Düzce University Journal of Science & Technology, 5 (2017) 429-440

Düzce University
Journal of Science & Technology

Research Article

Channel Capacity Analysis of Multiple Antenna Systems for Next Generation Wireless Communication Systems

Marwan DHUHEIR[a], Muhammad ASSHAD[b], Kerem KÜÇÜK[b,*]

[a] *Department of Electronics and Communication, Faculty of Engineering, Kocaeli University, Kocaeli, TURKEY*
[b] *Department of Computer Engineering, Faculty of Engineering, Kocaeli University, Kocaeli, TURKEY*
** Corresponding author's e-mail address: kkucuk@kocaeli.edu.tr*

ABSTRACT

Nowadays the wireless world demands to get high quality of service, wireless communication has been developed by time from using a single antenna at a transmitter and a single antenna (SISO) at a destination to use multiple antennas at a transmitter and multiple antennas at a receiver (MIMO). This method gives very efficient results in terms of high quality of services, channel capacity, high data rate, etc. In our studies, we will discuss the comparison of channel capacity between different multiple antenna systems and similarly what are their impact on the systems. Since the multiple antenna techniques offer the need from serving high channel capacity and high data rate, spatial multiplexing, and channel state information techniques are explained in detail to give the reader an overview of advantages of using these techniques. Moreover, at the end of this study, the comparison between single antenna systems and multiple antennas are made in regards that channel capacity increased by deploying multiple antennas on both sides and similarly it is one of the best solutions for the systems that require high channel capacity, high data rate as well as reliability.

Keywords: *MIMO, SISO, SIMO and MISO Capacity, Channel State Information, Diversity and Spatial Multiplexing*

Gelecek Nesil Kablosuz Haberleşme Sistemleri için Çoklu Anten Sistemlerin Kanal Kapasitesi Analizi

ÖZET

Günümüz kablosuz dünyasında daha yüksek kaliteli hizmete olan ihtiyaç sebebiyle, kablosuz haberleşme sistemlerinde, alıcı ve vericide bir tek anten kullanan sistemler (Single Input Single Output, SISO) yerine birden fazla anten kullanan çoklu giriş çoklu çıkış (Multiple Input Multiple Output, MIMO) sistemlerinin kullanılmasına başlanmıştır. Bu çalışmanın amacı, farklı mimarilerdeki çoklu anten sistemlerini farklı koşullar altında kanal kapasitesitelerinin belirlenmesi ve karşılaştırmasının yapılmasıdır. Bununla birlikte MIMO sistemler, yüksek kanal kapasitesi ve yüksek veri hızı ihtiyacını karşılamaya yönelik teknikler olduklarından, uzaysal çoğullama ve kanal durum bilgisi teknikleri ile sağlanabilecek kanal kapasitesi analizi de ortaya konulmaktadır. Ayrıca, çoklu antenlerin yüksek kanal kapasitesi gerektiren sistemler için çözüm olduğunu göstermek adına, tek anten sistemleri

Received: 04/03/2017, Revised: 24/04/2017, Accepted: 29/04/2017

ve çoklu antenler arasındaki detaylı karşılaştırma gösterilmektedir. Bunlara ek olarak, hem alıcı hem de vericide çoklu anten kullanımının sistem kapasitesini artırdığı gösterilmiştir. Sonuçlar göstermektedir ki, her iki tarafta daha fazla anten kullanımı çeşitlilik ve uzaysal çoğullama tekniklerinin kullanımına olanak sağlar. Ayrıca yüksek veri hızı ve güvenilirlik isteyen sistemler için en iyi seçim olarak öne çıkmaktadır.

Anahtar Kelimeler: *MIMO, SISO, SIMO ve MISO Kapasitesi, Kanal Durum Bilgisi, Çeşitlilik ve Uzaysal Çoğullama*

I. INTRODUCTION

Wireless communication systems with high data rates and high reliability are required by the users. Therefore the wireless systems always need to be improved, in addition to this, wireless engineers try to use different systems that offer this property to fulfill the demand of the users. As the communication systems got improved, there are many systems that approach to work at higher data rates and a channel which uses a higher capacity efficiency; consequently, it appears the need to intensify studies on the wireless communication systems which focus on deep analysis of time varying channel [1]. In order to offer the users need of high data rates, wireless systems wrestle with limited bandwidth and transmitted power, to achieve the required amount of high data rates and being acceptable by users but it’s harder to achieve it from the same system because of the limited bandwidth and transmitted power [2]. The main aim with 5G is to increase the data rates by using higher frequency spectrum than the existing frequency spectrums and using the wide bandwidth. However, wireless propagation loss maximizes in high-frequency spectrums, the application of massive element components each consisting of more than a dozen antenna elements is carried as 5G multi-antenna technology [3].

