ISSN: 1999-1630

SEU Journal of Science and Engineering, Vol. 11, No. 1, June 2017

Performance Evaluation of the Layered Space-Time Receiver in Frequency-Flat Fading MIMO Channel

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Abstract
The space-time (ST) architecture for wireless communication is of considerable current interest due to the needs for higher data rates to support future generation personal wireless multimedia systems. Recent research into multiple-input multiple-output (MIMO) systems has provided significant technical breakthroughs in the feasibility of this type of wireless system and these developments promise considerable improvements in capacity. Basically, MIMO systems use multiple antennas at both the transmitter and receiver to permit very high transmission rate, far exceeding the conventional communication technique. Together with intelligent space-time signal processing and detection techniques, higher traffic capacity and higher spectral efficiency are realizable. This article outlines the basic principles of space-time systems with different types of symbol detection algorithms. Simulation results demonstrate the performance metric as the bit error probability (*Pe*) against the mean signal-to-noise ratio (SNR) value for different MIMO configurations.

Keywords: MIMO, V-BLAST, Space-Time system, ZF, MMSE.

I. Introduction

Space-time techniques potentially provide significant increases in capacity compared with traditional wireless communication systems for wireless channels that suffer from severe multipath propagation. This is achieved by properly exploiting the diversity that exists within this type of rich scattering channel environment between the multiple antennas at both the transmitter and receiver (G. J. Foschini 1996). MIMO systems, such as V-BLAST (P. W. Wolniansky *et al;* 1998) use multiple antennas at both the transmitter and receiver to permit very high transmission rate.

In this paper, the basic V-BLAST receiver with different MIMO configurations will be initially assessed for its system performance under the flat fading channel condition. Each sub-channel from each transmit-receive antenna pair consists of a single path that is represented by a complex coefficient. The system performance of the V-BLAST receiver will be evaluated using four means of symbol detection algorithms as: a) the linear zero-forcing (ZF) algorithm, b) the linear minimum mean square error (MMSE) algorithm, c) the nonlinear ZF algorithm and d) the nonlinear MMSE algorithm. Flat-fading channel is initially assumed with only single propagation path for each transmit-receive antenna pair and each path is also assumed to be time-invariant. The channel matrix, H, specifies the MIMO transfer function that contains hji complex coefficients from ith transmit antenna to jth receive antenna. Also, the channel is assumed to be known or perfectly estimated. No distinction is made between H and its estimates at this point. Perfect synchronization with symbol-spaced sampling is also assumed (P. W. Wolniansky *et al.*, 1998)

The paper is organized as follows. Section 2 briefly describes the space-time model and detection algorithm. V-BLAST

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Nonlinear Detection and Symbol Cancellation are discussed in Section 3. Section 4 presents the simulation results using Matlab. Conclusions are given in Section 5.

II. Space-Time Model and Detection Algorithm

Figure-1 shows the architecture for the space-time communication system used in this paper. The system consists of M parallel transmit antennas and N parallel receive antennas operated at co-channel mode. The single transmit vector, a (which contains individual transmit symbols a_i from each i[th] transmit antenna) can be denoted as:

$$a = [a_1, a_2, \text{-----}, a_M]^T \qquad (1)$$

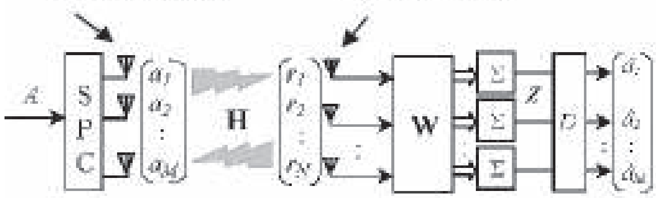


Figure 1: Space-time system model with symbol detection.

Each transmit symbol 'a' is a complex component mapped from the QPSK modulation scheme. Each substream is pre-multiplied with a factor of $\sqrt{\rho / M}$, where ρ is the expected signal to noise ratio at the receiver and the total power radiated by each transmit antenna is proportional to $1/M$ in order to provide a constant power to the receiver regardless of the changes in number of transmit antenna. The symbols are sent over a Rayleigh flat-fading MIMO channel, **H** with the matrix dimension of $(N \times M)$, where signals are distorted and superimposed at each receive antenna. The corresponding received signal vector, r, (contains N received signal r_j at each j^{th} receive antenna) can be expressed as:

$$r = Ha + n \qquad (2)$$

where $r = [r_1, r_2, \text{-------}, r_N]^T$ and n is the independent identically distributed, (i.i.d.) additive white Gaussian noise (AWGN) vector.

