A Spreading Sequence Allocation Procedure for MC-CDMA Transmission Systems

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Abstract

A novel spreading sequence allocation procedure for multi-carrier code division multiple access (MC-CDMA) systems is proposed and investigated. This new technique, which relies on an analytical evaluation of the multiple access interference (MAI), mitigates the interference between different users by optimizing the spreading sequence selection within a given spreading sequence family. For low-loaded transmissions over different realistic frequency correlated channels, it is shown that this new selection procedure outperforms systems where no specific allocation rule is employed. Furthermore, this technique affects the emitted signals and its performance improvement is observed whatever the detection technique used at the receiver side. Thus, this technique improves the capacity of MC-CDMA systems.

1. Introduction

Among the multiple access transmission systems with high bandwidth efficiency, the MC-CDMA transmission system proposed in [1] combines the Orthogonal Frequency Division Multiplex (OFDM) modulation and the CDMA scheme. The OFDM modulation provides robustness against multipath propagation as well as good spectral efficiency while the CDMA allows the transmission of different users in parallel by allocating to each one a distinct spreading sequence, which is uncorrelated with the sequences of other users. Instead of spreading the information in the time domain as in the Direct Sequence CDMA technique, the MC-CDMA spreading is performed in the frequency domain. Therefore, the orthogonality among users has to be ensured in the frequency domain. To ensure this orthogonality, Walsh-Hadamard sequences are often retained for spreading[2],[3]. In order to limit the peak-to-average power ratio, the Kasami or the Zadoff-Chu spreading sequences may also be considered [4]-[6] but at the expense of some orthogonality losses. However, the transmission channel is generally frequency selective, which breaks the orthogonality among theses sequences, and the resulting MAI drastically reduces the system performance.

Many detection techniques have been proposed to reduce the MAI degradation. The single-user detection techniques perform single tap equalization on each subchannel of the OFDM multiplex, which can consist in a simple phase equalization, a zero-forcing equalization, a Minimum Mean Square Error (MMSE) equalization or any other schemes as proposed in [2],[3]. Since these techniques do not take into account all the characteristics of a multi-user transmission, they give sub-optimal performance. Therefore, multi-user detection techniques were proposed in order to improve the performance of the transmission by considering the signals of all active users for the detection of the desired signal of one particular user [7]-[9]. These linear and non-linear methods are efficient but can result in some increase of complexity.

In this paper, we propose a simple MAI limitation technique for MC-CDMA transmission systems, which consists in an optimized spreading sequence assignment based on the network occupancy and the frequency correlation of the transmission channel. The spreading sequence allocation procedure is independent on the spreading sequence family. In section 2, we present the MC-CDMA system configuration and focus on the realistic case of frequency correlated fading channels. We evaluate the analytical expression of the MAI for the case of a multi-user downlink MC-CDMA transmission, which emphasizes the influence of the spreading sequences.

Based on this observation, we propose in section 3 a selection criterion of spreading sequences within a given spreading sequence family and derive a spreading sequence allocation strategy, which is also presented through an example. In section 4, we validate this optimized spreading sequence allocation strategy by simulation results of MC-CDMA transmissions over different realistic transmission channels and for different detection schemes. Finally, section 5 sums up the results and provides conclusions.

2. System Description

We consider the multiple access system originally described in [1] where K users are transmitting simultaneously and synchronously using OFDM modulation with N_C subcarriers, each having bandwidth $\Delta f = 1/T_S$. We focus on the downlink transmission, *i.e.* from the base station to the mobile station. To distinguish the signals issued from the different users, a spreading is performed in the frequency domain. Furthermore, spreading codes of length N_C are considered. Since the spreading is performed over all the subcarriers composing the OFDM modulation, the transmission benefits from the maximal available frequency diversity and no frequency interleaving is needed.

Figure 1 represents a block diagram of the baseband model of the MC-CDMA transmitter for "user j" associated with the spreading sequence $C^{(j)}$. The binary information is first mapped to modulation symbols $d^{(j)}(k)$, which represents the k-th symbol of user j.

