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PERFORMANCE EVALUATION OF A MASSIVE MIMO M-MMSE SYSTEM IN TERMS OF ENERGY EFFICIENCY BASED ON THE POWER CIRCUIT CONSUMPTION MODEL (PC)

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ABSTRACT

The implementation of massive MIMO technology presents a significant boost in throughput mobile networks. However, this technological advancement comes increases energy consumption. The amalgamation of Massive MIMO with M-MMSE serves as a strategic solution, effectively mitigating energy consumption while delivering substantial throughput and improved Energy Efficiency (EE) compared to alternative techniques. Our study delves into the Energy Efficiency of massive MIMO using the Power Circuit Consumption (PC) model, providing valuable insights into its performance. This analytical approach not only enables a reduction in energy usage but also facilitates a noteworthy enhancement in Spectral efficiency (SE) and EE concurrently. This concurrent improvement addresses the challenge posed by the initial surge in energy consumption associated with massive MIMO deployment, ensuring a sustainable and efficient integration into mobile networks.

Keywords: CP, Energy Efficiency, Massive MIMO, M-MMSE, Throughput

INTRODUCTION

Nowadays, communication services are available wirelessly almost everywhere on earth, thanks to the deployment of extensive cellular networks, local networks, and satellite services. Global connectivity needs are growing exponentially. With each new technology comes a digital revolution and enhanced human connection, from the ability to make phone calls anywhere and with a mobile phone to conducting transcontinental presentations through video calls-uses that were unimaginable just a few years ago but have become indispensable today.

An important question arises: how can we evolve current wireless communication technologies to meet the ever-increasing demand and thus avoid an imminent crisis in the network energy efficiency? Customers expect wireless services to work seamlessly everywhere and at all times, with reliable energy consumption for all devices.

This work is organized as follows: the first chapter discusses the evolution of mobile networks. We dedicate the second chapter to the study of massive MIMO technology. Energy efficiency is presented in the third chapter. The final chapter will be entirely devoted to the analysis and simulation of the Energy efficiency of massive MIMO using the Matlab.

Table 1. List of abbreviations

Abbreviation	Definition
G	Generation (mobile network)
ATP	Area Transmission Power
Mbps	Megabit per second
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
M-MMSE	Multi-cell MMSE
Gbps	Gigabit per second
PC	Power Consumption
RZF	Regularized Zero Forcing
SE	Spectral Efficiency
SNR	Signal-To-Noise Rate
Tbps	Terabit per second
UE	User Equipment
ZF	Zero Forcing
EE	Energy efficiency

STATE OF ART

Evolution of mobile network generation

i. Introduction

The evolution of mobile networks, from 1G to the current 5G era, represents a journey of constant improvement. Beginning with basic voice calls in 1G, each generation has brought significant advancements. 2G introduced digital communication, 3G marked the advent of mobile internet, and 4G revolutionized high-speed broadband. Now, 6G promises ultra-fast speeds, minimal latency, and massive device connectivity, driving transformative technologies. This ongoing evolution reflects a commitment to meeting growing connectivity needs while anticipating future challenges.

ii.Thirst generation

The first generation (1G), emerged in the 1980s, introduced the initial mobile networks with a primary focus on voice calls. Equipped with analog technology, it featured modest speeds of around 24 kbps and high latency. [1]

iii. Second generation (2G)

The second generation, deployed in the early 1990s, marked the transition to digital communication. It enabled digital voice calls, the introduction of text messages, with speeds reaching up to 64 kbps. [1] [2]

iv. Third generation 3G

The 2000s witnessed the advent of the third generation, providing enhanced data services and access to mobile internet. Speeds evolved to several Mbps, and latency was significantly reduced. [2]

v. Fourth generation 4G

The fourth generation, launched around 2009, revolutionized connectivity by popularizing high-speed access and reducing latency to 30-50 milliseconds, enabling the rise of modern mobile applications.

vi. Fifth generation 5G

The 5G is deployed since the 2020s promises ultra-high speeds, exceeding several Gbps, and latency aiming to be less than 1 millisecond, even approaching microseconds for certain applications. This advancement presents a major milestone in the evolution of mobile networks, providing significant opportunities for new application and services [3].

vii. Sixth generation 6G

Expert estimate that 5G will reach its final capacity by 2030. Therefore, we need to introduce the new generation of mobile communications, 6G, to benefit from advanced services, intelligent network management and compatibility. The maximum data rate in 6g is 1 Tbps, while for 5g it is 20 Gbps and the maximum latency of 6G is 0.1 millisecond. [04].

