Exploiting MIMO Technology in Wireless Communication

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Abstract **- Better communication is the need of the generation. No stone is left unturned in making the communication services better and better with each passing day, but the hostile environment poses new challenges with every new development making the earlier technologies obsolete. MIMO technology is one of the technologies promising to provide better and reliable communication. It has been employed in various modern technologies with the hope that it will also support the future genre. This paper analyses MIMO technology and its characteristics. An analytical MIMO system model is also explained to give an insight view of MIMO communication system.**

IndexTerms **- Multiple-input multiple-output (MIMO), Space-Time Block Code (STBC), Spatial Multiplexing (SM), Digital Subscriber Line (DSL), Long Term Evolution (LTE)**

I. INTRODUCTION

AWireless is one of the most rapidly developing technologies in our time, with a plethora of dazzling new products and services emerging with time. These developments present open challenges for communications engineers which need radical approach. The main technical issue in wireless communications is that of multipath-induced fading [1]. This multipath scattering is considered as impairment to wireless communication. But it can now also be seen as providing an opportunity to significantly improve the capacity and reliability of such systems. One such technology is MIMO technology where by using multiple antennas at the transmitter and receiver in a wireless system, the rich scattering channel can be exploited to create a multiplicity of parallel links over the same radio band, and thereby to either increase the rate of data transmission through multiplexing or to improve system reliability through the increased antenna diversity [3]. MIMO technology is a wireless networking technology which plays a vital role in increasing the range, capacity and throughput of a wireless communication system. It was in 2001 that the MIMO technology was first used in cellular systems by Iospan, Inc. Since then, various standards have evolved which are based on MIMO technology, for example, WiFi (IEEE802.11n), WiMAX (IEEE 802.16e), Enhanced HSPA, LTE (3.9G), LTE-Advanced (4G) etc. All these standards have implemented MIMO technique in different ways, but the underlying concept of MIMO is same in all these standards [10]. It actually includes various signal processing techniques which enhance the system performance by placing multiple antennas at the transmitter and receiver. MIMO technology basically exploits the concept of multipath propagation by using the idea of spatial multiplexing where the multiple data streams are transmitted using different spatial channels. In order to have reliable communication, the need is to combat the fading which is experienced by the transmitted signals [12].

Literature presents a lot of content regarding MIMO technology. In [3], the authors have provided a description of MIMO wireless communication. This paper discussed the environmental factors that affect MIMO capacity. The factors which have been considered are channel complexity, external interference, channel estimation error, etc. Examples of space-time codes, including space-time low-density parity-check codes and space-time turbo codes, are also discussed. This paper has also reported the experimental performance of these codes. A channel phenomenology parameterization is discussed in this paper. The reported experimental phenomenological results indicated that the observed channels can be typically characterized by high degrees of complexity. Experimental demodulation performance results are presented for a variety of environments, including those with wideband jammers. In the presence of the jammer, the MIMO system operated dramatically better than SISO systems. In [4], the authors have described that high data rate wireless communications, nearing 1-Gb/s transmission rates, is of prime interest in emerging wireless communications. The paper mentioned that designing very high speed wireless links that offer good quality-of-service and range capability in non-line-of-sight (NLOS) environments is a significant research and engineering challenge. The authors emphasized that it is possible, in principle, to meet the 1-Gb/s data rate requirement with a single-transmit single-receive antenna wireless system if the product of bandwidth and spectral efficiency is equal to 10^9. But there are a variety of cost, technology, and regulatory constraints make such a solution unattractive, if not impossible The use of multiple antennas at transmitter and receiver, popularly known as multiple-input multiple-output (MIMO)wireless is a cost-effective technology that offers substantial leverages in making 1-Gb/s wireless links a reality. This paper provides an overview of MIMO wireless technology covering channel models, performance limits, coding, and transceiver design. In [5], the authors have presented an overview of the progress in the area of multiple-input–multiple-output (MIMO) space–time coded wireless systems. Special attention is given to the different classes of techniques and algorithms which attempt to realize the various benefits of MIMO including spatial multiplexing and space–time coding schemes. These algorithms are analyzed under ideal independent fading conditions. In this paper, the state of the art in channel modeling and measurements is presented which leads to a better understanding of actual MIMO gains. Finally, the authors have addressed various current questions regarding the integration of MIMO links in practical wireless systems and standards. In [6], the authors have introduced space–time block coding as a new paradigm for communication over Rayleigh fading channels using multiple transmit antennas. The authors mentioned that the data is first encoded using a space–time block code and the encoded data is split into n streams which are simultaneously transmitted using n transmit antennas. The received signal at each receive antenna is a linear superposition of the n transmitted signals perturbed by noise. Further, it is mentioned in the paper that Maximum likelihood decoding is achieved in a simple way through decoupling of the signals transmitted from different antennas rather than joint detection. This decoupling uses the orthogonal structure of the space–time block codes. Space–time block codes are designed to achieve the maximum diversity order for a given number of transmit and receive antennas subject to the constraint of having a simple decoding algorithm. In this paper, the classical mathematical framework of orthogonal designs is applied to construct space–time block codes. Further, a generalization of orthogonal designs is shown to provide space–time block codes for both real and complex constellations for any number of transmit antennas.