In an ideal case which represents the system configuration of SISO, the channel capacity of this system is defined by Shannon formula [4]. This formula of channel capacity is defined by three major parameters, bandwidth which represented by B, transmitted power which represented by P, and noise that comes from interference which represented by N. By dealing with these parameters; we can achieve the goal of getting high data rates in SISO system. To achieve the specific target we can increase transmitted power, increase bandwidth, or reduce the amount of noise, nevertheless practically in SISO systems, bandwidth and transmitted power are limited or fixed, so there is no control on it. On the other hand noise factor N is limited too because it relies on other factors such as transferring of users between cells, the environment around, shadowing, fading, etc. [2, 4]. Consequently, the channel capacity of SISO systems is limited as we will see in the simulation part of this paper. The SISO systems offer limited data rates; researchers have been looking forward to new techniques to achieve high data rates. It is found that the multiple antenna configuration is one of the best solutions to overcome this problem. Therefore researchers have strained different techniques such as Multiple Input Single Output (MISO), Single Input Multiple Output (SIMO), and MIMO. Although SIMO and MISO use multiple antenna techniques, they do not offer the amount of data rates that are required. Nowadays, on the other hand, MIMO systems give solutions to these problems by getting an increment in channel capacity and system efficiency. MIMO is considered as the best solution because it uses many useful techniques such as spatial multiplexing. This technique deals with multiple antennas at the position of transmitter TX and the position of receiver RX. Since MIMO systems use techniques such as spatial multiplexing, we want to give a brief introduction in order to give the reader an overview about them. Moreover, Channel State

Information (CSI) which is an important parameter in MIMO systems to be known at transmitter or receiver side or else fully known on both sides. It has five cases, and they are mentioned in this paper. At the end of this paper, the comparison between SISO and a different number of MIMO systems are made by using Matlab simulation in order to show the improvement when the number of antennas is increased in MIMO systems.

II. TRANSMISSION SCHEMES

Depending on an antenna array, multiple antennas structures are classified into different categories like SISO, SIMO, MISO, and MIMO [1] in which MISO systems use a number of antennas array at the transmitter position while at receiving side only one. In the case of MIMO systems, it uses a number of antenna arrays at the transmitter position as well as at the receiver position [2]. In the following sections, we will discuss each type in detail, correspondingly the area usage in with they work efficiently.

A. SINGLE INPUT SINGLE OUTPUT (SISO)

SISO communication system is not considered to be numerously complicated when it is compared with the other four types. In this case, the system configuration consists of one transmitting antenna which is deployed at the transmitter position and one antenna which is deployed at the receiver position [4]. Assume the input data that comes from the transmitter side is S, the channel that is between transmitter and receiver is h_{11} the data that arrives at the receiver position is Y. The simple diagram of this system is shown in Fig. 1. As we discussed before, the capacity of SISO system is offered by Shannon formula which defines the capacity of systems that are controlled by three parameters as shown in Equation (1)[1, 3].

