



STUDY OF SPATIAL DIVERSITY SCHEMES IN MULTIPLE ANTENNA SYSTEMS

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ABSTRACT

One of the most common problems faced by designers of wireless communication systems is the spatio-temporal variations in the wireless channel which arise mainly due to the phenomenon of multipath fading which is inevitable in scattering environments that are subject to changes over time. A wide variety of pre/post processing techniques have been used to mitigate the degrading effects of such channels, but with limited improvements in performance. This paper provides an evaluation of the concept of Spatial Diversity (SD), applied to multi-antenna systems that demand modifications at the physical level - the use of multiple antennas at the transmitter and/or the receiver. The performance of SISO, SIMO, MISO and MIMO systems have been evaluated and compared in AWGN and fading channels.

Keywords: *Communication, MIMO, Multi antenna Systems, Spatial diversity*

1. INTRODUCTION

Multipath Fading is known to arise due to the non-coherent combination of signals arriving at the receiver antenna. Typically, this phenomenon is described as the constructive/destructive interference between signals arriving at the same antenna via different paths, and hence, with different delays and phases, resulting in random fluctuations of the signal level at the receiver. Deep-fades that may occur at a particular point in space, or at a particular time or frequency, result in severe degradation of the quality of signals at the receiver making it impossible to detect and decode. Several mathematical models have been developed to describe such channels, taking into account, the phenomenon of multipath fading and correlation between sub-channels. Common models employ Rayleigh, Rice and Nakagami-m distributions to approximate actual channel conditions and are described in [1],[2],[3].

The concept of diversity, that is, providing the receiver with multiple copies of the same message, is widely known to be effective in combating channel impairment arising due to multipath fading [3],[4]. This paper discusses the application of

Spatial Diversity (SD) techniques to multi antenna wireless communication systems as in the case of Single Input - Multiple Output (SIMO), Multiple Input - Single Output (MISO) and Multiple Input - Multiple Output (MIMO) systems. Spatial Diversity techniques are discussed in Section 2, in the context of SIMO, MISO and MIMO systems, with attention given to two combining techniques at the receiver: Maximal Ratio (MRC) and Equal Gain Combining (EGC). The assumed channel models are discussed in Section 3. The details of simulations and results are presented in Sections 4 and 5, and the conclusions are discussed in Section 6.

2. SPATIAL DIVERSITY

Diversity techniques help mitigate the effects of fading by providing multiple copies of the same signal to the receiver via different branches or paths (in frequency, time or even space) so that the probability that all paths will undergo the same amount of fading, or even deep-fades, is reduced to a great extent [4]. Thus the receiver can be provided good versions of the signal through one or more

paths. The use of time and frequency diversity-techniques requires extra temporal and spectral resources to ensure that the copies of the signal are sent through different channel conditions or paths. This situation can be avoided by using the additional dimension of space. Most wireless propagation media are rich scattering in nature, thereby introducing a limited degree of orthogonality between channel elements. This property of channels can be exploited using SD to transmit copies of signals via multiple paths to the receiver. Some amount of pre-processing or post-processing may be required at the transmitter and receiver, respectively, to enable the receiver to effectively combine the copies, or select the best copy, to maximize the Signal-to-Noise Ratio (SNR) at the output.

A. SISO

A SISO communication model, Fig. 1, provides the simplest description of a communication link between one transmit-antenna and one receive-antenna. This clearly implies that spatial diversity cannot be applied. Nevertheless, this case is included to assess its performance in fading channels and to bring out the clear advantage of spatial diversity schemes that employ multiple antennas.

The system is simulated as follows:

$$r = h \times c + n \tag{1}$$

where, r denotes the received symbol, h denotes the channel between the transmitter and receiver antennas and n denotes an AWGN component.

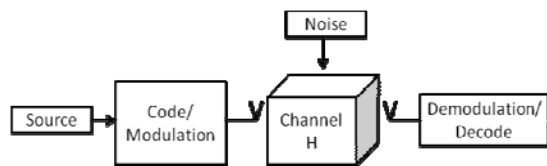


Fig. 1. Block diagram of a SISO System

By Shannon’s capacity theorem, the capacity per unit bandwidth of such a system is [5]

$$C_{SS} = \log_2 (1 + \rho |h|^2) \text{ b s}^{-1} \text{ Hz}^{-1} \tag{2}$$

where, ρ is the average SNR of the signal at the receiver and h is the normalized complex gain of the channel.

