

## Ergodic Capacity for Evaluation of Mobile System Performance

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### ABSTRACT

In this research the performance of 5G mobile system is evaluated through the Ergodic capacity metric. Today, in any wireless communication system, many parameters have a significant role on system performance. Three main parameters are of concern here; the source power, number of antennas, and transmitter-receiver distance. User equipment's (UEs) with equal and non-equal powers are used to evaluate the system performance in addition to using different antenna techniques to demonstrate the differences between SISO, MIMO, and massive MIMO. Using two mobile stations (MS) with different distances from the base station (BS), resulted in showing how using massive MIMO system will improve the performance than the standard SISO and MIMO techniques, under Rayleigh fading channel. Using MATLAB as a simulation tool it was found that the ergodic channel capacity enhance by increasing the power of the source and the base station antenna and it behaves in an opposite way with distance.

**Keywords:** Ergodic Capacity, SISO, MIMO, Massive MIMO, Rayleigh Fading Channel.

### القدرة الإرجودية لتقييم أداء النظام المحمول

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### الخلاصة

تم في هذا البحث دراسة الأداء شبكات المحمول من الجيل الخامس عن طريق معامل الاستيعاب الإرجودية (ergodic capacity). كما هو معلوم يمكن قياس الأداء شبكات المحمول عن طريق عدد من المتغيرات كعدد الهوائيات, المسافة بين المرسل و المستقبل و قدرة الأرسال. باستخدام محطة للبت تعتمد على اشكال مختلفة لهوائيات الأرسال (كمصفوفات الهوائيات)

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ومستخدمين (اثنين) على مسافات متفاوتة, تم الاعتماد على هينيتي للأرسال. الهيئة الأولى تعتمد على ارسال نفس القدرة الى المستخدمين, والثانية على ارسال قدرات متفاوتة. واعتمادا على قناة التوصيل الأضمحلالي رايلاغ ( Rayleigh fading channel) وبأستخدام معامل الأستيعاب الإرجوديكية تمكنا من ايضاح كيفية تحسين الأداء المنضومة عند استخدام قدرات ارسال مختلفة الى المستخدمين الذين هم على مسافات متفاوتة من محطة البث, وتم اظهار ان الأداء يتدهور في حالة استخدام نفس القدرة لنفس المستخدمين. للوصول الى هذه النتائج تم أستخدام برنامج الماتلاب كأداة محاكاة بأعتماد المعادلات الرياضية المتعلقة بموضوع البحث.

الكلمات الرئيسية: القدرة الإرجوديكية, SISO, MIMO, massive MIMO, Rayleigh fading channel.

## 1.INTRODUCTION

As usual for any communication system, transmission power and distance between broadcasting station and users has a significant role in the system performance. That is why for most communication systems the performance of near users is much better than the far users. Also the antenna techniques have a vital role in improving the systems performance for instance, in next generation wireless communication system massive MIMO systems have been under focus where large number of antennas at both transmitter and receivers are used. Deployment of massive MIMO increases channel capacity by much more extent than we can get through using standard SISO and MIMO (Sherif, et al., 2017).

Below we are going to address a number of papers concerned with mobile system's performance and we will start with (Mukesh, 2015), in his work defined capacity, spectral efficiency, energy efficiency, data rate, and cell average throughput for the performance requirements of 5G wireless communication systems. A new cellular architecture of 5G provided with separated indoor and outdoor applications using a distributed antenna system and massive MIMO technology. It also illustrated a brief overview of MIMO wireless technology for covering channel models, capacity, coding, receiver design, and performance limits. Then showed that the massive MIMO system could play a significant role in improving wireless systems capacity, range, and reliability which offer a significant growth in data throughput and link range without depending on bandwidth or the increasing transmitter's power.

(Jiancun, 2017), studied Ergodic capacity for downlink Multi user (MU-MIMO) systems. This research shows that when used for future wireless communication systems, the massive MIMO is a significant technology, the primary objects of this paper demonstrates the ergodic capacity of the Multi-User (MU-MIMO) downlink network using two correlative models (Kronecker and Weichselberger) over Rayleigh fading channels. The simulation of this work shows that the number of transmitting antennas is more important than the number of users. The results also shows that the loss of capacity is almost inconsistent even with a coefficient of correlation between the transmitting antennas reaching high as 0.6.