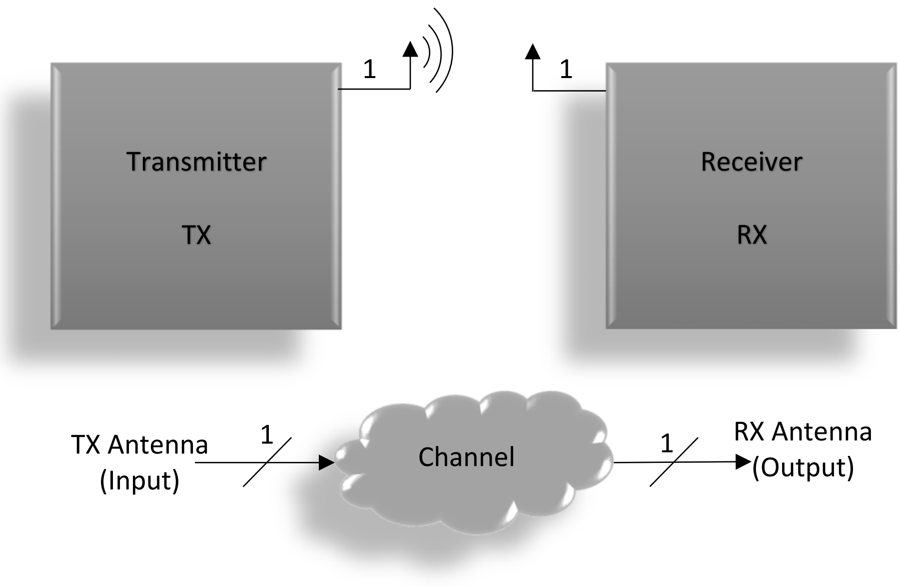

Figure 1. *Block Diagram of SISO system*

$$C_{SISO} = B * \log_2\left(1 + \frac{P}{N}\right) \quad bits/s \tag{1}$$

The parameters are defined as, *C* channel capacity of the system, *B* system's bandwidth, *P* the transmitted power, and *N* the noise power. In SISO systems, some data rates are not improved as shown in Fig. 2. This is because the parameters that can be changed is fixed. Hence the capacity is not good, and this system is not preferred by wireless engineers, however, on the other hand, this system we have an advantage, of simplicity of the system configuration because SISO systems used just only one transmitter and one receiver antenna on both sides but the diversity does not exist in this system. Now moving to the throughput of the system which relies on two important factors in which first is the channel bandwidth and second is the signal to noise ratio (SNR) as shown in equation (1). When the SNR is assumed to be 17 dB, the amount of channel capacity is found to be 5.676 bps. The amount of capacity in SISO is simple when comparing to multiple antenna systems that will be discussed later. In this system, there are many complications that degrade the system performance, in which one of them is the effect of multipath signals. When the transmitted signals hit an obstacle such as building, mountain, tree, etc., they got reflected, scattered and diffracted. As a result, these signals take many ways to end up at the receiver part which is known to be a multipath effect. These effects cause some time constructive and destructive role in the received signal. The degradation factors which effect on received signal are such as fading, power loss, shadowing, data speed will be slow, many errors will appear, and in the worse case, the signal might be lost or not arrived at the receiver [4]. The area usage of SISO systems includes in Bluetooth application, as well as in the Wi-Fi networks. Moreover, radio broadcasting of ground stations and television stations uses SISO systems too.

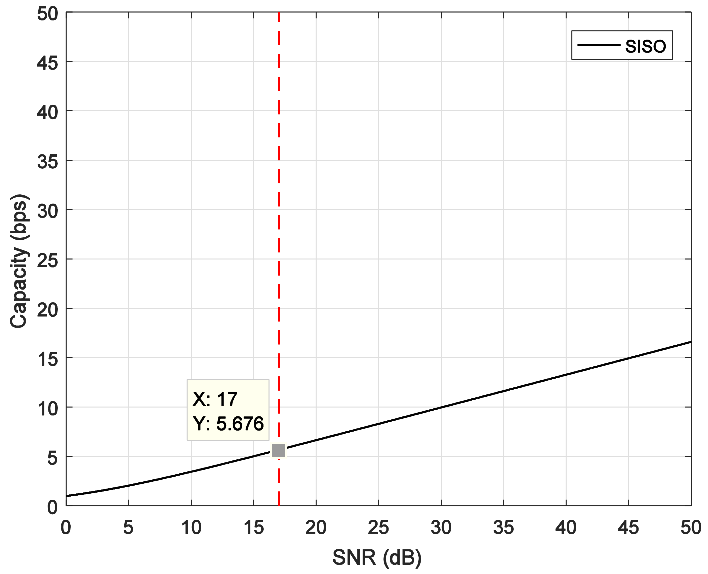

Figure 2. *Channel capacity of SISO system*

B. SINGLE INPUT MULTIPLE OUTPUT (SIMO)

SIMO systems use one antenna at the transmitter position and many antennas at the receiver position (M_r). In this case, input data stream *S*, that is transmitted from the single antenna, and the received signals are Y_1 and Y_2 that are received at the receiver by two different fading channel (h_1 and h_2) [1]. In this case, the simple block diagram that represents the shape of this system is shown in Fig. 3.

In SIMO systems, to make the data received at the receiver optimized, we use many schemes such as multiple receive diversity and the other scheme which is known as maximum gain combined (MGC). The area usage of SIMO systems are more in the part of short wave listening, and the station at the receiver as this system helps to overcome the obstacle of ionosphere fading problem. Many applications area are used by SIMO systems are considered preferable, but whenever the receiving part is in the mobile phones, the performance of the system might be limited by many factors such as size, cost and battery usage [5]. Although in SIMO systems the channel capacity has not got an improvement, the multiple antennas at the receiver can be helpful to strengthen the received signal by using the technique of diversity. The capacity of this system can be calculated by the Equation (2) [1, 4],

