Adaptive Coding in MC-CDMA/FDMA Systems with Adaptive Sub-Band Allocation

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Abstract. The OFDM-based MC-CDMA/FDMA transmission scheme is candidate for the air-interface of beyond 3G mobile communications. An efficient adaptive sub-band allocation (ASBA) approach has been recently shown to provide a considerable gain in the uncoded system performance. In this paper, adaptive coding is proposed for application in conjunction with ASBA. This is proved to yield a significant performance improvement, especially if a user-service prioritisation is considered in the ASBA.

Keywords: OFDM, MC-CDMA, Adaptive Frequeny Allocation, Adaptive Coding.

1. Introduction

The OFDM-based frequency and code division multiple access concepts OFDMA and MC-CDMA and their derived hybrid solutions are regarded as leading candidate for beyond 3G mobile communications, especially for the synchronous downlink [1]-[2].This is certainly due to the high robustness of OFDM to the radio channel time-dispersion, but also to the flexibility and adaptability offered by such schemes in the assignment of the frequency resources.

In this work, we consider the hybrid MC-CDMA/FDMA scheme [3]. The transmission bandwidth is sub-divided into a number of sub-bands, each allocated to a group of users (FDMA), which transmit in a MC-CDMA fashion. An efficient adaptive frequency mapping, referred to as adaptive sub-band allocation (ASBA) has been proposed in [4] for the downlink of MC-CDMA/FDMA. Under the assumption that an estimate of the channel experienced by each user over the whole bandwidth is available at the base station (e.g. from the uplink received signal in a time division duplex system), an optimisation algorithm produces a combination of user-grouping and sub-carrier grouping that maximises the overall link capacity. The ASBA has been shown to provide a significant gain in the uncoded system performance as compared to the usual fixed frequency mapping, based on the interleaving of the carriers assigned to different user-groups [4].

Starting point of this work has been the observation that the ASBA provides indeed a significant gain also in a coded system. Hence, our goal is that of finding a proper channel coding scheme for MC-

CDMA/FDMA systems with ASBA. It has to be observed that, since the considered ASBA optimises the overall link capacity, it is likely to produce a combination of user-grouping and sub-carrier grouping for which the signal-to-noise-plus-interference ratio (SNIR) experienced by the different users differ significantly. As a consequence, if a too low coding rate is chosen according to the performance of the users with the lowest SNIR, a waste in bandwidth efficiency may occur. We propose to use adaptive coding in conjunction with ASBA. By adaptive coding we mean here the adjustment of the coding rate for each user according to the actual SNIR seen by that user after the ASBA.

Moreover, we note that, in practice, within a cell some services may need to be guaranteed a certain throughput, while others may have very low throughput demands. We also consider a slight modification of the ASBA algorithm proposed in [4] in order to cope with a prioritisation among classes of user-services on the basis of their throughput requirements. Different but fixed coding rates can be used for users with different priority. We will show, however, that adaptive coding enables a significant performance gain over a much larger signal-to-noise ratio (SNR) range.

In Section 2, we briefly review the principle of ASBA. In Section 3, we explain how adaptive coding can be applied in conjunction with ASBA. In Section 4, simulation results on the performance of MC-CDMA/FDMA with joint adaptive coding and ASBA are reported and discussed. Finally, conclusions are drawn in Section 5.

2. Adaptive Sub-Band Allocation in MC-CDMA/FDMA

Let $B = \{B_1, B_2, \dots, B_Q\}$ be a partition of the whole set of N sub-carriers within the transmission bandwidth. The $q-$th sub-band B_q, $q = 1, 2, \dots, Q$, consists of N_{sb} not necessarily adjacent sub-carriers. Let then $U = \{U_1, U_2, \dots, U_Q\}$ be a partition of the set of all K active users, with the $q-$th user-group U_q consisting of $K_q \le K_{\text{MC}}$ users, which spread their data symbols in frequency direction over the same sub-band, only separated by orthogonal codes of length K_{MC}. Without loss of generality, the user-group U_q is assigned the sub-band B_q.

The normalised capacity of user k, $k = 1, 2, \dots, K$, over sub-carrier n, $n = 1, 2, \dots, N$, can be expressed as

$$C_{k,n} = \log_2 \left(1 + \frac{|H_{k,n}|^2}{\sigma_\eta^2} \right) \text{ bit/s/Hz}, \tag{1}$$

where $H_{k,n}$ is the channel transfer factor experienced by user k over sub-carrier n and σ_η^2 is the variance of an additive white Gaussian noise

(AWGN) including both the AWG channel noise and the multi-user interference (MUI) [4]. Under the hypothesis of transmit signal power equal to 1, we have SNIR $= \frac{|H_{k,n}|^2}{\sigma_\eta^2}$.

