

# STBC Based Pilot-Aided Channel Estimation Method for SFBC-OFDM Systems

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*Abstract*— In this paper, an iterative channel estimation algorithm with joint detection is proposed for Multiple Input Multiple Output (MIMO) systems combined with Orthogonal Frequency Division Multiplexing (OFDM) also known as MIMO-OFDM systems using Space Time Block Codes (STBC) and Space Frequency Block Codes (SFBC). The proposed algorithm is based on an iterative process where pilot subcarriers are used for channel estimation in the first time instant, and then in the second time instant, the estimated channel is used to decode the data symbol in the adjacent data subcarrier. Once data symbols are recovered, the system recursively performs a new channel estimation using the decoded data symbols as pilots. The iterative process is repeated until all MIMO-OFDM symbols are recovered. In addition, the proposed channel estimation technique is based on the maximum likelihood (ML) approach which offers linearity and simplicity of implementation. The method also reduces the processing time via the use of subcarrier grouping for transmitted data recovery. From this we further propose an STBC and SFBC alternating scheme for pilot and data subcarriers. In this scheme STBC and SFBC are used for pilot and data subcarriers respectively, or vice versa. In addition, the efficiency of the method is demonstrated through computer simulation using multiple transmit and receive antennas and different modulation schemes.

*Keywords*-MIMO; Channel Estimation; Space-Frequency Block Coding; Space-Time Block Codes; OFDM

## I. INTRODUCTION

High data rate, low complexity of implementation, good performance and bandwidth efficiency are the challenging requirements of future wireless broadband communications. However, in practice, broadband transmissions are typically non line of sight and therefore suffer from impairments such as time varying or frequency selective channels. Thus, research has led to spatial diversity also known as Multiple Input Multiple Output (MIMO) in combination with Orthogonal Frequency Division Multiplexing (OFDM) to combat the effects of fading without increasing the bandwidth [1]. The combination of MIMO with OFDM creates frequency-flat subchannels within the frequency selective channels and therefore is a promising technique for present and future wireless communications.

Research on STBC has been intensive over the past years [2, 3] as redundant copies of the original data are sent over independent fading channels. In addition to spatial and temporal diversity, the combination of STBC-OFDM offers a third dimension of coding known as frequency diversity. The

first STBC-OFDM system was proposed in [4]. Alternatives to STBC-OFDM known as Space-Frequency Block Coding (SFBC) and Space Time Frequency Block Coding (STFBC), which are respectively capable of achieving two dimensional coding over space and frequency and three dimensional coding over space, time and frequency have recently been proposed in the literature [5]. SFBC and STFBC offer, according to the properties of the channels, larger diversity gains than traditional STBC. In addition, coding through spatial and frequency dimension offers implementation advantages [6]. MIMO-OFDM has already been adopted by several standards such as IEEE 802.11a, IEEE802.16a and 3GPP. However, the knowledge of channel parameters at the receiver is crucial in order to recover the transmitted data symbols. Therefore, channel estimation with acceptable level of hardware complexity is a crucial challenge for MIMO-OFDM systems.

Two approaches for channel estimation have been proposed in the literature. Blind channel estimation [7], which relies on the exploitation of the statistical information of the received symbols, is very attractive due to its bandwidth-saving advantage but is limited to slow time varying channels and has higher complexity at the receiver. The other method, pilot aided channel estimation [8, 9] using pilot sequences scattered in the transmitted signal and known at the receiver, is simpler to implement and can be applied to different types of channels although the use of pilots affects the data rate. As low complexity algorithm is required with a trade-off between bandwidth efficiency and accurate channel estimation, in this paper, attention has been paid to a low complexity pilot aided channel estimation method for MIMO-OFDM systems.

