

Adaptive Switching between Space-Time and Space-Frequency Block Coded OFDM Systems in Rayleigh Fading Channel

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Received February 25, 2013; revised March 25, 2013; accepted April 25, 2013

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ABSTRACT

This work explores the performances of Space-Time and Space Frequency Coded Orthogonal Frequency Division Multiplexing (OFDM) with simple two branches transmit diversity scheme. The combination of multiple-antenna and orthogonal frequency division multiplexing (OFDM) provides reliable communications over frequency selective fading channels. We focus on the application of space-time block codes (STBC) and space-frequency block codes (SFBC) in OFDM systems over time-varying and frequency-selective channels. SFBC transmitter shows superior performance in fast varying channels while STBC shows better performance in frequency selective channels. A switching technique is presented that selects an appropriate transmission scheme between the STBC and SFBC assuming Rayleigh fading model.

Keywords: OFDM; MIMO; Rayleigh Fading Channel; STBC; SFBC

1. Introduction

Future Wireless communication systems have to be designed to integrate high data rates and high quality of service and multimedia wireless communications. This increasing demand has led to the demand for higher network capacity and performance. Multiple antenna architecture on the transmitter and receiver sides, which is called multiple input multiple output (MIMO) is a suitable technique to improve the channel capacity [1].

Two MIMO schemes can be exploited, Space diversity and Spatial Multiplexing. In Space Diversity scheme, Space-Time Block Coding (STBC) and Maximal Ratio Combining (MRC) can be used to exploit the maximum spatial diversity available in the channel [1].

Space diversity is employed to counter fight fading and it is widely used in wireless systems. The basic idea behind this approach is to transmit more copies of a signal which permits to be more resistant to deep fading: if the receiver is supplied with more than one replica of the signal, transmitted over independent fading channels, the probability that all the copies are in deep fade is greatly reduced. The MIMO diversity gain can be obtained ex-

ploiting every domain of the wireless transmission. Typical examples are time diversity and frequency diversity where signals are repeated over time or over different frequencies [2]. For multiple antennas, an effective way of providing diversity is through STBC; usually multiple transmissions are done over the two dimensions of space (antennas) and time (successive time slots), STBC system assume that the channel is constant over time for the whole duration of the STBC block, as the performance is degraded if the channel is varying over successive time slots.

The simplest STBC is the Alamouti code. In its basic version, it employs two antennas at the base station and one antenna at the mobile terminal. The scheme transmits two symbols from two antennas in two successive time slots, thus a total of four symbols per Alamouti-block are transmitted [3]. Alamouti has been widely adopted because it is simple and requires a low signal processing load at the receiver (*i.e.* a portable device, being mobile and energy-limited). A simple receiver, with a linear combiner and a single antenna, can extract an order of diversity equal to 2 if the assumption of constant channel over two time slots is met. Alamouti code with two transmit-

ting antennas and a single receiving antenna provides a diversity gain of two; if two receiving antennas are used, the diversity gain will be four [3]. No spatial gain is achieved with STBC. Over the recent years, the combination of Multiple Input Multiple Output (MIMO) with Orthogonal Frequency Division Multiplexing (OFDM) has gained significant interest and is considered as one of the most promising techniques for present and future wireless communication systems [4]. MIMO-OFDM system is used in many applications like WiMax, WiFi, WLANs. Block Coding is also possible over the two domains of antenna and frequency with Space-Frequency Block Coding (SFBC) in a Multi Carrier system, such as OFDM. This means that the SFBC coded blocks are transmitted during the same symbol time but from different antennas and over various sub carriers [5].

This paper is focused on the analysis of the performances of Space-Time and Space Frequency Coded MIMO-OFDM with simple two branches transmit diversity scheme over time frequency selective channels. The assumption of constant channel response during the transmission becomes critical in STBC-OFDM over time varying channels. Similarly, the channel gain can not be constant for neighboring subcarriers in SFBC-OFDM over frequency selective channels. Adaptive switching between STBC and SFBC has been proposed in [6]. It has been found that the adaptive system switching between STBC and SFBC provides remarkable performance improve-

ment. However, the proposed criteria in [6] can not be implemented at the transmitter side without perfect channel state information, channel correlation matrix is needed. Otherwise, this adaptive switching might cause some problems such as feedback delay, sensibility to channel estimation errors, etc.

