Design and Evaluation of a Channel Estimator for Realistic Space-Frequency Coded MIMO OFDM Wireless Systems

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Abstract: - This paper presents the design and evaluation of a channel estimation scheme that is efficient by means of both the mean square error (MSE) of channel estimation/tracking and its incorporation in a real MIMO system. The evaluation has been performed over the spatial channel model developed for MIMO simulations according to 802.16e case of 3GPP.25.996, taking also into account all IF and RF stages in the communication chain. Orthogonality has been applied in space-frequency dimension for both preamble and pilot symbols, as well as for the data symbols, with the application of Alamouti’s scheme. In 4G multicarrier systems that use space-time-frequency coding, orthogonal design turns into a key factor for the performance of the system since the channel has to remain about constant during the transmission of one orthogonal block, something which becomes quite challenging in highly time-variant propagation channels (e.g. 802.16e, 802.20). The estimation scheme is efficient in minimization the processing requirements at the receiver by estimating only the time-varying channel properties, and the presented results refer to MSE of the estimator, as well as to overall performance of the system (BER) in various propagation channels, data rates and FEC modes.

Key-Words: - MIMO transceivers, channel estimation and tracking, OFDM, correlated propagation channels, space-frequency block coding

1 Introduction

Wireless broadband systems have to support services that demand information transmission with very high data rates over the wireless propagation medium. It has been proven [1] that the use of multiple antenna elements at both ends of a wireless link offers both capacity gain and improvement of robustness and reliability. Therefore, multiple input multiple output (MIMO) architecture has been incorporated in the development of various wireless systems operating in challenging propagation environments. In addition, the various sources of diversity should be properly exploited by means of coding and transmission schemes [2]. Temporal diversity is realized through FEC schemes (scrambling, Reed-Solomon, convolution, interleaving). Frequency diversity is exploited by orthogonal frequency division multiple (OFDM) access systems and spatial diversity is obtained by multiple antennas. Furthermore, the above diversity options are combined in space-time, space-frequency, or space-time-frequency codes where the orthogonal property and the ability to be preserved through the propagation channel is a key factor in the total system performance.

Optimum space-frequency coding schemes that maximize the diversity gain are proposed in [3], but the processing requirements at the receiver are quite high. Space-time block codes proposed by Alamouti and extended in [4], provide a simple transmit diversity scheme with maximum diversity in flat fading MIMO channels, which are assumed about constant during the transmission of one orthogonal block. OFDM provides flat fading channel for each subcarrier making space-time block codes well suited for OFDM systems assuming that the channel coefficients remain constant during two or more consecutive OFDM symbols.

In propagation environments with high Doppler shift, loss of orthogonality assembled in space-time domain becomes possible, whilst in space-frequency structure the orthogonal design is not distorted. Furthermore, as the number of subcarriers increases, for a given total bandwidth of transmission, the probability of non constant affected neighbour subcarriers in severe frequency selective channels becomes quite small. Also, the greater number of subcarriers (WiMAX vs WiFi), the larger range is achieved, since larger delay spreads are tolerated (up to 10 times for WiMAX with respect to WiFi). MIMO technology constitutes the basis for next generation wireless communication systems, as for example in IEEE 802.11n or IEEE 802.16e.

Channel estimation is a crucial design parameter in the performance of a real system since it has to estimate, track and compensate all channel
distortions as well as the distortions caused in RF stages in transmitter and receiver units. Especially, in a MIMO-OFDM system the channel distortion is described by a complex factor per subcarrier requiring from the estimator $N\text{sym} \cdot N_c \cdot N_T \cdot N_R$ estimations/compensations per frame ($N\text{sym}=\text{number of OFDM symbols}$, $N_c=\text{number of subcarriers per OFDM symbol}$, $M_T=\text{number of Transmit antennas}$, $M_R=\text{number of receive antennas}$). Such an operation can be particularly demanding in terms of computational effort [5]. Following the design of space-frequency orthogonality also for the preamble and pilot transmission the proposed approach causes a pilot overhead of only 3.12% per OFDM symbol in which only phase estimation is applied the pilots that have been carefully placed in predefined positions.

In this paper, initially (section 2) the system model is depicted giving a detailed insight of transceiver architecture, as well as the channel models used for the evaluation. In section 3, the channel estimation is described giving rise to all advantages and trade offs caused by the low computational complexity at the receiver side. Finally (section 4), evaluation results of the channel estimation (MSE) and the overall system performance (BER) are given for 2x2, 2x3 and 2x4 cases evaluated in various propagation models according to 802.16e (Mobile Broadband Wireless Access, MBWA) case of 3GPP.25.996 standard [6] using various FEC codes and mapping formats.

