Efficient Channel Estimation for OFDM Systems with Hierarchical Constellations

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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 OFDM (Orthogonal Frequency Division Multiplexing) systems. 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 QAM 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- Hierarchical Constellations, Multi-Resolution, OFDM, channel estimation, 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 [2] and are also being considered for UTRA (Universal Mobile Telecommunications System Terrestrial Radio Access) Long Term Evolution (LTE) [3]. 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 (UMTS Terrestrial Radio Access Network) Release-6 [4] and 7 [5]. 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, due to their ability to provide unequal error protection to different information bit streams. 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, as studied in [6][7]. For this reason hierarchical 16-QAM and 64-QAM constellations have already been incorporated in the DVB-T (Digital Video Broadcasting - Terrestrial) standard [8].

To accomplish coherent detection at the receiver the channel estimation task plays a crucial role since the performance of QAM constellations can be severely affected due to inaccurate channel estimates. Typically, these channel estimates are obtained with the help of training symbols that are multiplexed with the data symbols, either in the time domain or in the frequency domain [9],[10],[11]. However this type of 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 first proposed in [12] and in [13] 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.

In this paper we consider the use of QAM hierarchical constellations combined with implicit pilots in a OFDM system with the aim of supporting broadcast and multicast services. One of the problems in this type of pilot transmission techniques relies on the interference levels between the data symbols and pilots which might be high. As a consequence the channel estimates will be corrupted by the data signals and will lead to irreducible noise floors (i.e., the channel estimates can not be improved beyond a given level, even without channel noise). Moreover, there is also interference on the data symbols due to the pilots. This has an important impact on the link performance, especially for M-QAM (M>4) modulations since they are very sensitive to interference and can lead to severe performance degradation. In order to deal with this problem of mutual interference between pilots and data in this paper we propose an iterative receiver capable of performing joint 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

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detection phases. Channel estimates can be further refined by considering the data symbols as extra pilots.

In this paper, although we design a receiver for any M-QAM constellation we will evaluate in particular its performance with 16-QAM and 64-QAM hierarchical constellations. The paper is organized as follows. First Section II defines the model of the OFDM system considered in this study. In Section III the proposed iterative receiver structure and respective channel estimation process are described. Section IV presents some performance results obtained with the proposed scheme while the conclusions are given on Section V.

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 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, as shown in Figure 1.

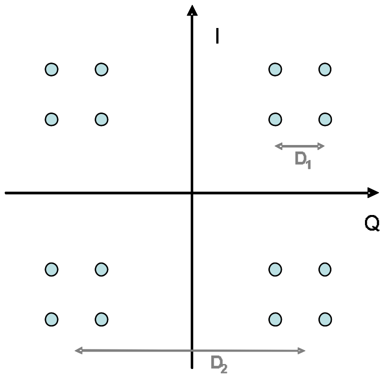

Figure 1. Non-uniform 16-QAM constellation.

The basic idea is that the 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 situation, the received bit rate is reduced to half. These constellations can be characterized by the parameter $k_1=D_1/D_2$ ($0<k_1\leq 0.5$), as shown in Figure 1. If $k_1=0.5$, the resulting constellation corresponds to a uniform 16-QAM. This approach can be naturally extended to any QAM constellation size M 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 OFDM transmission with implicit pilots. In the proposed scheme, there are $1/2\cdot\log_2 M$ parallel chains for the different input bit streams that will have unequal error protection. For 16-QAM we can use two parallel chains while for 64-QAM we can use three chains. Each stream is encoded, interleaved and mapped into the constellation symbols in the modulation mappers according to the importance attributed to the chain. Pilot symbols are then directly added to the modulated data symbols and the resulting sequence is then converted to the time domain using an IDFT (Inverse Discrete Fourier Transform).

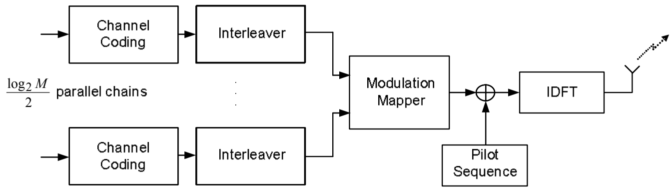

Figure 2. Transmitter chain.

