channel State Information. The process of controlling amplitude and phase of broadcast and/or received signals according to the needed application and channel environment is known as beamforming [11]. In Beamforming the beam focuses transmit or receive beams in one specific area to supress interference and enhances received signal power, gain and throughput. Beamformed transmission is the most extensively used technique in MIMO systems, and it could be implemented for both single user and multiuser systems.

Beamforming techniques can be classified based on signal processing into analogue beamforming, digital beamforming, and hybrid beamforming. Analogue beamforming provides advantages of low complexity, low cost phase shifters for massive MIMO systems relative to digital beamforming at the expense of limited performance since it support only a single data stream. Digital beamforming is beneficial for providing more precise and rapid foundation results for obtaining user signals [12]. However, it has high complexity, more power usage and expensive design. To obtain the advantages of analogue and digital beamforming hybrid beamforming has been developed for massive MIMO systems

2.2.1 Analogue Beamforming

Analog beamforming send the same signal from multiple antennas using phase-shifters but with different phases. RF components with phase shifting and potentially gain adjustment capabilities are used to process transmit and receive arrays. The basic idea of analogue beamforming is phase controlling of each transmitted signal simply using affordable phase shifters. So, analogue beamforming is less expensive to implement than digital beamforming. But On the other hand, its performance is poorer relative to digital beamforming since phase shifter amplitudes are not flexible. A single RF chain with numerous analog phase shifters is used to transmit a single data stream in such a system [13].

Analog beamforming hardware structure is simpler to construct. However, because only the phases of the transmit signals can be changed but not their amplitudes, this beamforming has low antenna gain and suffers from significant performance loss. Better performance achieved by combining analog and digital beamforming to harvest the advantage of both analog and digital beamforming which is referred as hybrid beamforming mostly used with massive MIMO systems [14]. Digital beamforming creates baseband signals, whereas the analog beamforming handle the effects RF chain by minimizing the number of ADCs or DACs, which enhance outputs of power amplifiers or alter mixers architecture for cost savings.

2.2.2 Digital beamforming

In Digital Beamforming, a single radio frequency chain is required for each antenna element providing good performance but at the expense of high power consumption and a complex architecture. RF chain includes down-converter, low-noise amplifier, digital to analog converter, analog to digital converter and others. Therefore, for large number of BS antennas the cost and power consumptions of mixed signal components is higher, such as high resolution DACs and ADCs, make that assignment of a separate RF chain for each antenna is highly inefficient. As a result, beamforming with a restricted number of RF chains is becoming increasingly crucial. [15].Hybrid beamforming is one way to attain this goal by deploying beamforming in both the digital and analog schemes. In the digital, beamforming is accomplished at the baseband frequency, whereas in the analog, beamforming is accomplished via low-cost phase shifters

Figure 2.4 show digital beamforming transmitter architecture where a base station with N antennas serving a K single antenna users. Equal number of RF chain and number of antenna present in digital beamforming. In every symbol duration, data symbols of are putted in vector form, $d = [d_1, d_2, \dots, d_k]$ where d_k is data symbol of k^{th} user. Then, multiplying k^{th} User symbol by its beamforming vector $b_k \epsilon \mathbb{C}^{N\times 1}$ to form the transmitted vector corresponding to the k^{th} User as $x_k = b_k d_k$ finally, adding up all transmitted vectors as $\bar{d} = \sum_{i=1}^{k} xi$, passed through the RF chains consisting of DAC for converting the digital samples to analog signal and transmitted to all antennas via power amplifiers. To transmit S_t symbols for each UE, the transmitter broadcast$[\bar{d}_1, \bar{d}_2, \dots, \bar{d}_{S_t}]$ sequences of information.

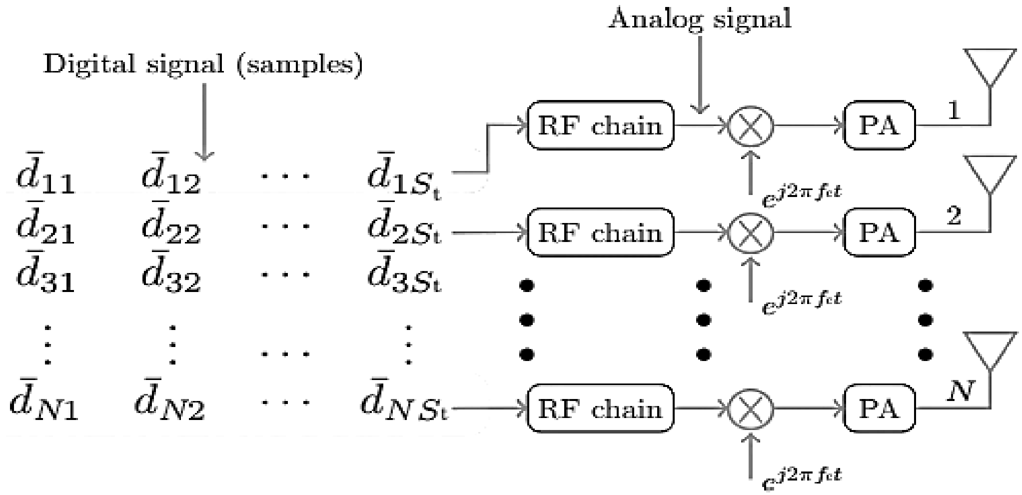

Figure 2.4 Transmitter architecture with Digital beamforming [16]

2.2.3 Hybrid beamforming

Hybrid beamforming is one type of beamforming which overcome limitations of digital or analog beamforming, by combining the advantages of both methods. Utilizing several simultaneous beam transmissions, hybrid beamforming lower the training overhead compared to analog only architectures. [17]. In hybrid beamforming the numbers of RF chains are substantially fewer than the number of antennas while keeping spatial multiplexing gain., thus compared to digital schemes they are with reduced complexity. They also gives more flexibility compared to traditional analog beamforming by splitting the multiple input multiple output optimization process between analog and digital domains. Digital precoder can compensate for the analog precoder's lack of precision, which is an advantage of the hybrid technique [18].

Figure 2.5 shows hybrid beamforming architecture for a system where a base station having N antennas and N_a Radio Frequency chain, having lower number of RF chains compared to the number of antennas combining a hybrid analog-digital beamforming utilize K single antenna User equipment's. The data symbol of all UEs in vector form $d = [d_1, d_2, \dots, d_k]$, multiplying k^{th} UE symbol by its beamforming vector $b_k \epsilon \mathbb{C}^{Na \times 1}$ to form the transmitted vector $x_k = b_k d_k$ which pass through the RF chains then it enters to analog beam forming matrix $A \epsilon \mathbb{C}^{N \times Na}$ then all of the transmitted vectors summed up and multiplied with analog beam forming matrix as $\bar{d} = A \sum_{i=1}^{k} x_i$ then, transmitted to antennas through power amplifiers. To transmit *St* Symbols for each UE, the transmitter broadcasts $[\bar{d}_1, \bar{d}_2, \dots, \bar{d}_{st}]$ sequences of information.

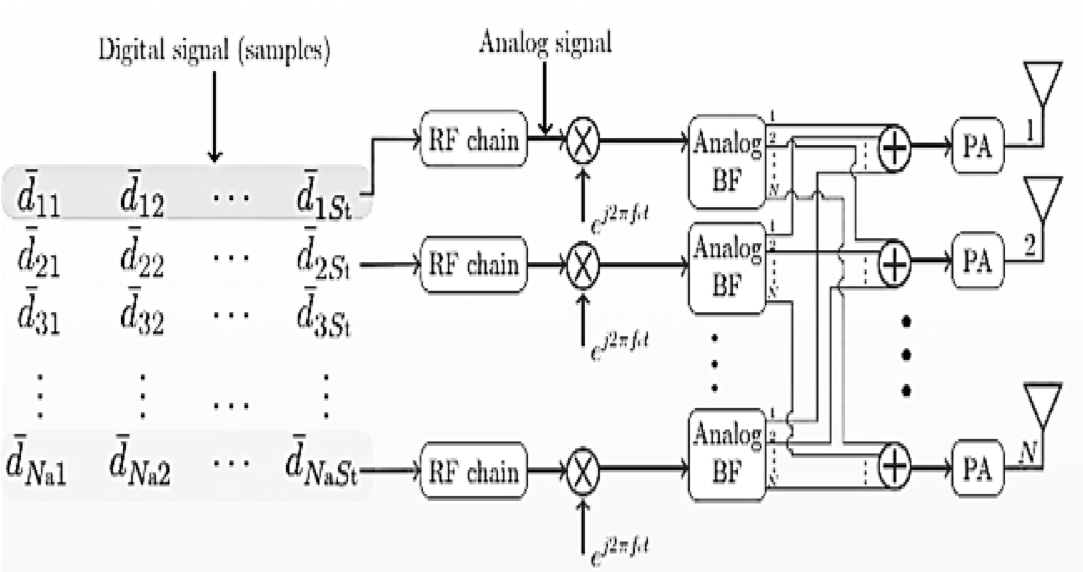

Figure 2.5 Transmitter architecture with hybrid beamforming [16]

2.3 Digital to Analog Converters

In Downlink Massive MIMO system low resolution DACs are utilized for every antenna at the Base Station to change the in phase and quadrature components of the digital representation of transmitted signal into analog before being transmitted over the wireless channel. Data converters with large speeds and resolution are power hungry. Therefore, low-resolution data converter architectures are very important for massive MIMO systems, where the total number of data converters at the base station could be in the hundreds or thousands.

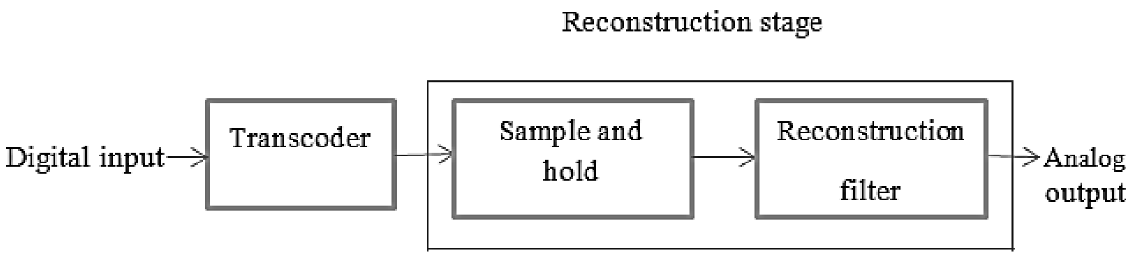

Figure 2.6 Digital to Analog Converters function block diagram [19]

Figure 2.6 illustrates block diagram for the basic function of DAC. The transcoder generates an analog sequence whose amplitude that corresponds to the digital code. The resolution of DAC which is the number of DAC bits determines the number of discrete amplitude levels at the transcoder output. Q bit DAC's transcoder which handles 2^Q voltage levels, can thus be described as a Q-bit quantizer. The reconstruction stage converts the pulse sequence into an analog waveform or continuous-time signal. A sample and hold circuit is usually followed by a low pass filter in this block.

A zero order hold filter is a typical sample and hold circuit that keeps the amplitude of each sample for a set amount of time. But, since a ZOH filter has an unlimited frequency response, it emit unwanted out of band emission. To limit the out of band emission a low pass filter is used after the sample and hold circuit. The use of low-resolution DACs in the Massive MIMO downlink is motivated by the fact that using DACs with unwanted high resolution will result in excessive power consumption so minimizing the resolution of DAC used to alleviate this problem [19].

2.4 Energy Efficiency

Due to the fact that faster transmission speeds necessitate more transmitter power, Energy Efficiency becomes one of important issue of 5G technologies. In massive MIMO EE is mostly concerned with component selection techniques like antenna selection and RF chain selection mechanisms. But these techniques reduce the capacity of Massive MIMO so, with the existing number of antenna or RF chain Components, reducing the power consumption of one of the most power consuming radio frequency chain component, DAC power consumption can be minimized by reducing the resolution DAC this method is considered in this thesis in order to enhance energy efficiency [20].

Massive MIMO provides significant energy efficiency improvements by achieving higher spectrum efficiency with lower power consumption, as energy efficiency is the ratio of spectral efficiency and total power consumption over a given band width. But increasing the number of antenna does not always result in increasing of energy efficiency since after some point energy efficiency decline since total power consumption increase to larger extent as the number of antennas increases relative to the capacity increase. Spectral efficiency unlike energy efficiency always increases with increasing number of antenna because power consumption rises with the number of antennas and number of users. To lower the power consumption of Massive MIMO there are many lower complex and inexpensive precoding, combining user scheduling techniques have been developed [21].

2.5 Spectral Efficiency

By allowing the antenna array to direct narrow beams towards a user, massive MIMO enhances spectral efficiency. In Massive MIMO it is possible to attain a spectral efficiency that is more than ten times that of the conventional MIMO system [22]. Spectral efficiency is a significant metric for assessing transmission capacity system performance. Because spectrum is a limited resource, the best choice for meeting the rising demand for wireless data traffic is to maximize the spectral efficiency of the existing spectrum. The huge numbers of antennas in massive MIMO systems provide a large number of degrees of freedom, allowing for more efficient wireless communication signals and thereby enhancing spectral efficiency and capacity. The rise in system achievable capacity leads to a large increase in spectral efficiency in Massive MIMO systems [23].

2.6 Related work

In [5] energy efficient downlink transmitter with low resolution DACs for mm Wave massive MIMO systems designed. To obtain the optimal number of RF chains to be use at the transmitter while minimizing power consumption, an optimization problem is developed. The information loss constrains this problem, resulting in a reduction in the number of RF chains, expressed in terms of capacity of the system. Switches are employed in the proposed system to maintain a connection between the digital baseband precoder and DAC; if that connection is active, that DAC connects baseband precoder to an RF chain. For various DAC resolutions, the rate and energy performance of several beamforming algorithms and architectures are compared.

In [24] performance analysis of Massive MIMO uplink systems with low-resolution analog-to-digital converters and effect of signal detection schemes investigated on the uplink multiple-input multiple-output systems energy efficiency. Optimal power allocation and their analytical approximations for zero-forcing and zero-forcing SIC receiver's derived assuming equivalent transmission rates for all users considering both perfect and imperfect channel state knowledge.

For the case of downlink transmission with low resolution DACs, [25] analysed the Energy Efficiency of hybrid precoders with DACs quantized depending on additive quantization noise and used a sub-optimal strategy to develop an optimal hybrid precoder using additive quantization noise model. It also compares the performance of hybrid precoders with a full or partially connected phase-shifting network made up of active or passive phase-shifters to quantized digital precoders. A single user MIMO system quantized model depending on an AQN approximation considering total power consumption used to analyze energy and spectral efficiencies of transmit precoding techniques.

In [26] the issue of downlink precoding for a narrowband Massive MIMO system with low-resolution digital-to-analog converters at the base station analysed. Linear precoders' performance, like zero-forcing and maximal-ratio transmission investigated, subject to quantization and a number of non-linear precoders proposed based on optimal MMSE downlink precoding problem. Closed-form approximation on the rate achievable under such coarse quantization derived using Bussgang's theorem. It was shown that nonlinear precoding algorithms significantly outperform the linear quantized methods for 1-bit DACs by approximating the optimal precoding problem. The results although focused on low-order modulation schemes like QPSK.

