Alamouti Coded OFDM in Rayleigh Fast Fading Channels - Receiver Performance Analysis

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***Abstract*— In this paper, the receiver performance of Alamouti coded orthogonal frequency division multiplexing (OFDM) systems is analyzed. When the channel is not constant during the period of Alamouti codeword transmission, the conventional linear maximum likelihood (ML) receiver suffers from performance degradation. We use three different receiver combining methods and study the error performance. The sensitivity of different receivers is investigated by varying the correlation coefficient. Our results can be easily extended to be applicable to other block coded OFDM schemes with different antenna configurations. The performance loss in linear ML receiver can be partially improved by employing a decision-feedback strategy. In the decision feedback steps preliminary decisions are used to subtract the intercodeword coupling. However this increases the computational complexity of the receiver.**

I. Introduction

Transmit diversity assisted space time block coded (STBC) orthogonal frequency division multiplexing (OFDM) systems improve the error performance in fading channels [1]. The popular Alamouti scheme and numerous other STBCs for different antenna configurations are reported previously [2], [3] and can be used in combination with transmit diversity OFDM [4]-[10]. In OFDM the Alamouti code can be applied along the symbols/time (STBC-OFDM) or subcarriers/frequency (SFBC-OFDM) [6], [7]. In both techniques the Alamouti scheme reduces the dimensionality of the complex maximum likelihood (ML) decoding problem by decoupling the symbols transmitted from different antennas. However in STBC-OFDM this receiver is optimum only when the channel remains time invariant during the OFDM codeword transmission period [4], [5]. In the SFBC-OFDM linear ML detector, the adjacent subcarrier channel coefficients must be equal for the decision variables to be decoupled.

The existing literature describing STBC single-carrier and STBC-OFDM systems usually assume a quasi-static block fading scenario where the optimal condition holds. However in practical channels this is seldom satisfied. Hence recent publications have analyzed the time varying channel effects on Alamouti STBC for single-carrier [11] and OFDM systems [9], [12]. In single-carrier systems depending on the channel coefficients used for linear combining, a possible loss in diversity order and spatial intercodeword coupling degrade the performance. Hence the authors of [11] proposed three novel receivers based on zero-forcing (ZF), an optimum joint ML and decision-feedback (DF) strategies to reduce the performance degradation.

OFDM transforms the broadband frequency selective channel required for high speed data transmission onto a set of frequency flat subchannels. By using a cyclic prefix it eliminates the intersymbol interference which is a problem in high rate single carrier systems. However in time varying channels, STBC-OFDM can suffer heavily due to its relatively longer symbol duration compared to single-carrier systems [9]. In addition to intercodeword coupling, inter-carrier interference (ICI) can further reduce the performance of STBC-OFDM over highly time varying channels [12]. If the channel variations within one OFDM symbol period are not negligible, ICI is introduced for the demodulated subcarriers. Similar drawbacks occur in SFBC-OFDM systems. In some applications the total number of subcarriers N is limited and the channel delay spread governs the frequency domain channel correlation among the subcarriers [7]. Hence in practice for SFBC-OFDM, the adjacent subcarrier frequency domain channel coefficients deviate from the idealistic assumption.

In this paper we investigate the performance degradation of STBC-OFDM in non quasi-static Rayleigh channels using different receiver combining schemes. Besides the conventional Alamouti linear ML receiver, two types of receivers are used. The first receiver guarantees the maximum diversity however suffers from intercodeword coupling. The second receiver completely decouples the decision variables but has a low diversity order due to the non quasi-static fading conditions. The channel is modeled as a first order autoregressive (AR) process [13]. The covariance coefficient ρ is an indicator of the time-varying channel characteristics. By varying ρ we investigate the resulting performance loss and the sensitivity of the different receivers. Simulation results confirm the degradation in all three receivers. Surprisingly the receiver capable of decoupling the decision variables performs similar to the linear ML receiver in quasi static conditions amidst reduced diversity order. The theoretical lower bound for the symbol error rate (SER) is derived in the case of M-QAM modulated STBC-OFDM. We also examine the performance of a decision feedback detection to mitigate the intercodeword coupling effects present in the linear ML receiver.