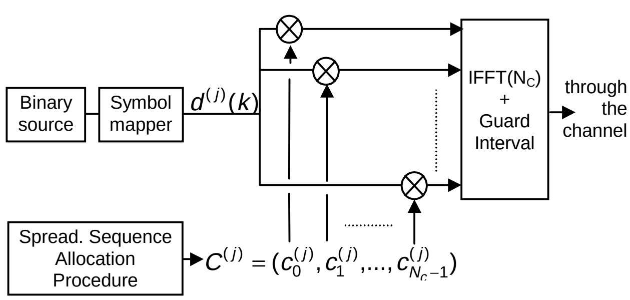

Figure 1: Block diagram of the MC-CDMA transmitter for user j.

Then, $d^{(j)}(k)$ is duplicated N_C times and multiplied by the elements $c_i^{(j)}, (i = 0, \ldots, N_c - 1)$ of the spreading sequence $C^{(j)}$. Each resulting value is associated to a subcarrier and sent to the OFDM modulator, which performs the Inverse Fast Fourier Transform (IFFT) operation and the guard interval insertion. The signal of user j is then added with the signals of other active users and sent through the channel.

The selection procedure of the spreading sequence $C^{(j)} = (c_0^{(j)}, c_1^{(j)}, \ldots, c_{N_c-1}^{(j)})$ for user j, depends on the network occupancy. In case of a fully loaded network, no spreading sequence remains available and the new user is rejected. However, most of the time, the network occupancy is relatively low, *e.g.* 30% to 40% of averaged network occupancy is considered in current French GSM network. Then, many spreading sequences are not allocated which gives a degree of freedom in the selection of the spreading sequence to be assigned. Currently, no specific rule is employed to process the spreading sequence allocation for MC-CDMA systems. We propose to use this degree of freedom to define a spreading sequence allocation procedure in order to minimize the MAI each time the network occupancy is modified.

We focus on the realistic case of frequency correlated Rayleigh fading channels, *e.g.* non-line-of-sight high-bit rate indoor propagation channels [10]. In this situation, the delay spread τ_m of the channel creates Inter Symbol Interference (ISI) and is such that $1/\tau_m > 1/T_S$. We assume that ISI is avoided thanks to the guard interval insertion so that only remains the channel frequency selectivity, which is correlated. Furthermore, the fading is assumed to be flat on each subcarrier and described by a complex channel coefficient following a complex Gaussian distributed random process.

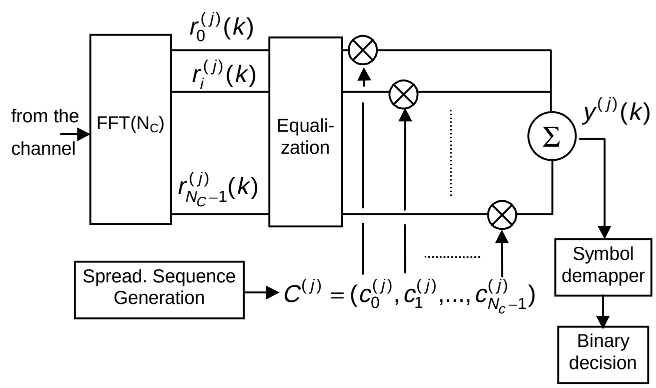

Figure 2: Block diagram of the MC-CDMA receiver for user j.

A block diagram of the baseband model of the MC-CDMA receiver for user j is represented on Figure 2. The signal received by user j during the k-th symbol interval is first OFDM-demodulated by applying an FFT of size N_C. The resulting components on each subcarrier can be written as:

$$r_i^{(j)}(k) = h_i^{(j)}(k) \sum_{m=1}^{K} [d^{(m)}(k).c_i^{(m)}] + n_i^{(j)}(k) \qquad (1)$$
$$for\ \ m = 1, \ldots, K \ and \ i = 1, \ldots, N_C$$

where $h_i^{(j)}(k)$ denotes the complex channel coefficient on subcarrier i associated to the signal propagation from the base station to the terminal of user j and $n_i^{(j)}(k)$ represents an Additive White Gaussian Noise (AWGN) on subcarrier i .

