SPREADING SEQUENCES SELECTION FOR UPLINK AND DOWNLINK MC-CDMA SYSTEMS

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Abstract. This paper deals with the selection of the spreading sequences for the downlink and the uplink Multi-Carrier Code Division Multiple Access systems with the aim of minimizing the Multiple Access Interference and the dynamic range of the transmitted multicarrier signal.

1. INTRODUCTION

In recent years, Multi-Carrier Code Division Multiple Access (MC-CDMA) has been receiving widespread interests for wireless broadband multimedia applications. Combining Orthogonal Frequency Division Multiplex (OFDM) modulation and CDMA, this scheme benefits from the main advantages of both techniques [1]: high spectral efficiency, multiple access capabilities, robustness in the case of frequency selective channels, high flexibility, narrow-band interference rejection, simple one-tap equalization, etc. In general, to reduce the Multiple Access Interference (MAI) in a synchronous system like the downlink mobile radio communication channel, the spreading sequences, or codes, are chosen orthogonal. Besides, spreading sequences have to be selected in order to mitigate the non-linear distortions introduced by the power amplifier on the OFDM transmitted signal.

This paper deals with the selection of the spreading sequences for the downlink and the uplink of high rate cellular networks with the aim of jointly minimizing the MAI and the non-linear distortions. The Peak to Average Power Ratio (PAPR) and the Crest Factor (CF) are used for the evaluation of the dynamic range of the transmitted multicarrier signal for various orthogonal and non-orthogonal spreading codes. Furthermore, in order to minimize the MAI, an optimized allocation of the spreading sequences is described. Finally, a selection of the spreading codes which jointly reduces the MAI and the non-linear distortions is proposed.

2. SYSTEM DESCRIPTION

In a MC-CDMA transmitter, as represented on figure 1, the data symbol D_j(t), assigned to user *j,* is multiplied in the frequency domain by the spreading code C_j(t) = [$c_{1,j}$, $c_{2,j}$, …,$c_{k,j}$, …,$c_{L,j}$]. In this figure, the length L of the spreading code is equal to the number N_c of subcarriers. After the multicarrier modulation, easily carried out by IFFT operation and the insertion of a guard interval, the signal $S_j(t)$ is transmitted thanks to a power amplifier which has a limited peak output power [2].

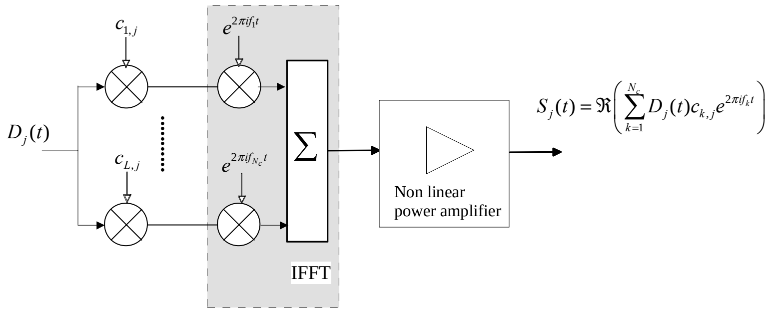

Figure 1. MC-CDMA transmitter for user j

Usually, for a synchronous system, using orthogonal codes such as Walsh-Hadamard spreading sequences guarantees the absence of MAI in a Gaussian channel. However, in a frequency selective fading channel, all the subcarriers of the MC-CDMA signal are received with different amplitude levels and different phase shifts, which generates MAI. To combat this interference, one may use various Single-user Detection (SD), linear or non-linear Multi-user Detection (MD) techniques [3].

In this study, we focus on the realistic case of frequency correlated Rayleigh fading channel. We assume that Inter Symbol Interference (ISI) is avoided thanks to the insertion of a guard interval, which is longer than the delay spread of the channel. Moreover, frequency non-selective fading per subcarrier and time invariance during one OFDM symbol are supposed. Besides, as we consider SD techniques, the complex channel response and the equalization coefficient for the *k*-th subcarrier of user *j* are respectively denoted $h_{k,j}$ and $g_{k,j}$.

