Paper

Performance Improvement for Vehicular Communications Using Alamouti Scheme with High Mobility

My Abdelkader Youssefi and Ahmed Mouhsen

Laboratoire d'Ingénierie, de Management Industriel et d'Innovation (LIMII), Faculté des Sciences et techniques (FST), Hassan First University of Settat, Settat, Morocco

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Abstract—The IEEE 802.11p standard is the basic protocol for wireless access in a vehicular environment (WAVE), providing high throughput for multimedia and high quality for vehicular transmissions. However, IEEE 802.11p fails to offer any multi-antenna approaches. In this paper, a multiple-input single-output (MISO) implementation with orthogonal frequency division multiplexing (OFDM), aiming to improve the performance of IEEE 802.11p, is proposed. The authors investigate the impact of time-varying channel on the performance of Alamouti space-time block codes (STBC) in OFDM systems. The Alamouti STBC approach shows good performance in slow time-varying environments, while its Alamouti space frequency block codes (SFBC) counterpart performs better over fast time-varying environments. An adaptive switching scheme is proposed to select appropriate space-block coding (STBC or SFBC) in vehicular channels with high mobility levels. It is shown that the proposed adaptive scheme provides better performance compared with traditional space-block codes.

Keywords—IEEE 802.11p, MIMO, MISO, OFDM, SFBC, STBC, vehicular channel.

1. Introduction

In recent years, vehicular technologies have been widely used to improve safety. Today, cameras and radars reduce accident rates and improve road safety, but safe and autonomous driving systems require high quality for communications between vehicles and their environment. The IEEE 802.11p standard is designed for vehicular networks and is based on OFDM modulation in the 5.9 GHz band. The traditional IEEE 802.11a standard was developed primarily for Wi-Fi wireless networks, characterized by low mobility of the receiver/transmitter [1]. The IEEE 802.11p variety is developed for use in typical outdoor vehicular networks with high mobility rates [2].

The emergence of vehicular technologies observed these days creates new requirements for wireless communications, such as high data rates for multimedia applications and high quality links for real time systems. Therefore, multiple-input multiple-output (MIMO) transmissions over wireless multipath channels will be a promising solution [3]. While the MIMO technique is already used in indoor wireless LAN (Wi-Fi) and cellular networks, such as LTE and WiMAX, the IEEE 802.11p comes without any particular MIMO scheme. However, MIMO approaches may considerably improve the robustness of IEEE 802.11p.

MIMO schemes may be classified as space diversity techniques used to improve link quality, and spatial multiplexing techniques used to improve data rates [1].

Space diversity MIMO techniques are widely used to improve link quality while dealing with channel fading effects. The basic idea behind space diversity is that multiple signal copies (redundant symbols) are transmitted. This significantly reduces the detection error rate at the receiver side by improving efficiency of the detection process. Such an approach improves the quality of wireless communications by transmitting more than one copy of the signal over multiple independent fading channels, while keeping the total transmitted power constant and while maintaining the same bandwidth (as in a single antenna scheme). The probability that all signal copies fall in deep channel fading may be greatly reduced compared to the single antenna scheme [4].

The typical examples of MIMO space diversity are time diversity, where the signal is repeated over successive time slots, and frequency diversity [5].

Space time block code (STBC) schemes are a promising MIMO space diversity approach, where diversity is provided over the space-time dimensions. It has been proved that MIMO STBC schemes improve wireless link quality without increasing transmitted power or frequency bandwidth [6]. However, MIMO STBC techniques assume that the transmission is made over a time-invariant channel, for the entire duration of the STBC block. This assumption is not always valid for wireless communications over fast time-variant channels, such as vehicular channels with high mobility of solo transmitters/receivers. Therefore, the performance of STBC will be seriously degraded in wireless time-variant channels, where the channel does not remain constant over the successive time slots.

The first STBC scheme, known as the 2×1 Alamouti scheme, involves two transmit antennas and one receive antenna. It has been shown that 2×1 Alamouti outperforms the traditional 1×1 single antenna scheme, maintaining the same transmit power and bandwidth. Alamouti codes provide full diversity and orthogonality [6]. Various STBC codes have been designed so far for massive MIMO technologies, but the Alamouti 2×1 scheme has been widely used because it is the only STBC approach capable of achieving full diversity and orthogonality.

The combination of MIMO and OFDM has attracted a lot of attention over the recent years. It is considered to be a promising technique for wireless high-speed data transmissions over mobile multipath channels [7]. Many wireless standards, such as WiMAX and Wi-Fi, are based on MIMO OFDM. The combination of MIMO and OFDM creates space-frequency block codes (SFBC) in MIMO OFDM systems. The difference between SFBC and STBC techniques consists in the fact that in SFBC, the code is done over frequency, while in STBC, the code is done over time [8].

This work investigates the performance of STBC and SFBC codes in vehicular communications in time and frequency selectivity domains. STBC's assumption of a time-invariant channel (over successive time slots) is not necessarily valid for high mobility vehicular channels. Similarly, SFBC's assumption of a frequency-invariant channel (for neighboring subcarriers) is not necessarily valid over mobile multipath channels (frequency-selective channels).

Adaptive switching has been proposed in order to overcome the problem of time and frequency selectivity in vehicular communications. The idea is based on dynamic switching between STBC and SFBC, according to channel conditions. It has been proved that the proposed scheme performs better than STBC and SFBC schemes applied on their own. Such adaptive switching has been already proposed earlier in [9]. However, the switching criteria adopted in [9] require perfect channel state information and a known correlation matrix at the transmitter side. This requirement cannot be satisfied in time-variant channels, such as the vehicular channel. Otherwise, implementation of the proposed adaptive switching might require periodic feedback from the receiver. Hence, the switching criteria proposed in [9] cannot be implemented for vehicular channels with high mobility. The switching criterion proposed here does not require any feedback and, hence, may be easily implemented at the transmitter side.

The presented development of MISO OFDM is aimed to enhance the IEEE 802.11p standard by improving adaptive switching between Alamouti STBC and SFBC schemes. The switching criterion is based on normalized maximum Doppler frequency and normalized delay spread. Being different from [9], the system requires only an estimation of channel delay spread and maximum Doppler frequency. Thanks to this, the switching decision may be easily made at the transmitter side.

