PERFORMANCE OF PILOT EMBEDDED OFDM SYSTEMS IN SIMULTANEOUS MULTI-USER TRANSMISSIONS

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ABSTRACT

Recently pilot embedding has been proposed for MIMO systems to overcome the throughput limitation implied by the training sequences. The proposed scheme relies on the simultaneous transmission of the training sequence and the information bits. We propose to evaluate this new scheme in a multi-user OFDM transmission system including synchronization and channel estimation. The receiver uses an iterative process to extract the informative bits that become training symbols for the channel estimation process. The packet error rate (PER) are evaluated and compared to the more classical preamble insertion and to the known channel cases.

1. INTRODUCTION

In [6], the idea of embedding pilot symbols for multiple input multiple output (MIMO) communications is proposed for a point to point system using a serially concatenated turbo-code. In this contribution a similar pilot embedding system is evaluated for a multi-user OFDM system relying on 802.11a/HiperLAN2 waveforms (using the same channel coding, signal shaping,...). Two advantages are foreseen for such a technique: rate increase and synchronization issues. The rate advantage is straightforward as all the time is dedicated to useful symbol transmission. The synchronization advantage comes from the fact that transmitters do not need a frame synchronization for the channel estimation to perform accurately unlike the classical pilot insertion system. Thus if one user transmits a long frame, the other users can transmit smaller packets during the same frame duration. An OFDM symbol synchronization is nevertheless required to avoid inter symbol interference (ISI). A drawback of pilot embedding is that it can lead to higher transmission power and thus to amplifier back-off. This drawback can be mitigated by lowering the pilot power level.

The advantage of OFDM the modulation in such scenarios is the possibility to detect the symbols transmitted by each user or antenna on each sub-carrier ignoring the ISI as in the single user case, and limiting the receivers task to the inter user interference removal.

In [4], multi-user receivers were presented for the up-link of OFDM systems. In [3], the performance of some of these receivers have been evaluated using a maximum likelihood channel estimator. Previously, the performance for OFDM modulations of spatial filtering techniques including channel estimators had been proposed in [5]. In this last reference, the channel estimation is performed in the frequency domain relying on pilot tones.

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This paper proposes the performance of iterative joint detection receivers applied to OFDM waveforms (802.11a) using pilot embedding schemes and including the synchronization and the channel estimation. The proposed scheme relies on an initial temporal channel estimation providing accurate timing and impulse response estimation. The iterative channel estimation are calculated in the frequency domain on decided (hard) symbols to limit the complexity. The achieved performance with this simple scheme are close to the performance achieved when the channel is known.

In the next section, the signal model for a multi-user transmission is proposed. In section 3 the turbo joint detection receiver is described including the channel estimator and in section 4 the performance of the receiver are proposed. At last, in section 5 we conclude and present some perspectives.

2. SIGNAL MODEL

In this section, we introduce the signal model in the frequency domain for the signals received form N_u users on multi-sensor receiver with N_r antennas. In this contribution we assume that the different receivers are synchronized within the cyclic prefix (CP) of length N_{CP} samples; i.e. the delay (N_H samples) between the first received path and the last received path does not exceed the CP duration. The signal model is given by:

$$\mathbf{y} = \mathbf{F}_2 \cdot \mathbf{I}_{\bar{CP}} \cdot \mathbf{H} \cdot \mathbf{I}_{CP} \cdot \mathbf{F}_1 \cdot (\mathbf{a} + \gamma \tilde{\mathbf{a}}) + \mathbf{n} \qquad (1)$$

