Exploiting Spatial Diversity in Overloaded MIMO LDS-OFDM Multiple Access Systems

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***Abstract*—In this paper, we consider the deployment of multiple antennas as a way to exploit spatial diversity in the uplink of multiple access systems that adopt low-density spreading (LDS) with orthogonal frequency-division multiplexing (OFDM). An overloaded LDS-OFDM system is assumed, i.e., the number of users served is assumed greater than the number of resources. A basic model is developed and from it we design multiplexing spreading signatures based on space-frequency block codes (SFBC) to enhance the system's error performance. Computer simulations results reveal that the proposed multiple-input multiple-output (MIMO) LDS-OFDM scheme achieves full spatial diversity gain regardless the level of fading correlation between neighboring subcarriers. In contrast, a standard LDS scheme is shown to achieve full spatial diversity gain only under perfectly uncorrelated frequency fading, which favors the proposed scheme. Moreover, the spatial diversity benefits of MIMO LDS-OFDM comes with no additional complexity, as an iterative message-passing algorithm with the same complexity for both the proposed and the standard schemes approaches the respective optimal performances with only 2 iterations. These features make the proposed MIMO LDS-OFDM scheme a strong candidate for future wireless networks.**

***Index Terms*—Low density spreading, multiple access, OFDM, spatial diversity.**

I. INTRODUCTION

Multiple access schemes rely on sharing the physical medium between users when transmitting to a base station. We herein consider the scenario where K users share N orthogonal resources (time slots or subcarriers, also known as "chips") to transmit their data symbols. Several orthogonal codes for code division multiple access (CDMA) systems have been proposed in the literature, restricted to the condition that the number of chips is larger than or equal to the number of users, i.e. $K \leq N$. However, when $K > N$ it is not possible to design an orthogonal multiple access scheme. In this situation, the system is said to be **overloaded**.

In recent years several non-orthogonal multiple access (NOMA) systems have been proposed in literature [1]–[3]. As explained in [4], NOMA includes two major categories of multiple access. The first one considers multiplexing symbols based on power-domain (PD-NOMA). In order to decode the symbols during multiple access transmissions, PD-NOMA considers a multiuser detection (MUD) technique based on successive interference cancellation (SIC) algorithms.

The second NOMA category is based on code domain, which includes Low Density Spreading (LDS) and Sparse Coded Multiple Access (SCMA) systems. Both LDS and SCMA exploit sparse multiple access, i.e. users spread their symbols over a few chips instead of spreading it over all available resources. Since it is possible to represent the multiple access of LDS and SCMA as a bipartite sparse graph, the authors of [1] proposed the application of iterative decoding by the message passing algorithm (MPA) as MUD.

Although the optimum MUD strategy (that achieves minimum probability of error) is the maximum *a posteriori* (MAP) detection [1], it is a NP-hard problem and its complexity becomes intractable for a large number of users [5]. The use of MPA approximates the MAP detector and has limited complexity by designing the maximum number of symbols colliding over the same resource.

In this paper our focus is on code domain NOMA, emphasizing LDS systems, which are a particular case of SCMA. Although LDS does not exploit the shaping gain of multidimensional codewords, its design is relatively simpler and allows the use of traditional constellations combined with forward error correction (FEC) codes. The LDS framework proposed in [1] consists of designing the sparse spreading sequences for NOMA in CDMA. By doing so, the number of collisions in each chip is limited to a number much lower than K.

Further work extending the LDS-CDMA strategy for orthogonal frequency division multiplexing systems (LDS-OFDM) can be found in [6]–[8]. These works follow the concepts originally presented in [1] by applying the spreading sequences over orthogonal subcarriers in the frequency domain rather than in the time slots. They also consider more realistic fading channel models, and include the design of some LDS-OFDM schemes by optimizing the load using extrinsic information transfer (EXIT) charts. In recent papers [9], [10], the authors proposed joint detection and decoding by combining the MPA-based MUD receiver and the low density parity check (LDPC) decoder graphs.

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However, to the best of our knowledge, there is no existing work considering the design of LDS schemes for multiple transmit or receive antennas (MIMO) systems or exploiting the diversity gains over the spreading signatures. In this work, aiming at improving the system's error performance, we propose a design of spreading matrices for MIMO LDS-OFDM systems, which is based on Space-Frequency Block Codes (SFBC) [11]. For concreteness, our proposal is presented considering a particular LDS-OFDM system with parameters $K = 8$ and $N = 4$, and the traditional Alamouti code [12]. We show via numerical simulations that full diversity for each user can be achieved with this framework by allowing the signatures to perform the SFBC strategy on the transmitted symbols.