In this paper, we propose a switching criterion based on normalized maximum Doppler frequency and normalized delay spread. Different from [6], the system needs only to estimate the channel delay spread and the Doppler frequency. Therefore, assumptions can be made at the transmitter side.

This paper is organized as follows. Section 2 presents Space-Time and Space Frequency Coded MIMO-OFDM system model. Section 3 describes time frequency selective channel. The proposed adaptive switching system is introduced in Section 4. The system simulation results are presented in Section 5.

2. MIMO-OFDM System Description

2.1. MIMO Alamouti Space Time Block Coding

Alamouti coding is defined by using two transmit antennas using an orthogonal space time coding which is presented in **Figure 1**.

It means that the first antenna transmit s_0 and $-s_1^*$ respectively, simultaneously the second antenna transmit s_1 and s_0^* .

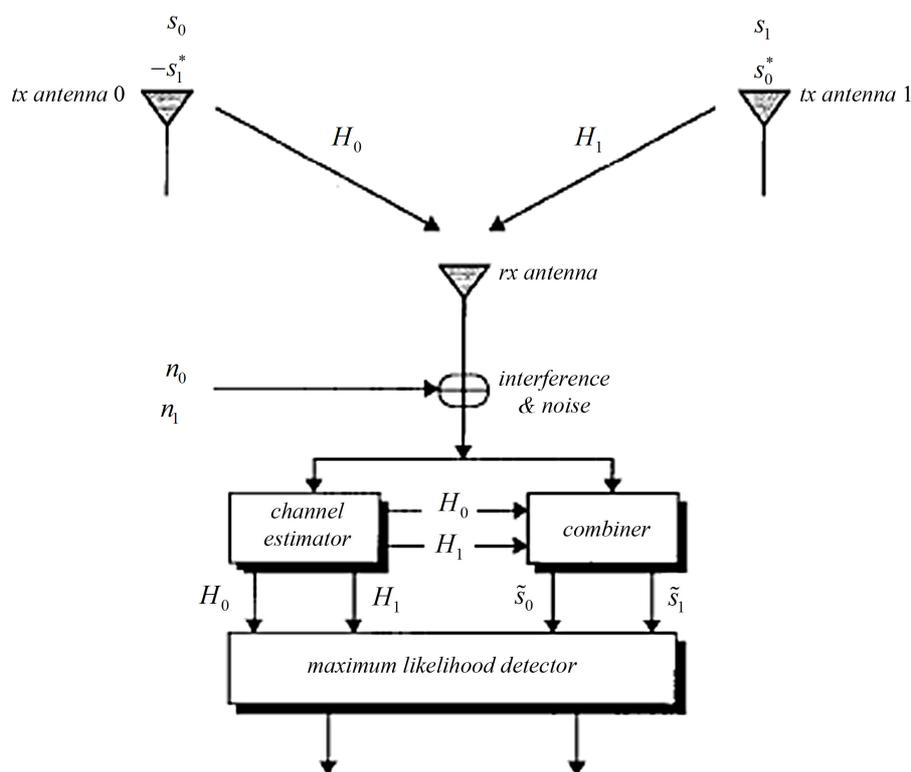


Figure 1. Space Time Alamouti coding [3].

If we assume that the channel is invariant between the first and second time of transmission, it results that the received signal can be expressed as:

$$r_0 = r(t) = s_0 \cdot H_0 + s_1 \cdot H_1 + w_0 \tag{1}$$

$$r_1 = r(t+T) = -s_1^* \cdot H_0 + s_0^* \cdot H_1 + w_1 \tag{2}$$

Equations (1) and (2) show the output r of the receiver at time t and $t + T$, w_0 and w_1 are complex random variables representing receiver noise. H_0 and H_1 are the channel coefficients.

The main advantage using this coding is that we can recover the signal using a simple linear operation without amplifying the noise [3]:

$$\tilde{s}_0 = H_0^* r_0 + H_1 r_1^* \tag{3}$$

$$\tilde{s}_1 = H_1^* r_0 - H_0 r_1^* \tag{4}$$

Equations (3) and (4) give the symbol's estimation by the Alamouti combining scheme. The combiner is shown in **Figure 1** and the two combined signals \tilde{s}_0 and \tilde{s}_1 are sent to the maximum likelihood detector.