Since the pioneering work introduced by Li in [10], various channel estimation algorithms have been proposed for STBC/SFBC-OFDM systems [11]. Among these methods, pilot aided channel estimation based on Discrete Fourier Transform (DFT) using minimum mean square error (MMSE) or Maximum likelihood (ML) have been studied for OFDM systems [12]. For a sufficient number of pilots, the two methods have comparable performance, therefore the proposed method is based on the development of a pilot aided channel estimation algorithm with ML since it is simpler to implement than the MMSE.

The proposed channel estimation method is applied to STBC-OFDM systems for different number of transmit and receive antennas. Unlike the method in [12], we propose in this paper an iterative channel estimation algorithm for STBC-OFDM

and SFBC-OFDM. The proposed iterative joint channel estimation and decoding algorithm improves the receiver performance and is specifically suited for mobile environments. This is largely because the algorithm is based on a processive re-estimation of channel parameters immediately after each set of symbols is decoded. The main contribution of this paper is that the proposed method employs STBC and SFBC designs to estimate channel parameters and decode the transmitted data symbols, respectively. Another contribution comes from the fact that the channel estimation technique presented in this work is based on ML detection which contrary to other methods proposed in the literature, does not require any matrix inversion at the receiver. As a result of the orthogonal property of STBC/SFBC, it has been possible to derive exact and simple analytical expressions to estimate the unknown channel parameters. Finally, in our proposed method, OFDM symbols are divided into groups, which are decoded simultaneously, according to the number of pilot subcarriers used. Once the number of groups is defined, each group is assigned a specific number of pilot subcarriers equal to the number of frequency slots required to transmit one STBC/SFBC coded training block. The grouping approach employed in this work reduces the number of computations which is linearly proportional to the number of pilot subcarriers used. Finally, the method is suitable for present and future technologies such as 3G-LTE, 4G or WiMax especially those operating in mobile environments.

The rest of the paper is organized as follows. Section II describes the system architecture as well as a brief introduction on OFDM. Section III presents the proposed iterative channel estimation method with a presentation on the frame structure for STBC-OFDM and SFBC-OFDM. A new set of codes is then introduced in section IV, where STBC-OFDM coded pilot subcarriers are used to decode SFBC-OFDM data subcarriers and vice versa. Simulation results and discussions are provided in Section V. Finally, Section VI concludes the paper.

*Notation:* A bold-face upper case letter denotes a matrix, while a bold-face lower case letter denotes a vector;  $(\cdot)^*$ ,  $(\cdot)^T$ ,  $(\cdot)^H$  denote conjugate, transpose and Hermitian respectively,  $\text{tr}(\cdot)$  and  $\text{arg}(\cdot)$  are the trace and argument function,  $E(\cdot)$  represents the expectation of a random variable respectively;  $\|X\|_F$  denotes the Frobenius norm of the matrix  $X$ ,  $|x|$  denotes the absolute value of  $x$ ,  $I_N$  is an  $N \times N$  identity matrix, finally  $j = \sqrt{-1}$ .

## II. SYSTEM MODEL

A MIMO-OFDM system with  $M_t$  transmit antennas and  $N_r$  receive antennas, employing  $N_{\text{FFT}}$  subcarriers from which  $N_s$  are used to transmit data symbols,  $N_p$  are used to transmit pilot symbols and the remaining  $N_{\text{FFT}} - N_s - N_p$  subcarriers are used as DC subcarrier and guard interval, is assumed in this paper. At time  $t$ , a binary data block  $X(t)$  of  $q$  bits is scrambled and mapped using a set of predefined constellation diagram (BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM) resulting in a symbol stream  $\{s = [s_0, s_1, \dots, s_k, s_{k+1}, \dots, s_{x-1}]^T, k = 0, 2, \dots, x\}$ . Simultaneously, a binary data block  $X_p(t)$  known at the receiver is modulated resulting in a pilot sequence

$$\{p = [p_0, p_1, \dots, p_{kp}, p_{kp+1}, \dots, p_{x_p-1}]^T, k_p = 0, 2, \dots, x_{p-1}\}$$