$$C_{SIMO} = M_r * B * \log_2\left(1 + \frac{P}{N}\right) \quad bits/s \tag{2}$$

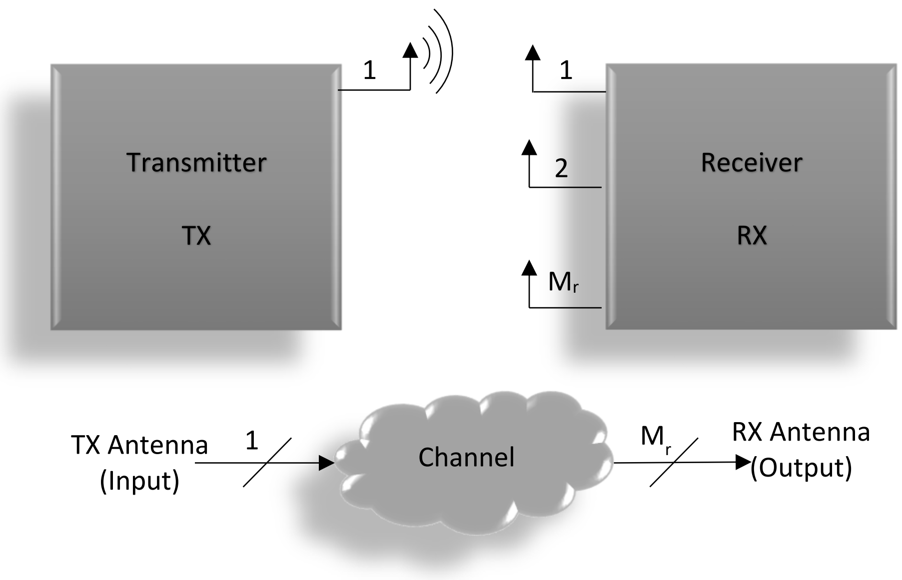

Figure 3. *Block Diagram of SIMO System*

C. MULTIPLE INPUT SINGLE OUTPUT (MISO)

MISO systems use many antennas at the transmitter position (M_t) and one antenna at the receiver position. Moreover, MISO system depends on four major parameters in which the first one is the number of transmitting antenna, second is the noise from the interference, third is the system's bandwidth, and the last one is the transmitted power from the receiver. In this system, we define that there are two transmitting signals from the transmitting antennas S_1 and S_2 which each signal has its channel parameter. The channel parameters are defined h_1 and h_2, respectively, and the data that is received by the receiver is Y [1]. Figure 4 represents the shape of this system.

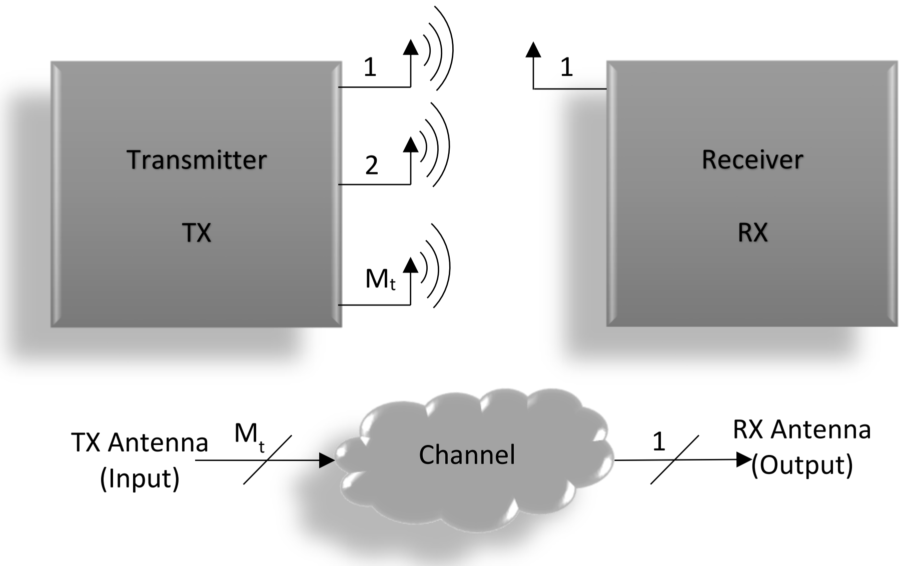

Figure 4. *Block Diagram of MISO System*

Using more than one antennas at the transmitting or the receiving site expose to us many advantages like reduction in the parameters that cause the signal to be weak such as the scattered signals that arrive at the receiver or the loss that occur in the packets that reach the destination. Multiple antennas are used in many applications such as in digital television and WLAN. In MISO systems, two important parameters have been transferred from the receiving site to the transmitting site which gives us an advantage in this system as compare to other systems which are redundancy and coding that give us lower power consumption and processing is needed at the receiving side as in the case of mobile phones [3]. Although the capacity of this system has not so good enhance but still the transmitting of two signals at the same time give the advantage of using the communication technique of diversity. The capacity of this system can be calculated using Equation (3) [1, 4],