This paper is organized as follows. In Section 2, the basic structure of IEEE 802.11p and the design of STBC/SFBC schemes in MISO OFDM systems are described. In Section 3, time frequency selectivity in vehicular channels is analyzed. The proposed adaptive switching design is developed in Section 4. The simulation results are shown in Section 5.

2. System Description

IEEE 802.11p is designed for vehicular networks and is an approved amendment to the IEEE 802.11a standard [10]. The physical layer of IEEE 802.11p is similar to the one used in IEEE 802.11a [11], [12], but the updated version has a lower overhead in order to provide low delays, real time data exchange and fast exchange of safety messages. In addition, IEEE 802.11p uses a narrower bandwidth (10 MHz channels).

2.1. Architecture of OFDM IEEE 802.11p

The physical layer of IEEE 802.11p is based on OFDM modulation employing 64 subcarriers. In wireless communications, channel state information is required by the receiver. Meanwhile, in OFDM transmissions, pilot subcarriers are used for wireless channel estimation. Therefore, 48 of the 64 subcarriers are used for data transmission and 4 subcarriers for pilot transmission (channel estimation purposes). IEEE 802.11p offers a data transmission rate of 3, 4.5, 6, 9, 12, 18, 24 and 27 Mbps (Table 1) [13], [14]. The frequency range used is 5.850-5.925 GHz, which is divided into 7 of 10 MHz channels. The standard is based on four complex modulations: BPSK, QPSK, 16-QAM and 64-QAM. The modulation scheme used depends on the required data rate and on wireless channel conditions [15].

Table 1
IEEE 802.11p parameters

Parameters	Values
Data subcarriers	48
Pilot subcarriers	4
Total subcarriers	52
IFFT/FFT size	64
TFFT: IFFT/FFT period	6.4 μs
TGI: GI duration	1.6 μs (TFFT/4)
T: symbol period	8.0 μs (TFFT + TGI)
Channel spacing	10 MHz
Signal bandwidth	8.3 MHz
Modulation	BPSK, QPSK, 16QAM, 64QAM
Data rate	3, 4.5, 6, 9, 12, 18, 24, 27 Mbps
Subcarrier spacing	156.2 KHz
Number of guard samples	16

2.2. MISO Alamouti STBC

The Alamouti STBC is considered to be an improved transmission scheme aiming to enhance the performance of wireless communications. MISO systems with STBC require less power than is needed by a single antenna system. The STBC technique expands the transmission into two dimensions: space (via many antennas) and time (by successive time slots) [6]. The Alamouti STBC scheme is based on the assumption of time-invariance of the channel during the STBC block (two successive time slots). Therefore, the assumption is not necessarily valid for wireless channels in high mobility applications. The Alamouti 2×1 scheme is designed to achieve spatial diversity with two transmit antennas and one receive antenna (Fig. 1) [6].

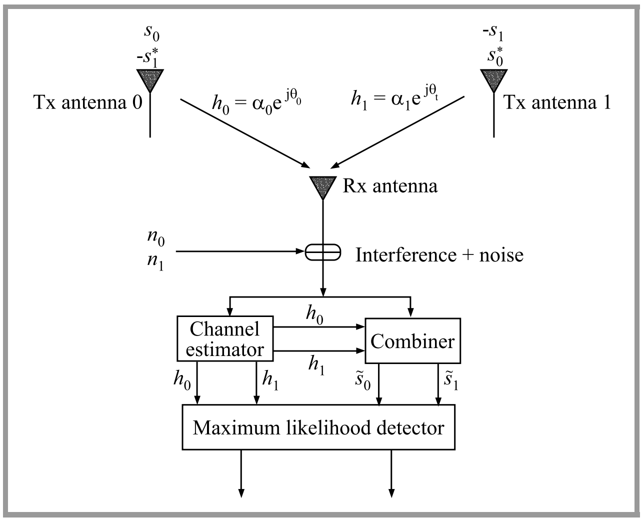

Fig. 1. Alamouti 2×1 STBC.

The first antenna transmits symbols s_0 at time t_0 and $-s_1^*$ at time t_0+T respectively. Symbols s_1 and s_0^* are simultaneously transmitted by the other antenna. Considering the Alamouti STBC assumption of a time-invariant channel between the two successive time slots, the symbols received at time t_0 and t_0+T may be expressed as:

$$r_0 = r(t_0) = s_0.H_0 + s_1.H_1 + w_0 \ , \tag{1}$$

$$r_1 = r(t_0+T) = -s_1^*.H_0 + s_0^*.H_1 + w_1 \ . \tag{2}$$

The symbols received at time t_0 and t_0+T are given by Eqs. (1) and (2), where H_0 and H_1 are the channel coefficients, w_0 and w_1 are the receiver noise.
The great advantage of the Alamouti 2×1 STBC scheme is that the received symbols may be recovered by a simple linear operation (without noise amplification) [6] (Fig. 1).

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

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

2.3. Alamouti STBC OFDM System

In this section, we consider a transmission sequence $\{s_1, s_2, \ldots, s_N\}$. In the single antenna scheme, we will transmit symbol s_1 at time t_0 (first time slot), symbol s_2 at time t_0+T (second time slot), s_3 at time t_0+2T (third time slot), etc. In the MISO 2×1 Alamouti scheme, two symbols will be transmitted at the same time by two transmit antennas. Alamouti suggested that in the first time slot we transmit symbols s_1 and s_2 from the first and second antenna, respectively, while in the second time slot – we transmit symbols $-s_2^*$ and s_1^* [6].
Considering the OFDM system with N subcarriers, if we apply 2×1 Alamouti STBC to our OFDM modulation, the encoded data will be transmitted over three dimensions: time, frequency (on subcarriers) and space (via many antennas) (Table 2).