In [27] the performance higher-order modulation techniques such as 8-PSK or 16-QAM investigated for massive MU-MIMO downlink systems with 1-bit DACs. Low-complexity nonlinear precoding algorithms, combined with channel-estimation algorithms at the user equipment introduced that achieve low error rates. The results showed that higher-order constellations enable reliable transmission and they can be transmitted effectively with nonlinear precoding algorithms which significantly outperform linear quantized methods.

In [28] spectral and energy efficiency of digital and hybrid beamforming in multi-user scenarios compared with a large number of antennas considering the effects of channel estimation, transmitter impairments and multiple simultaneous users. As the analog front-end of the receiver becomes very power hungry, hybrid and digital beamforming with low resolution Analog to Digital Converters are the two main techniques for reducing power consumption ADCs. It is shown as the SNR increases, the ADC resolution required to achieve optimal energy efficiency increases. It is also shown if different ADC resolutions are used the desired trade-off between power consumption and rate achieved close to those achieved with only one ADC resolution.

From the reviewed literatures researches done on low resolution ADCs in the uplink with different techniques like, using zero forcing among linear precoders and Hybrid and Digital beamforming comparison for spectral and energy efficiency. On the down link for low resolution DACs different techniques are used. First, for SU MIMO system fully and partially connected hybrid precoder performance compared. Then others work on MU massive MIMO systems, Digital beamforming using RF chain selection technique with low resolution DAC also some others on low order modulation techniques for low resolution 1-bit DAC.

Unlike those works this thesis focus on low resolution DAC relative to threshold capacity and the improvement of energy efficiency with this compared to without DAC resolution. Hybrid and digital beamforming are applied and their performance compared depending on low resolution DACs. In addition to applying these beamforming techniques with low resolution DACs, higher order modulation techniques is used to enhance the capacity and spectral efficiency of the system. So achieving energy and spectral efficiency is the overall goal that needs to be achieved.

CHAPTER THREE

3 SYSTEM MODEL

In this thesis different related literatures reviewed from different journals, IEEE papers and books on 5G technologies focusing on Massive MIMO, beamforming techniques and RF chain components particularly on DAC. Depending on these literatures and having the statement of problem, in order to achieve the desired objectives the following methodologies are designed:

1) System model and different mathematical formulation
   - Mathematical model for calculating DAC power consumption
   - Mathematical model for total power consumption of Hybrid and Digital Beamforming
   - Prepare Mathematical model for calculating capacity, energy efficiency and spectral efficiency
2) Use flow chart for DAC resolution
3) Identify Input parameters for the simulation
4) Perform simulation using MATLAB R2018a
   - Simulation for energy efficiency analysis of DAC resolution for both Hybrid and Digital Beamforming.
   - Simulation for energy efficiency analysis using Modulation for both Digital and Hybrid beamforming and spectral efficiency analysis through modulation.

3.1 System model and Mathematical Formulation

Considering the downlink of a single-cell Massive MIMO system where K single-antenna user terminals served by a base station having an array of $\mathrm{N_t}$ antennas. In Hybrid beamforming Base station antennas are much greater than the number of users, i.e. $N_t \gg K$

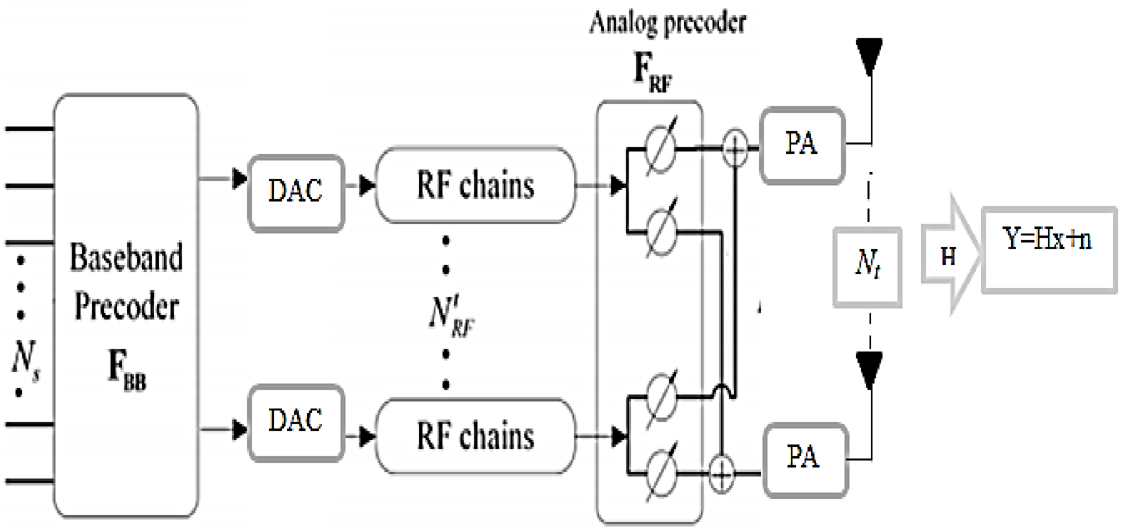

Figure 3.1 Fully connected Hybrid beamforming [29]

Base station is equipped with N_t transmitting antennas, transmit N_S data streams. Figure3.1 shows hybrid beamforming where, *N*s data symbols streams are sent which are denoted by the vector $s = [s_{1,\ldots}s_{Ns}]^{T}$ at the transmitter. They are assumed to be independent and Gaussian distributed with zero mean and unit variance, hence their covariance matrix is

$$Rss = E[s^H s] = \frac{I_{Ns}}{N_S} \tag{3. 1}$$

The number of RF chains at the transmitter, N^t_{RF} and the condition $N_S \leq N^t_{RF} \leq N_t$ followed. First the transmitted symbols are processed by $\mathbf{F_{BB}}$ digital baseband precoder with dimension, $N^t_{RF} \times N_S$ and $\mathbf{F_{RF}}$ Analog precoder with dimension $N_t \times N^t_{RF}$. After the analog precoding, each phase shifter is connected to each antenna element of the sub array and each data stream is transmitted using the corresponding sub array.

3.1.1 Quantized signal model

For downlink Massive MIMO, at the transmitter side the Digital signal converted to analog domain using Digital to Analog converters (DACs). A linear model approximation for the quantization noise of the DACs is assumed [5]. Given that $Q(u_i)$ denotes a uniform scalar quantizer then for the *i*-th RF chain we have,

$$Q(u_i) = \sqrt{1 - \rho bi}u + \epsilon_i \tag{3. 2}$$

Where, $\rho bi = \frac{\pi\sqrt{3}}{2} 2^{-2bi}$ is the quantization distortion parameter for bit resolution equal to *bi*. The input *u* is assumed to be Gaussian distributed, ϵi is the quantization noise uncorrelated with u, and $\epsilon i \sim N(0; \sigma\epsilon^2)$. Extending our formulation to the MIMO case we have,

$$Q(u) \approx cu + \epsilon \tag{3. 3}$$

Where, c is a diagonal matrix with values depending on the DAC resolution of each RF chain, while $\epsilon \in CN(0; \sigma^2\epsilon I)$. Let us define the linear approximation of the quantizer as $z \in C^{N_{RF}^t \times 1}$, and

$$z = cu + \epsilon \tag{3. 4}$$

This leads us to the following transmitted signal, $\mathbf{x} \in C^{Nt\times 1}$

$$x = F_{RF}\, z = F_{RF}(cu + \epsilon) = F_{RF}\, cu + F_{RF}\, \epsilon = F_{RF}\, c\, F_{BB}\, s + F_{RF}\epsilon \tag{3. 5}$$

The received signal can now be expressed as follows:

$$Y = Hx + n = HF_{RF}\, c\, F_{BB}\, s + HF_{RF}\epsilon + n \tag{3. 6}$$

Where, $Y = [y_1, y_2, \ldots, y_{Nr}]^T$ is received signal , n ~ $CN(0, I\, N_r)$ is the additive white gaussian noise vector affecting the received signal, and the channel matrix denoted by $H \in C^{Nr\times Nt}$. perfect channel state information of channel matrix is assumed, because the focus is on the design of Hybrid beamforming with low-resolution DACs.

3.2 Power Consumption Modelling

3.2.1 Total power consumption for Hybrid Beamforming

The total power consumption of fully connected architecture of hybrid beamforming is given by;

$$P_{tot}(HB) = P_{LO} + P_{PA} + N_{RF}N_tP_{PS} + N_{RF}(2P_{DAC} + P_{RF}) \tag{3. 7}$$

Where $\mathbf{P_{DAC}} = \boldsymbol{c_1 f_t b + c_2 2^b}$ is the power consumption of DACs, where b is the resolution of DACs or the number of bits, $c_1 = 9\times10^{-12}$ express the coefficient of static power consumption, c_2=1.5×10^{-5} is a coefficient of dynamic power consumption, and f_t is sampling frequency at the transmitter [25]. P_{LO}, P_{PA}, P_{PS}, P_{RF} denote power consumption of local oscillator, power amplifier, phase shifter, single RF chain respectively.

$$p_{PA=}\ \frac{p_{tx}}{\eta} \quad (3.8)$$

Where $p_{tx}$is the transmitted signal and η is the power amplifier efficiency

$$P_{RF} = 2P_M + 2P_{LF} + P_{HB} \quad (3.9)$$

Where, P_M is mixer power, P_{LF} is low pass filter power and P_{HB} is hybrid with buffer power.

We can compare the total power consumption of Digital beamforming with Hybrid beamforming as follows.

3.2.2 Total power consumption for Digital Beamforming

Digital beamforming total power consumption given by the formulation given below;

$$P_{tot}(DB) = P_{LO} + P_{PA} + N_t(2P_{DAC} + 2P_M + 2P_{LF} + P_{HB}) \quad (3.10)$$

Where, P_{LO} denotes power consumption of local oscillator and P_{PA} is power consumption of power amplifier. $\mathbf{P_{DAC}} = \boldsymbol{c_1 f_t b + c_2 2^b}$ is the power consumption of DACs. P_M,P_{LF} , P_{HB} is mixer power, low pass filter power and hybrid with buffer power respectively.

In Digital Beamforming, total power consumption formulations don't include the number of RF chain since the number of RF chains and numbers of Antennas are equal. While Hybrid Beamforming considers the number of RF chain, which are smaller than the number of antenna. Hybrid Beamforming have lower power consumption relative to digital since they have reduced number of RF chain.

3.3 Energy Efficiency formulation

Energy Efficiency is defined as a ratio of the total transferred bits or capacity to the total power consumption. It is evaluated as

$$EE = \frac{Capacity}{\text{Ptot}} \quad (3.11)$$

Where,

$$C = B * log_2[1 + SINR] \quad (3.12)$$

$$SINR = \frac{Ptx}{I + N_O * B} \tag{3. 13}$$

The interference supressed by the beamforming, then signal- to noise ratio can be defined as;

$$SNR = \frac{Ptx}{N_O * \mathrm{B}} \tag{3. 14}$$

Let B be the system bandwidth, P_{tx} is transmitting power, N_0 is noise power spectral density.

Then the ergodic capacity of the random MIMO channel is given by,

$$C = B[log_2 \det\{I_{NR} + \frac{SNR}{N_T} HH^H\}] \tag{3. 15}$$

Where, B, det and $I_{NR}$are the bandwidth for each user, the determinant of a matrix, and identity matrix respectively. H^H, denotes conjugate transpose of matrix H, H is $N_R \times N_T$ channel matrix and it can be decomposed as,

$$\mathrm{H}=\begin{bmatrix} h_{1,1} & h_{1,2} & \dots & h_{1,NT} \\ h_{2,1} & h_{2,2} & \dots & h_{2,NT} \\ \dots & \dots & \ddots & \dots \\ h_{NR,1} & h_{NR,2} & \dots & h_{NR,NT} \end{bmatrix} \tag{3. 16}$$

Considering, the total power equation 3.7 for hybrid Beamforming and equation 3.10 for digital Beamforming Energy Efficiency Hybrid and Digital Beamforming can be obtained respectively.

3.4 Spectral Efficiency formulation

Spectral Efficiency is the ratio of data rate or capacity per a given bandwidth. It's the capability of a given channel encoding techniques to utilize bandwidth efficiently.

Via Shannon's formula, then Spectral Efficiency (b/s/HZ) can be found

$$SE=log_2(1+SNR) \tag{3. 17}$$

Where, $SNR = \frac{Ptx}{N_O * \mathrm{B}}$

The downlink ergodic channel capacity of the user equipment lower bounded by [31]

$$SE = log_2 det\{I_{NR} + \frac{SNR}{N_T} HH^H\} \quad (3.\ 18)$$

Using the relationship between Spectral and Energy Efficiency shown below, spectral efficiency for Hybrid and Digital beamforming can be found.

3.5 Spectral Efficiency - Energy Efficiency relationship

The relation between spectral energy and energy efficiency is shown below using the following formulations.

Energy Efficiency is number of bits per unit time for the given total power consumption. While spectral efficiency is the capacity of the system for the given bandwidth

$$EE = \frac{Capacity}{Ptotal} \quad (3.\ 19)$$

$$SE = \frac{Capacity}{B} \quad (3.\ 20)$$

Where,

$$Capacity = EE \times Ptotal = SE \times B \quad (3.\ 21)$$

$$EE = SE \times \frac{B}{Ptot} \quad (3.\ 22)$$

$$SE = EE \times \frac{Ptot}{B} \quad (3.\ 23)$$

3.6 Digital Modulation

Higher capacity of information, faster system availability with better quality communication, privacy and security features provided by digital modulation schemes. Hence, digital modulation techniques are in greater demand, than analog modulation techniques due to their ability to convey larger amounts of data [32]. Digital communication scheme modulation order is determined by the number of the different symbols that can be transmitted using it. M-ary transmission is a type of digital modulation in which two or more bits are communicated simultaneously instead of one at a time.

Using this modulation techniques capacity of the system obtained by;

$$capacity = B \log_2 (1 + (\log_2 M) \times SNR)$$

Where, M is array of modulation.

The energy efficiency obtained with this capacity through modulation is higher as larger capacity helps to achieve higher energy efficiency.