One contribution related to this topic is the work proposed in [13], which proposes an SCMA scheme for mitigation of inter-cell interference yielding enhanced performance of cell-edge users. Instead of decoding each user and treating the others as interference, all the base-stations independently use the MPA algorithm to decode both the desired signal and the interference signal. Frequency and spatial diversity gains are analyzed for correlated subcarriers and base-station antennas. Initially, all users and base-stations have single-antenna transmitters and receivers, respectively, and the resulting SCMA graph is interpreted as a sparse MIMO channel. When the users are equipped with $N_t = 2$ antennas, they also apply 2×2 Alamouti Space-Time Block Code (STBC) considering two time-slots. The decoding complexity using Alamouti STBC becomes higher than in the first scenario. Their comparison system is an interference management scheme for frequency reuse aimed to orthogonalize the radio resources.

On the other hand, our work considers only one base-station during multiple access and a simpler LDS-OFDM spreading without FEC instead of SCMA codewords. We evaluate only the cases where users are equipped with $N_t = 2$ antennas in order to apply 2×1 Alamouti SFBC and only frequency correlation is analysed, while all transmit antennas are considered uncorrelated in spatial domain. Therefore we compare our scheme only to the optimal ML detection and an example of a parametric-equivalent standard LDS-OFDM system.

The paper is organized according to the following description. In Section II we review the basic model of LDS-OFDM systems and extend it to MIMO LDS-OFDM with N_t transmit antennas. Section III presents our proposed scheme based on SFBC for MIMO LDS-OFDM. We present numerical simulations of our scheme in Section IV and conclude our final remarks in Section V.

II. LDS SYSTEMS

Throughout this paper we employ the following mathematical notation. Lowercase bold letters $(\mathbf{x})$ denote column vectors and uppercase bold letters $(\mathbf{H})$ denote matrices. For any vector or matrix the superscript T represents the transpose, e. g. $\mathbf{x}^T$. For any complex constant (x), the superscript $*$ in x^* represents the complex cojugate. The set $\mathbb{C}$ denote the field of complex numbers, while $\mathbb{C}^n$ is the set of n-dimensional column vectors whose elements belong to $\mathbb{C}$. The operator $E[\cdot]$ corresponds to the expectation function and the function $\mathrm{diag}(\mathbf{h}) : \mathbb{C}^n \to \mathbb{C}^{n\times n}$ maps the column vector $\mathbf{h}$ to a diagonal matrix $\mathbf{H}$ whose diagonal elements $H_{n,n}$ correspond to the vector element h_n.

In this section we present a MIMO LDS-OFDM model for the multiple-access scenario. LDS systems consider multiplexing K different symbols over N shared resources by designing sparse sequences that spread the transmitted symbols over these resources in a non-orthogonal manner [1], [7]. Usually, the sequences are designed in order to ensure that at most d_f symbols will collide over the same resource.

When exploring time and frequency shared resources, one can design the spreading sequences assuming it is feasible to allocate symbols to different slots or subcarriers as desired. However, when the spatial domain is taken into account for MIMO systems, it is not as trivial to design spatial multiplexing without precoding or channel state information at the transmitter.

Usually, transmitting one symbol through a time-space sample of a given antenna spreads to all receive antennas in the same time-space resource. Additionally, users that transmit more than one symbol in an uplink scenario will get correlated channels in the same space-time-frequency resource. This correlation can be avoided ensuring that each user multiplexes its symbols orthogonally over the given resources. In the LDS-OFDM system proposed in [7], multiple symbols from different users are multiplexed over the frequency domain by carefully designing the spreading sequences of each user.