with $\mathbf{y}$ the vector of size $N_r N_{DFT}$ containing the samples of the (N_{DFT}) sub-carriers for all the receivers (the first N_r samples is the first snapshot from all antennas), $\mathbf{F}_2 = \tilde{\mathbf{F}}_2 \otimes \mathbf{I}_{N_r}$ where $\mathbf{I}_{N_r}$ is the identity matrix of size N_r and $\tilde{\mathbf{F}}_2$ a DFT matrix of dimension $N_{DFT} \times N_{DFT}$, $\mathbf{F}_1 = \tilde{\mathbf{F}}_1 \otimes \mathbf{I}_{N_u}$ with $\tilde{\mathbf{F}}_1$ the inverse DFT matrix of dimension $N_{DFT} \times N_{DFT}$, $\mathbf{I}_{\bar{CP}} = \tilde{\mathbf{I}}_{\bar{CP}} \otimes I_{N_r}$ with $\tilde{\mathbf{I}}_{\bar{CP}}$ is the matrix of dimension $N_{DFT} \times (N_{DFT} + N_{CP} + N_H)$ that does the synchronization and suppresses the CP, $\mathbf{H}$ is the multi-user channel matrix, $\mathbf{I}_{CP} = \tilde{\mathbf{I}}_{CP} \otimes \mathbf{I}_{N_u}$ with $\tilde{\mathbf{I}}_{CP}$ the $(N_{DFT} + N_{CP}) \times N_{DFT}$ matrix inserting the CP, $\mathbf{a}$ is the vector of size $N_{DFT} N_u$ containing the transmitted coded symbols (zeros values for non loaded sub-carriers), $\tilde{\mathbf{a}}$ contains the training symbols, γ is a constant determining the pilot power level and $\mathbf{n}$ is the vector containing the samples of the noise supposed to be white in the spatial and frequency domains of variance σ^2.

When the system is synchronized the matrix $\bar{\mathbf{H}} = \mathbf{I}_{\bar{CP}} \cdot \mathbf{H} \cdot \mathbf{I}_{CP}$ is bloc circulant and thus it can be written as $\bar{\mathbf{H}} = \mathbf{F}^* \Lambda \mathbf{F}$ where $\mathbf{F}$ is a DFT matrix and Λ is a bloc diagonal matrix

given by:

$$\Lambda = \begin{bmatrix} \mathbf{H}_1 & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \mathbf{H}_{N_u} \end{bmatrix}$$

where $\mathbf{H}_i$ is the matrix of dimension $N_r \times N_u$ containing the channel coefficients for the sub-carrier i. Thus the expression of the observation is given by $\mathbf{y} = \Lambda(\mathbf{a} + \gamma\tilde{\mathbf{a}}) + \mathbf{n}$. Recall this signal model is valid when the different received signals do not have frequency shifts and the time delay between first received path and the last received path does not exceed the length of the cyclic prefix (see [2] when a frequency offset exists). Thus for the sub-carrier i the observation reduces to:

$$\mathbf{y}_i = \mathbf{H}_i(\mathbf{a}_i + \gamma\tilde{\mathbf{a}}_i) + \mathbf{n}_i \tag{2}$$

where $\mathbf{y}_i$ is the vector of size N_r containing the samples of the received signal on the array of sensors for the sub-carrier i ($\mathbf{y} = \left[\mathbf{y}_1^T, \cdots, \mathbf{y}_{N_{DFT}}^T\right]^T$, $\mathbf{n} = \left[\mathbf{n}_1^T, \cdots, \mathbf{n}_{N_{DFT}}^T\right]^T$) and $\mathbf{a}_i$ contains the transmitted symbols on the sub-carrier i by the different users ($\mathbf{a} = \left[\mathbf{a}_1^T, \cdots, \mathbf{a}_{N_{DFT}}^T\right]^T$ with $\mathbf{a}_i^T = \left[a_i^1, \cdots, a_i^{N_u}\right]$ the same holds for $\tilde{\mathbf{a}}_i$). Using the linear model of equation (2), the joint detection techniques can be applied carrier-wise.