3.7 Flow chart description

The flow chart below shows how the DAC resolution reduces depending on some threshold capacity. To find the threshold capacity, First path loss for the given free space model calculated in order to obtain the minimum received power which is found at the cell edge. Then using the minimum received power the corresponding minimum SNR value calculated through the formulations below. Free space path loss is the loss in signal strength of a signal as it travels through free space.

$$FSPL = \frac{P_t}{P_r} = \left(\frac{4\pi R}{\lambda}\right)^2 \quad (3.24)$$

or

$$FSPL(dB) = 20\log(R) + 20\log(f) + 32.44 \quad (3.25)$$

Where, R is distance of the receiver from the transmitter (km), f is frequency (MHz), P_t is transmit power and P_r is received power, wavelength of the RF carrier $\lambda = \frac{c}{f}$ over a distance R. The minimum received power calculated as,

$$pr_{min} = pt\left(\frac{\lambda}{4\pi \mathrm{R}}\right)^2 \quad (3.26)$$

Then

$$SNR = \frac{pr_{min}}{N_O * \mathrm{Bw}} \quad (3.27)$$

Then threshold capacity calculated as,

$$C_{threshold} = B[log_2(1 + \mathrm{SNR})] \quad (3.28)$$

After obtaining the threshold capacity the DAC accept some random number of digital bit and DAC capacity calculated using that bit for the given period of time. Then the obtained capacity of DAC compared with the threshold capacity. If the DAC capacity is greater than or equal to the threshold it results in wastage of capacity so the number of bit has to be reduced by using low the resolution DAC. The number of bits reduced up to threshold capacity. This process on the right side of the flow chart used to minimize power consumption of DAC through low resolution DAC. The relation between power consumption of DAC and number of bit found by equation $\mathbf{P_{DAC}} = \boldsymbol{c_1 f_t b + c_2 2^b}$ as shown previously and this right side of the flow chart is used to achieve energy efficiency with reduced number of bit. The decrease in the total power consumption relative to the capacity decrease by reducing resolution is higher so that energy efficiency enhanced up to threshold.

On the left side of the flow chart, if the capacity of DAC is less than or equal to threshold capacity, resolutions isn't needed and higher order modulation is done to enhance the capacity of the system. When the capacity of DAC is lower than threshold capacity outage will occur so, modulation is used to solve this by increasing capacity. Then total power calculated and energy efficiency of the system obtained by the ratio of capacity enhanced through modulation to the total power. Spectral efficiency is also calculated using capacity obtained by modulation. Capacity by modulation is calculated as;

$$C_{M=}C_{DAC} \times \log_2 M \tag{3. 29}$$

Where, C_M-Capacity with modulation, C_{DAC-} Capacity of DAC and M=symbol

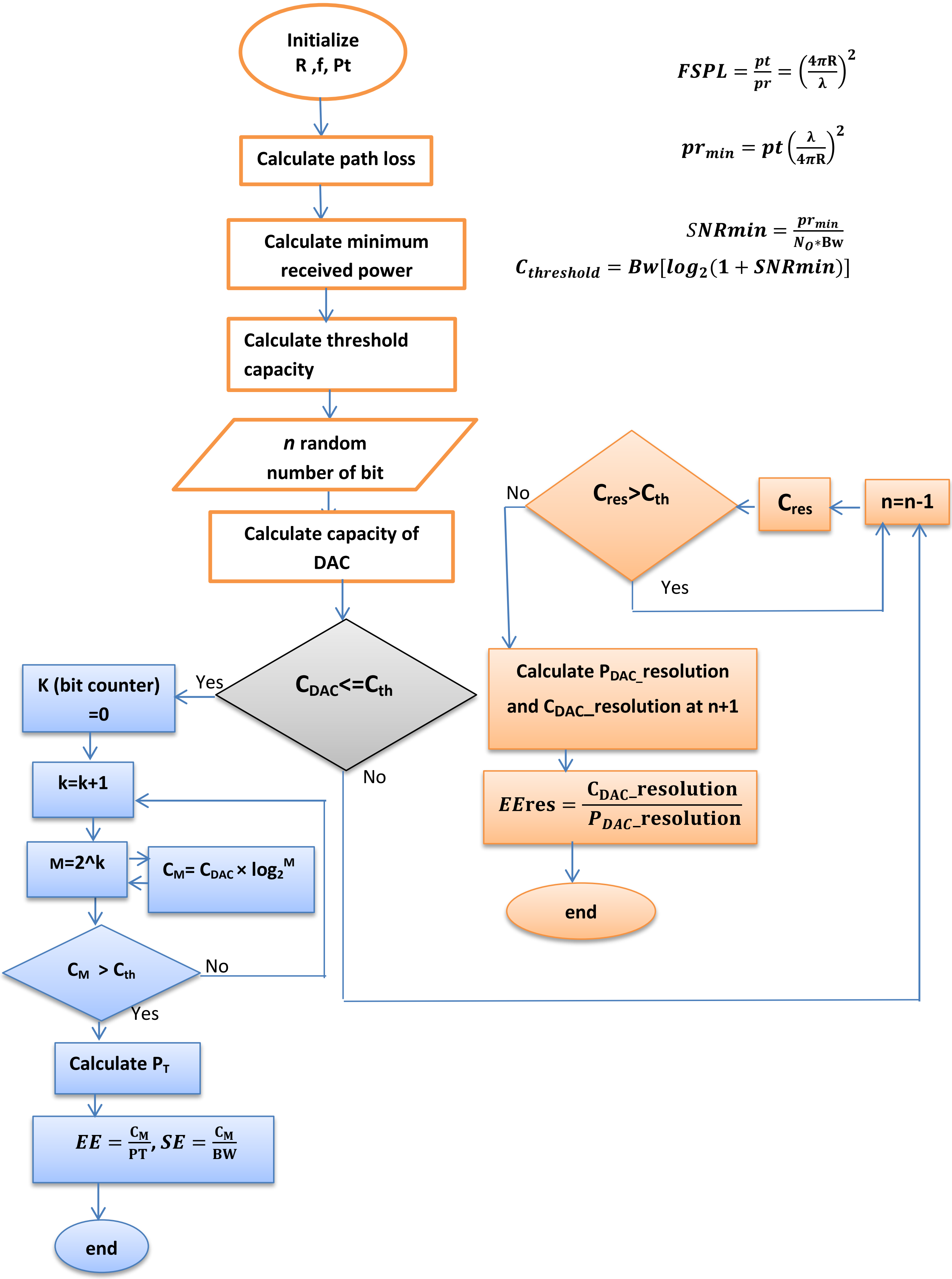

Figure 3.2 Flow chart for DAC resolution

Table 3.1 Simulation in put parameters

Input Parameters	Value
Number of transmit antenna	128
Number of users	20
number of RF chain	15
Transmit power	3 watts
power of local oscillator	0.0225 watts
phase shifter power consumption	0.0216 watts
Power due to mixer	0.0003 watts
Power due to filter	0.014 watts
Power of Hybrid with Buffer	0.003
Bandwidth	10 MHz
static power consumption coefficient	9×10^(-12)
dynamic power consumption coefficient	1.5×10^(-5)
Noise signal	$9\times10{-}8\ J/s$
sampling rate	1×10^9 Hz
power amplifier efficiency	0.48

CHAPTER FOUR

4 RESULTS AND DISCUSSIONS

In this section simulation results are shown to achieve energy and spectral efficiency for single cell downlink Massive MIMO. Hybrid and Digital beamforming performance also compared. The results are simulated using MATLAB software. The transmitter antenna considered to have 128 antennas, 20 users and the number of radio frequency chain, $N^t_{RF=}15$ as per the simulation in put parameters. For hybrid beamforming the number of RF chain is smaller than the number of antenna and for digital beamforming there are equal number of RF chains and number of antennas.

4.1 Plotting of number of bit for DAC power consumption and Energy Efficiency

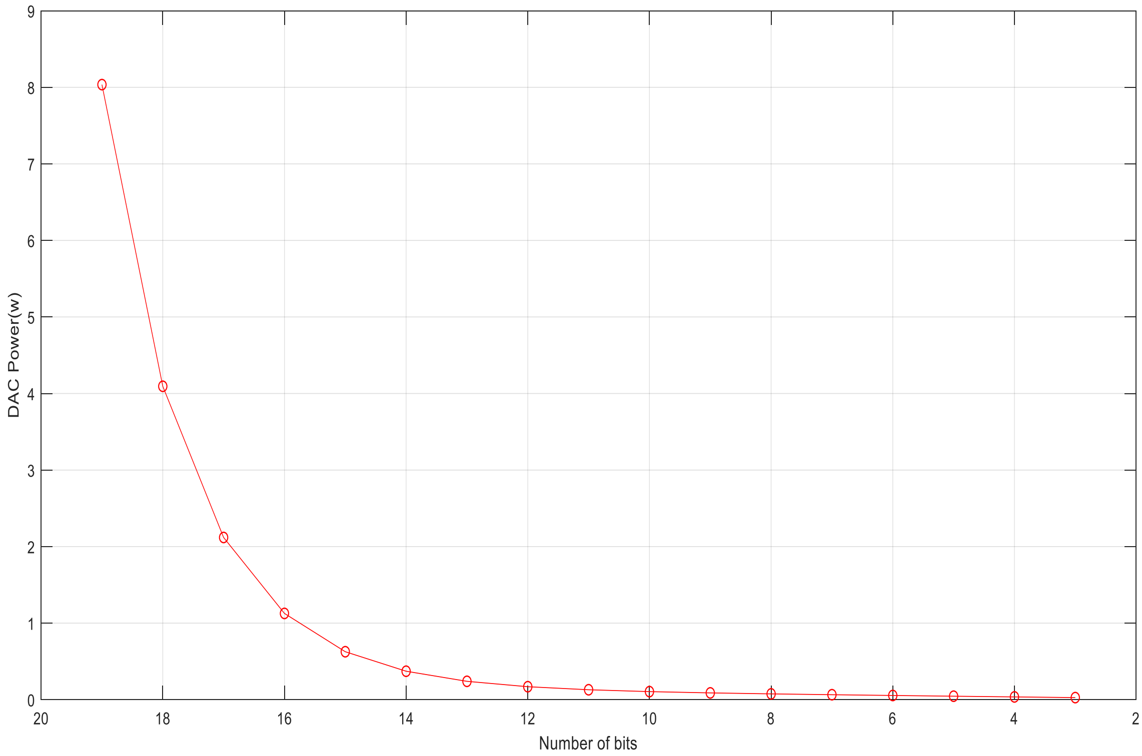

Figure 4.1 power consumption of DAC vs. number of bits

The relation between number of bits and power consumption of DAC is shown in Figure 4.1 for low resolution DAC, with reduced the number of bit the power consumption of DAC is minimized. As the number of bits reduce in the x axis, the DAC power consumption decay exponentially. Since DAC is one of the most power consuming radio frequency chain component minimizing its power consumption through resolution contributes to total power consumption reduction in Massive MIMO system.

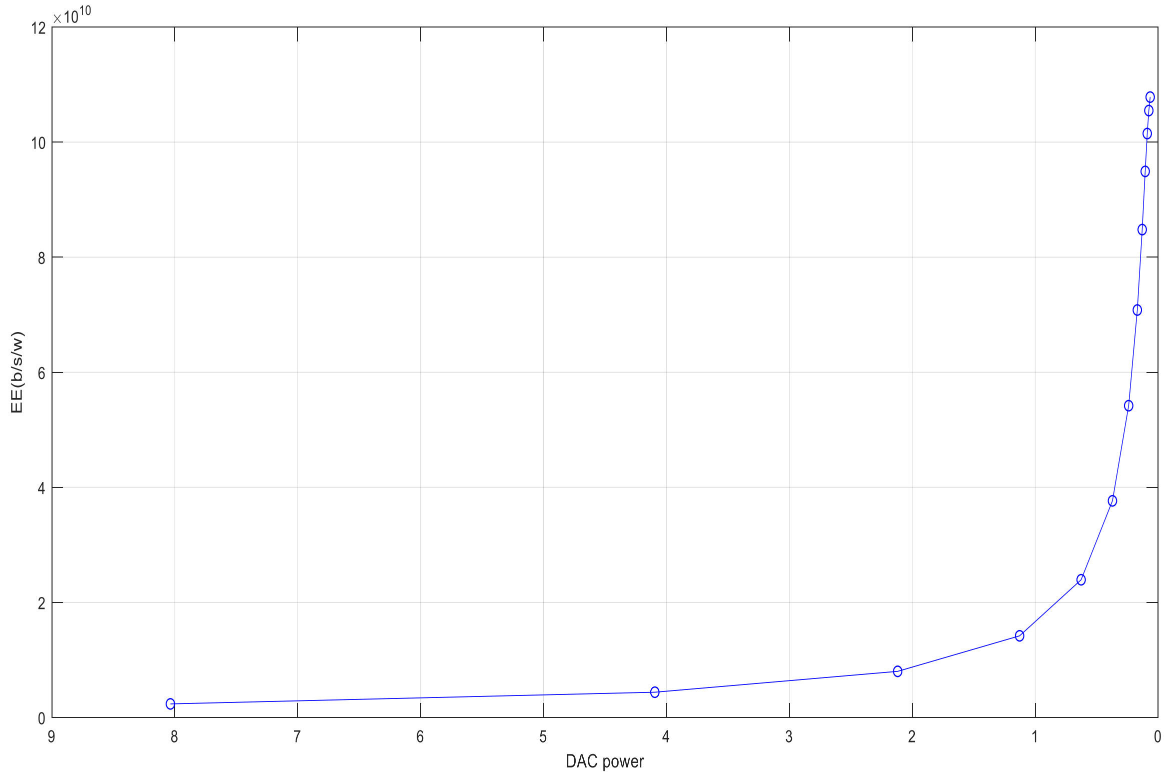

Figure 4.2 Energy efficiency vs. DAC power consumption

The relation between DAC power consumption and energy efficiency is illustrated in figure 4.2. As the power consumption of DAC decrease through resolution, the energy efficiency increases exponentially.

Table 4.1 Number of bits, power consumption of DAC, Energy Efficiency

No. of bits	DAC power(watt)	Energy Efficiency(b/s/w)
18	4	0.4
14	0.4	0.65
8	0.1	6
4	0.001	9

Table 4.1 shows as the effect of reducing the number of bit on power consumption of DAC and Energy Efficiency. Reducing the resolution of DAC by minimizing the numbers of bits decreases the DAC power consumption. When DAC power consumption declines

energy efficiency increases. As shown in the table, when number of bits decrease from 18 to 4, DAC power also decrease from 4 to 0.001watt and energy efficiency enhance from 0.4 b/s/watt to 9 b/s/watt.