The rest of the paper is organized as follows. In Section II we introduce the time-varying channel and the Alamouti

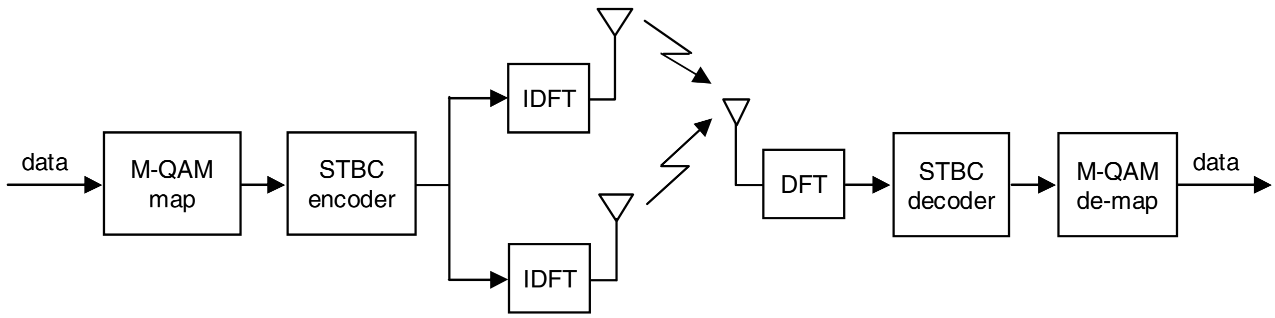

Fig. 1. Block digram of an STBC-OFDM system model.

coded OFDM model. Performance of the different receivers is discussed in Sections III and IV and the decision feedback scheme is explained. Simulation results appear in Section V and some conclusions are drawn in Section VI.

II. Alamouti Coded STBC-OFDM Model

In this Section we describe the Alamouti STBC-OFDM system and the channel model. Fig. 1 shows a basic block diagram of an STBC-OFDM system. Consider the combination of Alamouti STBC and OFDM with $n_T = 2$ transmit and $n_R = 1$ receive antennas. At the transmitter data bits are mapped onto a modulation alphabet $\mathcal{X}$ (For 4-QAM, $\mathcal{X} \in (\pm 1 \pm j)$, followed by Alamouti coding. These information values are multiplexed to the two antennas. In the OFDM block instant $(2i)$, $X_{1,k}$ and $X_{2,k}$ are mapped to the k-th subcarrier to be transmitted from antenna 1 and 2. Next at block instant $(2i+1)$, $-X_{2,k}^*$ and $X_{1,k}^*$ are mapped to the k-th subcarrier to be transmitted from antenna 1 and 2. The transmitted STBC-OFDM symbols are given by

$$\begin{pmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \end{pmatrix} \rightarrow \begin{pmatrix} \mathbf{X}_1 & -\mathbf{X}_2^* \\ \mathbf{X}_2 & \mathbf{X}_1^* \end{pmatrix} \begin{matrix} \rightarrow & \text{time} \\ \downarrow & \text{space} \end{matrix} \tag{1}$$

where $\mathbf{X}_i = [X_{i,0}, X_{i,1}, ..., X_{i,(N-1)}]$ is the transmit OFDM symbol from ith antenna $(i = 1, 2)$ and $(\cdot)^*$ denotes the complex conjugate. In a block fading channel this system experiences second order diversity on a subcarrier basis. Following Alamouti mapping an inverse discrete Fourier transform (IDFT) is applied on $\mathbf{X}_1$ and $\mathbf{X}_2$ to obtain the discrete time domain signals, a cyclic prefix greater than the channel memory is appended and transmitted to the channel using the two antennas. The total signal power dissipated from the two antennas is unity.