3. RECEIVER AND CHANNEL ESTIMATOR

In this section the turbo joint detector, the channel estimators and their interactions are presented. The turbo receiver is an all MAP (maximum a posteriori) receiver, i.e. at all stages the MAP detector is used (demodulator, demapping, decoding). The initial channel estimator is a temporal maximum likelihood channel estimator estimating the synchronization and the channel impulse response [3]. For complexity reduction, the iterative channel estimator is performed per sub-carrier in the frequency domain and relies on decided symbols. The advantage of the initial temporal channel estimate is its accuracy in both timing and impulse response estimation thus accelerating the convergence of the iterative process.

The general description of the receivers structure is depicted on figure 1.

3.1 Detector

At first a joint detection of the transmitted symbols is performed following the MAP criterion. As a channel estimate is available, the training sequences are subtracted from the observation prior to the detection. The new observation is given by: $\tilde{\mathbf{y}} = \mathbf{y}_i - \gamma\hat{\mathbf{H}}_i\tilde{\mathbf{a}}_i$. As the channel estimate is not perfect ($\hat{\mathbf{H}} = \mathbf{H} + \tilde{\mathbf{H}}$), the new observation is given by $\tilde{\mathbf{y}} = \mathbf{H}\mathbf{a} + \mathbf{n} - \gamma\tilde{\mathbf{H}}\tilde{\mathbf{a}} = \mathbf{H}\mathbf{a} + \tilde{\mathbf{n}}$ were $\tilde{\mathbf{n}}$ is considered as AWGN. The MAP computes the APP (a posteriori probabilities) $P(a_i^u = a|\tilde{\mathbf{y}}_i)$ knowing $P(a_i^u)$ from previous decoding. At the initial phase, we have $P(a_i^u) = \frac{1}{2}$. The users symbols are independent we have $P(\mathbf{a}_i) = \prod_{u=1}^{N_u} P(a_i^u)$. Thus the joint demodulation computes:

$$P(a_i^u = a^k|\tilde{\mathbf{y}}_i) \propto \sum_{\mathbf{a}_i \in A^k} e^{-\frac{1}{\sigma^2}\|\tilde{\mathbf{y}}_i - \mathbf{H}_i\mathbf{a}_i\|^2} \cdot P(\mathbf{a}_i)$$

where $A^k = \left\{\mathbf{a}_i / a_i^u = a^k\right\}$. These probabilities are then provided to the demapper. For presentation simplification we drop the carrier index i as we consider the sub-carriers are independent. The demapper outputs the LLR (log - likelihood ratio) of the coded bits c_k^u to which are subtracted from the a priori LLR:

$$L_D(c_k^u) \quad = \quad \ln \frac{\sum_{a \in A_-^k} P(a|\tilde{\mathbf{y}}_i)}{\sum_{a \in A_-^k} P(a|\tilde{\mathbf{y}}_i)} - \ln \frac{P(c_k^u = +1)}{P(c_k^u = -1)}$$

where A_+^k is the set of symbols for which the kth bit is 1 and A_-^k is the set of symbols for which the kth bit is -1. The a priori LLR $\ln\left(\frac{P(c_k^u=+1)}{P(c_k^u=-1)}\right)$ is given by the previous MAP channel code decoding stage and is null at the initial iteration. At last, after de-interleaving, the $L_D(c_k^u)$ values feed N_u BCJR MAP decoders [1] that provide the LLR for the coded bits c_k^u and the LLR for the useful bits b_k^u (figure 1). The L values of the coded bits are:

$$L_C(c_k^u) = \ln \frac{P(c_k^u = +1|\left\{L_D(c_k^u)\right\}_{|k})}{P(c_k^u = -1|\left\{L_D(c_k^u)\right\}_{|k})} - \ln \frac{P(c_k^u = +1)}{P(c_k^u = -1)}$$

and are fed back to a stage that computes the symbol a priori provided to the MAP joint detector.

3.2 Channel estimator

The channel estimation proceeds in two steps, the initial channel estimation and the iterative channel estimation. The initial channel estimation is performed in the temporal domain where the synchronization and the channel impulse response are estimated jointly for all the users. The iterative channel estimate operates in the frequency domain using the a priori information issued by the channel decoder. The channel is estimated recursively as in [6] to enhance the performance of the receiver.

