Performance of Space-Time Block Coded OFDM in Time-Selective Macrocell Channel Environments

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Abstract

Space-time coding was first introduced based on the qusi-static fading channel assumption. In this paper, this assumption is not used as we assumed that the channel is time-selective Rayleigh fading. As such the orthogonality between subcarries in time-selective channel will not hold, resulting in interchannel interference (ISI). To combat ISI, we tried different detection schemes in a comparative study. In this study we utilized a 2-by-1 space-time block coded OFDM (STBC-OFDM) under space-time geometrical channel model with hyperbolically distributed scatterers for microcell and macrocell mobile environments.

1 Introduction

Recently, combining space-time (ST) and frequency (SF) coding with Orthogonal Frequency Division Multiplexing (OFDM) has received a massive attention. The transmit diversity technique nowadays has gained significant attention from researchers and industry where hundreds of publications emerged. OFDM is widely used as an effective modulation technique for mitigating the effect of inter symbol interference (ISI) in frequency-selective fading channels and for providing high data rate transmission over wireless channels. Both ST and SF have proven to be effective techniques in enhancing the error performance and increasing the capacity of wireless channels. The first space-time coding scheme was introduced in 1998 by Alamouti's paper [1], in which maximum likelihood decoding decouples the signal transmitted from different antennas. It works well in time-invariant channels over Alamouti codeword period. Mostly, all literature describing single carrier and OFDM-STBC assumed that the channel is a quasi-static block fading, which is not practical at all in real channels (time-varying channels). In this paper, our channel model is based on the scattering model [6],[7] with the assumption that the wave between transmit and receive antennas is propagating through a single bounce scattering and that there is no refraction and diffraction (This is referred to as Geometrical Based Single Bounce (GBSB) model).

Organization of the Paper: In Section **II**, we present the system model. Section **III** contains the propagation channel model, and Section **IV** includes the numerical results. Finally, Section **V** concludes the paper.

2 System Model

The system under study is assumed to be deploying N_t and N_r antennas at the transmitter and receiver, respectively. It combines (STBC) with (OFDM). At the transmitter, data is mapped into a modulation alphabet χ using BPSK and QPSK, where $\chi \in (\pm 1 \pm j)$. This information is fed into Alamouti STBC block with two transmit antennas. The input symbols at the transmitter are divided into two symbol groups to be transmitted from antenna 1 and 2. In the instant $2i$, the two symbols in each group (x_1, x_2) are transmitted, where x_1 is transmitted from antenna 1 and x_2 is transmitted from antenna 2. In the next instant $(2i+1)$, the symbol $-x_{12}^*$ is transmitted from antenna 1 and x_1^* from antenna 2. After the Alamouti transform, an inverse discrete Fourier Transform (IDFT) is applied. Following the IDFT, a cyclic prefex is applied and the period of cyclic prefix must have a length greater than the channel delay spread to reduce the effect of Interblock Interference (IBI) caused by the dispersive Rayleigh fading. We consider here the channel to be time-selective (but frequency-flat). Let $\alpha_i, \beta_i, i = 1, 2$ represents the time-selective channel from the i^{th} transmit antenna to the receive antenna. During the first period α_1 and β_1 denote the complex channel coefficient between the transmit antenna and the receive antenna. During second period α_2 and β_2 are considered. The system equation is summarized as follows:

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} \alpha_1 & \beta_1 \\ -\beta_2 & \alpha_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \tag{1}$$

where, $w_i, i = 1, 2$ represent the noise process, which is assumed to be zero mean circularly symmetric complex white Gaussian noise with variance σ_w^2. The Following step was applying the linear combining scheme as suggested by Alamouti [1], which assumed that the channel is known at the receiver. The linear combining scheme can be written as:

$$\mathbf{z} = \mathbf{H}^H \mathbf{r} = \mathbf{H}^H \mathbf{H} \mathbf{x} + \mathbf{H}^H \mathbf{w} \tag{2}$$

We assume that the transmit energy per data symbol is E_s, hence $E_s/2$ per each antenna. Let $\mathbf{G} = \mathbf{H}^H \mathbf{H}$, which is the cascade of $\mathbf{H}$ with its matched filter and it is a nonnegative-definite Hermition matrix (where $\lambda_i \ i = 1, 2 > 0$). Then we have:

$$\mathbf{G} = \begin{bmatrix} |\alpha_1|^2 + |\beta_2|^2 & \alpha_2^* \beta_2 - \beta_1 \alpha_1^* \\ \beta_2^* \alpha_2 - \alpha_1 \beta_1^* & |\alpha_2|^2 + |\beta_1|^2 \end{bmatrix} \tag{3}$$

