Advances in MIMO : System Model and Potentials

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Abstract— **This document reflects the literature survey on Multiple-Input Multiple-Output (MIMO) systems and its signal processing applications in future trends, unveiling its potential in 4G and 5G. The mathematical modeling of MIMO systems is presented, highlighting the key aspects of this technology. A detailed review on latest development in MIMO domain such as Multi-user MIMO (MU-MIMO), Massive MIMO and MIMO-OFDM techniques then follows, emphasizing their importance in cellular communication systems.**

I. MOTIVATION

Since Shannon laid down the fundamental capacity limits for Single Input Single Output (SISO) system in 1948, both wire-line and wireless communication have come a long way. Wireless data traffic has increased dramatically over the years, driven mainly by the massive demand of data-hungry devices. In 1970s, *A.R. Kaye*, *D.A. George* and *W. van Etten* independently gave ideas of a Multiple Input Multiple Output (MIMO) system. In 1993 and 1994, a MIMO approach was proposed and the corresponding patent [2] was issued, where multiple transmit antennas are co-located at one transmitter with the objective of improving the attainable link throughput. Then, the first laboratory prototype was implemented to demonstrate the practical feasibility of MIMO technology. MIMO is an evolving technology that offers considerable increase in data bandwidth without any extra transmission power, and has been accepted as one of key technologies in the Fourth Generation(4G) wireless communications systems. MIMO systems gainfully exploit fading in a rich scattering environment to achieve capacities inconceivable by SISO systems. As counter-intuitive as it may seem, using scattering and by employing more radio carriers, MIMO takes spectral efficiency to a whole new level.

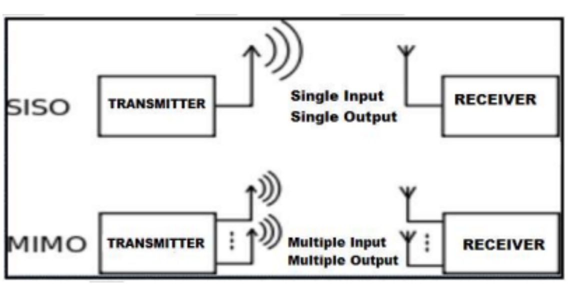

Fig. 1. Basic difference b/w SISO and MIMO systems

II. INTRODUCTION

MIMO can be termed as replica of smart antennas array group. Formally, MIMO systems employ multiple transmit and receive antennas to increase the transmission data rate using spatial multiplexing to improve system reliability. MIMO systems exploit scattering from multiple paths to achieve these benefits, without the expense of additional bandwidth. Each antenna on a MIMO system operates on the same frequency and therefore does not require extra bandwidth. Although a channel may be affected by fading and this will impact the error rate, the principle of MIMO is to provide the receiver with multiple versions of the same signal. If these can be made to be affected in different ways by the signal path, the probability that they will all be affected at the same time is considerably reduced, which helps to stabilize a link and improves performance by reducing error rate. As a result of the use multiple antennas, MIMO technology is able to considerably increase the capacity of a given channel. By increasing the number of receiving and transmitting antennas, it is possible to linearly increase the throughput of the channel with every pair of antennas added to the system. More recent MIMO techniques like the geometric mean decomposition (GMD) technique proposed in [5] to combine the diversity and data rate maximization aspects of MIMO in an optimal manner. These advantages make MIMO a very promising option for future mobile communication systems especially when combined with the benefits of orthogonal frequency-division multiplexing (OFDM).

III. CATEGORIES

Functioning of MIMO systems can be categorized into: Precoding, Spatial Multiplexing (SM), and Diversity coding.

A. Precoding

It is a pre-processing technique that performs transmit diversity such that the receiver is able to decode the received signal without the pre-knowledge of the channel. For example if we are sending information s and it will pass through the channel h that adds white Gaussian noise n. The received signal at the receiver front-end will be

$$\mathbf{r} = h\mathbf{s} + \mathbf{n}$$

. For the receiver to extract the information, it should have the pre-knowledge of h (we can nullify the effect of $\mathbf{n}$ by increasing the SNR). This can increase the complexity of the receiver, but it is desired to keep the receiver cheap and simple. To accomplish this goal we predict the channel at the transmission end (base station). Let us call the predicted channel h_{est}. Now, instead of transmitting s, we transmit $\frac{s}{h_{est}}$.