A. Time Varying Channel

We model the time selectivity of the channel by a first order AR process [13]. The AR process is sufficiently accurate in modeling typical Rayleigh time selective channels encountered in mobile propagation conditions [11]. Hence the fading samples are given by

$$h_i(n) = \rho h_i(n-1) + v_i(n), \quad i = 1, 2 \tag{2}$$

where ρ is the correlation coefficient for $h_i(n)$ and $h_i(n-1)$ and the noise $v_i(n)$ is a zero mean and variance σ_v^2 complex Gaussian process. We assume that $h_i(n)$ is zero mean and normalized complex Gaussian.

$$\begin{aligned} \rho &= E\{h_i(n)h_i^*(n-1)\} \\ \sigma_v^2 &= 1 - |\rho|^2 \end{aligned} \tag{3}$$

In (3) $E\{\cdot\}$ is the expectation operator. For typical time selective mobile channels ρ is [14]

$$\rho = J_0(2\pi f_d T_s) \tag{4}$$

where $J_0(\cdot)$ is the zeroth-order Bessel function, f_d is the maximum Doppler spread and T_s is the OFDM symbol duration. Furthermore we assume that our time-varying channel is constant during a single OFDM symbol duration. Hence the possible ICI among the demodulated subcarriers is neglected and our focus is only on the time-selective degradation effects at the output of the Alamouti combiner. The two channel paths are identically distributed and spatially independent. Symmetric correlation conditions are assumed with $E\{h_1(n-1)h_1(n)\} = E\{h_2(n-1)h_2(n)\} = \rho$. In the following the time evolution of the channel during OFDM symbol $(2i)$ and $(2i+1)$ will be denoted H^t and H^{t+1} respectively.

III. Performance Analysis of Linear ML Receiver

In this Section we analyze the performance of the conventional Alamouti STBC-OFDM receiver in the time varying channel described earlier. At the receiver, the knowledge of perfect channel state information and synchronization error free conditions are assumed.

The received time domain signals after discarding the cyclic prefix are passed through an N-point DFT operation to obtain the k-th subcarrier values for symbol period $(2i)$ and $(2i+1)$. After DFT processing the k-th subcarrier received signals $Y^t(k)$ and $Y^{t+1}(k)$ are given by

$$Y^t(k) = H_1^t(k)X_1(k) + H_2^t(k)X_2(k) \tag{5}$$

$$Y^{t+1}(k) = -H_1^{t+1}(k)X_2^*(k) + H_2^{t+1}(k)X_1^*(k) \tag{6}$$

Consider the case where decision variables must be formulated for conventional linear ML decoding [2]. For this $Y^t(k), Y^{t+1}(k)$ are combined with the pairs $[H_1^*(k), H_2(k)]$

and $[H_2^*(k), -H_1(k)]$ to obtain the decision variables $\hat{X}_1, \hat{X}_2$ respectively.

$$\begin{aligned}\hat{X}_1 &= (|H_1^t|^2 + \rho|H_2^t|^2 + H_2^t v_2^t)X_1 \\ &+ (1-\rho^*)H_2^t H_1^{*t} X_2 - H_2^t v_1^{*t} X_2 \\ &+ N^t H_1^{*t} + N^{*t+1} H_2^t\end{aligned} \tag{7}$$

and

$$\begin{aligned}\hat{X}_2 &= (|H_2^t|^2 + \rho|H_1^t|^2 + H_1^t v_1^t)X_2 \\ &+ (1-\rho^*)H_2^{*t} H_1^t X_2 - H_1^t v_2^{*t} X_2 \\ &+ N^t H_2^{*t} - N^{*t+1} H_1^t\end{aligned} \tag{8}$$

where W denotes the complex zero mean and variance σ_N^2 circularly symmetric additive white Gaussian noise (AWGN) component, $W \backsim \mathcal{CN}(0, \sigma_W^2)$. If $\rho = 1$ $\hat{X}_1, \hat{X}_2$ reduce to assumed expressions in previous literature. Eqs. (7) and (8) show the impact of channel not remaining constant during the period of the Alamouti codeword transmission. At the combiner output the decision variables are no longer orthogonal and inter codeword coupling effects are introduced for X_1 and X_2.

