

MIMO Transceiver Combining Space-Frequency Spreading and Block-Coding

André L. F. de Almeida⁽¹⁾ and Gérard Favier⁽²⁾

⁽¹⁾GTEL-Wireless Telecom Research Group, Federal University of Ceará, Brazil.

⁽²⁾I3S Laboratory, University of Nice Sophia Antipolis, CNRS, France.

E-mails: andre@gtel.ufc.br, favier@i3s.unice.fr

Abstract—This paper presents a multiple-access MIMO wireless transceiver combining space- and frequency-domain spreadings with a frequency-domain block-coding strategy. Spreading across space (transmit antennas) and frequency (subcarriers) adds resilience against deep channel fades while providing space and frequency diversities, and block-coding enables multiple-access transmission. The merits of the proposed MIMO transceiver using a Zero Forcing (ZF) receiver is confirmed by means of some computer simulation results.

I. INTRODUCTION

Signal processing solutions based on the use of multiple transmit and receive antennas date back to over a decade. Wireless communication systems employing multiple antennas at both ends of the link, commonly known as multiple-input multiple-output (MIMO) systems, are being considered as one of the key technologies to be deployed in current and upcoming wireless communications standards [1]. On the other hand, combinations of orthogonal frequency division multiplexing (OFDM) and code division multiple access (CDMA) technologies have been proposed in a number of different works [2]. Multi-carrier (MC)-CDMA performs spreading of the information symbols across the different subcarriers but suffers from limited frequency diversity gains like conventional CDMA [3], [4]. Multi-carrier direct-sequence (MCDS)-CDMA differs from MC-CDMA by performing the spreading operation in the time-domain at each subcarrier [5]. For combating frequency-selective fading, MCDS-CDMA requires forward error-correction coding and frequency-domain interleaving which implies a loss of useful bandwidth. In [6], a hybrid of MC-CDMA and OFDM system with orthogonal transmission in the frequency-domain is proposed which ensures MUI-free transmission/reception regardless of the multipath channel profile. A related approach, called multi-carrier block-spread (MCBS)-CDMA, was introduced in [7] by capitalizing on redundant block spreading and frequency-domain linear precoding to preserve orthogonal multiple-accessing and to enable multipath diversity gains.

By exploiting the spatial dimension at the transmitter, in addition to time and frequency dimensions, a number of different space-time-frequency (STF) transceivers were proposed to enable orthogonal multiple-access in multiuser multiple-input multiple-output (MIMO) systems combining OFDM and CDMA principles. The work [8] proposed space-frequency spreading codes for the downlink of a multiuser MIMO-OFDM system. The transmission is designed to support more

multiplexed signals than transmit antennas and to provide space-frequency diversity for each multiplexed signal. Another spread spectrum-based STF transmission framework was proposed in [9], therein called multi-carrier spread space spectrum multiple access (MC-SSMA), with the idea of fully spreading each user symbol over space, time and frequency. Despite the achieved spectral efficiency gains, the design of [9] was restricted to the case where the number of transmit and receive antennas is equal to the spreading gain. In [10], STF spreading was proposed for MC-CDMA based on the concatenation of a space-time spreading code with a frequency-domain spreading code.

In this paper, we present a space-frequency multiple-access transceiver for MIMO wireless communication systems. The proposed MIMO transceiver combines both space and frequency spreadings with a frequency-domain block-coding strategy. On one hand, spreading across space (transmit antennas) and frequency (subcarriers) potentially provides robustness against frequency-selective fading and channel ill-conditioning, while providing full transmit diversity gains. On the other hand, a block-coding enables multiple-access transmission. The proposed transceiver architecture is close in spirit to that of [7] in the sense that frequency-domain block-coding and frequency spreading are jointly used.

This paper is organized as follows. Section II presents the MIMO transceiver architecture, where the main building blocks of the transmitter are detailed. In Section III, the received signal model is formulated. A joint zero forcing (ZF) receiver is described in Section IV. In Section V, the performance of the proposed MIMO transceiver is evaluated by means of computer simulations under different system settings. The paper is concluded in Section VI.