A. Quasi-static channel In the case of quasi-static channels, which means that the channel does not change during the transmission intervals, we have $\alpha_1 = \alpha_2 = \alpha$ and $\beta_1 = \beta_2 = \beta$. The above assumption in equation (3) reduces $\mathbf{G}$ to $\mathbf{G}_{static}$:

$$\mathbf{G}_{static} = \begin{bmatrix} |\alpha|^2 + |\beta|^2 & 0 \\ 0 & |\alpha|^2 + |\beta|^2 \end{bmatrix} \tag{4}$$

where $\alpha_1, \alpha_2, \beta_1, \beta_2$ are identically distributed zero mean unit variance circularly symmetric complex jointly Gaussian random with $E[|\alpha_1|^2] = E[|\alpha_2|^2] = E[|\beta_1|^2] = E[|\beta_2|^2] = 1$.

After the liner combining at the receiver, data is fed into a maximum likelihood detector (MLD) to make decision about $\mathbf{x}$ via

$$\hat{\mathbf{x}} = \arg\min \|\mathbf{z} - \sqrt{\frac{Es}{2}} \mathbf{G} \mathbf{x}\| \tag{5}$$

The average single to noise ratio (SNR) per bit is $E[\gamma] = E_s/w_0$ where $\gamma = (|\alpha|^2 + |\beta|^2)E/2w_0$ which has a central chi-square distribution with four degrees of freedom and its probability density function (pdf) is defined as

$$P(\gamma) = \frac{\gamma}{(E/2w_0)^2} \exp(-2\gamma w_0/E) \tag{6}$$

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The bit error probability can be measured by averaging $Q(\sqrt{2\gamma})$ over (6), i.e.,

$$P_e = \int_0^\infty Q(\sqrt{2\gamma}) P(\gamma) d\gamma \tag{7}$$

which yields [4]

$$P_e = \frac{1}{4}(1 - \frac{1}{\sqrt{1 + \frac{2}{E/w0}}})^2 (2 + \frac{1}{\sqrt{1 + \frac{2}{E/w0}}}). \tag{8}$$

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B. Fast Fading Channel A quasi-static channel assumption is not valid in time-varying or time-selective channels (due to the increase of Doppler frequency shift). In this case, ICI over the an OFDM block and the crosstalk over the duration of a space-time codeword are introduced, both resulting in performance loss due to the increase in the error floor of conventional receiver. From (2) and (3), the estimated vector is observed as:

$$\hat{x_1} = (|\alpha_1|^2 + |\beta_2|^2)x_1 + \rho x_2 + \alpha_1^* w_1 + \beta_2 w_2^* \tag{9}$$

$$\hat{x_2} = \rho^* x_1 + (|\alpha_2|^2 + |\beta_1|^2)x_2 + \beta_1^* w_1 - \alpha_2 w_2^*. \tag{10}$$

Note that the second component in (9) represnts the the crosstalk and ρ refers to $\beta_2^* \alpha_2 - \alpha_1 \beta_1^*$. Therefore, the signal-to-interference plus noise (SINR) at the decoder output is found to be

$$\gamma_1 \approx \ \gamma_2 \approx \frac{(|\alpha_1|^2 + |\beta_2|^2)E_s}{w_0 + E[|\rho|^2]} = \frac{(|\alpha_2|^2 + |\beta_1|^2)E_s}{w_0 + E[|\rho|^2]}. \tag{11}$$

Proper detection schemes have been introduced [4] to detect received symbols. Different detection techniques perform differently. They are: 1) Normal Match Filter (NMF), 2) Joint Maximum-Likelihood (JMD), 3) Decision Feedback (DF), and 4) Zero Forcing (ZF).

B.1 Normal Match Filter (NMF)

The received vector $\mathbf{z}$ in (2) is written as

$$\mathbf{z} = \mathbf{H}^H \mathbf{r} = \mathbf{G}_{varying} \mathbf{x} + \mathbf{H}^H \mathbf{w} \tag{12}$$

where $\mathbf{G}_{varying}$ refers to (3); the off-diagonal of the matrix refers to the crosstalk between two adjacent symbols (ICI). The NMF detects the signal about $\mathbf{x_1}$ and $\mathbf{x_2}$ without taking the correlation of the noise $\mathbf{w}$ into consideration. The main drawback of NMF is that the orthogonality does not hold because of the crosstalk between adjacent symbols. The estimated vector can be found via

$$\hat{\mathbf{x}} = \arg\min |\mathbf{z} - \mathbf{H}\mathbf{x}|^2 \tag{13}$$

B.2 Joint Maximum-Likelihood Detector (JMD)