4.2 Total power with DAC resolution for Hybrid and Digital beamforming

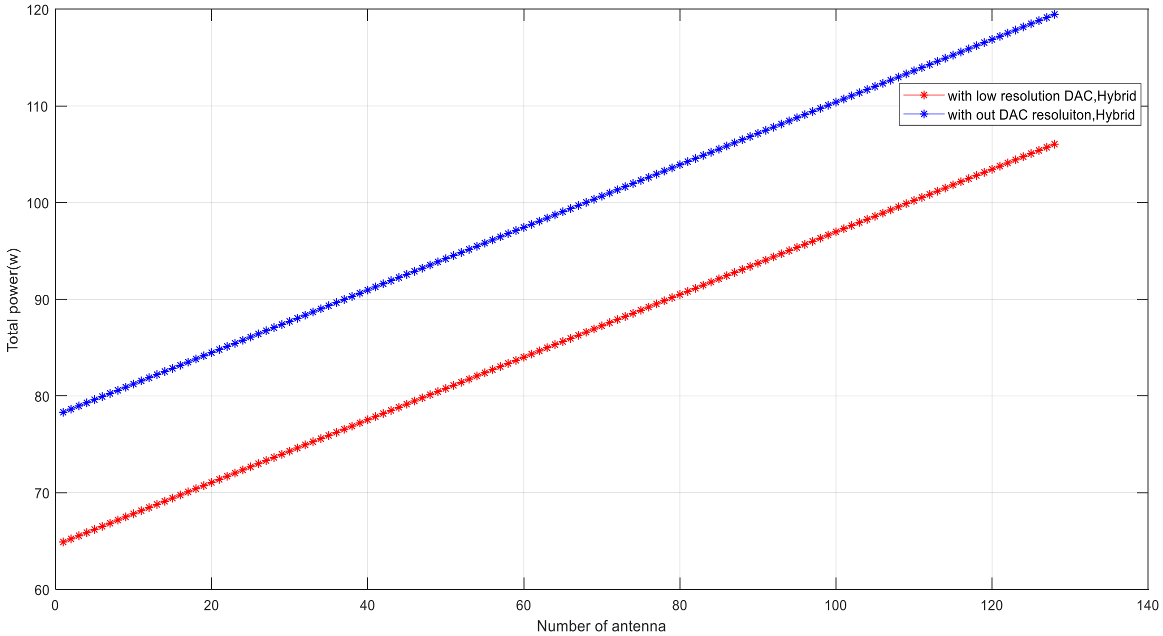

Figure 4.3 Number of antenna versus total power consumption with low resolution DAC and without resolution, Hybrid beamforming

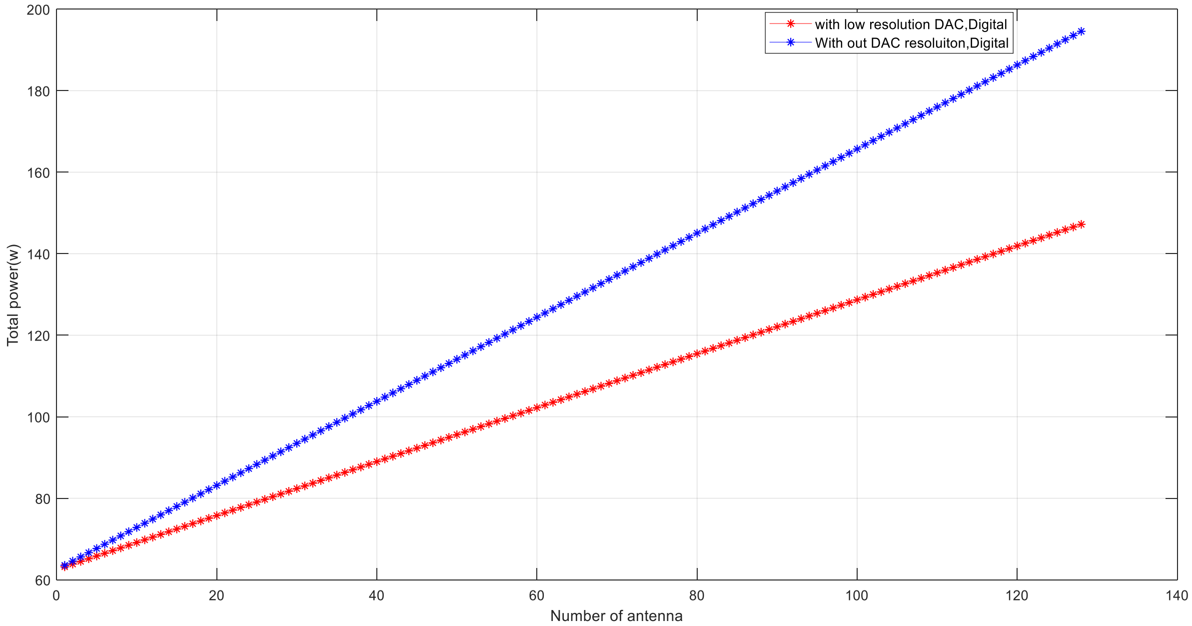

Figure 4.4 Number of antenna versus total power for resolution and without resolution, Digital beamforming

Figure 4.3 shows the effect of resolution on the total power consumption for hybrid beamforming for increasing number of antenna. With low resolution DAC the total power consumption is lower. Since DAC is one of the main power consuming RF chain components, reducing its power consumption helps in reduction of total power as the result energy efficiency can be enhanced. But taking without resolution case the total power consumption is much higher. For both case the total power consumption is increasing linearly with the number of antennas.

The relation between number of antenna and total power consumption with low resolution and without resolution for digital beamforming is illustrated in figure 4.4. As the number of antenna increase total power also increase linearly for both cases. Both low resolution DAC and without resolution cases start at nearly the same power consumption. But as the number of antenna increase power consumption of without DAC resolution dominates low resolution. The power consumption for low resolution DAC is low and this in turn reduces the total power consumption.

Table 4.2 comparison of total power for low resolution DAC and without DAC resolution considering Hybrid and Digital beamforming: users, K=20

Number of Antennas	Total power(watt)			
	Hybrid beamforming		Digital beamforming	
	With low resolution DAC	Without DAC resolution	With low resolution DAC	Without DAC resolution
40	77	91	89	103.8
80	90	104	115.4	145
120	102	117	142	186.3

Table 4.2 shows total power consumption for low resolution DAC and Without resolution considering hybrid and Digital Beamforming with increasing number of antenna particularly taking 40,80,120 antennas. As the numbers of antenna increase total power consumption also increase but low resolution DAC have lower power consumption than without resolution case for both hybrid and digital case.

4.3 Energy Efficiency with DAC resolution for hybrid and digital beamforming

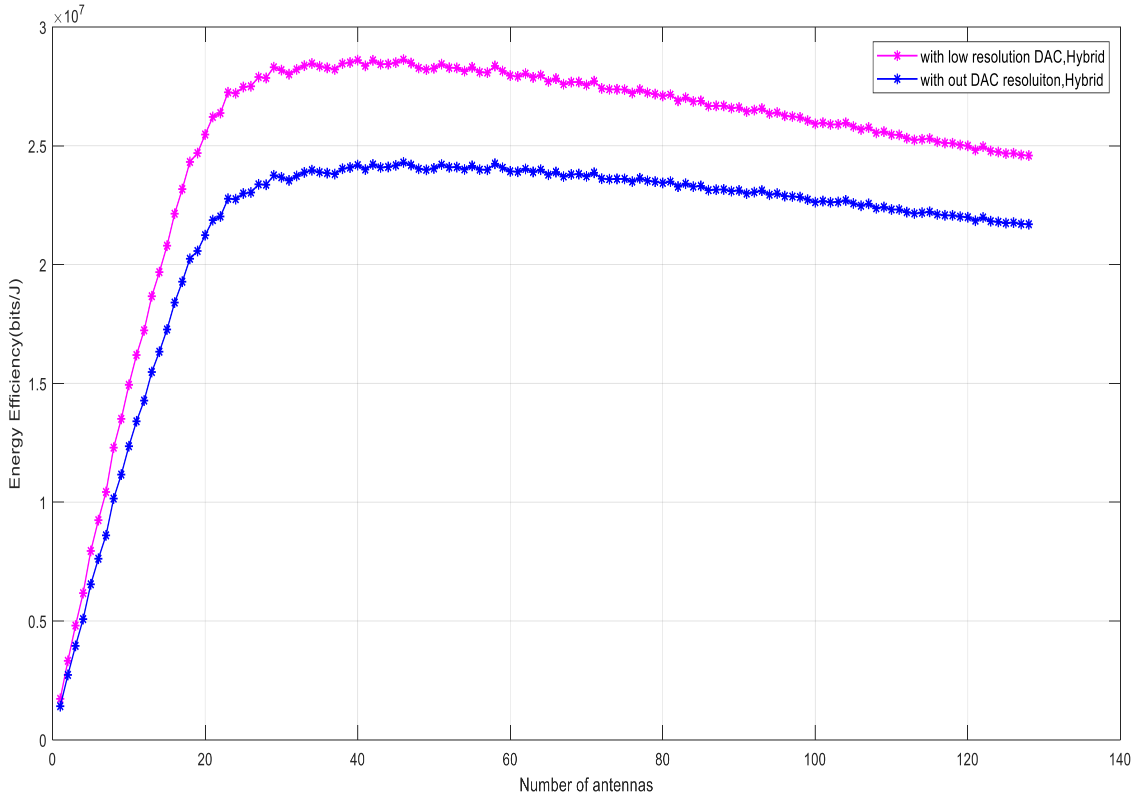

Figure 4.5 Number of antenna versus Energy efficiency for resolution and without resolution, hybrid beamforming

The relation between energy efficiency and number of antenna considering the low resolution DAC and without resolution cases are shown in figure 4.5. As the number of antenna increase the energy efficiency also increase up to peak point then decline. When considering low resolution DAC the energy efficiency became higher than without resolution and comparing the peak Energy Efficiency with low resolution DAC 28.7 Mbits/J while without resolution 24.3 Mbits/J even if the peak point starts to decline after some point. Relative to the capacity increase the total power consumption is much higher as the number of antennas increase which is the reason for energy efficiency to decline after some point since energy efficiency is the ratio of capacity to total power.

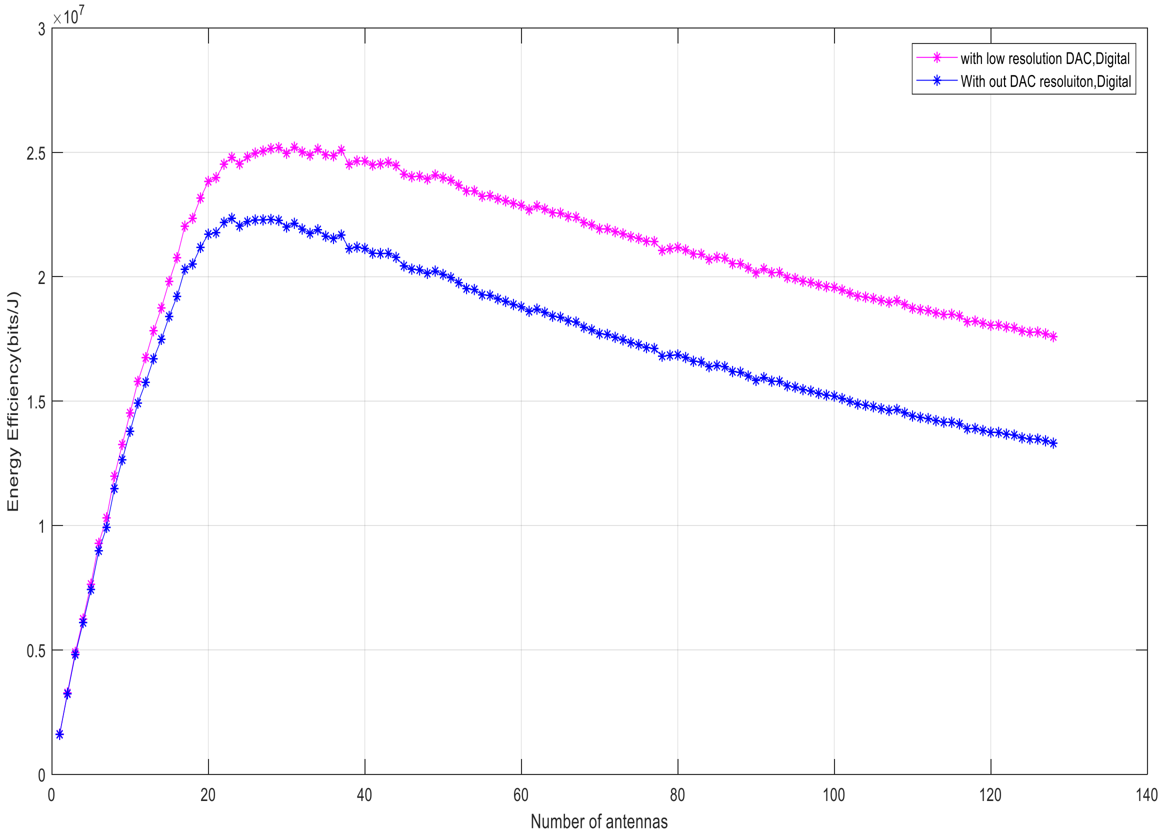

Figure 4.6 Number of antenna versus Energy efficiency for resolution and without resolution, Digital beamforming

Considering digital beam forming, the relation between energy efficiency and number of antennas with low resolution DAC and without resolution case is shown in figure 4.6 Energy efficiency increase as the number of antenna increase up to peak point and then decline, when considering low resolution DAC the energy efficiency became higher than without resolution. Comparing the peak Energy Efficiency, low resolution DAC have 25.3 Mbits/J and without resolution 22.5 Mbits/J. In Digital beamforming the energy efficiency decline rapidly after the peak point relative to hybrid beamforming for both low resolution DAC and without DAC resolution.

Table 4.3 comparison of Energy Efficiency for low resolution DAC and without DAC resolution considering Hybrid and Digital beamforming: users, K=20

Number of Antennas	Energy Efficiency (Mb/J)			
	Hybrid beamforming		Digital beamforming	
	With low resolution DAC	Without DAC resolution	With low resolution DAC	Without DAC resolution
40	28.6	24.2	25	21.3
80	27.2	23.5	21.1	16.8
120	25	22	18	13.7

Energy Efficiency for increasing numbers of antenna taking 40, 80,120 antennas for low resolution and without resolution DAC, hybrid and Digital cases is shown in Table 4.3. As the numbers of antenna increase Energy Efficiency decreases after attaining peak point. But low resolution DAC achieves higher energy efficiency relative to without DAC resolution for both digital and hybrid Beamforming.

