Iterative Decoding and Channel Estimation of MIMO-OFDM Transmissions with Hierarchical Constellations and Implicit Pilots

Nuno Souto[1], *Rui Dinis*[2], *João Carlos Silva*[1]

[1] ISCTE / Instituto de Telecomunicações/ADETTI, Lisboa, Portugal, nuno.souto@lx.it.pt, joao.carlos.silva@lx.it.pt,
[2] ISR/IST, Lisboa, Portugal, rdinis@ist.utl.pt

ABSTRACT

In this paper we consider the use of M-QAM hierarchical constellations (Quadrature Amplitude Modulation) combined with implicit pilots for the transmission of multicast and broadcast services in a MIMO-OFDM (Multiple Input Multiple Output - Orthogonal Frequency Division Multiplexing) system. This method of pilot transmission allows coherent detection at the receiver while avoiding the spectral degradation associated with the usual pilot multiplexing techniques but results in mutual interference between pilots and data. Due to the demanding channel estimation requirements and the high sensitivity to interference resulting from the usage of several antennas and hierarchical constellations, an enhanced receiver based on the turbo concept is developed which is capable of dealing with the inherent interference between pilots and data.[1]

Keywords- *OFDM, iterative decoding, implicit pilots.*

I. INTRODUCTION

It is widely recognized that OFDM modulations (Orthogonal Frequency Division Multiplexing) [1] are suitable for broadband wireless systems. For this reason they were selected for several digital broadcast systems and wireless networks and are being considered for UTRA (Universal Mobile Telecommunications System Terrestrial Radio Access) Long Term Evolution (LTE) [2]. Regarding LTE UTRA, special attention is being devoted to the support of Multimedia Broadcast and Multicast Service (MBMS) which has already been standardized in 3GPP UTRAN (UTRA Network) Release-6 [3]. The goal is to enable an efficient support of downlink streaming (from the base station to the mobile terminal) and download-and-play type services to large groups of users. From the radio perspective, MBMS includes point-to-point (PtP) and point-to-multipoint (PtM) modes.

With these objectives in mind, it seems attractive to employ hierarchical modulations for broadcast and multicast OFDM transmissions since it is a simple and flexible enhancement technique that can increase the transmission efficiency. With this type of constellations there can be several classes of bits with different error protection, to which different streams of information can be mapped. Depending on the propagation conditions, a given user can attempt to demodulate only the more protected bits or also the bits that carry the additional information. This type of approach is possible whenever the information can be scalable like the cases of coded voice or video signals [4][5]. For this reason hierarchical 16/64-QAM constellations have already been incorporated into DVB-T (Digital Video Broadcasting - Terrestrial) standards [6].

Multiple-input multiple-output (MIMO) schemes have emerged as one of the most promising methods for capacity increase in a communication system [7][8]. In MIMO systems with coherent detection the channel estimation plays a crucial role since the performance of the spatial signal processing in the receiver depends on the accuracy of the channel estimates. Typically, these estimates are obtained with the help of training symbols that are multiplexed with the data, either in the time domain or in the frequency domain [9],[10]. This approach can result in an inefficient use of the available bandwidth which is of crucial importance for any communication system. Therefore it is desirable to reduce the overheads required for channel estimation purposes. An alternative method was proposed in [11][12] and relies on the idea of pilot embedding where a pilot sequence is summed to the data sequence and transmitted simultaneously. This approach, usually referred to as implicit pilots transmission, demands that some of the power be spent on the pilot sequence but allows us to increase significantly the pilots' density without sacrificing system capacity. In fact, we can have a pilot for each data symbol. One of the problems in these type of pilot transmission techniques relies on the interference levels between data and pilots which might be high, specially when employing multiple antennas since each pilot symbol will be affected by interference of several data symbols simultaneously. As a result this can lead to irreducible noise floors. Moreover, there is also interference on the data symbols due to the pilots, leading also to performance degradation.