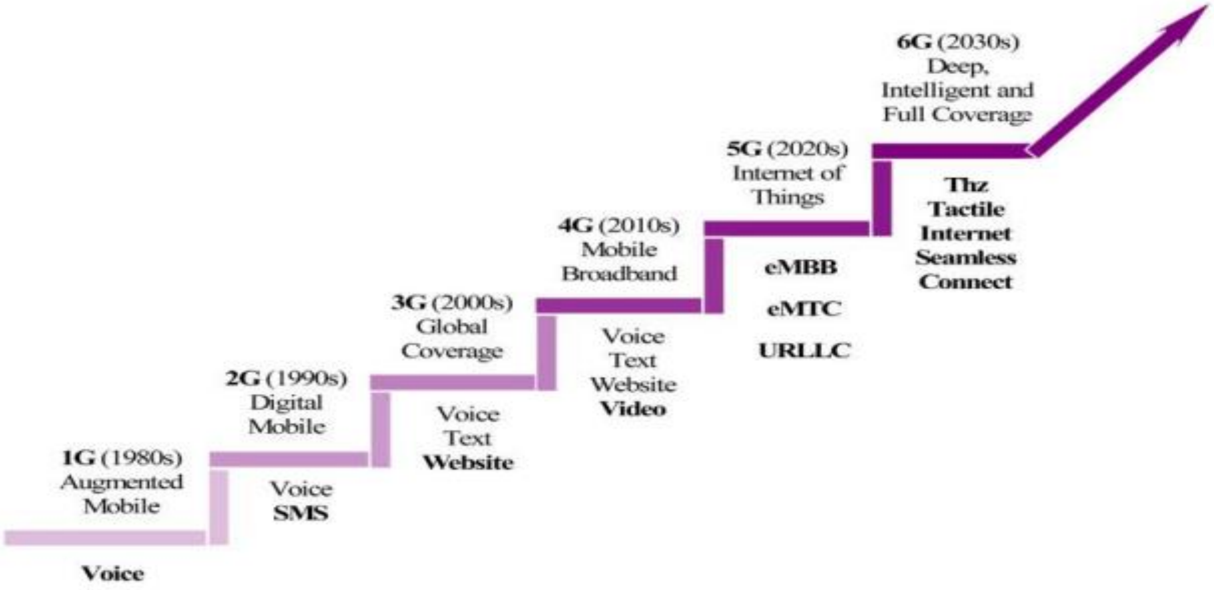

Fig.1. Evolution of mobile network generation

Massive MIMO antenna technique

To achieve goals in terms of high throughput, reduced energy consumption, latency; the combination of various technologies will be necessary. One of the solutions is the introduction of Massive MIMO for the next generation, which involves the use of massively scaled multiple antennas. Massive MIMO increases the number of transmit antennas (tens or mot than 100 elements) on a base station.

i. MIMO system

MIMO technologies use networks of antennas in transmission and/or reception to enhance the Signal-To-Noise Ratio (SNR) quality and/or transmission throughput. The central concept involves simultaneously transmitting the same message on different antennas during emission. The signals received on each reception antenna are then phase-aligned and summed. A simplified version prioritizes only the signal from the best antenna at a given moment, thereby increasing the SNR through diversity gain. The effectiveness of this technique relies on the decorrelation of MIMO sub-channels. [4] [5]

ii. Massive-MIMO Antenna technique

Massive MIMO is an advanced antenna technology that significantly expands on traditional MIMO systems by employing a large number of antennas at the base station. This technique allows for simultaneous communication with multiple users, improving spectral efficiency and enhancing the overall capacity of the wireless network. Massive MIMO is a key enabler for achieving the ambitious goals of 5G networks. [5]

iii. Advantages of massive-MIMO

Massive MIMO antenna technique represents a groundbreaking advancement in wireless communication, using an extensive array of antennas to redefine the capabilities of next-gen networks. This innovative approach promises several advantages in [6]:

- Spectral efficiency
- Interference reduction
- Power transmission efficiency
- Energy efficiency

Energy efficiency in the Massive MIMO System

i. Energy crisis

Most useful approach to enhance the energy efficiency of wireless networks can be grouped into four main categories as follows [7]:

- ➢ Resource allocation
- ➢ Network planning and deployment
- ➢ Energy harvesting and transfer
- ➢ Hardware solutions

ii. Energy efficiency

The EE refers to the amount of energy required to accomplish a certain amount of work [8].