Thus, the capacity of user k over the sub-band B_q, hereafter referred to as user-capacity per sub-band, is given by

$$C_{k,B_q} = \sum_{n \in B_q} C_{k,n}, \tag{2}$$

from which the capacity of the user-group U_q over the sub-band B_q can be derived as $C_{U_q,B_q} = \sum_{k \in U_q} \sum_{n \in B_q} C_{k,n}$. The overall link capacity reads then as $C_{TOT} = \sum_{q=1}^{Q} C_{U_q,B_q}$. The optimisation addressed by the ASBA consists in selecting the pair of partitions B and U which maximises C_{TOT} for a given channel estimate. For details on the optimisation algorithm the reader is referred to [4].

In order to let the ASBA take a given prioritisation among users into account, the user-capacity per sub-carrier $C_{k,n}$ can be multiplied by a proper weighting factor $F > 1$. Let us assume that the set of K active users is sub-divided into P priority classes, in such a way that the users in class $P-1$ have the highest priority and the users in class 0 have the lowest priority. Then, in order to guarantee that highly-proritised users are allocated the sub-bands where they experience the highest SNIR, we assign to their user-capacity higher weights than for other, lower priority, users. That is, the ASBA optimisation algorithm is fed with the modified user-capacity per sub-carrier $C_{k,n} = F^{i_k} C_{k,n}$, where i_k is the priority of user k and F is the chosen weighting factor.

3. Adaptive Coding

By adaptive coding we mean the adjustment of the coding rate for each user according to its SNIR, while keeping the codeword length and the decoding parameters fixed. Since we assume to apply adaptive coding jointly with ASBA, the single user-capacity per sub-band (cf. 2) provided by the ASBA can be used as an indicator of the SNIR. According to its value, the coding rate of the single user is selectedin order to optimise the system performance with respect to a given criterion. A block diagram of the transmission scheme with adaptive coding in conjunction with ASBA is given in Fig. 1 for the general case in which the code is given by the concatenation of an outer and an inner code.

We observe that the BER or the Frame Error Rate (FER) are not appropriate performance measures. Indeed, the probability of decoding error can be minimized by selecting the lowest possible coding rate.

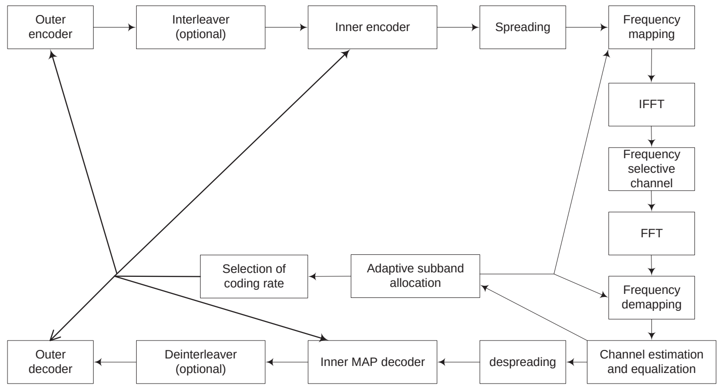


Figure 1. Transmission scheme with adaptive coding and ASBA

This would introduce, however, very high redundancy. If, on the one hand, it is desirable to minimize the FER, on the other hand, as much as possible data should be transmitted within each data packet, i.e. codeword. Therefore, by means of adaptive coding we aim to maximise the user throughput defined as the average number of received data symbols per codeword. For a code of dimension s and codeword length n over the Galois Field GF(2^m), the throughput can be expressed as

$$S(s, n, m, C) = s \cdot (1 - P_e(s, n, m, C)), \tag{3}$$

where s denotes also the number of received data symbols in case of successful decoding and $P_e(s, n, m, C)$ is the probability of incorrect decoding for a given user-capacity per sub-band C (cf. 2).

Given a fixed codeword length n, in order to maximise the average user throughput an optimisation process is carried out that results in a list of intervals of user-capacity per sub-band, $[T_i; T_{i+1})\,, i = 1..L$, with each interval associated to a code dimension s_i. That is, a code with parameters (n, s_i) is used whenever the user capacity per sub-band yielded by the ASBA is $C \in [T_i, T_{i+1})$. The values T_i are the switching thresholds for which the system throughput is maximized for the considered operational environment, which includes the channel propagation conditions, e.g. the noise level and the fading characteristics, and the ASBA settings, e.g. the initial assumptions and the number of iterations of the ASBA optimisation algorithm.

Since both the propagation conditions and the ASBA setting represent random variables, the resulting user-capacity per sub-band C is also a random variable with some probability density function $p(C)$. As a consequence, by defining the set $\{\mathbf{T}\}$ of all possible lists of switching thresholds $\mathbf{T} = (T_0, T_1, \ldots, T_L)$, with $T_i < T_{i+1}$, the optimization problem can be stated as finding

$$\bar{\mathbf{T}} = \arg\max_{\mathbf{T}} \int_0^{\infty} \tilde{S}(n,m,C,\mathbf{T})p(C)dC, \tag{4}$$

where $\tilde{S}(n,m,C,\mathbf{T})$ is the average user throughput obtained by the adaptive system for given switching thresholds $\mathbf{T}$ and user-capacity per sub-band C, that is

$$\tilde{S}(n,m,C,\mathbf{T}) = S(s_i,n,m,C),\; i : C \in [T_i;T_{i+1})\,. \tag{5}$$

Since it is difficult to find an analytical expression for this function (cf. 3), we have approximated it by means of simulations. More specifically, the optimisation has been performed as follows:

– Simulations have been run for different values of the code dimension s and for different values of SNR $= E_b/N_0$, where E_b is the average received energy per information bit and N_0 is the one-sided power spectral density of the channel noise.

– For each value of s, the obtained values of user-capacity per sub-band and the corresponding throughput values have been recorded.

– For each of the considered list of capacity intervals $\mathbf{T} = (T_0, T_1, \ldots, T_L)$, the code dimension s_i yielding the highest throughput has been determined for the single capacity intervals to approximate the function (5) as shown in Fig 2.

– The last step has been repeated for many different lists of capacity intervals and the maximum of (4) has been determined.

Two adaptive coding schemes have been considered. The first is constructed through the concatenation of a Reed-Solomon (RS) code and a convolutional code (CC) and it is referred to as ARSCC in the sequel. The second is given by an adaptive turbo coding (ATC). We note that the rate of the ARSCC scheme can be changed either by changing the dimension of the RS code or by changing the rate of the CC. The latter task is usually accomplished by puncturing and/or by changing the number of generator polynomials. However, to achieve a sufficient number of different coding rates, it might be necessary to use very long puncturing patterns and/or very high number of generator polynomials, which may represent design and implementation issues. In this work, we restrict ourselves to changing the rate of the RS code. Since the turbo codes are given by the parallel concatenation of convolutional codes [5], their rate can be changed as for the CC.

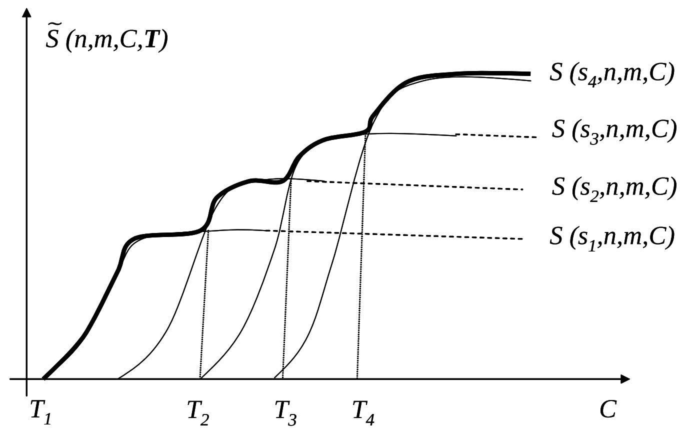


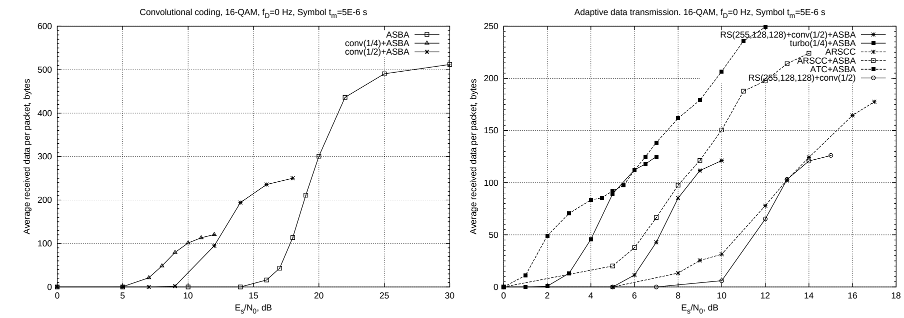
Figure 2. Approximation of the average user-throughput as a function of the user-capacity per sub-band and of the set of switching thresholds.

4. Simulation Results

In the simulations, a bandwidth $B = 20$ MHz and a carrier frequency of $f_c = 5.5$ GHz are assumed. The channel is chosen to be a Rayleigh fading channel with exponential power delay profile and maximum delay spread $\tau_{\max} = 5\,\mu$s. $N = 512$ sub-carriers and $Q = 8$ MC-CDMA sub-systems with up to $K_{\mathrm{MC}} = 8$ users each are considered as in [4]. Moreover, 16−QAM modulation is assumed. For a fair comparison of the different coding schemes, the codeword length has been fixed to 512 bytes. The considered Reed-Solomon codes are RS$(255, k, 256 - k)$ over GF(2^8). The concatenated convolutional code is the rate 1/2 recursive systematic code based on the generator polynomials 0133 and 0171 (octal). The turbo code has the encoder structure specified in [6]. Performance results are reported in terms of average user throughput (cf.(3)) versus SNR.

Fig. 3.a illustrates the results for a MC-CDMA/FDMA system with ASBA when only fixed convolutional coding with different coding rates is adopted. It can be seen that the system without coding can achieve the maximum throughput of 512 bytes per packet for very high SNR. However, for SNR below 15 dB the system fails to transmit any data. On the other hand, the system with coding is able to transmit data at low SNR, but it is efficient only in a narrow SNR range.

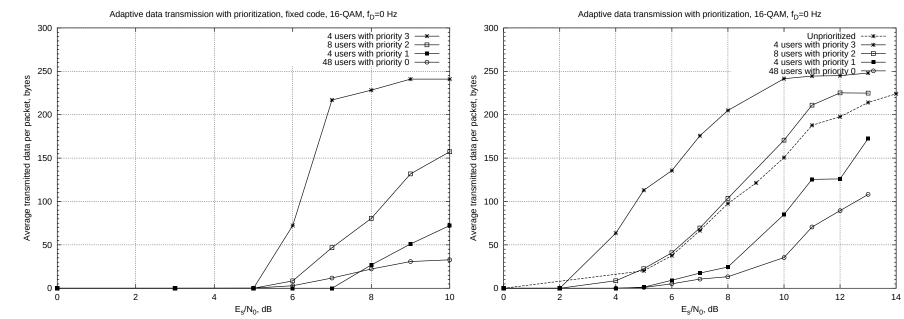
The beneficial effect of adaptive coding can be observed in Fig. 3.b, which reports the results obtained with the two considered adaptive coding methods. For the ARSCC, the comparison of the results achieved with and without ASBA proves that ASBA provides a significant gain also in the presence of channel coding. Moreover, the



a. Fixed convolutional coding with ASBA

b. ARSCC, with and without ASBA, and ATC, with ASBA.

Figure 3. Performance of the unprioritized system



a. ASBA and fixed RS-CC coding

b. ASBA and adaptive coding.

Figure 4. Performance of different priority users

ARSCC yields a considerable gain as compared to a fixed rate 1/4 code given by the concatenation of the RS$(255, 128, 128)$ code with the rate 1/2 CC. The ATC gives even a higher gain. However, a lack of flexibility in the selection of the turbo coding parameters leads to a non-smooth behaviour near 4 dB. In this SNR region, in fact, the sub-carrier assignment provided by the ASBA is good enough to achieve almost error-free transmission using a rate 1/6 turbo code, but still too bad to use a rate 1/4 turbo code. Hence, the lower coding rate has to be chosen, so limiting the throughput.

The results obtained with ASBA in the presence of a user prioritisation are reported in Fig. 4.a and Fig. 4.b, for fixed and adaptive coding, respectively. $P = 4$ priority classes are assumed over $K = 64$ users, of which 4 with priority 3, 8 with priority 2, 4 with priority 1 and 48 with priority 0.

In case of fixed coding the concatenated RS-CC scheme has been chosen and fixed, but different coding rates have been selected for users with different priorities. More specifically, on the basis of the average user throughput at $E_b/N_0 = 10$ dB, the dimension s of the RS code is chosen equal to 241,170,85 and 35 for users with priority 3,2,1,0, respectively. From Fig. 4.a it can be inferred that fixed average throughput values are achieved depending on the user priority at high SNR. With fixed coding it is not possible neither to improve the throughput in case of very good channels (higher E_b/N_0), e.g. when the ASBA provides a favourable allocation, nor to achieve satisfactory throughputs in bad channels (lower E_b/N_0). By using adaptive coding, in contrast, a gain in throughput is observed over a large SNR region in Fig. 4.b. For lower priority users a significant throughput improvement is achieved at high SNR. Moreover, the adaptive coding enables a full exploitation of the prioritisation, i.e. a significant difference in the throughput of users belonging to different priority groups can be noticed.

5. Conclusions

An adaptive coding approach has been proposed and investigated for application in MC-CDMA/FDMA systems jointly with the adaptive frequency mapping known as ASBA. Through adaptive coding, the coding rate of the single users is changed according to the SNIR provided by the ASBA, in such a way that the average user throughput is maximised. Simulation results have shown that adaptive coding yields in general a significant improvement of the throughput at higher SNRs, while enabling satisfactory throughput at low SNRs. Moreover, the application of adaptive coding results to be particularly advantageous when a user prioritisation is considered in conjunction with ASBA.

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