Table 4.4 comparison of Energy Efficiency and total power with low resolution DAC and without resolution for Hybrid and Digital beamforming (Number of antenna, NT=128 and users, K=20)

	With low resolution DAC		Without DAC resolution	
	Hybrid beamforming	Digital beamforming	Hybrid beamforming	Digital beamforming
Total power(watt)	105.5	147.2	119	194.5
Energy Efficiency (Mb/J)	24.5	17.6	21.6	13.4

From table 4.4 hybrid beam forming achieve higher energy efficiency with lower power consumption compared to Digital beamforming when applying low resolution DAC for the given same number of antenna and users. This is because hybrid beamforming is with lower number of RF chain than the number of antenna and applying DAC resolution to it reduce the more power than digital beamforming. Reducing the resolution up to threshold capacity helps to achieve more reduced power than the capacity decrease by applying lower resolution. So energy efficiency enhanced by applying lower resolution and relative to the digital beamforming more energy efficiency achieved with hybrid beam forming

4.4 Total power and Energy Efficiency with DAC resolution for users=10, 15

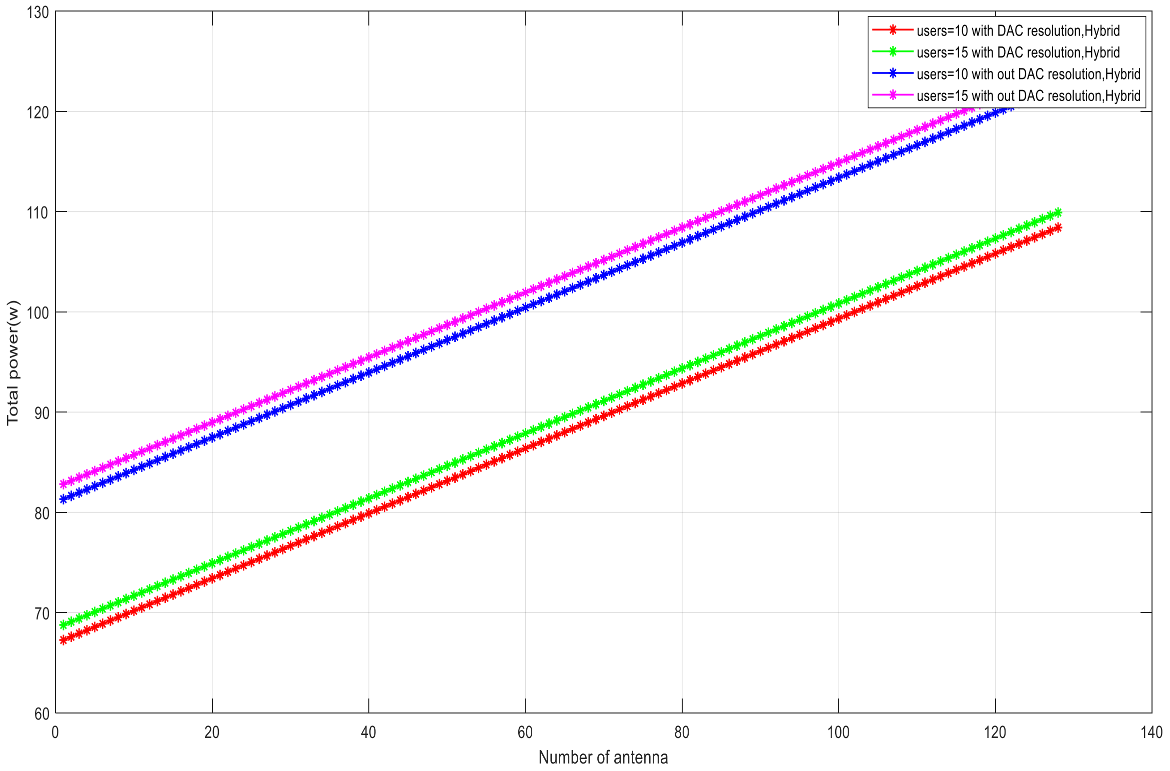

Figure 4.7 Number of antenna versus Total power for (users, K=10 and 15 with and without resolution of DAC) for Hybrid beamforming

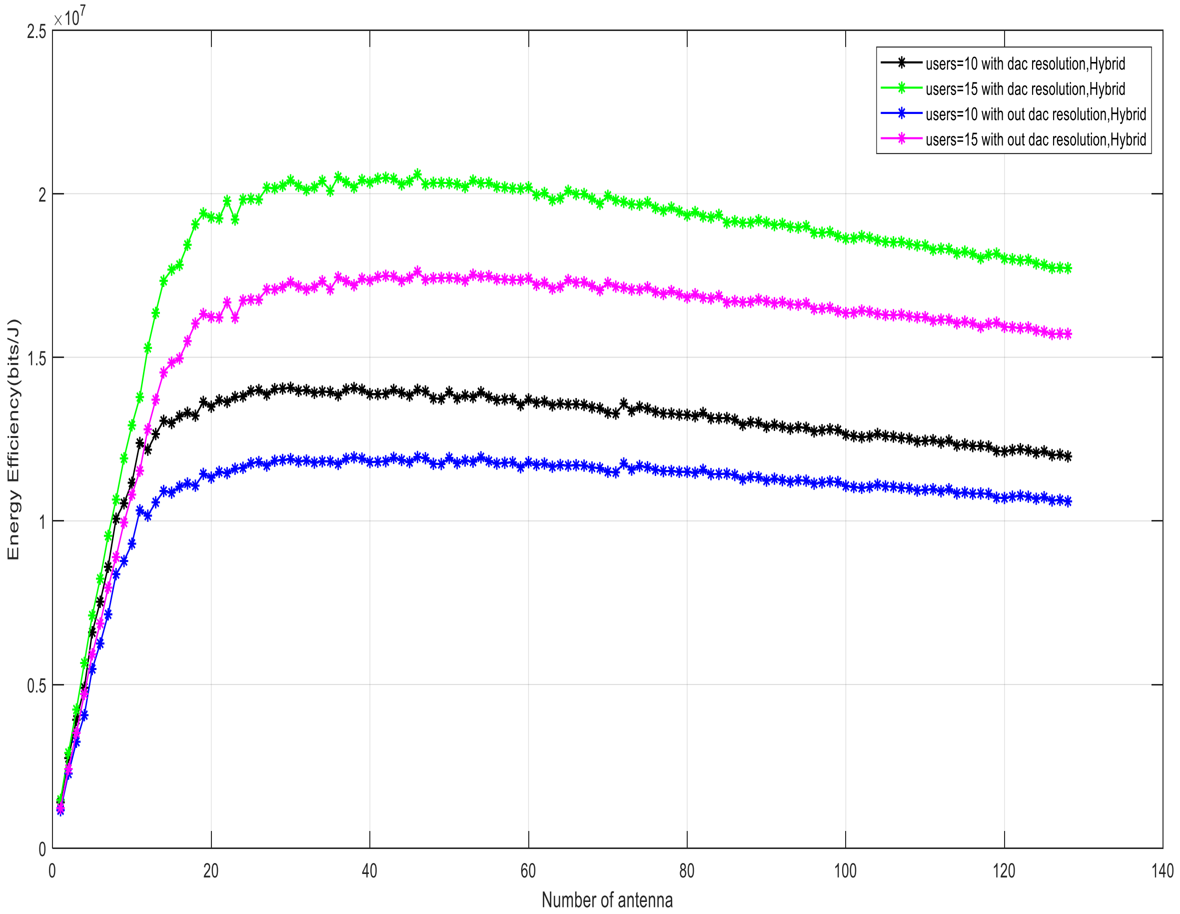

Figure 4.8 Number of antenna versus Energy Efficiency for (users, K =10 and 15 with and without resolution of DAC) for Hybrid beamforming

In the figure 4.7 total power consumption versus number of antenna for 10 and 15 users shown comparing the low resolution DAC and without resolution case considering hybrid beamforming. Total power consumption increase linearly with the number of antenna, while taking low resolution DAC the total power consumption is lower relative to without resolution and as the number of users increase there is higher total power consumption where 15 users consume more power than 10 users as shown in the simulation result.

Figure 4.8 shows the relation between number of antenna and energy efficiency with and without resolution of DAC for the given 10 and 15 users, as the number of antenna increase energy efficiency increase logarithmically and gradually decline after some point because of the increase in the total power relative to capacity is higher. With DAC resolution we achieve higher energy efficiency than without resolution and as the number of users increases the energy efficiency also increase. Total power consumption is reduced with low resolution DAC as shown in figure 4.7 which results in enhanced energy efficiency as total power and energy efficiency are inversely related.

Table 4.5 comparison of Energy Efficiency and total power with low resolution DAC and without resolution for (users, K=10, 15 and number of antenna, NT=128) for Hybrid beamforming

	With low resolution DAC		Without DAC resolution	
	K=10	K=15	K=10	K=15
Energy Efficiency (Mb/J)	12	17.8	10.6	15.7
Total power(watt)	108.4	110	122.5	124

Energy Efficiency improvement and the minimization of total power with low resolution DAC for the given number of users and antennas compared to without resolution is shown in Table 4.5. As the numbers of users increase from 10 to 15 both the power consumption and energy efficiency increases.

4.5 Capacity and spectral efficiency for users =10, 15, 20

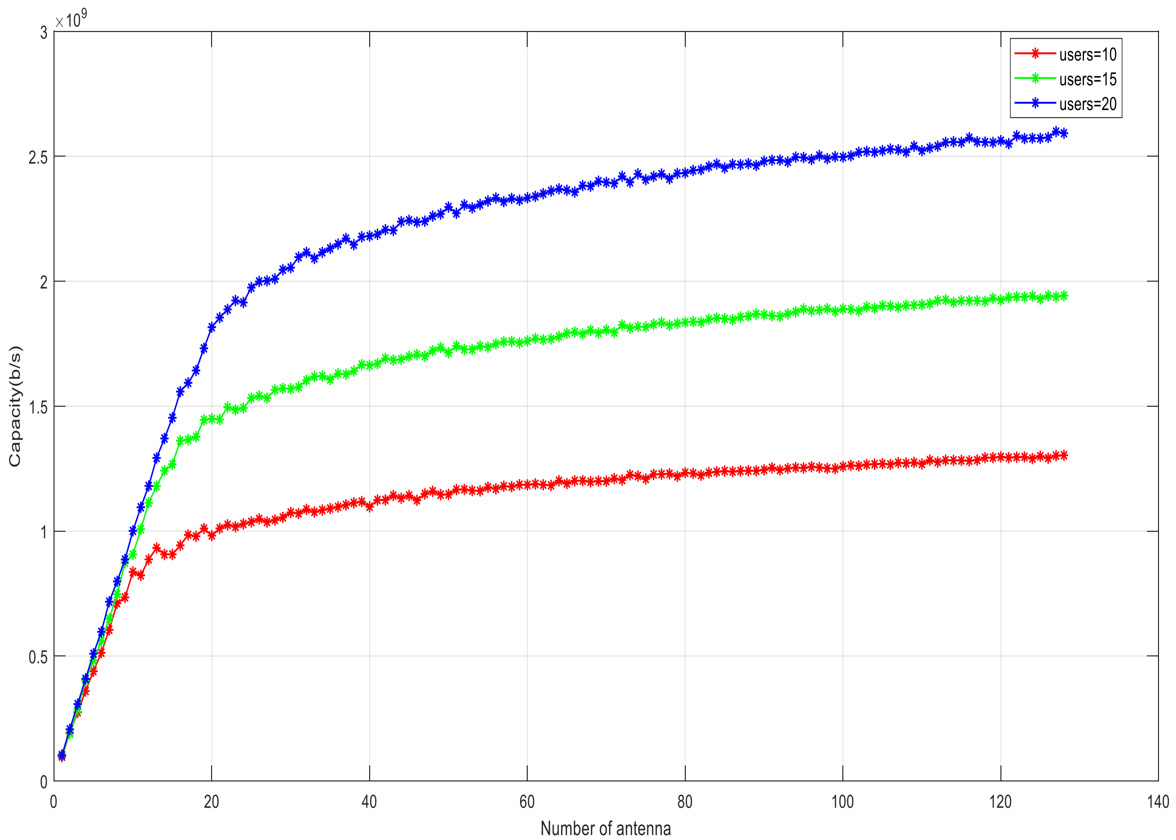

Figure 4.9 Number of antenna versus capacity for (K, users=10, 15, 20)

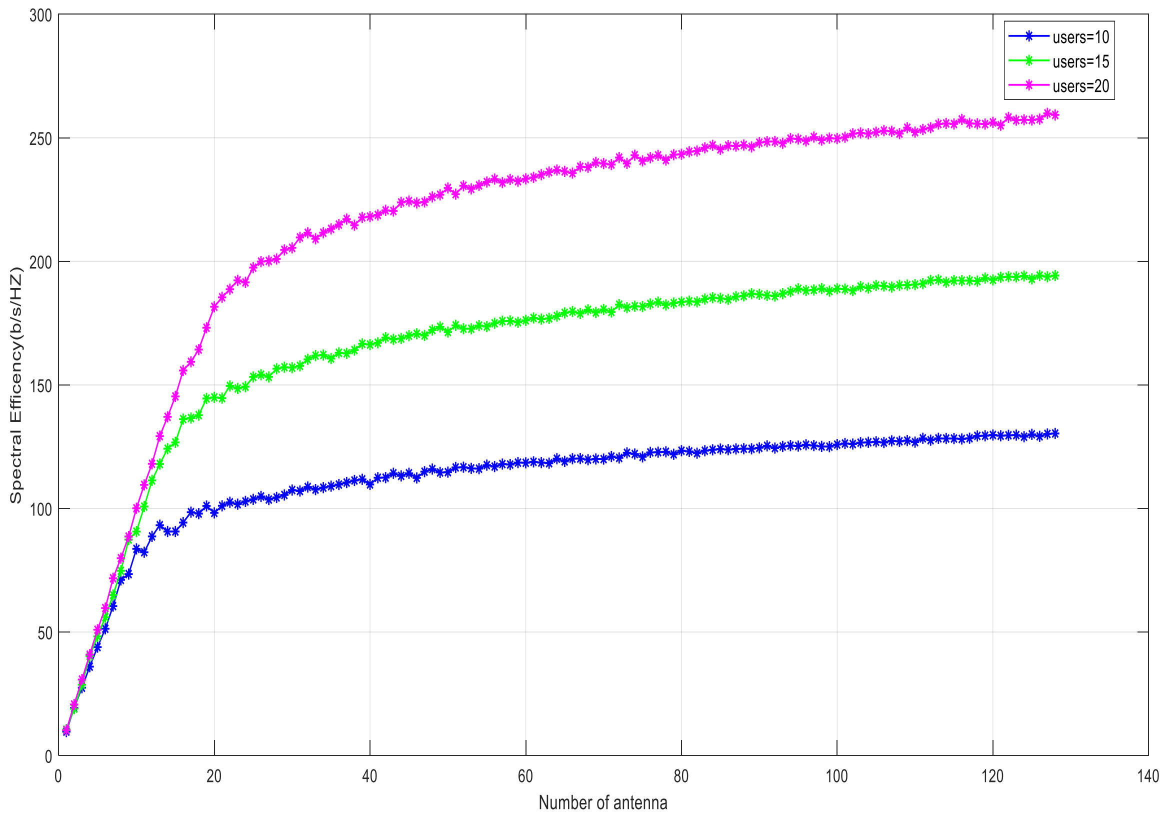

Figure 4.10 Number of antenna versus Spectral Efficiency for (K users=10, 15, 20)

The relation between capacity, spectral efficiency versus number of antenna for the given different number of user (K=10, 15, 20) shown in the figure 4.9 and 4.10 respectively. As the number of antenna increase capacity and spectral efficiency increase logarithmically. Spectral efficiency enhance as the by increasing the capacity of the system and as shown in these two figures.

Table 4.6 comparison of Capacity, total power, Energy Efficiency and Spectral Efficiency for Hybrid beamforming (users, K=10, 15, 20 and Number of antenna, NT=128)

Users, K	Capacity(Gb/s)	Spectral Efficiency (b/s/Hz)
10	1.3	130
15	1.93	193
20	2.58	258

Table 4.6 shows as the number of users increase both capacity and spectral efficiency increase for the given 128 antennas. Spectral efficiency is obtained from capacity since it is the ratio between capacity per the given band width. As given in the simulation

parameters bandwidth is 10MHz. Using this bandwidth and capacity for each user spectral efficiency is found. This spectral efficiency is used to show the trade-off between energy efficiency and spectral efficiency for low resolution DAC and without resolution which is shown in figure 4.11 below considering hybrid beamforming.