$$\mathrm{EE} = \frac{\mathrm{Throughput[Bits\ per\ second\ per\ cell]}}{\mathrm{Power\ Consumption[Watt\ per\ cell]}} \qquad (1)$$

Where EE is the energy efficiency

a. Formulation of the energy efficiency optimization

The total EE of the uplink and downlink connections is expressed as:

$$\mathrm{EE} = \frac{\sum_{k=1}^{K}\left(\mathbb{E}\left\{R_k^{(ul)}\right\} + \mathbb{E}\left\{R_k^{(dl)}\right\}\right)}{P_{TX}^{(ul)} + P_{TX}^{(dl)} + P_{PC}} \qquad (2)$$

With $P_{TX}^{(ul)}$ et $P_{TX}^{(dl)}$ are the power amplifier at the base station and UE levels, respectively. P_{PC} is the total circuit consumption.

$R_k^{(ul)}$: The achievable downlink data rate (in bits / second) of the $k-\mathrm{th}$ UE.

b. Transmission energy consumption

A metric used to measure the transmission power consumed by a wireless network is the Area Transmission Power (ATP), defined as the average electrical consumption of the network for data transmission per unit area. This metric is measured in Watt per square kilometer (W/km^2):

$$\mathrm{ATP} = \text{transmission power } [\mathrm{W/cell}].\, \mathrm{D}[\text{cellular per km}^2\ ] \qquad (3)$$

Where D is the average cell density, defined as:

$$\text{Area Throuhput}[\mathrm{bit/\ km^2}] = \mathrm{B[Hz]}.\, \mathrm{D[cells/km^2]}.\, \mathrm{ES[bit/s/Hertz/cell]} \qquad (4)$$

c. Energy efficiency amelioration in the M-MIMO systems

M-MIMO systems with a large number of antennas at the base station, can concentrate energy in small regions, reducing interference between users. However, this increases computational complexity. Advanced linear precoding and detection techniques are needed for the base station to full realize M-MIMO benefits, especially with a growing number of users.

Antenna selection (AS) involves choosing the best antennas based on performance reducing power consumption for receivers/transmitters by decreasing the number of required RF chains. Selecting a subset of antennas based on channel conditions is a feasible way to reduce complexity in MIMO systems, maximizing performance in terms of achievable rates or energy efficiency.

iii. 5G and energy efficiency

The energy efficiency of multiple base stations and small cells could lead to increased energy consumption due to the deployment of additional cells. However, by introducing sleep mode in base stations, cellular networks can now surpass traditional counterparts consisting solely of macrocells in terms of EE.

Two approaches are considered to determine when the base station should be active of inactive: The random approach and a strategic approach. The random approach involves assigning a probability to each possible sleep level independently for each base station. The strategic approach takes into account traffic load, aiming to maximize base station utilization for serving active users.

iv. 6G and energy efficiency

Low energy consumption and the reduction of operational maintenance costs for the network are key objectives of 6G, following the path set by 5G. Future devices may not require charging, as the development of power supply technology utilizing radio signals is anticipated. Additionally, Energy transfer and harvesting technology in 6G networks enable wireless energy transfer from base stations to devices like sensors and implants.This technology also devices to harvest energy and distribute it to other devices [4].

Energy efficiency simulation based on the PC model

We will analyze the EE of Massive MIMO based on a realistic model of circuit power consumption (PC). Subsequently, we will present EE results based on the PC model and compare them with M-MMSE, S-MMSE, RZF, ZF, and MR techniques.

- Firstly, we will examine combiner/precoder techniques and their computational complexities [9].

$$v_j^{M-MMSE} = \left(\sum_{l=1}^{L} \widehat{H}_l^j \, P_l \left(\widehat{H}_l^j\right)^H + \sum_{l=1}^{L} \sum_{i=1}^{K_l} p_{li} C_{li}^j + \sigma_{UL}^2 I_{M_j} \right)^{-1} \widehat{H}_j^j P_j \qquad (5)$$

Where $\widehat{H}_l^j$ is the matrix containing the channel estimation of all user equipment in cell i to the base station j.