Among the different schemes that can be considered to proceed the detection at the downlink receiver, we consider the single user detection technique, which consists in a carrier-per-carrier equalization followed by a despreading. The equalization coefficient for subcarrier i is denoted $g_i^{(j)}(k)$. Different single user detection techniques have been proposed such as equal gain combining (EGC), orthogonality restoring combining (ORC), minimum mean square error combining (MMSEC) or any other methods as presented in [2],[3].

After equalization, despreading with the sequence allocated to user j and summing the components of each subcarrier, the signal for user j can be written as:

$$\begin{aligned} y^{(j)}(k) = \quad & d^{(j)}.\sum_{i=0}^{N_C-1}\left\{g_i^{(j)}(k).h_i^{(j)}(k)\right\} \\ &+ \sum_{m=1,m\neq j}^{K} d^{(m)} \sum_{i=0}^{N_C-1}\left\{g_i^{(j)}(k).h_i^{(j)}(k).c_i^{(m)}.c_i^{(j)}\right\} \\ &+ \sum_{i=0}^{N_C-1}\left\{g_i^{(j)}(k).n_i^{(j)}(k)\right\} \end{aligned} \tag{2}$$

where the first term represents the desired contribution of user j , the second term is the MAI coming from the other active users and the third term is the contribution of AWGN.

From (2), the MAI power $\sigma^2_{MAI,j}$ associated to user j is defined by relation (3) as:

$$\sigma^2_{MAI,j} = (K-1).R(0).N_C + \sum_{m=1,m\neq j}^{K} \left\{ \begin{aligned} &2R(1)\sum_{i=0}^{N_C-2} w_i^{(j,m)} w_{i+1}^{(j,m)} + \\ &2R(2)\sum_{i=0}^{N_C-3} w_i^{(j,m)} w_{i+2}^{(j,m)} + \ldots \\ &+ 2R(N_C-1) w_0^{(j,m)} w_{N_C-1}^{(j,m)} \end{aligned} \right\}$$

where $R(k)$ is the autocorrelation defined as $R(p-q) = E[a_p(k)a_q(k)]$, $a_i(k) = h_i^{(j)}(k)g_i^{(j)}(k)$ is the real coefficient affecting the i -th subcarrier after equalization, $w_i^{(j,k)} = c_i^{(j)}c_i^{(k)}$ defines the product between the chip element used by users j and k at the i -th subcarrier.

Relation (3) emphasizes the influence of the $w_m^{(j,k)}w_n^{(j,k)}$ products, which can greatly differ depending on the spreading sequences to be assigned. An optimal MAI minimization would be to properly design the K spreading sequences required by the active users as a function of the fading channel coefficients and the associated equalization scheme. However, since this method is not realizable, we consider a suboptimal technique that consists in optimizing the selection of the K required spreading sequences among a given family of P ($P > K$) spreading sequences without taking into account the precise channel characteristics. This selection is dynamically activated, *i.e.* each time K is modified in order to satisfy a variable number of active users. Since equivalent performance is considered for each user, we choose an iterative minimax approximation of a cost function computed over all the sequences as selection criterion of the K spreading sequences.

3. Selection Criterion and Allocation Procedure

Let Ω be a given spreading sequence family and let N_T be the number of elements of Ω. Let Ω_K be a subgroup of Ω that could be used in order to satisfy the required number K ($K < N_T$) of spreading sequences in order to satisfy K active users. A cost function $J^{(\Omega_K)}$ is proposed and defined as:

$$J^{(\Omega_K)} = \max_{j\in\Omega_K, k\in\Omega_K, j\neq k} I^{(j,k)} \tag{4}$$

where $I^{(j,k)}$ is a function that is representative of the interference on the k -th spreading sequence due to the transmission of the j -th spreading sequence. In other words, the $J^{(\Omega_K)}$ only takes into account the maximal degradation that is experienced by two of the K spreading sequences of Ω_K . This criterion suggests that the BER performance of a MC-CDMA multi-user transmission over a frequency correlated channel mainly results from the MAI caused by the two spreading sequences that mostly interfere each other.