(Sarun, 2017), presented the detection of "Data Symbol" in Massive MIMO Systems for 5G Wireless Communication. This paper demonstrated how a massive MIMO technique had played the most crucial role in 5G wireless communication. The new techniques employed in massive MIMO will not only improve peak service data rates (significantly) but also enhance capacity, coverage, low-latency, efficiency flexibility, compatibility, and convergence. The work presents the optimal detection of data symbols in massive MIMO for 5G wireless communication based on the frequency non-selective fading MIMO channel. Recovering the transmitted data symbols and evaluating their performance for Rayleigh fading and additive white Gaussian noise (AWGN) using three different detectors was the used approach.

(Widad, 2017) investigated the ergodic capacity of the downlink massive multi-user (MU-MIMO) network under spatially correlated Rayleigh fading channels. Their findings are valid in the presence of arbitrary comparisons between them for situations with several transmitting antennas that are greater than the number of users. The result shows that the power loss is almost negligible. Taking the surveyed papers as input, the main objectives of this research is to improve the performance of 5G mobile systems that uses small cell scheme. Different power settings are proposed for different users and the effect of these settings on the system performance have been shown using the Ergodic capacity metric.

This paper starts with a survey on related research works in this area and the objectives behind this work. The next section describes antenna techniques. Section 3 is about the problem statement, the used procedure and describes the Ergodic Capacity, the equations and parameters related to it. The next two sections are on obtained results and discussions related to them. The last is the conclusion.

## 2. ANTENNA TECHNIQUES

In this section we describe three main types of antenna techniques respectively, Single Input Single Output (SISO), Multi Input Multi Output (MIMO), and Massive MIMO.

### 2.1 From SISO to MIMO system

Single Input Single Output (SISO) systems use single antennas for transmitters (BSs) and receivers (UEs), while MIMO systems use multiple antennas for both. MIMO provides better capacity and reliability than SISO systems because its channels have significant advantages over SISO channels in terms of multiplexing, diversity, and array gain (Yong, et al., 2015). Fig .1 shows an example of a MIMO system model. It demonstrates that substantial capacity gains are feasible in MIMO systems compared to traditional single-input single-output (SISO). Many factors influence the performance of MIMO systems. All critical factors are the number of antennas, the arrangement of antennas, channel characteristics (line-of-sight or non-line-of-sight), and the choice of codes and methods for combining signals (Sherif, et al., 2017).

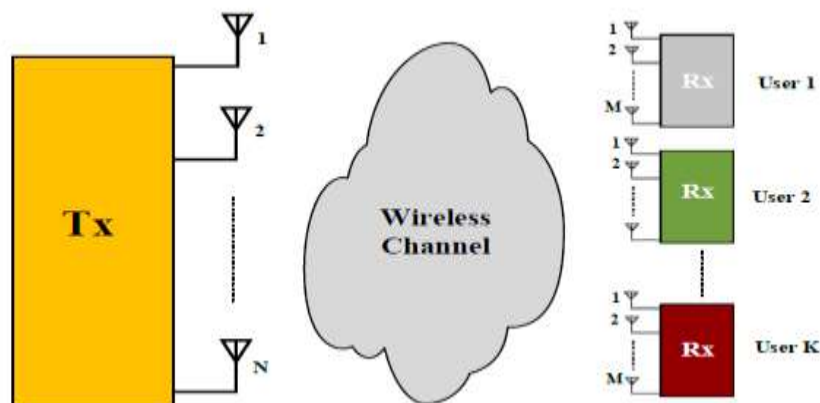


Figure1. Wireless communication system model.