$$C_{MISO} = M_t * B * \log_2\left(1 + \frac{P}{N}\right) \tag{3}$$

D. MULTIPLE INPUT MULTIPLE OUTPUT (MIMO)

MIMO systems use many transmit antennas at the transmitter position, and many receive antennas at the receiver position by using this we have N number of antennas at the transmitter side, and M number of antennas at the receiver side. MIMO systems are described by the term multiple element antennas (MEAs) at both transmitter and receiver. MIMO systems were first worked by a scientist called Winter, and he took a great attention through the next years of firstly suggesting this. As a result, intensive studies were made especially in the years of 1990s. After these researchers work out both in the practical and theoretical side on MIMO systems for making it more efficient and reliable. The communication terminal of MEAs has been used for four main reasons. First reason is beamforming which refers to forwarding coverage area into specific zone, second is the diversity which refers to the use of more than one antenna to expose the reliability, third is the interference suppression which refers to the reduction in the amount of interference, and the last one is the spatial multiplexing which offers to the transmitted data through more than one antenna in parallel scheme. In smart antenna technique, the concepts of beamforming, diversity and interference suppression are the same as they used in MIMO systems.

However, the term of spatial multiplexing is considered interesting belonging in MIMO systems, and it takes more attention to this new technique to get the required progress in data rates. This new technique gives the improvement in the aspect for allowing of transmitting multiple high data rates at the same time. Hence the system capacity got improved accordingly [6]. In MIMO system the channel can be described by the number of signals transmitted according to N×M of the matrix H. The H matrix is defined to be channel matrix. The received data stream y which consists of N×1 is defined by the Equation (4) [6],

$$\mathrm{y} = \mathrm{H}\mathbf{s} + \mathrm{n} \tag{4}$$

where the parameters in equation (4) are defined by, s is known to be the transmitted symbols of (S_1, S_2, S_3,...,S_{NT}), n is known to be the noise, while y is known to be the received MIMO signal. Similarly important factor of transmitted signal having a matrix known as covariance matrix which is defined in as follow,

$$R_{ss} = \frac{E_s}{N_T} I_{NT} \tag{5}$$

where the parameters in equation (5)[6] are defined by, E_s/N_T represents the power that is transmitted from every antenna, N_T is the number of transmit antennas, R is correlation matrix, E_s is total transmitted power, and I_{NT} is the identity matrix. In the Equation (4) the channel matrix which is denoted H is defined as defined in equation (6) [5, 6],

$$H = \begin{bmatrix} h_{11} & h_{12} & \dots\dots & h_{1M} \\ h_{21} & h_{22} & \dots\dots & h_{1M} \\ \cdot & \cdot & \dots\dots & \cdot \\ h_{N1} & h_{N2} & \dots\dots & h_{NM} \end{bmatrix} \tag{6}$$

where the parameters of Equation (6) is defined by, h_{ij} is known to be a complex Gaussian random variable which helps to shape the fading gain between the available number of transmitting antennas (j^{th}) and the available number of receiving antennas (i^{th}) [7]. In Fig. 5, we can observe that at the transmitter site, the number of bits that are required to be transmitted enters the transmitter block represented by the encoder, after that from the encoder the bits are transmitted through the channel by the N_T transmit antennas. Two cases describe the channel, the first case if it is stated, it will be quasi-static. In the second case which when the channel does not state, and it is considered as frequency-flat. In the case of quasi-static occurred, it means that we can transmit a large number of bits in a specific time because the coherence time, in this case, is pretty long [6].