2.2. Combining MIMO with OFDM

As well as known, the OFDM is a promising technology, which transforms a frequency selective channel into flat fading sub channels. In this paragraph we will present how the OFDM is used with MIMO systems.

2.2.1. Alamouti STBC-OFDM Scheme

Let us consider that we have a transmission sequence $\{s_1, s_2, \dots, s_N\}$. In normal transmission, we will be sending s_1 in the first time slot, s_2 in the second time slot, s_3 and so on. However, Alamouti suggested that we group the symbols into groups of two. In the first time slot, we send s_1 and s_2 from the first and second antenna. In second time slot we send $-s_2^*$ and s_1^* from the first and second antenna. In the third time slot send s_3 and s_4 from the first and second antenna and so on.

According to Alamouti Space time code applied for the OFDM system, we have the signals transmitted at times t and $t + T$ from antennas 1 and 2 respectively given by:

$$\text{Antenna 1: } S_0 = [s_1 s_3 \dots s_{2N-1}, -s_2^* - s_4^* \dots -s_{2N}^*];$$

$$\text{Antenna 2: } S_1 = [s_2 s_4 \dots s_{2N}, s_1^* s_3^* \dots s_{2N-1}^*].$$

Where S_0 and S_1 are the outputs for pathways 1 and 2 respectively of the space time encoder, $s_1, s_2, s_3, s_4, \dots, s_{2N}$ are the signal symbols, $2N$ is representing the total symbol number and N is equal to the number of subcarriers.

The encoded data are passed through a serial to parallel block where data are regrouped according to the subcarrier and time as shown in **Table 1**.

The MIMO-OFDM system model based on STBC is shown in **Figure 2** [7].

We suppose that the channel is invariant, by assuming $H(n+1, k) = H(n, k)$ the received signal can be expressed as:

$$R = H_0 \cdot S_0 + H_1 \cdot S_1 + W \tag{5}$$

where

$$H_0 = [H_0(n,1) \dots H_0(n,N), H_0(n+1,1) \dots H_0(n+1,N)]^t$$

$$H_1 = [H_1(n,1) \dots H_1(n,N), H_1(n+1,1) \dots H_1(n+1,N)]^t$$

$$R = [R(n,1) \dots R(n,N), R(n+1,1) \dots R(n+1,N)]^t$$

Table 1. STBC-OFDM scheme for two antennas.

	Subcarrier	Time t	Time $t + T$
Antenna 1	1	s_1	$-s_2^*$
	2	s_3	$-s_4^*$

	N	s_{2N-1}	$-s_{2N}^*$
Antenna 2	1	s_2	s_1^*
	2	s_4	s_3^*

	N	s_{2N}	s_{2N-1}^*

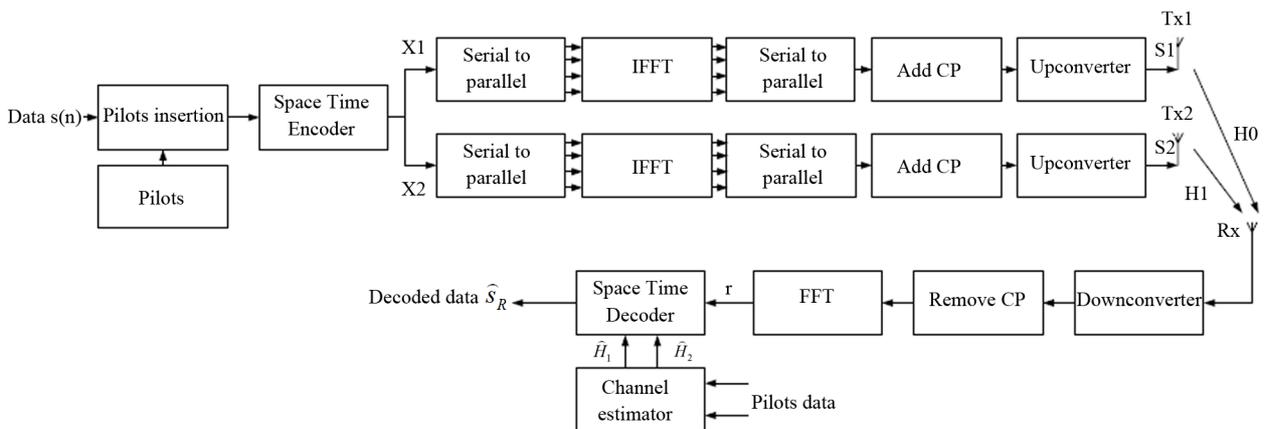


Figure 2. Block diagram of a two transmit and one receive antennas MIMO-OFDM system In Space Time Alamouti coding.