4.6 The trade-off between Energy Efficiency and Spectral Efficiency with DAC resolution for users=10, 15

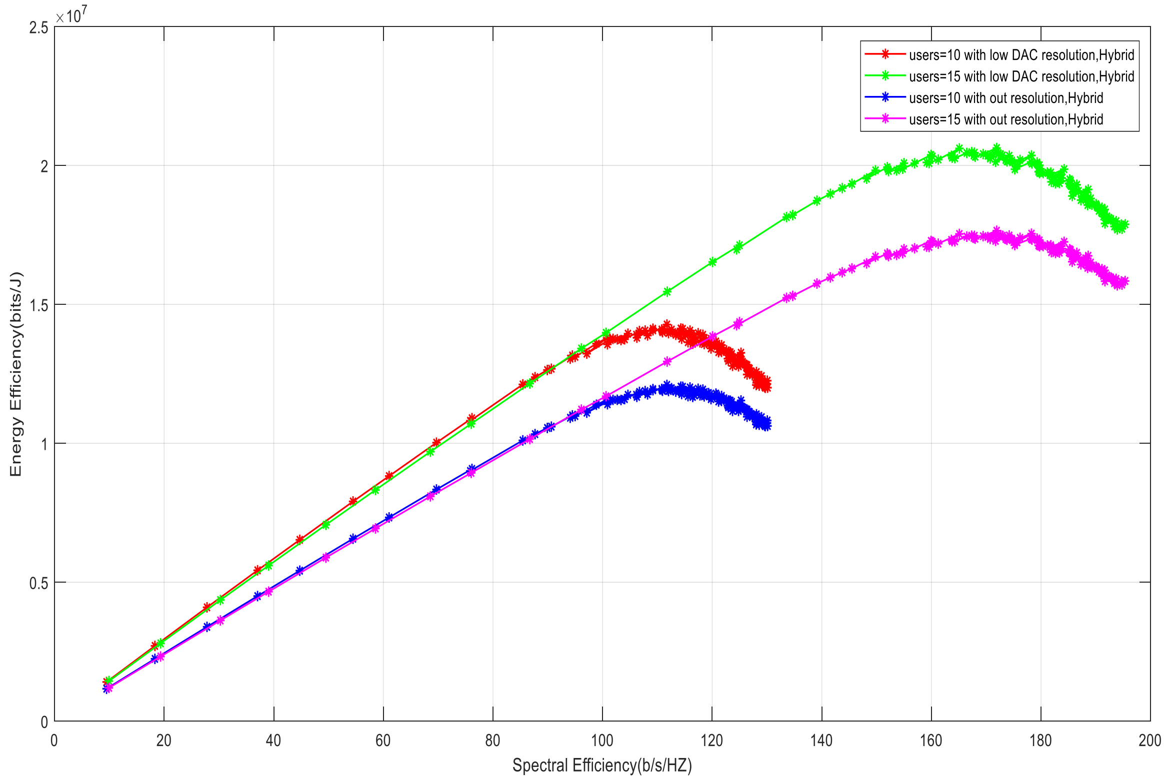

Figure 4.11 Spectral Efficiency versus Energy Efficiency for (users, K =10 and 15 with low and without resolution of DAC, NT=128) with Hybrid beamforming

The trade-off between Spectral and Energy Efficiency for the 10 and 15 users with and without DAC resolution is shown in the above figure 4.11 considering hybrid beamforming. As the spectral efficiency increase the energy efficiency increase up to some point and then decline for both case because in Massive MIMO as the number of antenna increasing the power consumption increases, which shows that the energy efficiency first increases and then decreases gradually after some point. Also with respect to the capacity the power increase is higher as the number of antenna increase so after some point the energy efficiency decreases.

Table 4.7 Energy Efficiency vs. Spectral Efficiency for low resolution and without resolution, using Hybrid beamforming, NT=128 (a) for K=10 users and (b) for K=15 users

Spectral Efficiency (b/s/Hz)	Energy Efficiency (Mb/J)	
	With low resolution DAC, K=10	Without DAC resolution, K=10
60	8.68	7.09
115	14.1	12
120	13.6	11.7
130	12.1	10.7

(a)

Spectral Efficiency (b/s/Hz)	Energy Efficiency (Mb/J)	
	With low resolution DAC, K=15	Without DAC resolution, K=15
60	8.5	7.09
120	16.5	13.8
170	20.5	17.5
190	18.4	16.2

(b)

Table 4.7 shows the trade-off between spectral and energy efficiency for low resolution DAC and without resolution in (a) 10 users considered and for the given increasing Spectral efficiency value listed in the table energy efficiency increase up to peak point and then declines. The peak points of Energy Efficiency achieved are 14.1 Mb/J with DAC resolution and 12 Mb/J without DAC resolution for spectral efficiency=115 b/s/Hz value. So, low resolution DAC enhances the peak values of energy efficiency. (b)15 users considered and similarly peak value of Energy rise form 17.5 Mb/J to 20.5 Mb/J with low resolution DAC for spectral efficiency=170 b/s/Hz. After the peak point energy efficiency decline. The reason for the decline in energy efficiency after peak point for increasing spectral Efficiency is, as the number of antenna increase in massive MIMO total power consumption rises more compared to the capacity and spectral efficiency. But using low resolution DAC, peak energy efficiency enhanced.

4.7 Capacity, Energy Efficiency and Spectral Efficiency with Modulation and without modulation.

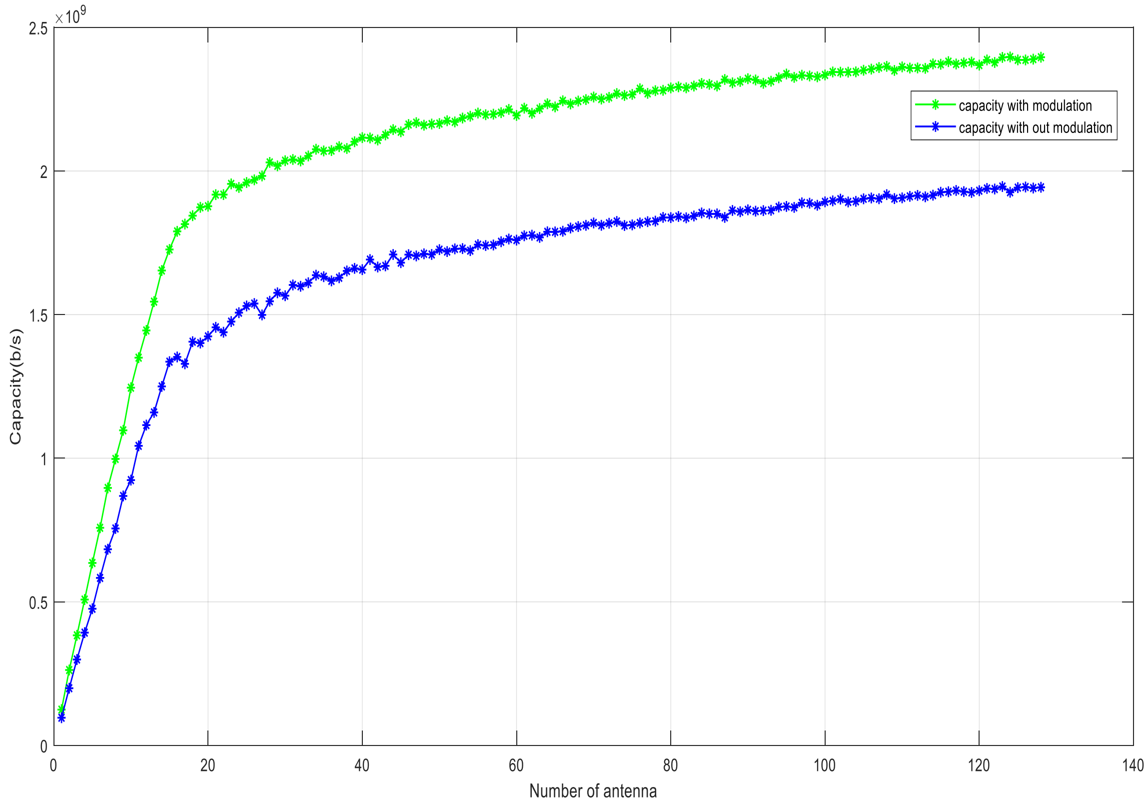

Figure 4.12 Number of antenna versus capacity with modulation and without modulation

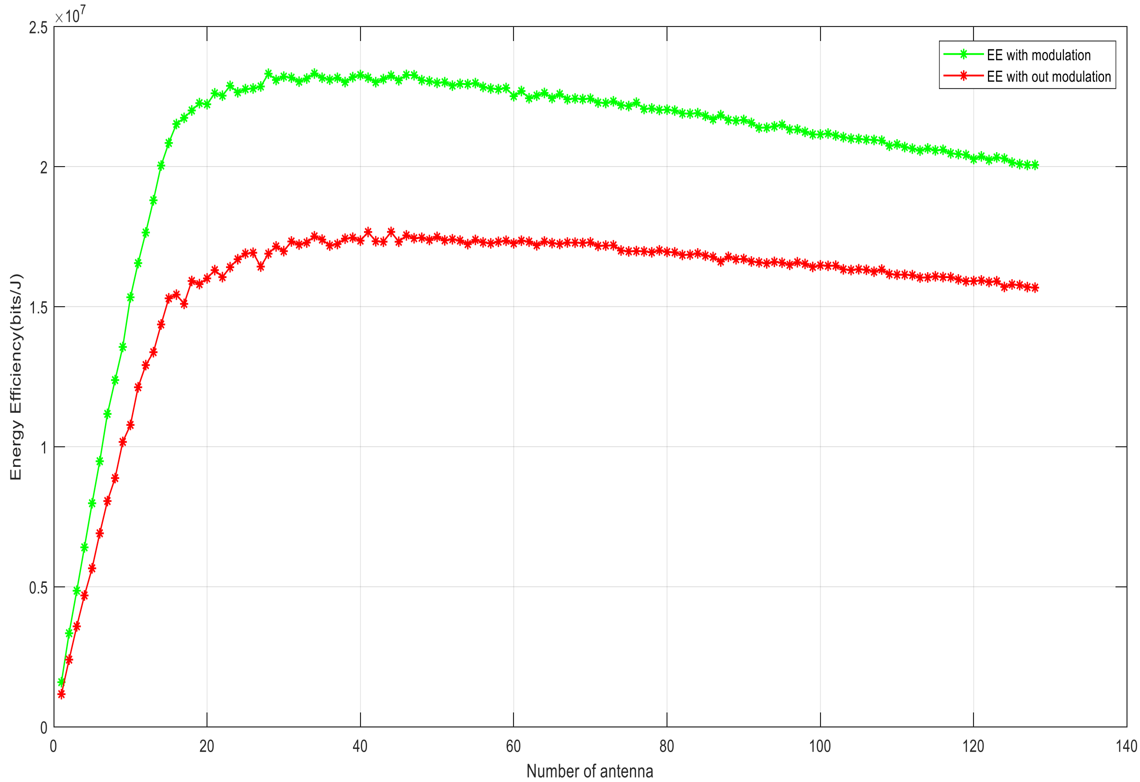

Figure 4.13 Number of antenna versus Energy efficiency with and without modulation

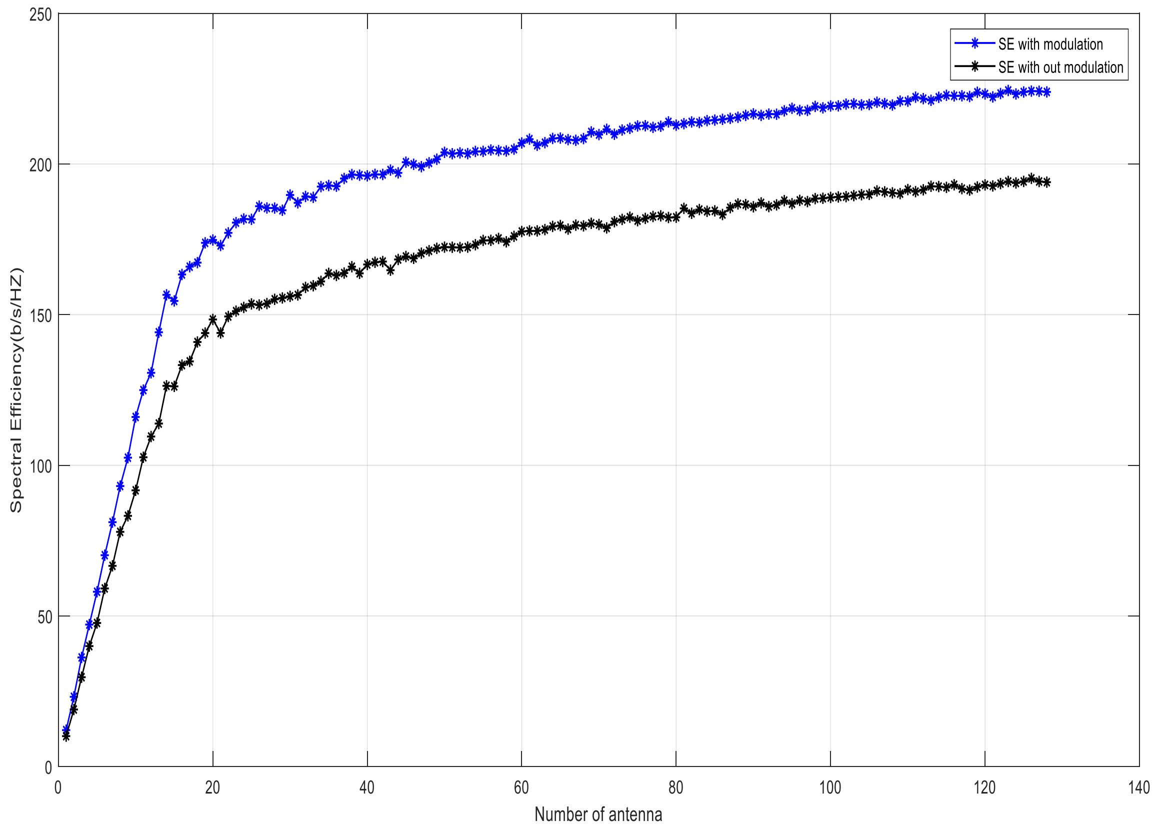

Figure 4.14 Number of antenna versus Spectral efficiency with and without modulation

The above figure 4.12 compares the capacity increase with modulation and without modulation as the number of antenna increase. With higher order modulation as the number of bits increase the capacity of the system will be higher. As the result energy efficiency also increases which is shown in figure 4. 13. With modulation the energy efficiency is higher than without modulation for increasing antennas. Therefore higher order modulation enhances the system capacity which can be applied when the DAC capacity is lower than the threshold capacity as shown in the flow chart of the system. Energy efficiency is also enhanced when applying higher order modulation up to a certain peak point since the increase in capacity is more than the increase in the total power as the number of antennas increase. But after peak point it declines at this point the increase in total power is higher compared to capacity as the number of antenna increases more. Figure 4.14 shows number of antenna versus spectral efficiency with and without modulation. As the number of antenna increases spectral efficiency increase logarithmically, with modulation higher spectral efficiency is achieved since the capacity is increasing with modulation as illustrated in figure 4.12.