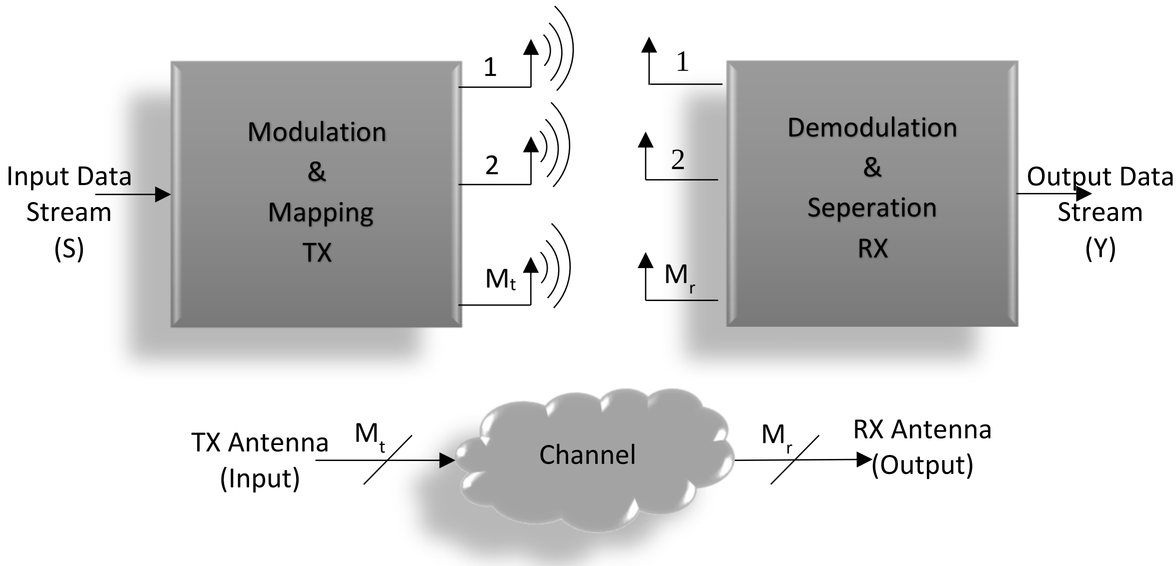

Figure 5. *Block Diagram of MIMO model*

The amount of min(N_T,N_R) is considered the value of increment in the MIMO systems that normally consist of N_T antennas at the transmitter side and N_R antennas at the receiver side. In increasing the factor of min(N_T,N_R), the channel capacity will be increased without the need of any increment in the power at the transmitter similarly bandwidth of the system improve channel capacity as compared to conventional single antenna systems. Recently the demand for faster data transmission speed must be increased. Therefore new techniques are required to achieve the specific goals. However multiple antenna techniques have been studied, and they are used for exposing many other techniques that are defined to be used in broadband wireless access networks like Mobile WiMAX. Even though a communication system that has more channel capacity is available to be used, nevertheless there is still need to figure out other suitable techniques to achieve higher data rates and higher reliability as compared to conventional techniques offer; therefore technique of using many antennas are the sophisticated technology that can be used. Multiple antenna techniques are categorized into two major techniques. The first one is diversity techniques, and second is spatial-multiplexing techniques. The diversity techniques are aimed to receive the same data from the signals in the various receiving antennas or to transmit data through multiple antennas. As a result, the reliability of the transmitter is improved. The main objective of using diversity is to convert Rayleigh fading wireless channel into higher stable additive white Gaussian noise (AWGN) such as the signals that send data without any catastrophic fading. On the other hand, the main idea of spatial multiplexing techniques is that various data are sent using various transmit antennas at the same time; hence we can achieve a higher transmission speed. When the comparison between diversity and spatial multiplexing are made, it is concluded that following results, firstly by using the technique of spatial, the speed of the transmission will be maximum, and it is equal to the capacity of MIMO channel. Secondly on the other hand, when we use the technique of diversity, the transmission speed will be much lower than the capacity of MIMO channel [8]. If the channel capacity of a MIMO system, which contains N transmitting antennas and M receiving antennas, is needed to be estimated, transfer matrix (H) of the system must be determined. Moreover, there is one another important parameter in MIMO system is channel state information (CSI), which may be known or not known at the transmitter or receiver. There are five cases of CSI in MIMO system. If the CSI is considered not to be known at the transmitter side, then the capacity of the system is defined by the Equation (7) [7],

$$C = \log_2(\det(I_N + \frac{SNR}{n} HH^H)) \quad (7)$$

where the parameters of Equation (7) is defined by, *det{.}* is known as the determinate of the matrix and *{.}H* is known as Hermitian of a matrix, SNR is considered the total average signal to noise ratio, equally distributed to each transmit antenna element and I_N is considered the N×N identity matrix [7].

In spatial multiplexing, the system uses MEAs at the transmitter side to transmit data using parallel mode. The main data stream is multiplexed in order to give various parallel data, where every data stream is transmitted via separate antenna element. In the channel phase, all data streams are mixed. At the receiver side, every receiver antenna receives all of these mixed data. In the case of the channel worked correctly, the signal at the receiver will be independently combined with these signals. If this occurred at the transmitter, the transmitter would be able to distinguish the data from each other easily. To detect the signal correctly, the number of antennas at the receiver should be at least as large as the number of data that is transmitted. This technique gives the amount of increment that is required to improve the channel capacity while the increment depends mainly on the factor min(N_T,N_R) [6].

Algorithms for MIMO transmission can be categorized by the amount of CSI that is required. According to CSI that may be fully known on both sides or to be half known at transmitter or receiver, we distinguish the following cases,

1. Full channel state information at the transmitter (CSIT) and full channel state information at the receiver (CSIR). According to this ideal case, both TX and RX have full and perfect knowledge of the channel. This case obviously results in the highest possible capacity. However, it is difficult to obtain the full CSIT.