Table 2
2×1 STBC OFDM system basics

	Subcarrier	Time t_0	Time t_0+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}^*

The transmitted symbols at time t_0 and time t_0+T are:

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

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

where S_0 and S_1 are the transmitted sequences from the first and second antenna, respectively, N is the number of subcarriers in OFDM modulation and $2N$ represents the number of transmitted symbols at time t_0 and time t_0+T. The MISO OFDM scheme based on 2×1 Alamouti STBC is shown in Fig. 2 [16].
Under the assumption of the time-invariant channel, $H(n+1,k) = H(n,k)$, the received signal may be represented in a matrix notation as [6], [7]:

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

where

$$H_0 = \left[H_0(n,1) \ldots H_0(n,N), H_0(n+1,1) \ldots H_0(n+1,N)\right]^t \ ,$$

$$H_1 = \left[H_1(n,1) \ldots H_1(n,N), H_1(n+1,1) \ldots H_1(n+1,N)\right]^t \ ,$$

$$R = \left[R(n,1) \ldots R(n,N), R(n+1,1) \ldots R(n+1,N)\right]^t \ ,$$

$R(n,k)$ is the received symbol loaded onto the k-th subcarrier from the n-th OFDM block, S_0 and S_1 are the transmitted symbols from the first and second antenna, respectively, and W is the noise vector. According to Eqs. (3) and (4), the recovered signals are:

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

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

where i refers to symbol number ($i = 1, 3, 5 \ldots, , N-1$), knowing that $2N$ symbols are transmitted during the two

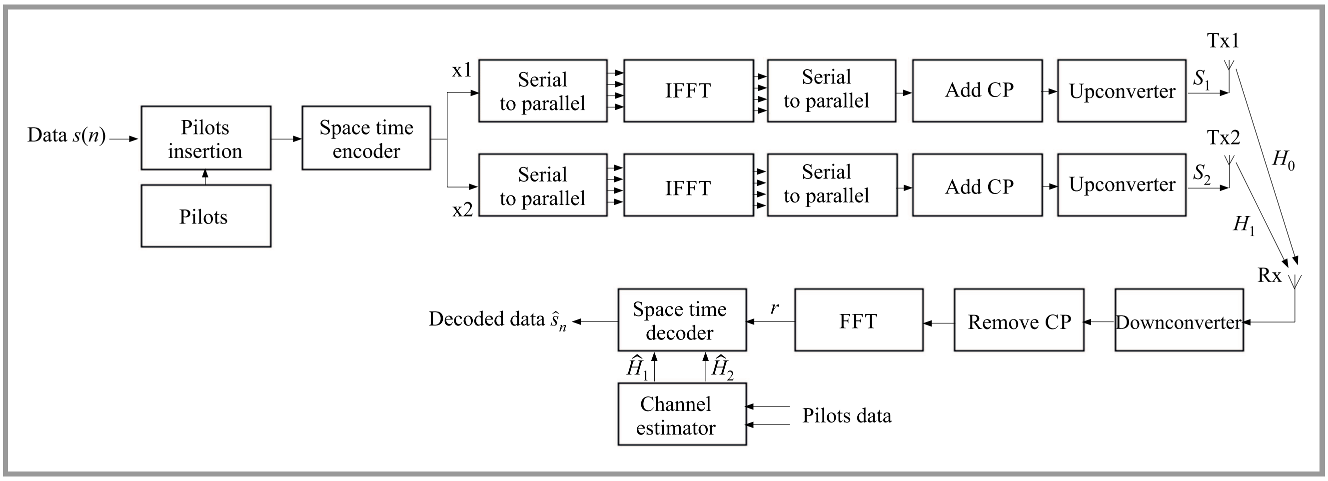

Fig. 2. Block diagram of a 2×1 antennas MISO OFDM system in STBC.

time slots (the first time slot starts at time t_0 and the second time slot starts at time t_0+T), n refers to the n-th OFDM block and k refers to the k-th subcarrier ($k = 1, 2, \ldots, ,N$). Parameters H_0 and H_1 are the channel coefficients for antenna 1 and antenna 2, respectively. Knowing that channel estimation is required on the receiver side to estimate H_0 and H_1, the receiver may produce $\hat{s}_i$ and $\hat{s}_{i+1}$.

2.4. Alamouti SFBC-OFDM Scheme

In OFDM systems, channel frequency response remains almost invariant on neighboring subcarriers of the same OFDM symbol. Alamouti space-frequency block coding (SFBC) transmits symbols on neighboring subcarriers over the frequency domain rather than the time domain that is used in Alamouti STBC. OFDM transforms a frequency-selective channel into several flat fading channels. Then, expansion of the transmission to the space-frequency dimension becomes an interesting opportunity with SFBC schemes [16], [17].

Alamouti STBC suffers from susceptibility to fast fading variation over time. Therefore, the SFBC design is an attractive approach for robust transmissions over time selective channels. In SFBC OFDM, transmission redundancy is achieved over both space and frequency, as for each OFDM symbol, neighboring subcarriers k and $k+1$ ($k = 1, \ldots, N$) are used for data encoding over the space-frequency dimension. Instead of transmitting one (n-th) OFDM symbol $S(n) = \left[s_1(n), s_2(n), \ldots, s_N(n)\right]$, in two OFDM symbols by two transmit antennas are used:

$$S_1(n) = \left\lfloor s_1(n), -s_2^*(n), \ldots, s_{N-1}(n), -s_N^*(n) \right\rfloor ,$$

$$S_2(n) = \left\lfloor s_2(n), s_1^*(n), \ldots, s_N(n), s_{N-1}^*(n) \right\rfloor ,$$

$S_1(n)$ is transmitted from the first antenna and $S_2(n)$ is transmitted simultaneously from the other antenna (Fig. 3).

$$R_k = H_0(f_k).s_k + H_1(f_k).s_{k+1} + W_k \ , \tag{8}$$

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

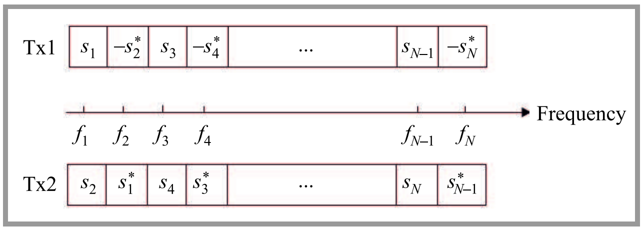

Fig. 3. 2×1 Alamouti SFBC design.