We define $I^{(j,k)}$ as:

$$I^{(j,k)} = -T(W^{(j,k)}) \tag{5}$$

where $W^{(i,j)}$ denotes the vector of N_C components $w_n^{(i,j)}$ ($n = 0,\ldots,N_C-1$) resulting from the chip-to-chip product between the i -th and the j -th spreading sequence at the n -th subcarrier, and $T(x)$ defines the number of transitions of vector x ($T(x) \geq 0$) :

$$T(x) = \frac{1}{2}\sum_{i=0}^{N_c-2}\left|\text{sgn}(x_{i+1}) - \text{sgn}(x_i)\right| \tag{6}$$

Coming back to relation (3), minimizing $J^{(\Omega_K)}$ leads to retain a group of K spreading sequences for which the different product vectors $W^{(i,j)}$ present a maximum number of transitions. This leads to make the multiplication coefficient of $R(1)$ in relation (3) be a large negative value that can mitigate the large positive value of the first term.

The allocation procedure is performed for the K spreading sequences on the basis of the criteria presented through relations (4) and (5) among a given spreading sequence family. This procedure re-allocates all the K needed spreading sequences each time the value of K is modified. Among a total number of N_T spreading sequences, the $\frac{N_T!}{K!.(N_T-K)!}$ different groups Ω_K of K spreading sequences are compared in order to minimize (4), so that the subgroup $\Omega_K^{(opt)}$ is retained according to:

$$\begin{aligned}\Omega_K^{(opt)} &= \arg\min_{\Omega_K\in\Omega}[J^{(\Omega_K)}] \\ &= \arg\min_{\Omega_K\in\Omega}[\max_{j\in\Omega_K,k\in\Omega_K,j\neq k} I^{(j,k)}]\end{aligned} \qquad (7)$$

As the spreading sequence family is pre-defined by the transmission system, the optimum selection subgroup $\Omega_K^{(opt)}$ can be computed a priori for each K and the result can be stored in a look-up table. According to the spreading sequence family, it may happen several equivalent optimal subgroups. Then, the selection procedure can be done arbitrary between these subgroups or it can include other system criteria in order to select the proper subgroup.

As an example, let us consider the Walsh-Hadamard sequence family with length $N_C = 4$ that is composed of 4 spreading sequences: $C^{(0)} = (+1,+1,+1,+1)$, $C^{(1)} = (+1,+1,-1,-1)$, $C^{(2)} = (+1,-1,+1,-1)$, $C^{(3)} = (+1,-1,-1,+1)$. Let us suppose also that $K = 2$ spreading sequences are needed and that the use of the sequence $C^{(2)}$ is mandatory as first allocated sequence. Then, 3 subgroups Ω_K of 2 spreading sequences including $C^{(2)}$ have to be evaluated according to (7): $\Omega_{K0} = \{C^{(2)}, C^{(0)}\}$, $\Omega_{K1} = \{C^{(2)}, C^{(1)}\}$ and $\Omega_{K2} = \{C^{(2)}, C^{(3)}\}$. The cost function is then computed over the 3 possible subgroups which leads to $J^{\Omega_{K0}} = -3$, $J^{\Omega_{K1}} = -2$ and $J^{\Omega_{K2}} = -1$. Then, according to (7), the optimal subgroup $\Omega_K^{(opt)}$ of 2 spreading sequences is $\Omega_{K0} = \{C^{(2)}, C^{(0)}\}$ since $J^{\Omega_{K0}}$ is minimum, *i.e.* it has the largest negative value.