### 2.2 Massive MIMO system

Massive MIMO is also called Large Scale Antenna Systems (LSAS), Full Dimension MIMO (FD-MIMO), Very Large MIMO, and Hyper MIMO. Massive MIMO is a new concept that requires



hundreds of antennas at the base station (BS) to support tens of users in the same time-frequency resource simultaneously (Emil, et al., 2019). By using vast numbers of antennas at the BS, different UEs are orthogonal to each other, and inter-user interference decreases (Sabuj, et al., 2017). Therefore, the use of low complexity signal processing techniques will be available as the data rates improve.

### 2.3 Channels in Wireless Communication System

In a wireless communication system, the main factor affecting the performance is channel physics. While due to the physical characters of the environment, it is not achievable to accurately estimate the behavior of the wireless channel. The existence of reflectors in a transmitter and receiver environments creates multiple paths that can be traversed by a transmitted signal. As a result, the receiver sees the overlapping of multiple copies of the transmitted signal (Qisun, et al., 2015). One of the types of channel models is Rayleigh fading channel is the most appropriate model for signal propagation in troposphere and ionosphere and it is the most useful model when many obstacles in the environment scatter the radio signal before it arrives at the destination. The Rayleigh distribution has a probability density function (PDF) given by (Bzhar, 2016).

$$f(x; \sigma) = \frac{x}{\sigma^2} e^{\frac{-x^2}{2\sigma^2}} \quad , \quad x \geq 0, \quad (1)$$

## 3. METHODOLOGY

This part explains the problem statement, the used procedure and performance metric (Channel capacity and Ergodic capacity) for three main types of antenna techniques SISO, MIMO, and Massive MIMO.

### 3.1 Problem Statement

Although the complete figure of the 5G system is not in its final state, however location and power of the users at the base station (BS) play an essential role in this work. For small cells used in 5G, the impact of transmitter power for user equipment's (UEs) when each of them has different distances from the base station (BS), performance-wise has been investigated. Such that the BS can assign more power for the weak state users, on the other hand, it assigns less power to more influential channel state information (CSI) users. In both cases the users in the small cell can be classified based on their signal-to-noise ratio (SNR).

### 3.2 The Procedure

One cell radius of 200 meters has been used to conduct the work. One base station (BS) and two user equipment's (UEs) is setup. The ergodic capacity of SISO, MIMO, massive MIMO is used as the main evaluation parameter (using Rayleigh fading channel). Two schemes have been used, equal and non-equal power. The first for the equal power case is described below:

#### *Equal power:*

In this one same power is sent from the base station (BS) to both users equipment's (UEs). For example, if used 35 dBm at the BS, this power will be used to send signals to both UEs that are at distances of 70 and 162 meters, respectively.



*Non-equal power:*

Two power setting are used in this case. The base station (BS) sends unequal power to both user equipment (UEs), 25dBm to the first user (when the distance between BS and user is 70 meter) and 45dBm to the next user (with distance of 162 meter). The main aim of this process is to save more power and to improve system performance.

### 3.3 Channel Capacity and Ergodic Capacity

We will start with single input-single output (SISO) is composed of a BS (Tx) and a UE (Rx), each with a single antenna. When the number of transmitter antenna ( $N_T=1$ ), and number of receiver antenna ( $N_R=1$ ). Given that the general modeling of the received signal  $y$  is as follows (Sherif, et al., 2017):

$$y = Hx + n \tag{2}$$

Where  $H$ ,  $x$ , and  $n$  represent the channel matrix, transmit signal vector, and the noise vector respectively, while  $n$  is assumed to be the additive white Gaussian noise (AWGN) following a complex normal distribution  $\mathcal{CN}(0, \sigma)$  with zero mean and  $\sigma$  standard deviation.

For SISO, the channel matrix in (2) becomes one-dimensional and scalar. The received signal  $y$  reduces to:

$$y = hx + n \tag{3}$$

The expression of the achievable capacity (bits/s/Hz) of the single link can thus take place as follows:

$$C_{SISO} = \log_2(1 + \gamma) \tag{4}$$

Where:  $\gamma = h^2 \frac{P_t}{\sigma_n^2}$

Also, the reduction of the equation (4) transpires to:

$$C_{SISO} = \log_2 \left( 1 + h^2 \frac{P_t}{\sigma_n^2} \right) \tag{5}$$

Where  $\gamma$  is the signal-to-noise ratio (SNR),  $P_t$  is transmitting (signal) power,  $\sigma_n^2$  is the noise power, and  $h$  is the channel coefficient.

