Data Detection Based Iterative Channel Estimation for Coded SM-OFDM Systems

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***Abstract*—The combination of spatial modulation (SM) and orthogonal frequency division multiplexing (OFDM) as SM-OFDM is a recently proposed efficient modulation scheme with exploiting the index of transmit antenna to convey information bits for multiple-input multiple-output (MIMO) wireless communication systems due to its low complexity feature. The pioneering works assume that the perfect channel state information (P-CSI) or pilot symbols aided channel estimation (PSA-CE) is available at the receiver. The open question is whether the accuracy of pilot based channel estimation is satisfactory to accomplish high data rate transmission in SM-OFDM systems. This paper explores the iterative channel estimation (ICE) problem for the coded SM-OFDM systems. We showed that the quality of the channel estimation can be further enhanced by the detection of symbols at the receiver. Through comparative simulations, we show that the proposed ICE method has notable bit error rate (BER) performance compared with the PSA-CE method for the binary phase shift keying (BPSK) modulation over the typical urban (TU) channel model.**

Keywords*—*MIMO, spatial modulation, OFDM, iterative channel estimation, interpolation.

I. INTRODUCTION

Instead of the classical digital modulation techniques, the spatial modulation (SM) introduces a third dimension where the data streams are transmitted over a wireless channel by a chosen active antenna of a multiple-input multiple-output (MIMO) transmitter at random [1]. With the SM technique, the indices of transmit antennas are exploited to transfer data as well as two dimensional signal constellation. The SM technique which provides the high spectral efficiency with a low complexity has also a very flexible mechanism [2].

Orthogonal frequency division multiplexing (OFDM) is one of the most efficient multicarrier techniques by reason of its robustness to frequency selective fading by low computational complexity and has a key role in current wireless applications. Therefore, the spatial modulation and OFDM techniques have been currently integrated to manage reliable communication through wireless links [1]. The SM-OFDM technique has the potential to be new transmission technique for the next generation wireless communication systems while taking the advantages of both SM and OFDM techniques.

In the literature, the earliest works for the SM-OFDM systems have accepted that the perfect channel state information (P-CSI) is known at the receiver. However, the SM-OFDM technique needs the channel estimation in practice. One of the simple and practical techniques is the pilot symbols aided channel estimation (PSA-CE) for the frequency selective channels. Pilot symbols are exploited to determine the channel parameters in wireless systems such as IEEE 802.16m worldwide interoperability for microwave access (WiMAX) [3], the third generation partnership project (3GPP), and long term evolution (LTE) [4]. The PSA-CE for OFDM systems was proposed in [5] with various interpolation techniques. It was presented that owing to its characteristic simplicity and easy implementation, the favorite interpolation technique is the piecewise linear interpolation (PLI).

Recently, the PSA-CE for SM-OFDM systems was introduced in [6] while large number of pilots inserting reduces spectral efficiency of the system. It is clear that the iterative receiver compared with the non-iterative one exploits less pilot symbol [7]. In [8], the polynomial fitting based iterative channel estimation (ICE) is suggested for the SM systems. However, the iterative channel estimation technique has not been investigated for the SM-OFDM systems in the literature yet.

In this work, data detection based ICE for coded SM-OFDM system is studied. Firstly, pilot symbols are placed in the frequency domain regularly to determine the channel frequency response (CFR) at pilot symbols with least squares (LS) algorithm, and then a PLI technique is employed for the CFR at data symbols. To form a PSA-CE with interpolation in SM-OFDM systems which have special structure is quite different and troublesome than the typical PSA-CE techniques. On account of being only one active antenna all the while each of the symbols are transmitted in the SM system, other channels could not be known at that time. Secondly, the channel parameters at data positions are updated with detected data symbols then PLI method is used to get all channel parameters. Finally, by using the maximum likelihood (ML) principle, the data symbols are re-detected by the updated channel parameters.

The paper is organized as follows. In Section II the SM-OFDM system model is given to introduce the notations. We develop the iterative channel estimation based on the detected data symbols in Section III. Simulation results are demonstrated in Section IV, finally conclusions are presented in Section V.