3.2.1 Temporal channel estimation

This first channel estimate [3] is used to perform an initial estimate of the transmitted symbols. The synchronization is not re-estimated in the iterative process due both to the complexity it induces and the good performance achieved with the initial estimate.

The temporal channel estimator (first channel estimation) is a maximum likelihood channel estimator relying on the embedded pilot symbols The useful data symbols are considered as AWGN. The samples are stacked in a $N_s \times N_r$ matrix $\mathbf{X}$:

$$\mathbf{X} = \mathbf{S}(\tau)\Gamma + \mathbf{N}$$

where the $N_s \times N_{CP}N_u$ matrix $\mathbf{S}(\tau)$ contains the known samples of the pilot sequence shifted by the unknown delay (τ) and the $N_u \times N_r$ matrix Γ contains the channel (temporal) impulse responses for all the users. The matrix $\mathbf{N}$ of dimension $N_s \times N_r$ contains the samples of the AWGN and the useful data signals. The noise matrix $\mathbf{N}$ is modeled as AWGN . The matrix $\mathbf{S}(\tau)$ is organized as follows:

$$\mathbf{S}(\tau) = [\mathbf{S}_1(\tau) \cdots \mathbf{S}_{N_u}(\tau)]$$

with the $N_s \times N_{CP}$ matrix $\mathbf{S}_u(\tau)$ is given by $\mathbf{S}_u(\tau) =$

$$\begin{bmatrix} s_u(LT_e - \tau) & & s_u(-\tau) \\ \vdots & \ddots & \vdots \\ s_u(N_sT_e - \tau) & & s_u((N_s - L + 1)T_e - \tau) \end{bmatrix}$$

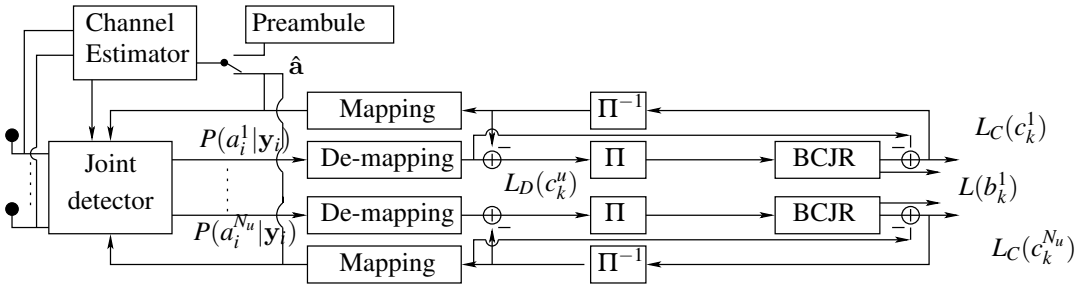

Figure 1: General scheme of the turbo receiver

where $s_u(t)$ is the known embedded pilot sequence for user u, T_e the sample period and N_s the number of samples.

With the previous model of the received signal, the likelihood of the observation can be derived:

$$L(\mathbf{X}|\tau,\Gamma,\sigma^2) \propto -N_u N_r \log(\sigma^2) - \frac{1}{\sigma^2}\|\mathbf{X}-\mathbf{S}(\tau)\Gamma\|^2$$

We consider that the noise and the impulse response are nuisance parameters. Nulling the derivative of the likelihood, we obtain the following estimators:

$$\begin{aligned}\widehat{\sigma}^2 &= \frac{1}{N_u N_r}\|\mathbf{X}-\mathbf{S}(\tau)\Gamma\|^2 \\ \widehat{\Gamma} &= (\mathbf{S}^\dagger(\tau)\mathbf{S}(\tau))^{-1}\mathbf{S}^\dagger(\tau)\mathbf{X}\end{aligned}$$