The received signal vector is processed by weighting each element of $\boldsymbol{r}$ with the elements of the weighting matrix, **W**. The weights, ω_{ij} in **W** are obtained according to one of two possible criteria: Zero-Forcing (ZF) or Minimum Mean Square Error (MMSE) **(Su Weifeng *et al;* 2013)** The weighted signals are combined to form $\boldsymbol{Z} = [z_1, z_2, \text{----}, z_M]^T$. Each element in vector $\boldsymbol{Z}$ can be expressed as:

$$z_i = \sum_{j=1}^{N} \omega_{ij} r_j \qquad (3)$$

Using the zero forcing criterion as an example, estimates of the symbol vector, $\hat{\boldsymbol{a}} = [\hat{a}_1, \text{---}, \hat{a}_M]^T$ are recovered by applying the inverse of **H** to, $\boldsymbol{r}$, assuming that the fading coefficients in **H** are perfectly known by the receiver and each element in the received vector $\boldsymbol{r}$ is totally uncorrelated. The process is represented as follows:

$$\mathbf{W} = \mathbf{H}^{+} \qquad (4a)$$

$$\boldsymbol{Z} = \mathbf{W}\boldsymbol{r} \qquad (4b)$$

$$\hat{\boldsymbol{a}} = D(\boldsymbol{Z}) \qquad (4c)$$

Where D is the 'slicing' operator that decides upon the symbol estimate, according to the decision threshold for the modulation scheme employed. The $^{+}$ sign denotes the pseudo-inverse operation and is applied for the case when $N \geq M$. In practice, the channel coefficients must be estimated by some method (Chen Liang *et al;* 2010).

III. V-BLAST Nonlinear Detection and Symbol Cancellation

The symbol detection algorithm of (Chen Liang *et al;* 2010) is a linear process where all symbols in the transmitted vector $\boldsymbol{a}$ can be resolved simultaneously, assuming perfect symbol synchronization. However, superior performance can be obtained if nonlinear detection methods, such as symbol cancellation, are used. The nonlinear detection method resolves each symbol by treating the already-detected symbol components of vector $\boldsymbol{a}$ as symbol interference and they are subsequently eliminated from the received signal vector $\boldsymbol{r}$ one at a time (P. W. Wolniansky *et al;* 1998). The V-BLAST process can be separated into two parts; namely a) the optimum ordering process and b) the symbol detection process, as follows:

a) The optimum ordering process:

Initialization

$$i \leftarrow 1 \tag{5a}$$

$$\mathbf{G}_1 = \mathbf{H}^{+} \tag{5b}$$

$$v_l = \underset{j}{\arg\min} \left\|(\mathbf{G}_1)_j\right\|^2 \tag{5c}$$

Recursion

$$\mathbf{G}_{i+1} = \left\{ Z(\mathbf{H})_{vi} \right\}^{+} \tag{5d}$$

$$v_{i+1} = \underset{j \notin \{v_1 \cdots v_i\}}{\arg\min} \left\| (\mathbf{G}_{i+1})_j \right\|^2 \tag{5e}$$

$$i \leftarrow i+1 \tag{5f}$$

b) The symbol detection process:

Initialization

$$i \leftarrow 1 \tag{6a}$$

Recursion

$$\mathbf{w}_{vi} = (\ \mathbf{G}_i\ )_{vi} \tag{6b}$$

$$\hat{\boldsymbol{a}}_{vi} = D(\mathbf{w}_{vi}^{T} \boldsymbol{r}_i\ ) \tag{6c}$$

$$\boldsymbol{r}_{i+1} = \boldsymbol{r}_i - \hat{\boldsymbol{a}}_{vi}\,(\mathbf{H})_{vi} \tag{6d}$$

$$i \leftarrow i+1 \tag{6e}$$

where, v_i is the order in which the subsequent symbol detection will be carried out and is determined by the post-detection SNR, as described in (P. W. Wolniansky *et al;* 1998) The *'Z'* operator in (5*d*) sets the respective column of **H** to zero according to the value of 'v_i'. The same *'D'* operator from (4*c*) is used in (6*c*). The values of the matrix **G** are stored following each iteration of the ordering process and may subsequently be used in the symbol detection process. On completion of the optimum detection ordering process (5*a*)-(5*f*), the detection ordering set is obtained and written as:

$$\Re_{VBLAST} = \{v_1, v_2, \text{-----}, v_M\} \tag{7}$$

The order in (Fernando Domene *et al;* 2015) may be obtained by other methods that avoid the pseudo-inverse process (Hufei Zhu *et al;* 2004. In this paper, we assume that we have been able to obtain the optimum ordering and the paper concentrates on the symbol detection proce ss described in the next section.