Notation: Throughout the paper, bold and capital letters '**A**' denote matrices, while bold and small letters '**a**' denote

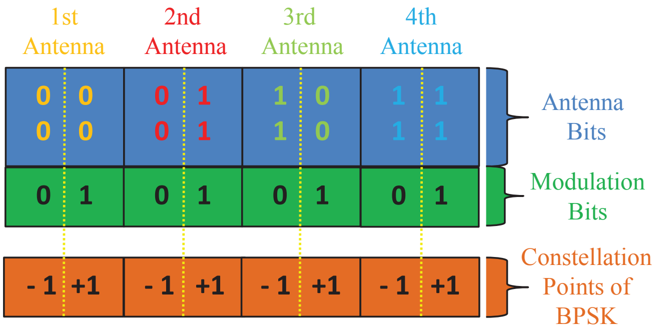

Fig. 1: SM-OFDM mapping table structure

vectors. The notations, $(.)^*$, $(.)^T$, $(.)^\dagger$ and $\|.\|_F$ denote conjugate, transpose, Hermitian, and Frobenius norm, respectively.

II. SM-OFDM SYSTEM

Let's consider a binary matrix $\mathbf{B}$ of size $b \times N$, where b is the total number of bits per symbol per subcarrier (bits/symbol/subcarrier) and N is the total number of OFDM subcarriers. In this case, the column vectors of $\mathbf{B}$ represent the data which are transmitted in one subcarrier. As shown in Fig. 1, SM system converts $\mathbf{B}$ data bits into a $\mathbf{X}$ of size $N_t \times N$, where N_t denotes the total number of transmit antennas. $\mathbf{X}$ has some values out of zero (0) at the position of the mapped transmit antenna indices-in other words, it has only one nonzero value in each column. By binary phase shift keying (BPSK) and four transmit antennas, three bits can be sent on each subcarrier as shown in Fig. 1, while the identical number of bits can be sent by quadrature phase shift keying (QPSK) with two transmit antennas. The quantity of bits which are able to be conveyed on each OFDM subchannel can be written as follows:

$$m = \log_2(N_t) + \log_2(M) \tag{1}$$

where M is the modulation degree. After the SM mapping process, each row vector of $\mathbf{X}$ is passed through N-point inverse discrete Fourier transform (IDFT) process. A guard interval which consists of G sample cyclic extension is added to the N output samples of the IDFT. To avoid the ISI, the length of this cyclic extension is decided to be longer than the expected channel delay spread. A digital-analog converter (DAC) transforms the resulting signal into an analog signal. It is pulse shaped by a raised-cosine filter, and then it is ready to be transmitted with the total symbol duration of $T = PT_s$, where T_s is the sampling period and $P = N + G$. Eventually OFDM symbols at each transmit antenna are transmitted over the MIMO channel at the same time. At the receiver, firstly, the received signal is passed through analog-digital converter (ADC) and cyclic prefix (CP) is removed. After that a discrete Fourier transform (DFT) is employed for each N_r receiver antenna. For k-th subcarrier, the output of the OFDM demodulator can be written as follows:

$$\begin{bmatrix} y_1(k) \\ \vdots \\ y_r(k) \\ \vdots \\ y_{N_r}(k) \end{bmatrix} = \begin{bmatrix} h_{1,1}(k) & h_{1,2}(k) & \cdots\cdots & h_{1,N_t}(k) \\ h_{2,1}(k) & h_{2,2}(k) & \cdots\cdots & h_{2,N_t}(k) \\ \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r,1}(k) & h_{N_r,2}(k) & \cdots\cdots & h_{N_r,N_t}(k) \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ x_q(k) \\ \vdots \\ 0 \end{bmatrix} + \begin{bmatrix} w_1(k) \\ \vdots \\ w_r(k) \\ \vdots \\ w_{N_r}(k) \end{bmatrix} \tag{2}$$

where $h_{r,j}(k)$ is the channel parameter among antennas which are j-th transmitter antenna and r-th receiver antenna, $x_q(k)$ is the q-th symbol within the M-ary constellation diagram which is conveyed by j-th transmitter antenna, and $w_r(k)$ is complex-valued, zero mean additive white Gaussian noise (AWGN) with variance σ_w^2.

