Space Diversity and MIMO Techniques for Wireless Communications

Ajay Kumar Kadel, B.E. (Electrical & Electronics), Toshak Raj Uprety B.E.(Electronics & Comm.)

***Abstract*--Diversity techniques are powerful techniques to combat multipath fading. This paper explains space diversity as a technique to mitigate multipath fading. This paper highlights the use of Alamouti's scheme as an efficient transmit diversity scheme. The transmit diversity gave rise to multiple input multiple output (MIMO) communications. The different decoding techniques of MIMO wireless communications are discussed. The paper presents the simulation results of the different diversity and MIMO decoding techniques in both the Rayleigh and ricean fading channels environments.**

***Index Terms*--Diversity, space diversity, diversity combining methods, multipath fading, Alamouti's transmit diversity shceme, MIMO, Rayleigh channel, Ricean Channel**

I. Introduction

In the last century, the advances in very large scale integration and digital signal processing technologies have enabled the implementation of complicated algorithms and coding systems in small devices with low power consumption, as required in modern mobile communications. Such technical breakthroughs have promoted the rapid growth of the global market in wireless communication equipment and services. Furthermore, the demands for higher network capacity and improved performance of wireless communications are continuously growing. With the advent of applications such as multimedia data transmission (audio and video streams) or online gaming networks, a much higher spectral efficiency is needed to provide the services with adequate quality [1].

While transmitting a signal from a transmitter to a receiver in wireless communications, there are naturally multiple paths for the signal to propagate. In the course of propagation these individual paths act as a separate channel. Consequently, a receiver in wireless communication receives multiple signals with varying amplitude and phase. The amplitudes and phases are continuously changing due to movement of the transmitter, receiver or surrounding structures. Hence, the signal replicas change from adding constructively to adding destructively at the receiver, and vice-versa. The consequence is a phenomenon known as fading, consisting of a rapid fluctuation of the received signal strength over short periods of time. This fading invariably results in a low signal to noise ratio (SNR) in comparison to a non-fading channel. An improvement in SNR demands further increase in transmitted power. This option is not feasible as transmission powers are limited by regulatory bodies and it also results in further interference to other wireless transmissions. Diversity is one of the ways to combat this multipath fading.

The main idea behind diversity is to provide different replicas of the transmitted signal to the receiver. If these different replicas fade independently, it is less probable to have all copies of the transmitted signal in deep fade simultaneously [2]. Therefore, the receiver can reliably decode the transmitted signal using these received signals. Diversity techniques can be implemented into different ways.

In *time diversity* different time slots are used to achieve diversity. This method requires that the different samples be transmitted sufficiently far apart in time so that they undergo uncorrelated fading processes. If the fading is slow, that is the coherence time of the channel is large, the separation between time slots used for time diversity is high. Increasing the time gap between the different samples is not always an option, especially in applications such as voice communications. In addition to this time diversity is not bandwidth efficient because of the underlying redundancy [3].

In *frequency diversity* different frequency bands are used to achieve diversity. The utilized spectrum has to be broad enough to ensure that fading is uncorrelated at the different frequencies. This is also not a bandwidth efficient option as it requires several frequency bands for the transmission of the signal.

In *space diversity* multiple antennas are deployed at either the transmitting end or the receiving end to achieve diversity. The distance between the multiple antennas must be sufficiently far apart to ensure that the signals from the individual antennas face uncorrelated fading processes. Space diversity is an attractive alternative in modern scenario where bandwidth is a precious commodity. Space diversity can further be divided into receive and transmit diversity.

II. Receive Diversity

Receive diversity is achieved using multiple antennas on the receiving end of the communication link. The method of using multiple antennas on the receiving end has been in use for a number of years to improve the bit error rate (BER) performance. The basic idea is to have multiple signals with different degree of fading or different channel transfer function 'h'. The signals are then appropriately combined with the help of diversity

Ajay Kumar Kadel is working as an Assistant Lecturer in Kathmandu Engineering College (email: collective.ajay@gmail.com). Toshak Raj Uprety is also working as an Assitant Lecturer in Kathmandu Engineering College. (email:truprety@hotmail.com)

combining techniques. The basic configuration for receive diversity is shown in fig. 1.