$R(n, k)$ is the received symbols in subcarrier k . S_0 and S_1 are the transmitted symbols, W the Gaussian noise, n refers to the n -th OFDM block.

According to (3) and (4) the combined signals \tilde{s}_i and \tilde{s}_{i+1} sent to the maximum likelihood detector are given by:

$$\tilde{s}_i(n, k) = H_0^*(n, k)R(n, k) + H_1(n, k)R^*(n+1, k) \quad (6)$$

$$\tilde{s}_{i+1}(n, k) = H_1^*(n, k)R(n, k) - H_0(n, k)R^*(n+1, k) \quad (7)$$

where $i = 1, 3, 5, \dots, N-1$, represent the symbol number and k refers to the k^{th} subcarrier, $k = 1, 2, \dots, N$.

The receiver need to estimate the channel H_0 and H_1 in order to use the Maximum Likelihood Decision Rule to produce \hat{s}_i and \hat{s}_{i+1} .

2.2.2. Alamouti SFBC-OFDM Scheme

The main idea behind the use of SFBC in OFDM is that the channel frequency response of adjacent subcarriers remains almost constant in such a system. The space-time block code STBC has been applied to frequency selective channels by using OFDM, which transforms a frequency selective channel into flat fading sub channels. The use of OFDM offers the opportunity for coding in the frequency domain in the form of space-frequency block codes SFBC [8].

The use of frequency diversity SFBC has an impact on spectral efficiency but this problem can be overcome by an increase of modulation order.

For 2 transmitter antennas, for each OFDM symbol, adjacent subcarriers k and $k + 1$ ($k = 1, \dots, N$) are used in space-frequency code. The n^{th} OFDM symbol vector, $S(n) = [s_1(n), s_2(n), \dots, s_N(n)]$, is coded into two vectors $S_1(n) = [s_1(n), -s_2^*(n), \dots, s_{N-1}(n), -s_N^*(n)]$ and

$S_2(n) = [s_2(n), s_1^*(n), \dots, s_N(n), s_{N-1}^*(n)]$ by

space-frequency block encoder. $S_1(n)$ is transmitted from the first antenna while $S_2(n)$ is transmitted simultaneously from the second antenna. The symbol assignment of the 1st OFDM symbol vector is shown in **Figure 3**.

According to the symbol assignment given in **Figure 3**, the receiver output for subcarriers k and $k + 1$ for adjacent subcarriers can be written as

$$R_k = H_0(f_k) \cdot s_k + H_1(f_k) \cdot s_{k+1} + W_k \quad (8)$$

$$R_{k+1} = -H_0(f_{k+1}) \cdot s_{k+1}^* + H_1(f_{k+1}) \cdot s_k^* + W_{k+1} \quad (9)$$

By assuming that adjacent subchannels in the OFDM spectrum have the same channel transfer functions [7], we have $H_0(f_k) = H_0(f_{k+1})$ and $H_1(f_k) = H_1(f_{k+1})$, in this case Equations (8) and (9) are similar to (1) and (2) and maximum diversity is achieved [3].

$$\tilde{s}_k = H_{0k}^* \cdot R_k + H_{1k} R_{k+1}^* \quad (10)$$

$$\tilde{s}_{k+1} = H_{1k}^* R_k - H_{0k} R_{k+1}^* \quad (11)$$

3. Time Frequency Selective Channel

In the design and implementation of a transmitter/receiver for wireless communications, it is very important to understand the wireless radio channel. The channel is characterized by two important parameters: the delay spread τ_{max} and the maximum Doppler frequency $f_{d\text{max}}$. Channels with long delay spread τ_{max} and high Doppler frequency f_d , exhibit a lower coherence bandwidth and a lower coherence time, corresponding to time-frequency selective channel as it is indicated in **Figure 4**. In other words, the frequency selectivity of the channel depends on the delay spread τ_{max} , and time selectivity depends on the Doppler frequency [8].