2 System Architecture

2.1 Transmission Scheme
The MIMO-OFDM transmitter with two branches employing space-frequency block coding (SFBC) is shown in fig.1. A binary data block $D[k]$ of $k$ bits is scrambled, encoded by a concatenated Reed-Solomon and Convolutional encoder, followed by a puncturer and an interleaver.

The resultant bit stream is mapped using a set of predefined constellation diagrams (BPSK-1/2, QPSK-1/2, QPSK-3/4, 16QAM-1/2, 16QAM-3/4, 64QAM-2/3, and 64QAM-3/4) giving a symbol stream $S[m]$ of $m$ symbols.

The same procedure is followed as well as for the frame control header (FCH) [7] with fixed QPSK mapping. These symbol streams are then frequency multiplexed with 8 pilot symbols and the output is SFB coded based on Alamouti’s scheme. The output symbols are packetized in blocks of 200 symbols, zero padded and inserted in a 256-IFFT OFDM modulator. Subsequently, the outputs are time multiplexed with the OFDM output of the SFB coded preamble symbols P. Space-frequency block coding (SFBC) becomes more efficient as the number of subcarriers increases.

The produced digital signals at the two chains are converted to analogue ones and up-converted to the carrier frequency through RF stages with common oscillator. Hence, time synchronization and frequency offset compensation at the receiver are exactly the same as in the case of a SISO system. The framing structure of the signal before transmit antennas (time domain) and just after the receive antennas is depicted in figs 3, 4 and 5, where 4 frames have been captured. In each frame, it is observed the synchronization OFDM symbol, the preamble OFDM symbol, as well as the data OFDM symbols. It has to be noted the in antenna No2 the synch preamble is absent since only one is required.
2.2 Reception Scheme

At the receiver an equivalent procedure is followed. Alamouti’s encoding scheme [8] (applied on a basis of 2 neighbour subcarriers) offers a simple combining scheme assuming, that the channel estimates are available. Hence, extra attention has been paid in the channel estimation stage as shown in fig.5. The received signal in frequency domain, either for data symbol stream, or for preamble symbol stream at the receiver chain is expressed as follows:

\[ R_{ij} = \sum_{j=1}^{M_F} H_{ij}^{(m^x_j)} \cdot S_{ij} + N_{ij} \]  

where \( i \) corresponds to the subcarrier index at the \( m^x \)-th receive antenna, \( j \) corresponds to the transmitter antenna index out of \( M_T \) transmit antennas \((M_T = 2)\), \( N \) corresponds to additive complex Gaussian noise per subcarrier \( i \) with zero mean and variance \( \sigma_n^2 \). Also, \( H_{ij}^{(m^x_j)} \) corresponds to the channel coefficient between the \( j \)-th transmit antenna and the \( m^x \)-th receive antenna for \( i \)-th subcarrier.

The combiner outputs are fed to the maximum likelihood detector (ML) which estimates the most probable symbol stream [9] according to the equation:

\[ J = \arg \min_{S_k} \sum_{k=1}^{N_c} \| R_k - \hat{H} \cdot S_k \|^2 \]  

where \( C = [S_0, S_1, ..., S_{N_c-1}] \). Time and frequency synchronization are performed based on the time correlation properties of the relative preamble. The correction factor is fed back to the oscillator causing a delay. During this session, the automatic gain controller (AGC) is adapted and remains constant during the subsequent frame period.

2.3 Channel Models

The evaluation of SFBC MIMO-OFDM scheme has been performed over realistic conditions taking into account not only the channel propagation characteristics, like time variability (Doppler shift) and multipath propagation (frequency selectivity), but also the correlations between the antennas at the transmitter and the receiver (described by Tx and Rx correlation matrices). The physical parameters used for link level modelling have been based on pedestrian level of mobility with line of sight (Rice factor K=6dB) according to the relative standard [6]. Also, the proposed correlation values have been taken into account for an inter-element spacing of \( \lambda/2 \), where \( \lambda \) denotes the wavelength.

3 Channel Estimation

Channel state information (CSI) is acquired by the receiver on a two-step procedure (fig.5) whereas no CSI is fed back to the transmitter, establishing an open-loop system with equal transmission power on the antennas. The first step in the channel estimation procedure employs the OFDM preamble symbols which are orthogonal on a SFBC subcarrier basis. The estimation has been implemented using a MMSE approach. In the second step, the pilot symbols are used only for the phase estimation compensating the Doppler distortion. Then, using interpolation the correction factor for each subcarrier is taken into account in the preamble based estimation. The final channel estimates are used for both channel compensation and soft decision stages. Furthermore, Doppler estimation gives a figure of merit of the channel’s time variation which can be potentially used to increase the number of pilot data in time dimension or for adapting a higher order interpolation filter.
The MIMO channel estimation problem can be decomposed into several MISO channel estimations in parallel [9]. The initial channel estimation is based on the preamble OFDM symbols that have been transmitted from the 2 antennas in an orthogonal space frequency format. Taking into account only the adjacent subcarriers $i$ and $i + 1$, that convey pilot information in an orthogonal format, it will be:

$$
\begin{align*}
R_i^{(1)} &= H_i^{(1)} \cdot S_i^{(1)} + H_i^{(12)} \cdot S_i^{(2)} \\
R_i^{(2)} &= H_i^{(2)} \cdot S_i^{(1)} + H_i^{(22)} \cdot S_i^{(2)}
\end{align*}
$$

where $R_{i}^{(m)}$ is the received signal at $m_{th}$ receive antenna in $i$-th subcarrier, $H_{i}^{(m,p)}$ is the channel coefficient from $p_{th}$ transmit antenna to $m_{th}$ receive antenna in $i$-th subcarrier, and $S_{i}^{(m)}$ is the transmitted symbol from $p_{th}$ antenna in $i$-th subcarrier. Since, the Alamouti scheme has been adapted in space-frequency dimension the transmitted symbols in $i$-th and $(i+1)$-th subcarriers will be: $a_i^{(PS)} = 1, b_i^{(PS)} = 0, a_i^{(PS)} = 0, b_i^{(PS)} = 1$, where $(.)^*$ denotes complex conjugate operation. In addition the channel is assumed constant for the subcarriers $i$ and $(i+1)$ giving: $H_i^{(1)} = H_{i+1}^{(1)} = H_{i}^{(1)}$, $H_i^{(21)} = H_{i+1}^{(21)} = H_{i}^{(21)}$, $H_i^{(12)} = H_{i+1}^{(12)} = H_{i}^{(12)}$, $H_i^{(22)} = H_{i+1}^{(22)} = H_{i}^{(22)}$. Hence, expressing eq.3 in matrix notation it will be:

$$
\begin{bmatrix}
R_i^{(1)} \\
R_i^{(2)}
\end{bmatrix} =
\begin{bmatrix}
H_i^{(1)} & H_i^{(12)} \\
H_i^{(21)} & H_i^{(22)}
\end{bmatrix}
\begin{bmatrix}
P_a \\
P_b
\end{bmatrix} \Leftrightarrow R_p = H_p \cdot S
$$

where the index $p$ denotes the processed nature of the relative receive vector and the channel matrix. The matrix $H_p$ has unitary properties, i.e.

$$
H_p^H \cdot H_p = \left( |H_p^{(1)}|^2 + |H_p^{(12)}|^2 + |H_p^{(21)}|^2 + |H_p^{(22)}|^2 \right) \cdot I_2
$$

$$
= \mu \cdot I_2
$$

where $I_2$ is the identity matrix of dimension 2, and $(.)^H$ denotes conjugate transpose matrix operation. In a real system the MIMO channel has been estimated at the receiver $\hat{\mathbf{H}}$ non perfectly giving the following soft decision metric:

$$
\mathbf{S} = \frac{1}{\mu} \hat{\mathbf{H}}_p^H \cdot \mathbf{R}_p = \frac{1}{\mu} \hat{\mathbf{H}}_p^H \cdot (\mathbf{H}_p \cdot \mathbf{S} + \mathbf{N}) \Leftrightarrow
$$

$$
\mathbf{S} = \mathbf{H}_{res} \cdot \mathbf{S} + \mathbf{N}
$$

where the subscript $res$ indicates the residual channel effect that have to be compensated by the ML decoder. For cases of severe channel variations during the transmission of an orthogonal scheme, the orthogonality is lost causing intersymbol interference. Hence, in order to preserve the orthogonality, the sampling theorem has to be applied determining the relative distances in time and frequency dimension, where the pilots have to be placed. In space-time block codes the distance is proportional to the coherence time, while in space-frequency block coding is proportional to the coherence bandwidth. The channel tracking is performed through the phase estimation at the pilot positions based on the ML criterion according to the equation:

$$
\hat{\theta}_i = \arg \min_{\theta} \sum_{i=1}^{8} \left( \hat{\mathbf{H}}_i \cdot \hat{\mathbf{H}}_i^{(pre)} \right)^* \Leftrightarrow
$$

$$
\hat{\theta}_i = \arg \min_{\theta} \sum_{i=1}^{8} \hat{\mathbf{H}}_i \cdot \hat{\mathbf{H}}_i^{(pre)} \Leftrightarrow
$$

where $\hat{\mathbf{H}}_i$ and $\hat{\mathbf{H}}_i^{(pre)}$ are the current channel estimates at pilot positions (8 pilots per OFDM symbol) and the estimates at the same subcarrier during the preamble OFDM symbol, respectively. The estimated phase difference updates the preamble based estimation. For the case of 2x4 MIMO-OFDM at 64-QAM, total coding (RS-CC) 2/3, a propagation channel of type A (IEEE-802.16e) and in Eb/No=17dB, a snapshot of the channel compensated symbols, just before the detector, is given in fig.6. The blue dots are the transmitted ones before SFBC. Also, QPSK modulation is observed due to FCH symbols.