- Secondly, while M-MMSE is optimal, it is not commonly used in the literature due to the computational complexity, especially when the number of antennas at the base station is very high. The complexity is influenced by the need for channel estimation and acquiring channel statistics for all UE. It will present for this expression bellow:

$$v_j^{S-MMSE} = \left(\widehat{H}_j^j P_j \left(\widehat{H}_j^j\right)^H + \sum_{i=1}^{K_j} p_{ji} C_{ji}^j + \sum_{\substack{l=1 \\ l\neq j}}^{L} \sum_{i=1}^{K_l} p_{li} R_{li}^j + \sigma_{UL}^2 I_{M_j} \right)^{-1} \widehat{H}_j^j P_j \qquad (6)$$

With R_{li}^j is the correlation matrix between base station j and UE I in cell l.

$$\begin{aligned}[R]_{l,m} &= \sum_{n=1}^{N_{path}} \mathbb{E}\{|g_n|^2\}\mathbb{E}\left\{e^{2\pi j d_H (l-1)\sin(\bar{\varphi}_n)} e^{-2\pi j d_H (m-1)\sin(\bar{\varphi}_n)}\right\} \\ &= \beta \int e^{2\pi j d_H (l-m)\sin(\bar{\varphi}_n)} f(\bar{\varphi}) d\bar{\varphi}\end{aligned} \qquad (7)$$

-To continue, we will present the simulation of complexity for receiver schemes. To better represent the results, we choose L=9, et $\tau_u = 200 - K$ samples for the data transmit and M=100 ($K_j = K$ and $M_j = M$ for $j = 1 \ldots . L$).

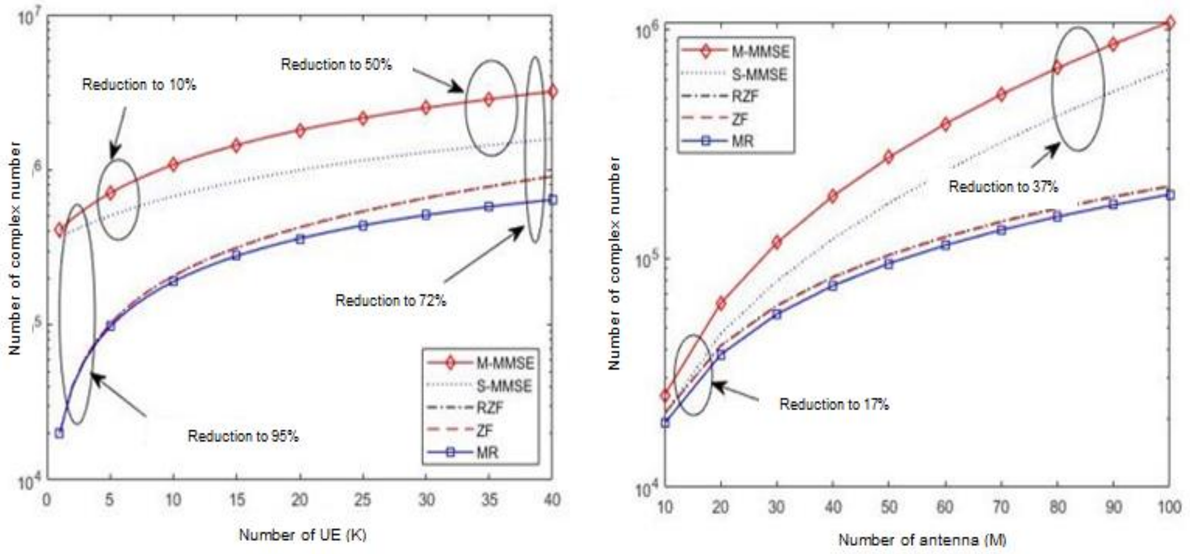

Fig.2. a) complexity for M=100 while varying K, b) K=10 while varying M

In figure 2, the complexity increases with the number of UE and BS antennas for all combinations. MMSE has the highest complexity, followed by S-MMSE. The use of S-MMSE reduces complexity by 10% to 50% compared to M-MMSE because channel estimates are not used in the calculation. The complexity reduction for K=10 is from 17% to 37%, as illustrated in figure on the right.

- Next, we will analyze the asymptotic behaviour of emission power as the number of base station antennas increases towards infinity. We describe the power that establishes the effective signal (ES) and the transmit power working together as the number of antennas increases. This result demonstrates that M-MIMO can operate at very low levels of transmission power. The downlink channel capacity of UE k in cell j whit MR precoding is lower bounded by $\underline{ES}_{jk}^{DL}$[bit/s/Hz], given by:

$$\underline{ES}_{jk}^{DL} = \frac{\tau_d}{\tau_c} log_2\left(1 + \underline{SINR}_{jk}^{DL}\right) \qquad (8)$$