The received signal will be

$$\mathbf{r} = \mathbf{s}\frac{h}{h_{est}} + \mathbf{n}$$

If our prediction is accurate, i.e. $h = h_{est}$, we receive

$$\mathbf{r} = \mathbf{s} + \mathbf{n}$$

B. Spatial multiplexing

Stream is an independent and separately encoded data signal. In spatial multiplexing, a high-rate signal is split into multiple lower-rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel. It is a very powerful technique for increasing channel capacity at higher SNR. This technique can also be used for simultaneous transmission to multiple receivers, also known as space-division multiple access or multi-user MIMO, in which case channel state information (CSI) is required at the transmitter.

C. Diversity coding

This technique is used when there is no channel knowledge at the transmitter. In diversity coding a single stream (unlike multiple streams in spatial multiplexing) is transmitted, but the signal is coded using techniques called space-time coding. The signal is emitted from each of the transmit antennas with full or near orthogonal coding.

IV. MATHEMATICAL MODEL

MIMO systems are composed of three main elements, namely the transmitter (T_X), the channel (H), and the receiver (R_X). The Multiple-Inputs are located at the output of the T_X, and similarly, the Multiple Outputs are located at the input of the R_X.

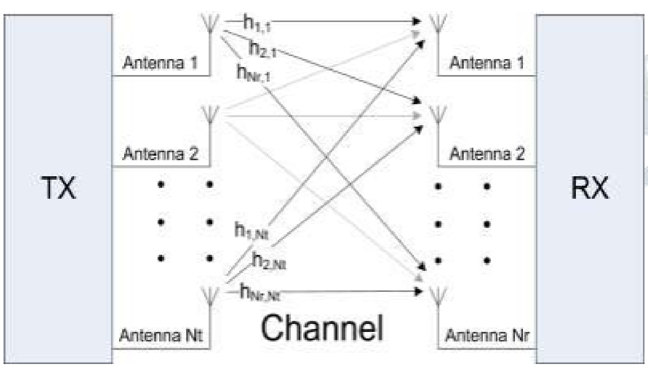

Fig. 2. MIMO system model

Define

$$R : \text{data rate (bits/symbol)}$$
$$RS : \text{symbol rate (symbols/second)}$$
$$W : \text{allotted BW (Hz)}$$
$$SNR : \text{Signal-to-Noise ratio}$$
$$P_e : \text{Probability of error}$$
$$N_R : \text{Number of receivers}$$
$$N_T : \text{Number of transmitters}$$

Spectral efficiency of the system η is given by

$$\eta = \frac{RR_s}{W}$$

For proper signal reconstruction, we must have $R_s \le W$. Hence, $\eta \le R$. So, if we transmit data at a rate $R \le C$, C being the capacity of the channel, we can achieve an arbitrarily low P_e.

A MIMO system model is described as

$$\vec{y} = H\vec{s} + \vec{n}$$

where $\vec{s}$ is the transmitted vector; $\vec{y}$ is the received vector; $\vec{n}$ is the noise vector with each element modeled as independent identically distributed (i.i.d.) white Gaussian noise with variance $\sigma = (2 \times \text{SNR})$ and H is the channel matrix and

$$H = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1N_T} \\ h_{21} & h_{22} & \dots & h_{2N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R1} & h_{N_R2} & \dots & h_{N_RN_T} \end{bmatrix}$$

where h_{ij} is a complex Gaussian random variable that represents the attenuation(along with its phase) transfer function(viz. fading gain) between transmitter i and receiver j. In further discussion, assume $\vec{n}$ to be *normalized* white Gaussian noise(AWGN).

The maximum error free transmission rate is given by the Shannon's capacity:

$$C = \log_2(1 + \text{SNR})$$
$$\text{Here, } C = \log_2 |I_{N_R} + HQH^H|$$

where I_{N_R} is the $N_R \times N_R$ identity matrix and Q is the input covariance matrix given by $Q = E\{\mathbf{ss}^H\}$, where the expectation is defined with respect to the channel matrix H, and A^H is the *Hermitian* transpose of A ($A^H = (A^*)^T$).