Under the assumption of invariant channel over the neighboring subcarriers [16], we can assume that $H_0(f_k) = H_0(f_{k+1})$ and $H_1(f_k) = H_1(f_{k+1})$, and Eqs. (8) and (9) may be simplified as:

$$\tilde{s}_k = H_{0k}^*.R_k + H_{1k}R_{k+1}^* \ , \tag{10}$$

$$\tilde{s}_{k+1} = H_{1k}^*R_k - H_{0k}R_{k+1}^* \ , \tag{11}$$

Equations (10) and (11) are similar to (1) and (2), hence maximum diversity for this SFBC design is achieved.

3. Vehicular Channel

The multipath channel is an emerging field of research due to its great impact on wireless communications. Wireless channels are time-frequency selective. The time or frequency selectivity refers to the variation of the channel as a function of time or frequency (Fig. 4). Formally, time-frequency selectivity is characterized by maximum delay spread $\tau_{\max}$, that depends on wave reflections from obstacles, and maximum Doppler frequency $f_{d\max}$, that depends on transmitter/receiver mobility. Time selectivity of a channel may be measured by the maximum Doppler frequency, and its frequency selectivity may be evaluated by the maximum delay spread [17]. In other words, a wireless channel with a long delay spread is frequency selective. These types of channels exhibit lower bandwidth coherence. Similarly, a wireless channel with a high Doppler frequency is time selective and exhibits lower coherence time.

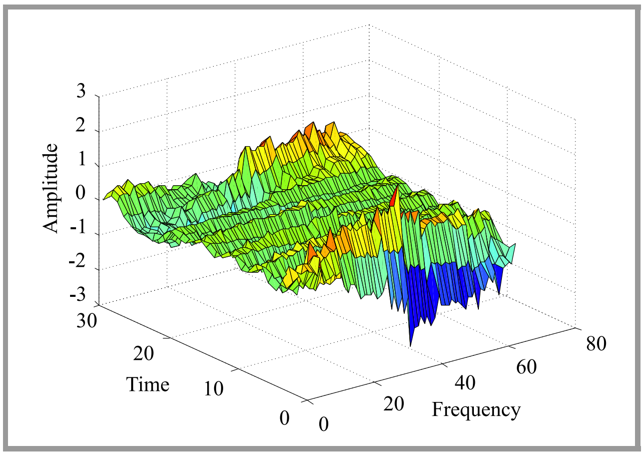

Fig. 4. Time frequency selective channel. (For color pictures see the electronic version of the paper.)

3.1. Vehicular Channel Model

In the time domain, the wireless multipath channel is described by its channel impulse response [18], [19]:

$$h(t,\tau) = \sum_{l=1}^{L} \alpha_l(t)\delta\left[\tau - \tau_l(t)\right] , \tag{12}$$

where L refers to the number of pathways of the multipath channel, α_1 is the l-th path complex gain and τ_l is the l-th path propagation.

In discrete-time systems, the signal is transmitted in regular time slots T_s, where T_s refers to the sampling period. Under the assumption of fixed and known number of channel paths L, the channel impulse response may be written as:

$$h(t,\tau) = \sum_{l=1}^{L} \alpha_l(t)\delta(\tau - \tau_l.T_s) . \tag{13}$$

$\alpha_l(t)$ the l-th path channel gain are function of time, this variation depends on Doppler frequency $f_d = v_m.f.\cos(\theta)/c$, where v_m is the transmitter/receiver velocity, θ is the arrival azimuth of the electromagnetic wave, f is the signal frequency and c the electromagnetic wave speed.

3.2. Time Selectivity in Vehicular Channels

In vehicular channels, time-selective fading, known as channel time selectivity, is a consequence of the Doppler effect experiences sue to the mobility of the transmitter/receiver. Time selectivity of a channel is usually evaluated by its time coherence T_c which is used to characterize the time-varying nature of channel attenuation [17]:

$$T_c \approx \frac{9}{16\pi f_{d,\max}} , \tag{14}$$

where the maximum Doppler frequency $f_{d,\max}$ is:

$$f_{d,\max} = \frac{v_m f}{c} . \tag{15}$$

In OFDM systems, a wireless channel is considered time-selective or fast time-varying when the channel's coherence time is lower than OFDM block duration $T_c < T$ [19]. Figure 5 shows results of simulations for different vehicle speeds over a Rayleigh fading channel. At varying speeds ranging between 30, 60 and 220 km/h, one can observe a significant impact on the channel's time selectivity.

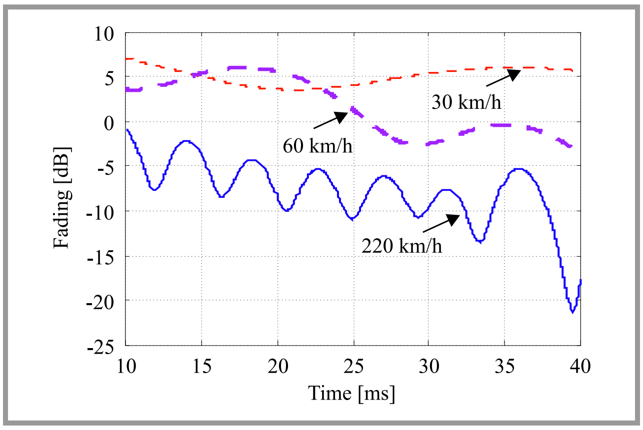

Fig. 5. Wireless fading channel for varying vehicle speeds.

At the operating frequency of 5.9 GHz, the time duration of an OFDM symbol is 8 μs (IEEE 802.11p).

If the expected speed of the vehicle is 30 km/h, the Doppler shift is given by 163.88 Hz and, thus, the coherence time is in the order of 1.1 ms. For 60 km/h, the Doppler shift is 327.77 Hz, and the coherence time is 0.5 ms. At 220 km/h, the Doppler shift is increases to 1201.9 Hz and, thus, the coherence time is in the order of 0.1 ms.

Time selectivity is caused by the mobility of the vehicle transmitter/receiver due to the induced Doppler shift that might easily reach 1200 Hz at the carrier frequency of 5.9 GHz [20]. This large value may harm the performance of the system, especially if MISO Alamouti STBC systems are used. The Alamouti assumption of an invariant channel over the STBC block is not valid here. The channel's time selectivity is a serious challenge in MISO STBC schemes used for high mobility vehicular communications.