We will consider the frame structure of Figure 3 for a OFDM system N carriers. According to this structure the pilot grid is generated using a spacing of ΔN_T symbols in the time domain and ΔN_F symbols in the frequency domain. The transmitted sequences are thus given by

$$X_{k,l} = S_{k,l} + S_{k,l}^{Pilot}, \tag{1}$$

where, $S_{k,l}$ is the data symbol transmitted by the kth subcarrier of the lth OFDM block and $S_{k,l}^{Pilot}$ is the corresponding implicit pilot. The resulting sequences are converted to the time domain through $\{x_{i,l}, i=0,1,...,N-1\} = \text{IDFT}\{X_{k,l}, k=0,1,...,N-1\}$. The transmitted OFDM signals can be expressed as

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

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

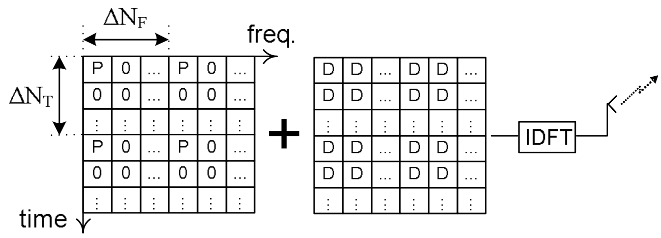

Figure 3. Frame structure for a OFDM transmission with implicit pilots (P – pilot symbol, D – data symbol).

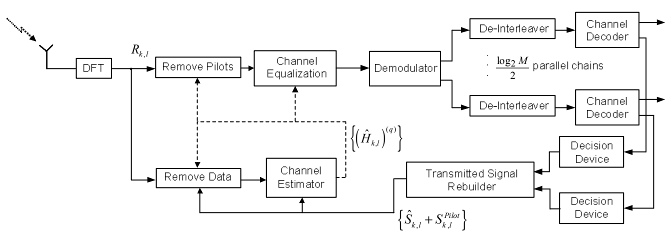

Figure 4. Iterative receiver structure.

III. Iterative Receiver

A. Receiver Structure

The transmission of pilot symbols superimposed on data will clearly result in interference between them. To reduce the mutual interference and achieve reliable channel estimation and data detection we propose a receiver capable of jointly performing these tasks through iterative processing. The structure of the proposed iterative receiver is shown in Figure 4.

According to the figure, the signal, which is considered to be sampled and with the cyclic prefix removed, is converted to the frequency domain after an appropriate size-N DFT operation. If the cyclic prefix is longer than the overall channel impulse response the resulting sequence is given as

$$R_{k,l} = \left(S_{k,l} + S_{k,l}^{Pilot}\right) H_{k,l} + N_{k,l}\,, \tag{3}$$

with $H_{k,l}$ denoting the overall channel frequency response for the kth frequency of the lth time block and $N_{k,l}$ denoting the corresponding channel noise. Before entering the equalization block, the pilot symbols are removed from the sequence resulting

$$\left(Y_{k,l}\right)^{(q)} = R_{k,l} - S_{k,l}^{Pilot}\left(\hat{H}_{k,l}\right)^{(q)}, \tag{4}$$

where $\left(\hat{H}_{k,l}\right)^{(q)}$ are the channel frequency response estimates and q is the current iteration. The equalized samples are then simply computed as

$$\left(\tilde{S}_{k,l}\right)^{(q)} = \frac{\left(\hat{H}_{k,l}\right)^{(q)*}\left(Y_{k,l}\right)^{(q)}}{\left|\left(\hat{H}_{k,l}\right)^{(q)}\right|^2}, \tag{5}$$

The sequences of equalized samples are then demodulated into the $1/2 \cdot \log_2 M$ different bit streams. These streams can be processed in parallel, passing each through a de-interleaver and a channel decoder. Each channel decoder 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 are passed through the Decision Device which outputs either soft-decision or hard decision estimates of the code symbols. These estimates enter the Transmitted Signal Rebuilder which performs the same operations of the transmitter (interleaving, modulation). The reconstructed symbol sequence can then be used for improving the channel estimates, as will be explained next, for the subsequent iteration.