Our aim is to maximize the capacity of the system subject to the constraint that sum of powers of each transmitter can not be greater than the average power available per symbol period(say P), i.e.

$$\sum_{i=1}^{N_T} |s_i|^2 \le P$$

But, $\sum_{i=1}^{N_T} |s_i|^2 = tr(Q)$, tr(A) being the trace of A ($tr(A) = \sum_{i=1}^{n} A_{ii}$). Then,

$$C = \max_{Q:tr(Q) \le P} \log_2 |I_{N_R} + HQH^H|$$

By decomposing the channel using singular value decomposition(SVD) of H, Telatar showed that the optimal choice for blind transmission is when users transmit at equal power, and they are uncorrelated [7]. Then, we have $Q = \frac{P}{M} I_{N_T}$, and the capacity turns out to be

$$C_{EqualPower} = \log_2 |I_{N_R} + \frac{P}{N_T} HH^H|$$

For large SNR(or large P since $\vec{n}$ is assumed to be normalized), the capacity at equal power distribution can be approximated as

$$C_{EqualPower} \approx (\min(N_R, N_T) \times \log_2 |P|) + \text{constant}$$

It can be seen that, at high SNR, the capacity of a MIMO channel has a multiplexing gain of $min(N_T, N_R)$. Similarly, on keeping SNR constant, and increasing N_T and N_R, [8] shows that capacity varies as

$$C_{EqualPower} \approx \min(N_R, N_T) \times \text{constant}$$

i.e., capacity linearly increases with number of antennas when we have large number of antennas. Note that at

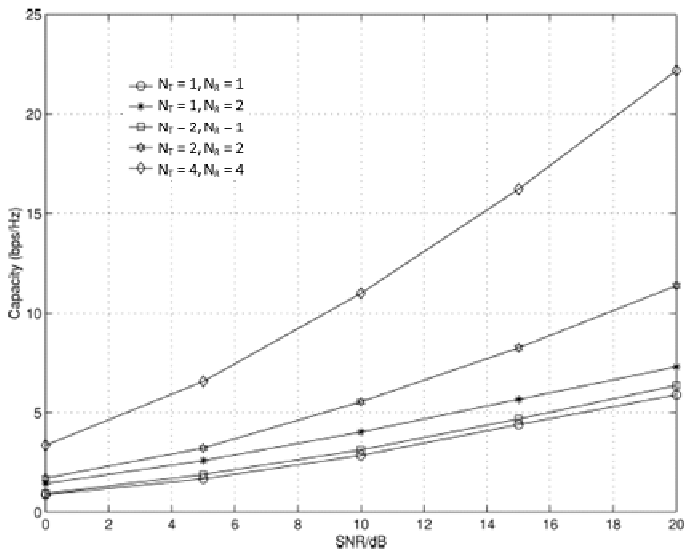

Fig. 3. Capacity vs. SNR at different system sizes

high SNR, the slopes of the lines having equal value of $min(N_R, N_T)$ have similar slopes.

V. Advantages

1) *Capacity:* MIMO systems outclass traditional communication systems in terms of capacity as was discussed earlier. They have considerably high spectral efficiency compared to systems like BPSK, 16-QAM,etc. One of the primary motivations behind the development of MIMO is the rapidly increasing demand of higher data rates .
2) *SNR:* Because of the increased antenna array gain, MIMO systems have a higher signal to noise ration. Several antennas at both the transmitter and receiver used in MIMO systems create multiple independent channels for sending multiple data streams, thereby increasing signal power considerably relative to the noise without requiring additional bandwidth.
3) *Reliability:*MIMO enhances link reliability in challenging propagation conditions. Even when the signal strength is low and fading poses problems for traditional systems, MIMO has lower bit error rate.
4) *Throughput:* The bandwidth available increases since multiple signals use same bandwidth as they can utilize different paths which a signal may follow to reach a device. This results in an increased throughput because more users can be served on the same band.
5) *Datarate:* MIMO provide a wireless alternative to cable and digital subscriber line (DSL) for last mile broadcast and is used in mobile Worldwide Interoperability for Microwave Access (WIMAX) system. It provides high speed mobile data and telecommunication services for 4G and Long Term Evolution (LTE).
6) *Security:* MIMO systems have positional accuracy, i.e. they work accurately in a very precise antenna arrangement. Thus, they provide increased security because if someone wished to intercept the transmitted signals, they would need to be at the same location as the receiver.

VI. Disadvantages

1) *Complex:* The most disadvantageous aspect of MIMO systems is their complexity compared to traditional antennas. This means that faults or problems are be harder to diagnose and more likely to occur.
2) *Multiple Antennas:* The underlying idea of MIMO framework demands multiple antennas for reducing error rate, which in turn makes the system much larger in size than traditional systems. This can also be a problem in a social context, since antennas may seem unsightly.
3) *More expensive:* As a result of the complexity and the number of antennas used, MIMO systems are far more expensive than traditional communication systems.
4) *Location:* The location of smart antennas needs to be considered for optimal operation. Since fading and scattering provide for the better accuracy of MIMO systems, they need to be placed in areas crowded with buildings. Placing antennas in crowded public places is a pretty hard, if not an impossible task.