3.3. Frequency Selectivity in Vehicular Channels

In vehicular communication, the wireless channel environment is characterized by the presence of electromagnetic wave scattering. Due to wave reflections, refractions and diffractions, the received signal is a superposition of several delayed copies of the transmitted signal, and multipath propagation leads to frequency selectivity of the wireless channel.

The channel is considered as frequency flat fading when the channel delay spread is much lower than the signal sampling period. Analogically, the wireless channel is frequency flat fading when it has only one pathway ($\tau_{\max} = 0$).

Channel frequency selectivity is evaluated by the coherence bandwidth B_c, measured for the frequency range over which the channel is frequency flat fading.

In OFDM systems, the channel is considered severely frequency selective when the coherence bandwidth is lower than the bandwidth of two subcarriers $\Delta f < B_c < 2\Delta f$, where B_c is the coherence bandwidth and Δf is the subcarrier bandwidth in the OFDM system. An OFDM wireless channel is considered non-frequency-selective when $B_c > 2\Delta f$, and when the neighboring subcarriers have the same frequency response. In the Rayleigh fading model, the coherence bandwidth is approximated as [17]:

$$B_c \approx \frac{1}{\tau_{\max}} . \qquad (16)$$

A wireless channel is considered non-frequency-selective (or moderately selective) when the signal bandwidth is lower than the channel coherence bandwidth $B < B_c$, knowing that $B = 1/T_s$ and $T = N$, where T_s and T refer to the sampling period and OFDM block duration, respectively. In other words, the channel is non-frequency-selective, when its maximum delay spread τ_{max} is lower than the sampling period $T_s (T_s > \tau_{\max})$.

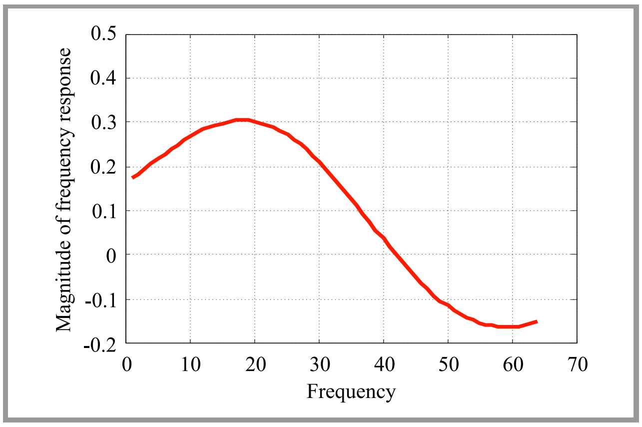

Fig. 6. Frequency response of a vehicular channel when delay spread is $3T_s$ ($T_s = 0.1$ μs).

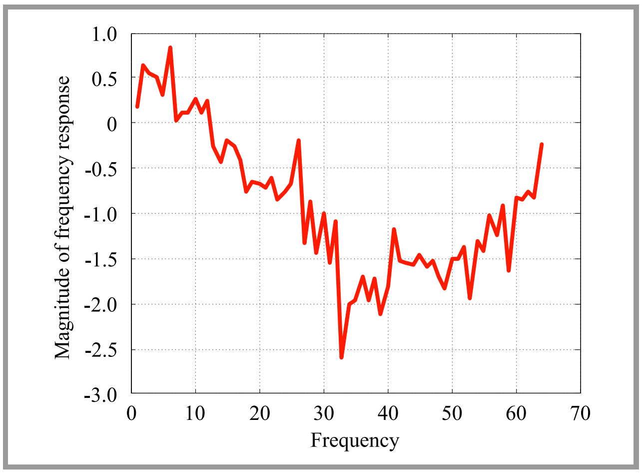

Fig. 7. Frequency response of a vehicular channel when delay spread is $32T_s$ ($T_s = 0.1$ μs).

A wireless channel is considered frequency-selective when the channel's coherence bandwidth B_c is lower than signal bandwidth B, and then $T_s > \tau_{\max}$.

Frequency selectivity is an important parameter of vehicular channels due to the presence of many scatterers in the propagation environment [20]. Frequency response of the channel is calculated by converting its impulse response to the frequency domain. As shown in Figs. 6 and 7, vehicular channels offer high frequency selectivity when delay spread is higher. In this simulation, coherence bandwidth equals 3.3 MHz in Fig. 6, and 0.5 MHz in Fig. 7. It is important to note that coherence bandwidth decreases when the vehicular environment is saturated with scatterers (very high delay spread), i.e. as the vehicle is moving along a highway. Therefore, coherence bandwidth may be lower than 0.1 MHz.

In IEEE 802.11p, subcarrier spacing is in the order of 0.1 MHz ($\Delta f = 10$ MHz/64). A vehicular channel is considered severely frequency-selective when delay spread is greater than 3.2 μs ($\tau_{\max} > 32T_s \rightarrow B_c < 2\Delta f$). In severely frequency-selective channels, the assumption of Alamouti SFBC invariant channel transfer function over adjacent subchannels is not valid, unfortunately, and the frequency selective channel degrades the performance of SFBC. Therefore, in order to design robust MISO schemes, the choice of SFBC or STBC coding for vehicular channels will be based on channel conditions.

4. Proposed Adaptive Switching Technique

Since STBC and SFBC schemes show contradicting behaviors over time frequency-selective channels, a switching technique is proposed in order to select the appropriate transmission scheme (STBC or SFBC) according to vehicular channel characteristics.

4.1. Time Frequency Correlation Strength

Channel fading is a consequence of multipath wave propagation and the received signal is a superposition of different waves originating from different paths. A vehicular channel may be modeled statistically as a Ricean or Rayleigh fading channel. These two models describe the received power correlation over a multipath channel. If there is one dominant wave with line-of-sight (LOS) propagation between the sender and the receiver, and several indirect waves, Ricean fading channel occurs. If no LOS propagation is possible and multiple indirect waves are available only, Rayleigh fading channel occurs [21]. The Ricean fading model is similar to the Rayleigh fading model, except that in the Ricean model LOS propagation is present and a dominant wave component is transmitted directly from the sender to the receiver.