Notations: Some notations and properties are now defined. Scalars are denoted by lower-case letters ($a, b, \dots, \alpha, \beta, \dots$), vectors are written as boldface lower-case letters ($\mathbf{a}, \mathbf{b}, \dots$), and matrices as boldface capitals ($\mathbf{A}, \mathbf{B}, \dots$). \mathbf{A}^T and \mathbf{A}^\dagger stand for transpose and pseudo-inverse of \mathbf{A} , respectively. The operator $\text{diag}(\mathbf{a})$ forms a diagonal matrix from its vector argument. The Kronecker and the Khatri-Rao products are denoted by \otimes and \diamond , respectively:

$$\mathbf{A} \diamond \mathbf{B} = [\mathbf{A}_{\cdot 1} \otimes \mathbf{B}_{\cdot 1}, \dots, \mathbf{A}_{\cdot R} \otimes \mathbf{B}_{\cdot R}], \quad (1)$$

with $\mathbf{A} = [\mathbf{A}_{\cdot 1} \dots \mathbf{A}_{\cdot R}] \in \mathbb{C}^{I \times R}$, $\mathbf{B} = [\mathbf{B}_{\cdot 1} \dots \mathbf{B}_{\cdot R}] \in \mathbb{C}^{J \times R}$. We shall make use of the following property of the Khatri-Rao

product:

$$\text{vec}(\mathbf{A}\text{diag}(\mathbf{x})\mathbf{B}^T) = (\mathbf{B} \diamond \mathbf{A})\mathbf{x}. \quad (2)$$

with $\mathbf{A} \in \mathbb{C}^{I \times R}$, $\mathbf{B} \in \mathbb{C}^{J \times R}$ and $\mathbf{x} \in \mathbb{C}^R$.

II. SYSTEM MODEL

We consider the uplink of a single-cell multi-carrier multiple-access MIMO system with Q active co-channel users transmitting data across the same set of F subcarriers. Each user terminal is equipped with M_t transmit antennas and transmits R data streams, with $M_t \geq R$. The base station is equipped with M_r receive antennas. The transmission is composed of three main operations: i) space spreading, ii) frequency spreading and iii) frequency-domain block-coding. For notational simplicity, we begin by limiting ourselves to a single-user transmission model in order to facilitate the presentation. Later on, we show that the multiuser signal model is readily obtained with minor changes in notation.

After being modulated, the input sequence is serial-to-parallel (S/P) converted into R data streams, each one being constituted by N symbols. For the n -th symbol period, let us define the following symbol vector

$$\mathbf{s}(n) = [s_1(n), \dots, s_r(n), \dots, s_R(n)]^T \in \mathbb{C}^R, \quad (3)$$

where $s_r(n) \doteq s((n-1)R+r)$ denotes the n -th symbol associated with the r -th data stream.

A. Space-domain spreading

Figure 1 depicts the block diagram of the transmission system by focusing on the transmission of the n -th symbol of the r -th data stream. The first operation is the space spreading, which consists in spreading each data stream on the M_t transmit antennas using a different code. Let us define $\mathbf{\Omega} \doteq [\mathbf{\Omega}_1, \dots, \mathbf{\Omega}_r, \dots, \mathbf{\Omega}_R] \in \mathbb{C}^{M_t \times R}$ as the matrix collecting the code vectors of the R data streams. The space-domain precoded signal associated with the r -th data stream is defined as the following $M_t \times 1$ vector:

$$\bar{\mathbf{s}}_r(n) = \begin{bmatrix} \bar{s}_{r,1}(n) \\ \vdots \\ \bar{s}_{r,M_t}(n) \end{bmatrix} = \mathbf{\Omega}_{\cdot,r} s_r(n) \in \mathbb{C}^{M_t}. \quad (4)$$

This code structure adds robustness to the transmission in the space domain by providing a diversity gain while avoiding performance loss due to ill-conditioned/rank-deficient MIMO channels [11]. We choose the Vandermonde design, with complex generators $\rho_{m_t} = e^{-j2\pi(m_t-1)/M_t}$, $m_t = 1, \dots, M_t$, i.e.:

$$\mathbf{\Omega}(\rho_1, \dots, \rho_{M_t}) \doteq \frac{1}{\sqrt{M_t}} \begin{bmatrix} 1 & 1 & \dots & 1 \\ 1 & \rho_2 & \dots & \rho_2^{R-1} \\ \vdots & \vdots & \dots & \vdots \\ 1 & \rho_{M_t} & \dots & \rho_{M_t}^{R-1} \end{bmatrix}. \quad (5)$$