II. MIMO TECHNOLOGY

The use of multiple antennas at the transmitter and receiver in wireless systems is known as MIMO (multiple-input multiple-output) technology. It has rapidly gained in popularity over the past decade due to its powerful performance-enhancing capabilities. Communication in wireless channels is impaired predominantly by multi-path fading [3]. Multi-path is the arrival of the transmitted signal at an intended receiver through differing angles or differing time delays or differing frequency (i.e., Doppler) shifts due to the scattering of electromagnetic waves in the environment. Consequently, the received signal power fluctuates in space (due to angle spread) or frequency (due to delay spread) or time (due to Doppler spread) through the random superposition of the impinging multi-path components [7]. This random fluctuation in signal level, known as fading, can severely affect the quality and reliability of wireless communication. Additionally, the constraints posed by limited power and scarce frequency bandwidth make the task of designing high data rate, high reliability wireless communication systems extremely challenging [8]. MIMO technology constitutes a breakthrough in wireless communication system design. The technology offers a number of benefits that help meet the challenges posed by both the impairments in the wireless channel as well as resource constraints. In addition to the time and frequency dimensions that are exploited in conventional single-antenna (single-input single-output) wireless systems, the leverages of MIMO are realized by exploiting the spatial dimension (provided by the multiple antennas at the transmitter and the receiver) [9].

The first commercial MIMO system was developed in 2001 by Iospan Wireless Inc. Since 2006, several companies such as Broadcom and Intel have introduced a novel communication technique based on the MIMO technology for improving the performance of wireless Local Area Network (LAN) systems. The new standard of wireless LAN systems is named IEEE 802.11n. Nowadays, MIMO systems are implemented in many advanced technologies such as various standard proposals for the Fourth Generation (4G) of wireless communication systems and LTE. MIMO technology was shown to boost the communication system capacity and to enhance the reliability of the communication link since it uses several diversity schemes beyond the spatial diversity [12].

III. MIMO SYSTEM MODEL

MIMO system model is depicted in Figure 1. We present a communication system with N_T transmit antennas and N_R receive antennas. Antennas T_{x_1} …….. , $T_{x_{N_T}}$ respectively send signals $x_1, \ldots, x_{N_T}$ to receive antennas $R_{x_1}, \ldots, R_{x_{N_R}}$. Each receive antenna combines the incoming signals which coherently add up. The received signals at antennas $R_{x_1}, \ldots, R_{x_{N_R}}$ are respectively denoted by $y_1 \ldots, y_{N_R}$. We express the received signal at antenna T_{x_q} where q = 1, . . . , N_R as:

$$y_q = \sum_{p=1}^{N_T} h_{qp} \cdot x_p + b_q \qquad \text{where } q=1,\ldots\ldots N_R$$