In this paper we consider the use of QAM hierarchical constellations combined with implicit pilots in a OFDM system with multiple antennas at the transmitter and at the receiver aimed at improving the transmission rate. In order to deal with the problem of mutual interference between pilots and data we propose an iterative receiver capable of performing joint MIMO detection and channel estimation. In the first iteration, the channel is estimated by averaging the received signal (data plus pilots) over several OFDM blocks. For the subsequent iterations we remove the undesirable signal (pilots or data) using the most updated version of it before the estimation and detection phases. Channel estimates can be further refined by considering the data symbols as extra pilots. In the receiver different MIMO equalization techniques can be employed during the iterative process.

II. SYSTEM DESCRIPTION

A. M-QAM hierachical Signal Constellations

In hierarchical constellations there are two or more classes of bits with different error protection and to which different streams of information can be mapped. By using non uniformly spaced signal points (where the distances

[1] This work was elaborated as a result of the participation in the C-MOBILE project (IST-2005-27423).

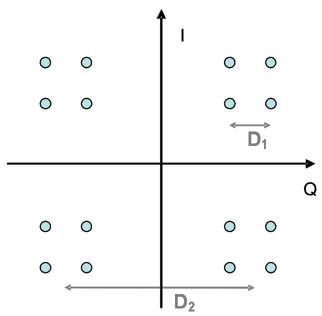

Figure 1. Non-uniform 16-QAM hierarchical constellation.

along the I or Q axis between adjacent symbols are different) it is possible to modify the different error protection levels. As an example, a non-uniform 16-QAM constellation can be constructed from a main QPSK constellation where each symbol is in fact another QPSK constellation (Figure 1). This constellation can be viewed as a 16-QAM constellation if the channel conditions are good enough or as a QPSK constellation otherwise. In the latter case, the received bit rate is reduced to half. These constellations can be characterized by the parameter $k=D_1/D_2$ ($0<k\leq 0.5$). If $k=0.5$, the resulting constellation corresponds to a uniform 16-QAM. This approach can be naturally extended to any M-sized QAM constellation, where the number of possible classes of bits with different error protection is $1/2\cdot\log_2 M$.

B. Transmitted Signals

In Figure 2 we show a transmitter chain that incorporates QAM hierarchical constellations into an MIMO-OFDM transmission with implicit pilots. In this scheme, there are $1/2\cdot\log_2 M$ parallel chains for the different input bit streams that will have unequal error protection. For example, for 16-QAM we can use two parallel chains. Each stream is encoded, interleaved and mapped into the constellation symbols according to the importance attributed to it. Pilot symbols are directly added to the modulated data symbols and the resulting sequence is converted to the time domain using an IDFT (Inverse Discrete Fourier Transform). The resulting stream is then split into several smaller streams that are transmitted simultaneously by M_{tx} antennas.

In this paper we consider the frame structure of Figure 3 for a MIMO-OFDM system with N carriers. According to this structure, the implicit pilots are generated using a grid with a spacing of ΔN_T symbols in the time domain and ΔN_F symbols in the frequency domain. To avoid interference between implicit pilots of different transmitting antennas, FDM (Frequency Division Multiplexing) is employed for the pilots, which means that pilot symbols cannot be transmitted over the same subcarrier in different antennas. Therefore, the minimum allowed spacing in the frequency domain is $\left(\Delta N_F\right)_{\min}=M_{tx}$. The transmitted sequences are thus given by

$$X_{k,l}^{m}=S_{k,l}^{m}+S_{k,l}^{m,Pilot}, \qquad (1)$$

where, $S_{k,l}^{m}$ is the data symbol transmitted by the kth subcarrier of the lth OFDM block using antenna m, and $S_{k,l}^{m,Pilot}$ is the corresponding implicit pilot. The resulting sequences are converted to the time domain through the usual process, $\left\{x_{i,l}^{m}, i=0,1,...,N-1\right\}$=IDFT{ $X_{k,l}^{m}$, k = 0,1,…,N-1}, before being transmitted. The transmitted OFDM signals are then expressed as

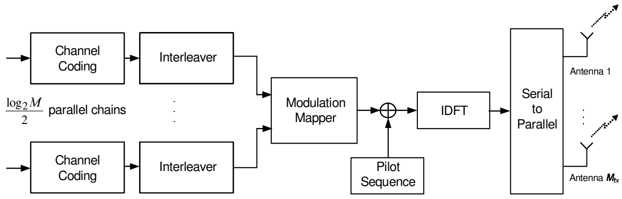

Figure 2. Transmitter chain.