B. Frequency-domain spreading

The second operation consists in spreading each component $\bar{s}_{r,m_t}(n)$, $m_t = 1, \dots, M_t$, of the symbol vector $\bar{\mathbf{s}}_r(n)$ in the frequency-domain. Let $\mathbf{\Theta} \doteq [\mathbf{\Theta}_{\cdot,1}, \dots, \mathbf{\Theta}_{\cdot,r}, \dots, \mathbf{\Theta}_{\cdot,R}] \in \mathbb{C}^{F \times R}$ be the frequency spreading matrix. The r -th output of this linear precoder is an $M_t F \times 1$ vector given by:

$$\tilde{\mathbf{s}}_r(n) = \begin{bmatrix} \bar{s}_{r,1}(n) \\ \vdots \\ \bar{s}_{r,M_t}(n) \end{bmatrix} = \begin{bmatrix} \mathbf{\Theta}_{\cdot,r} \bar{s}_{r,1}(n) \\ \vdots \\ \mathbf{\Theta}_{\cdot,r} \bar{s}_{r,M_t}(n) \end{bmatrix} \in \mathbb{C}^{M_t F}. \quad (6)$$

Using (4), we can rewrite (6) in terms of both space- and frequency-domain codes as:

$$\tilde{\mathbf{s}}_r(n) = (\mathbf{\Omega}_{\cdot,r} \otimes \mathbf{\Theta}_{\cdot,r}) s_r(n) = \mathbf{U}_{\cdot,r} s_r(n), \quad (7)$$

where

$$\mathbf{U}_{\cdot,r} = \mathbf{\Omega}_{\cdot,r} \otimes \mathbf{\Theta}_{\cdot,r} \in \mathbb{C}^{M_t F} \quad (8)$$

is the joint space-frequency spreading vector associated with the r -th data stream to be transmitted. We introduce such a spreading operation to combat frequency-selective fading and thus guarantee symbol detection even in the presence of deep channel fades over one or more subcarrier channels. At the same time, it affords both frequency diversity and coding gains. The frequency spreading can be redundant ($F > R$) or non-redundant ($F \leq R$). Some designs for $\mathbf{\Theta}$ have been reported in the literature (see e.g. [12]). As for the space precoder, here we also choose $\mathbf{\Theta}$ as a Vandermonde matrix with complex generators $\xi_f = e^{-j2\pi(f-1)/F}$, $f = 1, \dots, F$, i.e.:

$$\mathbf{\Theta}(\xi_1, \dots, \xi_F) \doteq \frac{1}{\sqrt{F}} \begin{bmatrix} 1 & 1 & \dots & 1 \\ 1 & \xi_2 & \dots & \xi_2^{R-1} \\ \vdots & \vdots & \dots & \vdots \\ 1 & \xi_F & \dots & \xi_F^{R-1} \end{bmatrix}. \quad (9)$$

Note that spreading in the space-domain consists in multiplying the symbol $s_r(n)$ by a complex code that depends on the transmit antenna number m_t while spreading in the frequency-domain results in a multiplication of the same symbol by a complex code that depends on the frequency number f .

C. Frequency-domain block-coding

The third operation of our transmitter consists in a block-coding of the space- and frequency-domain spread sequence $\tilde{\mathbf{s}}_r(n)$. Instead of performing a *symbol* spreading, as in a classical CDMA system, we consider a frequency-domain block-coding approach. In our context, the precoded symbols $\tilde{s}_1(n), \dots, \tilde{s}_r(n), \dots, \tilde{s}_R(n)$ are spread by a factor P using frequency-domain spreading codes. Let $\mathbf{C} \doteq [\mathbf{C}_{\cdot,1}, \dots, \mathbf{C}_{\cdot,r}, \dots, \mathbf{C}_{\cdot,R}] \in \mathbb{R}^{P \times R}$ be the spreading code matrix the columns/rows of which belong to a (possibly truncated) Walsh-Hadamard (WH) code matrix.