B. SIMO

SIMO communication-systems utilize one antenna at the transmitter and multiple antennas at the receiver, Fig. 2. Thus, any signal transmitted from the single transmit-antenna will arrive at all receiver antennas through different sub-channels. It is assumed that each sub-channel, and hence, each channel element is completely decorrelated. As multiple independent copies of the same signal arrive at the receiver, it is possible to exploit the concept of spatial diversity, in this case receiver-diversity. Assuming that perfect channel information is available at the receiver, it is possible to use combining techniques at the receiver based on the channel state information.

Two combining techniques are used here: *Maximal Ratio Combining (MRC)* and *Equal Gain Combining (EGC)*. Both these techniques involve the use of a matched filter at the receiver to optimally combine the received signals (at each antenna) to maximize the SNR at the output. Consider a $1 \times N_r$ system, where N_r denotes the number of receiver antennas. The transmission of the message symbol c (after modulation) through a fading channel is simulated as follows:

$$\mathbf{r} = \mathbf{h} \times c + \mathbf{n} \tag{3}$$

where, \mathbf{r} denotes the received vector of dimensions $N_r \times 1$, \mathbf{h} denotes the channel matrix of dimensions $N_r \times 1$, each element giving the complex gain between the transmitter and each receiver; \mathbf{n} denotes an additive noise vector of dimensions $N_r \times 1$; c denotes a transmitted symbol. At the receiver, a matched filter is applied to combine the individual received signals.

In the case of MRC, the filter ‘ \mathbf{f}_m ’ is designed as follows:

$$\mathbf{f}_m = \mathbf{h}^H \tag{4}$$

$$y = \mathbf{f}_m \times \mathbf{r} \tag{5}$$

where, \mathbf{h}^H denotes the complex conjugate-transpose of \mathbf{h} , and y denotes the decision.

In the case of EGC, the filter \mathbf{f}_e is designed as follows:

$$\mathbf{f}_e = \exp(-1 \times \arg(\mathbf{h})) \quad (6)$$

$$\mathbf{y} = \mathbf{f}_e \times \mathbf{r} \quad (7)$$

where, \mathbf{h}^H denotes the complex conjugate-transpose of \mathbf{h} , and \mathbf{y} denotes the decision.

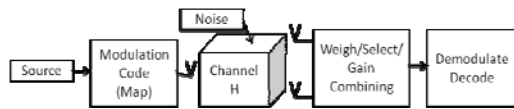


Fig. 2. Block diagram of a SIMO System

The capacity of a SIMO system can be derived as [5]

$$C_{SM} = \log_2 \left(1 + r \sum_{i=1}^{N_r} |\mathbf{h}_i|^2 \right) \text{bs}^{-1}\text{Hz}^{-1} \quad (8)$$

where, \mathbf{h}_i represents the gain between the transmitter antenna and the i^{th} receiver antenna.

Since the channel energy is combined coherently at the receiver, there is a significant array gain. The capacity increases logarithmically with the number of receiver antennas.

C. MISO

MISO communication-systems utilize multiple antennas (N_t) at the transmitter and a single antenna at the receiver, Fig. 3. Assuming that perfect channel knowledge is available at the transmitter, it is possible to achieve transmit-diversity using MRC and EGC at the transmitter. Applying MRC at the transmitter, also known as beamforming, requires the use of a filter \mathbf{f}_m defined as

$$\mathbf{f}_m = (\mathbf{h}^H) / \|\mathbf{h}\| \quad (9)$$

where, \mathbf{h} denotes a $1 \times N_t$ channel vector. This filter is applied to the symbol to be transmitted, \mathbf{c} ; $\mathbf{s} = \mathbf{f}_m \times \mathbf{c}$.

The filtered symbol, when transmitted through all antennas travels to the single receiver antenna. The combining takes place as the copies travel through different sub-channels as follows:

$$\mathbf{y} = \mathbf{h} \times \mathbf{s} + \mathbf{n} \quad (10)$$

where, \mathbf{n} denotes an additive noise variable.