Table 4.8 Comparison of capacity, Energy Efficiency and Spectral Efficiency with and without modulation (K=15)

Number of Antennas	With Modulation			Without Modulation		
	Capacity (Gb/s)	EE (Mb/J)	SE (b/s/Hz)	Capacity (Gbit/s)	EE (Mb/J)	SE (b/s/Hz)
40	1.96	21.6	196	1.672	17.5	167
80	2.134	20.45	213	1.827	16.85	182
128	2.249	18.75	225	1.93	15.6	193

Table 4.8 summarizes the effect of modulation on capacity, energy efficiency and spectral efficiency as the number of antenna increases. This entire three metrics enhance with modulation. But as the number of antenna increases energy efficiency decline while capacity and Spectral efficiency enhanced.

4.8 Hybrid and Digital beamforming comparison with DAC resolution and Modulation

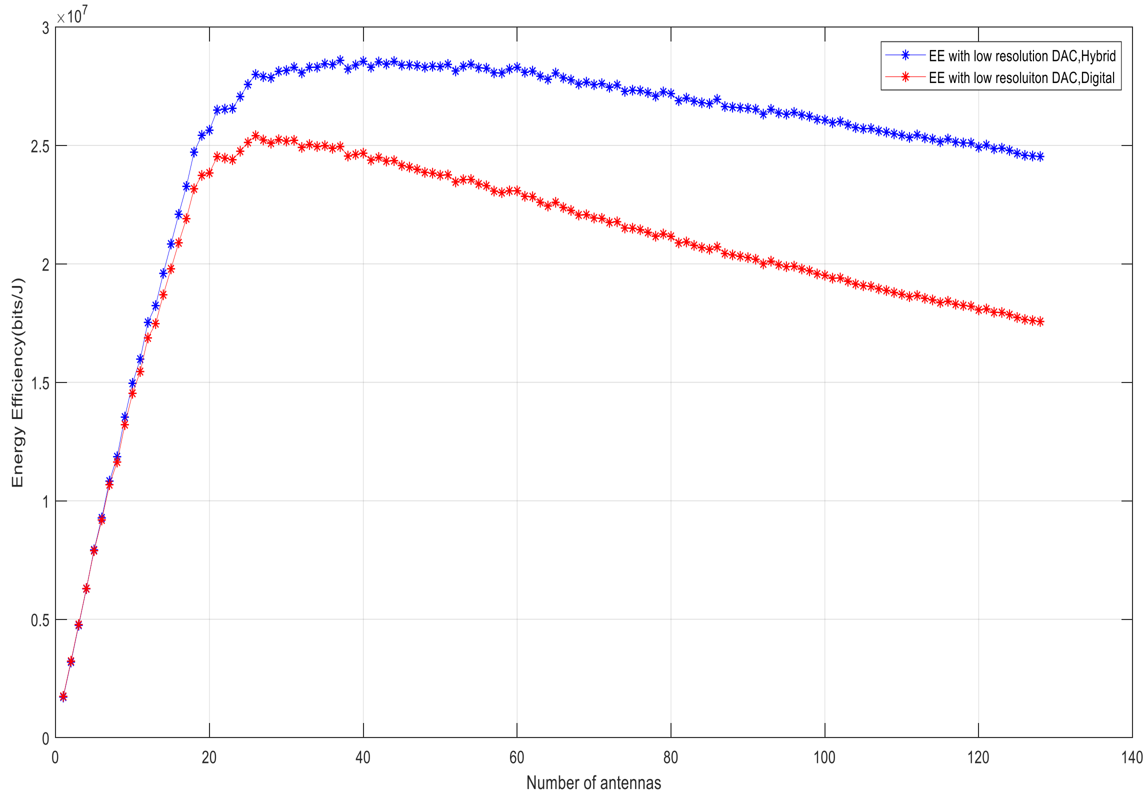

Figure 4.15 Number of Antenna versus Energy Efficiency for low resolution of DAC (Hybrid, Digital beamforming)

Figure 4.15 shows number of antennas versus energy efficiency for low resolution DAC considering both Hybrid and Digital beamforming. Hybrid beamforming with low resolution DAC achieve higher energy efficiency compared to digital beamforming since it have reduced number of RF chain and applying lower resolution DAC reduce the DAC power consumption which in return decreases the total power so that the energy efficiency is enhanced compared to Digital. For NT 128 antennas and 20 user energy efficiency as well as total power value obtained from table 4.4 then spectral efficiency found from the relation between them for the given bandwidth=10MHz.

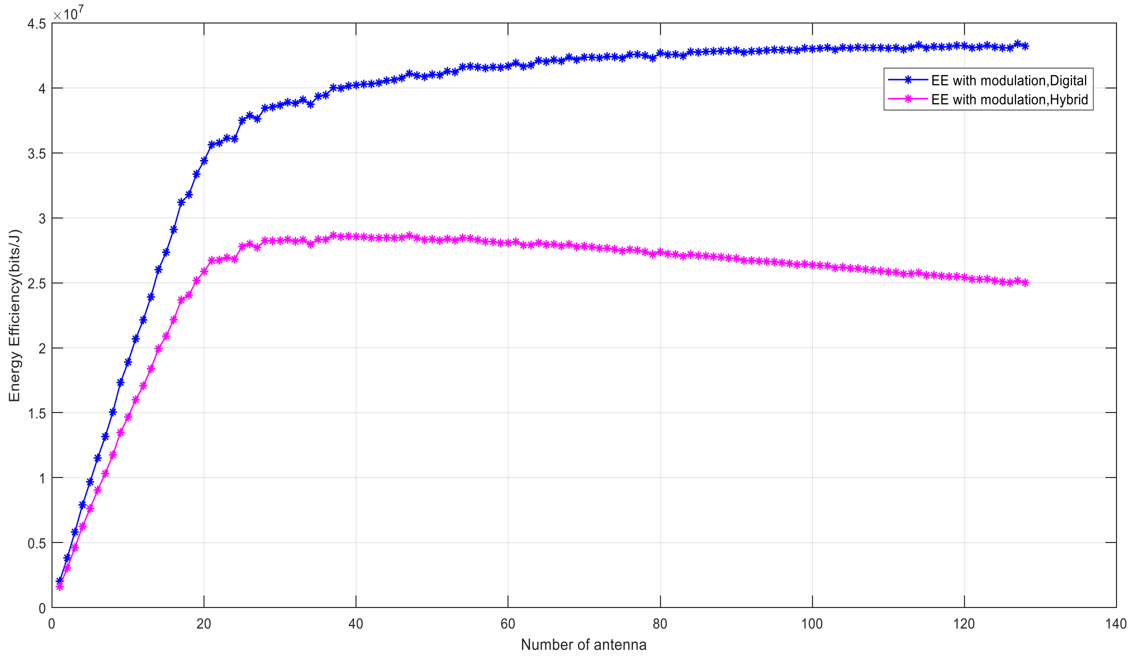

Figure 4.16 Number of Antenna versus Energy Efficiency with modulation (Hybrid, Digital beamforming

Figure 4.16 shows number of antenna versus energy efficiency with modulation considering both Hybrid and Digital beamforming. Using modulation the energy efficiency of Digital precoder is higher compared to Hybrid since Digital precoder have higher capacity compared to Hybrid and applying modulation to it enhance the energy efficiency compared to hybrid.

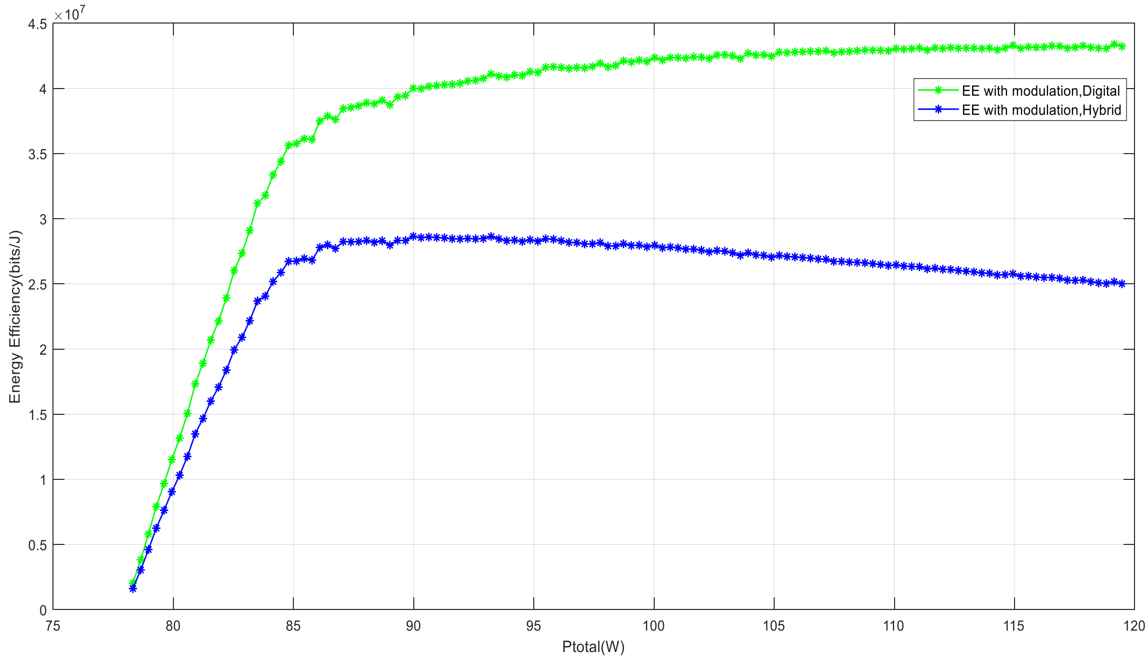

Figure 4.17 Power vs. Energy Efficiency through modulation for hybrid and digital beamforming

Figure 4.17 illustrates the relation between total power and Energy efficiency with modulation comparing hybrid and digital beamforming. Digital beamforming have higher energy efficiency compared to Hybrid but after peak point it decline rapidly as the total power consumption increases. Spectral efficiency through modulation for digital and hybrid beamforming obtained from the total power and energy efficiency at the given 10MHz bandwidth.

Table 4.9 Comparison of Hybrid and Digital Beamforming with low resolution and modulation (NT= 128, K=20)

	Low resolution DAC			Modulation		
Hybrid beamforming	P_{total}(w)	EE (Mb/J)	SE(b/s/Hz)	P_{total}(w)	EE (Mb/J)	SE(b/s /Hz)
	105.5	24.54	258.9	90	27.2	244.8
Digital beamforming	147.2	17.6	259.072	90	41.6	374.4

Table 4.9 summarizes the value of spectral efficiency, energy efficiency and total power consumption for low resolution and modulation by comparing the Digital and Hybrid beamforming. Hybrid beamforming achieve higher energy efficiency with more reduced total power consumption for low resolution DAC compared to digital. While digital beam forming achieves higher energy efficiency with modulation compared to Hybrid. Spectral efficiency is better for digital beamforming with both low resolution DAC and modulation techniques compared to hybrid beamforming.

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The huge numbers of antennas present in Massive MIMO are beneficial to enhance the capacity, reliability and data rate for the wireless communication system. As there are large numbers of antennas there are also many radio frequency chain components corresponding to each antenna. So, the power consumption of massive MIMO is very high. In this thesis for downlink Massive MIMO system, among radio frequency chain components one of the most power consuming DAC is considered, the power consumption of DAC minimized by using low resolution DACs considering threshold capacity.

Energy efficiency is enhanced with low resolution DAC as the total power consumption reduced because of the DAC power consumption minimization. With low resolution DAC the peak point of energy efficiency is higher compared to without DAC resolution. After the peak point energy efficiency decline as the number of antenna increases this is because of the increase in total power consumption became higher relative to capacity increase as the number of antenna increases. Higher order modulation is also used to enhance the capacity of massive MIMO when the capacity of DAC is less than the threshold capacity. It also enhances energy efficiency and spectral efficiency,

Beamforming techniques along with Massive MIMO improve the capability of 5G wireless network. Digital and Hybrid beamforming techniques are the two beamforming techniques used in thesis. Digital beamforming have dedicated RF chain for each antenna element being more complex and costly while hybrid beamforming have lower number of RF chain compared to number of antenna so they are less complex and less costly. The performance of both beamforming compared using low resolution DAC and modulation techniques. From the result it is observed the hybrid beamforming achieve higher energy efficiency with lower power consumption relative to digital beamforming for low resolution DAC. With modulation, digital beamforming have higher energy efficiency compared to hybrid. Spectral efficiency is greater for digital beamforming for both modulation and low resolution DAC relative to hybrid.