B. Channel Estimation

To obtain the frequency channel response estimates the receiver applies the following steps in each iteration:

(1) Data symbols estimates are removed from the pilots. The resulting sequence becomes

$$\left(\tilde{R}_{k,l}\right)^{(q)} = R_{k,l} - \left(\hat{S}_{k,l}\right)^{(q-1)}\left(\hat{H}_{k,l}\right)^{(q-1)}, \tag{6}$$

where $\left(\hat{S}_{k,l}\right)^{(q-1)}$ and $\left(\hat{H}_{k,l}\right)^{(q-1)}$ 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 $\left(\tilde{R}_{k,l}\right)^{(1)} = R_{k,l}$.

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

$$\left(\tilde{H}_{k,l}\right)^{(q)} = \frac{1}{W}\sum_{l'=l-\lfloor W/2\rfloor}^{l+\lceil W/2\rceil-1}\frac{\left(\tilde{R}_{k,l'}\right)^{(q-1)}}{S_{k,l'}^{Pilot}}\,. \tag{7}$$

(3) After the first iteration the data estimates can also be used as pilots for channel estimation refinement. This is specially useful if the spacing of pilot symbols in the time domain is $\Delta N_T > 1$. The respective channel estimates are computed as

$$\left(\tilde{H}_{k,l}\right)^{(q)} = \frac{\left(Y_{k,l}\right)^{(q-1)}\left(\hat{S}_{k,l}\right)^{(q-1)*}}{\left|\left(\hat{S}_{k,l}\right)^{(q-1)}\right|^2} \tag{8}$$

(4) These 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 of (7) and (8) through $\{\left(\tilde{h}_{i,l}\right)^{(q)}$; $i = 0, 1, \ldots, N\text{-}1\}$ = DFT$\{\left(\tilde{H}_{k,l}\right)^{(q)}$; $k = 0, 1, \ldots, N\text{-}1\}$, followed by the truncation of this sequence according to $\{\left(\hat{h}_{i,l}\right)^{(q)} = w_i\left(\tilde{h}_{i,l}\right)^{(q)}$; $i = 0, 1, \ldots, N\text{-}1\}$ 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 simply computed using $\{\left(\hat{H}_{k,l}\right)^{(q)}$; $k = 0, 1, \ldots, N\text{-}1\}$= IDFT$\{\left(\hat{h}_{i,l}\right)^{(q)}$; $i = 0, 1, \ldots, N\text{-}1\}$.

IV. Numerical Results

To study the behaviour of the proposed OFDM scheme and respective iterative receiver, several simulations were performed for 16-QAM and 64-QAM hierarchical constellations. For 16-QAM two classes of bits with different error protection were used while for 64-QAM there were three classes of bits available. Each information stream was encoded with a block size of 3584 bits.

The channel impulse response employed is characterized by the PDP (Power Delay Profile) of Figure 5 which 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. A symbol duration of T_s=260ns was used. 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 was used within the turbo encoders. At the receiver 12 turbo decoding iterations were employed for the conventional receiver (i.e. one receiver iteration) while 4 receiver iterations each with 3 turbo decoding iterations were applied in the iterative scheme.

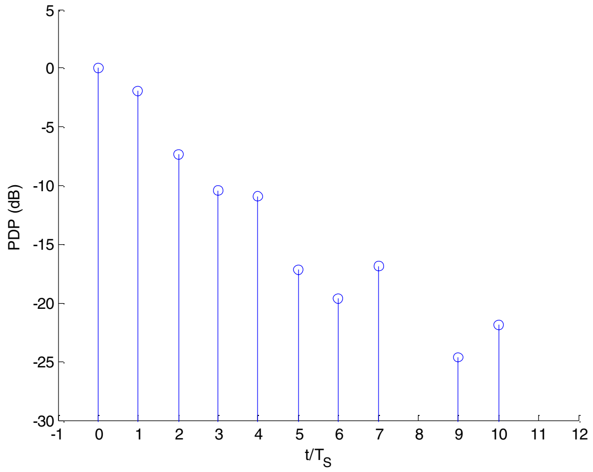

Figure 5. PDP employed in the simulations.