For the MIMO system with multi-antenna transmitter and receivers when ( $N_T > 1$ ) and ( $N_R > 1$ ), where only one active user is served or scheduled in a transmission time interval (TTI), the received signal vector,  $y_m \in \mathbb{C}^{N_R \times 1}$ , can be expressed as:

$$y_m = \sqrt{\rho} H_{m,n} x_n + n_m \tag{6}$$

Where  $n = \{1, 2, \dots, N_T\}$  is transmit antennas and  $m = \{1, 2, \dots, N_R\}$  is receive antennas.  $x_n \in \mathbb{C}^{N_T \times 1}$  (transmit signal vector),  $n_m \in \mathbb{C}^{N_R \times 1}$  (noise and interference vector),  $H_{m,n} \in \mathbb{C}^{N_T \times N_R}$  (assumed



narrow-band time-invariant channel with deterministic and constant channel matrix) and  $\rho$  is a scalar representing the normalized transmit power (the total power of the transmit signal sum to unity,  $E\{\|x_n\|^2\}=1$ ). When the transmitter does not know the channel, it means that the (CSI) is unknown to the transmitter, power will spread equally over all transmitter antennas. For MIMO capacity with  $N_T$  and  $N_R$  antennas, it can be given in terms of bit per second per hertz by (Dalveer and Neeraj, 2019):

$$C_{MIMO} = \log_2 \left[ \det \left( I_M + \frac{1}{\sigma_n^2} H R_T H^* \right) \right] \text{ bps/Hz} \tag{7}$$

$I_M$  is the identity matrix, (\*) which means transpose-conjugate,  $H$  is the  $N_T \times N_R$  channel transmission matrix.  $R_T$  is transmitted covariance, and it demonstrates that the power allocated is to transmit signal, and det is determined by:

$$R_T = \frac{P_T}{N_T} * I_M \tag{8}$$

By submitting the value  $R_T$  in equation (7), the writing of the channel capacity is as follows:

$$C_{MIMO} = \log_2 \left[ \det \left( I_M + \frac{P_T}{N_T \sigma_n^2} H H^* \right) \right] \text{ bps/Hz} \tag{9}$$

Also, the reduction of the equation of (9) is as follows:

$$C_{MIMO} = \sum_{i=1}^k \log_2 \left( 1 + \frac{P_T}{N_T \sigma_n^2} \lambda_i \right) \text{ bps/} \tag{10}$$

When  $k = \min(N_T, N_R)$ ,  $\lambda_i$  are the Hz

eigenvalues of  $H H^*$ , known that the square roots of  $\lambda_i$  are the diagonal matrix.

Let us assume that the numbers of transmitting antenna are larger than the number of receiving antenna ( $N_T \gg N_R$ ). In this case  $H H^* = N_T I_M$ , by putting this value in equation (9) the channel capacity can be rewritten as:

$$C_{MIMO} = \log_2 \left[ \det \left( I_M + \frac{P_T}{\sigma_n^2} I_M \right) \right] \text{ bps/Hz} \tag{11}$$

$$\left( I_M + \frac{P_T}{\sigma_n^2} I_M \right) = \left( 1 + \frac{P_T}{\sigma_n^2} \right)^{N_R} \tag{12}$$

putting the equation (12) in equation (11), we can get

$$C_{MIMO} = N_R \log_2 \left( 1 + \frac{P_T}{\sigma_n^2} \right) \text{ bps/Hz} \tag{13}$$

When ( $N_T \gg N_R$ ), the writing of the equation (13) occurs as:

$$C_{MIMO} = \min(N_T, N_R) \log_2 \left( 1 + \frac{P_T}{\sigma_n^2} \right) \text{ bps/Hz} \tag{14}$$