A. Single Antenna Transmitter LDS-OFDM: System Model

In this subsection we review the basic aspects of the single antenna transmitters in LDS-OFDM systems [7]. Consider the transmission of K symbols from independent sources to a common single antenna receiver over N shared chips (subcarriers) during a multiple access stage. Each symbol is transmited by a single antenna using a specific spreading sequence $\mathbf{s}_k \in \mathbb{F}_2^N$, where $k = 1, \ldots, K$ is the symbol index. The received signal $\mathbf{r} \in \mathbb{C}^N$ is given by

$$\mathbf{r} = \sum_{k=1}^{K} \mathrm{diag}\left(\mathbf{h}_k\right) \mathbf{s}_k x_k + \mathbf{z}, \tag{1}$$

where $x_k \in \mathbb{X}$ is the k-th transmitted symbol belonging to the constellation $\mathbb{X}$, $\mathbf{h}_k \in \mathbb{C}^N$ are the fading coefficients for the N resources of the channel path of the k-th symbol to the receiver and $\mathbf{z} \sim \mathcal{CN}\left(0, \mathbf{I}\right)$ is the additive white Gaussian noise (AWGN). Elements of $\mathbf{h}_k$ are denoted $h_{n,k}$, where $n = 1, \ldots, N$ is the subcarrier index.

The vectors $\mathbf{s}_k$ are sparse vectors with binary elements (0s and 1s) responsible for spreading the symbol over different resources. In SCMA systems, similar vectors are used to index the non-null positions of the multidimensional codewords. These vectors can be grouped in a $N \times K$ spreading matrix $\mathbf{S} = \begin{bmatrix}\mathbf{s}_1 & \cdots & \mathbf{s}_K\end{bmatrix}$ that characterizes the LDS-OFDM scheme.

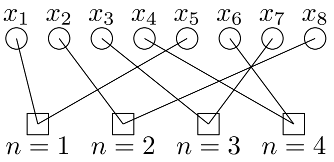

Fig. 1. Example of a LDS scheme with 200% load.

The parameters of an LDS scheme are the maximum number of colliding symbols in a chip, denoted d_f, and the maximum number of chips that a symbol can spread, denoted d_c. We assume that these parameters are the same for every chip or symbol, respectively.

A simple LDS-OFDM example is given for $K = 8$, $N = 4$, $d_c = 1$, and $d_f = 2$. This scheme is illustrated as a bipartite graph in Figure 1 and it can be represented by the following matrix:

$$\mathbf{S}_{4\times 8} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \end{bmatrix}. \tag{2}$$

The load factor of the LDS scheme is defined as

$$\mathrm{Ov}(\%) = \frac{\mathrm{K}}{\mathrm{N}} \times 100. \tag{3}$$

The spreading matrix, and the d_c and d_f parameters play a major role in the LDS-OFDM system design. The main feature of LDS systems is the sparsity of the spreading signatures. By designing a sparse spreading matrix $\mathbf{S}$ for a given (K, N)-LDS system, the receiver can exploit the limited number of d_f collisions and apply the message passing algorithm (MPA) over the resulting graph as a MUD.

B. MIMO LDS-OFDM: System Model

To the best of our knowledge no related work has considered LDS-OFDM systems with $N_t > 1$ transmit antennas. Without loss of generality, we assume that the receiver of the multiple-access scenario has only $N_r = 1$ antennas. In order to keep the notation used in the current LDS literature, we modify Equation (1) by including the transmit antenna index $m = 1, \ldots, N_t$ in order to associate N_t transmit antennas with each transmitted symbol. We also allow the signal of each transmit antenna to be some coded version of the original symbols, allowing for space-frequency code design. The new received vector $\mathbf{r} \in \mathbb{C}^N$ can be written as

$$\mathbf{r} = \sum_{m=1}^{N_t} \sum_{k=1}^{K} \operatorname{diag}\left(\mathbf{h}_k^{(m)}\right) \mathbf{s}_k^{(m)} c_k^{(m)} + \mathbf{z}, \tag{4}$$

where $c_k^{(m)}$ is a function of x_k designed to spread over d_c out of the N resources of the m-th transmit antenna via the spreading vector $\mathbf{s}_k^{(m)}$, and $\mathbf{h}_k^{(m)} = \left[h_{1,k}^{(m)} \quad \cdots \quad h_{N,k}^{(m)}\right]^T$ are the fading coefficients for the N resources of the m-th transmit antenna between symbol k and the receiver.

When considering $N_t > 1$, one must design the spatial-frequency multiplexing carefully in order to achieve the desired d_c and d_f parameters of the system. Therefore, the system design must take into account all the N_t matrices $\mathbf{S}^{(m)}$, i.e. $N_t K$ sparse spreading vectors $\mathbf{s}_k^{(m)}$ for all possible (k, m)-tuples, in order to ensure the performance and decoding complexity of the scheme. To the best of our knowledge no related work has considered this design and no optimal procedure has been published regarding its aspects.