The STBC-OFDM theoretical SER lower bound in the dual transmit single receive antenna channel can be calculated by averaging the fading statistics over the AWGN SER expression. The channel is assumed to be block fading. The SNR after combining $\gamma = (|H_{1,k}|^2 + |H_{2,k}|^2 \sigma_X^2)/(n_T \sigma_W^2)$ is a χ^2 distributed random variable with 4 degrees of freedom. Hence the averaged SER P_E is given by $P_E = \int_0^\infty P_M(\gamma) P_\gamma(\gamma)\, d\gamma$. The SER for M-QAM modulation $P_M(\gamma)$ is [15]

$$P_M(\gamma) = 2a \times \text{erfc}\left(\sqrt{\frac{\gamma}{b}}\right) - a^2 \times \text{erfc}^2\left(\sqrt{\frac{\gamma}{b}}\right) \tag{9}$$

where $a = 4(1 - 1/\sqrt{M})$, $b = 2(M-1)/(3\log_2 M)$ and the complementary error function $\text{erfc}(x) = 2/\sqrt{\pi}\int_x^\infty e^{-t^2} dt$. The first integral I_1 to calculate P_E can be solved using integration by parts method and an integral result of [16, (2.8.5-6)].

$$\begin{aligned}I_1 &= \frac{2a}{\bar{\gamma}^2}\int_0^\infty \gamma \,\text{erfc}\left(\sqrt{\frac{\gamma}{b}}\right)\exp\left(-\frac{\gamma}{\bar{\gamma}}\right) d\gamma \\ &= 2a - 3a\sqrt{\frac{\bar{\gamma}}{b}}\; {}_2F_1\left(\frac{1}{2}, \frac{5}{2}; \frac{3}{2}; -\frac{\bar{\gamma}}{b}\right)\end{aligned} \tag{10}$$

where ${}_2F_1(x_1, x_2; x_3; x_4)$ is the Gauss hypergeometric function [17] defined by

$${}_2F_1(x_1, x_2; x_3; x_4) = \sum_{n=0}^{\infty} \frac{(x_1)_n (x_2)_n}{(x_3)_n n!} x_4^n \tag{11}$$

and $(x)_n = x(x+1)...(x+n-1)$ is the Pochhammer symbol. Similarly the second integral I_2 can be evaluated by

$$\begin{aligned}I_2 &= \frac{a^2}{\bar{\gamma}^2}\int_0^\infty \gamma \,\text{erfc}^2\left(\sqrt{\frac{\gamma}{b}}\right)\exp\left(-\frac{\gamma}{\bar{\gamma}}\right) d\gamma \\ &= -\frac{\bar{\gamma}\beta^{3/2}}{2b} + \frac{2\bar{\gamma}\beta^2}{\pi b}\; {}_2F_1\left(\frac{1}{2}, 2; \frac{3}{2}; -\beta\right) \\ &- \frac{\bar{\gamma}^2\beta^{1/2}}{b^2} + \frac{2\bar{\gamma}^2\beta}{\pi b^2}\; {}_2F_1\left(\frac{1}{2}, 1; \frac{3}{2}; -\beta\right)\end{aligned} \tag{12}$$

where $\beta = 1/(1 + \frac{b}{\bar{\gamma}})$. Finally the total average SER P_E in the static case is given by $P_E = I_1 + I_2$. Finally the total SER is obtained by averaging P_E for all N subcarriers. When the channel is non-quasi static it is difficult to analysis the performance for this detector. Instead we have resorted to computer simulations.

IV. Different Combining Schemes

Instead of using the channel coefficients used in the previous Section if we combine the received signals of $Y^t(k)$ and $Y^{t+1}(k)$ with the pairs of $H_1^{*t}(k), H_2^{t+1}(k)$ and $H_2^{*t}(k), -H_1^{t+1}(k)$ we get

$$\begin{aligned}\hat{X}_1 &= (|H_1^t|^2 + |H_2^{t+1}|^2)X_1 \\ &+ (1-\rho^*)H_2^t H_1^{*t} X_2 - H_2^t v_1^{*t} X_2 \\ &+ N^t H_1^{*t} + N^{*t+1} H_2^t\end{aligned} \tag{13}$$

and

$$\begin{aligned}\hat{X}_2 &= (|H_1^{t+1}|^2 + |H_2^t|^2)X_2 \\ &+ (1-\rho^*)H_2^{*t} H_1^t X_2 - H_1^t v_2^{*t} X_1 \\ &+ N^t H_2^{*t} - N^{*t+1} H_1^t\end{aligned} \tag{14}$$