3. SPREADING SEQUENCES SELECTION CRITERIA

3.1 Peak-to-Average Power Ratio and Crest Factor

The MC-CDMA technique offers many advantages but presents also a significant drawback, which is due to the multicarrier feature. Indeed, the MC-CDMA signal consists of the sum of several subcarriers, which may result in a large dynamic transmitted signal. The envelope variation of a multicarrier signal can be estimated by the PAPR or the CF which are for a signal defined on the interval [0,T[equal to [4]:

$$\mathrm{CF}(S_j(t)) = \sqrt{\mathrm{PAPR}(S_j(t))} = \sqrt{\frac{\max\left|S_j(t)\right|^2}{\frac{1}{T}\int_0^T \left|S_j(t)\right|^2 dt}} \tag{1}$$

As a power amplifier has a limited peak output power, an increased PAPR or CF results in a reduced average radiated power in order to avoid non-linear distortions. For the uplink mobile radio communication, each user's signal is transmitted by a different amplifier and the PAPR or CF of the spreading codes must be compared individually. By contrast, for the downlink, the different data multiplied by the orthogonal spreading codes of the N_u active users are added and transmitted synchronously by the same power amplifier at the base station. So, in that case, the quantity, which is of interest for the comparison between the different classes of sequences, is the global CF (GCF) of the global transmitted signal:

$$\mathrm{GCF}\left(\sum_{j=1}^{N_u} S_j(t)\right) = \sqrt{\frac{\max\left|\sum_{j=1}^{N_u} S_j(t)\right|^2}{\frac{1}{T}\int_0^T \left|\sum_{j=1}^{N_u} S_j(t)\right|^2 dt}} \tag{2}$$

3.2 Multiple Access Interference

A simple MAI limitation technique for downlink synchronous MC-CDMA transmission system, which consists in an optimized spreading sequence assignment has been proposed in [5]. Considering SD techniques, the analytic expression of the MAI power associated to user j for the case of a synchronous MC-CDMA transmission is given by:

$$\sigma^2_{MAI,j} = \underbrace{(N_u - 1)R(0)L}_{\alpha} + \sum_{m=1, m\neq j}^{Nu} \left\{ \begin{array}{c} \underbrace{2R(1)\sum_{k=1}^{L-1} w_k^{(j,m)} w_{k+1}^{(j,m)} +}_{\beta} \\ \underbrace{2R(2)\sum_{k=1}^{L-2} w_k^{(j,m)} w_{k+2}^{(j,m)}}_{\gamma} + \ldots \\ 2R(L-1) w_1^{(j,m)} w_L^{(j,m)} \end{array} \right\} \tag{3}$$

where $R(i)$ is the autocorrelation defined as $R(p\text{-}q) = E[a_{p,i}.a_{q,i}]$, $a_{k,i}=h_{k,i}.g_{k,i}$ is the coefficient affecting the k-th subcarrier after equalization, $w_k^{(j,m)} = c_{k,j}.c_{k,m}$ defines the product between the chip element used by users j and m at the k-th subcarrier, and $N_u < L$ is the number of active users.

Whatever the frequency correlation of the transmission channel, the MAI minimization procedure detailed in [5] leads to retain a subgroup of N_u spreading sequences for which the minimum number of transitions (+1/-1) among each possible product vector $W^{(j,m)} = (w_1^{(j,m)}, w_2^{(j,m)}, \ldots, w_L^{(j,m)})$ is maximum. In that case, the negative term β of (3) is minimized which reduces the MAI. Nevertheless, we may obtain several equivalent optimized subgroups. Then, the selection procedure can include a second criterion in order to further reduce the MAI.

For that purpose, as a second complementary criterion, we compare the three following approaches:

- maximizing the average number of transitions among the different product vectors $W^{(j,m)}$ (Second crit: MEAN),
- minimizing the standard deviation of the number of transitions among the different product vectors $W^{(j,m)}$ (Second crit: STD),
- maximizing the minimum number of transitions (+1/-1) among each possible second order product vectors $W'^{(j,m)} = (w_1^{(j,m)},w_3^{(j,m)},\ldots,w_{L-3}^{(j,m)},w_{L-1}^{(j,m)})$ and $W''^{(j,m)} = (w_2^{(j,m)},w_4^{(j,m)},\ldots,w_{L-2}^{(j,m)},w_L^{(j,m)})$ (Second crit: 2nd order). This last approach aims to minimize the negative term γ of (3) which reduces the MAI.

4. SIMULATION RESULTS

4.1 Crest factor minimization

The CF of orthogonal and non-orthogonal spreading sequences has been evaluated by simulation. Figure 2a represents the individual CF obtained for different orthogonal spreading sequences with sequence length L = 32: Walsh-Hadamard (W-H), orthogonal Gold [6] and Golay codes [7]. It can be seen that the set of Golay sequences individually produces the best CF (always equal to 2), while the Walsh-Hadamard sequences produce the worst. Indeed, Walsh-Hadamard CF lies from 8 to 4. Similar results have been obtained for different sequence lengths L = 16, 64, 128. Then, for synchronous uplink applications, as far as the dynamic range of the transmitted signal is concerned, it is more advisable to use Golay sequences than Walsh-Hadamard sequences, which are however considered in most synchronous systems.