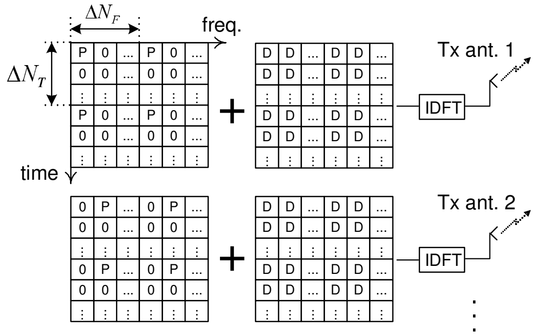

Figure 3. Proposed frame structure for a MIMO-OFDM transmission with implicit pilots (P – pilot symbol, D – data symbol).

$$x^{m}\left(t\right)=\sum_{l}\sum_{i=-N_G}^{N-1}x_{i,l}^{m}\cdot h_T\left(t-i\cdot T_s\right), \qquad (2)$$

with T_s denoting the symbol duration, N_G the number of samples at the cyclic prefix ($x_{-i,l}^{m}=x_{N-i,l}^{m}$, i= 1,...,$N_G$) and $h_T(t)$ the adopted pulse shaping filter.

III. ITERATIVE RECEIVER

A. Receiver Structure

To reduce the mutual interference between pilots and data, which will be particularly high in MIMO systems, and achieve reliable channel estimation and data detection we propose a receiver whose structure is shown in Figure 4. According to the figure, the signal arriving at each of the N_{rx} antennas, which is considered to be sampled and with the cyclic prefix removed, is converted to the frequency domain with an appropriate size-N DFT operation. If the cyclic prefix is longer than the overall channel impulse response the resulting sequence can be expressed as

$$R_{k,l}^{n}=\sum_{m=1}^{M_{tx}}\left(S_{k,l}^{m}+S_{k,l}^{m,Pilot}\right)H_{k,l}^{m,n}+N_{k,l}^{n}\ , \qquad (3)$$

with $H_{k,l}^{m,n}$ denoting the overall channel frequency response between transmit antenna m and receiving antenna n for the kth frequency of the lth time block and $N_{k,l}^{m}$ denoting the corresponding channel noise. The pilot symbols are then removed from the sequence resulting

$$\left(Y_{k,l}^{n}\right)^{(q)}=R_{k,l}^{n}-\sum_{m=1}^{M_{tx}}S_{k,l}^{m,Pilot}\left(\hat{H}_{k,l}^{m,n}\right)^{(q)}\ , \qquad (4)$$

where $\left(\hat{H}_{k,l}^{m,n}\right)^{(q)}$ is the channel frequency response estimate and q is the current iteration. Since only one of the antennas can transmit a pilot in each carrier the summation in (4) has only one term. The sequences of samples (4) enter the spatial demultiplexer block which can apply an ML (Maximum Likelihood) based equalizer, a MMSE (Minimum Mean Squared Error) equalizer, a ZF (Zero Forcing) equalizer or a RAKE with an interference canceller (IC) [13] for extracting the simultaneous transmitted streams. Different equalization

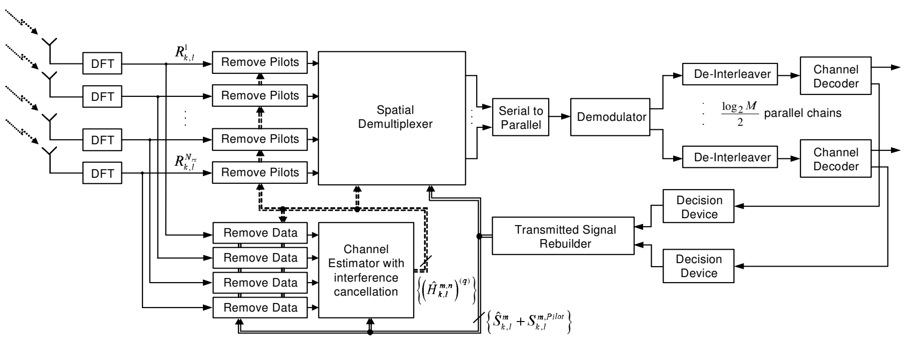

Figure 4. Iterative receiver structure.

methods can be used in each receiver iteration, as was studied in [13]. The demultiplexed symbol sequences are then serialized, demodulated, de-interleaved and enter the channel decoder which has two outputs. One is the estimated information sequence and the other is the sequence of log-likelihood ratio (LLR) estimates of the code symbols. These LLRs pass through the Decision Device which outputs soft-decision of the code symbols that enter into the Transmitted Signal Rebuilder block. The resulting reconstructed symbol sequences can then be used for a refinement of the channel estimates and possible improvement of the spatial demultiplexing task (in case of employing a RAKE with IC) in the subsequent iteration.