Note that this receiver can achieve the available full diversity order of two amidst intercodeword coupling. The performance of this receiver depends on the intercodeword coupling. As expected when $\rho = 1$ the intercodeword interference disappears. The instantaneous effective SNR γ_i for $\hat{X}_1$ is

$$\gamma_i = \frac{(|H_1|^2 + |\tilde{H}_2|^2)\sigma_X^2/2\sigma_W^2}{\left(\frac{|H_2 H_1^* - \tilde{H}_2 \tilde{H}_1^*|^2}{|H_1|^2 + |\tilde{H}_2|^2}\right)\sigma_X^2/2\sigma_W^2 + 1} \tag{15}$$

Let us defined two random variables $x = (|H_1|^2 + |\tilde{H}_2|)/2\sigma_W^2$ and $y = \frac{|H_2 H_1^* - \tilde{H}_2 \tilde{H}_1^*|^2}{|H_1|^2 + |\tilde{H}_2|^2}$. y is distributed as $y \backsim (1-\rho^2)u_1$ where u_1 is a χ^2 distribution of 2 degrees of freedom. Hence we can write the approximate SER as

$$\begin{aligned}P_{S,E} =& E_y\left(E_x\left(2a \times \text{erfc}\left(\sqrt{\frac{x}{b(y+1)}}\right)\right.\right. \\ &\left.\left. - a^2 \times \text{erfc}^2\left(\sqrt{\frac{x}{b(y+1)}}\right)\right)\right)\end{aligned} \tag{16}$$

where the double expectation in (16) is with respect to the variables x and y. Since we have defined the pdfs of x and y, P_E is analytically completed. On the other hand if one assumes the spatial interference is approximately Gaussian distributed a simple SER expression can be derived.

Finally one can use the intercodeword coupling free ZF combiner of [11]. For this system the decision variables at the output of the combiner is

$$\begin{aligned}\hat{X}_1 &= (H_1^t H_1^{*t+1} + H_2^t H_2^{*t+1})X_1 \\ &+ N^t H_1^{*t+1} + N^{*t+1} H_2^t\end{aligned} \tag{17}$$

and

$$\begin{aligned}\hat{X}_2 &= (H_1^{*t+1} H_1^t + H_2^t H_2^{*t+1})X_2 \\ &+ N^t H_2^{*t+1} - N^{*t+1} H_1^t\end{aligned} \tag{18}$$

The error performance of this receiver for the general case of ρ has been studied in [11].

A. Decision Feedback Detection

The above analysis showed that in fast fading, the conventional Alamouti ML and the maximum diversity receiver performance is reduced by intercodeword coupling. Hence to improve the SER in both the receivers, we investigated the possibility of DF detection. The idea is to first detect a symbol and then use this tentatively decided symbol to subtract out the interference from the other decision variable. Note that this can be implemented recursively. This is summarized as follows assuming X_1 is detected initially.

1) `Estimate` $\hat{X}_1$ `using` (7) `or` (13).
2) `Cancel the contribution of` X_1 `from` (8) or (14) `using the estimated` $\hat{X}_1$. `Estimate` $\hat{X}_2$.
3) `Cancel the contribution of` X_2 `from` (7) or (13) `using the estimated` $\hat{X}_2$. `Estimate` $\hat{X}_1$.
4) `Repeat steps` (2) `and` (3) `if necessary.`

Note that in the case of a maximum diversity receiver, if the initially estimated $\hat{X}_1$ is correct then we can achieve the optimum performance for X_2 (i.e., static Alamouti condition of $\rho = 1$). Using different combining coefficients several variations of this DF scheme are also possible. For example, one can initially use the interference free ZF detector of [11] to estimate $\hat{X}_1$ and then to use the maximum diversity combiner to detect $\hat{X}_2$ canceling out the contribution of X_1.