The output of the OFDM demodulation in (2) can be represented in a matrix notation like this:

$$\mathbf{y}(k) = \mathbf{H}(k)\mathbf{x}_j(k) + \mathbf{w}(k), \quad k = 1, 2, \cdots, N. \tag{3}$$

where

$$\mathbf{x}_j(k) \triangleq [0 \cdots \underbrace{x_q(k)}_{\substack{transmitted\, symbol\, from\, the \\ j-th\, antenna}} \cdots 0]^T \tag{4}$$

The optimum receiver which exploits the ML principle is applied in the frequency domain to discover the transmitted symbol and transmitter antenna index which is used for sending that symbol. For a single OFDM subchannel, optimal detector which operates the ML algorithm is written as follows:

$$\left[\widehat{j}_{ML}, \widehat{q}_{ML}\right]_k = \arg\max_{j,q} \left(p_Y(\mathbf{y}(k) \mid x_q(k), \mathbf{h}_j(k))\right) \tag{5}$$

where $\mathbf{h}_j(k)$ is j-th row of $\mathbf{H}$. The probability density function (pdf) of $\mathbf{y}(k)$ conditioned on $x_q(k)$ and $\mathbf{h}_j(k)$ can be written as:

$$p_Y(\mathbf{y}(k) \mid x_q(k), \mathbf{h}_j(k)) = \pi^{-N_r} \exp(\|\mathbf{y}(k) - \mathbf{h}_j(k)x_q(k)\|_F^2) \tag{6}$$

With exploiting (6), the optimal detector indicated in (5) can be rewritten as:

$$\left[\widehat{j}_{ML}, \widehat{q}_{ML}\right]_k = \arg\max_{j,q} \left(\|\mathbf{g}_{j,q}(k)\|_F^2 - 2\Re e\left\{\mathbf{y}^\dagger(k)\mathbf{g}_{j,q}(k)\right\}\right) \tag{7}$$

where $\mathbf{g}_{j,q}(k)$ is:

$$\mathbf{g}_{j,q}(k) = \mathbf{h}_j(k)x_q(k), 1 \leq j \leq N_t, 1 \leq q \leq M. \tag{8}$$

If both $\widehat{j}_{ML}$ and $\widehat{q}_{ML}$ are accurately discovered by the receiver, to combine them and get transmitted bits are trivial operations. Notwithstanding this, it is obviously seen that to know P-CSI is necessary.

III. CHANNEL ESTIMATION FOR THE SM-OFDM SYSTEM

In practice, the CSI must be determined at the receiver to discover modulated symbols and active transmitter antenna indices. For the SM-OFDM systems, we propose an efficient channel estimation technique which has low complexity and is implemented in three steps as follows:

1st Step: The block diagram of the proposed receiver structure for the SM-OFDM system is demonstrated in Fig. 3. In the first step of the proposed algorithm, the pilot symbols