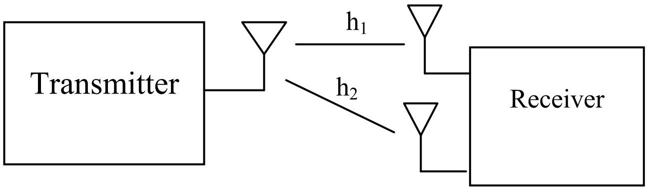

Fig.1 Receive Diversity with two antennas

III. TRANSMIT DIVERSITY

Transmit diversity is achieved using multiple antennas on the transmitting end of the communication link. The transmit diversity is far more advantageous in comparison to the receive diversity. This is due to the fact that in general the number of receivers is greater than the number of transmitters. The transmit diversity is a modern phenomenon. The basic configuration for transmit diversity is shown in fig. 2.

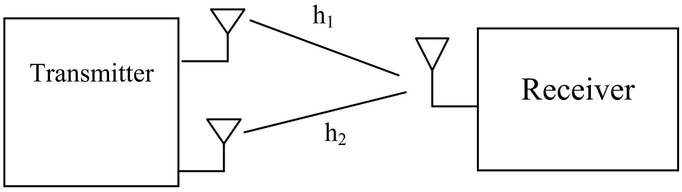

Fig.2 Transmit Diversity with two antennas

IV. ALAMOUTI'S TRANSMIT DIVERSITY SCHEME

In the past receive diversity was widely used. This was due to the fact that receive diversity were simpler and also the receiving devices were generally passive producing little or no interference. Transmit diversity was difficult because of the following two reasons.

- The multiple signals from the transmitting end would combine to produce only one value of signal level at a given point resulting in no diversity.
- The transmitted signals would sometimes produce objectionable nulls in the radiation at some angles.

Alamouti proposed a remarkable diversity scheme in [4] utilizing both space and time diversity known as space time coding. The new transmit diversity proposed by Alamouti in [4] states that " Using two transmit antennas and one receive antenna the scheme provides the same diversity order as maximal-ratio receiver combining (MRRC) with one transmit antenna, and two receive antennas". The salient features associated with this diversity scheme are described as follows.

1. Redundancy is applied in space across multiple antennas, not in time or frequency which implies that it doesn't require any bandwidth expansion.
2. It doesn't need any feedback from the receiver to the TX.
3. Its computation complexity is similar to MRRC.
4. Two transmit antennas and M receive antennas provides a diversity order of 2M.

A. TWO TRANSMITTER AND ONE RECEIVER SCHEME

The block diagram of Alamouti's diversity scheme for two transmitters and one receiver is illustrated in fig.3 and the symbol transmission technique is shown in table 1.

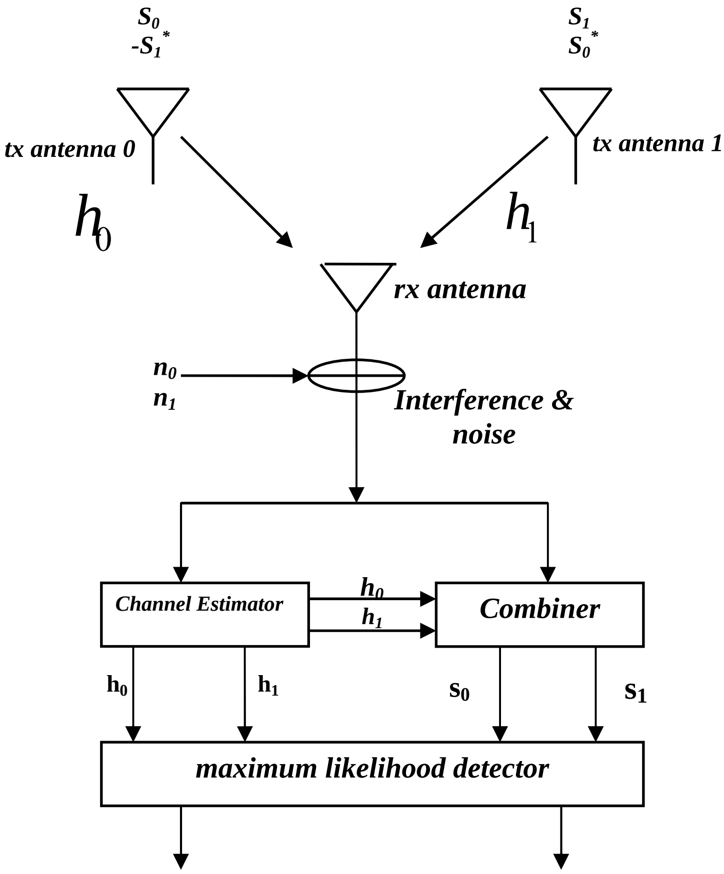

Fig.3 Alamouti's transmit diversity scheme with one receiver [4]