IV. Results and Discussions

Before results are presented for the general MIMO case, perhaps it is useful examine the basic spatial diversity scheme from a single-input multiple-output (SIMO) model where single transmit antenna and multiple receive antennas are used. The linear *ZF* algorithm is used with the setting of M = 1 and N = 1, 2 & 4 respectively to demonstrate the performance achieved by the reception diversity. (The diversity gain or order is defined as N/M).

Figure-2 demonstrates the performance of the basic diversity scheme for a SIMO system. The results demonstrate that reception diversity does improve the overall performance of the wireless system. Next, the performance of MIMO system is assessed over a flat-fading Rayleigh channel where multiple transmit-receive antennas are used. First, equal number of receive antennas N and transmit antennas M is employed with no diversity gain since $N = M$. The immediate question from this test is that can we achieve better bit error probability performance while achieving increased data rate simultaneously.

It can be observed in figure-3 that, the performance of the MIMO system with no diversity gain becomes deteriorated in a flat-fading MIMO channel condition as M and N increase simultaneously. Although, the data rate has been improved by M-fold, having multiple links with no diversity will not be beneficial in this case or even worsen the system performance when the linear ZF detection algorithm is used.

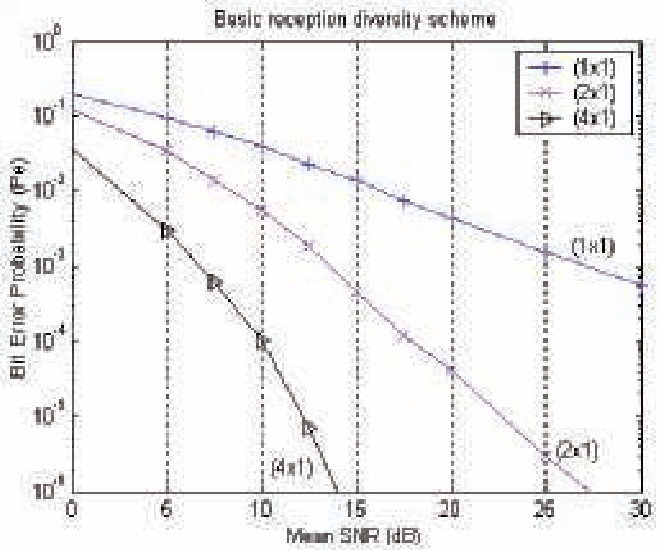


Figure 2: Performance of diversity scheme using linear ZF algorithm in a SIMO system.

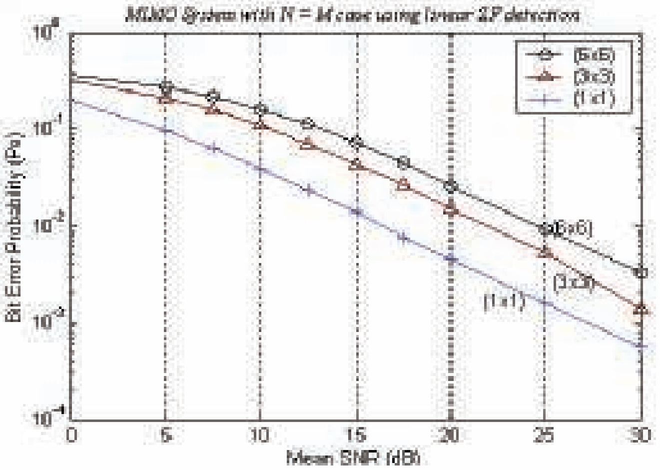


Figure 3: Performance of $N = M$ system with linear ZF algorithm.

This makes sense because the performance of the (1×1) system has already reached the state of "as good as it gets" under typical Rayleigh condition. Having more links with no diversity (in linear ZF detection) simply means further deterioration in the overall channel condition thereby worsening the system performance. Also, each antenna in the MIMO case is now transmitting power in reduced proportion of $1/M$ in order to maintain the same transmitting power as in the single antenna case of SISO system. The degradation in performance is expected when the ZF algorithm is used. This is mainly due to the noise enhancement during the matrix inversion, which worsens the system performance of the MIMO system as the matrix's size grows when M and N increases simultaneously. (Ming Fei Siyau *et al;* 2010) (Fernando Domene chen *et al;* 2015) However, when added diversity order is presented in the MIMO systems (where $N > M$ case), the system performance can be improved accordingly as shown in the following figure.