3.1. Channel Model

In the analogue domain, the multipath channel is described by the following complex-valued impulse response [9]:

$$h(t, \tau) = \sum_{l=1}^L \alpha_l(t) \delta(\tau - \tau_l(t))$$

where α_l is the complex gain of the l^{th} path, τ_l is the propagation delay for the l^{th} path. In digital transmission systems, symbols are often transmitted in regular time interval T_s , called the sampling period. This period is often small in comparison with the maximum delay time τ_{max} .

The discrete multipath model is regarded as a reference for most of the contemporary wideband terrestrial wireless systems under a reasonable approximation of constant

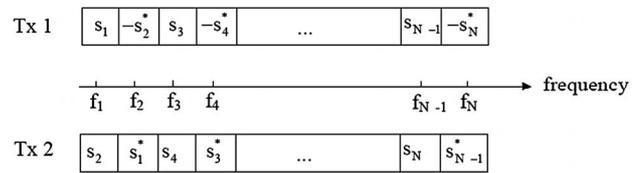


Figure 3. Symbol assignment for subcarriers in SFBC.

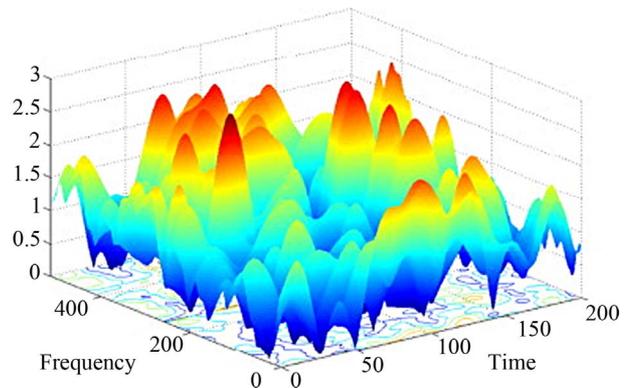


Figure 4. Time frequency selective channel.

number of multipath components L and slow variation of the delay values $\tau_i(t)$. The multipath channel is then modeled as

$$h(t, \tau) = \sum_{l=1}^L \alpha_l(t) \delta(\tau - \tau_l \cdot T_s)$$

$\alpha_l(t)$ depends on Doppler frequency f_d which is caused by the velocity v_m of the receiver.

$f_d = v_m \cdot f \cdot \cos(\theta)/c$, θ is the azimuth of arrival of the radio wave, f is the carrier frequency, and c is the speed of the impacting radio wave.

3.2. Time Selectivity in Mobile Radio Channel

The channel time selectivity is due to the movement of the transmitter and/or the receiver. The frequency changes due to the Doppler effect depends on the relative motion between the source and receiver and on the speed of propagation of the wave.

The Doppler effect is characterized by two parameters: The coherence duration T_c and the Doppler spread B_d .

- Coherence time T_c is a statistical measure of the time duration over which the channel impulse response is essentially invariant.
 - The Doppler spread B_d given by $B_d = f_{d \max} = v_m \cdot f/c$
- The Doppler spread B_d , and the coherence time T_c , are reciprocally related (within a multiplicative constant) [8].

$$T_c \approx \frac{1}{f_d}$$

A channel is referred to as fast fading channel if

$$T_c < T$$

where T is the time duration of an OFDM symbol.

The below Figure (Figure 5) shows simulation results obtained with Rayleigh fading model for different Dop-

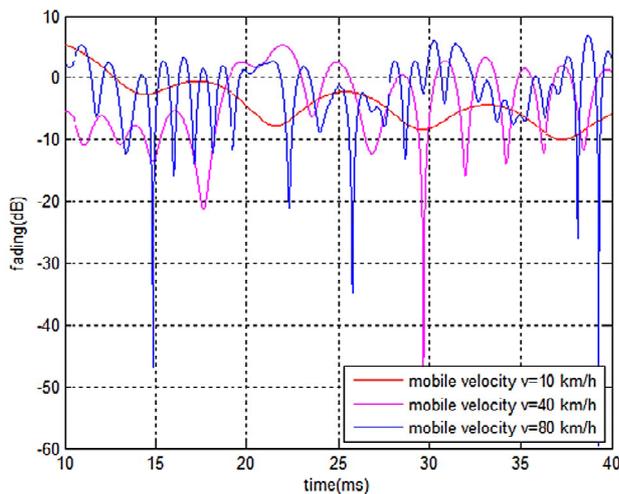


Figure 5. Rayleigh fading channel for varying mobile velocities.

pler frequency at varying mobile velocity ranging 80, 40 and 10 km/hour.