2. Average CSIT and full CSIR. In this case, the RX has full information of the instantaneous channel state, but the TX knows only the average CSI for example, the correlation matrix of H or the angular power spectrum. This is easier to achieve and does not require reciprocity or fast feedback; however, it does require calibration (to eliminate the nonreciprocity of transmitting and receive chains) or slow feedback.

3. No CSIT and full CSIR this is the case that can be achieved most easily, without any feedback or calibration. The TX simply does not use any CSI, while the RX learns the instantaneous channel state from a training sequence or using blind estimation.

4. Noisy CSI, when we assume "full CSI" at the RX, this implies that the RX has learned the channel state perfectly. However, any received training sequence will be affected by additive noise as well as quantization noise. It is thus more realistic to assume a "mismatched RX," where the RX processes the signal based on the observed channel H_{obs}, while in reality, the signals pass through channel H_{true}, as in equation (8) [7],

$$H_{true} = \mathrm{H}_{obs} + \Delta \tag{8}$$

5. No CSIT and no CSIR: it is remarkable that channel capacity is also high when neither the TX nor the RX has CSI, for example by using a generalization of differential modulation for high SNR, capacity no longer increases linearly with $m = min(N_T, N_R)$, but rather increases as $\breve{m}(1 - \breve{m}/T_{coh})$, where $\breve{m} = min(Nt, Nr \downharpoonleft T_{coh}/2 \downharpoonright)$, and T_{coh} is the coherence time of the channel in units of symbol duration [6].

III. RESULTS

In Fig. 6, SISO, MIMO 2×2, MIMO 4×4 and MIMO 6×6 are drawn in order to make a comparison between them according to their channel capacity. We consider that increased or decreased differently in numbers of antennas effects on the channel capacity. The SNR which is assumed to be 35 dB constant and B is assumed to be 1 Hz for making calculation simple. SISO system which uses a single antenna at the transmitter and a single antenna at the receiver has channel capacity equal to 11.63 bps. In MIMO 2×2, which uses two antennas at the transmitter and two antennas at the receiver, has channel capacity of 25.29 bps. In MIMO 4×4, the channel capacity goes up to be 51.13 bps. Moreover, in MIMO 6×6, the channel capacity is found to be 68.58 bps, which is the highest channel capacity in this calculation. As the number of antennas got increased on both sides, we get more improvement in the channel capacity. For example, in Fig. 7 if we use a different number of MIMO such MIMO 8×8, MIMO 16×16 and MIMO 100×100, we can see the significant improvement in channel capacity which is equal to 89.92 bps, 178.7 bps, and 1121 bps respectively versus the constant number of SNR which is 35dB. In 5G telecommunication systems, which is the technique of massive MIMO which uses the MIMO 100×100, we see the considerable increment in channel capacity that is preferred and required by telecommunication engineers to offer the need for high data rates. It is perceived that the amount of channel capacity is increased when the number of antennas is increased, which this improvement refers to the spatial multiplexing and diversity that antennas offer. Moreover, diversity means that sending information of a message by more than one channel. As the number of channels increases, the diversity of the system will be improved as well. The diversity that exists in MIMO systems offers to us high reliability that is required by the telecommunication engineers to improve the data rates.