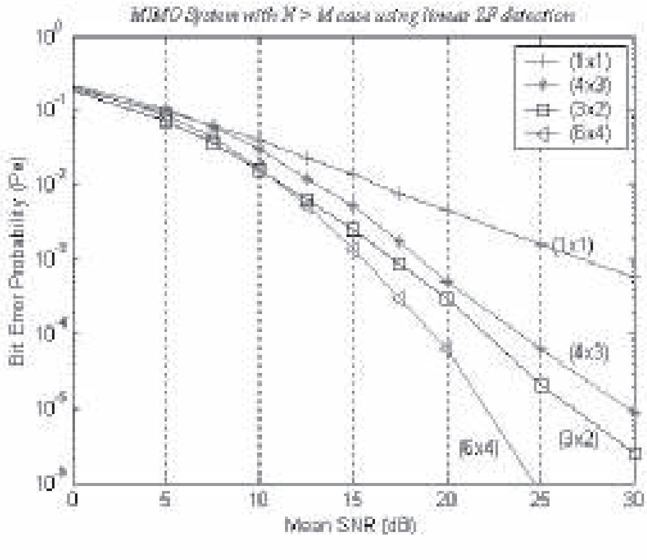


Figure 4: Performance of $N > M$ system with linear ZF algorithm.

It can be seen in figure-4 that the bit error probability performance is improved for any system with $N > M$, where diversity gain is present. Therefore, improvement in the system performance and the data rate can be achieved at the cost of extra hardware. The results showing the performance achieved by different detection algorithms in the MIMO systems for different ($N \times M$) configurations. First, the performance of the ($N > M$) system is always better than the ($N = M$) system regardless of the detection algorithms used for symbol recovery. This is due to the fact that spatial diversity is achieved by the multiple antenna arrangements in conjunction with the proper combiner by means of weighting matrix to effectively exploit the multipath. The larger the number of receive antennas relative to the number of transmit antennas, the better the reception diversity.

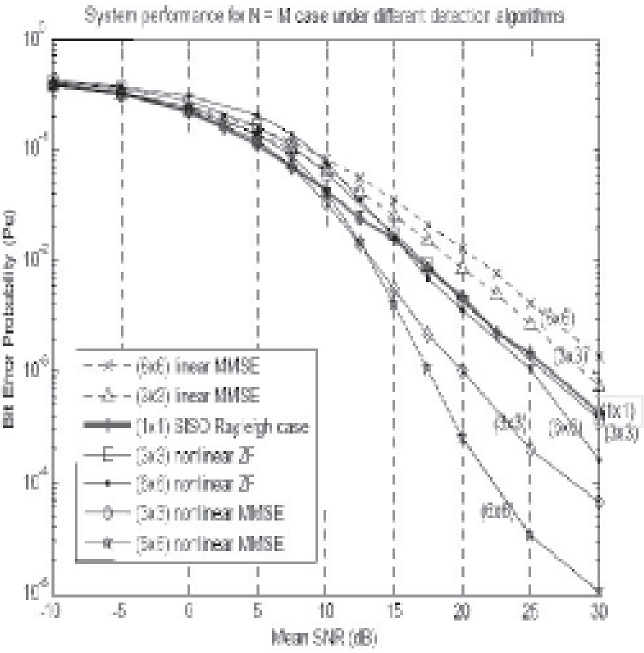
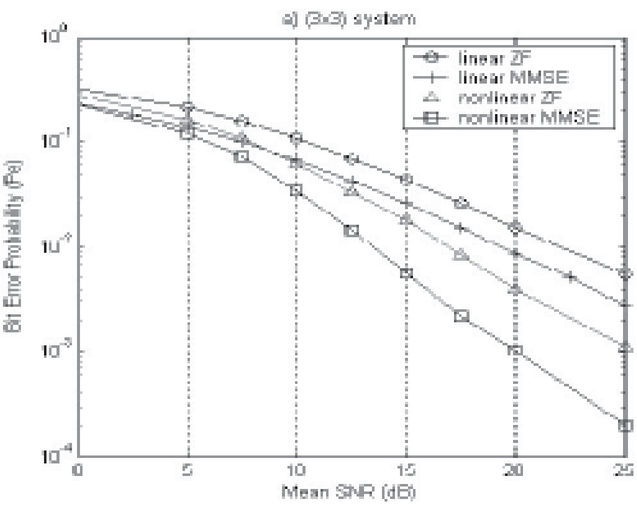


Figure 5: Performance of $N = M$ system with linear ZF algorithm.