where the value of  $x$  and  $x_p$  are determined by the encoding technique employed, the number of transmit antennas and the rank of the matrix. For example for two transmit antennas,  $x=2N_s-1$  ( $x_p=2N_p-1$ ) and  $x=N_s-1$  ( $x_p=N_p-1$ ) for STBC and SFBC respectively. Each block of pilot and data is then sent to the STBC and SFBC, or SFBC and STBC encoder, respectively. Data is then split to the different antennas according to the encoding used for data and pilot subcarriers such that  $\{s_i(n, k_T), k_T = 1, 2, \dots, (N_s + N_p)\}$ . Then, once encoded, the known pilot sequence is added to the generated signal and allocated to the different antennas. For each antenna, an  $N$ -point inverse Fast Fourier Transform (IFFT) is applied to convert the coded data from frequency domain to time domain. Finally, cyclic prefix is added to each OFDM symbol and data is transmitted simultaneously from different antennas. It is assumed that time and frequency synchronization of the system is perfect.

At the receiver, an inverse procedure is employed. Data is received and down converted, cyclic prefix is removed and FFT operation is performed. Alamouti's encoding scheme offers a simple decoding algorithm when channel parameters are known at the receiver. Therefore, extra attention has been paid to the channel estimation aspect.

The transmitted sequences across all transmit antennas pass through a fast frequency selective channel with adaptive white Gaussian noise (AWGN). The received signal between the transmit antenna and the receive antenna, after OFDM demodulation is applied, can be expressed in matrix form as:

$$R_{j,k}(n) = \sum_{i=1}^{M_t} H_{i,j,k}(n) S_{i,k}(n) + N_{j,k}(n) \quad (1)$$

where  $S_{i,k}(n)=[s_0, s_1, \dots, s_{x-1}]$  represents the transmitted signal from the antenna of the OFDM symbol and where  $N_{j,k}(n)$  represents the white Gaussian noise with variance per dimension and  $H_{i,j,k}(n)$  is the time varying channel tap between the transmit antenna and the receive antenna of the OFDM symbol.

Data is then sent to the channel estimator in order to estimate channel parameters at pilot subcarriers. The estimated channel is sent to Space-Time/Frequency Decoder in order to be used to recover the transmitted data sequence which is finally detected using ML detection.

## III. CHANNEL ESTIMATION STRATEGY

Traditionally, the pilot and data signals are subjected to the same STBC in STBC-OFDM systems and SFBC in SFBC-OFDM systems. They are also modulated by the same modulation scheme. Since STBC and SFBC are orthogonal codes, channel estimation and data detection become simple. In this work, we propose to use different coding schemes for pilot and data subcarriers, that is, using STBC and SFBC to encode the pilot and data respectively, or encoding the pilot and data subcarriers using SFBC and STBC respectively.

As mentioned in Section II,  $N_p$  pilot and  $N_s$  data subcarriers are used to estimate the channel parameters and recover the transmitted sequence. A grouping strategy is also applied where the number of data subcarriers per group is pre-

determined such that  $L_{\text{sub/group}} = N_s/N_p$  and the number of groups is equal to  $N_{\text{group}} = N_s/L_{\text{sub/group}} = N_p$  for STBC/SFBC-OFDM. In the case of SFBC/STBC-OFDM,  $L_{\text{sub/group}} = N_s/(N_p/N_{\text{FS}})$  which results in a number of groups per OFDM symbol equal to  $N_{\text{group/OFDM}} = N_s/L_{\text{sub/group}}$  where  $N_{\text{FS}}$  being the total number of subcarriers. According to the encoding scheme used, for two transmit antennas, 1 or 2 pilot subcarriers are assigned to each group for STBC/SFBC-OFDM and SFBC/STBC-OFDM system respectively.