Since $\mathbf{G}$ is Hermitian, it possesses Cholesky factorization of the form $\mathbf{G} = \mathbf{L}^*\mathbf{L}$, where $\mathbf{L}$ is lower triangular with real diagonal elements, it can be written as:

$$\mathbf{L} = \begin{bmatrix} \frac{|\alpha_1\alpha_2^* + \beta_1\beta_2^*|}{\sqrt{|\alpha_1|^2+|\beta_2|^2}} & 0 \\ \frac{\beta_2^*\alpha_2 - \alpha_1\beta_1^*}{\sqrt{|\alpha_1|^2+|\beta_2|^2}} & \frac{|\alpha_2|^2+|\beta_1|^2}{\sqrt{|\alpha_1|^2+|\beta_2|^2}} \end{bmatrix} \quad (14)$$

where $\mathbf{L}$ can be shown in simplified form using $\upsilon_0 = |\alpha_1|^2 + |\beta_2|^2$, $\upsilon_1 = |\alpha_2|^2 + |\beta_1|^2$, $\rho = \beta_2^*\alpha_2 - \alpha_1\beta_1^*$ and $\xi = |\alpha_1\alpha_2^* + \beta_1\beta_2^*|$ as:

$$\mathbf{L} = \begin{bmatrix} \xi\upsilon_1^{-1/2} & 0 \\ \rho^*\upsilon_1^{-1/2} & \upsilon_1^{1/2} \end{bmatrix} \quad (15)$$

Multiplying both sides of (2) by $(\mathbf{L^{-H}})\mathbf{H^H}$ we get:

$$\mathbf{z} = (\mathbf{L^{-H}})\mathbf{H^H}\mathbf{r} \quad (16)$$

which represents the white matched filtering. The new combiner has the following form

$$\mathbf{z} = \mathbf{L}\mathbf{x} + \mathbf{w_n} \quad (17)$$

where the $\mathbf{w}_n$ is the white Gaussian noise with covariance matrix $E[\mathbf{w_n}\mathbf{w_n}^H] = \sigma_n^2\mathbf{I}$. The estimated signal $\hat{\mathbf{x}}$ using JML can then be expressed as

$$\hat{\mathbf{x}} = \arg\min \|\mathbf{z} - \mathbf{L}\mathbf{x}\|. \quad (18)$$

B.3 Decision Feedback Detector (DFD) It can be noticed from (15) and (17) that $\hat{x_1}$ can be estimated without interference from x_2. The contribution of $\hat{x_1}$ can be cancelled from z_2 by replacing x_1 with $\hat{x_1}$ to make a decision about x_2.

B.4 Zero Forcing Detector (ZFD) This forces the crosstalk in (1) to be zero as follows:

$$z = Fr \quad (19)$$

where F can be designed to force the crosstalk to zero which is given by

$$F = AH^{-1} = \begin{bmatrix} \xi\upsilon_1^{-1/2} & 0 \\ 0 & \xi\upsilon_0^{-1/2} \end{bmatrix} H^{-1} \quad (20)$$

The received vector after applying (ZF) can be written as

$$z = Ax + w_z \quad (21)$$

w_z is correlated noise vector and both noise components for antenna 1 and 2 are identically distributed. The drawback of ZFD is that the power of the effective noise $w_z = w_0 H^{-1}$ is higher than the original noise w_0, where $E[w_z w_z^H] = w_0(HH^H)^{-1}$. Making a decision about the input vector x can be expressed via

$$\hat{\mathbf{x}} = \arg\min \|\mathbf{z} - \mathbf{A}\mathbf{x}\|. \quad (22)$$

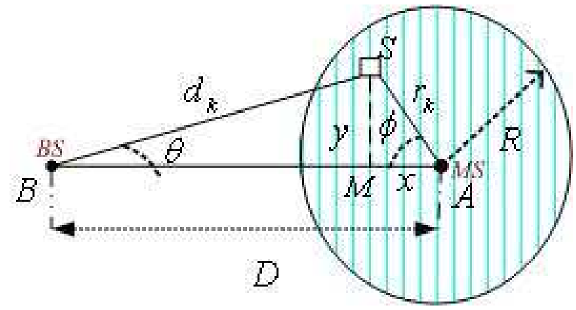

Figure 1. General structure of Geometry of the Geometrical Hyperbolic Scattere Model

3 Propagation Channel Model

In this Section we provide general description for the geometrical-based hyperbolically distributed scatterers (GBHDS) channel model for macrocell environments. A comprehensive study of this model (at theoretical and simulation levels) as well as its validation with practical data has been considered in [6]. It proved to be more realistic than other models in the literature when tested against practical data. Fig. 1 shows the geometry of this model.