The space-frequency precoded sequence $\tilde{\mathbf{s}}_r(n)$ is repeated P times and multiplied by the r -th spreading code with period

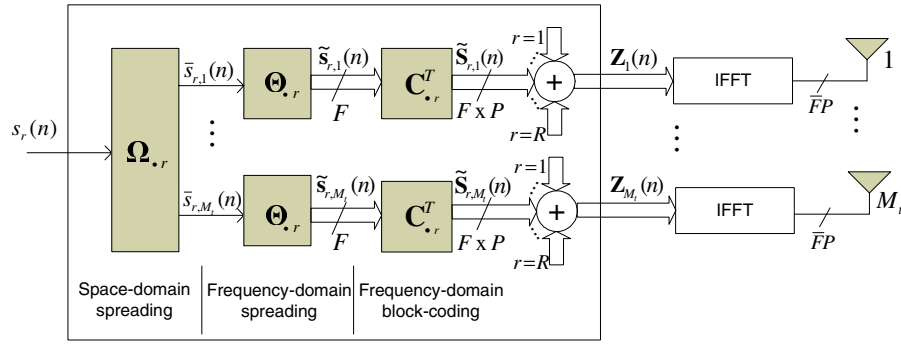


Fig. 1. Transmitter block diagram

$T_c = T/P$, where T_c corresponds to the chip period and T corresponds to the duration of an OFDM symbol. Defining

$$\tilde{\mathbf{S}}_{r,m_t}(n) = \tilde{s}_{r,m_t}(n)\mathbf{C}_{\cdot,r}^T = \Theta_{\cdot,r}\mathbf{C}_{\cdot,r}^T\tilde{s}_{r,m_t}(n) \in \mathbb{C}^{F \times P}, \quad (10)$$

as the r -th frequency-domain block-coded signal associated with the m_t -th transmit antenna and n -th symbol, we can write the multi-stream STF signal as:

$$\mathbf{Z}_{m_t}(n) = \sum_{r=1}^R \tilde{\mathbf{S}}_{r,m_t}(n) \in \mathbb{C}^{F \times P}. \quad (11)$$

We now define the STF signal $\mathbf{Z}(n) \in \mathbb{C}^{M_t F \times P}$ as the row-wise concatenation of M_t matrix blocks:

$$\mathbf{Z}(n) = \begin{bmatrix} \mathbf{Z}_1(n) \\ \vdots \\ \mathbf{Z}_{M_t}(n) \end{bmatrix} = \sum_{r=1}^R \tilde{\mathbf{s}}_r(n)\mathbf{C}_{\cdot,r}^T. \quad (12)$$

Substituting (7) into (12), gives:

$$\mathbf{Z}(n) = [\mathbf{U}_{\cdot,1}, \dots, \mathbf{U}_{\cdot,R}] \begin{bmatrix} s_1(n) & & \\ & \ddots & \\ & & s_R(n) \end{bmatrix} \begin{bmatrix} \mathbf{C}_{\cdot,1}^T \\ \vdots \\ \mathbf{C}_{\cdot,R}^T \end{bmatrix},$$

i.e.

$$\mathbf{Z}(n) = \mathbf{U}\tilde{\mathbf{S}}(n)\mathbf{C}^T, \quad (13)$$

where

$$\tilde{\mathbf{S}}(n) = \text{diag}(\mathbf{s}(n)) \in \mathbb{C}^{R \times R} \quad (14)$$

with $\mathbf{s}(n)$ defined in (3), and $\mathbf{U} \in \mathbb{C}^{M_t F \times R}$ represents the combined space and frequency spreading structure, which can be viewed as a joint space-frequency linear precoder. Using (8), we can factorize \mathbf{U} as the Khatri-Rao product of space and frequency spreading matrices:

$$\mathbf{U} = [\Omega_{\cdot,1} \otimes \Theta_{\cdot,1}, \dots, \Omega_{\cdot,R} \otimes \Theta_{\cdot,R}] = \Omega \diamond \Theta. \quad (15)$$

Before being transmitted, the STF block-coded signal passes through the OFDM modulator. An inverse fast Fourier transform (IFFT) is applied to $\mathbf{Z}_{m_t}(n)$, $m_t, 1 \dots, M_t$, and a transmit redundancy in the form of a cyclic prefix (CP) of N_{cp} chips is appended to each length- F chip sequence at each transmit antenna, resulting in the following time-domain signal:

$$\mathbf{X}_{m_t}(n) = \mathbf{T}_{cp}\mathbf{F}^H\mathbf{Z}_{m_t}(n) \in \mathbb{C}^{\bar{F} \times P} \quad (16)$$