VII. Multi-User MIMO

When MIMO is used to communicate with several terminals(wireless users) at the same time, we speak of Multi-User MIMO (MU-MIMO). Here, technology relies on multiple antennas to simultaneously transmit multiple streams of data coming to and from multiple terminals in wireless communication systems.

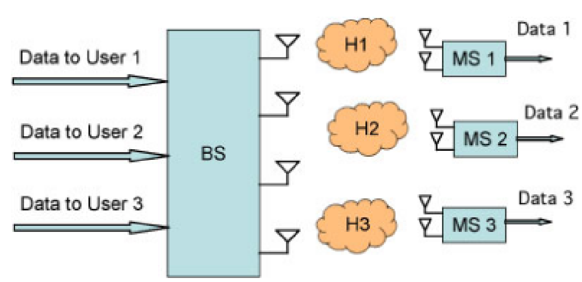

Fig. 4. MU-MIMO system model

MU-MIMO technology for wireless communications is being incorporated in its conventional form into recent wireless broadband standards like 4G LTE and LTE-Advanced (LTE-A). The more antennas the base station(or terminals) are equipped with, better is the performance in all aspects: *increased data rate*, *enhanced reliability*,*improved energy efficiency* and *reduced interference*, at least for operation in time-division duplexing (TDD) mode. The advantages of using multi-user MIMO come at a cost of additional hardware - antennas and processing - and also obtaining the channel state information which requires the use of the available bandwidth.

VIII. MASSIVE MIMO

Massive MIMO is an emerging technology, that scales up MIMO by possibly orders of magnitude compared to current state-of-the-art. Massive MIMO can be viewed as MIMO systems that use antenna arrays consisting of a few hundred antennas, simultaneously serving tens of terminals in the same time-frequency resource. A key feature of massive MIMO technology is that the number of terminals is much less than the number of base station antennas. As noted earlier, both capacity and efficiency of MIMO systems increase with the number of antennas. This is the basic premise behind massive MIMO: to reap all the benefits of conventional MIMO, but on a much greater scale. In a rich scattering environment, the full advantages of the massive MIMO system can be exploited using simple beamforming strategies such as maximum ratio transmission (MRT) or zero forcing (ZF) [10]. To achieve these benefits of massive MIMO, accurate CSI must be available perfectly.

A. Advantages

1) *Capacity:* Massive MIMO increases the the capacity by 10 times or more which results form the aggressive spatial multiplexing used.
2) *Datarate:* We have increased data rate because more the antennas, more are the independent data streams for data to be sent out and consequently, more terminals can be served simultaneously.
3) *Cost:* It can be built with inexpensive low-power components, e.g. ultra-linear 50 Watt amplifiers used in conventional systems are replaced by hundreds of low-cost amplifiers with mW output power range. It reduces the constraints on accuracy of components because we use a very large number of antennas and hence, error rate is already very low.
4) *Efficiency:* Energy efficiency of massive MIMO systems increase because the base station can focus its emitted energy into the spatial directions where it knows that the terminals are located.
5) *Latency:* Massive MIMO enables a significant reduction of latency on the air interface, which follows from the law of large numbers. It relies on beamforming[10] in order to avoid fading dips, so that fading no longer limits latency
6) *Robustness:* Massive MIMO increases the robustness to intentional jamming since it offers many excess degrees of freedom that can be used to cancel signals from intentional jammers. Although the implementation using uplink pilots for channel estimation is prone to harmful interference by smart jammers, more clever implementations using joint channel estimation and decoding substantially diminish that problem.
7) *Degrees of Freedom:* A massive MIMO system has a large surplus of degrees of freedom which can be used for hardware friendly signal shaping, e.g. with 200 antennas serving 20 terminals, 180 degrees of freedom are unused.