Here, a vehicular Rayleigh fading channel model is considered and channel selectivity is evaluated by analyzing channel correlation. The temporal selectivity of the channel is examined by computing time correlation strength ρ_t.

Furthermore, frequency selectivity is investigated by computing frequency correlation strength ρ_f. The basic idea of adaptive switching is to select an appropriate transmission scheme (STBC or SFBC) for a given vehicular channel. This switching process is governed by the channel's time-frequency selectivity, and then the time and frequency correlation strength of the vehicular channel are needed in order to choose the appropriate transmission mode.

In the OFDM system, the time correlation strength ρ_t is evaluated by measuring correlation for the same subcarrier between adjacent OFDM blocks, while frequency correlation strength ρ_f is evaluated by measuring correlation between adjacent subcarriers for the same block. The strength of time and frequency correlations is compared in order to select the appropriate transmission scheme. Time and frequency correlation strength is evaluated for OFDM transmissions over the Rayleigh fading channel in the following manner [22]:

$$\rho_t = \frac{1}{N^2}\sum_{l=-N+1}^{N-1}(N-|l|)J_0\left[2\pi f_d T\left(1+\frac{G}{N}+\frac{l}{N}\right)\right], \quad (17)$$

$$\rho_f = \frac{(1-\lambda)\left(1-\lambda^M e^{\frac{-j2\pi M}{N}}\right)}{(1-\lambda^M)\left(1-\lambda e^{\frac{-j2\pi M}{N}}\right)}\frac{1}{N^2}\sum_{l=-N+1}^{N-1}(N-|l|)J_0\left[\frac{2\pi f_d T l}{N}\right], \quad (18)$$

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

4.2. Dynamic STBC/SFBC Allocation in Vehicular Communications

Here, a comparative and correlational study of time and frequency correlations is presented. Figure 8 shows the magnitude of time correlation strength $|\rho_t|$ and frequency correlation strength $|\rho_f|$ in terms of normalized Doppler spread $f_{d,\max} \cdot T$, and normalized delay spread $\frac{\tau_{\max}}{T}$, where $f_{d,\max}$ is the maximum Doppler frequency, $\tau_{\max}$ is the channel's maximum delay spread and T is the OFDM symbol duration. The time correlation strength is governed by one parameter, i.e. Doppler spread $f_{d,\max} \cdot T$, see Eq. (17). From Fig. 8, we can see that time correlation is strong ($|\rho_t| \gg |\rho_f|$) when normalized Doppler spread is considerably lower than one ($f_{d,\max} \cdot T \ll 1$), which is typical of a slow time-varying channel, such as the vehicular channel with $f_{d,\max} \cdot T = 0.01$ or $f_{d,\max} \cdot T = 0.05$. In these channel conditions, the STBC scheme will perform better than its SFBC counterpart. However, time correlation is very weak in a fast time-varying channel, such as the vehicular channel with $f_{d,\max} \cdot T = 0.8$ or $f_{d,\max} \cdot T = 0.9$, where the frequency correlation may be stronger. The frequency correlation ρ_f depends on two parameters, the first one being normalized Doppler spread $f_{d,\max} \cdot T$ and the other one being normalized delay spread $\frac{\tau_{\max}}{T}$, see Eq. (18). Therefore, the performance of STBC schemes depends only on the channel's time selectivity (transmitter/receiver mobility), while the performance of SFBC scheme is related to

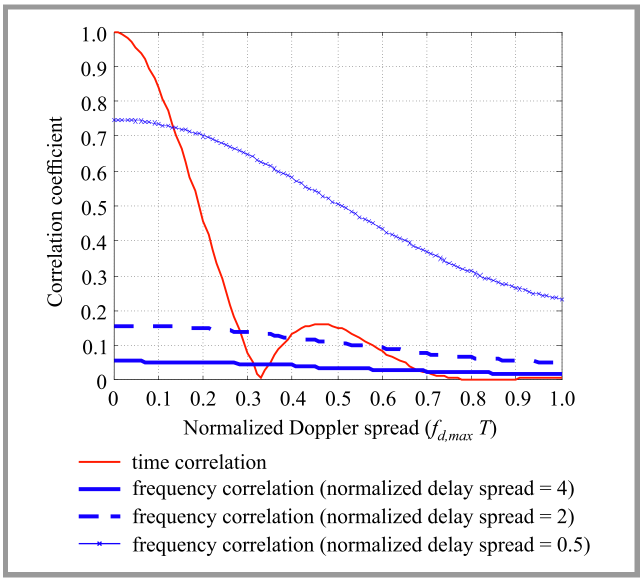

Fig. 8. Time frequency correlation strength in terms of $f_d.T$ ($f_0 = 5.9$ GHz, $T_s = 0.1$ μs).

both time and frequency selectivity, i.e. transmitter/receiver mobility and vehicular environment.

Figure 8 shows that the channel correlation strength can be weak or strong. It is related to vehicle speed and channel delay spread. So, wireless performance may be significantly improved by adaptive switching between STBC and SFBC, based on current channel conditions. The proposed switching criterion is based on channel correlation in terms of time and frequency. Therefore, at the transmitter side, the system switches between STBC and SFBC schemes according to channel selectivity values computed based on channel correlation strength, using Eqs. (17) and (18).

The transmitter makes an estimation of time correlation strength ρ_t and frequency correlation ρ_f strength, and then decides where the correlation is stronger (in time or frequency). The vehicular transmission system only needs to estimate the maximum Doppler frequency and the channel delay spread. Specific assumptions may be made by the sender based on the maximum speed of vehicles and the maximum delay spread of the multipath channel. The proposed adaptive switching scheme is presented in Fig. 9.

Correlation strengths ρ_t and ρ_f are calculated in order to select the appropriate transmission scheme (STBC or SFBC), knowing that the channel's time selectivity depends only on the speed of the vehicle (normalized Doppler spread), while the channel's frequency selectivity depends on the speed of the vehicle and on the scatterers present in the environment (normalized Doppler spread and normalized delay spread).

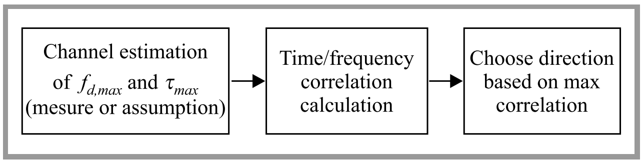

Fig. 9. Adaptive STBC/SFBC switching in vehicular networks.