Where

$$\underline{SINR_{jk}^{DL}} = \frac{\rho_{jk} p_{jk} \tau_p tr\left(R_{jk}^{j} \psi_{jk}^{j} R_{jk}^{j}\right)}{\sum_{l=1}^{L} \sum_{i=1}^{K_l} \rho_{li} \frac{tr\left(R_{jk}^{l} R_{li}^{l} \psi_{li}^{l} R_{li}^{l}\right)}{tr\left(R_{li}^{l} \psi_{li}^{l} R_{li}^{l}\right)} + \sum_{(l,i) \in P_{jk}/(j,k)} \rho_{li} \frac{\mathrm{p_{jk}} \tau_{\mathrm{p}} \left|\mathrm{tr}\left(\mathrm{R_{li}^{l}} \psi_{\mathrm{li}}^{\mathrm{l}} \mathrm{R_{li}^{l}}\right)\right|^2}{\mathrm{tr}\left(\mathrm{R_{li}^{l}} \psi_{\mathrm{li}}^{\mathrm{l}} \mathrm{R_{li}^{l}}\right)} + \sigma_{\mathrm{DL}}^2} \qquad (9)$$

And

$$\psi_{\mathrm{li}}^{\mathrm{j}} = \left(\sum_{(\mathrm{l}', \mathrm{i}') \in \mathrm{P_{li}}} \mathrm{p_{l'i'}} \tau_{\mathrm{p}} \mathrm{R_{l'i'}^{j}} + \sigma_{\mathrm{DL}}^2 \mathrm{I_{M_j}} \right).^{-1} \qquad (10)$$

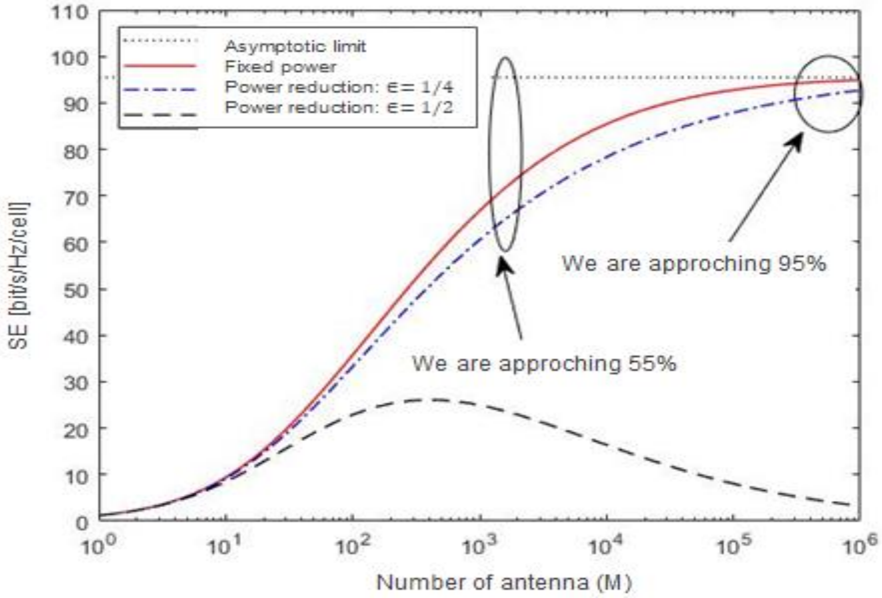

Fig.3. ES per cell as a function of the number of BS antennas for ε = 1

In the figure 3, the UL emission power per UE is P=20 dBm, and the total DL emission power is KP=30 dBm, for M=1. If p_{jk} and ρ_{jk} are decreased by $1/\sqrt{M}$, we approach a non-zero asymptotic limit. This limit is nearly identical to the case of fixed power.