A lower bound on the performance of maximum diversity receiver with DF detection can be derived by following the same arguments in [11]. The approximate average SER of this detector is given by

$$\tilde{P}_E = \frac{1}{2}P_1 + \frac{1}{2}P_2 \tag{19}$$

where P_1, P_2 denote the probability of erroneous detection for X_1 and X_2 respectively [11]. $P_i = \Pr(\hat{X}_i \neq X_i)$ and $\tilde{P}_E$ is lower bounded by

$$\tilde{P}_E > \frac{1}{2}P_{S,E} + \frac{1}{2}P_E \tag{20}$$

In (20) we have assumed that X_1 is *almost* correctly detected and that when its contribution is canceled, the decision variable for X_2 appears to be similar to the non-static scenario.

V. Simulation Results

Matlab simulations were performed to study the SER performance of the previously described detection methods. The number of subcarriers is $N = 64$ and 16-QAM modulation was used. For comparison we have also presented the results for the perfect block fading scenario. $E\{|N|^2\} = N_0$ and a cyclic prefix length of 3 was assumed.

Figs. 2-4 show the SER against E_b/N_0 for different ρ using the three different combining methods namely the linear ML Alamouti combiner, receiver-A and receiver-B. In Figs. 2-3 SER results for the linear ML and receiver-A show premature error floors due to the non block fading nature of the considered channel. Also the performance degradation in SER is significant even for $\rho \approx 1$. The conventional receiver and receiver-A exhibits a very similar error performance. However surprisingly receiver-A has a slightly higher degradation than the conventional Alamouti receiver. Note that the receiver-A has the maximum diversity order out of all three receivers. As seen from Fig. 4 the performance of receiver-B is very much better than the previous two receivers. Note that the simulated values of ρ are also higher than the previous cases. No error floor can be observed.

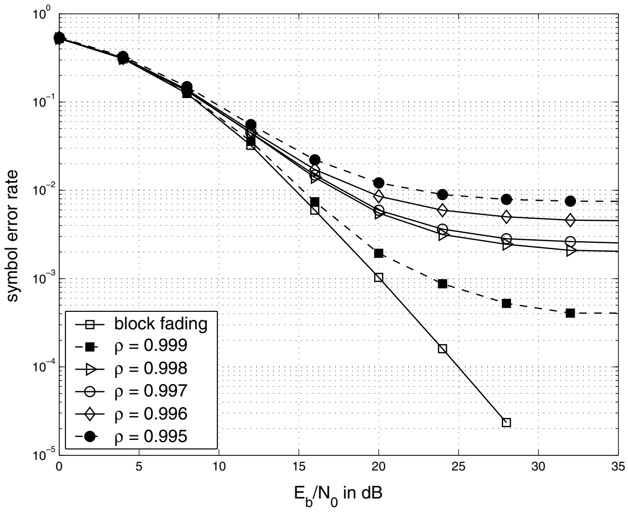

Fig. 2. SER against E_b/N_0 performance for the linear ML receiver.

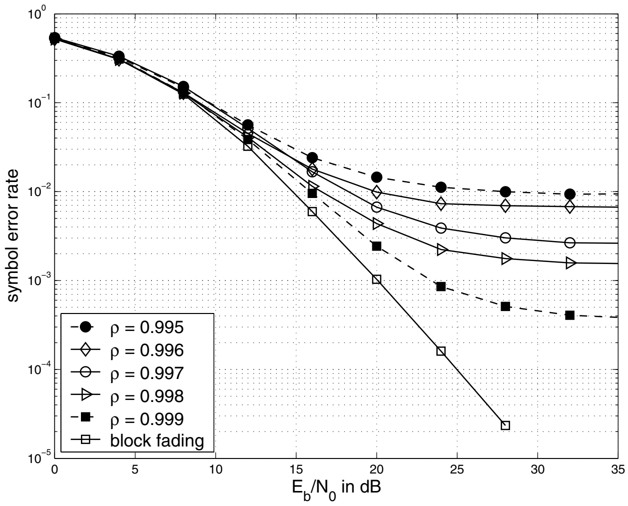

Fig. 3. SER against E_b/N_0 performance for the receiver-A.