This model assumes that the scatterers are arranged within a circle of Radius R around the mobile. The distance r_k between the mobile station (MS) and the scatterers are distributed according to the hyperbolic probability density function (pdf). The probability density function of the distance r_k has the form [6],[7]:

$$f_{r_k}(r_k) = \begin{cases} \frac{1}{B\cosh^2(ar_k)} & \text{for } 0 \le r_k \le R \\ 0 & \text{elsewhere} \end{cases} \quad (23)$$

where R is the radius of the scatterers' circle, a is the spread control parameter which lies in the interval (0, 1) and controls the spread (standard deviation) of the scatterers around the mobile. B is the normalization factor for the pdf which is given by $\tanh(aR)/a$. We considered a base station (transmit antennas) equipped with n_T antennas, with n_R antennas at the receiver. The entries (n_T, n_R) between the transmitter and receiver are independently identically distributed (i.i.d) complex Gaussian random variables. For simplicity, uniform linear arrays (ULAs) are used as antenna geometry. The channel matrix can be described via steering vector:

$$\mathbf{a}(\phi_T) = \frac{1}{\sqrt{N}}[1, e^{\frac{-j2\pi\delta_T}{\lambda}\sin(\phi_T)}, \cdots, e^{\frac{-j2\pi(N-1)\delta_T}{\lambda}\sin(\phi_T)}]. \quad (24)$$

$$\mathbf{a}(\theta_R) = \frac{1}{\sqrt{N}}[1, e^{\frac{-j2\pi\delta_R}{\lambda}\sin(\theta_R)}, \cdots, e^{\frac{-j2\pi(M-1)\delta_T}{\lambda}\sin(\theta_T)}]. \quad (25)$$

where δ_T and δ_R are the antenna spacing at the transmitter and receiver, respectively; $\mathbf{a}(\phi_T)$, $\mathbf{a}(\theta_R)$ represent the steering vector for the transmitter (ϕ_T refers to the angle of departure AOD) and receiver(θ_R is the angle of arrival AOA) arrays, respectively.

We assume that there are L scatterers within one cluster between the transmitter and the receiver and one physical MIMO channel for this cluster is

$$h_{l,n,m}(t) = \frac{1}{\sqrt{L}} \sum_{l=0}^{L-1} \sqrt{P(\tau_l)} a_m(\theta_l^R) a_n(\phi_l^T) \beta_{l,m,n}(t) \quad (26)$$

where P is the average power of the L^{th} scatter and τ_l is the delay for the L^{th} scatter. The two array propagation phase shifts $a_m({\theta_l}^R)$and $a_n({\phi_l}^T)$ refer to the spatial characteristic of the fading process and $\beta_{l,m,n} = \alpha(t) e^{j2\pi f_d \cos({\phi_l}^T - \gamma)t}$ is the temporal correlation characteristic of the fast fading process, $\alpha(t)$ being the attenuation of scatter which is assumed to have resulted from a random process with variance $\sigma = 1$, and f_d is the maximum frequency shift (Doppler) which is equal to $f_c v/c$, v being the velocity of the object, (γ is the direction of the object) and c is the speed of light. The correlation between signals form different antennas is referred to as spatial fading correlation which can be defined at the transmitter Tx:

$$R_n{}^{Tx} = \sum_{l=0}^{L-1} a_n({\phi_l}^T) a_n^H({\phi_l}^T) \quad (27)$$

which is based on the antennas separation and AOD. High correlation can be observed for small antenna separation and low angular spreads.

4 Numerical Results

We show the performance of Alamouti scheme with different detectors in time-varying multipath Rayleigh fading channels. In the simulation conducted, the following parameters were adopted: BPSK, Number of carrier N_c is 128, $N_t = 2$ and $N_r = 1$. ULA is considered at the base station(BS).

In Fig.2, we demonstrate the performance of different detection schemes NML, JML, DF and ZF over the GBHDS macrocell and microcell channel models. The parameters for macrocell are: distance between the transmitter and receiver is D =4000 and angular spread is $AS = 7°$. For microcell, $D = 1000$ and

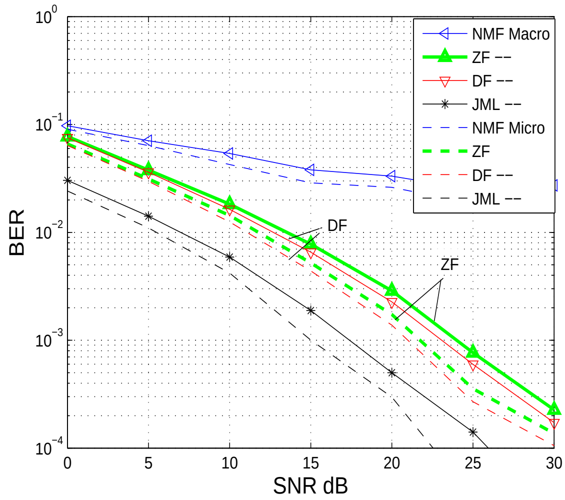

Figure 2. Error rate performance of STBC-OFDM over time-varying GBHDS channel in macro- and microcell environments.