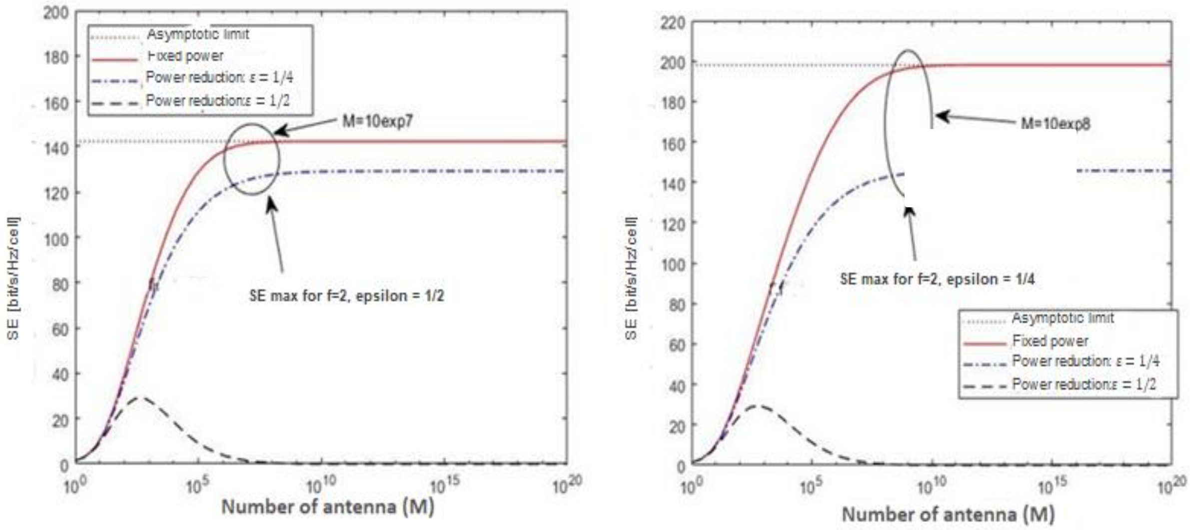

Fig.4. ES per cell as a function of the number of antennas with f=2 and f=4

We observe that for f=2, the ES increases with an asymptotic value of 140 bit/s/Hz/cell, reaching the maximum value at M=107 for $\varepsilon = 1/4$ and M=103 for $\varepsilon = 1/2$. ES = 0 for M $\geq 10^7$for $\varepsilon = 1/2$, while the ES value remains the same for any M $\geq 10^7$for $\varepsilon = 1/4$

Now, we are going to the simulation of the EE based on the PC model. We compare the PC with various combination/precoding schemes. We have M antennas in the BS and K UE in the cell.

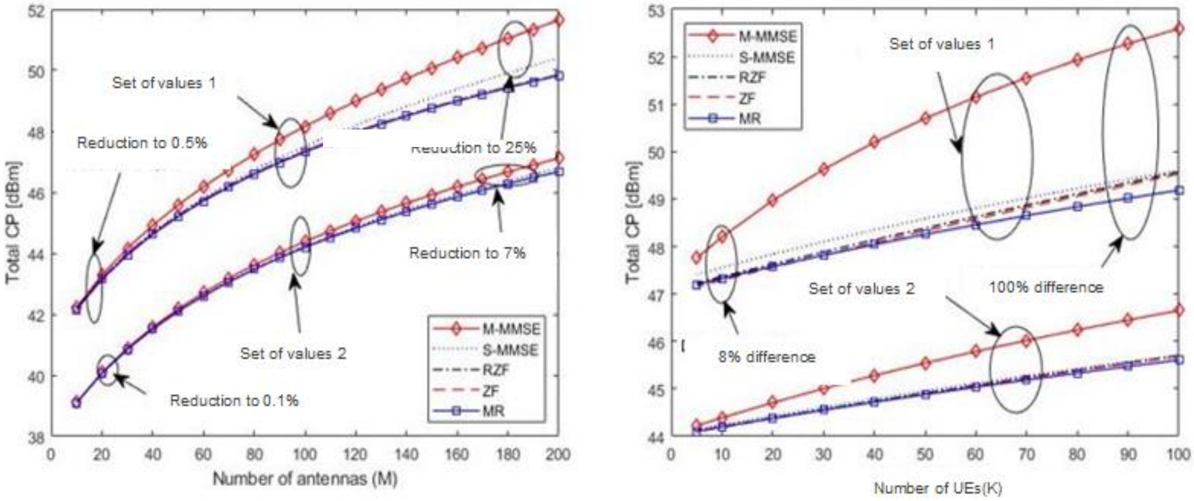

Fig.5. (a) total PC for K=10 while varying M, (b) M=100 while varying K

The power consumption increases with M and for both sets of values. The highest power consumption is required by M-MMSE, followed by S-MMSE. In other words, M-MMSE has higher power consumption. PC increases with the number of UE, but with a shallower slope than when M is modified.

Now, we will examine the results of the simulation regarding the relationship between EE and throughput using the PC model.