	...t+4T	t+3T	t+2T	t+T	t
Antenna 0	... S_4	$-S_3^*$	S_2	$-S_1^*$	S_0
Antenna 1	... S_5	S_2^*	S_3	S_0^*	S_1

Table 1 Alamouti's transmission technique

The receiving equations are given as

$$r_0=r(t)=h_0S_0+h_1S_1+n_0 \quad \text{...............................} 1$$

$$r_1=r(t+T)=-h_0S_1^*+h_1S_0^*+n_1 \quad \text{.......................} 2$$

The combining scheme is deployed as shown in equations 3 and 4

$$s_0=h_0^*r_0+h_1r_1^* \quad \text{....................} 3$$

$$s_1=r_1^*r_0-h_0r_1^* \quad \text{......................} 4$$

These combined signals are then sent to the maximum likelihood detector which, for each of the signals and uses the decision rule expressed in as

$$d^2(s_0, s_i) <= d^2(s_0, s_k) \qquad \text{for all } i \neq k$$

The resulting combined signals in 3 and 4 are equivalent to that obtained from two-branch MRRC. Implementing the above decision rule, s_i is chosen whenever

$$d^2(s_0, (\alpha_0^2 + \alpha_1^2)\, s_i) <= d^2(s_0, (\alpha_0^2 + \alpha_1^2)\, s_k)$$

B. TWO TRANSMITTER AND TWO RECEIVER SCHEME

The block diagram of Alamouti's proposed scheme in regarding two transmitters and two receivers is shown in fig.4.

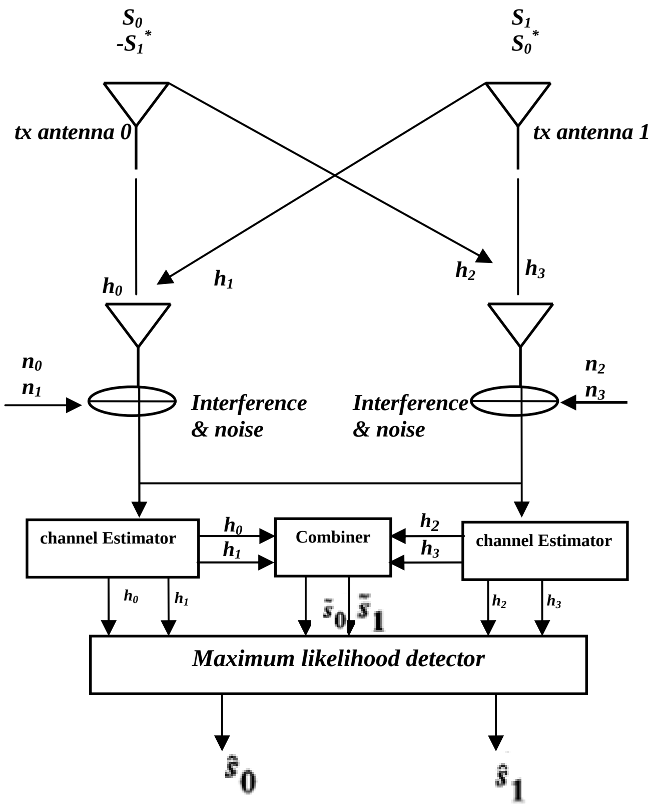

Fig.4 Alamouti's transmit diversity scheme with two receivers [4]

In this scheme the symbols are transmitted as illustrated in table 1. The symbols are then combined as

$$\begin{pmatrix} r_0 & r_1 \\ r_2 & r_3 \end{pmatrix} = \begin{pmatrix} h_0 & h_1 \\ h_2 & h_3 \end{pmatrix} \begin{pmatrix} s_0 & -s_1^* \\ s_1 & s_0^* \end{pmatrix} + \vec{n}$$