It can be observed from Figure 5 that the mobile velocity affect channel time selectivity.

3.3. Frequency Selectivity in Mobile Radio Channel

New applications such as wireless local area networks (LANs) require very high data rate transmissions. These applications are usually used in indoor environments. The result of radio signal multipath propagation in real environment is signal spread in time and it leads to the frequency selectivity of the channel.

Indoor fading channels are usually frequency selective for data rates over several Mbps.

Coherence bandwidth B_c is a statistical measure of the range of frequencies over which the channel can be considered “flat”.

We define severely frequency selective channel when coherence bandwidth is smaller than a pair of sub-carrier bandwidth, $\Delta f < B_c < 2\Delta f$, where B_c denote the coherence bandwidth and Δf the sub-carrier spacing in the OFDM spectrum.

In relation to severely frequency-selective channel, we define moderately frequency-selective channel when $B_c > 2\Delta f$, and in that case we can easily say that neighboring sub-carriers have identical channel frequency response.

For the Rayleigh fading model, the relation between the coherence bandwidth and delay spread was stated [8]

$$B_c \approx \frac{1}{\tau_{\max}}$$

- A channel is said to exhibit frequency nonselective or flat fading if $B < B_c$, this inequality can be expressed as $T_s > \tau_{\max}$, where B is the signal bandwidth ($B = 1/T_s$), T_s is the sampling time ($T = N \cdot T_s$). In this case, all the received multipath components of a symbol arrive within the symbol time duration.
- A channel is said to exhibit frequency selective fading if $B > B_c$, this inequality can be expressed as $T_s < \tau_{\max}$. This condition occurs when the received multipath components of a symbol extend beyond the symbol's time duration.

4. Proposed Adaptive Switching Technique

4.1. The Time-Frequency Correlation

The basic idea of adaptive switching is to choose the appropriate transmission mode at the given channel condition. In [6], the correlation for the same subcarrier between adjacent blocks, ρ_t , and the correlation between adjacent subcarriers for the same block, ρ_f , are compared to choose an appropriate transmission mode. In [10],

the theoretical value of ρ_t and ρ_f over Rayleigh fading channels are represented as

$$\rho_t = \frac{1}{N^2} \sum_{l=-N+1}^{N-1} (N-|l|) J_0 \left[2\pi f_d T \left(1 + \frac{G}{N} + \frac{l}{N} \right) \right]$$

$$\rho_f = \frac{(1-\lambda)(1-\lambda^M e^{-j2\pi M/N})}{(1-\lambda^M)(1-\lambda e^{-j2\pi/N})} \frac{1}{N^2} \sum_{l=-N+1}^{N-1} (N-|l|) J_0 \left[\frac{2\pi f_d T l}{N} \right]$$

where $\lambda = e^{-T/\tau_{\max}}$, G is the number of guard samples, N number of OFDM subcarriers and T is the duration of an OFDM block. $J_0[\]$ is Bessel function of order zero.

The correlation coefficients ρ_t and ρ_f between subcarriers along time and frequency respectively is needed to decide the switching mode (STBC or SFBC).

4.2. Dynamic Allocation of STBC and SFBC in an OFDM System

The proposed adaptive switching system is illustrated in **Figure 6**.

The transmitter or receiver calculates ρ_t and ρ_f . Then it decides where the correlation is higher. The system needs only to estimate the channel delay spread and the Doppler frequency. Therefore, assumption can be made in the transmitter side.

Notice that, for a Rayleigh fading channel, ρ_t depends only on $f_d \cdot T$. ρ_f depends on $f_d \cdot T$ and $\frac{\tau_{\max}}{T}$.

5. Simulation Results

In this section, we verify the theory by simulation and we test the performance of the proposed adaptive switching technique. The channel model is Rayleigh with parameters shown in **Table 2**.

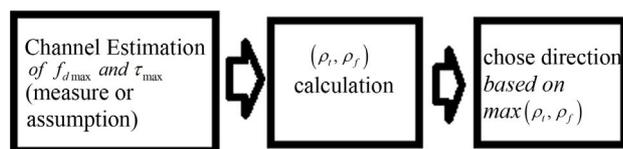


Figure 6. Adaptive switching system.

Table 2. Simulation parameters.