Significant benefits are realized for SFBC-OFDM systems, for example when 8 pilot subcarriers are utilized, the OFDM symbol is divided into 4 groups. As it can be deduced, higher number of subcarriers results in a higher number of groups and therefore the channel estimation is more accurate.

When using STBC for channel estimation in SFBC-OFDM systems, it is assumed that channel parameters remain constant over  $n_t$  OFDM symbols and over  $n_t$  adjacent subcarriers which may be a disadvantage in high mobility environments especially when the number of transmit antennas exceed 2. For the scenario where SFBC is used for pilot subcarriers in STBC-OFDM systems, the assumption that the channel parameters remain constant over  $n_t$  OFDM symbols already exists for STBC-OFDM systems. However, an additional assumption that the channel parameters will remain constant over  $n_t$  adjacent subcarriers will be required.

In the following we consider the joint estimation and detection method that pilot and data subcarriers are coded according to the coding rules of STBC-OFDM and SFBC-OFDM respectively. Details of the organisation of STBC and SFBC OFDM symbols can be found in Figure 1.

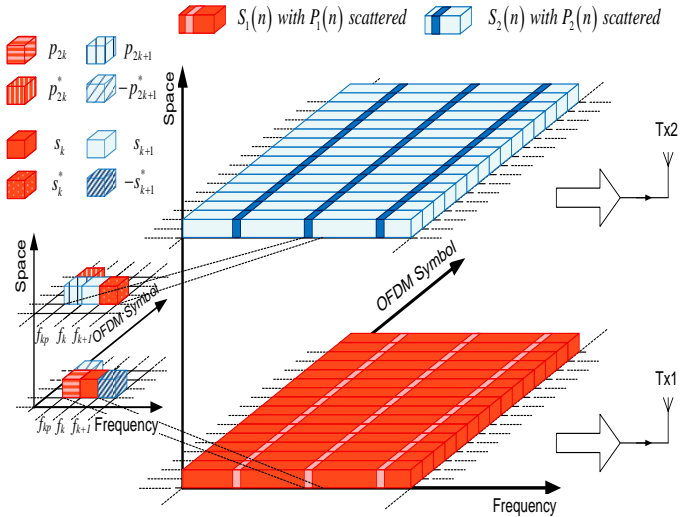


Figure 1: Organisation of Pilot and Data Symbol for 2 Transmit Antennas

Therefore, to transmit two consecutive OFDM symbols, four vectors are required for pilot subcarriers while two vectors are required for the data subcarriers:

$$\begin{aligned}
 P_1(n) &= [p_0, p_2, \dots, p_{2N_p-4}, p_{2N_p-2}]^T \\
 P_2(n) &= [p_1, p_3, \dots, p_{2N_p-3}, p_{2N_p-1}]^T \\
 P_1(n+I) &= [-p_1^*, -p_3^*, \dots, -p_{2N_p-3}^*, -p_{2N_p-1}^*]^T = -P_2^*(n) \\
 P_2(n+I) &= [p_0^*, p_2^*, \dots, p_{2N_p-4}^*, p_{2N_p-2}^*]^T = P_1^*(n)
 \end{aligned} \quad (2)$$

$$\begin{aligned}
 S_1 &= [s_0, -s_1^*, \dots, s_k, -s_{k+1}^*, \dots, s_{N_s-2}, -s_{N_s-1}^*]^T \\
 S_2 &= [s_1, s_0^*, \dots, s_{k+1}, s_k^*, \dots, s_{N_s-1}, s_{N_s-2}^*]^T
 \end{aligned} \quad (3)$$