B. *Channel Estimation*

To obtain the frequency channel response estimates for each transmitting/receiving antenna pair the receiver applies the following steps in each iteration:

(1) Data symbols estimates are removed from the pilots using

$$\left(\tilde{R}^{n}_{k,l}\right)^{(q)} = R^{n}_{k,l} - \sum_{m'=1}^{M_{tx}} \left(\hat{S}^{m'}_{k,l}\right)^{(q-1)} \left(\hat{H}^{m,n}_{k,l}\right)^{(q-1)}, \qquad (5)$$

where $\left(\hat{S}^{m'}_{k,l}\right)^{(q-1)}$ and $\left(\hat{H}^{m,n}_{k,l}\right)^{(q-1)}$ are the data and channel response estimates of the previous iteration. This step can only be applied after the first iteration. In the first iteration we set $\left(\tilde{R}^{n}_{k,l}\right)^{(1)} = R^{n}_{k,l}$.

(2) The channel frequency response estimates is computed using a moving average with size W as follows:

$$\left(\tilde{H}^{m,n}_{k,l}\right)^{(q)} = \frac{1}{W} \sum_{l'=l-\lfloor W/2 \rfloor}^{l+\lceil W/2 \rceil-1} \frac{\left(\tilde{R}^{n}_{k,l'}\right)^{(q-1)}}{S^{m,Pilot}_{k,l'}}. \qquad (6)$$

(3) After the first iteration the data estimates can also be used as pilots for channel estimation refinement.

(4) The channel estimates are enhanced by ensuring that the corresponding impulse response has a duration N_G. This is accomplished by computing the time domain impulse response through $\{\left(\tilde{h}^{m,n}_{i,l}\right)^{(q)}$; i=0,1,…,N-1}= DFT{$\left(\tilde{H}^{m,n}_{k,l}\right)^{(q)}$; k=0,1, …,N-1}, followed by the truncation of this sequence according to {$\left(\hat{h}^{m,n}_{i,l}\right)^{(q)} = w_i \left(\tilde{h}^{m,n}_{i,l}\right)^{(q)}$; i=0,1,…,N-1} with $w_i = 1$ if the ith time domain sample is inside the cyclic prefix duration and $w_i = 0$ otherwise. The final frequency response estimates are then obtained as {$\left(\hat{H}^{m,n}_{k,l}\right)^{(q)}$; k=0,1,…,N-1}= IDFT{$\left(\hat{h}^{m,n}_{i,l}\right)^{(q)}$; i=0,1,…,N-1}.

IV. NUMERICAL RESULTS

To study the behaviour of the proposed OFDM scheme and respective iterative receiver, several simulations were performed for a 16-QAM hierarchical constellation which has two classes of bits with different error protection available. Each individual information stream was encoded with a block size of 3584 bits. The channel impulse response is based on the Vehicular A environment from [14]. Uncorrelated Rayleigh fading was assumed for the different paths and a velocity of 30 km/h was considered. The number of carriers employed was N=256, each carrying a QAM data symbol. The channel encoders were rate-1/2 turbo codes based on two identical recursive convolutional codes with two constituent codes characterized by G(D)=[1 $(1+D^2+D^3)/(1+D+D^3)$] [15]. A random interleaver is employed within the turbo encoder. Most of the BER (Bit Error Rate) results presented next will be shown as a function of E_S/N_0, where E_S is the average symbol energy and N_0 is the single sided noise power spectral density. Unless otherwise stated, the pilot symbols spacing is the minimum possible, i.e., $\Delta N_T = 1$ and $\Delta N_F = M_{tx}$. The moving average window size used was W=12.