B. Challenges

1) *CSI Estimation:* Massive MIMO relies on the base station having enough channel knowledge, both on the uplink and the downlink. On the uplink, this is accomplished by having the terminals send pilots(known signals), from which the base station estimates the channel responses to each of the terminals. The downlink is more difficult in massive MIMO systems because optimal downlink pilots should be mutually orthogonal between the antennas. Since the amount of time-frequency resources needed for downlink pilots scales as the number of antennas, a massive MIMO system would require up to a hundred times more such resources than a conventional system. Also, the number of channel responses that each terminal must estimate is proportional to the number of base station antennas. Hence, the uplink resources needed to inform the base station about the channel responses would be up to a hundred times larger than in conventional systems. Nevertheless, [11] shows some promising algorithms for channel estimation of massive MIMO systems. Also, time-division duplexing(TDD) is used instead of frequency-division duplexing(FDD).
2) *User Location:* Users located close to line-of-sight(LOS) face the difficulty of spatial separation, which may cause high correlation between the channels to different users, which in turn leads to higher BER. The non-line-of-sight(NLOS) condition with rich scattering is necessary for providing more favorable propagation and thus allowing better spatial separation of the users which results in higher de-correlation between users[12].
3) *Non-CSI operation:* Before a link has been established with a terminal, the base station has no way of knowing the channel response to the terminal. This means that no array beamforming(spatial filtering) gain can be harnessed. In this case, some other form of space-time block coding is optimal. But, once the terminal has been contacted, the base station can learn the channel response and operate in coherent MU-MIMO mode, reaping the power gains offered by having a very large array.
4) *Pilot Contamination* Pilot contamination is encountered in *multi-cell* MIMO systems(multiple base stations having multiple users each) when the channel estimate at one base station becomes polluted by users from other cells. The use of non orthogonal training(pilot) sequences causes this contamination [13].

5) *New Users:* Acquisition and synchronization for newly joined terminals is a challenge in massive MIMO systems. Addition of new users affects the channel synchronization, and the synchronization has to be repeated all over again.

IX. Application of MIMO in 4G/5G

A. 4G

4G is synonymous with LTE technology, which was an evolution of the 3G wireless standard. In fact, LTE is an advanced form of 3G that marks an audacious shift from hybrid data and voice networks to a data-only IP network. There are two key technologies that enable LTE to achieve higher data throughput than predecessor 3G networks: MIMO and OFDM. OFDM is a transmission technique that divides a radio channel into a large number of closely spaced subchannels to provide more reliable communications at high speeds. MIMO technique further improves data throughput and spectral efficiency of the system. It uses complex digital signal processing to set up multiple data streams on the same channel. The early LTE networks supported 2×2 MIMO in both the downlink and uplink. The LTE standard uses both forms of duplex operations: FDD and TDD.

B. MIMO-OFDM

The combination of MIMO and OFDM techniques is the dominant air interface for 4G and 5G broadband wireless communications. It brings together the multiplied capacity, increased data-throughput and spectral efficiency of MIMO & bandwidth-sharing ability and simplicity of OFDM architecture to provide more reliable communications at higher speeds compared to 3G. Research conducted during the mid-1990s showed that while MIMO can be used with other popular air interfaces such as time division multiple access (TDMA) and code division multiple access (CDMA), the combination of MIMO and OFDM is most practical at higher data rates.

MIMO-OFDM is the foundation for advanced wireless local area network (wireless LAN) and mobile broadband network standards. Raleigh showed [1] that different data streams could be transmitted at the same time on the same frequency by taking advantage of the fact that signals transmitted through space bounce off objects(such as the ground nad buildings) and take multiple paths to the receiver. That is, by using multiple antennas and precoding the data, different data streams could be sent over different paths.

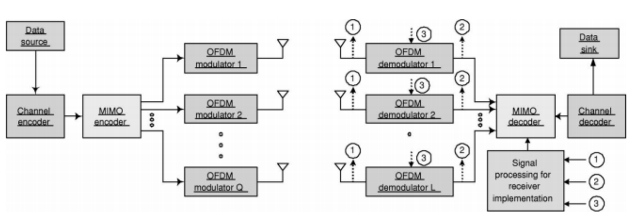

Fig. 5. MIMO-OFDM system model [15]

MIMO multiplies the capacity of a radio link by transmitting multiple signals over multiple, co-located antennas. This is accomplished without the need for additional power or bandwidth. Spacetime codes are employed to ensure that the signals transmitted over the different antennas are orthogonal to each other, making it easier for the receiver to distinguish one from another. OFDM enables reliable broadband communications by distributing user data across a number of closely spaced, narrowband subchannels. This arrangement makes it possible to eliminate the biggest obstacle to reliable broadband communications, intersymbol interference (ISI). Normally, high data rates require shorter duration symbols, increasing the risk of ISI. By dividing a high-rate data stream into numerous low-rate data streams, OFDM enables longer duration symbols. A cyclic prefix (CP) may be inserted to create a (time) guard interval that prevents ISI entirely.