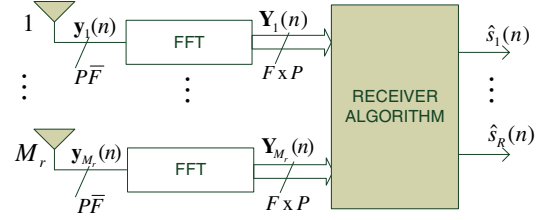


Fig. 2. Receiver block diagram

where $\bar{F} = F + N_{cp}$, $\mathbf{F}^H \in \mathbb{C}^{F \times \bar{F}}$ represents the IFFT matrix with $[\mathbf{F}^H]_{i,j} = e^{-j2\pi(i-1)(j-1)/F}$, $\mathbf{T}_{cp} = [\mathbf{I}_{cp}^T, \mathbf{I}_F]^T \in \mathbb{C}^{\bar{F} \times F}$ represents the CP-adding matrix, and \mathbf{I}_{cp} is a matrix formed from the N_{cp} last rows of \mathbf{I}_F .

The bandwidth efficiency of the proposed system is given by:

$$\epsilon = \frac{R}{\bar{F}P}. \quad (17)$$

III. RECEIVED SIGNAL MODEL

We adopt a discrete-time baseband equivalent model for the received signal. The block diagram of the receiver is depicted in Fig. 2. We assume perfect chip- and symbol-level synchronization at the receiver. The M_r received sequences are denoted by $\mathbf{y}_1(n), \dots, \mathbf{y}_{M_r}(n)$, each one of length $\bar{F}P$ samples. Let us define $\bar{\mathbf{Y}}_{m_r}(n) = \text{unvec}[\mathbf{y}_{m_r}(n)] \in \mathbb{C}^{\bar{F} \times P}$, $m_r = 1, \dots, M_r$, as matrices collecting the S/P converted sequences. After removal of the CP and the application of the fast Fourier transform (FFT), the noiseless received signal $\mathbf{Y}_{m_r}(n)$ can be written as [2]:

$$\mathbf{Y}_{m_r}(n) = \sum_{m_t=1}^{M_t} \text{diag}(\bar{\mathbf{h}}_{m_r,m_t})\mathbf{Z}_{m_t}(n). \quad (18)$$

Concatenating the received signal of the M_r receive antennas and eliminating the summation, we get the following compact expression:

$$\mathbf{Y}(n) = \mathbf{H}\mathbf{Z}(n) \in \mathbb{C}^{M_r F \times P} \quad (19)$$

where

$$\mathbf{Y}(n) = \begin{bmatrix} \mathbf{Y}_1(n) \\ \vdots \\ \mathbf{Y}_{M_r}(n) \end{bmatrix}$$

and

$$\mathbf{H} = \begin{bmatrix} \text{diag}(\bar{\mathbf{h}}_{1,1}) & \cdots & \text{diag}(\bar{\mathbf{h}}_{1,M_t}) \\ \vdots & \vdots & \vdots \\ \text{diag}(\bar{\mathbf{h}}_{M_r,1}) & \cdots & \text{diag}(\bar{\mathbf{h}}_{M_r,M_t}) \end{bmatrix} \in \mathbb{C}^{M_r F \times M_t F}.$$

Using (12), we can rewrite (19) as:

$$\mathbf{Y}(n) = \mathbf{H} \left(\sum_{r=1}^R \tilde{\mathbf{s}}_r(n) \mathbf{C}_{\cdot r}^T \right) = \mathbf{H} \tilde{\mathbf{S}}(n) \mathbf{C}^T, \quad (20)$$

where $\tilde{\mathbf{S}}(n) = [\tilde{\mathbf{s}}_1(n), \dots, \tilde{\mathbf{s}}_R(n)] \in \mathbb{C}^{M_t F \times R}$.

Multuser case: The extension of the transmitted and received signal models to the multuser case is straightforward. Assuming that Q users are transmitting to the base station (uplink transmission) and that all users have the same number M_t of transmit antennas, the multuser signal model follows that of the single-user case by working with a block-partitioned matrix notation for the spreading, symbol and channel matrices. We have omitted the details of the multuser signal formulation due to a lack of space.