As explained previously, the iterative receiver can employ different MIMO decoding techniques in different iterations. Figure 5 compares the results accomplished with different MIMO decoding methods for a 2×2 transmission employing a 16-QAM (with k_l=0.4) hierarchical constellation. Perfect channel estimation is assumed. In the legend "N1turbo/N2DEC1/N3DEC2/" represents the sequence of MIMO equalization methods in each receiver iteration and the number of turbo decoding iterations. N1 is the number of turbo decoding iteration per receiver iteration, N2 is the number of total receiver iterations that employed DEC1 decoding method, N3 is the total number of receiver iterations that employed DEC2 decoding method, and so on. DEC1, DEC2,…, can be either ML, MMSE or IC (RAKE with interference cancellation). Also in the legend, MPB designates Most Protected Bits while LPB corresponds to Least Protected Bits. Comparing the results obtained when applying a ML or a MMSE equalizer alone, with those obtained when applying also an IC in the last receiver iterations it is clear that the performance can be improved using this last approach. As expected, the best performance is accomplished when a ML equalizer is applied in the first iteration but it is important to note that the ML equalizer is more complex than the MMSE. For the remainder of the paper the receiver configuration considered will be 3turbo/2MMSE/2IC.

Figure 6 presents BER results obtained for a MIMO 2×2 transmission considering different values of power ratio β_P which is defined as $\beta_P = E\left[\left|S^{m,Pilot}_{k,l}\right|^2\right] \Big/ E\left[\left|S^{m}_{k,l}\right|^2\right]$ (averaged

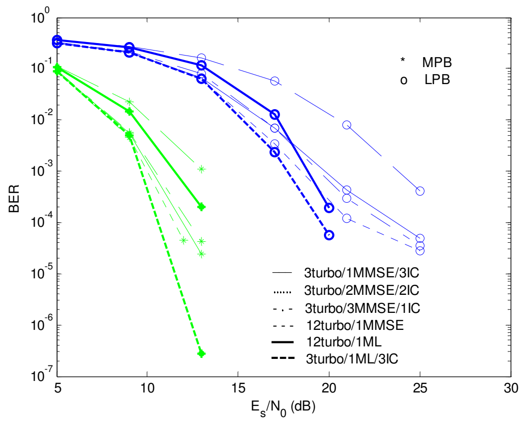

Figure 5. Performance of a 16-QAM (k_l=0.4) hierarchical constellation with perfect channel estimation. (MIMO 2×2)

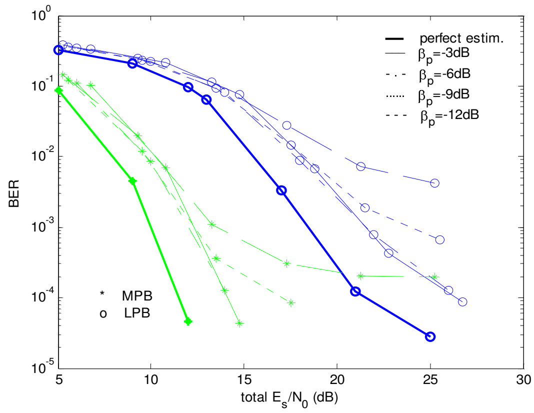

Figure 6. Performance of a 16-QAM (k_l=0.4) hierarchical constellation for different β_P values. (MIMO 2×2)

over all positions k and l). The curves are plotted as a function of total E_S/N_0 which includes the power spent on the pilots. From the results we can conclude that if the power of the pilots is too low (for example β_P=-9dB or β_P=-12dB) then the interference of the data symbols and noise result in inaccurate channel estimates causing a BER increase. When the pilots' power is increased, the channel estimates become more accurate and the performance improves. However this can also result in a high penalty in the total E_S/N_0 required to achieve a specific BER and the overall performance can start deteriorating as can be seen if we compare the curves for β_P =-3dB and β_P =-6dB. Figure 7 shows the BER results obtained for the LPB of a 16-QAM (with k_l=0.4) hierarchical constellation considering different pilots spacings in a MIMO 2×2 transmission. The same overall average power ratio of β_P=7.8dB was used in all cases. It is visible that instead of using a very dense pilot distribution it can be advantageous to use a more spaced pilot grid with stronger powers (but same overall average power), since only some of the data symbols will be suffering from interference from the pilots.