Equation (14) illustrates that the channel capacity of the MIMO system is growing propositionally with the number of both transmitter and receiver without increasing the transmitter power and bandwidth of the channel. When the number of antennas grows large such that  $N_T \gg N_R$  and  $N_T = \infty$ , the achievable rate for MIMO in (9) becomes:

$$N_R \log_2(1 + \rho) \tag{15} C_{massive MIMO} \approx$$

Where  $\rho$  is the average signal to noise ratio

And when  $N_R \gg N_T$  and  $N_R = \infty$ , the achievable rate in (9) approximates to

$$N_T \log_2 \left( 1 + \frac{\rho N_R}{N_T} \right) \tag{16} C_{massive MIMO} \approx$$

The equations (15) and (16) represent the vectors of row or column of the channel  $H$ , which are asymptotically orthogonal and also shows the advantages of massive MIMO, where the capacity grows linearly with the number of the active antennas at the BS or the UE. The Ergodic capacity of the channel as the statistical average of the mutual information taking place, where the expectation takes over  $|h|^2$  (Yazen and Ghassan, 2019) for SISO type is given by:

$$E[f(x)] \leq f(E[x]) \tag{17}$$

Also, by applying ergodic capacity of equation (8) we get:

$$E \left[ \log_2 \left( 1 + \frac{P_t}{\sigma_n^2} |h|^2 \right) \right] \leq \log_2 \left( 1 + \frac{P_t}{\sigma_n^2} E[|h|^2] \right) \tag{18}$$

This equation illustrates that the Ergodic capacity of a fading channel cannot exceed that of an AWGN channel with constant gain. Also, the channels of MIMO are random and for this reason the channel capacity is also random,  $H$  is a channel matrix and by taking the aggregate mean of the information rate over dispersion of the elements of the channel matrix  $H$ , we obtains the ergodic capacity of the MIMO system. Therefore the capacity of the MIMO channel can be formed as (Yazen and Ghassan, 2019)..

$$C = E\{C(H)\} \tag{19}$$

When the (CSI) is not available at the transmitter, the ergodic capacity of the channel is given as a follows:

$$C = E \left\{ \sum_{i=1}^m \log_2 \left( 1 + \frac{P_T}{N_T \sigma_n^2} \lambda_i \right) \right\} \tag{20}$$



#### 4. RESULTS AND DISCUSSION

In this part, the simulation and discussion of our results for the performance metric (Ergodic capacity) is presented, using different system parameters.

##### 4.1 System parameters

The explanation of all the observed system parameters in the simulated system is described in this section. Three useful parameters that have a significant effect on the system performance are the source power range, number of antennas and the transmitter-receiver distances. **Table 1.** Illustrates the design parameters of the simulated system.

**Table1.** The parameters of the simulated system.

Part	Design Parameters	Variations
Transmitter	Power	25 dBm – 45 dBm
	Number of users	2
	Number of antennas	1 - 128
Channel	Channel	Rayleigh fading
Receiver	Performance metric	Ergodic Capacity
	Users distance from the (BS)	70 meter, 162 meter
	Number of antennas	1 - 4

##### 4.2 Using Ergodic Capacity of Equal Power

The use of the ergodic capacity which is one of the performance metrics is used in this study. **Fig. 2** shows that the base station is sending 35 dBm to two users with different distances using all antennas schemes SISO, MIMO, and massive MIMO.

From the figure it is clear that the channel capacity of the near distance user gives better performance compared with the far distance user. Also, the result illustrates that the massive MIMO has better channel capacity compared with the MIMO and SISO. It also shows that the systems performance will remarkably enhance as long as number of antennas and powers increases. In contrast, the system's performance will degrade when the user's distance increases. Parameters of the simulated system are shown in tabular form in **Table2.**





Table2. The parameters of the simulated system in Fig.2.