Applying EGC requires the same operation in (10), using a different filter

$$\mathbf{f}_e = \exp(-1 \times \arg(\mathbf{h})) \quad (11)$$

If the total transmit power is fixed and equally divided amongst all antennas, the capacity of a MISO system can be derived as [5]

$$C_{MS} = \log_2 \left(1 + \left(\frac{\rho}{N_t} \right) \times \sum_{i=1}^{N_t} |\mathbf{h}_i|^2 \right) \text{bs}^{-1}\text{Hz}^{-1} \quad (12)$$

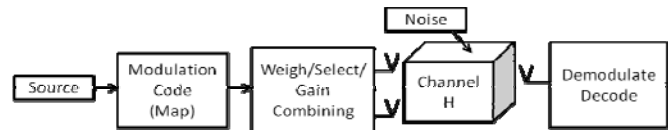


Fig. 3. Block diagram of a MISO System

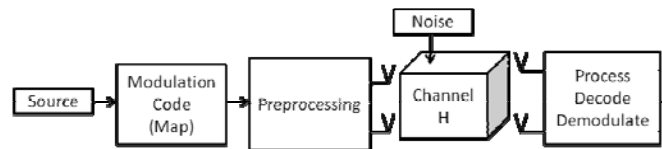


Fig. 4. Block diagram of a MIMO System

D. MIMO

MIMO systems utilize multiple antennas at both the transmitter and receiver, Fig. 4. The most common form of diversity employed in MIMO systems is the space – time diversity, exploiting both space and time diversity. The Alamouti space time block code [5] is the simplest of the family of orthogonal space time codes. The capacity of MIMO systems is expressed as



$$C_{MM} = \log_2 \left(1 + \left(\frac{\rho}{N_t} \right) \mathbf{h} \mathbf{h}^H \right) \text{ b s}^{-1} \text{ Hz}^{-1} \quad (13)$$

Along with diversity, MIMO also provides multiplexing capabilities: allowing users to transmit different symbols from different transmit antennas, thereby improving the throughput of the system.

3. CHANNEL MODELS

A. Additive White Gaussian Noise (AWGN) Channel

The simulated linear AWGN channel has a bandwidth greater than that of the message signal. The noise \mathbf{n} is a complex Gaussian-distributed stationary random process with zero mean and is generated as a vector with the same number of elements as the message to be transmitted:

$$\mathbf{n} = \langle \text{noise_power} \rangle \times (\mathbf{N}(\mathbf{0}, \mathbf{1}) + i \times \mathbf{N}(\mathbf{0}, \mathbf{1})) \quad (14)$$

where $\mathbf{N}(\mathbf{0}, \mathbf{1})$ is a vector of the same length as the message signal consisting of normal (Gaussian) random variables. The noise power is calculated as $\text{noise_power} = (\text{signal power})/\text{SNR}$. This noise is added to the message vector \mathbf{c} to obtain the received signal \mathbf{r} .

$$\mathbf{r} = \mathbf{c} + \mathbf{n} \quad (15)$$

B. Rayleigh Flat Fading Channel

The Rayleigh flat fading channel is commonly used to describe multipath fading channels when there is no Line-Of-Sight (LOS) component, the number of independent copies (multipath) of the signal arriving at the receiver is large, and the coherence bandwidth of the channel is greater than the bandwidth of the signal itself. It can be shown by central limit theorem that such a channel, where each arriving signal is of approximately equal energy, can be modeled as a zero mean circularly symmetric complex Gaussian random variable $h = i.i.d. \mathbf{CN}(\mathbf{0}, \mathbf{1})$. The envelope of this fading channel can then be modeled using a Rayleigh distribution. For the purpose of simulation, a single channel is generated as follows:

$$h = \mu + \sigma \times (\mathbf{N}(0,1) + i \times \mathbf{N}(0,1)) \quad (16)$$

where, μ is the mean of the random variable (assumed to be zero), σ is the standard deviation of the random variable (assumed as one or 0.707) and $\mathbf{N}(0,1)$ denotes a Normal (Gaussian) distributed random variable with zero-mean and unit-variance. The channel is assumed to be slow-fading, with variations occurring at intervals equal to the symbol duration.