V. Conclusions

In this paper we have studied a MIMO-OFDM scheme employing implicit pilots. To deal with the problem of the interference between pilots and data symbols we proposed the use of an iterative receiver capable of performing joint data detection and channel estimation. It was verified through simulations that very good performances can be obtained especially when using different MIMO decoding methods in different receiver iterations.

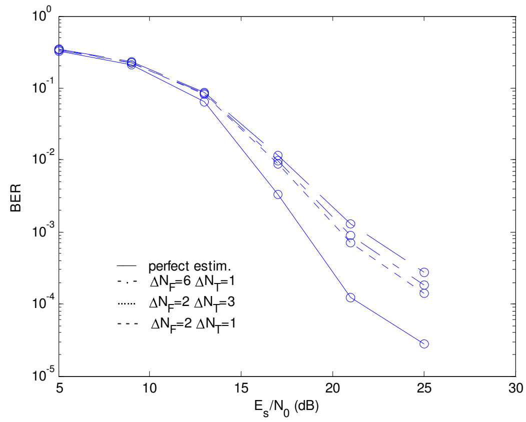

Figure 7. Performance of the LPB of a 16-QAM (k_l=0.4) hierarchical constellation for different pilot spacings. (MIMO 2×2)

VI. References

[1] L.Cimini, "Analysis and Simulation of a Digital Mobile Channel using Orthogonal Frequency Division Multiplexing", IEEE Trans. on Comm., Vol. 33, No. 7, July 1985.

[2] 3GPPP TR 25.814, "3rd Generation Partenership Project: Technical Specification Group Radio Access Network; Physical Layers Aspects for Evolved UTRA", 2006.

[3] 3GPP, 25.346 - v.6.9.0, 'Introduction of Multimedia Broadcast/Multicast Service (MBMS) in RAN', 3GPP, June 2006.

[4] T. Cover, "Broadcast channels", IEEE Trans. On Inform. Theory, vol.IT-18, pp.2-14, Jan. 1972.

[5] K. Ramchandran, A. Ortega, K. M. Uz, and M. Vetterli, "Multiresolution broadcast for digital HDTV using joint source/channel coding", IEEE J. Select. Areas Commun., vol. 11, Jan. 1993.

[6] 'Digital video broadcasting (DVB) framing structure, channel coding and modulation for digital terrestrial television (DVB-T)', Mar. 1997. ETSI, European Telecommunication Standard ETS 300 744.

[7] E. Telatar, "Capacity of multiantenna Gaussian channels," *AT&T Bell Laboratories*, *Technical Memorandum*, June 1995.

[8] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Pers.Commun.*, vol. 6, pp. 311–335, Mar. 1998.

[9] P. Hoher, S. Kaiser, and P. Robertson, "Pilot-Symbol-Aided Channel Estimation in Time and Frequency", IEEE GLOBECOM'97, pp. 90-96, 1997.

[10] F. Sanzi and J. Speidel, "An adaptive Two-dimensional Channel Estimator for Wireless OFDM with Application to Mobile DVB-T", IEEE Trans. on Broadcasting, Vol.46, pp. 128–133, Jun. 2000.

[11] B. Farhang-Boroujeny, "Pilot-based channel identification: A proposal for semi-blind identification of communication channels", *Electronics Letters*, vol.31, no. 13, pp. 1044-1046, June, 1995.

[12] A. Orozco-Lugo, M. Lara and D. McLernon, "Channel Estimation Using Implicit Training", IEEE Trans. on Signal Processing , Vol. 52, No. 1, Jan. 2004.

[13] N. Souto, R. Dinis, F. Cercas J. Silva, A. Correia "An Iterative Receiver for WCDMA Systems with MIMO Transmissions and Hierarchical Constellations", Proc. IEEE ISSSTA 2006, August 2006, Manaus, Brasil.

[14] 'Selection procedures for the choice of radio transmission technologies of UMTS', ETSI, TR 101 112 v3.2.0, Sophia Antipolis, France, 1998

[15] 3GPP, 25.212-v6.2.0, 'Multiplexing and Channel Coding (FDD)'.