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.

Figure 6 and Figure 7 refer to a 16-QAM (with k_1=0.4) and a 64-QAM (with k_1=0.4 and k_2=0.4)hierarchical constellation transmission, respectively. Both figures compare the performances of the perfect channel estimation case with the cases realistic channel estimation using a conventional receiver (i.e. only one iteration) and the proposed iterative receiver. One pilot was used for each data symbols, i.e., $\Delta N_T = 1$ and $\Delta N_F = 1$, with the ratio between pilots' powers and data symbols' powers being β_P=-9dB, where

$$\beta_P = E\left[\left|S_{k,l}^{Pilot}\right|^2\right] \Big/ E\left[\left|S_{k,l}\right|^2\right]. \quad (9)$$

For channel estimation purposes, the moving average window size used was W=12. In the graphs legends, MPB designates Most Protected Bits, IPB means Intermediate Protected Bits while LPB corresponds to Least Protected Bits. Looking at the results we see that the performances of the most protected bits are very close to the perfect estimation case for both receivers. This is due to the fact the power level of the pilots is low and thus causes a low interference level in the data but at the same time allows a sufficiently accurate channel estimation due to a long average window W. However, when the level of protection of the bit streams becomes lower these bits become more sensitive to interference. In this situation the performance of the conventional receiver starts to deteriorate and only the iterative receiver is able to keep the performances close to the perfect channel estimation case.

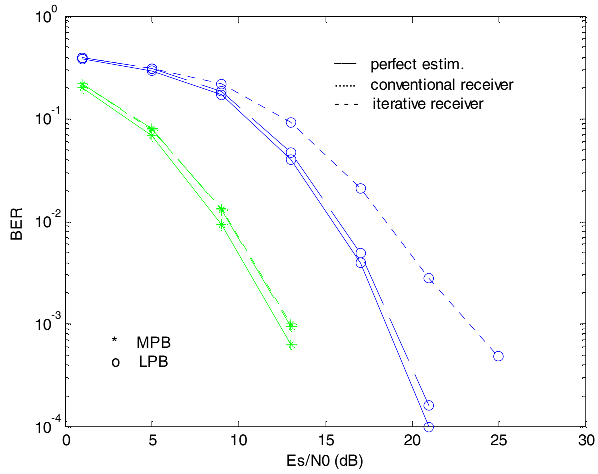

Figure 6. BER performance of a 16-QAM (k_1=0.4) hierarchical constellation with a conventional and an iterative receiver.

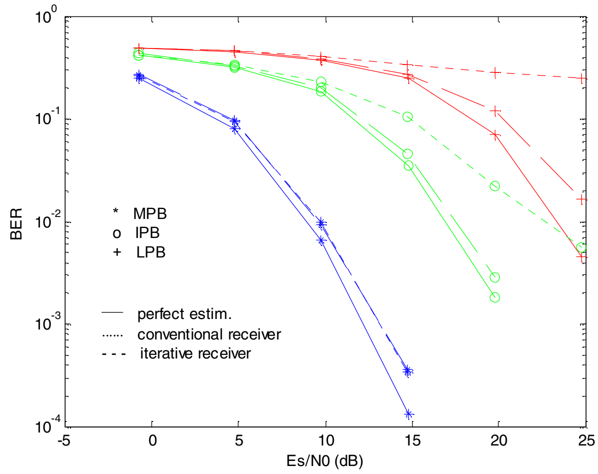

Figure 7. BER performance of a 64-QAM (k_1=0.4, k_2=0.4) hierarchical constellation with a conventional and an iterative receiver.

Figure 8 present the BER results obtained for a 16-QAM (with k_1=0.4) hierarchical constellation considering different values of power ratio β_P, using the iterative scheme. Once again a fully dense pilot grid was employed, i.e., $\Delta N_T = 1$ and $\Delta N_F = 1$. The curves are plotted as a function of total E_S/N_0 which includes the power spent on the pilots. It is clear that the iterative receiver is able to accomplish accurate channel estimation even with very lower pilot powers. Only when the power ratio β_P is -18dB the receiver is not be able to attain reliable channel estimates and the performance starts to show irreducible BER floors. It is important to note that when the pilot powers is high, like 0dB or 6dB, although the receiver is able to obtain accurate channel estimates (no BER floor is visible), the powers spent on the pilots result in a high penalty in the total E_S/N_0 required to achieve a specific BER..