C. Ricean Flat Fading Channel

The Ricean flat fading channel is used to describe multipath fading channels that consist of a large number of multipath components and a strong LOS component. The Ricean K-factor is used to specify the power in the LOS component to the power in the scattered components. The Ricean channel is modeled using non-zero mean circularly symmetric complex Gaussian random variables as follows:

$$h = \mu + \sigma \times (\mathbf{N}(0,1) + i \times \mathbf{N}(0,1)) \quad (17)$$

where, μ is the mean of the random variable (non-zero value), which is a contribution of the LOS component, σ is the standard deviation of the random variable, and $\mathbf{N}(0,1)$ denotes a Normal (Gaussian) distributed random variable with zero-mean and unit-variance.

4. SIMULATIONS

Monte-Carlo simulations were carried out to analyze the performance of each of the mentioned multi-antenna configurations. MRC and EGC schemes were used to obtain the output at the receiver in SIMO and MISO systems. The performance was measured by plotting the average Symbol/Bit Error Ratio (SER or BER) over a range of SNR values. The simulations were repeated for Rayleigh and Ricean fading channels. The digital data was modulated using Binary Phase Shift Keying (BPSK). The performance of the SISO configuration was evaluated to demonstrate the impact of fading on system performance.

For evaluating the MIMO system, the concept of space time diversity was applied to a 2×1 and 2×2 case. A matched filter was applied at the receiver to retrieve the data.

5. RESULTS

Fig. 5 shows the simulation results for a SISO system. It is clearly seen that the performance of SISO system in a fading channel is very poor compared to that of an AWGN channel, even for higher values of SNR. The destructive interference between multipath signals at the receiver results in severe degradation. It is noted that the performance in a Ricean channel slightly better than that in a Rayleigh fading channel. This is due to the strong LOS component present in the former case.

Fig. 6 and 7 show the results of simulations of 1×4 and 1×2 SIMO systems. The availability of multiple copies of the same signal at the receiver enables the receiver to effectively combine these multipath components, resulting in diversity gain at the receiver. Clearly, MRC provides a better performance when compared with EGC. This is due to the optimal nature of MRC, which maximizes SNR at the output.