In a similar way, the received pilot and data symbols can be expressed by the  $1 \times N_p$  and  $1 \times N_s$  vectors:

$$R p_j(n) = [r p_{j,0}, r p_{j,2}, \dots, r p_{j,2N_p-4}, r p_{j,2N_p-2}]^T \quad (4)$$

$$R p_j(n+I) = [r p_{j,1}^*, r p_{j,3}^*, \dots, r p_{j,2N_p-3}^*, r p_{j,2N_p-1}^*]^T$$

$$R_j(n) = [r_{j,0}, r_{j,1}, \dots, r_{j,2N_s-2}, r_{j,2N_s-1}]^T \quad (5)$$

From (1), and with the help of (2), (3), (4) and (5), the received signals can be expressed as:

$$R p_{j,k}(n) = r p_{j,2kp} = h p_{1,j,2kp} p_{2kp} + h p_{2,j,2kp} p_{2kp+1} \quad (6)$$

$$R p_{j,k}(n+I) = r p_{j,2kp+1} = -h p_{1,j,2kp} p_{2kp+1} + h p_{2,j,2kp} p_{2kp}$$

$$r_{j,k} = h_{1,j,k} s_k + h_{2,j,k} s_{k+1} \quad (7)$$

$$r_{j,k+1} = -h_{1,j,k+1} s_{k+1}^* + h_{2,j,k+1} s_k^*$$

Pilot sequence known at the receiver is then used to estimate the channel parameter at the pilot subcarriers. With the assumption that channel parameters remain constant over two adjacent subcarriers and two adjacent OFDM symbols, channel parameters can be expressed with the help of (6) as:

$$\tilde{H} p_{1,j,2kp}(n) = \tilde{H} p_{1,j,2kp}(n+I) = \tilde{h} p_{1,j,2kp} = \frac{r p_{j,2kp} p_{2kp}^* - r p_{j,2kp+1} p_{2kp+1}^*}{|p_{2kp}|^2 + |p_{2kp+1}|^2} \quad (8)$$

$$\tilde{H} p_{2,j,2kp}(n) = \tilde{H} p_{2,j,2kp}(n+I) = \tilde{h} p_{2,j,2kp} = \frac{r p_{j,2kp} p_{2kp+1}^* + r p_{j,2kp+1} p_{2kp}^*}{|p_{2kp}|^2 + |p_{2kp+1}|^2}$$

The detection formulas for the data signals can be derived with the help of (7) and (8). Assuming  $h p_{i,j,2kp} = h_{i,j,k} = h_{i,j,k+1}$ , equations can be derived.

$$\begin{aligned}
 \tilde{S}_{1,k}(n) &= \sum_{j=1}^{N_s} (\tilde{H} p_{1,j,2kp}(n) R_{j,k}(n) + \tilde{H} p_{2,j,2kp}(n) R_{j,k}(n+I)) \\
 &= \tilde{s}_k = \sum_{j=1}^{N_s} (\tilde{h} p_{1,j,2kp}^* r_{j,k} + \tilde{h} p_{2,j,2kp} r_{j,k+1}^*)
 \end{aligned} \quad (9)$$

$$\begin{aligned}
 \tilde{S}_{2,k}(n) &= \sum_{j=1}^{N_s} (\tilde{H} p_{2,j,2kp}^*(n) R_{j,k}(n) + \tilde{H} p_{1,j,2kp}(n) R_{j,k}^*(n+I)) \\
 &= \tilde{s}_{k+1} = \sum_{j=1}^{N_s} (\tilde{h} p_{2,j,2kp}^* r_{j,k} - \tilde{h} p_{1,j,2kp} r_{j,k+1}^*)
 \end{aligned}$$

Replacing the channels parameters by the estimated expressions obtained in (8), (9) becomes:

$$\begin{aligned}
 \tilde{s}_k &= \frac{1}{\Delta_p} (A p_{kp+1}^* + B p_{kp}) \\
 \tilde{s}_{k+1} &= \frac{1}{\Delta_p} (B p_{kp+1} - A p_{kp}^*)
 \end{aligned} \quad (10)$$

where  $\Delta_p = |p_{2kp}|^2 + |p_{2kp+1}|^2$  and A and B can be expressed as:

$$\begin{aligned}
 A &= \sum_{j=1}^{N_r} (rp_{j,2kp}r_{j,2k+1}^* - rp_{j,2kp+1}r_{j,2k}^*) \\
 &= \Delta_h (p_{2kp+1}s_k - p_{2kp}s_{k+1}) + N_{j,1} \\
 B &= \sum_{j=1}^{N_r} (rp_{j,2kp}r_{j,k}^* + rp_{j,2kp+1}r_{j,k+1}^*) \\
 &= \Delta_h (p_{2kp}^*s_k + p_{2kp+1}^*s_{k+1}) + N_{j,2}
 \end{aligned} \tag{11}$$

where  $\Delta_h = \sum_{j=1}^{N_r} (|hp_{1,j,kp}|^2 + |hp_{2,j,kp}|^2)$  and  $N_{j,1}$  and  $N_{j,2}$  are white Gaussian Noise vectors.

Substituting (11) into (10) leads to:

$$\begin{aligned}
 \tilde{s}_k &= \Delta_h s_k + N_3 \\
 \tilde{s}_{k+1} &= \Delta_h s_{k+1} + N_4
 \end{aligned} \tag{12}$$

where  $N_3$  and  $N_4$  are noise terms.

#### IV. SIMULATION RESULTS

The performance of the proposed iterative channel estimation technique has been evaluated according to the specifications described in the WiMax standard for fixed wireless communications [13]. The MIMO-OFDM system with STBC for pilot and SFBC for data was simulated. Simulations were conducted for two and four transmit antennas and one and two receive antennas. Moreover, simulations were carried out using different number of pilot subcarriers, different channel environments and different modulation orders. The system has a 3.5 MHz channel bandwidth and a carrier frequency of 2.5GHz. Specific simulation parameters are presented in Table 1.

Allocation of the subcarriers of the OFDM frame is made according to the IEEE802.16e (WiMax) standard [13]; indices of -128~-101 and 101~127 are reserved for guard intervals, 0 is for the DC subcarrier, -100~-1 and 1~100 are defined as the chosen subcarriers in which -88, -63, -38, -13, 13, 38, 63 and 88 are pilot subcarriers and the remaining are specified as data subcarriers.

Table 1: Simulation Parameters for STBC/SFBC-OFDM Systems

FFT Size ( $N_{FFT}$ )	256
Number of Active Subcarriers ( $N_{used}$ )	200 (192 for data, 8 for pilot)
Number of Guard Subcarriers	28 low, 27 high
Channel Bandwidth	3.5MHz
Sampling Rate ( $F_s$ )	2.28MHz ( $n=57/50$ )
Distance between Adjacent	8.9kHz

Subcarriers ( $\Delta f$ )	
Useful Symbol Duration ( $T_b$ )	0.112ms
Guard Time ( $T_g$ )	28.07 $\mu$ s
Total Symbol Duration ( $T_s$ )	140 $\mu$ s
Cyclic Prefix length (CP)	1/4
Modulation	BPSK, 16 QAM, 64QAM
SUI	1,3
Transmit Antennas	2, 4
Receive Antennas	1, 2

Simulation results are presented for different modulation orders, pilot and data subcarriers. In addition, different numbers of transmit and receive antennas have been used as well as different numbers of pilot subcarriers. The difference between the ideal case where CSI is known at the receiver and the iterative channel estimation technique is about 2 to 10dB. Moreover, from Figure 2 and Figure 3, it can be seen that reducing the modulation order of the pilot subcarriers leads to 2-3dB improvement compared to the case where the same modulation order is used. An improvement of 2-3 dB is also possible when a larger number of pilot subcarriers are used. From Figure 2 and Figure 3, it can also be noticed that increasing the number of transmit or receive antennas improves the performances as well as the use of a lower modulation order. In addition, low modulation orders perform better than higher ones at the cost of bandwidth inefficiency.