The result of the combining signals are given as

$$\begin{bmatrix} \tilde{S}_0 \\ \tilde{S}_1 \end{bmatrix} = \begin{bmatrix} h_0^* & h_1 & h_2^* & h_3 \\ h_1^* & -h_0 & h_3^* & -h_2 \end{bmatrix} \cdot \begin{bmatrix} r_0 \\ r_1^* \\ r_2 \\ r_3^* \end{bmatrix}$$

Which is equivalent to

$$\begin{bmatrix} \tilde{s}_0 \\ \tilde{s}_1 \end{bmatrix} = (\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2) \cdot \begin{bmatrix} s_0 \\ s_1 \end{bmatrix} + \begin{bmatrix} h_0^* & h_1 & h_2^* & h_3 \\ h_1^* & -h_0 & h_3^* & -h_2 \end{bmatrix} \cdot \vec{n}$$

In this transmit diversity scheme we see that the combined signals from the two receive antennas are the addition of the combined signals from each antenna i.e. the combining scheme is identical to a single receive antenna.

The value of si is chosen whenever the following condition is satisfied.

$$d^2(s_0, (\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2)\, s_i) <= d^2(s_0, (\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2)\, s_k)$$

if signals are of equal constellations:

$$d^2(s_0, s_i) <= d^2(s_0, s_k)$$

V. OUR SIMULATION RESULTS OF ALAMOUTI'S DIVERSITY TECHNIQUE

During the simulation of both receive diversity and New scheme the following assumptions are made

1. The total transmit power from the two antennas for the new scheme is the same as the transmit power from the single transmit antenna for MRRC.
2. The amplitudes of fading from each transmit antenna to each receive antenna are mutually uncorrelated Rayleigh distributed and that the average signal powers at each receive antenna from each transmit antenna are the same.
3. The receiver has perfect knowledge of the channel.
4. The transmitted signal is BPSK with equal error probabilites for both logic 1 and logic 0.

As far as the simulation methods are concerned the monte carlo simulation technique is adopted with a sample size of 1000000. The number of tranmitting and receiving antennas is allocated. The SNR values are generated. After that the normalized valued of the

Variance is calculated. The Rayleigh fading channel is modeled and error is counted by transmitting the BPSK symbol. The BER is then subsequently calculated and plotted against the SNR. The BER performance curve obtained through simulation is plotted in fig. 5.

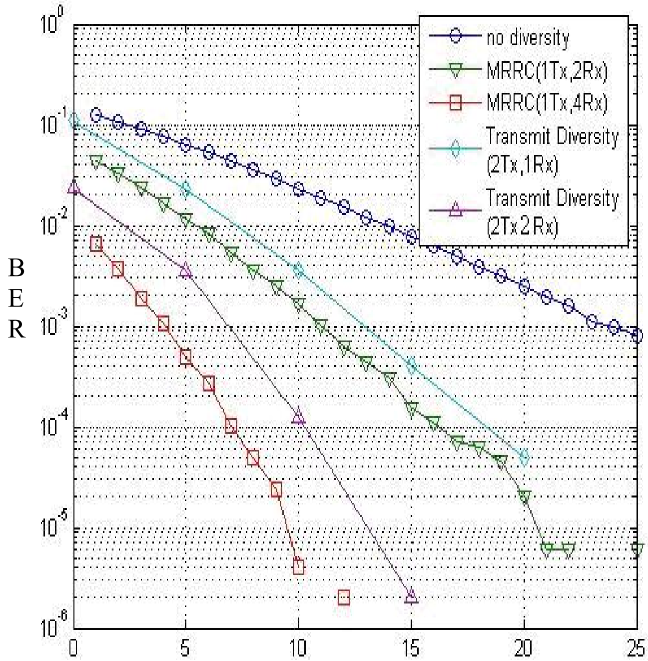

Fig. 5 BER performance comparison of classical receiver scheme and Alamouti's scheme.

VI. MIMO WIRELESS TECHNOLOGY

With the rapid proliferation of wireless communications there is an ever increasing demand for higher data rates, better quality service, and higher network capacity. To meet these needs there is a requirement for techniques that improve the spectral efficiency and increase the reliability of system.