4. Performance Evaluation

In this section, we present simulation results that illustrate the performance of different spreading sequences allocation strategies in the realistic case of MC-CDMA transmissions over frequency correlated fading channels. We consider a simulation environment that is quite similar to the ETSI BRAN HIPERLAN/2 physical layer, *i.e.* an indoor transmission with 64FFT-based OFDM modulation. The data rate is 20 MHz so that the subcarrier bandwidth is 0.31 MHz. Two propagation channels issued from [10] are taken into account with a different coherence bandwidth B_c, as presented in Table 1. In order to deal with multiple access and to benefit from the maximal frequency diversity, a synchronous transmission with Walsh-Hadamard spreading sequences of length 64 is considered, which will allow a maximum number of 64 simultaneous active users. With no restriction on the results, we assume that an active user only uses one sequence. Single-user detection based on EGC or MMSEC techniques are used at the receiver side. The signals of all active users are transmitted with equal power, the guard interval is designed to entirely compensate the ISI and the channel transfer function is power normalized.

Table 1: Characteristic of the channel models [10].

Channel A	B_C = 2.5 MHz
Channel B	B_C = 1.3 MHz

We compare the performance of our optimised spreading sequence allocation procedure to other allocation choices in terms of averaged Bit-Error-Rate, which is computed after demodulation and detection over all the active users.

Figure 3 represents the results for Channel A and EGC detection, where the curves differ by the spreading sequence allocation strategy and/or the number of simultaneous active users.

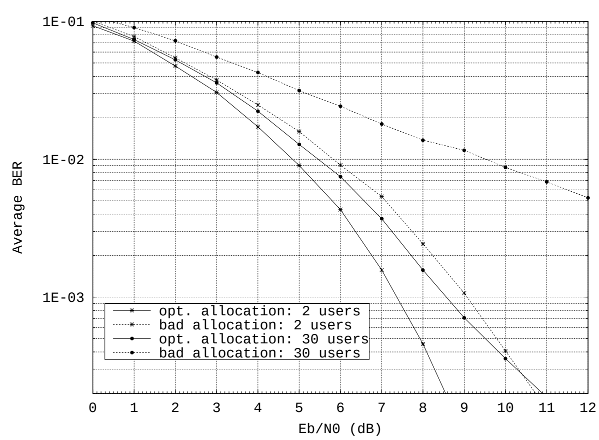

Figure 3: Performance comparison of different Walsh-Hadamard spreading sequence allocation strategies. (Channel A, EGC detection).

For 2 users with a bad spreading sequence allocation, BER=10^{-3} is achieved for a Eb/N0 equal to 9.1 dB while our optimized allocation procedure requires 1.7 dB less. As bad allocation for 2 users, we choose the “all one”

Walsh-Hadamard sequence and the sequence with one transition "+1/-1" in the middle of the sequence. Moreover, the transmission of 30 active users based on the optimized procedure performs better that the transmission of 2 active users with a bad allocation. Compared with the optimized allocation for 30 active users, the transmission of 30 active users with a bad allocation requires 5 dB more to achieve BER=510^{-3}. This result emphasizes the great impact of the spreading sequence allocation strategy that can drastically increase the multiple access interference and then the BER, even if only one user interferes on the desired one.

In order to evaluate the influence of the channel frequency correlation, Figure 4 depicts for a transmission over Channel B the influence of the allocation strategies that were compared on Figure 3.

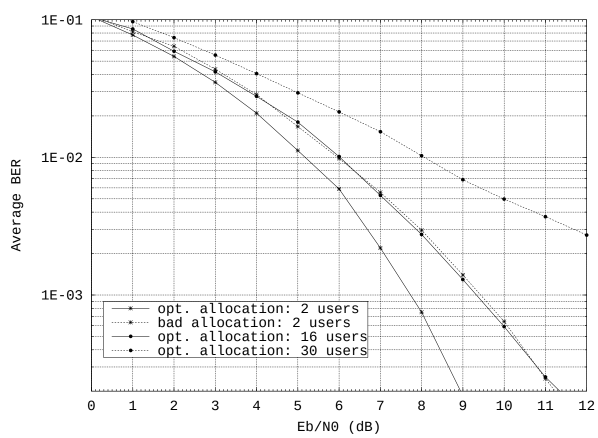

Figure 4: Performance comparison of different Walsh-Hadamard spreading sequence allocation strategies (Channel B, EGC detection).