A key advantage of OFDM is that fast Fourier transform(FFT) may be used to simplify implementation. Discrete Fourier Transforms(DFT) may be applied to composite OFDM signals, avoiding the need for the banks of oscillators and demodulators associated with individual subcarriers. Fast Fourier transforms are numerical algorithms used by computers to perform DFT calculations [14]. FFTs also enable OFDM to make efficient use of bandwidth. The subchannels must be spaced apart in frequency just enough to ensure that their time-domain waveforms are orthogonal to each other.

MIMO-OFDM is a particularly powerful combination because MIMO does not attempt to mitigate multipath propagation and OFDM avoids the need for signal equalization. MIMO-OFDM can achieve very high spectral efficiency even when the transmitter does not possess channel state information(CSI). When the transmitter does possess CSI, it is possible to approach the theoretical channel capacity.

C. 5G

The next generation of wireless data networks, called the fifth generation or 5G, must address not only future capacity constraints but also existing challenges such as network reliability, coverage, energy efficiency, and latency with current communication systems. Unlike its 4G counterpart, 5G network will offer the ability to handle a plethora of connected devices and a myriad of traffic types. Massive MIMO, a candidate for 5G technology, promises significant gains in wireless data rates and link reliability by using significantly more antennas at the base transceiver station (BTS) than in current wireless technologies. These antennas, attached to a base station, focus the transmission and reception of signal energy into small regions of space using precoding techniques, providing new levels of efficiency and throughput. By directing the wireless energy to specific users, radiated power is reduced and, at the same time, interference to other users is decreased. This is particularly attractive in todays interference-limited cellular networks.

Another focus of research for 5G wireless is cooperative MIMO(CO-MIMO). In CO-MIMO, clusters of base stations work together to boost performance. This can be done using macro diversity for improved reception of signals from handsets or multi-cell multiplexing to achieve higher downlink data rates. However, CO-MIMO requires high-speed communication between the cooperating base stations.

X. Performance Comparison

The following table compares the spectral efficiency and datarate of MIMO systems with those of other contemporary wireless systems. [16]

Technology	Max. Spectral Efficiency (bits/s/Hz)	Max. Bitrate (Mbits/s)
3G	2.5	3.075
3.5G	4.22	21.1
4G SISO	4	72
4G MIMO (4X4)	16.32	81.6
4G MIMO (8X8)	30	75

The given figure compares the bit error rates in different technologies having same number of antennas.

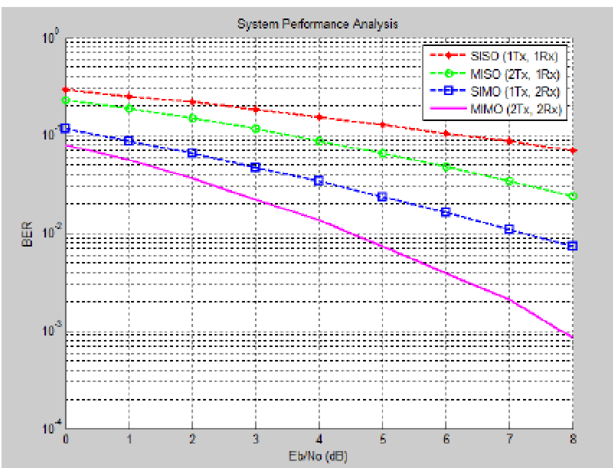

Fig. 6. BER Performance comparison of SISO, MISO, SIMO and MIMO systems [21]

XI. Summary

MIMO system delivers higher data rate due to transmission of multiple data symbols simultaneously using multiple antennas. MIMO communications channels gives solution to the fading and multipath challenge by requiring multiple antennas to transmit same signal. MIMO systems use a combination of multiple antennas and multiple signal paths to gain knowledge of the communications channel. In MIMO, a receiver can recover independent streams from each of the transmitter's antennas. It can be observed that MIMO configuration exceeds the capacity given by the Shannon-Hartley limit at all data rates, making MIMO systems attractive for higher data throughput. While MIMO systems provide users with clear benefits at the application level, the design and test of MIMO devices is not without significant challenges. System benefits such as improvements in data rate, capacity and resilience to multipath are likely to motivate continued development of MIMO-OFDM, MU-MIMO and Massive MIMO communications systems. If the promise of advanced MIMO techniques hold true, 5G networks of the future will be faster and accommodate more users with better reliability and increased energy efficiency.

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