Replacing in the log-likelihood the nuisance parameters by their estimates leads to the estimator of the global synchronization:

$$\widehat{\tau} = \arg\min_{\tau}\left\|\Pi_{\mathbf{S}}^{\perp}(\tau)\mathbf{X}\right\|^2$$

where $\Pi_{\mathbf{S}}^{\perp}(\tau)$ is the projector on the noise sub-space given by:

$$\Pi_{\mathbf{S}}^{\perp}(\tau) = \mathbf{I} - \mathbf{S}(\tau)(\mathbf{S}^\dagger(\tau)\mathbf{S}(\tau))^{-1}\mathbf{S}^\dagger(\tau)$$

This first estimate is thus used to perform the initial symbol synchronization and impulse response estimation. The same temporal synchronization is used to re-estimate the channel in the frequency domain.

3.2.2 Frequency domain channel estimation

The second channel estimation is thus performed in the frequency domain using the N OFDM symbols of the burst. The signal model is given by equation (2) and the per sub-carrier channel estimate is given by:

$$\hat{\mathbf{H}} = \mathbf{Y}\hat{\mathbf{A}}^H\left(\hat{\mathbf{A}}\hat{\mathbf{A}}^H\right)^{-1}$$

where $\hat{\mathbf{A}} = \left[\hat{\mathbf{a}}^1+\gamma\tilde{\mathbf{a}}^1,\cdots,\gamma\hat{\mathbf{a}}^N+\gamma\tilde{\mathbf{a}}^N\right]$ is the estimated symbols on the carrier of interest and $\mathbf{Y} = \left[\mathbf{y}^1,\cdots,\mathbf{y}^N\right]$ with $\hat{\mathbf{a}}^n$ the vector of the estimated users symbols for the nth OFDM symbol.

4. PERFORMANCE

The performance presented hereafter have been realized with the 802.11a parameters, channel code (133,171) and interleaver: $N_{SC} = 52$, $N_{DFT} = 64$, $N_{CP} = 16$, $N_H = 16$. We chose $N_{CP} = N_H$ random Rayleigh channel samples and the channels are normalized. The signals arrive at the receiver with sufficient symbol synchronization i.e. $\tau_{max} - \tau_{min} \leq N_{CP}$ with τ_{max} the last received path and τ_{min} the first received path. The propagation channel is constant over a burst and each burst contains 40 useful BPSK symbols. The embedded pilot symbols (known symbols) are random BPSK symbols and change at each burst for each user.

The performance of the turbo receiver are proposed for a 3 transmitters 3 receivers scenario in different cases (known channel, preamble inserted, pilot embedded). Each curve represents the PER at the output of the channel decoder for each iteration.

Figure 2 gives the PER for the known propagation channel (left figure) and the classical preamble insertion scheme (right figure). For the preamble based system 4 additional random OFDM symbols are inserted, the other parameters and receiver parts being similar. The preamble symbols are used in the iterative channel estimation offering a potential advantage to this system. Figure 3 presents the performance of the pilot embedding system with a pilot power 8 time lower than the useful data (left figure) and the pilot embedding system with the pilot power 10 time lower than the useful data (right figure). The achieved performance by the systems estimating the propagation channel (preamble and pilot embedding) are similar and result in a $0.6dB$ loss in Eb/No to achieve a 10^{-3} PER compared to the known channel case. Notice that to converge, the pilot embedding system requires an additional iteration compared to the preamble inserted system. At last notice that for the pilot embedded system the first iteration has a dramatic performance loss. It is due to the fact that the channel is estimated on the embedded pilot symbols with the useful part of the signal considered as noise.