Digital communication using multiple-input–multiple output (MIMO), sometimes called a "volume-to-volume" wireless link, has recently emerged as one of the most significant technical breakthroughs in modern communications. The technology figures prominently on the list of recent technical advances with a chance of resolving the bottleneck of traffic capacity in future Internet-intensive wireless networks [5].

MIMO communications can simply be defined as the communication link consisting of multiple numbers of transmitters and receivers. A generic MIMO system is shown in fig. 6.

Previous to the discovery of MIMO technology, multi-path propagation was seen as a hindrance to wireless communication systems. In contrast, MIMO technology accepts multi-path propagation as an opportunity to address the challenges of wireless technology. MIMO systems serve as a solution to these challenges by providing an increase in signal performance and reliability while handling restricted spectrum. For example, wireless local area network (LAN) products implementing MIMO have demonstrated in laboratory tests, field test and commercial applications the ability to cover areas at least twice as large as conventional wireless LAN products at comparable or better data rates with comparable or better reliability[6].

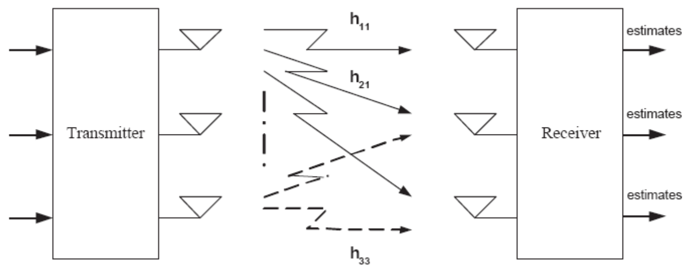

Fig. 6 Generic MIMO System

VII. MIMO SYSTEM MODEL

The MIMO system can be modeled as

$$\begin{bmatrix} r_1(k) \\ \vdots \\ r_{N_R}(k) \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{N_T 1} \\ \vdots & \ddots & \vdots \\ h_{1N_R} & \cdots & h_{N_T N_R} \end{bmatrix} \begin{bmatrix} x_1(k) \\ \vdots \\ x_{N_T}(k) \end{bmatrix} \quad \begin{bmatrix} n_1(k) \\ \vdots \\ n_{N_R}(k) \end{bmatrix}$$

$$\mathbf{r}(k) = \mathbf{H} \cdot \mathbf{x}(k) + \mathbf{n}(k)$$

Where,

r(k):- received vector

H:- quasi-static channel matrix

x(k):- transmitted vector

n(k):- white Gaussian noise vector

VIII. APPROACHES TO MIMO COMMUNICATIONS

There are two popular approaches to MIMO communications. One is the diversity and the other is the spatial multiplexing [7]. Diversity is an approach whereby information is spread across multiple transmit antennas to maximize the diversity advantage in fading channels. Spatial multiplexing, on the other hand, is an approach where the incoming data is divided into multiple sub-streams and each sub-stream is transmitted on a different transmit antenna [8].

IX. MIMO CAPACITY

The capacity of MIMO wireless communications is huge in comparison to its single input Single output (SISO) counterpart. In ideal conditions, Shannon capacity of SISO channel depends upon available bandwidth (B), transmit power (P) and interference from noise (N). In order to achieve maximum SISO capacity for SISO channel, we have to increase the B or P or reduce the noise level (N). In practical systems we have limitations on B and P i.e. fixed available spectrum and power constraint. Noise factor in wireless communication depends upon many factors including fading, shadowing, mobility of user and environment both. Hence we have a limited wireless capacity [9]. In [8], authors have shown that higher spectral capacity and hence efficiency can be achieved by using multiple antennas at transmitter and receiver. It was shown that capacity increases linearly with the increase of number of antennas. Using MIMO system, parallel transmit streams of single user or multiple users can be sent and received. Hence using these parallel sub-channels very high capacity can be achieved. It is then MIMO systems which will make giga-bit wireless systems a reality [10].

X. MIMO RECEIVERS

The MIMO receivers can be categorized into two sections namely linear receivers and optimal receivers.