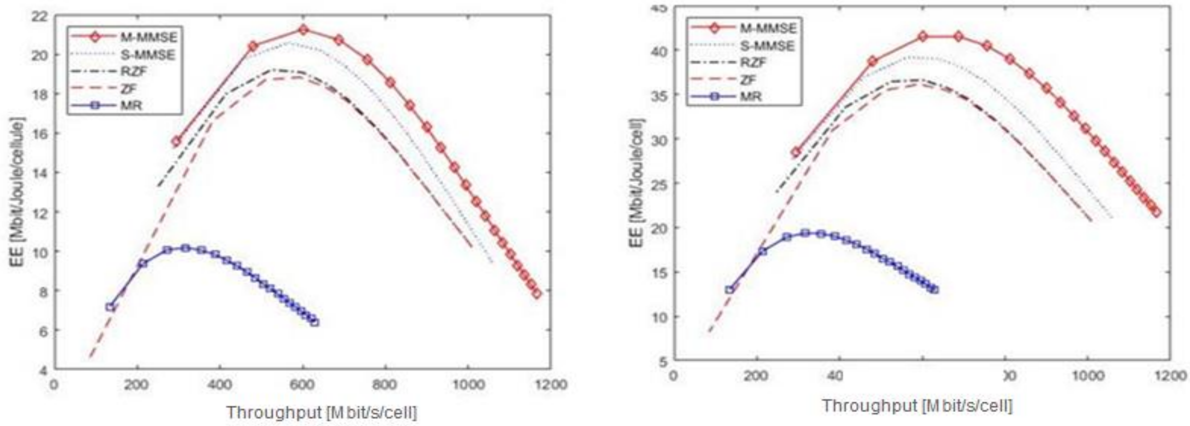

Fig.6. (a) EE and throughput with K=10 for PC for the entire range of values 1, (b) for the entire range of values

The maximum value of EE with M-MMSE is 21.26 Mbit/Joule, achieve at M=30 for a throughput of 600 Mbit/s/cell, followed by S-MMSE with a value of 20 Mbit/Joule. RZF and ZF exhibit similar performance, reaching maximum EE of around 19 Mbit/Joule.

- Finally, a personal contribution towards EE based on spectral efficiency will be discussed. The ES of a cell can be increased by using more transmission power, deploying multiple BS, antennas. All these approaches inevitably increase the network's power consumption and may reduce EE. However, there are operational conditions in which it is possible to use these techniques to increase both ES and EE.

For simplicity, we focus on UL for two cells (i.e, L=2) and consider only uncorrelated Rayleigh fading channels over a bandwidth B. the BS are equipped with M antennas and use MMSE combination. We assume there is only one active UE (i.e., K=1) in cell 0, and no interfering signal comes from cell 1. An achievable ES for the UE in cell 0 is:

$$\mathrm{ES_0} = \log_2(1 + (\mathrm{M} - 1)\mathrm{SNR_0}) = \log_2(1(\mathrm{M} - 1)\frac{\mathrm{p}}{\sigma^2}\beta_0^0) \qquad (11)$$

Where P is the emission power, σ^2 is the noise power and β_0^0 denotes the average channel gain of the active UE.

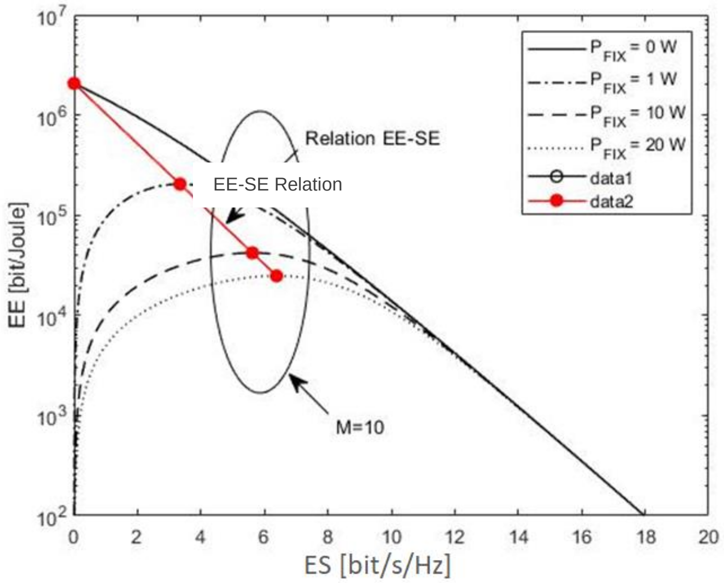

Fig.8. Relationship between EE and ES as a function power

The curve decrease with the power value, meaning that as ES increases, EE decreases.

$$\mathrm{EE_0} = \frac{\mathrm{B.ES_0}}{(2^{\mathrm{SE}} - 1)\frac{\mathrm{u_0}}{\mathrm{M} - 1}} \qquad (12)$$