5.2 Recommendation

Massive MIMO total power consumption minimization using low resolution DAC for downlink system with beamforming and modulation techniques considered in this thesis. In future low resolution ADC for uplink with modulation and beamforming is recommended to be done. In this thesis only single cell is considered along with hybrid and Digital beamforming in the future multi cell systems can be used to for low resolution DAC. When using higher order modulation, the effect of probability of error doesn’t considered here but in the future it can be considered

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Appendix

Code for comparison of total power and Energy Efficiency with low resolution DAC and without DAC resolution for Hybrid Beamforming

```
clc;
clear all;
close all;
n=1;% noise
c1=9*10^(-12)% static power consumption
c2=1.5*10^(-5) % dynamic power consumption
ft=1*10^9; % sampling rate
NT=128;%number of transmit antenna
NR=20;%number of user
Nrf=15;%number of RF chian
%SNR=20;
No=9*10^(-8); %noise signal
B=10*10^(6);% bandwidth in hz
eta=0.48;%power amplifier efficiency
ptx=30;%transmit power
pLO=0.0225;%power of local oscillator
pps=0.0216;%phase shifter power consumption
pmix=0.0003;% power of mixer
pLF= 0.014;%power of lowpass filter
phb=0.003;% hu=ybrid with buffer power
PRF=(2*pmix)+(2*pLF)+phb;% RF chain power consumption
p_dac=0.5;%power of digital to analog converter
pamp=ptx/eta;% power of amplifier
%ptx2=2*ptx;%transmit power doubled
I=eye(NR,NR); % identy vector
for i=6:-1:1
    %d=i;
  M=2^i; % number of symbols
  b=log2(M);
  rho_b(i)=((3.14*sqrt(3))/2)*(2^(-b));
%   bb=M(i)
Q(i)=real(sqrt(1-rho_b(i)))+n;
P_dac(i)=c1*ft*b+c2*(2^b) ;
pdac1=P_dac(i);
end
y=rho_b';%distortion
z=Q'% quantization
  pdac1=P_dac'
pdac_avg=mean(pdac1)

 %------------------------------------------------------
pdac_avg=0.0318
sq=sqrt(NT);
%%%%  EE Evaluation with NT
for i=1:NT
    NT=i;
pckt=pLO+NT*Nrf*pps+Nrf*PRF+Nrf*2*pdac_avg;
pcktdac=pLO+NT*Nrf*pps+Nrf*PRF+Nrf*2*p_dac;
```

```
SNR=round(ptx)/(No*B);
ptotal(i)=pamp+pckt;
ptotaldac(i)=pamp+pcktdac;
H = (randn(NR,NT)+j*randn(NR,NT));%channel matrix for perfect
channel state information
cap=B*log2(real(det(I+(SNR)*H*H')));%capacity calculation %for
perfect CSI
capacity(i)=cap;
% power=ptotal
% powerdac=ptotaldac;
EE(i)=capacity(i)/ptotal(i);% energy efficiency calculation %with
perfect CSI
EEdac(i)=capacity(i)/ptotaldac(i);
ptotal1=ptotal(i);
ptotaldac1=ptotaldac(i);
p_avg=mean(ptotal);
p_avgddd=mean(ptotaldac);
EE1=EE(i);
EE1dac=EEdac(i);
end
EE1=EE';
EE1dac=EEdac';
ptotal1=ptotal';
ptotaldac1=ptotaldac';
%plotting for total power with DAC resolution and without
%resolution for Hybrid Beamforming
%------------------------------------------------------
figure
NT=1:NT
plot(NT,ptotal1,'r-*'); hold on
plot(NT,ptotaldac1,'b-*','linewidth',.5); hold on
xlabel('Number of antenna')
ylabel('Total power(w)')
legend('with low resolution DAC,Hybrid','without DAC
resoluiton,Hybrid')
grid

%plotting for Energy Efficiency with resolution and without
%resolution for Hybrid Beamforming
%------------------------------------------------------------
figure
plot(NT,EE1,'m-*','linewidth',1); hold on
plot(NT,EE1dac,'b-*','linewidth',1); hold on
xlabel('Number of antennas')
ylabel('Energy Efficiency(bits/J)')
legend('with low resolution DAC,Hybrid','without DAC
resoluiton,Hybrid ')
grid
```

Code for comparison of Total power and Energy efficiency with low resolution DAC and without DAC resolution for and Digital Beamforming

```
clc;
clear all;
```

```
close all;
n=1;% noise
c1=9*10^(-12)% static power consumption
c2=1.5*10^(-5) % dynamic power consumption
ft=1*10^9; % sampling rate
NT=128;%number of transmit antenna
NR=20;%number of users
%SNR=20;
No=9*10^(-8); %noise signal
B=10*10^(6);% bandwidth in hz
eta=0.48;%power amplifier efficiency
ptx=30;%transmit power
pLO=0.0225;%power of local oscillator
pmix=0.0003;% power of mixer
pLF= 0.014;%power of lowpass filter
phb=0.003;% hu=ybrid with buffer power
PRF=(2*pmix)+(2*pLF)+phb;% RF chain power consumption
p_dac=0.5;%power of digital to analog converter
pamp=ptx/eta;% power of amplifier
I=eye(NR,NR); % identy vector
for i=6:-1:1
    %d=i;
  M=2^i; % number of symbols
  b=log2(M);
  rho_b(i)=((3.14*sqrt(3))/2)*(2^(-b));
Q(i)=real(sqrt(1-rho_b(i)))+n;
P_dac(i)=c1*ft*b+c2*(2^b)
pdac1=P_dac(i);
 end
 pdac1=P_dac
 pdac_avg=mean(pdac1)

 %------------------------------------------------------
pdac_avg=0.315
%sq=sqrt(NT)
%%%%  EE Evaluation with NT
for i=1:NT
    NT=i;
%   M=2^i; % number of symbols
%   b=log2(M);
%   rho_b(i)=(3.14*sqrt(3))/(2*2^(b));
% %   bb=M(i)
% Q(i)=real(sqrt(1-rho_b(i)))+n;
% P_dac(i)=c1*ft*b+c2^(2*b)
% pdac1=P_dac(i);
% pdac_avg=mean(pdac)
pcktDi=pLO+NT*PRF+NT*2*pdac_avg;
pcktdacDi=pLO+NT*PRF+NT*2*p_dac;
SNR=round(ptx)/(No*B);
ptotal(i)=pamp+pcktDi
ptotaldac(i)=pamp+pcktdacDi;
H = (randn(NR,NT)+j*randn(NR,NT));%channel matrix for perfect
channel state information
cap=B*log2(real(det(I+(SNR)*H*H')))%capacity calculation for
perfect CSI
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capacity(i)=cap;
% power=ptotal
% powerdac=ptotaldac;
EE(i)=capacity(i)/ptotal(i);% energy efficiency calculation with
perfect CSI
EEdac(i)=capacity(i)/ptotaldac(i);
ptotal1=ptotal(i)
ptotaldac1=ptotaldac(i)
p_avg=mean(ptotal)
p_avgddd=mean(ptotaldac)
EE1=EE(i);
EE1dac=EEdac(i);
SE(i)=(EE(i).*(p_avg))/B
SE1=SE(i)
SEdac(i)=(EEdac(i).*(p_avgddd))/B
SEdac1=SEdac(i)
end
EE1=EE'
EE1dac=EEdac'
ptotal1=ptotal'
ptotaldac1=ptotaldac'
SE1=SE'
SEdac1=SEdac'
%-------------------------------------------------------
figure
NT=1:NT
plot(NT,ptotal1,'r-*','linewidth',.25); hold on
plot(NT,ptotaldac1,'b-*','linewidth',.25); hold on
xlabel('Number of antenna')
ylabel('Total power(w)')
legend('with low resolution DAC,Digital','With out DAC
resoluiton,Digital')
grid
figure
plot(NT,EE1,'m-*','linewidth',.5); hold on
plot(NT,EE1dac,'b-*','linewidth',.5); hold on
xlabel('Number of antennas')
ylabel('Energy Efficiency(bits/J)')
legend('with low resolution DAC,Digital','With out DAC
resoluiton,Digital ')
grid
%-------------------------------------------------------------
Code for the trade-off between energy and Spectral Efficiency
clc;
clear all;
close all;
no=1;% noise
c1=9*10^(-12)% static power consumption
c2=1.5*10^(-5) % dynamic power consumption
ft=1*10^9; % sampling rate
NT=128;%number of transmit antenna
NR=10;%number of user
NR1=15;%number of user
NR2=20;%number of user
Nrf=15;%number of RF chian
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%SNR=20;
No=9*10^-8; %noise signal
B=10*10^6;% bandwidth in hz
eta=0.48;%power amplifier efficiency
ptx=30;%transmit power
pLO=0.0225;%power of local oscillator
pps=0.0216;%phase shifter power consumption
pmix=0.0003;% power of mixer
pLF= 0.014;%power of lowpass filter
phb=0.003;% hu=ybrid with buffer power
PRF=(2*pmix)+(2*pLF)+phb;% RF chain power consumption
pdac=0.5;%power of digital to analog converter
pamp=ptx/eta;% power of amplifier
  pckr=0.3;%power circuit of user(receiver)
ptx2=2*ptx;%transmit power doubled
I=eye(NR,NR); % identy vector
I1=eye(NR1,NR1); % identy vector
I2=eye(NR2,NR2); % identy vector
for i=1:6
    %d=i;
  M=2^i; % number of symbols
  b=log2(M);
  rho_b(i)=((3.14*sqrt(3))/2)*(2^(-b));
%   bb=M(i)
Q(i)=real(sqrt(1-rho_b(i)))+no;
P_dac(i)=c1*ft*b+c2^(2*b)
pdac1=P_dac(i);
end
M=[2 4 8 16 32 64];
b=log2(M);
bb=b';
y=rho_b';%distortion
z=Q'% quantization
    pdac1=[0.0090  0.0180  0.0270  0.0360   0.0450   0.0540]
%P_dac=P_dac'
pdac_avg=mean(pdac1)
for i=1:NT
    NT=i;
 M=2^i; % number of symbols
 b=log2(M);
 rho_b(i)=(3.14*sqrt(3))/(2*2^(b));
 %   bb=M(i)
 Q(i)=real(sqrt(1-rho_b(i)))+no;
 P_dac(i)=c1*ft*b+c2^(2*b)
pdac1=P_dac(i);

pckt=pLO+NT*Nrf*pps+Nrf*PRF+Nrf*2*pdac_avg+(NR*pckr)
pcktdac=pLO+NT*Nrf*pps+Nrf*PRF+Nrf*2*pdac+(NR*pckr)
pckt1=pLO+NT*Nrf*pps+Nrf*PRF+Nrf*2*pdac_avg+(NR1*pckr)
pcktdac1=pLO+NT*Nrf*pps+Nrf*PRF+Nrf*2*pdac+(NR1*pckr)
pckt2=pLO+NT*Nrf*pps+Nrf*PRF+Nrf*2*pdac_avg+(NR2*pckr)
pcktdac2=pLO+NT*Nrf*pps+Nrf*PRF+Nrf*2*pdac+(NR2*pckr)
SNR=round(ptx)/(No*B);
ptotal(i)=pamp+pckt
ptotaldac(i)=pamp+pcktdac;
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ptotal1(i)=pamp+pckt1
ptotaldac1(i)=pamp+pcktdac1;
ptotal2(i)=pamp+pckt2
ptotaldac2(i)=pamp+pcktdac2;
ptotala=ptotal(i)
ptotaldaca=ptotaldac(i)
ptotalb=ptotal1(i)
ptotaldacb=ptotaldac1(i)
ptotalc=ptotal2(i)
ptotaldacc=ptotaldac2(i)
H = (randn(NR,NT)+j*randn(NR,NT));%channel matrix for user
number=5
H1= (randn(NR1,NT)+j*randn(NR1,NT));%channel matrix for user
number=10
H2 = (randn(NR2,NT)+j*randn(NR2,NT));%channel matrix for user
number=20
cap=B*log2(real(det(I+(SNR)*H*H')))%capacity calculation for user
number=5
cap1=B*log2(real(det(I1+(SNR)*H1*H1')))%capacity calculation for
user number=10
cap2=B*log2(real(det(I2+(SNR)*H2*H2')))%capacity calculation for
user number=20
capacity(i)=cap;
capacity1(i)=cap1;
capacity2(i)=cap2;
EE(i)=capacity(i)/ptotal(i);% energy efficiency calculation user
number=5
FF1(i)=capacity1(i)/ptotal1(i);% energy efficiency calculation
user number=10
EE2(i)=capacity2(i)/ptotal2(i);% energy efficiency calculation
user number=20
EEdac(i)=capacity(i)/ptotaldac(i);
EEdac1(i)=capacity1(i)/ptotaldac1(i);
EEdac2(i)=capacity2(i)/ptotaldac2(i);
EE1=EE(i);
EEa=FF1(i);
EEb=EE2(i);
EEdaca=EEdac(i)
EEdacb=EEdac1(i)
EEdacc=EEdac2(i)
SE=log2(real(det(I+(SNR)*H*H')))
SE1=log2(real(det(I1+(SNR)*H1*H1')))
SE2=log2(real(det(I2+(SNR)*H2*H2')))
SEFF(i)=SE
SEFF1(i)=SE1
SEFF2(i)=SE2
end
SE=SEFF'
SE1=SEFF1'
SE2=SEFF2'
EE1=EE'
EEa=FF1'
EEb=EE2'
EEdaca=EEdac'
EEdacb=EEdac1'
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EEdacc=EEdac2'
cap=capacity'
cap1=capacity1'
cap2=capacity2'
ptotala=ptotal'
ptotalb=ptotal1'
ptotalc=ptotal2'
ptotaldaca=ptotaldac'
ptotaldacb=ptotaldac1'
ptotaldacc=ptotaldac2'
%NT(USER vary)vs ptotal-------------------------------------------
figure
NT=1:NT
plot(NT,cap,'r-*','linewidth',1); hold on
plot(NT,cap1,'g-*','linewidth',1); hold on
plot(NT,cap2,'b-*','linewidth',1); hold on
legend('users=10','users=15','users=20')
xlabel('Number of antenna')
ylabel('Capacity(b/s)')
grid
figure
plot(NT,SE,'b-*','linewidth',1); hold on
plot(NT,SE1,'g-*','linewidth',1); hold on
plot(NT,SE2,'m-*','linewidth',1); hold on
legend('users=10','users=15','users=20')
xlabel('Number of antenna')
ylabel('Spectral Efficency(b/s/HZ)')
grid
%NT(USER vary)vs EE-------------------------------------------
figure
plot(NT,EE1,'b-*','linewidth',1); hold on
plot(NT,EEa,'g-*','linewidth',1); hold on
%plot(NT,EEb,'c-o','linewidth',1); hold on
plot(NT,EEdaca,'k-*','linewidth',1); hold on
plot(NT,EEdacb,'m-*','linewidth',1); hold on
%plot(NT,EEdacc,'r->','linewidth',1); hold on
xlabel('Number of antenna')
ylabel('Energy Efficiency(bits/J)')
%legend('NR=5 with dac resolution','NR=10 with dac
resolution','NR=15 with dac resolution','NR=5 with out dac
resolution','NR=10 with out dac resolution','NR=15 with out dac
resolution')
legend('users=10 with dac resolution,Hybrid','users=15 with dac
resolution,Hybrid','users=10 with out dac
resolution,Hybrid','users=15 with out dac resolution,Hybrid')
grid
%NT(USER vary)vs ptotal-------------------------------------------
figure
plot(NT,ptotala,'r-*','linewidth',1); hold on
plot(NT,ptotalb,'g-*','linewidth',1); hold on
plot(NT,ptotaldaca,'b-*','linewidth',1); hold on
plot(NT,ptotaldacb,'m-*','linewidth',1); hold on
%plot(NT,ptotalc,'k-o','linewidth',1); hold on
%plot(NT,ptotaldacc,'r->','linewidth',1); hold on
xlabel('Number of antenna')
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ylabel('Total power(w)')
%legend('NR=5 with DAC resolution','NR=5 with out DAC
resolution','NR=10 with DAC resolution','NR=10 with out DAC
resolution','NR=15 with DAC resolution','NR=15 with out DAC
resolution')
legend('users=10 with DAC resolution,Hybrid','users=15 with DAC
resolution,Hybrid','users=10 with out DAC
resolution,Hybrid','users=15 with out DAC resolution,Hybrid')
grid
figure
plot(SE,EE1,'r-*','linewidth',1); hold on
plot(SE1,EEa,'g-*','linewidth',1); hold on
%plot(SE2,EEb,'m-o','linewidth',1); hold on
plot(SE,EEdaca,'b-*','linewidth',1); hold on
plot(SE1,EEdacb,'m-*','linewidth',1); hold on
%plot(SE2,EEdacc,'m-o','linewidth',1); hold on
legend('users=10 with low DAC resolution,Hybrid','users=15 with
low DAC resolution,Hybrid','users=10 with out
resolution,Hybrid','users=15 with out resolution,Hybrid')
xlabel('Spectral Efficiency(b/s/HZ)')
ylabel('Energy Efficiency(bits/J)')
grid
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