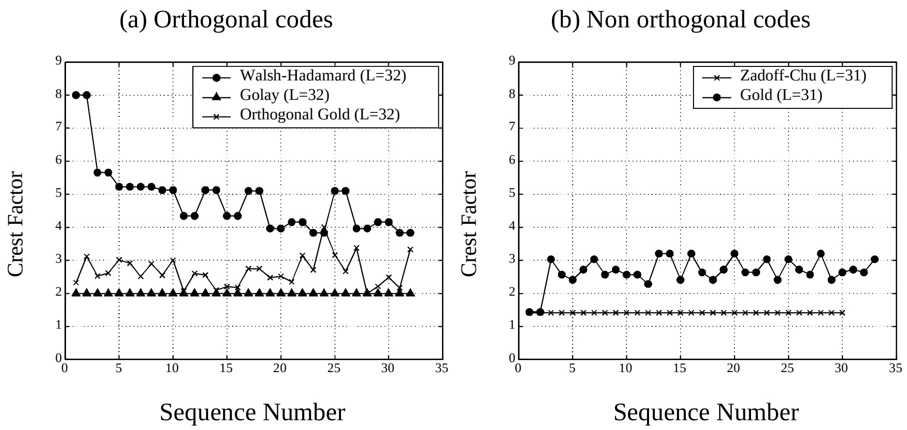

Figure 2. Crest factor of each individual spreading sequences
(a) orthogonal codes - (b) non orthogonal codes

As regards non orthogonal codes for asynchronous uplink applications, Zadoff-Chu complex sequences [8] with constant magnitude periodic crosscorrelation functions equal to $\sqrt{L}$, have a lower CF than Gold sequences. Indeed, Zadoff-Chu sequences CF is constant and equal to $\sqrt{2}$ when Gold codes CF is about 3 as shown on figure 2b.

For the synchronous downlink, it is necessary to estimate the PAPR or the GCF of the global transmitted signal. Figure 3 shows the GCF of the global signal transmitted by the base station, which corresponds to the synchronous addition of the different user signals. The results are presented for L = 16 W-H and Golay codes versus the number N_u of active users. For each number N_u of active users, the GCF of the subsets offering the minimum and the maximum GCF are calculated.

As expected, the difference between the minimum and the maximum GCF is larger for W-H codes than for Golay codes. Furthermore, a good selection of the W-H codes allows to keep the GCF lower than 2 while the GCF of Golay codes increases linearly with N_u. In this case, using W-H codes is appropriate to limit the PAPR for the downlink.

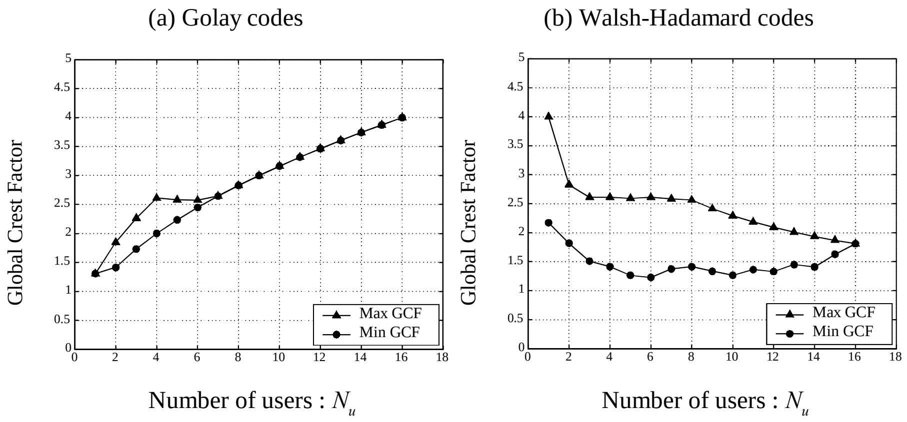

Figure 3. Global crest factor of different spreading sequences (L=16)
(a) Golay codes - (b) Walsh-Hadamard codes

4.2 MAI minimization

The spreading sequence allocation procedure based on the MAI criterion has been validated by simulation results for a downlink MC-CDMA synchronous transmission over indoor propagation channels. A 64 FFT-based OFDM modulation, W-H or Golay spreading sequences of length L = 16 and SD based on Minimum Mean Square Error Combining (MMSEC) are considered. The simulation environment is inspired by ETSI BRAN HIPERLAN/2 specification. The signal bandwidth is equal to 20 MHz and the propagation channel issued from [9] has a coherence bandwidth equal to 2.56 MHz.