Parameters	Setting		
Power	35 dBm (Sherif, et al., 2018)		
Number of users	2 (Qisun, et al., 2015)		
Number of antennas	SISO	MIMO	Massive MIMO
	1x1	32x2 (Sherif, et al., 2017)	128x4 (Sherif, et al., 2017)
Distance of the users	70 meter – 162 meter (Jan, et al., 2015)		
Channel	Rayleigh fading (Sherif, et al., 2018), (Qisun, et al., 2015)		
Metric performance	Ergodic Capacity		

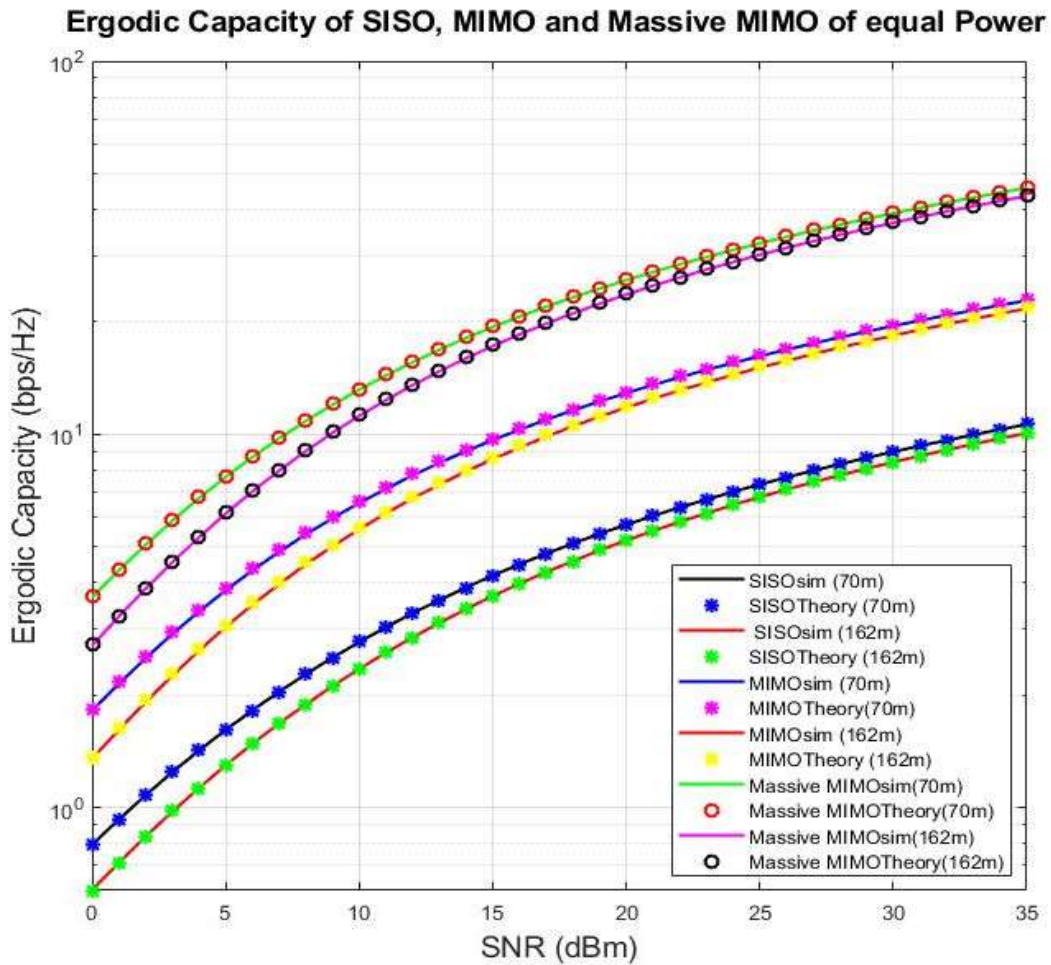


Figure2. Ergodic capacity for equal power.

From the figure we can also deduce that the capacity of massive MIMO is higher than MIMO and SISO. It is clear that the numbers of antenna plays a significant role in performance improvement, on the other hand and as it is already being known distances play a significant role in communication systems, hence near distances give better results than far distances. Power has its known role and it is shown in the figure that the capacity of the system proportionally increases with increasing power.