Parameters	Values
Channel model	Rayleigh
System Bandwidth (MHz)	10
modulation	4-QAM
Sample time (ns)	88
Number of subcarriers	64
Number of guard samples	16

We assume a perfect channel estimation since the aim of our simulation is to study the performance under different channel conditions by varying channel delay spread and Doppler frequency.

5.1. The Comparison between STBC-OFDM and SFBC-OFDM

The performance of OFDM STBC and SFBC schemes are evaluated depending on the BER versus the signal-to-noise ratio (SNR) in E_b/N_0 .

Two types of channels slow fading and fast fading channel are examined. The performance comparison between STBC and SFBC in OFDM system over slow fading channel ($f_d = 20$ Hz) is shown in **Figure 7**, the performance of the two systems STBC and SFBC-OFDM in fast fading channel ($f_d = 100$ Hz) are shown in **Figure 8**, and the performance of STBC and SFBC-OFDM in slow fading ($f_d = 20$ Hz) over frequency selective channel is shown in **Figure 9**.

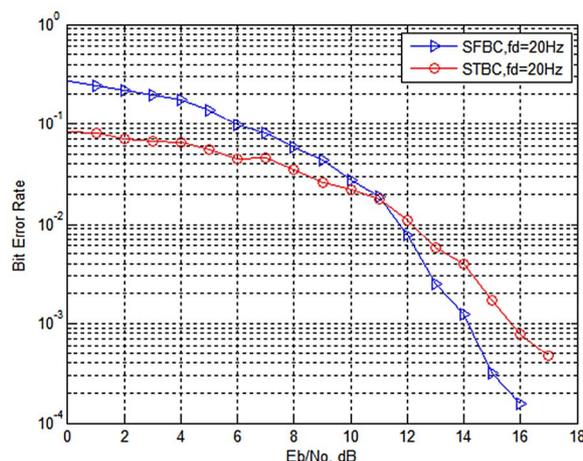


Figure 7. Performance of STBC and SFBC-OFDM for ($f_d = 20$ Hz).

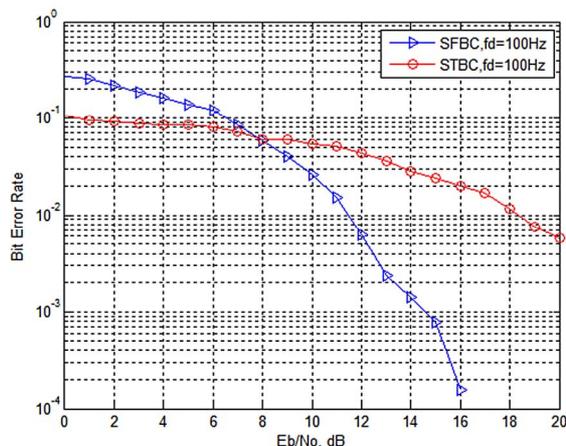


Figure 8. Performance of STBC and SFBC-OFDM for ($f_d = 100$ Hz).

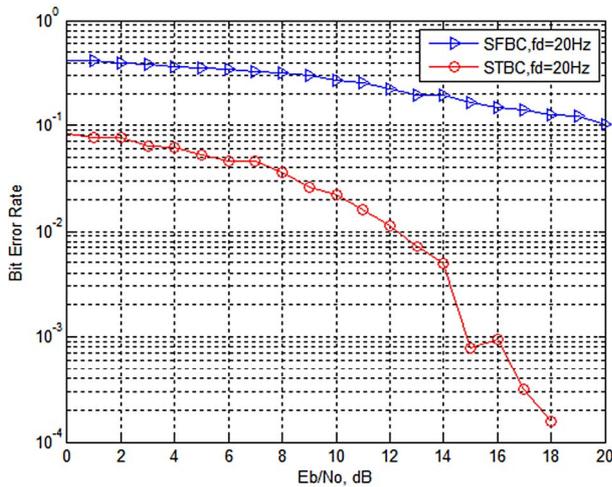


Figure 9. Performance of STBC and SFBC-OFDM over severely frequency selective channel.

In Figure 7, it can be observed, that SFBC OFDM achieves similar performance as STBC-OFDM in slow fading channel. It can be observed that SFBC-OFDM performs better in fast varying channel (Figure 8).