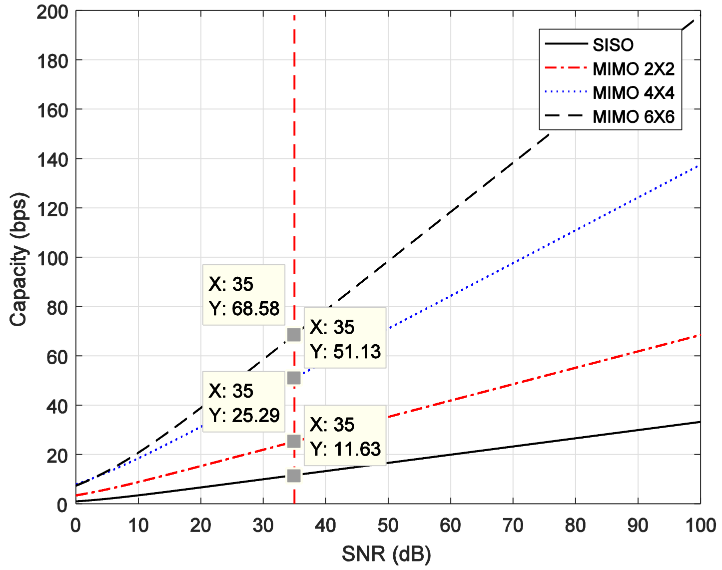

Figure 6. *Channel capacity of SISO and different MIMO models*

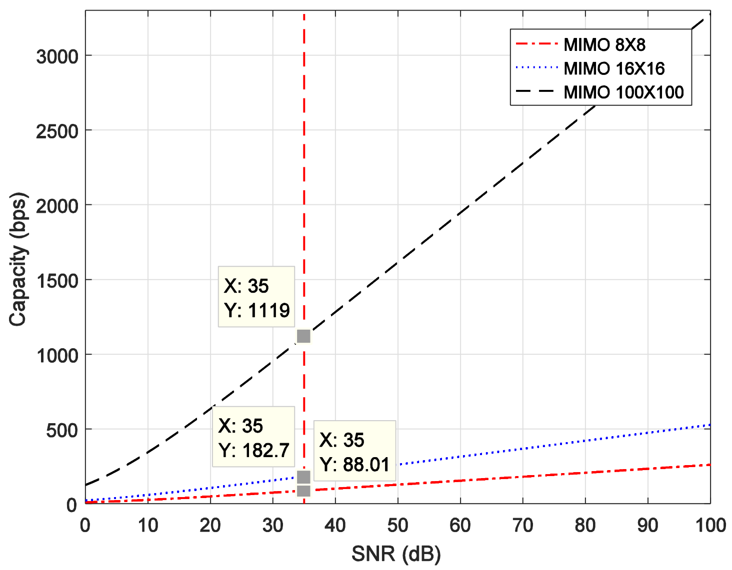

Figure 7. *Channel capacity of different MIMO models*

IV. Discussion

During this article, we demonstrated the improvement of using multiple antennas on both sides at the transmitter and the receiver. The article started with SISO system, and it showed poor channel capacity. Then we go through using diversity by using SIMO and MISO systems, and we have seen a little improvement in the channel capacity by using more than one antenna at the transmitter or the receiver side. In MIMO systems, as the number of transmitting and receiving antennas increased, the quality of getting an improvement will be increased accordingly. Recently researchers use the number of a hundred or thousand antennas at both sides which are called the technology of massive MIMO. In massive MIMO technology, the number of antenna increases and we get high diversity and high data rate. Increasing the number of antennas will help us to increase the robustness of the system, and the power consumption will be improved, and these are the ideas which are forwarding the researchers work out on the Massive MIMO technology which is explained in the 5G systems.

V. CONCLUSION

Multiple antennas are the promising technique for improving channel capacity while on the other hand, it fulfills users' demand for high data rate and reliability. MISO and SIMO showed higher capacity than SISO in regards to limited diversity and spatial multiplexing matter; however, MIMO showed the highest capacity among other systems. As the number of antennas increases in MIMO, the capacity linearly increased. During this procedure, the calculation proved in results, show that the MIMO system indicated the maximum capacity as compared to other. Moreover, MIMO inherently possesses spatial diversity which increases the robustness of the system by eliminating the fading factors. It is also concluded that MIMO system gives perceptible increment in the system throughput with the aid of spatial multiplexing.

VI. REFERENCES

[1] N. C. Giri, A. Sahoo, J. R. Swain, P. Kumar, A.Nayak and P. Debogoswami, "Capacity and Performance Comparison of SISO and MIMO System for Next Generation Network (NGN)", *International Journal of Advanced Research in Computer Engineering & Technology*, v. 3, n. 9, pp. 3031-3035, 2014.

[2] M. A. Khalighi, K. Raoof and G. Jourdain, "Capacity of Wireless Communication Systems Employing Antenna Arrays, a Tutorial Study", *Wireless Personal Communications*, v. 23, pp. 321–352, 2002.

[3] Y. Kishiyama, S. Nagata, and T. Nakamura, "NTT Docomo 5G Activities-Toward 2020 Launch of 5G Services," *NTT Docomo Technical Journal*, v. 17, n. 4, pp. 4-15, 2016.

[4] K. Sengar, N. Rani, "Study and Capacity Evaluation of SISO, MISO and MIMO RF Wireless Communication Systems," *International Journal of Engineering Trends and Technology*, v. 9, n. 9, 2014.

[5] Y. Devlal and M. Awasthi, "Capacity Analysis of MIMO Technology", *International Journal of Engineering and Computer Science*, v. 4, pp. 9819-9824, 2015.

[6] Andreas F. Molisch, *Wireless Communication*, 2nd Edition, University of Southern California, USA, 2011.

[7] R. Ahmad, D. P. Singh and M. Singh, "Ergodic Capacity of MIMO Channel in Multipath Fading Environment", *International Journal Information Engineering and Electronic Business*, v. 3, pp. 41-48, 2015.

[8] Y. S. Cho, J. Kim, W. Y. Yang, and C. G. Kang, *MIMO-OFDM Wireless Communication with Matlab*, IEEE PRESS, John Wiley & Sons, 2010.