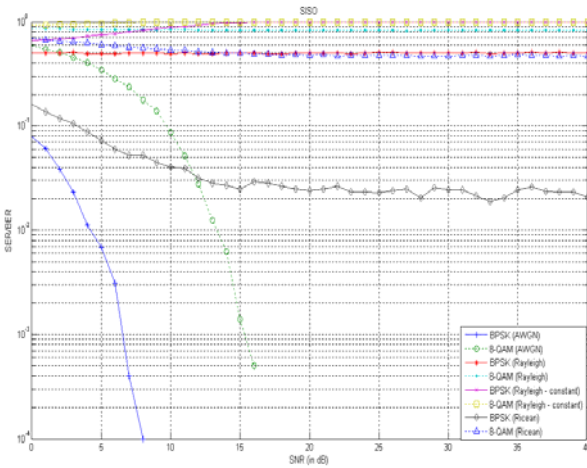


Fig. 5. Error Plots for SISO configuration

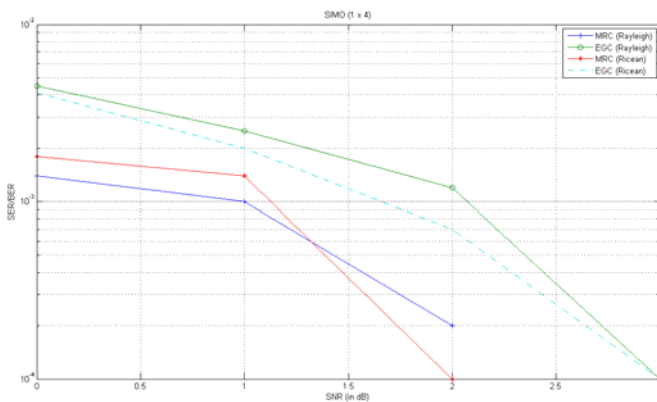


Fig. 6. Error Plots for SIMO (1×4) configuration

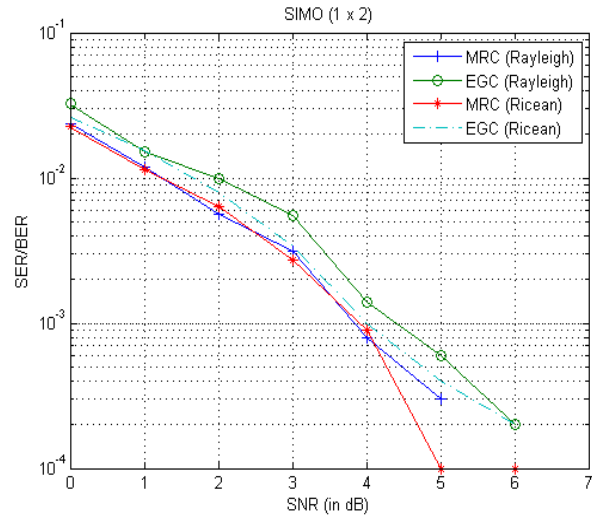


Fig. 7. Error Plots for SIMO (1×2) configuration

A comparison of the results in Fig. 6 and Fig. 7 show that there is a significant improvement in system-performance (by the reduction of BER) as the number of receiver antennas are increased. This is clearly because of the increase in the number of copies of the signal provided to the receiver.

Fig. 8 shows the result of simulation of a 4×1 MISO system. Here, EGC shows slightly better results when compared with MRC. Also, the performances in Rayleigh and Ricean channels are quite similar. Again, it can be noted that there is a definite improvement in performance (reduction in BER) as the number of transmit-antennas are increased. Fig. 9 shows the result of the simulations of MIMO system. Space time block codes were employed to exploit both space and time diversity.

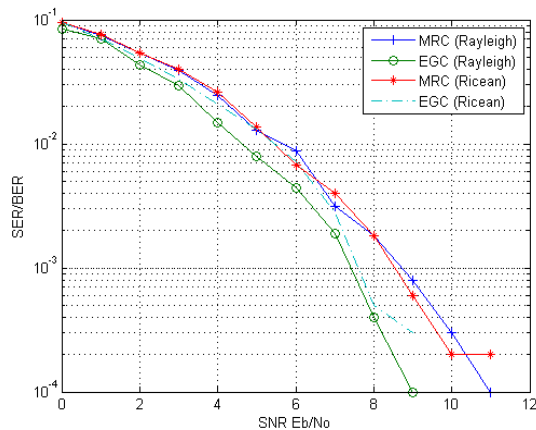


Fig. 8. Error plots for MISO (4×1) configuration

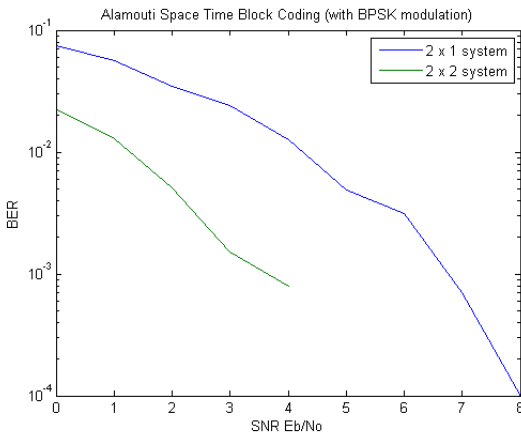


Fig. 9. Error plot for a 2×1 and 2×2 system employing space time block coding

6. CONCLUSIONS

It is clearly seen that by exploiting diversity, it is possible to effectively mitigate the effects of multipath fading, and in fact, turn it to the advantage of the system. The rich scattering nature of the channel severely affects SISO systems and steps are taken to avoid it. But this inherent property of channels can be easily exploited to improve the performance of the system by providing the receiver with multiple copies of the data. The introduction of time diversity to space diversity further improves the performance of the system [5]-[6], and further widens the scope for new ways to exploit channel properties. The concepts of Space time coding is already well-developed, atleast in theory, in the form of Space Time Block Codes (STBC), Space Time Trellis Codes(STTC), Turbo-Space Time Block Codes, Differential Space Time Block Codes and Layered Space Time Block Codes. Furthermore, a trade-off can be achieved by sacrificing some of the diversity gain for multiplexing gain, resulting in a significant improvement in data-rates without loss of quality [7].

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