Next, back to the case for $N = M$ systems, the results obtained using the linear detections are quite different from the case where a nonlinear detection is used. It can be seen in figure-5 that for the case of linear detection the performance becomes poorer as the antenna configuration increases from (1×1) system to (6×6) system (similar to the earlier case in figure-3.) This is true for both linear ZF and linear MMSE cases but the distinction in performance is greater in the ZF case than the MMSE case.

However, in the nonlinear case, contrary results are observed in which a 'switch' in the performance curve is observed at certain mean SNR value whereby the performance of the higher $N = M$ system, i.e. the (6×6) system, is better than the lower $N = M$ system, i.e. the (3×3) system, at higher SNR. This demonstrates the potential of the nonlinear detection that uses successive interference cancellation scheme, which improves the BER performance of the Layered Space Time (LST) system. The results also show the nonlinear detection is capable of providing a breakthrough over the linear detection when sufficient SNR is available. (Su Weifeng *et al;* 2013) (Ming Fei Siyau chen *et al;* 2010)

The two main observations that can be deduced from figure-6 are that a) the MMSE algorithm always gives better performance than the ZF algorithm and b) the use of the nonlinear symbol detection (with the SIC scheme) further improves the performance of the layered space-time system by a great margin as compared with the linear detection methods. The results are extracted for the (3×3), (4×3), (3×2) and (6×4) systems and shown as follows:



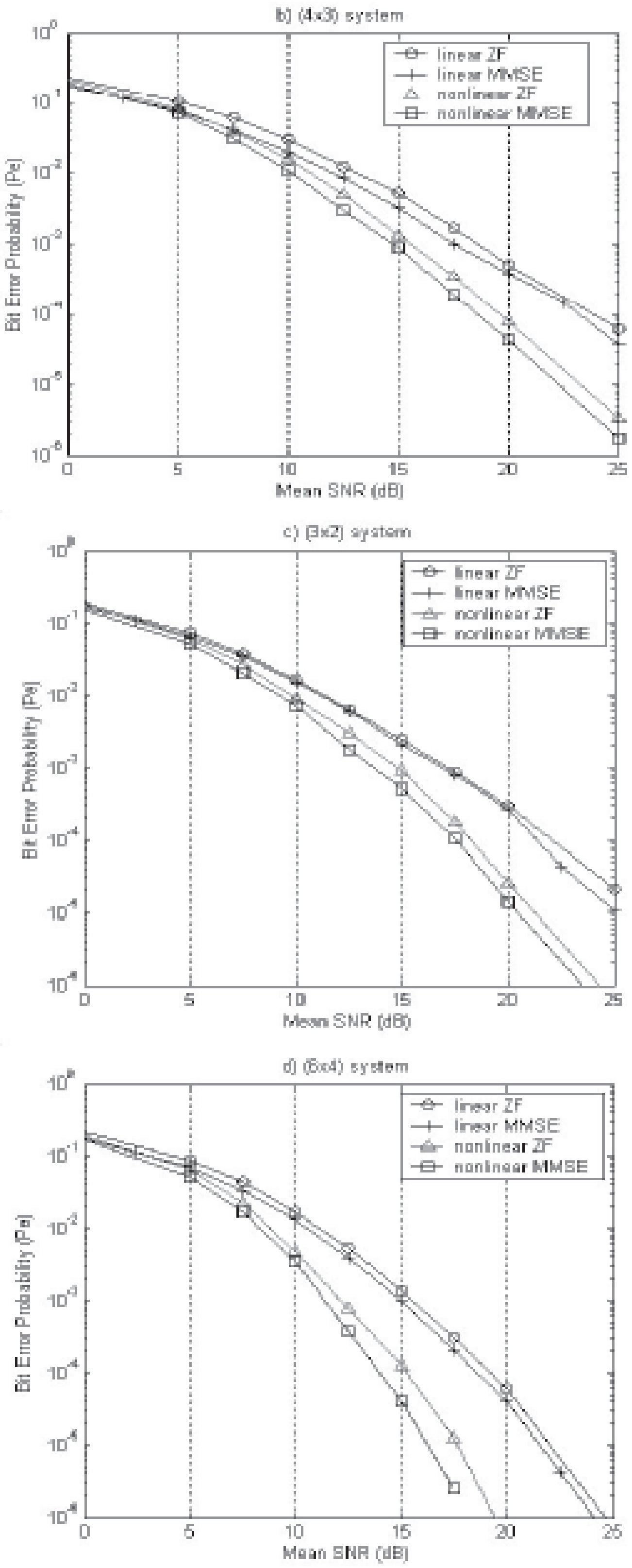


Figure 6(a-d): Performance comparison using different detection algorithm for various *(NxM)* systems.

