MC-CDMA System with Double Spreading Codes for MAI Reduction in the Multi-Path Fading Downlink Channel

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Abstract

Most of the techniques for Multiple Access Interference (MAI) reduction in Code-Division Multiple Access (CDMA) systems are applicable to the uplink, where the base-station knows the signature of all users and can apply a Multi-User Detection (MUD) strategy. A technique is proposed here to reduce the influence of MAI on the downlink of a Multi-Carrier CDMA (MC-CDMA) system, without resorting to MUD. The technique is based on the use of a spreading sequences pair for each subscriber. Its limiting factor is that the system capacity, in terms of the active users' maximum number, is halved as compared to the case in which a single spreading code per user is adopted.

1 - Introduction

It is known that the design of orthogonal codes for a large number of users in a Code-Division Multiple Access (CDMA) system is a complex task. Furthermore, even if simple orthogonal codes (like Walsh-Hadamard) are used in a synchronous downlink, multi-path propagation destroys the orthogonality among the users' signals, leading to degradation in performance and system capacity due to Multiple Access Interference (MAI). There are a number of techniques for MAI reduction in CDMA systems, but most of them are designed to operate in the uplink, where the base-station knows the signatures of all users and can apply Multi-User Detection (MUD). However, this would not be feasible in the downlink, where the subscriber only knows his own signature.

Recently, H. Zare and D. Liu proposed a novel technique for MAI reduction in the synchronous downlink of a CDMA system [1]. Their idea is based on a proper selection of a pair of codes for each user.

In this paper, the method proposed in [1] is adapted to the downlink of a Multi-Carrier CDMA (MC-CDMA) system, for operation on a fixed or time-varying, multi-path fading channel. The proposed system is named Double Spreading Code MC-CDMA (DC-MC-CDMA). It will be shown that this system can almost eliminate the error floor caused by MAI, even if the channel is time varying.

The remaining of this paper is organized as follows: Section 2 describes the idea suggested in [1]. In Section 3, the MC-CDMA system architecture is revisited. In Section 4 it is suggested an adaptation of the Zare and Liu's idea to the MC-CDMA presented in Section 3. Simulation results are presented and discussed in Section 5. The main conclusions are drawn in Section 6.

2 - MAI Cancellation for the Downlink of a Single-Carrier CDMA System

In the scheme proposed by H. Zare and D. Liu for MAI cancellation in the downlink of a Single-Carrier CDMA (SC-CDMA) system [1], the information of each subscriber j, $j = 1, 2, \ldots, J$ is spread using two signature sequences (or spreading codes), $\{c_j\}$ and $\{c_j'\}$, depending on the bit to be transmitted. The resulting spread waveforms corresponding to the sequences $\{c_j\}$ and $\{c_j'\}$ are $\{s_j\}$ and $\{s_j'\}$, respectively. A user j transmits $\{s_j\}$ representing the symbol +1, and $\{s_j'\}$ representing the symbol −1. The following paragraphs of this section describe the technique suggested in [1], under the same assumptions considered there.

Assuming that the i-th information bit to be transmitted by the subscriber j is $\{b_j(i)\}$, the corresponding base-band transmitted signal is given by:

$$x_j(t) = A\sum_i \bar{s}_j(t-iT) \quad j = 1,2,\ldots,J \tag{1}$$

where A is the amplitude of the user's signal and $\bar{s}_j = \{s_j\}$ if $b_j(i) = 1$ or $\bar{s}_j = \{s_j'\}$ if $b_j(i) = -1$. Assuming that the signals from the base-station arrive at a specific subscriber with the same power level, the base-band signal referring to all users received by the j-th subscriber is given by:

$$r_j(t) = \sum_{j'=1}^{J}\sum_{l=1}^{L}\alpha_{jl}x_{j'}(t-\tau_{jl}) + n(t) \tag{2}$$

where $n(t)$ is the Additive White Gaussian Noise (AWGN) component, α_{jl} is the l-th path gain for the channel between the base-station and the j-th subscriber, and τ_{jl} is the corresponding path delay.

At the receiver side, correlations between the received signal $r_j(t)$ and each of the two subscriber signatures, $\{c_j\}$ and $\{c_j'\}$, are performed to generate two decision variables. The received symbol is then estimated by comparing these two decision variables and choosing in favor of the greatest one.

According to [1], to combat the multi-path effect and, consequently, the MAI, it is mandatory that the two subscriber's signatures $\{c_j\}$ and $\{c_j'\}$ have their first $L_{\max}$ chips in common. The value of $L_{\max}$ is given by:

$$L_{\max} = \left\lceil \frac{\tau_{\max}}{T_c} \right\rceil \tag{3}$$

where $\tau_{\max}$ is the maximum path delay for the channel between the base-station and the user j, R_c is the chip rate and $T_c = 1/R_c$ is the chip duration.

If the spreading sequences $\{c_j\}$ and $\{c_j'\}$ have their first $L_{\max}$ chips in common, the cross-correlation of both sequences with parts of other subscriber's codes will be approximately the same [1].

It can also be shown that for m-sequences, which have length $N = 2^m - 1$, it is possible to find $(N - 1)/2$ pairs of codes with the first $m - 1$ chips in common.