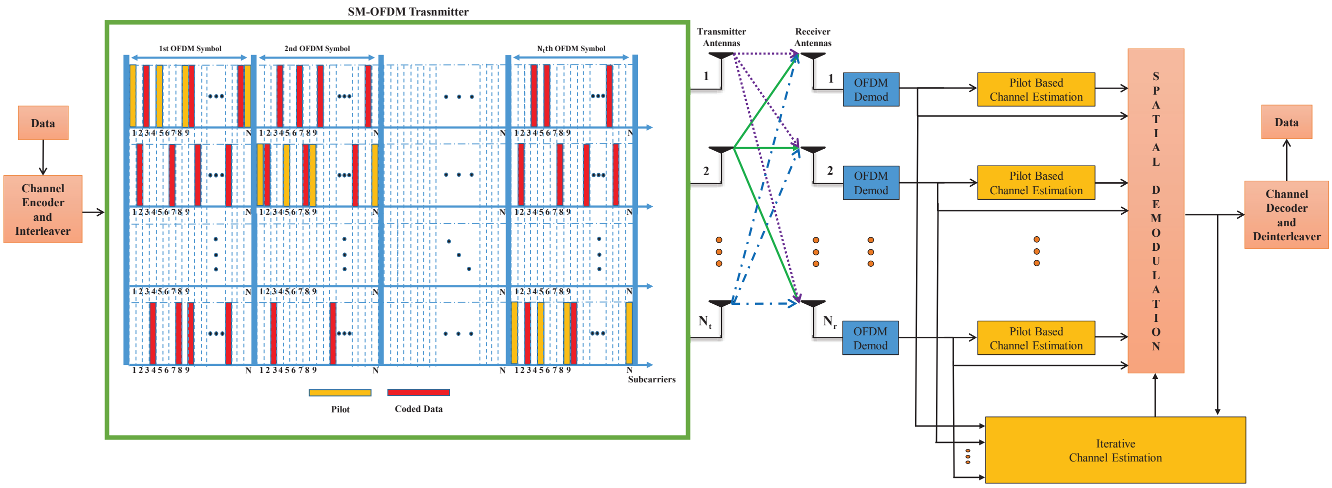

Fig. 2: Block diagram and frame structure of SM-OFDM system

for the corresponding OFDM symbol number are conveyed by each transmitter antenna as shown in Fig. 2. As can be seen from Fig. 2, pilot symbols are active for different OFDM symbol durations. Note that, pilot arrangement for the SM-OFDM systems is quite different and challenging than the conventional pilot arrangement because of the special structure of the SM-OFDM scheme. For example, as shown in Fig. 2, pilot symbols for second OFDM symbol are sent by the second transmitter antenna and other transmit antennas are inactive. It is clear that the frame structure and proposed channel estimation is suitable for a quasi-static fading model where the channel state is assumed to be constant during the transmission of a block consisting of several SM-OFDM symbols.

2nd Step: In this step, PSA-CE is applied to SM-OFDM system. The CFR at pilot symbols are determined by the LS algorithm, then determined channel parameters at pilot positions are interpolated to discover the CFR at data symbols. In this paper, we use the PLI method for interpolation due to its easy implementation and characteristic simplicity [9]. The PLI can be easily shown for $r = 1, 2, ..., N_r$ and $k_p = 1 : PIR : N$ as follows:

$$h_{r,j}(k) = \hat{h}_{r,j}(k_p) + \left(\hat{h}_{r,j}(k_{p+1}) - \hat{h}_{r,j}(k_p)\right) \times \left(\frac{k - k_p}{PIR}\right) \quad (9)$$

where PIR is the pilot insertion rate, k_p is the subcarrier position where pilot symbols are transmitted, $\hat{h}_{r,j}(k_p)$ is the estimated CFR at pilot positions, and $h_{r,j}(k)$ denotes the determined CFR at all data positions. After that, data symbols are detected according to ML principle.

3rd Step: At the final step, the detected SM-OFDM data is applied as a virtual pilot to refine the estimation of the current CSI. In other words, we have more observations for the channel estimation as follows:

- Channel parameters at data positions
- Channel parameters at pilot positions

Then whole channel parameters are obtained via the PLI method. Finally, data symbols are re-detected with the updated

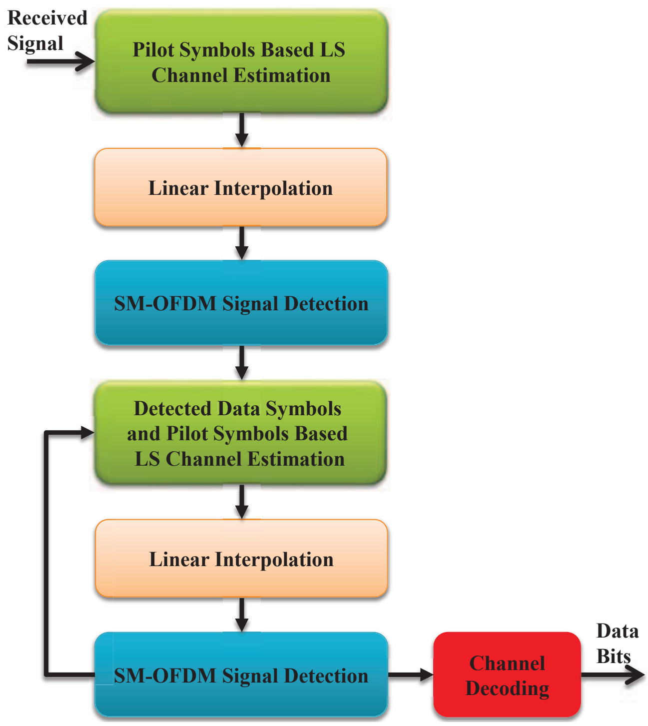

Fig. 3: Block diagram of proposed iterative receiver

channel parameters. Note that, the channel parameters could be updated by one more iteration using both new detected data symbols and pilot symbols. However, in this work, we only used one iteration to minimize the complexity of the proposed method.