In Section III we propose a particular scheme for MIMO LDS-OFDM systems. This is done by exploiting some aspects of this model. The design of its spreading matrices and space-frequency codes are shown.

C. Review of the Multiuser Detection with MPA

We consider the original work of [1], which derived the MPA equations in order to approximate the optimal maximum *a posteriori* (MAP) detection. The derivation of MPA equations and more details on their application for LDS will be omitted here since they are described in [1].

We only highlight that the complexity of the MPA based MUD is $\mathcal{O}\left(|\mathbb{X}|^{d_f}\right)$, while the optimal MAP detector has complexity $\mathcal{O}\left(|\mathbb{X}|^{K}\right)$. By ensuring that $|\mathbb{X}|^{d_f}$ has reasonable size, we can consider the feasibility of the MPA based MUD for LDS schemes.

According to [3], the parameter d_f is given as $\binom{N-1}{d_c-1}$ when intending to achieve maximum overload factor. For a given sparsity degree d_c of the symbol nodes, we notice that d_f increses exponentially with the number of available resources N. Therefore it is not reasonable to consider MAP or even the classical MPA MUD for larger values of N. On the other hand, as illustrated in [14], replication of simple LDS or SCMA schemes (with reasonable values of d_f) orthogonally multiplexed over the full spectrum can be used for larger number of resources.

For simplicity, in this paper we focus on binary modulation, i.e. $|\mathbb{X}| = 2$, allowing for the messages of the MPA to represent log-likelihood ratios (LLRs) of the respective symbols, exactly as the original work in [1].

Generalization of the MPA MUD for LDS-OFDM systems with higher order modulations can be found in [7]. However, higher spectral efficiency can be better exploited by considering SCMA systems, which generalizes LDS systems, and allows for codebook design shaping gains due to the use of mapping from bits to multidimensional codewords instead of simple symbol spreading [3].

III. PROPOSED SCHEME

In this section we consider a multiuser system with 4 users (we may refer as users A, B, C and D), each one with $N_t = 2$ transmit antennas. Each user transmits two symbols to a single antenna receiver ($N_r = 1$) over $N = 4$ shared resources in a multiple access scenario, according to Table I. Therefore, a total of $K = 8$ symbols are transmitted.

The scheme is illustrated in the bipartite graph representation of Figure 2. It is equivalent to the MIMO LDS-OFDM

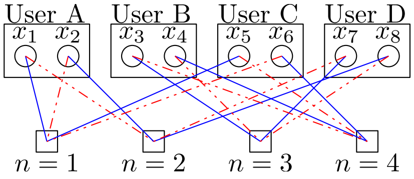

Fig. 2. Proposed LDS scheme with 200% load. Solid edges are for transmit antenna $m = 1$ and dot-dashed edges are for transmit antenna $m = 2$.

scheme presented in subsection II-B with parameters $N_r = 1$, $N_t = 2$, $K = 8$, $N = 4$, $d_c = 2$, $d_f = 4$, Ov $= 200\%$. It is assumed that nodes from the same user can cooperate to transmit N_t symbols (for example, from Table I we observe that symbols x_1 and x_2 belong to user A, allowing for joint encoding).

A. Combining Alamouti SFBC and MIMO LDS-OFDM

By exploiting joint encoding of some symbols, we propose a LDS scheme based on Alamouti Space-Frequency Block Coding (SFBC). First, consider the following vector

$$\mathbf{c}^{(m)} = \begin{bmatrix} c_1^{(m)} & \cdots & c_K^{(m)} \end{bmatrix}^T$$

as the space-frequency codeword sent by the m-th transmit antenna. We proposed the following encoding scheme for $N_t = 2$ transmit antennas and $K = 8$ symbols:

$$\mathbf{c}^{(1)} = \begin{bmatrix} x_1 & -x_2^* & x_3 & -x_4^* & x_5 & -x_6^* & x_7 & -x_8^* \end{bmatrix}^T \quad (5)$$

$$\mathbf{c}^{(2)} = \begin{bmatrix} x_1^* & x_2 & x_3^* & x_4 & x_5^* & x_6 & x_7^* & x_8 \end{bmatrix}^T. \quad (6)$$

For the LDS-OFDM spreading of each antenna, we propose the following $N \times K$ spreading matrices:

$$\mathbf{S}^{(1)} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \end{bmatrix}, \quad (7a)$$

$$\mathbf{S}^{(2)} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}. \quad (7b)$$

Observe that in this way, by applying Equation (4), the conjugated symbols are transmitted in the even subcarriers. The proposed spreading matrices are illustrated in the graph representation of the multiple-access in Figure 2, where solid blue edges and dash-dotted red edges represent the spreading matrices $\mathbf{S}^{(1)}$ and $\mathbf{S}^{(2)}$ for transmit antennas $m = 1$ and 2, respectively.