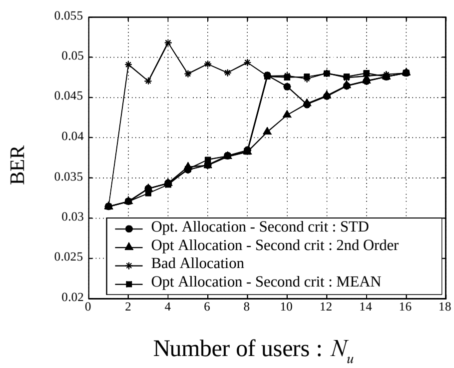

Figure 4. BER versus the number Nu of active users for Eb/N0=6dB;
Nc=64, L=16, MMSEC detection

Figure 4 represents the average Bit Error Rate (BER) versus the number N_u of active users for *Eb/N0 = 6 dB* and for different subsets matching the selection criteria defined in section 3.2. Results concern both W-H and Golay spreading sequences which offer exactly the same performance. As a bad allocation case, we consider the subset defined by a minimum number of transitions in each possible product vector $W^{(i,j)}$. As in [4], we confirm the gain obtained by the optimization of the spreading sequence allocation procedure. A bad allocation results in a BER close to 4.8 10^{-2} for any number N_u of users varying from 2 to 16 while optimized allocations leads to lower BER, increasing almost linearly with N_u. However, the BER performance obtained with the three second criteria are really close. We can only notice a slight difference from N_u = 9 to 16 in favor of the 2nd order criterion curve. Consequently, using a second MAI criterion to further optimize the selection does not provide significant gain. In order to optimize the performance of the downlink transmission system, the best choice is then to jointly minimize the MAI according to the first criterion and then the *GCF*.

4.3 Joint MAI and GCF minimization

In order to optimize the performance of the downlink transmission system, we may propose a selection of spreading sequences based on a joint minimization of the MAI and the GCF. Figure 5a shows the GCF of W-H codes for the synchronous downlink. Curves (1) and (2) already presented in figure 3b corresponding to the maximum and the minimum GCF are given as reference.

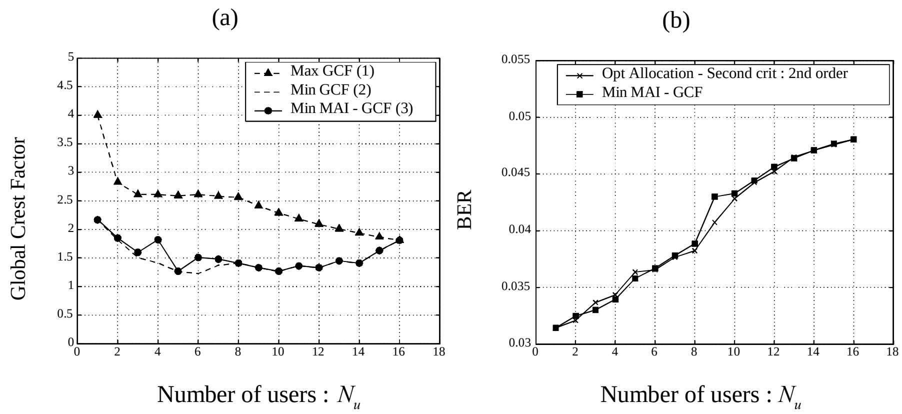

Figure 5. Joint MAI and GCF minimization
(a) GCF of subsets which minimize first the MAI and the GCF
(b) BER versus the number Nu of active users for Eb/N0=6dB, Nc=64, L=16, MMSEC detection

Curve (3) gives the GCF of subsets which minimize first of all the MAI according to the first criterion and then the GCF. It can be noticed that there is only a slight difference with curve (2) for 4 and 6 users.

Furthermore, as shown in figure 5b, the BER performance obtained by these subsets are really close to the performance of the subsets which only minimize the MAI according to the first and the second criterion. Then, it is shown that it is possible to select the subset in order to jointly minimize the GCF and the MAI.

5. CONCLUSION

For a given transmission context (number of users, up- or downlink) and depending on the criterion which is privileged in each application, i.e., minimization of the MAI or minimization of the non-linear distortions, the optimum spreading sequence subsets may be different. In this paper, we propose to select spreading sequences subsets that jointly reduce the MAI and the non-linear distortions.

For a synchronous uplink, the low CF of the Golay codes is undoubtedly an advantage compared to W-H codes, whereas on the other hand both sequence families have the same performance as far as the minimization of the MAI is concerned. For asynchronous applications, Zadoff-Chu complex sequences offer a low CF.

For the downlink, it is possible to shortlist the subgroups which minimize the MAI according to the first MAI criterion and then to select the subgroup offering the minimal GCF.

6. REFERENCES

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