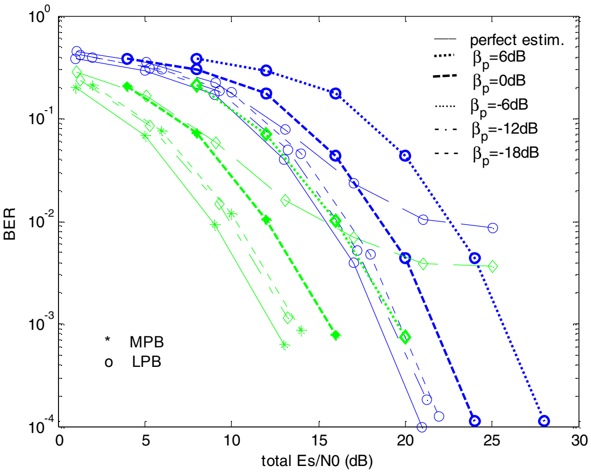

Figure 8. BER performance of a 16-QAM (k_l=0.4) hierarchical constellation with the iterative receiver for different pilot powers.

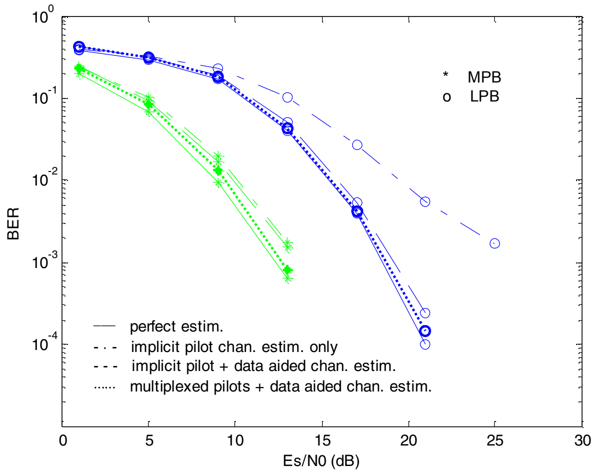

Figure 9. Effect of data aided channel estimation on the BER performance of a 16-QAM (k_l=0.4) hierarchical constellation with the iterative receiver for $\Delta N_T = 7$.

Figure 9 compares the behaviour of the iterative receiver when only the pilots are used for channel estimation and when the data symbols are also used as additional pilots after the first receiver iteration. For these results a lower density of pilots was employed, namely $\Delta N_T = 7$ and $\Delta N_F = 1$, with a power ratio of β_P=-9dB. A 16-QAM (with k_l=0.4) hierarchical constellation was considered. While the most protected bits only show a slight improvement with the use of the data symbols as pilots, the least protected bits clearly present a significant difference between the two approaches. If only the pilots are used for channel estimation the performance becomes far worse than the perfect estimation case but when the data symbols are also considered in the estimation the performance curve gets very close to the perfect case. For comparison it is also shown the performance accomplished when using pilots multiplexed with data symbols (and same average power ratio β_P) instead of implicit pilots. It is clear that though data multiplexed pilots achieve better performances than with implicit pilots, the difference is small and the use of implicit pilots has the advantage of avoiding spectral degradation.

V. CONCLUSIONS

In this paper we have studied the use of QAM hierarchical constellations in a OFDM system employing implicit pilots with the aim of supporting multicast and broadcast transmissions. To deal with the problem of the mutual interference between pilots and data symbols, which can severely affect the performance of QAM modulations, we proposed the use of an iterative receiver capable of accomplishing joint channel estimation and data detection.

It was verified through simulations that, even with low power pilots, the proposed iterative receiver scheme is able to provide performances close to the perfect channel estimation case for all the bit streams, including those with lower error protection levels.

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