TABLE I
TRANSMITTED SYMBOLS BY EACH USER FOR THE PROPOSED SCHEME.

User	**Transmitted Symbols**
A	x_1, x_2
B	x_3, x_4
C	x_5, x_6
D	x_7, x_8

In order to consider the Alamouti SFBC encoding in the receiver side, the receiver conjugates the signals of the even chips $n = 2$ and $n = 4$, obtaining

$$\mathbf{y} = \begin{bmatrix} r_1 & r_2^* & r_3 & r_4^* \end{bmatrix}^T, \quad (8)$$

where r_n corresponds to the n-th element of the vector $\mathbf{r}$ from Equation (4).

This results in the following effective channel:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z}, \quad (9a)$$

where the effective channel matrix $\mathbf{H}$ is

$$\mathbf{H} = \begin{bmatrix} h_{1,1}^{(1)} & h_{1,2}^{(2)} & 0 & 0 & h_{1,5}^{(1)} & h_{1,6}^{(2)} & 0 & 0 \\ {h_{2,1}^{(2)}}^* & -{h_{2,2}^{(1)}}^* & 0 & 0 & 0 & 0 & {h_{2,3}^{(2)}}^* & -{h_{2,8}^{(1)}}^* \\ 0 & 0 & h_{3,3}^{(1)} & h_{3,4}^{(2)} & 0 & 0 & h_{3,7}^{(1)} & h_{3,8}^{(1)} \\ 0 & 0 & {h_{4,3}^{(2)}}^* & -{h_{4,4}^{(1)}}^* & {h_{4,5}^{(2)}}^* & -{h_{4,6}^{(1)}}^* & 0 & 0 \end{bmatrix}$$

and $\mathbf{x} = \begin{bmatrix} x_1 & \cdots & x_8 \end{bmatrix}^T$ is the vector stacking up all transmitted symbols. With a slight abuse of notation, we keep the noise vector $\mathbf{z}$ since the conjugation of noise samples will not change the distribution of the noise vector.

By observing the effective channel matrix $\mathbf{H}$ we can notice that some submatrices resemble the effective channel of the traditional Alamouti scheme. Observe also that since each user transmits two symbols using $N_t = 2$ antennas, we have that $\mathbf{h}_l^{(m)} = \mathbf{h}_{l+1}^{(m)}$ for $l = 1, 3, 5, 7$ and $m = 1, 2$.

The vector $\mathbf{y}$ given in Equation (9a) can then be used as the input vector for the previously discussed MPA based MUD in order to decode the transmitted symbols. Figure 3 illustrates the framework of the proposed MIMO LDS-OFDM scheme.

B. Channel correlation and spatial diversity aspects

The Alamouti SFBC is proposed to exploit spatial diversity from the d_c chips in which each symbol is spread by transmitting every symbol using the $N_t = 2$ uncorrelated antennas. In LDS-OFDM schemes, these will require the $N = 4$ chips to be adjacent subcarriers, which are strongly correlated (ideally a flat subband). However, since the MUD is based on an approximation of the MAP detection, the scheme will be also robust to uncorrelated subcarrier fadings in the channel for a given antenna, exploiting spatial diversity regardless of frequency correlation present in the channels.

Channel uncorrelation across the N chips can be a result of small coherence bandwidth or intended interleaving across a large number of the subcarriers. A standard LDS-OFDM scheme could benefit from it by interleaving its symbols over frequency domain in order to explore d_c degrees of frequency diversity. However, without aid of a SFBC scheme, it would not achieve full diversity if the channels become correlated (i.e., it cannot achieve full diversity with adjacent subcarriers without spatial diversity).

Additionally, interleaving for LDS or SCMA schemes must be designed jointly for all considered users in the multiple access stage, since the number of collisions per chip d_f must be kept constant for a given scheme. In this sense, our proposed Alamouti SFBC scheme for LDS-OFDM systems have the advantage of exploiting frequency diversity regardless

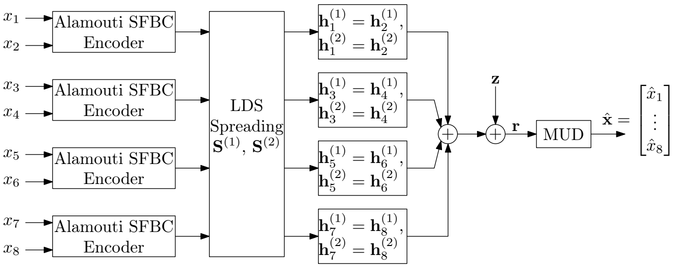

Fig. 3. Framework of the proposed MIMO LDS-OFDM scheme.

of the level of frequency correlation between channel fadings or complicated interleaving sequences.

IV. SIMULATION RESULTS

In this section we evaluate the performance of the proposed scheme with Monte Carlo numerical simulations. Each simulated point considers as stop criteria either achieving 1000 errors or reaching $10^5 \times 1000 \div 8$ maximum number of iterations.

We consider uncoded transmission with BPSK modulation. The performance metric is the symbol error rate (SER). Since none of the related works have similar characteristics to the proposed one, we compare our scheme with ML detection and with an equivalent MIMO LDS-OFDM scheme without the Alamouti SFBC, which is specified by the following transmit spreading matrices

$$\mathbf{S}^{(1)}_{\text{Std.}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}, \tag{10a}$$

$$\mathbf{S}^{(2)}_{\text{Std.}} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \end{bmatrix}. \tag{10b}$$

This scheme is chosen as a similar approach from previous LDS-OFDM systems, and uses the same parameters as the proposed one, i.e. $N_t = 2$, $K = 8$, $N = 4$, $d_c = 2$ and $d_f = 4$. By comparing with a scheme with the same d_f we ensure that the MPA-based MUD have the same order of complexity $\mathcal{O}\left(|\mathbb{X}|^{d_f}\right)$. We refer to this system as “standard LDS” scheme (labeled ”Std. LDS” in the legends).

We consider four different channel models according to Table II. In all cases, fadings are normalized to ensure that $E[|h_{n,k}|^2] = 1$ for all k and n. Since the transmitters have $N_t = 2$ transmit antennas, the BPSK symbols have a 3 dB penalty in the transmitted power for fair comparison. Therefore, SNR is defined as $P/2$, where P is the average power of a constellation symbol x_k, i.e. $E[|x_k|^2] = P$.

TABLE II
DIFFERENT CHANNEL MODELS CONSIDERED IN SIMULATIONS.

Channel Model	**Description**
Flat channel	strongest correlation between subcarriers, i.e., $h_{n,k} = h_k$ for all $n = 1, 2, 3, 4$.
FFT channel	we take the first 4 out of 64 subcarriers of a 1 MHz baseband frequency selective channel with 5 consecutive taps of equal fading gains; we consider it as a channel with an intermediate correlation level.
FFT channel interleaved	we take 4 separated subcarriers out of a total of 64 subcarriers of a 1 MHz baseband frequency selective channel with 5 consecutive taps of equal fading gains; we consider it as a realistic uncorrelated channel. The subcarriers indexes are 1, 22, 43 and 64, i.e. equally spaced over frequency domain.
uncorrelated channel	ideally uncorrelated rayleigh fading channels across the 4 chosen subcarriers.

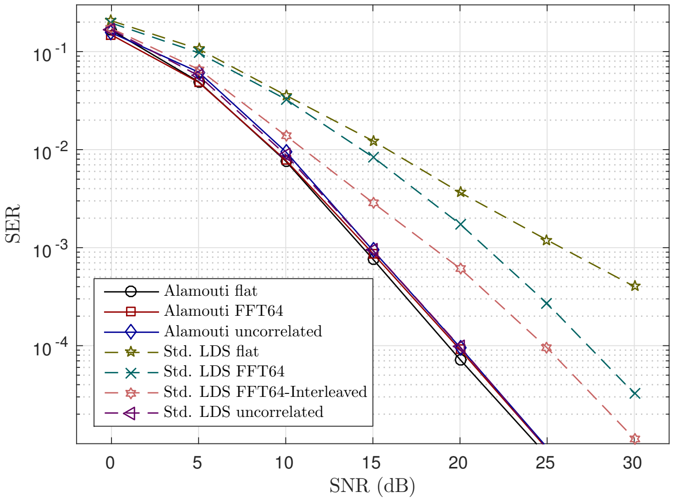

Fig. 4. ML detection performance for different channels.