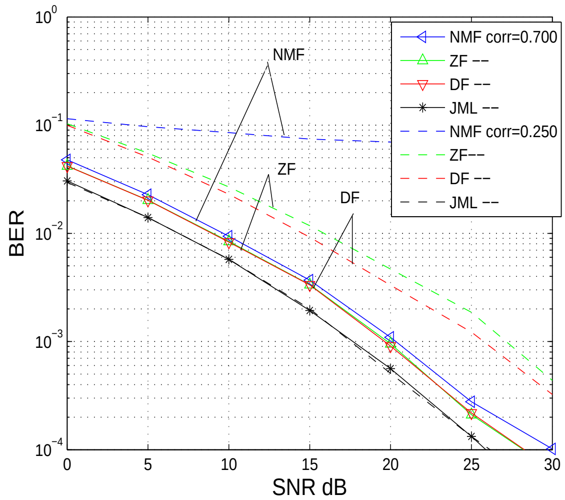

Figure 3. Error rate performance of STBC-OFDM over time-varying GBHDS channel in a macrocell environment.

$AS = 24.5°$ are considered, where the values are extracted from experimental data. It can be noticed that all detectors perform better in microcell environment. Detectors have different performance, where JML detector is always performing the best among all the others as a result of taking off the crosstalk and noise. By varying the channel correlation ρ, different results can be achieved. The channel is quas-static when $\rho = 1$, where all detectors perform the same. The DF detector has a degrade in its performance due to the the feedback erroneous decision. Furthermore, the loss in the ZF detector performance is due to the drawback that the power of the effective noise $w_z = w_0 H^{-1}$ is higher than the original noise w_0. The NMF fails in the highly time-varying channel due to the crosstalk and the colored noise.

Fig.3 demonstrates the performance of all detectors in macrocell environment by varying the ρ values. It can be noticed that JML is performing the same for both values; which is approximately similar to the performance in qusi-static channel ($\rho = 1$). In addition, DF and ZF suffer from degradation when the value of ρ goes down. The NML is not a practical scheme when the channel varies rapidly.

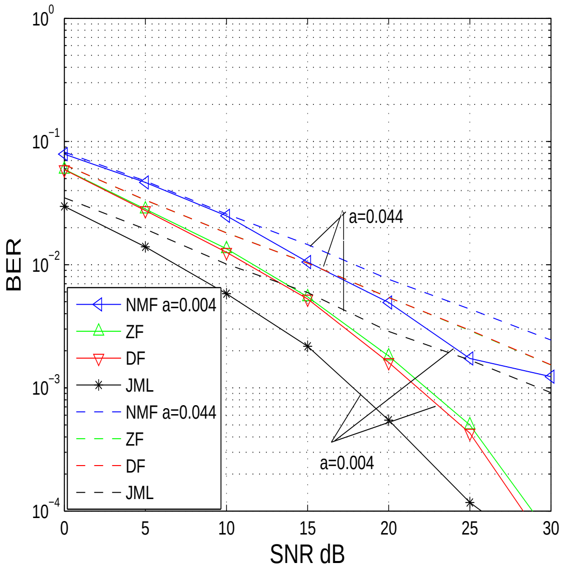

Figure 4. The impact of the spread parameter a on the system's performance.

Fig.4 shows the performance of all detectors by varying the spread parameter a which has a significant impact on the signal level (in dB), where increasing a reduces the angle spread of the scatterers (i.e., reduces the diameter of the scatterers around the mobile). The JML detector has a significant performance loss when the spread parameter a increases. The DF and ZF detectors have the same performance when the diameter of the scatterers around the mobile is large.

5 Conclusion

In this paper, the performance of STBC OFDM in time-varying channels was studied. We assessed the performance of various detectors and the results indicated a significant loss in performance of all detectors due to time-varying nature of the channel. The joint maximum likelihood (JML) detector outperforms other detectors when the channel correlation is small. We have considered a practical channel using GBHDS model for both macro- and micrcell environments.

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