5. Simulation Results

In this section, theoretical considerations are verified by Matlab simulations. Performance of the proposed adaptive approach is evaluated and compared with conventional STBC and SFBC schemes. The simulations are based on the Rayleigh fading channel model and OFDM transmissions in an IEEE 802.11p physical layer.

The normalized channel model is Rayleigh, as recommended by the European Telecommunications Standards Institute (ETSI). The simulation parameters are given in Table 3.

Table 3
Simulation parameters

	Parameters		Values
Systems parameters	System bandwidth		$B = 10$ MHz
	Modulation		4 QAM
	Sampling time		$T_s = 0.1\ \mu$s
	OFDM subcarriers		52
	OFDM guard samples		16
Rayleigh channel model	Path number	Average power [dB]	Normalized delay
	1	-7.219	0
	2	-4.219	0.4
	3	-6.219	1
	4	-10.219	3.2
	5	-12.219	4.6
	6	-14.219	10

The performance is evaluated under vehicular channel conditions, and time frequency selective channels are simulated for different vehicle speeds and different channel delay spreads.

5.1. Performance Evaluation of Alamouti STBC Scheme

Next, sets of MISO Alamouti STBC data are used as space-time block coding on a vehicular channel. The system is simulated on both time-selective (high mobility) and time non-selective (low mobility) channels in order to evaluate their performance.

Two types of vehicular channels are evaluated. Performance of the 2×1 STBC OFDM scheme and the OFDM single antenna scheme is compared over a flat fading channel ($f_d = 0$ Hz, vehicle speed $= 0$), and the results are shown in Fig. 10. Performance of both systems (2×1 STBC OFDM and single antenna OFDM) in a fast fading channel ($f_d = 500$ Hz) is shown in Fig. 11. From the figures, we may clearly see that in slow fading channels, STBC-OFDM achieves good performance compared to the single antenna system. STBC offers poorer performance, but still outperforms a single OFDM system in the case of a fast fading channel ($f_d = 500$ Hz).

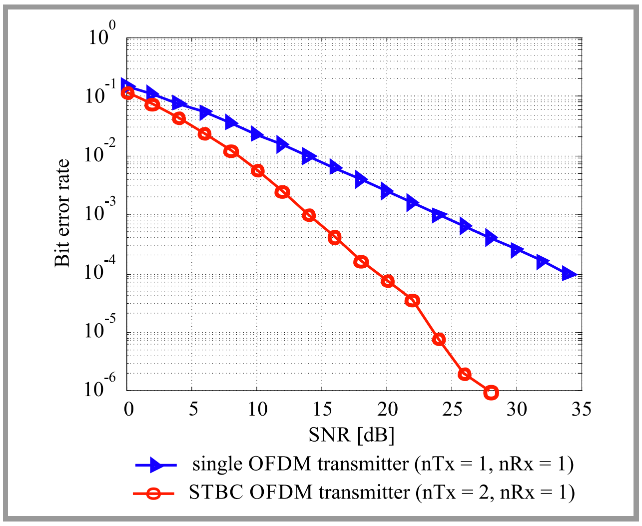

Fig. 10. Performance of single OFDM and STBC-OFDM for time invariant channel ($f_d = 0$).

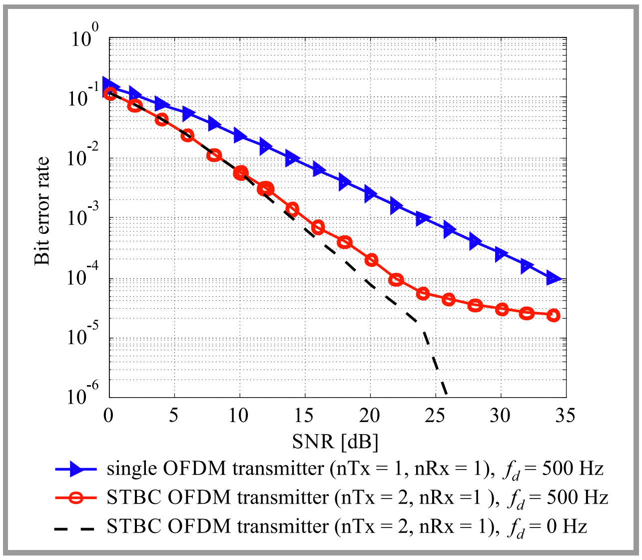

Fig. 11. Performance of single OFDM and STBC-OFDM for moderate time varying channel ($f_d \cdot T = 500$ Hz).

5.2. Performance Comparison of STBC and SFBC

OFDM STBC and SFBC systems are simulated in order to compare the performance of the two schemes under different vehicular channel conditions. Two types of vehicular channels are simulated: the first channel is time-selective with flat frequency fading ($f_d = 500$ Hz, $\tau_{\max} = 0$), and the results are shown in Fig. 12. The other channel is frequency selective with flat time fading ($f_d = 0$ Hz, $\tau_{\max} = 32 \cdot T_s$) – the results are shown in Fig. 13.

SFBC performs better over time-selective channels, but both schemes (STBC and SFBC) achieve similar performance over time-invariant channels (Fig. 12).

Figure 13 shows that STBC performs better over a vehicular channel with severe frequency selectivity. The performance of SFBC is lost, because the assumption of $B_c > 2\Delta f$ is not fulfilled under these channel conditions. Alamouti STBC is more sensitive to time selectivity (vehicle speed), while

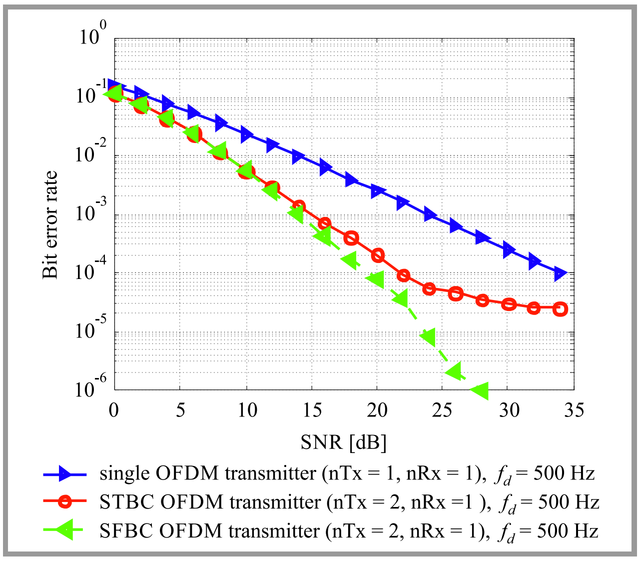

Fig. 12. Performance comparison of STBC and SFBC for a time-selective channel ($f_d = 500$ Hz, $\tau_{\max} = 0$).