Figure 4 shows the results for ML detection for the proposed and the standard scheme, considering different channels. We assume that the ML detection is a lower bound on the SER. We notice that the proposed Alamouti SFBC scheme is robust to channel correlation, achieving the best performance for a flat channel. The standard LDS scheme fails to achieve full diversity when the channel is correlated, even when the FFT-64 with interleaving (i.e., very light channel correlation) is used.

Figure 5 shows the results for the proposed scheme considering $J = 1$ and $J = 2$ iterations of the MPA algorithm used in the MUD at the receiver. Different channel models are considered in the analysis. In general, by increasing the number of iterations from 1 to 2, we already observe a 5 dB gain, bringing the performance of the scheme very close to the ML lower bound.

In Figure 6 we fix the SNR in 15 dB in order to observe the convergence of the MPA algorithm. It is shown that for these channels, it is only necessary $J = 2$ iterations to achieve the best performance of the MUD detector.

V. CONCLUSION

In this paper, we proposed an Alamouti SFBC scheme for a simple MIMO LDS-OFDM system with fixed parameters. We derived the basic model and designed the multiplexing spreading signatures of standard LDS systems in order to allow

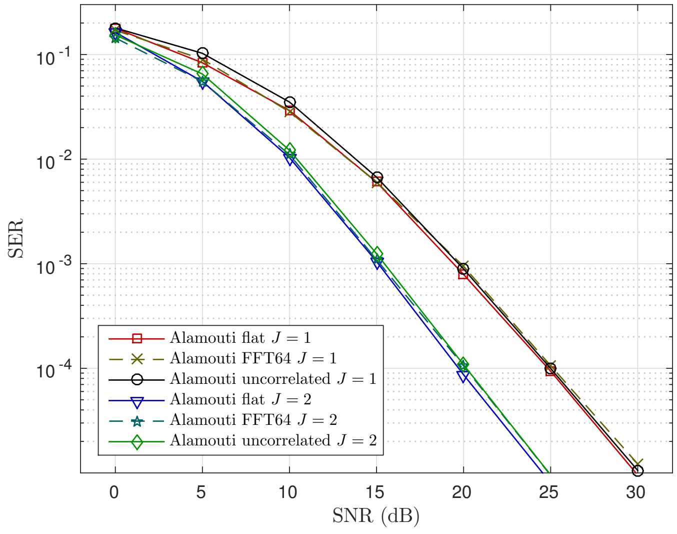

Fig. 5. Proposed scheme performance with different MPA iterations and for different channels.

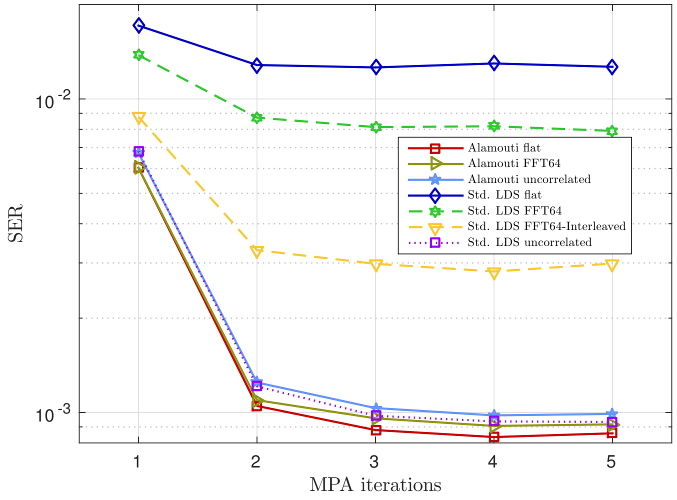

Fig. 6. Performance comparison and convergence of the MPA-based MUD for different channels, considering SNR of 15 dB.

the use of SFBC. Our scheme exploits full spatial diversity and is robust to the frequency correlation of the involved subcarrier fadings without the need of designing any interleaving strategy. Additionally, the iterative MPA based MUD converges to near optimal performance with only 2 iterations.

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