Key points from figure they are tabulated in **Table3** and **Table4** (in addition to table2 mentioned before).

**Table3.** The results in Fig.2 of distance 70m.

Ergodic Capacity	SNR(dBm)		
	SISO	MIMO	Massive MIMO
$10^2$	>>35	>>35	>>35
$10^1$	33	15	7
$10^0$	1.5	0	0
0	0	0	0

**Table4.** The results in Fig.2 of distance 162m.

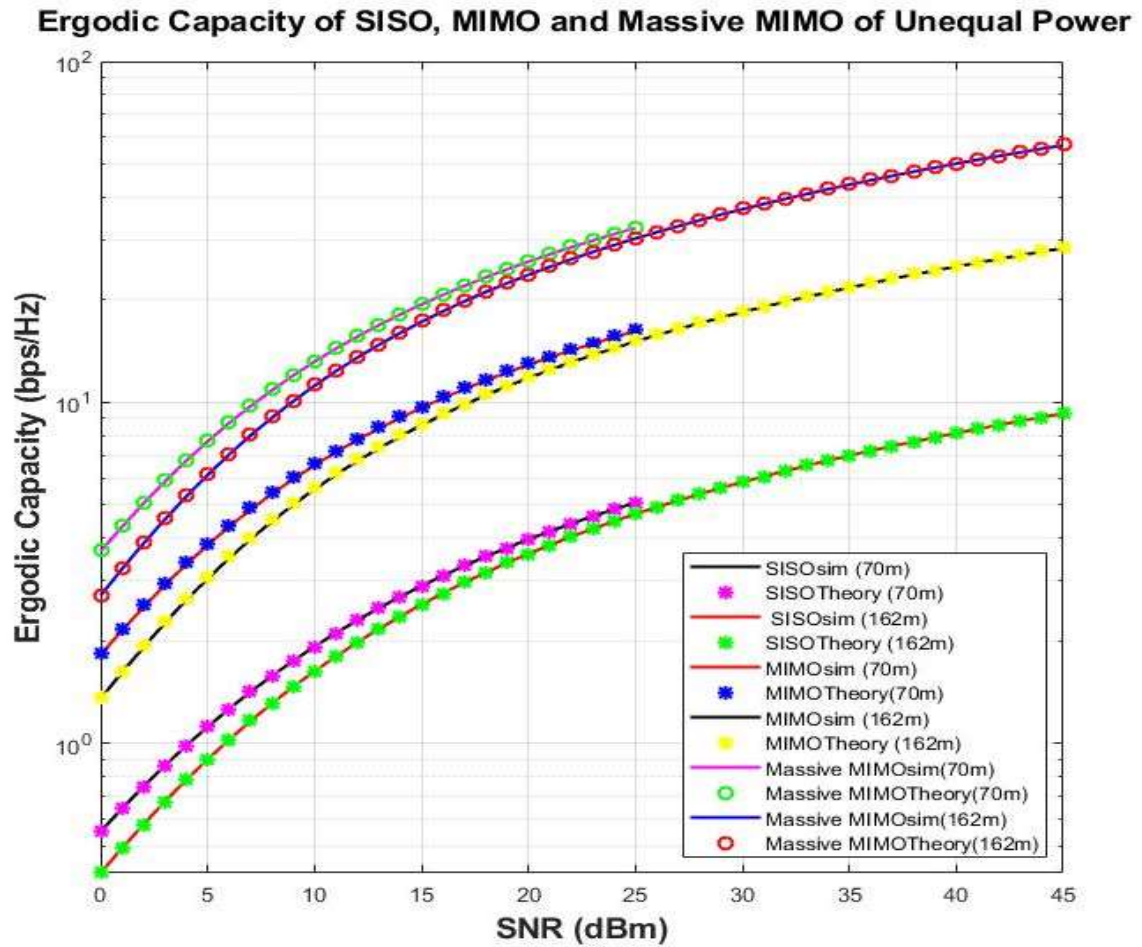
Ergodic Capacity	SNR(dBm)		
	SISO	MIMO	Massive MIMO
$10^2$	>>35	>>35	>>35
$10^1$	35	17	9
$10^0$	3	0	0
0	0	0	0

### 4.3 Using Ergodic Capacity of Unequal Power

In this section we will show how using different power setting (while keeping all other parameters constant) will have an effect on SNR. **Fig.3** shows a scenario where a base station sends unequal power to two users equipment (UEs), 25 dBm to the first user (when the distance between BS and user is 70 m) and 45 dBm to the next user (with distance of 162 m). Parameters of concern are tabulated in **Table5**.