For a transmission of 2 active users, the optimized spreading sequence allocation requires almost 1.7 dB less to achieve BER=10^{-3} than a bad allocation. Moreover, compared with the case of a bad allocation for 2 users, 16 users can be tolerated with an optimized allocation to achieve the same BER. If 30 users are transmitting with an optimized allocation, then a large degradation occurs. Compared with the results of Figure 3 where 30 users were tolerated, the smaller frequency correlation of the channel, *i.e.* the smaller coherence bandwidth B_C = 1.3 MHz, limits the performance improvement due to the allocation strategy in terms of additional number of users. These results confirm the influence of the multiplication coefficient of $R(1)$ in relation (3), which is lower for Channel B than for Channel A.

Figure 5 represents the BER obtained for different spreading sequence allocation strategies for a transmission over Channel A when the detection is performed by a MMSEC algorithm, which is known to provide better performance than EGC detection [3]. For comparison, the BER obtained after EGC detection (Cf. Figure 3) for the transmission of 2 users with optimized and bad spreading sequence allocation is also plotted. Compared with the optimized allocation strategy, a degradation of 2.6 dB is experienced to achieve BER=10^{-3} for 2 users with MMSEC detection if a bad allocation strategy is chosen. This degradation is much higher than the degradation of 1.7 dB that is experienced with EGC detection as plotted in Figure 3. With an optimized allocation procedure, the MMSEC detection performs better than the EGC detection, *i.e.* it requires 0.5 dB less to provide BER=10^{-3}: the spreading sequence allocation limits the MAI in the transmission and the intrinsic performance of the MMSEC detection is achieved.

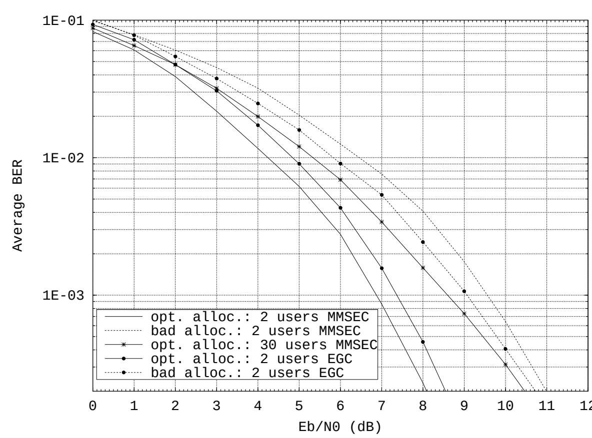

Figure 5: Performance comparison of different Walsh-Hadamard spreading sequence allocation strategies (Channel A, MMSEC detection).

In contrast, if a bad allocation is performed for 2 users, then the MMSEC detection performs worse than the EGC detection. Thus, the amplitude equalization seems to make the receiver less robust in case of a bad allocation. At last, as in Figure 3, the transmission of 30 active users with optimized spreading sequences gives much better performance than the transmission of 2 users with a bad spreading sequence allocation. This result confirms the great impact of the spreading sequence allocation procedure.

5. Conclusions

In this paper, a MAI mitigation scheme for MC-CDMA transmission systems was investigated. The proposed technique is based on a particular selection, within a given spreading sequence family, of the spreading sequences that are requested by the network to satisfy a given number of active users. On the basis of an analytical evaluation of the MAI, a spreading sequence allocation procedure was derived. The efficiency of this technique was illustrated by simulation results for Walsh-Hadamard spreading sequences with different realistic channel configurations and different detection algorithms.

On one hand, because of the frequency correlation of the channel, the performance of MC-CDMA systems is dependent on the spreading sequences that are selected within a given spreading sequence family with uniform characteristics in AWGN transmission conditions. On the other hand, the non-full-loaded network occupancy, which is a frequent transmission case, gives a degree of freedom in the allocation of spreading sequences so that this allocation can be optimized in order to improve the performance of the transmission.

Besides, since this technique affects the emitted signals, it is likely to improve the system capacity whatever the detection method used by the receiver. It is also applicable to any spreading sequence family and is simple to implement. Further research will consist in a performance evaluation of this technique with more robust detection algorithms such as multi-user detection ones.

References

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