In Figure 9 it is seen that in the frequency selective channel the performance of SFBC is lost. The reason is that in this case the condition $B_c > 2\Delta f$ is not fulfilled as well as the past.

5.2. The Adaptive Switching under Rayleigh Fading Channel

Comparing the values $|\rho_t|$ and $|\rho_f|$ from Figure 10, we note that the correlation coefficient can be lower in the time or frequency domain, depending on the terminal velocity and delay spread.

Figure 10 shows the correlation $|\rho_t|$ and $|\rho_f|$ in terms of $f_d \cdot T$. We notice that the time correlation is strong ($|\rho_t| > |\rho_f|$) under slow time varying channels such as $f_d \cdot T = 0.01$ and $f_d \cdot T = 0.05$ ($f_d \cdot T \ll 1$). Under these conditions STBC performs better than SFBC.

In rapid time varying channels such as $f_d \cdot T = 0.8$ and $f_d \cdot T = 0.9$, the frequency correlation can be higher. However, frequency correlation, ρ_f , is governed by the two parameters: $f_d \cdot T$ and $\frac{\tau_{max}}{T}$.

Therefore, the performance of STBC-OFDM is only related to the channel time selectivity. Indeed, the performance of SFBC-OFDM is governed by both channel time and frequency selectivity.

The performance of the proposed adaptive switching system is illustrated in Figure 11. We note that the bit error rate of the adaptive scheme remains below the STBC-OFDM and SFBC-OFDM, as expected. Figure 11 shows that adaptive switching scheme performs better than STBC and SFBC over time frequency selective

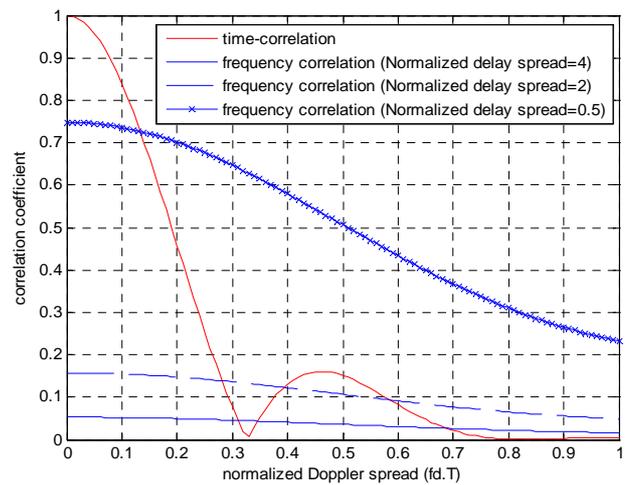


Figure 10. Time and Frequency correlation in terms of $f_d \cdot T$.

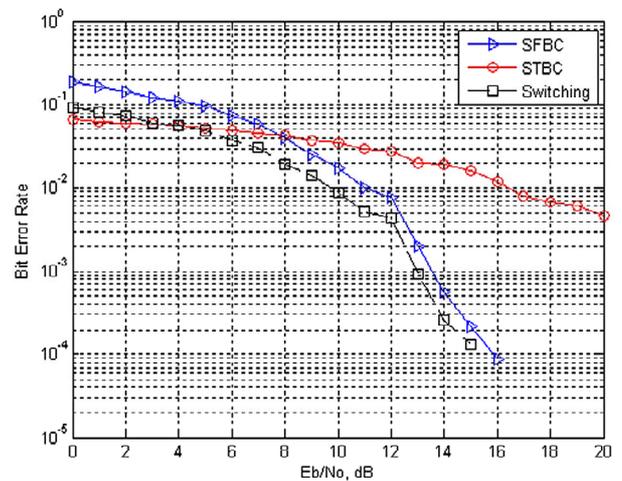


Figure 11. Performance of adaptive switching over time varying channel.

channels.

6. Conclusions

A combination of STBC in MIMO system with OFDM over time frequency selective channels has been presented. STBC-OFDM system is very tolerant to slow time varying environments where the channel time variation is slow but when the channel variation is increased due to the mobility of users, the system performs poorly. In this paper, it is found that SFBC has the same performance as STBC in slow fading channels, thus, SFBC improve the system performance better than STBC over high mobility environments. However, SFBC performs poorly in severely frequency selective channels.

Based on the proposed adaptive switching technique, we showed that adaptive switching between STBC and SFBC provides performance improvement over time frequency selective channels.

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