The flat fading MIMO channel model is described by the input-output relationship as:

$$y = H \cdot x + b$$

where H is the ($N_R \times N_T$) complex channel matrix given by:

$$H = \begin{pmatrix} h_{11} h_{12} & \cdots & h_{1N_T} \\ \vdots \quad \vdots & \ddots & \vdots \\ h_{N_{R_1}} h_{N_{R_2}} & \cdots & h_{N_R N_T} \end{pmatrix}$$

h_{qp} where p = 1, . . . , N_T and q = 1, . . . , N_R is the complex channel gain which links transmit antenna Tx_p to receive antenna Rx_q.

Here $x = [x_1, \ldots \ldots \ldots, x_{N_T}]^T$ is the ($N_T \times 1$) complex transmitted signal vector.

$y = [y_1, \ldots \ldots .. y_{N_r}]^T$ is the ($N_R \times 1$) complex received signal vector.

$b = [b_1, \ldots \ldots .. b_{N_R}]^T$ is the ($N_R \times 1$) complex additive noise signal vector.

The continuous time delay MIMO channel model of the ($N_R \times N_T$) MIMO channel H associated with time delay τ and noise signal b(t) is expressed as:

$$y(t) = \int H(t,\tau)\, x(t-x)d\tau$$

where y(t) is the spatio-temporal output signal , x(t) is the spatio-temporal input signal , b(t) is the spatio-temporal noise signal.

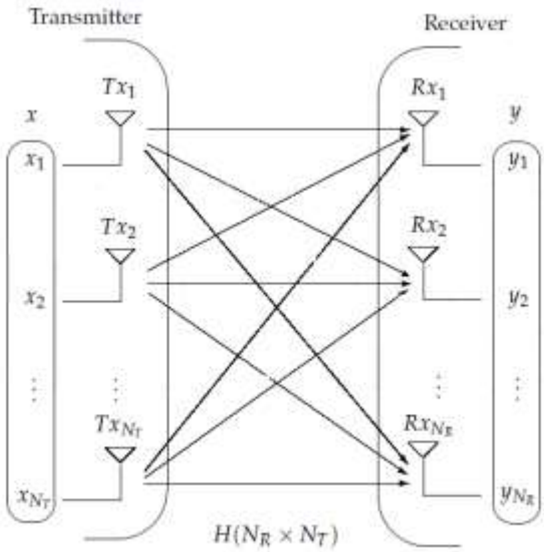

Fig.1 MIMO system model

MIMO technology has been shown to improve the capacity of the communication link without the need to increase the transmission power. MIMO system capacity is mainly evaluated according to the following scenarios:

When no Channel State Information (CSI) is available at the transmitter, the power is equally split between the N_T transmit antennas, the instantaneous channel capacity is then given by:

$$C(H) = \log_2\left[\det(I_{N_R} + \frac{\gamma}{N_T}\ .HH^*)\right] \quad \text{bits/s/Hz}$$

where γ denotes SNR , $(.)^*$ denotes conjugate transpose operator

When CSI is available at the receiver, Singular Value Decomposition (SVD) is used to derive the MIMO channel capacity which is given by:

$$C_{SVD}(H) = R\ \log_2\left[\det(1 + \frac{\gamma}{N_T}\ .HH^*)\right] \text{bits/s/Hz}$$

where R = min(N_R, N_T) is the rank of the channel matrix H

When CSI is available at both the transmitter and the receiver, the channel capacity is computed by performing the water-filling algorithm. The instantaneous channel capacity is then:

$$C_{WF}(F) = \sum_{p=1}^{R} \log_2\left[\left(\frac{\lambda_{H,p}.\mu}{\sigma_b{}^2}\right)^+\right] \quad \text{bits/s/Hz}$$

where a^+=max(a,0) , $\lambda_{H,p}$ is the p − th singular value of the channel matrix H , μ is a constant scalar which satisfies the total power constraint, $\sigma_b{}^2$ is the noise signal power [7].