Figure 6: Constellation map of the channel compensated symbols for 2x4 MIMO-OFDM at Eb/No=17dB.
4 Evaluation Results

The performance of the channel estimation scheme is evaluated in 2x2, 2x3, and 2x4 MIMO-OFDM systems, with orthogonal space frequency design, taking also into account all stages in RF, IF and baseband level. The simulated system achieves information data rates of 6.9Mbps at BPSK-1/2, of 13.8Mbps at QPSK-1/2, of 20.7Mbps at QPSK-3/4, of 27.7Mbps at 16QAM-1/2, of 41.5Mbps at 16QAM-3/4, of 55.3Mbps at 64QAM-2/3, and of 62.2Mbps at 64QAM-3/4 in a frequency bandwidth of 20MHz at a carrier frequency of 5.2GHz. The channel adaptation is based on 8 pilot symbols per OFDM symbol placed in blocks of 2 adjacent subcarriers in 4 positions across the OFDM symbols. OFDM stages are based on a 256-point FFT/IFFT with cyclic prefix of 1/4. Each frame carries 2400 information bits and the evaluation is performed on the basis of achieving BER estimation relative variance of $10^{-4}$ with an upper limit of 1000 frames.

Based on these results, the channel estimator for the 2x2 case is characterized by an irreducible error floor at 3dB, achieving the limit at $Eb/No=13dB$ for all schemes and channel conditions tested. Similarly, in 2x4 MIMO case, the error floor is reduced to 0.7dB and it is achieved for values $Eb/No$ greater than 13dB.

System performance for 2x2, 2x3, and 2x4 cases has been evaluated based on the information bit error rate giving simultaneously an insight at the sensitivity of the channel estimation errors. For the probability of error ($P_e$) measurement to be statistically significant, the relative variance ($R_{var}$) of $P_e$ is taken into account for the transmitted bits indicating the confidence interval of $P_e$. In fig.9 the probability of error is depicted for 2x3 and 2x4 MIMO-OFDM cases under propagation channel conditions of type A as determined in IEEE-802.16e, for all modulation formats and coding modes. For information data rate of 13.8Mbps a value of $E_b/N_0 = 7$dB is enough to achieve $P_e = 10^{-4}$ for 2x3 system, while the same value for 62.2Mbps requires almost 12dB increase in $Eb/No$.

In fig.10 the performance of a 2x2 OFDM system is depicted under various propagation conditions, according to IEEE-802.16e proposed channel models. The system efficiency is high for the channel model of type A, but for more demanding channels (E,F,G models), with higher mobility and frequency selectivity order, the system fails to support increased data rates.

Finally, in fig.11 the performances of 2x3 and 2x4 are compared over various propagation channels and...
data rates. The proposed scheme is quite efficient in propagation channels that follow the channel model of type A, while for propagation channels of higher time-variant nature, an increase of pilot overhead is required in order to sample the channel suitably.

Figure 10: BER comparisons for 2x2 MIMO system, over various channel propagation conditions and data rates.

Figure 11: BER comparisons for 2x3 and 2x4 MIMO systems, with QPSK and RS-CC=¾, over various channel propagation conditions.

5 Conclusions
In this paper a MIMO OFDM system has been designed on a real basis and evaluated giving rise to space-frequency orthogonality with no CSI available at the transmitter. In addition, all the RF stages at the transmitter and the receiver were taken into account approaching a real architecture as close as possible. An efficient channel estimation scheme was incorporated in the system achieving not only a good efficiency, but also low computational requirements at the receiver side, as well as pilot overhead of only 3.12%. Furthermore, the performance of the estimator can be improved, either by increasing the number of subcarriers for a given bandwidth, or by increasing the pilot overhead, or by switching the orthogonal scheme in space-time dimension.

Finally, the overall system performance of SFBC MIMO OFDM was evaluated over various number of transmit and receive antennas indicating that schemes with more than 2 antennas at the receiver are capable of operating efficiently in various types of challenging propagation channels. Based on this approach an adaptive scheme is under development that utilizes also the space-time domain according to the current channel properties and the ability of the system to preserve the orthogonality.

References: