Iterative Detection and Channel Estimation for WCDMA Systems Employing Non-Uniform QAM Constellations

Nuno Souto*, Rui Dinis**, João Carlos Silva*
*Instituto Superior Técnico-Instituto de Telecomunicações/
**ISR-IST
Torre Norte 11-11, Av. Rovisco Pais 1, 1049-001
Lisboa, Portugal,
nuno.souto@lx.it.pt, rdinis@ist.utl.pt,
joao.carlos.silva@lx.it.pt

Francisco Cercas, Americo Correia
ISCTE / Instituto de Telecomunicações/ADETTI
Torre Norte 11-08, Av. Rovisco Pais 1, 1049-001
Lisboa, Portugal
francisco.cercas@lx.it.pt, americo.correia@iscte.pt

Abstract—**In this paper we consider the use of non-uniform QAM constellations (Quadrature Amplitude Modulation) for broadcast or multicast transmissions within WCDMA-based systems (Wideband Code Division Multiple Access). These constellations are employed so as to increase the transmission efficiency, since they are able to provide unequal error protection. This allows the transmission of several simultaneous bit streams with different error protection depending on the associated importance. With this strategy, the most important information streams can be received by all users while the less relevant information will only be extracted by users with good propagation conditions. However, these constellations are very sensitive to inter-symbolic interference introduced by multipath propagation, especially for large constellations. Moreover, large non-uniform constellations are also very sensitive to channel estimation errors. For this reason, we propose an iterative receiver for joint detection and channel estimation. The proposed receiver takes advantage of the presence of a turbo-code in the transmission system, and uses feedback information from the turbo-decoder to estimate and suppress the interference, as well as to provide enhanced channel estimates.**

Keywords- Non-uniform QAM constellations, channel estimation, iterative interference cancellation, , WCDMA, broadcast and multicast services.

I. INTRODUCTION

In wireless communication networks it is often necessary to transmit the same information to all the users (broadcast transmission) or to a selected group of users (multicast transmission) in the cells. Usually different users will have different propagation conditions and thus different capacities. Cover [1] showed that in broadcast transmissions it is possible to exchange some of the capacity of the good communication links to the poor ones and the tradeoff can be worthwhile. A very simple method to accomplish this is to employ non-uniform signal constellations (also called hierarchical constellations) which are able to provide unequal bit error protection. 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. A possible application of these techniques is in the transmission of coded voice or video signals, as studied in [1]-[3]. Non-uniform 16-QAM and 64-QAM constellations have already been incorporated in the DVB-T (Digital Video Broadcasting - Terrestrial) standard [4].

In wideband code division multi-access (WCDMA) systems, the mobile propagation conditions result in frequency selective channels that produce multipath interference due to arriving replicas with relative delays superior to one chip period. Although the downlink connection uses orthogonal spreading codes for transmitting several physical channels in parallel, the presence of other multipath replicas destroys this orthogonality, leading to interference effects. This has an important impact on the link performance, especially for M-QAM (M>4) modulations. These modulations are very sensitive to interference and their performance is severely degraded in frequency selective fading channels. A possible low complexity solution to decrease the performance degradation, when using these higher order modulations, is the implementation of a RAKE receiver with an interference canceller. In [5] and [6] the use of a multipath interference canceller (MPIC) was proposed for High Speed Downlink Packet Access (HSDPA) transmissions [7] that use 16-QAM modulation. These MPICs are based on the concepts of the sub-optimal interference cancellation performed by subtractive multiuser detector schemes usually employed in the reverse link. In [8], an iterative receiver that uses feedback information from the turbo-decoder for estimating and removing the inter-path interference was proposed for WCDMA broadcast transmissions using non-uniform QAM constellations. It was shown that this turbo-MPIC performed better than the MPIC with no feedback information at the cost of a small complexity increase. Only perfect channel estimation was admitted in the paper and therefore in here we extend the work and incorporate a channel estimation block in the iterative receiver. Considering that a pilot channel is transmitted simultaneously with the data channels, it is possible to improve the channel estimation by applying also the interference cancellation for the pilot channel in each iteration. Additionally, the estimates of encoded data provided by the decoder can be used as new training sequences for channel estimation in the following iteration.

The paper structure is as follows. In Section II we present the non-uniform constellations and the modifications required in the transmitter structure of a WCDMA system to incorporate these constellations. In Section III the iterative receiver structure and operation is described. Section IV shows some performance results using the proposed transmission scheme and Section V presents the conclusions of this paper.

II. PROPOSED WCDMA DOWNLINK TRANSMISSION SCHEME

A. *Non-Uniform QAM Signal Constellations*

Non-uniform signal constellations (also called hierarchical constellations) are constellations where the distances along the I or Q axis between adjacent symbols can be different depending on their position. These constellations are thus able to provide unequal bit error protection. 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. 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 $k=D_1/D_2$ ($0<k\leq 0.5$), as shown in Figure 1. If $k=0.5$, the resulting constellation corresponds to a uniform 16-QAM. This approach can be naturally extended to any QAM constellation size. The general expression for the definition of a symbol is

$$s = \sum_{l=1}^{\log_2(\sqrt{M})} \left(\pm \frac{D_l}{2} \right) + \sum_{l=1}^{\log_2(\sqrt{M})} \left(\pm \frac{D_l}{2} \right) j \,, \quad j=\sqrt{-1} \,. \quad (1)$$

The number of possible classes of bits with different error protection that can be obtained is $m = 1/2 \cdot \log_2 M$.

B. *Transmitter Structure*

We considered the HS-DSCH (High Speed Downlink Shared Channel) of the UMTS HSDPA mode [9] as the base WCDMA system and implemented the necessary modifications to incorporate 16-QAM and 64-QAM non uniform constellations. Figure 4 shows the corresponding transmission chain. Note that Hybrid-ARQ is not considered since the aim is the transmission of broadcast services. In the proposed scheme, there are *m* parallel chains for the *m* input bit streams (*m*=2 for 16-QAM and *m*=3 for 64-QAM). Each stream is turbo encoded (using the 3GPP rate 1/3 specified turbo code [9]) and rate matching is performed (usually puncturing) for fitting the output stream to the frame format. After that, each stream is segmented into *P* physical channels which are individually interleaved. The physical channels of the *m* processing chains are then mapped into the constellation symbols in the modulation mappers according to the

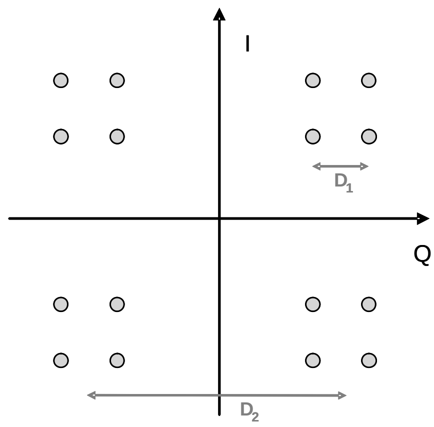

Figure 1. Non-uniform 16-QAM constellation.

importance attributed to the respective stream. The modulated symbols are spread (each physical channel is spread by a different OVSF – Orthogonal Variable Spreading Code) and scrambled and the resulting physical channels are summed. Before transmission, a pilot channel similar to the UMTS CPICH (Common Pilot Channel) channel [7], composed of known pilot symbols and spreaded by a reserved OVSF code of spreading factor 256 (the all ones code) is added to the data signal. This pilot channel is orthogonal to all data channels and in the receiver the pilot symbols can be used for channel estimation.

III. PROPOSED ITERATIVE RECEIVER

A. *Structure and operation of the iterative receiver*

Turbo-codes were first introduced in [10] and were shown to achieve near-capacity performance in an AWGN channel. The usual turbo-decoder is iterative and is composed of two component decoder blocks that share information about the transmitted information bits for each decoding iteration. It is possible to expand each of the turbo decoder iteration loops so that the interference cancellation processing is also incorporated inside the loop. This way, the channel decoder can provide feedback information about the coded bits for the estimation of the transmitted signal and thus of the multipath interference. This is the idea employed for the design of the proposed iterative receiver, whose structure is presented in Figure 5.

For the operation of the receiver it is assumed that all the parallel physical channels present in the transmitted signal carry information for that receiver or at least that it has some knowledge about all physical channels being transmitted. In each iteration the RAKE performs a Maximal Ratio Combining (MRC) of all despreaded signals processed by the fingers. The result then goes into the sequence of processing blocks that perform the inverse operations of the transmitter. The demodulator computes the likelihood probabilities of the received coded bits to be used by the turbo decoders. Each turbo 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 LLR's 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. The reconstructed signal then goes into a channel emulator that generates the estimated discrete multipath replicas multiplied by the respective fading coefficients. The estimated multipaths are then fed into the Interference Canceller which subtracts the interference from the signals fed to each RAKE finger for the next iteration. This interference is composed by the sum of all paths except the one that is going to be extracted by the finger. Since in the first iterations the confidence in the estimated transmitted signal is usually lower, the interference signals can be weighted before the subtraction.

For the general case of a DS-CDMA system the t^{th} received signal sample can be expressed as

$$r_t = \sum_{l=1}^{L} \alpha_{l,t-\tau_l} \left(\sum_{p=1}^{P} s_{p,\left\lfloor \frac{t-\tau_l}{SF} \right\rfloor +1} \cdot c_{p,t-\tau_l} + s_{pilot,\left\lfloor \frac{t-\tau_l}{SF_{pilot}} \right\rfloor +1} \cdot c_{pilot,t-\tau_l} \right) + n_t \,, \quad (2)$$

where $\alpha_{l,t}$ and τ_l are the complex-valued channel gain and the time delay (in samples) of the l^{th} path, L is the number of resolvable paths, P represents the number of physical channels, SF is the spreading factor, SF_{pilot} is the spreading factor of the pilot channel (which is 256), $s_{p,t}$ and $c_{p,t}$ represent the modulated symbol and spreading sequence of the p^{th} physical channel. The term n_t is the AWGN noise component.

The k^{th} despreaded symbol associated with the l^{th} finger of the p^{th} physical channel is represented as

$$y_{p,l,k} = \frac{1}{SF} \sum_{t=(k-1)\cdot SF+1}^{k\cdot SF} r_{t+\tau_l} \cdot c^*_{p,t} \;. \quad (3)$$

The RAKE MRC combined data sequence of the k^{th} symbols of the p^{th} code channel is expressed as

$$\hat{s}_{p,k} = \sum_{l=1}^{L} \hat{\alpha}^*_{l,k} \cdot y_{p,l,k} \;, \quad (4)$$

where $\hat{\alpha}_{l,k}$ is the estimated channel coefficient for path l in the k^{th} symbol period.

The estimated modulated symbols associated to each physical channel are demodulated into LLRs and split into m different streams. After the physical channel desegmentation and rate de-matching, the LLRs of the coded bits of stream m', $\lambda_{m',i}$, are fed into the turbo-decoder. The turbo decoder performs one decoding iteration and outputs an estimate for each jth information bit, $\hat{b}^{(q)}_{m',j}$, and also the LLR estimates of the code symbols $\tilde{\lambda}^{(q)}_{m',i}$ (q is the iteration number and i is the coded bit number). The decision device then uses these LLRs to estimate the coded bits values using a soft decision function [11] according to

$$\tilde{d}^{(q)}_{m,i} = \tanh\left(\frac{\tilde{\lambda}^{(q)}_{m',i}}{2} \right) \;. \quad (5)$$

These coded bit values are then modulated into the symbols $\tilde{s}_{p,k}$ (p denotes the pth physical channel). The mapping of the bits into the constellation symbols, for a M-QAM constellation, is performed according to

$$\begin{aligned} \tilde{s}_{p,k} = & \sum_{l=1}^{\log_2\sqrt{M}} (-1)^l \frac{D_{\log_2\sqrt{M}-l+1}}{2} \prod_{m'=1}^{l} \tilde{d}^{(q)}_{m',p,2k-1} \\ & + \sum_{l=1}^{\log_2\sqrt{M}} (-1)^l \frac{D_{\log_2\sqrt{M}-l+1}}{2} \prod_{m'=1}^{l} \tilde{d}^{(q)}_{m',p,2k} \cdot j \end{aligned} \;. \quad (6)$$

These symbols are then used to reconstruct the estimate of the transmitted signal

$$\tilde{x}^{(q)}_t = \sum_{p=1}^{P} \tilde{s}_{p,\left\lfloor \frac{t}{SF} \right\rfloor +1} \cdot c_{p,t} \;. \quad (7)$$

After this the multipath interference (MPI) associated with the lth path is estimated as

$$\hat{I}^{(q)}_{l,t} = \hat{\alpha}_{l,t} \cdot \tilde{x}^{(q)}_t \;. \quad (8)$$

The interference subtracted from the signals fed to each RAKE finger is the sum of all paths (with their corresponding relative delays) except the one that is going to be extracted by that finger. Thus, the input to l^{th} finger in the q^{th} MPIC iteration can be represented as

$$r^{(q)}_{t,l} = r_t - w_q \sum_{\substack{j=1 \\ j\neq l}}^{L} \hat{I}^{(q-1)}_{j,t-\tau_j} \;, \quad (9)$$

where w_q is a real valued weight that takes values from the interval [0 1] and usually increases with the iteration number [8]. This weight factor is used to reduce the impact of possible data decision errors present in the estimated MPI components which are usually higher in the first iterations. After Q iterations the $\hat{b}^{(Q)}_{m',j}$ values are used as final estimates for the information bit streams.

B. *Channel Estimation*

The transmission of a pilot channel, orthogonal to the data channels, allows a simple channel estimation processing at the receiver. To obtain the channel estimates for each path l the receiver performs the following tasks in the first iteration.:

1. Despread the received signal using

$$y_{pilot,l,k'} = \frac{1}{SF_{pilot}} \sum_{t=(k'-1)\cdot SF_{pilot}+1}^{k'\cdot SF_{pilot}} r_{t+\tau_l} \cdot c^*_{pilot,t} \;. \quad (10)$$

2. Obtain noisy channel estimates, $\hat{\alpha}^{noisy}_{l,k'}$, in each pilot symbol position, k', by multiplying the despreaded pilot symbols, $S^*_{pilot,k'}$, by its conjugates, with

$$\hat{\alpha}^{noisy}_{l,k'} = \frac{s^*_{pilot,k'}}{\left| s_{pilot,k'} \right|^2} \cdot y_{pilot,l,k'} \;. \quad (11)$$

3. The noisy channel estimates are then passed by a moving average filter with length *W*. This filter is employed since it has low complexity, does not require knowledge of the fade rate or autocorrelation of the channel and for slowly varying channels it can achieve good performance. The final channel estimates are thus computed according to

$$\hat{\alpha}_{l,k'} = \frac{1}{W} \sum_{i=k'-\lfloor W/2 \rfloor}^{k'+\lceil W/2 \rceil -1} \hat{\alpha}_{l,i}^{noisy} \qquad (12)$$

4. Since the data channels can have different data rates compared with the pilot symbol rate, interpolation can be performed over the channel estimates for matching the rates. A simple repeater can be used since it is assumed that the channel is approximately stable for pilot symbol duration.

After the first decoding iteration the transmitted symbols estimates can be used as pilots for improving the channel estimation. An interference canceller is applied inside the channel estimator to improve the estimates even further. So, using the estimated transmitted signals (7) and the received signal with interference cancellation employed (9) results the noisy channel estimates

$$\hat{\alpha}_{noisy,l,t} = \frac{\left(\left(\tilde{x}_t\right)^{(q)}\right)^*}{\left|\left(\tilde{x}_t\right)^{(q)}\right|^2} \cdot \left(r_{t,l}\right)^{(q)}. \qquad (13)$$

These noisy channel estimates can then be passed by a moving average filter with length *W* for obtaining final channel estimates.

IV. NUMERICAL RESULTS

Several computer simulations were performed using the Monte Carlo method to study and evaluate the proposed scheme. All the results are presented as a function of E_S/N_0 (E_S - symbol energy, N_0 – white noise spectral density) instead of E_b/N_0 (E_b –bit energy) since it seems a more natural choice for comparing the performances of different classes of bits that are transmitted with unequal amounts of energy. The environments used in the simulations are based on the discrete channel impulse response models of 3GPP test environments [12]. Each tap is assumed to have Rayleigh fading. Eight iterations were employed for the iterative receiver and the weight factors were the same as those used in [8]. The MAP algorithm was used in the turbo decoder. Figure 2 presents the results corresponding to a 5.4 Mbps transmission (split in three 1.8Mbps streams with different error protection) using a 64-QAM non-uniform constellation (k_1=k_2=0.4) in Indoor A environment while Figure 3 refers to a transmission rate of 3.6Mbps (split in two 1.8Mbps streams with different error protection) using 16-QAM uniform constellation (k=0.5) in Vehicular A environment. The frame duration is 2ms. Perfect channel estimation (but with the transmission of CPICH also, for fair comparison) and four different non ideal channel estimation cases are considered in both figures. The first is the standard channel estimation using the CPICH channel only, the second case uses the CPICH only but removes the estimated inter-path interference in each iteration before the estimation, the third

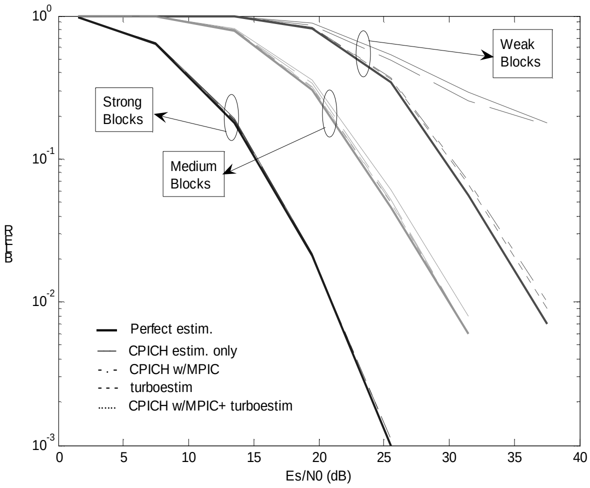

Figure 2. Simulation results for transmission rate of 5.4 Mbps using a 64-QAM non-uniform constellation (k_1=k_2=0.4) in Indoor A environment, v=3km/h.

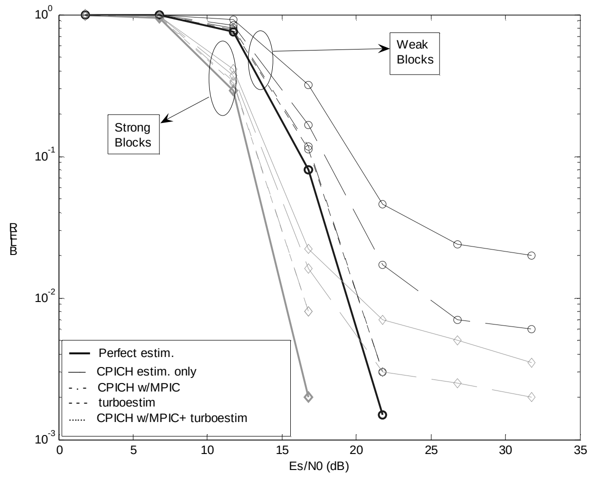

Figure 3. Simulation results for a transmission rate of 3.6 Mbps using 16-QAM uniform constellation (k=0.5) in Vehicular A environment, v=120km/h.

uses the CPICH and the data channels (called turbo-estim) and the last case uses the two previous approaches simultaneously. Looking at the results it seems clear that with the standard estimation using the CPICH only, the performance is severely degraded and cannot achieve a BLER target of 10^{-2}, similar to the one used in MBMS. The enhanced channel estimation technique that uses the estimated data channels as new pilots is able to improve the performance but it is still far from the ideal case. When the channel is estimated using the CPICH with interference cancellation a substantial improvement is obtained and the results get very close to the case of perfect estimation. When using turbo estimation and interference cancellation the results are practically the same of those obtained for the case of CPICH with interference cancellation which means that it is not necessary to use the estimated data channels to improve the channel estimation as long as an interference canceller for the CPICH is employed in each iteration. The improvements achieved are clearer in Figure 3 since it refers to an environment with higher delay spread and thus more interpath interference.

V. CONCLUSIONS

In this paper we have proposed an iterative receiver for broadcast and multicast WCDMA transmissions employing QAM non-uniform constellations. These constellations constitute a very simple method for achieving unequal error protection and can be easily incorporated into a WCDMA system. To support their use in typical WCDMA environments to attain very high transmission rates, the proposed iterative receiver uses feedback information from the turbo-decoder to estimate and remove the interpath interference from the received signal. Additionally the channel fading coefficients can be re-estimated iteratively and thus improved. It was verified through simulations that if a pilot channel is transmitted in parallel with the data, the channel estimates can be improved iteratively by simply applying the interference cancellation for removing the interpath interference of the pilot channel. It was concluded that it is not required to use the data channels as additional pilots since the gains are negligible. It was also verified that the improved channel estimation had a greater impact for the least protected bit streams which were shown to be more sensitive to a poor channel estimation.

VI. ACKNOWLEDGMENT

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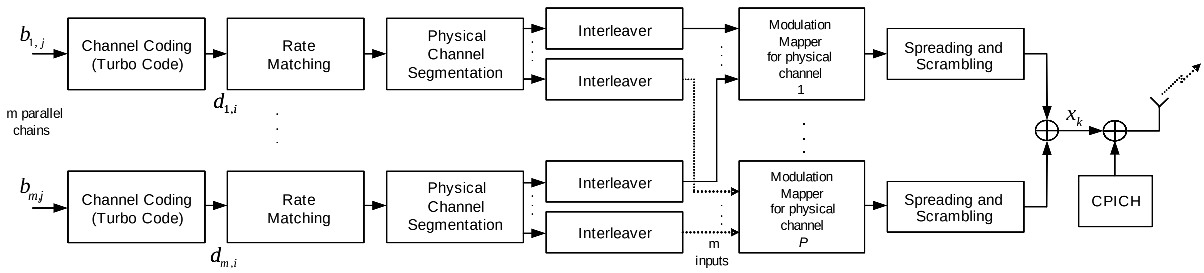

Figure 4. Proposed transmitter chain.

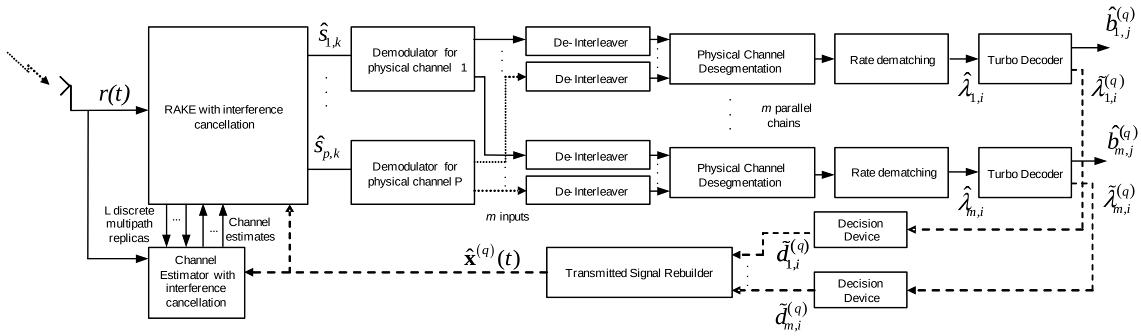

Figure 5. Iterative Receiver Structure