A. *LINEAR RECEIVERS*

Linear detection is relatively simple to implement and has less computational complexity which in turn reduces the processing time in the receiver. However, these receivers have intermediate performance. Some of the common types of Linear Detection techniques are Selection Combining (SC), Equal Gain Combining (EGC), Maximum Ratio Combining (MRC), Zero Forcing (ZF) and Minimum Mean Squared Error detection (MMSE). Linear detection is a simple process in which the received signal vector is multiplied with a weight matrix to produce the signal estimate [3]. The zero forcing and MMSE schemes are described below.

Zero forcing

Zero Forcing (ZF) is a linear spatial multiplexing detection scheme which is simple and widely used. As the name suggests, this scheme forces the interference to zero [11]. However, it may sometimes result in noise inflation. The weight matrix for ZF for same number of transmit and recceive antenna is given by

$$W^{\Psi}=H^{-1}$$

The estimated signal vector is given by

$$\hat{s} = W^{\Psi}r$$

MMSE

Improved performance compared to ZF can be obtained by attempting to minimize both interference and noise at the same time. This is done by the Minimum Mean Squared Error (MMSE) detection scheme, which is a trade off between noise inflation and interference suppression. The weight matrix for MMSE detection when it is assumed that

$$E|si|^2 = 1$$

is given as

$$W^{\Psi}= H^{\Psi} (\sigma^2 I_M + HH^{\Psi})^{-1}$$

Which is also equivalent to

$$W^{\Psi}=(\sigma^2 I_N + H^{\Psi}H)^{-1} H^{\Psi}$$

Where I_M and I_N are the M × M and N × N identity matrices respectively. It can be seen that in this case, interference is not totally nullified as in the case of ZF but the noise term is less inflated than that of ZF [11].

B. *OPTIMAL RECEIVER*

Maximum Likelihood (ML) is the optimal detection scheme but it has very high computational complexity and hence becomes the most time consuming detection procedure. The procedure is non-linear and basically consists of a search through all possible signal vectors. It's complexity increases with increases in the number of antennas or the size of the signal constellation. The ML detector has the desirable property that, under the statistical assumption on s being random variables uniformly distributed over a constellation S, it minimizes the probability of error,

$$P_e = P(s \neq \hat{s})$$

The likelihood of $\hat{s}$ is obtained by minimizing noise power, the ML estimate of s, i.e.

$$\hat{s}_{ML} = \arg\min_{\hat{s}\in S^N} |r - H\hat{s}|^2$$

Thus, the ML detector chooses the message $\hat{s}$ which yields the smallest distance between the received vector r, and hypothesized message, H $\hat{s}$ [11].

XI. SIMULATION RESULTS OF MIMO RECEIVERS

The different MIMO receivers were simulated using the monte-carlo simulation method. The simulation process was carried out in both the rician and rayleigh fading channels. The simulation results are presented below.

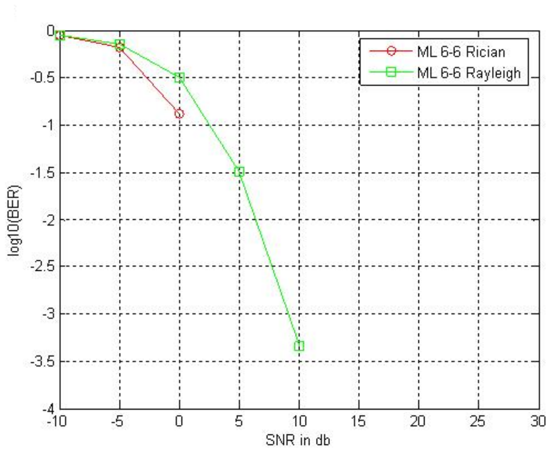

Fig. 7 BER performance comparison of ML reciever in rayleigh and rician channel environments

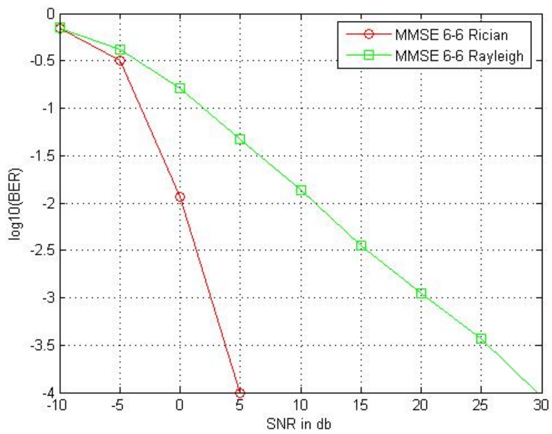

Fig.8 BER performance comparison of MMSE reciever in rayleigh and rician channel environments