**Table5.** The parameters of the simulated system in **Fig.3**.

Parameters	Setting		
Power	25 dBm (Jianguo, et al., 2019)		45 dBm (Sherif, et al., 2018)
	70 meter (Jan, et al., 2015)		162 meter (Jan, et al., 2015)
Number of users	2 (Qisun, et al., 2015)		
Number of antennas	SISO	MIMO	
	1x1	32x2 (Sherif, et al., 2017)	128x4 (Sherif, et al., 2017)
Distance of the users	70 meter – 162 meter (Jan, et al., 2015)		
Channel	Rayleigh fading (Sherif, et al., 2018), (Qisun, et al., 2015)		
Metric performance	Ergodic Capacity		



**Figure3.** Ergodic capacity for Unequal power.

The figure illustrates that having different power settings have a big role on the system. It is clear that by decreasing the power of the near user and giving more power to the far user, the channel capacity will be better than the case of having equal power. Further outcomes from the figure are explained in a tabular form in **Table6** and **Table7**.

**Table6.** The results in Fig.3 of distance 70m.

Ergodic Capacity	SNR(dBm)		
	SISO	MIMO	Massive MIMO
$10^2$	25	25	25
$10^1$	25	15	7
$10^0$	4	0	0
0	0	0	0



**Table7.** The results in Fig.3 of distance 162m.

Ergodic Capacity	SNR(dBm)		
	SISO	MIMO	Massive MIMO
$10^2$	$\gg 35$	$\gg 35$	$\gg 35$
$10^1$	45	9	17
$10^0$	5	0	0
0	0	0	0

### 5. CONCLUSIONS

The main outcomes of this work are summarized in the below bullets:

- For dual-users with equal power the Ergodic Capacity changes with SNR in a square root like behavior. The same response is obtained for the non-equal power case. It increases proportionally by increasing the source power and number of antennas, and it behaves in an opposite way with distance. Therefore the ergodic channel capacity gets the best performance through increasing the power of the source and the base station antennas.
- Massive MIMO system has the best performance compared with MIMO and SISO. This is due to having hundreds of transmitting antennas at the base station.
- The distance of the users has a significant role in system performance and for near user it is much better than the far user (although this is a logical common-sense expected response).
- By using dual-power scheme the base station (BS) sends less power to the near user and higher power to the far user. By which we save power and improve system performance.

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### NOMENCLATATURE

<i>Symbol</i>	<i>Description</i>
$H^*$	Channel matrix hermitian.
*	Transpose conjugate.
h	Channel matrix coefficient.
y	Received signal vector of the base station.
n	The additive noise vector.
$\sigma_n^2$	Noise power.
x	Transmit signal vector.
$\gamma$	Signal to noise ratio (SNR).
$P_t$	Transmitting signal power.
$I_M$	MXM identity matrix.
$R_T$	Transmits covariance.



$\lambda_i$	Diagonal matrix.
$C_{SISO}$	Channel capacity of single input single output (SISO).
$C_{MIMO}$	Channel capacity of Multi-input multi-output (MIMO).
$C_{Massive MIMO}$	Channel capacity of Multi-input multi-output (MIMO).
<b>Abbreviations</b>	<b>Description</b>
BS	Base Station
UE	User Equipment
CSI	Channel State Information
SISO	Single Input Single Output
MIMO	Multi-Input Multi-Output
MU-MIMO	Multi User-Multi Input Multi Output
SNR	Signal to Noise Ratio
AWGN	Additive White Gaussian Noise
PDF	Probability Density Function

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