IV. SIMULATION RESULTS

In this section, the BER performance of the proposed channel estimation technique is evaluated for 4×4 coded SM-OFDM system. It should be noted that the total transmitted

TABLE I: Typical Urban Channel Model

Path Number	Path Delays (μs)	Average Path Gain (dB)
1	0.0	-4.0
2	0.2	-3.0
3	0.4	-0.0
4	0.6	-2.0
5	0.8	-3.0
6	1.2	-5.0
7	1.4	-7.0
8	1.8	-5.0
9	2.4	-6.0
10	3.0	-9.0
11	3.2	-11.0
12	5.0	-10.0

power is normalized for the transmitter antennas. Uncorrelated data symbols are created and BPSK signal constellation is selected as modulation technique. System performance is decided by calculating the bit error rate (BER) for different energy per symbol to noise power spectral density ratios (E_s/N_0), and the optimum receiver is also used for the system.

Convolutional coding which has $1/2$ code rate and 7 constraint length is used for the channel coding. Its code generator polynomials are $[171\ 133]$ in octal representation and random interleaver is applied. We consider a system with $N = 256$ tones with a cyclix prefix of length $G = 32$ within the 1 MHz band and 4 OFDM symbols take part in each frame. Please note that the cyclix prefix is kept greater than delay spread of the channel to avoid ISI and the number of pilot subcarriers per SM-OFDM symbol N_p = 16 is selected.

We consider a quasi-static fading model, which allows the channel state to be constant during the transmission of a block consisting of several SM-OFDM symbols. MIMO wireless channels are modeled based on the typical urban (TU) channel model. The tapped-delay line impulse response parameters for this TU model is given in Table I where length of channel is selected as $L = 12$ [10]. All the paths characterized by uncorrelated Rayleigh flat fading.

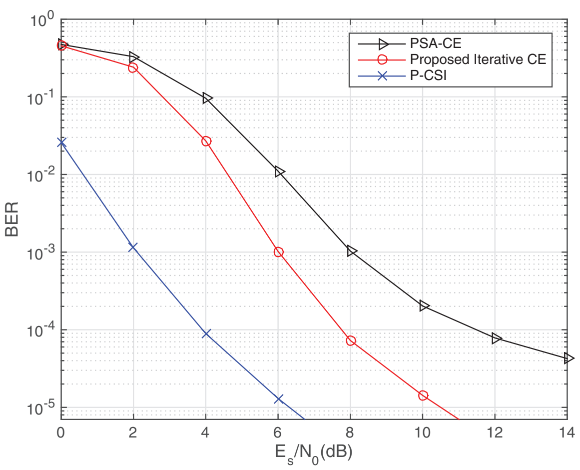

Fig. 4: The BER performance of $4{\times}4$ coded BPSK-SM-OFDM with channel estimation under TU channel model

In Fig. 4, the BER performance of the proposed data detection based iterative channel estimation is compared with the PSA-CE scheme. Simulation results in Fig. 4 show that the BER performance of the data detection based iterative channel estimation is better than that of the PSA-CE. In particular, it is shown that about 2 dB gain is achieved at BER value of 10^{-3}, as compared with the PSA-CE. It is also shown that the PSA-CE exhibits an error floor at high Eb/N0.

V. CONCLUSIONS

The channel estimation is essential at the receiver in order to coherently detect the received signal of the SM-OFDM system which is a novel transmission method that exploits multiple antennas. The channel estimation for the SM-OFDM systems can be done over frequency-selective channels with the help of pilot symbols. The PIR has a significant role in determining the overall performance of the system. It is desired to use less pilots to increase bandwidth efficiency and not to waste energy. However, the lower PIR values also limits the ability of the estimator to track the channel fluctuation. Therefore, in this work, a data detection based ICE estimation technique for SM-OFDM systems is proposed. It is shown that significant performance improvements can be achieved by the proposed ICE technique over the conventional PSA-CE.

VI. ACKNOWLEDGMENT

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