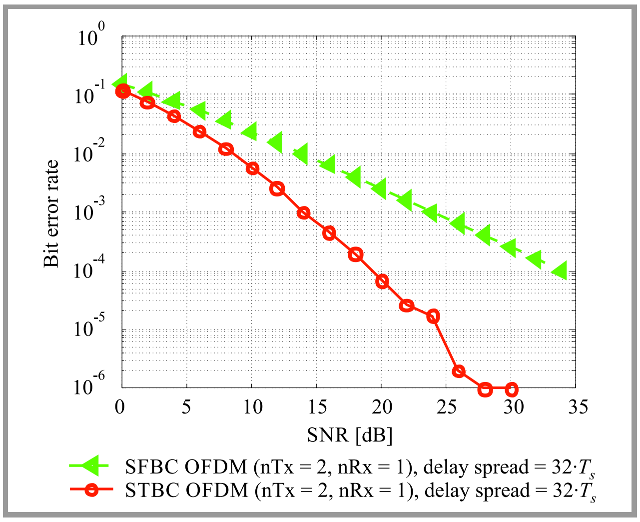

Fig. 13. Performance comparison of STBC and SFBC for a severely frequency-selective channel ($f_d = 0$, $\tau_{\max} = 32 \cdot T_s$).

SFBC is sensitive to frequency selectivity (propagation environment). The proposed switching scheme is compared with the two conventional STBC and SFBC schemes.

5.3. Performance Evaluation of The Proposed Adaptive Switching Method

In this section, a time-frequency selective channel is generated by varying the vehicle speed and the propagation environment. The channel's Doppler frequency is randomly generated between 0 and 500 Hz in order to simulate real vehicular channel conditions. Similarly, channel delay spread is randomly generated between 0 and $32T_s$.

The performance is illustrated in Fig. 14. The bit error rate (BER) of the proposed switching design remains below that of STBC and SFBC schemes. As expected based on theoretical analysis, it is shown that the proposed design is better than STBC and SFBC schemes performing solo in vehicular channels with varying time-frequency selectivity levels. The proposed technique may be extended to MIMO 2×2 or massive MIMO configurations.

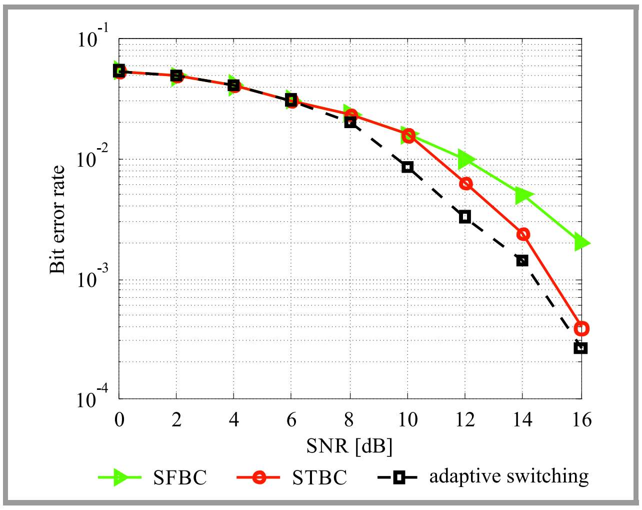

Fig. 14. Adaptive switching performance over time frequency selective channel.

6. Conclusion

The proposed adaptive switching technique improves the performance of vehicular communications over time-frequency selective channels. The combination of MISO STBC/SFBC with OFDM for the IEEE 802.11p standard is capable of satisfying new requirements concerning vehicular communications. It has been found that the SFBC design outperforms STBC under high mobility environments. However, the SFBC scheme offers poor performance in severely frequency-selective channels. Based on the previous results, an adaptive switching method is proposed, improving the performance of conventional STBC and SFBC schemes in vehicular channels.

From the simulation results concerning single antenna IEEE 802.11p systems and upgraded systems with MISO STBC/SFBC adaptive switching deployed, it may be concluded that the MISO system requires lower transmission power to achieve the same BER as a single antenna system, simultaneously offering higher data rate communications and increasing system reliability. Furthermore, the adaptive design proposed in this paper offers good performance when deployed in dynamic vehicular channels.

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My Abdelkader Youssefi received his engineering degree in telecommunications from National Institute of Telecommunications (INPT), Rabat, Morocco, in 2003, and received his Ph.D. degree from Mohammadia School of Engineers (EMI) at Mohammed V University in 2015. Between September 2003 and May 2016, he worked as a telecommunications engineer. Currently, Youssefi is a teacher at Hassan I University, Settat, Morocco. His research interests include cognitive radio, channel estimation, massive MIMO, OFDM and Internet of Things security in wireless networks.

E-mail: ab.youssefi@gmail.com
Laboratoire d'Ingénierie, de Management Industriel
et d'Innovation (LIMII)
Faculté des Sciences et techniques (FST)
Hassan First University
BP: 577, route de Casablanca
Settat, Morocco

Ahmed Mouhsen received his Ph.D. degree in Electronics from the University of Bordeaux, France, in 1992, and he is currently a Professor at the Electrical Engineering Department, Faculty of Sciences and Technologies, Hassan I University, Settat, Morocco. His research interest focuses on embedded systems, wireless communications and information technology.

E-mail: mouhsen.ahmed@gmail.com
Laboratoire d'Ingénierie, de Management Industriel
et d'Innovation (LIMII)
Faculté des Sciences et techniques (FST)
Hassan First University
BP: 577, route de Casablanca
Settat, Morocco