Subcarrier grouping: In order to reduce the receiver complexity, especially when using multuser detection receivers, we propose to use subcarrier grouping [13], [14]. It consists in dividing the set of F subcarriers into J nonintersecting subsets of $K \geq L$ equispaced subcarriers. Assuming L independent multipaths, it is known that spreading over $K = L$ subcarriers suffices to obtain the best diversity performance. Note that we have precluded the subcarrier grouping from the previously described space-frequency signal model in order to avoid unnecessary complication in mathematical notation. Throughout the rest of the paper, we take subcarrier grouping into account in our signal model by replacing F by K , i.e. K will denote the number of subcarriers across which a given data stream is spread while F will denote the total number of subcarriers. We call attention to the fact that receiver processing will be performed in a group-wise fashion by means of J parallel detection layers under the assumption of subcarrier orthogonality. For notational simplicity, our developments will now focus on a particular group of K subcarriers.

IV. JOINT ZERO FORCING RECEIVER

Based on the received signal model formulated previously, a ZF receiver can be straightforwardly derived. Instead of decoupling the despreading operation and the ZF equalization in two consecutive stages, we propose a joint-ZF receiver that directly and simultaneously estimates all the R transmitted data streams without despreading.

Combining (13) with (19), we obtain:

$$\mathbf{Y}(n) = \mathbf{H} \mathbf{U} \tilde{\mathbf{S}}(n) \mathbf{C}^T. \quad (21)$$

Using property (2), we can rewrite (21) as:

$$\mathbf{y}(n) = \text{vec}(\mathbf{Y}(n)) = (\mathbf{C} \diamond (\mathbf{H} \mathbf{U})) \mathbf{s}(n) \in \mathbb{C}^{PM_r K}, \quad (22)$$

where $\mathbf{s}(n)$ is defined in (3). Let us consider the following cost function:

$$J(\mathbf{s}(n)) = \|\mathbf{y}(n) - (\mathbf{C} \diamond (\mathbf{H} \mathbf{U})) \mathbf{s}(n)\|^2.$$

Minimizing this cost function in the least squares sense, the joint-ZF receiver provides a simultaneous estimate of the R transmitted data streams as:

$$\hat{\mathbf{s}}(n) = \mathbf{W} \mathbf{y}(n) \in \mathbb{C}^R, \quad (23)$$

$n = 1, \dots, N$, where

$$\mathbf{W} = (\mathbf{C} \diamond (\mathbf{H} \mathbf{U}))^\dagger. \quad (24)$$

Since $\mathbf{C} \diamond (\mathbf{H} \mathbf{U}) \in \mathbb{C}^{PM_r K \times R}$ must be full column-rank, the joint-ZF receiver requires that $PM_r K \geq R$.

V. SIMULATION RESULTS

We first present a set of preliminary computer simulation results to access the bit-error-rate (BER) performance of the proposed space-frequency MIMO transceiver for some transmit configurations. Our aim is to study the influence of the main transmit parameters of interest on the BER performance. We simulate the system operating at a transmission rate of $R_c = 1/T_c = 4.096 \times 10^6$ chips per second (cps), using a total of $F = 64$ subcarriers divided into J groups of K subcarriers each. Note that $F = 64$ is a fixed parameter, while K is a transmission design parameter that will be varied in our simulations. Due to subcarrier grouping, each OFDM symbol contains RJ information symbols. We assume the transmission of $N = 10$ OFDM symbols per data stream. At each run, the transmitted symbols are drawn from a pseudo-random quaternary phase shift keying (QPSK) alphabet. The channel is assumed quasi-static, which means that the channel impulse responses do not change during the transmission of N symbols. Perfect time and frequency synchronization is assumed. Table I summarizes the main system parameters.

TABLE I
SYSTEM PARAMETERS

Chip rate	4.096×10^6 cps
Number of subcarriers (F)	64
Number of subcarriers per group (K)	2 or 4
Number of subcarriers groups (J)	32 or 16
CP length (N_{cp})	5 (Ch. A) / 20 (Ch. B)
Number of symbols per data stream (N)	10
Modulation	QPSK

We adopt two frequency selective channel models for modeling the channel between each pair of transmit and receive antenna. Both are ITU's outdoor-to-indoor models, and are valid for typical urban propagation environments: i) the 4-ray pedestrian channel A ($L = 4$) and ii) the 6-ray pedestrian channel B ($L = 6$) [15]. We consider the case of single-user transmission ($Q = 1$).