To obtain the optimal point of EE, we take the derivative of $\mathrm{EE_0}$ in (11) with respect to $\mathrm{ES_0}$ and set it equal to zero. It is observed that the maximum EE (referred to as EE^*) and its corresponding ES (referred to as ES^*) satisfy the following identity:

$$\log_2(\mathrm{EE}^*) + \mathrm{ES}^* = \log_2\left((\mathrm{M} - 1)\frac{\mathrm{B}}{\mathrm{u_0}\log_2(2)}\right) \qquad (13)$$

Such that ES^*:

$$\log_2\left(2^{\mathrm{EE}^*}\log_2(2)\right) = \left(2^{\mathrm{EE}^*} - 1\right) + \frac{\mathrm{M} - 1}{\mathrm{u_0}}\mathrm{P_{FIX}} \qquad (14)$$

$$\mathrm{ES}^* = \frac{\mathrm{W}\left((\mathrm{M} - 1)\frac{\mathrm{P_{FIX}}}{\mathrm{u_0 e}} - \frac{1}{\mathrm{e}}\right) + 1}{\log_{\mathrm{e}}(2)}\mathrm{P_{FIX}} \qquad (15)$$

Where W(.) is the Lambert function and e is the number of Euler.

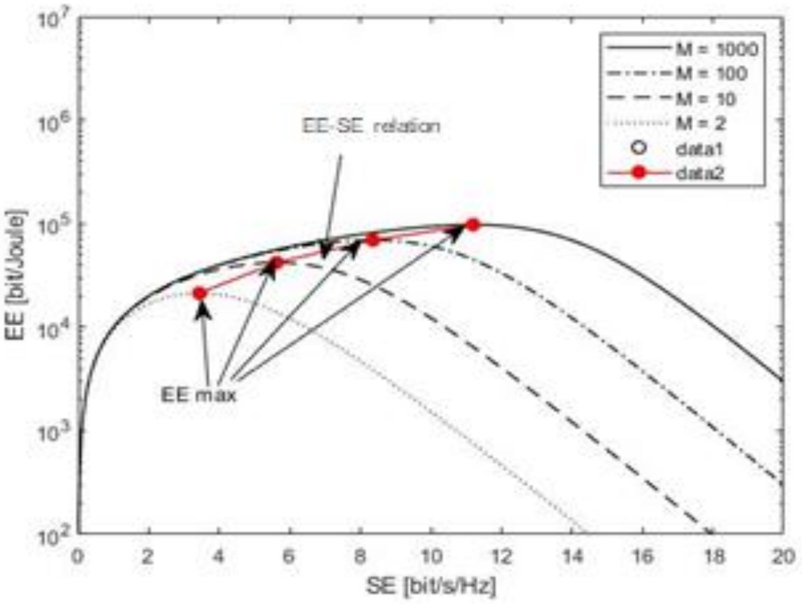

Fig.9. Relationship between EE and ES as a function of the number of antennas

The red points represent the points on each curve where EE reaches its maximum. It can be observed that if one desire better EE and ES, increasing the number of antennas is necessary while adhering to equation (14).

MOTIVATION AND DISCUSSION

We initiated this work by studying the network evolution, beginning with the technologies employed and their objectives. Following that, a chapter was dedicated to the study of massive MIMO technology. In this section, we outlined the operational principles of massive MIMO technology, including linear precoding and MMSE techniques. Lastly, we delved into a detailed analysis. To deepen the examination, we discussed EE using power consumption model, covering PC in the transmission chain, coding/decoding, backhaul link, channel estimation, and vector combination/precoding calculations. Based on our analysis, it can be concluded that EE varies based on the number of BS antennas and the precoders/combiners used.

CONCLUSION AND PERSPECTIVES

We have observed that massive MIMO operates effectively even at very low transmit powers. Power consumption models are necessary to assess power consumption for different numbers of antennas and UE. The MR scheme has the lowest power consumption, while interference suppression schemes, such as RZF and M-MMSE, require higher power consumption. Massive MIMO enables a simultaneous increase in both EE and throughput compared to a system with fewer antennas. M-MMSE provides the highest EE for any given throughput when using more energy-efficient hardware. MR achieves the lowest EE. An analysis of EE and spectral efficiency (SE) can be conducted by fixing the power and varying the number of antennas while adhering to the equations.

This work can be further enhanced by considering other parameters such as cell density, antenna size, pilot contamination, and the computational complexity of M-MMSE.

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