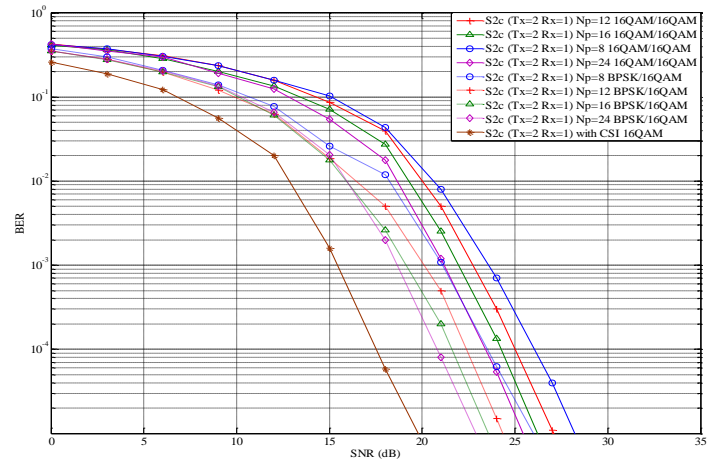


Figure 2: Effect of the use of Different Modulation and Pilot Length for 2 Transmit and 1 Receive Antennas (Modulation A/B: A for Pilot, B for Data)

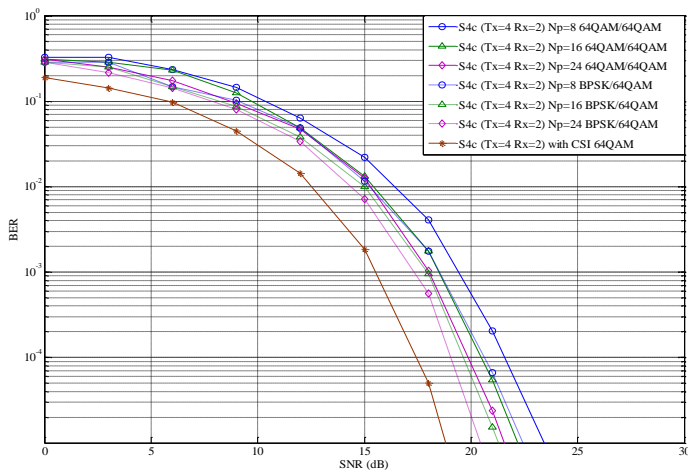


Figure 3: Effect of the use of Different Modulation and Pilot Length for 4 Transmit and 2 Receive Antennas (Modulation A/B: A for Pilot, B for Data)

## V. CONCLUSIONS

In this paper, a new channel estimation method is proposed based on the combination of STBC, SFBC and OFDM. Alternating the type of coding at the pilot and data subcarriers offers an efficient and computation-effective algorithm where the use of groups helps to improve the performance of the system without increasing the complexity at the receiver. Using STBC to encode the pilot subcarrier offers the possibility to generate more groups due to the fact that symbols are coded across OFDM symbols and therefore allows for more data symbols to be decoded simultaneously. The length of the training sequence offers trade-off between accurate channel estimation and efficient bandwidth usage as more pilots would allow the algorithm to perform more accurate channel estimation at the cost of less transmitted data. In addition, the problem of SFBC-OFDM in terms of generating fewer decoding groups than STBC-OFDM for the same number of pilot subcarriers has been addressed by combining STBC and SFBC for pilot and data respectively. The accuracy level of the method when STBC is used to estimate channel parameters is similar to the level of accuracy achieved by SFBC-OFDM systems in low mobility scenarios. The significant difference is that STBC offers the possibilities to generate a higher number of groups of data at the cost of a slight increase in the complexity of the system while achieving higher bandwidth efficiency. Indeed, the higher number of group reduces the error propagation from one symbol block to another for the same number of pilot subcarrier, similar to that

observed in SFBC-OFDM system. The method has been simulated under various conditions, different numbers of transmit and receive antennas, different modulation schemes at the pilot and data subcarriers.

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