Next, the system performance of the LST system is tested with different degree of spatial correlation in the flat-fading MIMO channel. The spatial correlation defines the degree of similarity between the fading coefficients of the two independent streams being received at antennas spaced by a given *distance, usually measured in wavelength* λ of the transmitted signal (Fernando Domene *et al;* 2015) In general, the mechanisms that give rise to spatial correlation are based on several factors: the distance between each antenna's spacing in the multiple antenna setting, the number & distribution of the scatterers and the angular spreads of the incoming waves to the receiver (Mohammed Abdo Saeed *et al;* 2009) Lower correlation is expected when the antenna's spacing is large and wider angular spread of received signals is assumed when scatterers are largely distributed around the receiver. In contrast, two independent paths are said to be highly correlated when antenna's spacing is very small, causing the two paths to fade almost in the same way in term of its phase change and amplitude. The distribution of scatterers that result in the angular spreads is also vital since the MIMO systems are assumed to work better in the rich scattering environment. When fewer scatterers are present (particularly in rural areas) with narrowly distributed spread angle, it also results in highly correlated channel.

Results are shown for identical correlation coefficient ρ, *in both the transmit* correlation matrix and receive correlation matrix. (Here, antennas are assumed to be equally spaced and correlation between neighbouring antenna is larger in proportion than that of distant antenna). Also, the channel model is assumed to be Rayleigh faded for each path in the MIMO channel. The results are plotted using the nonlinear MMSE detection method for (3×3) system and (6×4) system in the following:

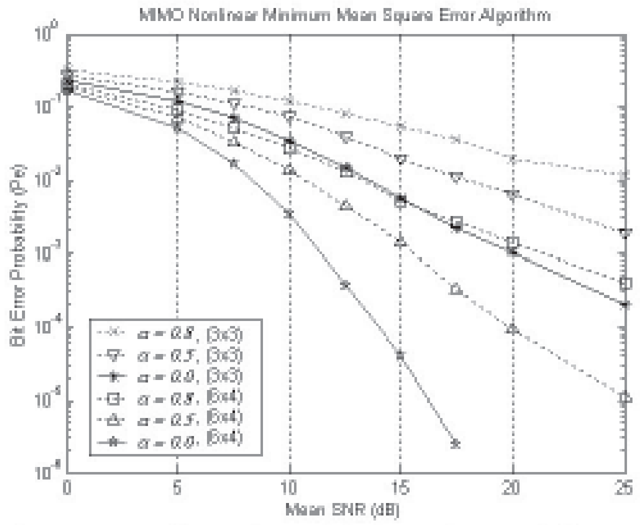


Figure 7: Effect of spatial channel correlation on performance.

It can be seen clearly from figure-7 that the spatial correlation in the frequency-flat MIMO channel has severe effect on the system performance of the layered space-time system. The performance becomes degraded as the spatial correlation coefficient of the MIMO channel increases. Clearly only the antenna arrangement with zero or no spatial correlation provides the best performance for MIMO systems.

V. Conclusion

In this paper, the V-BLAST system (with M transmit antennas and N receive antennas) have been successfully implemented using four different detection algorithms, namely linear ZF, linear MMSE, nonlinear ZF and nonlinear MMSE. Results were obtained for various ($N \times M$) system configurations. Nonlinear detection methods (with symbol interference cancellation – SIC scheme) achieved better system performance as compared to the linear detection methods. MMSE technique was marginally better than the ZF technique. MIMO systems with higher reception diversity order (N/M) achieved better results than the one with lower diversity order. MIMO systems with no SIC feature & diversity gain, (i.e. $N = M$) tend to perform poorer as the number of antenna increases, although data rate is increased by M-fold. Results with single transmit antenna and multiple receive antennas resembled the pure diversity and equal gain combining scheme of a SIMO system. Fading correlation degraded the performance of the V-BLAST system.

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