As previously discussed, by spreading the transmitted signals across different subcarriers allows to benefit from the frequency (multipath) diversity gain. Coding gain is also obtained when $K > L$. Figure 3 depicts the performance of a system with $M_t = 3$ and $M_r = 2$, $P = 4$, using i) $K = 2$ and $R = 3$ and ii) $K = 4$ and $R = 6$. Note that both configurations have the same ratio R/K which leads to the same bandwidth efficiency. We can observe a remarkable performance improvement obtained for channel B when more

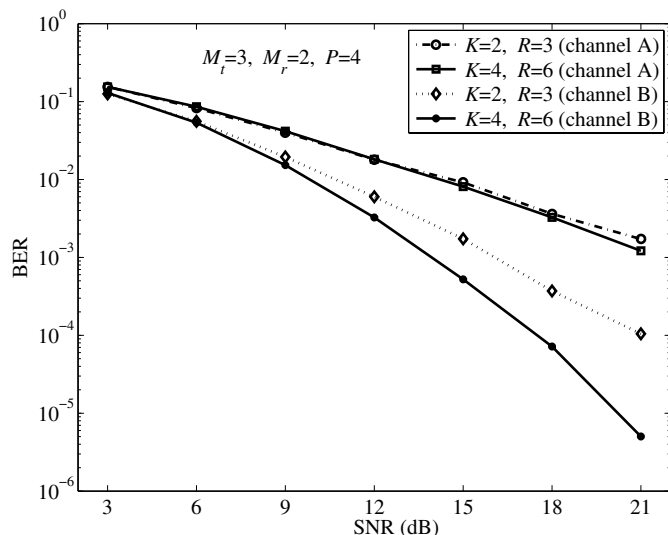


Fig. 3. Impact of frequency spreading with ITU channels A and B

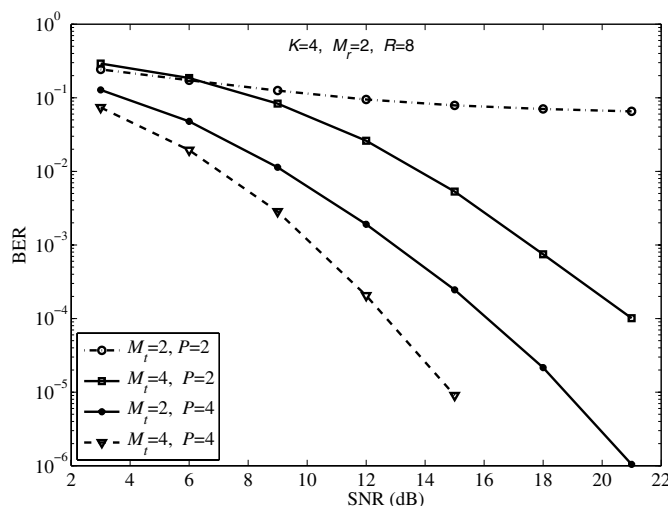


Fig. 4. Impact of space spreading with ITU channel B

subcarriers are used. This is not the case for channel A where less multipath diversity is available.

The next experiment evaluates the impact of space spreading on the system performance in the case of channel B. We consider $M_r = 2$ receive antennas and $R = 8$ transmitted data streams. Frequency spreading uses $K = 4$ subcarriers. Space spreading uses $M_t = 2$ and 4 transmit antennas. Figure 4 shows that for $P = 2$, an irreducible BER floor exists when using $M_t = 2$ transmit antennas. The BER performance, however, improves significantly when spreading the transmitted data across $M_t = 4$ transmit antennas. For $P = 4$, a higher coding gain is present so that the gap between the two space spreading configurations is reduced. In any case, these results confirm that use of the space dimension is important and even complementary to the frequency dimension, in particular when using small spreading factors.

More simulation results concerning the multiuser case and a comparison with existing algorithms are presented in [16].

VI. CONCLUSION

In this paper, a new transceiver architecture for multiple-access multiple-antenna MIMO transmissions has been proposed. This transceiver architecture combines multi-stream space and frequency spreading along with frequency-domain block-coding. It merges the advantages of OFDM and CDMA to handle multiple access interference while providing space and frequency diversity gains. We have evaluated the performance of the proposed space-frequency MIMO transceiver using a ZF-based receiver. Perspectives of this work include the optimal design of the space and frequency spreading matrices from the viewpoint of diversity and coding gains, as well as the development of a blind multiuser detection receiver that capitalizes on the multilinear algebraic structure of the received signal.