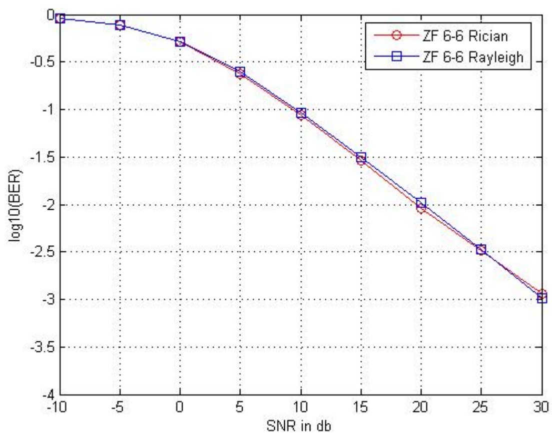

Fig.9 BER performance comparison of ZF reciever in rayleigh and rician channel environments

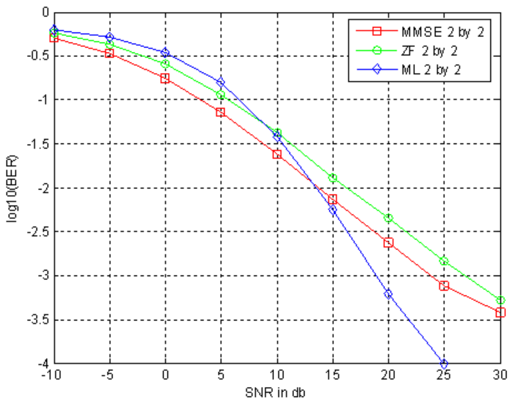

Fig.10 BER performance comparison for 2 Tx-2Rx systems using various MIMO receivers

XII. CONCLUSION

This tutorial paper described the use of space diversity and MIMO techniques in modern wireless communications. The alamouti diversity scheme was highlighted in the paper. We also compared the various MIMO receiving schemes through monte carlo simulation and found ML decoding to be the best receiver for MIMO systems. MIMO technique seems to be very attractive in future wireless communications owing to it's vast capacity. Thus the impact of MIMO systems in future wirless devices seems to be very promising indeed.

REFERENCES

[1] A. F. Naguib, N. Seshadri, and A. R. Calderbank, “Increasing data rate over wireless channels," *IEEE Signal Processing Mag.*, pp. 76-92, May2000.

[2] H.Hourani, “An overview of diversity techniques in wireless communication systems,” *IEEE JSAC* , pp. 1200-5, October 2004.

[3] Hamid Jafarkhani, “*Space Time Coding:Theory and Practice*,” Cambridge University, 2005.

[4] S. Alamouti, “Space block coding: A simple transmitter diversity technique for wireless communications,” *IEEE J. Select. Areas. Commun.*, vol. 16, pp. 1451–1458, Oct. 1998.

[5] D. Gesbert, M. Shafi, D. S. Shiu, P. Smith, and A. Naguib, “From theory to practice: An overview of MIMO space-time coded wireless systems,” *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 3, pp. 281-302, Apr. 2003.

[6] Gabriel Oliphant, “MIMO Wireless Communication Systems” in MIMO Wireless Communication, December 2005.

[7] Robert W. Heath, Jr. and Arogyaswami J. Paulrajacomm, “Switching Between Diversity and Multiplexing in MIMO Systems” *IEEE transactions on communications*, vol. 53, no. 6, June 2005.

[8] G. J. Foschini, “Layered space-time architecture for wireless communication in a fading environment when using multiple antennas,” *Bell Labs. Tech. J.*, vol. 1, no. 2, pp. 41–59, 1996.

[9] A. Khan and R. Vesilo, “A tutorial on SISO and MIMO channel capacities,”

[10] Arogyasawami Paulraj, et al,”An overview of MIMO communications-A key to gigabit wireless,” *Proc. of the IEEE* Feb. 2004.

[11] M. Khatiwada, “A Brief Overview of MIMO Wireless Communication as a Significant Technical Breakthrough in Modern Communications” in *SCITECH.*