IV. CHARACTERISTICS OF MIMO TECHNOLOGY

MIMO technology helps in providing reliable and secure communication by focusing on the following two important techniques:

- Spatial diversity to combat fading effects by creating spatial diversity through the use of baseband space-time coding techniques;
- Spatial multiplexing to use spatial multiplexing techniques to exploit multipath in order to achieve higher data rates than are possible with conventional systems having the same bandwidth.

Spatial diversity

Diversity techniques may exploit the multipath propagation resulting in a diversity gain. In space diversity (antenna diversity), the signal is transmitted over several different propagation paths [8]. Here no additional bandwidth or power is needed in order to take advantage of spatial diversity. Based on whether diversity is applied to the transmitter or to the receiver , space diversity can be further classified as in the following sub-headings.

- ***Receive diversity:*** It involves the simplest and most common multi-antenna configuration of using multiple antennas at the receiver side. Receive diversity places no particular requirements on the transmitter but requires a receiver that processes the *Nr* received streams and combines them in some fashion [9]. The figure 2 shows the architecture of a communication system with receive diversity combining.

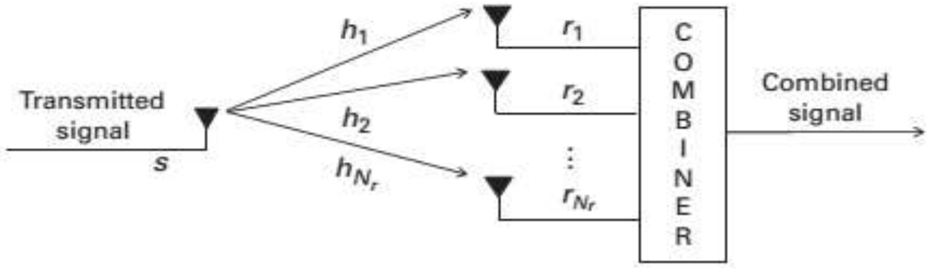

Fig 2. Architecture of a communication system with receive diversity combining.

- ***Transmit diversity:*** Transmit spatial diversity is a newer phenomenon than receive diversity and has become widely implemented only in the early 2000s. Because the signals sent from different transmit antennas interfere with one another, processing is required at both the transmitter and the receiver in order to achieve diversity while removing or at least attenuating the spatial interference [11]. It is an attractive choice due to its simple implementation, good performance, and no feedback requirement. It is used mainly for downlink transmission. In this approach, delayed versions of a signal are sent at the transmit antennas. It converts spatial diversity into frequency diversity by transmitting the data signal from the first antenna and a delayed replica thereof from the second antenna. The delay process at the transmitter results in a frequency selectivity in the received channel response [12]. The figure 3 shows the architecture of a communication system with transmit diversity combining.

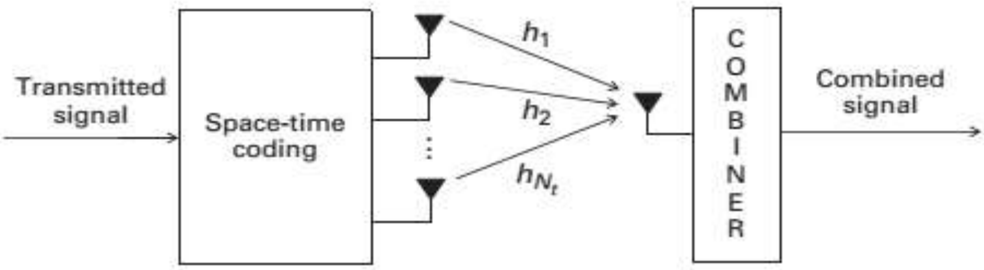

Fig. 3 Architecture of a communication system with transmit diversity combining.