REFERENCES

- [1] A. J. Paulraj, D. A. Gore, R. U. Nabar, and H. Bolcskei, "An overview of MIMO communications: A key to gigabit wireless," *Proc. of IEEE*, vol. 92, no. 2, pp. 198–218, Feb. 2004.
- [2] R. Prasad and S. Hara, "Overview of multicarrier CDMA," *IEEE Commun. Magazine*, pp. 126–133, December 1997.
- [3] N. Yee, J.-P. Linnartz, and G. Fettweis, "Multi-carrier CDMA in indoor wireless radio networks," in *Proc. IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Yokohama, Japan, September 1993, pp. 109–113.
- [4] K. Fazel, S. Kaiser, and M. Schnell, "A flexible and high performance cellular mobile communications system based on orthogonal multicarrier SSMA," *Wireless Personal Communications*, vol. 2, no. 1/2, pp. 121–144, 1995.
- [5] V. M. DaSilva and E. S. Sousa, "Multicarrier orthogonal CDMA signals for quasi-synchronous communication systems," *IEEE Journal on Selected Areas in Communications*, vol. 12, no. 5, pp. 842–852, 1994.
- [6] G. B. Giannakis, Z. Wang, A. Scaglione, and S. Barbarossa, "AMOUR-generalized multicarrier transceivers for blind CDMA regardless of multipath," *IEEE Trans. on Communications*, vol. 48, no. 12, pp. 2064–2076, 2000.
- [7] F. Petr, G. Leus, M. Moonen, and H. De Man, "Multi-carrier block-spread CDMA for broadband cellular downlink," *EURASIP Journal on Applied Signal Processing*, no. 10, pp. 1568–1584, August 2004.
- [8] R. Doostnejad, T. J. Lim, and E. S. Sousa, "On spreading codes for the down-link in a multiuser MIMO-OFDM system," in *Proc. of IEEE Vehic. Tech. Conf.*, vol. 1, Orlando, FL, October 2003, pp. 498–502.
- [9] B. K. Ng and E. S. Sousa, "Multicarrier spread space-spectrum multiple access for the MIMO forward link transmission," in *Proc. IEEE Int. Symp. Pers. Ind. Mob. Radio Commun. (PIMRC)*, Lisbon, Portugal, September 15-18 2002.
- [10] L.-L. Yang and L. Hanzo, "Broadband MC DS-SS-CDMA using space-time and frequency-domain spreading," in *Proc. IEEE Vehic. Tech. Conf. (VTC Fall)*, Vancouver, Canada, September 24-29 2002, pp. 1632–1636.
- [11] S. Mudulodu and A. J. Paulraj, "A simple multiplexing scheme for MIMO systems using multiple spreading codes," in *Proc. 34th ASILOMAR Conf. on Signals, Systems and Computers*, vol. 1, Pacific Grove, USA, 29 Oct- Nov 1 2000, pp. 769–774.
- [12] Z. Wang and G. B. Giannakis, "Complex-field coding for OFDM over fading wireless channels," *IEEE Trans. on Information Theory*, vol. 49, no. 3, pp. 707–720, 2003.
- [13] Z. Liu, Y. Xin, and G. Giannakis, "Linear constellation precoding for ofdm with maximum multipath diversity and coding gains," *IEEE Trans. on Commun.*, vol. 51, no. 3, pp. 416–427, March 2003.
- [14] N. Tran, H. Nguyen, and T. Le-Ngoc, "Subcarrier grouping for ofdm with linear constellation precoding over multipath fading channels," *IEEE Trans. on Vehicular Technology*, vol. 56, no. 6, pp. 3607–3613, Sept. 2007.
- [15] "ITU-R recommendation M.1225," *Guidelines for Evaluation of Radio Transmission Technologies for IMT-2000*, 1997.
- [16] A. L. F. de Almeida and G. Favier, "Tensor-based blind multiuser detection for space-frequency multiple-access MIMO communication systems," *submitted to IEEE Trans. on Signal Process.*, April 2010.