On figure 4, the difference (in dB) of the required Eb/No to achieve the 10^{-3} PER for both systems (pilot embedded and preamble insertion) is plotted as a function of the power penalty induced by the pilot insertion. We can see that up to a power ratio between the useful data and the pilot sequence of 8 (power penalty or additional back-off of $0.5dB = 10log10(1+1/power\,ratio)$) the Eb/No loss when compared to pilot insertion system is negligible. Also notice that when the pilot has equivalent or even higher power than the useful data, a little performance gain is possible. On the other hand, when the pilot power is to small compared to the useful part of the signal, the performance degrade rapidly.

In the studied system, the throughput is increased of 10% when only not needing to transmit the preamble and an addi-

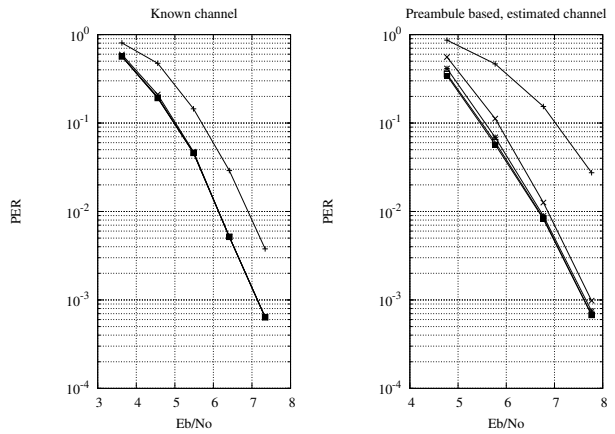

Figure 2: Performance of the known channel case (left) and the classical preamble insertion system

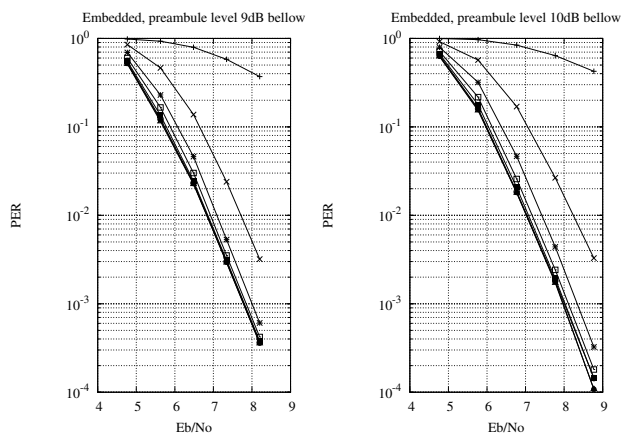

Figure 3: Performance of the pilot embedded system with pilot power 8 times lower than the useful data (left) and 10 times lower (right)

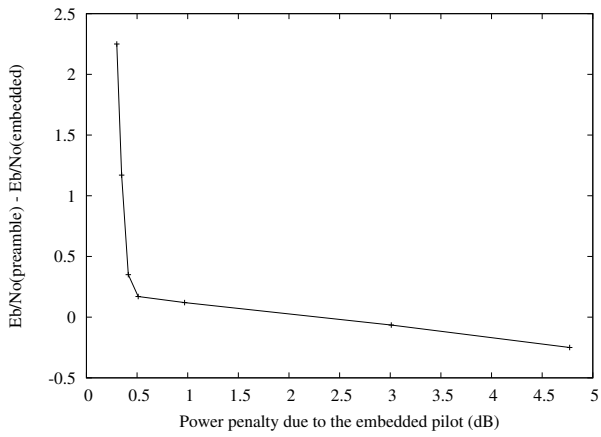

Figure 4: Eb/No difference (in dB) between pilot the embedded system and the preamble inserted system as a function of the power transmission increase.

tional 8% if not transmitting the 4 pilot tones generally used for frequency synchronization.

5. CONCLUSION

We have evaluated the recently proposed pilot insertion system on a multi-user OFDM system including the synchronization. The performance degradation brought by the pilots embedding has been evaluated by comparing required Eb/No to achieve a given PER. We have shown that in our case, with small packets, the performance degradation with low power level pilots is small but bring a system through increase.

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