Space-time block coding is a simple yet ingenious transmit diversity technique in MIMO technology. The combination of coding with spatial diversity has proved very useful in wireless communications by helping in realizing reliable high-speed wireless communication links. Space-time block coding is a simple and effective form of achieving transmit diversity [3]. To have a proper coding design is the need for a digital communication system which takes into account several design factors like coding gain, channel characteristics, source coding requirements, modulation, etc. MIMO technology with the block of space time coding (STBC) represents an interesting candidate for communication systems due to its ability to withstand high speeds, high capacity and robustness to multipath fading [4]. Spatial diversity technique in terms of the technique designed to encode multiantenna transmissions is referred to as Space-Time Coding (STC). STC schemes map the source symbols to the transmit antennas. These schemes were popularized with the discovery of Space-Time Block Code (STBC). Orthogonal STBs are an important subclass of linear STBCs that guarantee that the ML detection of different symbols is decoupled [6]. An OSTBC is a linear space-time block code S that has the following unitary property:

$$S^H S = \sum_{n=1}^{N} |s_n|^2 I$$

The orthogonality enables us to achieve full transmit diversity and at the same time, it allows the receiver to do simple ML decoding. The antennas are separated in such a way the individual signals are uncorrelated. Therefore, coding over MIMO systems is fundamental to the realization of the promises offered by MIMO systems in terms of reliability and achievable transmission rates [15].

Spatial multiplexing

Transmit diversity does not help with any boost in data rate but only contributes to the increased robustness against channel fading and improves the link quality. While as the spatial multiplexing contributes directly to the increased data rate [8]. Spatial multiplexing (SM) refers to transmitting multiple data streams over a multipath channel by exploiting multipath. By so doing, multiple data channels are able to be transmitted simultaneously over the same frequency band, enabling potentially large numbers of bits per second to be transmitted per Hertz of spectrum [9]. In SM, multiple signals are assigned to different spatial channels instead of time or frequency slots, so the signals are transmitted at the same time over the same bandwidth. As a result, SM does not suffer from bandwidth expansion the way that TDM and FDM do [10].

Fig 4. Generic diagram of a MIMO communication system that uses spatial multiplexing

Figure 4 shows a high-level block diagram of a MIMO system that uses spatial multiplexing. There are three main components of a spatial multiplexing system. The first component is precoder whose purpose is to map the multiple input streams of data that are to be transmitted onto the set of transmit antennas. The second component of an SM system is the postcoder, which processes the signals from the receive antennas and generates estimates of the original input data streams that originally went into the precoder at the transmitter [8]. The third component of an SM system is the communications channel itself. In order for spatial multiplexing to work, the channel must have a significant amount of multipath scattering. This may seem odd since multipath is normally regarded as the enemy by communications engineers since it degrades the performance of conventional communication systems. However, since spatial multiplexing exploits multipath, its presence is necessary for SM techniques to work [11].

V. BENEFITS OF MIMO TECHNOLOGY

The benefits of MIMO technology that help achieve such significant performance gains which are given as under [11]

- ***Array gain :***Array gain is the increase in receive SNR that results from a coherent combining effect of the wireless signals at a receiver. The coherent combining may be realized through spatial processing at the receive antenna array and/or spatial pre-processing at the transmit antenna array. Array gain improves resistance to noise, thereby improving the coverage and the range of a wireless network[11].
- ***Spatial diversity gain:***Spatial diversity gain mitigates fading and is realized by providing the receiver with multiple (ideally independent) copies of the transmitted signal in space, frequency or time. With an increasing number of independent copies (the number of copies is often referred to as the diversity order), the probability that at least one of the copies is not experiencing a deep fade increases, thereby improving the quality and reliability of reception. A MIMO channel with M_T transmit antennas and M_R receive antennas potentially offers $M_T \times M_R$ independently fading links, and hence a spatial diversity order of $M_T \times M_R$
- ***Spatial multiplexing gain :***MIMO systems offer a linear increase in data rate through spatial multiplexing i.e., transmitting multiple, independent data streams within the bandwidth of operation. Under suitable channel conditions, such as rich scattering in the environment, the receiver can separate the data streams. Furthermore, each data stream experiences at least the same channel quality that would be experienced by a single-input single-output system, effectively enhancing the capacity by a multiplicative factor equal to the number of streams. In general, the number of data streams that can be reliably supported by a MIMO channel equals the minimum of the number of transmit antennas and the number of receive antennas, i.e., min [M_T ,M_R]. The spatial multiplexing gain increases the capacity of a wireless network [9].
- ***Interference reduction and avoidance:***Interference in wireless networks results from multiple users sharing time and frequency resources. Interference may be mitigated in MIMO systems by exploiting the spatial dimension to increase the separation between users. Interference reduction and avoidance improve the coverage and range of a wireless network [15].

In general, use of MIMO technology will result in improved capacity, coverage and reliability in communication. It is because of the above said reasons that MIMO technology finds its applications in many areas and is nowadays exploited in 3GPP LTE, Release 8 of LTE ,Release 9 of LTE,LTE advanced, Multiple-cell networks, Digital Subscriber Line (DSL) ,etc [12] [14].

VI. CONCLUSION

MIMO technology is one of the technologies which have the potential to raise the bar of communication services. It provides array gain, spatial multiplexing gain, spatial diversity gain and helps in interference mitigation. This paper provides a brief description of MIMO technology with its system model and characteristics. The need is to incorporate MIMO technology with other communication technologies so as to provide better constructive results.

REFERENCES

[1] Ezio Biglieri et al., “MIMO Wireless Communications”, Cambridge University Press 2007
[2] Tim Brown et al., “Practical guide to MIMO radio channel with MATLAB examples”, Wiley Publications
[3] Bliss D.W., Forsythe K.W.,Chan A.M.,“MIMO Wireless Communication” Lincoln Laboratory Journal, Vol. 15, No. 1, 2005
[4] Paulraj Arogyaswami J. , Gore Dhananjay A. , NabarRohit U. , Bolcskei H. , “An Overview of MIMO Communications—A Key to Gigabit Wireless”, Proceedings of the IEEE, Vol. 92, No. 2, February 2004

[5] Gesbert D. , Shafi M. ,ShiuD.S. , Smith P. J.,NaguibA. , "From Theory to Practice: An Overview of MIMO Space–Time Coded Wireless Systems", IEEE Journal on Selected Areas in Communications, Vol. 21, No. 3, April 2003.
[6] Tarokh V., Jafarkhani H. , Calderbank A. R. , "Space–Time Block Codes from Orthogonal Designs", IEEE Transactions on Information Theory, Vol. 45, No. 5, July 1999
[7] George Tsoulos "MIMO SystemTechnology For WirelessCommunications", CRC Press Taylor & Francis Group,2006
[8] Gordon L. Stüber et al., "Broadband MIMO-OFDM WirelessCommunications",Proceedings of the IEEE, Vol. 92, No. 2, February 2004
[9] Sreco Plevel et al., "MIMO: Wireless Communications", Taylor & Francis, Encyclopedia of Wireless and Mobile Communications,2008
[10] Lajos Hanzo et al., "MIMO-OFDM for LTE, Wi-Fi and WiMAX", Wiley Publications, 2011
[11] Yong Soo Cho et al.,"MIMO-OFDM Wireless Communications with MATLAB", Wiley Publications, 2010
[12] Miang Jiang et al., " Multi user MIMO-OFDM for Next Generation Wireless Systems", Proceeding of IEEE, Vol.95 , No.7, July 2007
[13] Rui Zhang & Ying-Chang Liang , " Exploiting Multi-Antennas for Opportunistic Spectrum Sharing in Cognitive Radio Networks", IEEE International Symposium on Personal, Indoor and Mobile Radio Communication, September 2007
[14] Erik G. Larsson et al.,"Massive MIMO for Next GenerationWireless Systems",IEEE Communications Magazine , February 2014
[15] Mohinder Jankiraman "Space-Time Codes and MIMO Systems", Artech House, 2004
[16] Nidhi Sharma et al., "Space Time Block Code for Next Generation Multi-user MIMO Systems", Elsevier, Procedia Computer Science 34 (2014) 172 – 179