In time varying fading conditions, the channel estimation process is challenging and the accuracy of this heavily impacts the performance. Hence in practical systems further SER degradation must be expected. The maximum diversity receivers-A and B assume correct channel coefficients obtained at the two Alamouti codeword symbol periods. When the channel is fast time varying this assumption is not realistic. Fig. 5 shows the SER performance of the DF approach for

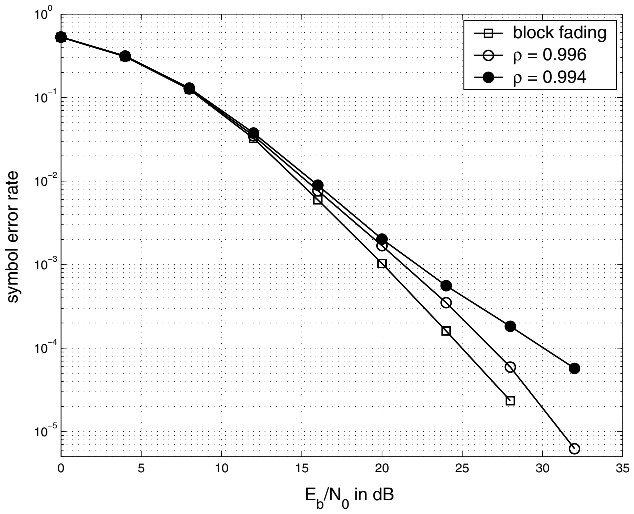

Fig. 4. SER against E_b/N_0 performance for the receiver-B.

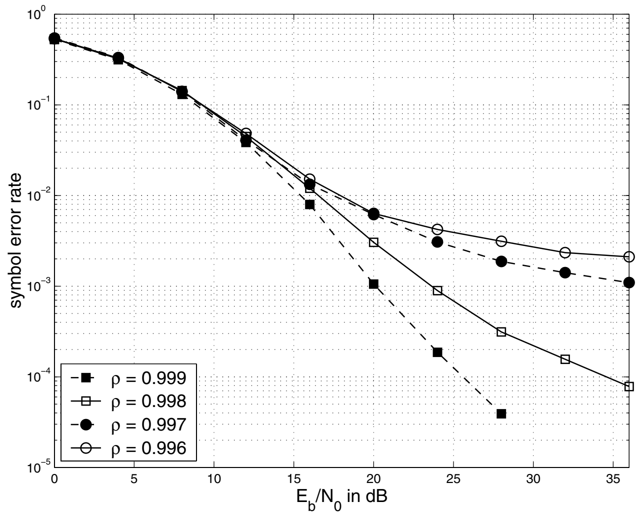

Fig. 5. SER against E_b/N_0 performance for the decision feedback receiver.

the linear ML combiner using an iteration step of one. when formulating the intercodeword coupling term to be subtracted from the decision variables, we have only assumed the knowledge of $H_1^t(k)$ and $H_2^t(k)$ for practical reasons explained earlier. This introduces a residual component of intercodeword coupling. Simulation results for the DF detector are more accurate because they consider the occasional error in feedback. These results exhibit an improvement over same in Fig. 2, however the receiver complexity is also increased. Simulation results indicated a greater performance improvement for higher values of ρ. For small ρ the initial detection values of $\hat{X}_1$ and $\hat{X}_2$ are unreliable hence the improvement after decision feedback becomes marginal.

VI. Conclusions

In this paper the performance Alamouti coded OFDM receivers in Rayleigh time varying channels was studied. The time varying nature of the channel results in a significant performance loss. Simulation results showed that the maximum diversity combiner has a high sensitivity to time varying effects of the channel among all the receivers investigated. We also considered a DF approach to mitigate the intercodeword coupling effects in the conventional Alamouti detector. The performance improvement in the decision feedback receiver is significant in near quasi-static ($\rho \approx 1$) channels. However simulations indicated that for highly time varying channels the performance improvement in SER is marginal.

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