In [1], a "RAKE" receiver with just one finger (one correlator or matched filter) was used, synchronized with the strongest path. The weighting coefficient at the input of this matched filter, corresponding to the weight that would be used by a Maximum Ratio Combining (MRC) rule, is the channel gain imposed to the strongest path. Although this weighting coefficient was used in [1], it has no influence on the system performance if a one-finger RAKE will be used.

Then the two decision variables for the user j are given by:

$$y_1 = \alpha_{kl_m}^{*} \int_{iT+\tau_{kl_m}}^{iT+T+\tau_{kl_m}} r_j(t) s_j(t - iT - \tau_{kl_m}) dt \tag{4}$$

$$y_2 = \alpha_{kl_m}^{*} \int_{iT+\tau_{kl_m}}^{iT+T+\tau_{kl_m}} r_j(t) s_j'(t - iT - \tau_{kl_m}) dt \tag{5}$$

Assuming that the i-th transmitted symbol for user j is +1, the decision variables y_1 and y_2 are given by [1]:

$$y_1(i) = A\left|\alpha_{kl_m}\right|^2 + I_1 + n_1 \tag{6}$$

$$y_2(i) = \rho A\left|\alpha_{kl_m}\right|^2 + I_2 + n_2 \tag{7}$$

where n_1 and n_2 are thermal noise components and I_1 and I_2 are MAI components. By recalling that the desired user's correlator is time-aligned with the strongest path, in (7) ρ is a correlation measurement between the spreading waveform of the desired user and the signals from other users that are aligned in time with that strongest path.

On the other hand, if the i-th transmitted symbol for user j is -1, y_1 and y_2 are given by [1]:

$$y_1(i) = \rho A\left|\alpha_{kl_m}\right|^2 + I_1 + n_1 \tag{8}$$

$$y_2(i) = A\left|\alpha_{kl_m}\right|^2 + I_2 + n_2 \tag{9}$$

Since the pair of spreading codes for each user has its first $L_{\max}$ chips in common, the values of the MAI components, I_1 and I_2, will be approximately the same, not influencing the decision variable. The MAI remaining is related to ρ and, for sufficient small noise components, the system proposed in [1] can always make correct decisions. This concludes the explanation about the Zare and Liu's idea.

As it will be seen later on in this paper, it was identified a limitation in the Zares's system that makes it not able to suppress the MAI when the channel is time varying. It will also be seen that our scheme does not suffer from this limitation and is less vulnerable to the operating conditions variation.

3 - The MC-CDMA System Revisited

It is somewhat a consensus that multi-carrier systems, especially those one combined with code-division multiple access techniques, are potential candidates to be used in fourth-generation wireless communication systems. One of these candidates is the MC-CDMA system proposed by N. Yee, J. P. Linnartz e G. Fettweis in [2]. It combines frequency-domain spreading with Orthogonal Frequency-Division Multiplexing (OFDM). As it can be seen from Figure 1, in this system G_{nc} copies of each information symbol $\in \{\pm 1\}$ are generated, and a chip $\in \{\pm 1\}$ of the user-specific spreading sequence of length G_{nc} multiplies each copy. The resulting signals modulate G_{nc} orthogonal carriers using, for instance, a BPSK (Binary Phase-Shift Keying) modulation.

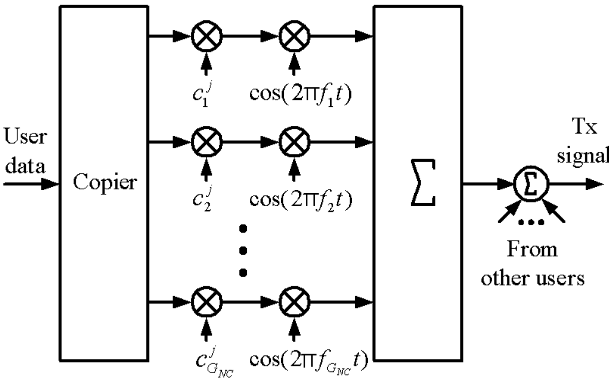

Figure 1 – The MC-CDMA transmitter

In Figure 1, G_{nc} is the system processing gain and $C_j = [c_1^j \ c_1^j \ \ldots \ c_{Gnc}^j]$ is the spreading code of the j-th subscriber.

In a frequency-selective fading channel, the frequency diversity offered by the MC-CDMA system is of particular interest and can be fully explored if the system parameters are chosen in such a way that the fading is flat in each modulated carrier and independent from one carrier to another.

4 - Description of the DC-MC-CDMA System

The proposed Double Spreading Code MC-CDMA (DC-MC-CDMA) scheme adapts the idea suggested in [1] to the MC-CDMA system considered in [2], aiming at obtaining a high frequency diversity and keeping the system almost free from MAI, even if the channel is time-varying. The DC-MC-CDMA transmitter structure is shown in Figure 2. It can be noted that, unlike the conventional MC-CDMA system shown in Figure 1, the information symbols are not frequency-spread by one user-specific code. Instead, one of the two spreading sequences per user is transmitted per each information symbol interval, depending on the current information symbol: If $b_j(i) = 1$, $C_j = [c_1^j \; c_1^j \; \ldots \; c_{Gnc}^j]$; if $b_j(i) = -1$, $C'_j = [c_1^{'j} \; c_2^{'j} \; \ldots \; c_{Gnc}^{'j}]$. Both sequences, C_j and C'_j, are chosen according to the rules stated in [1] and summarized in Section 2.

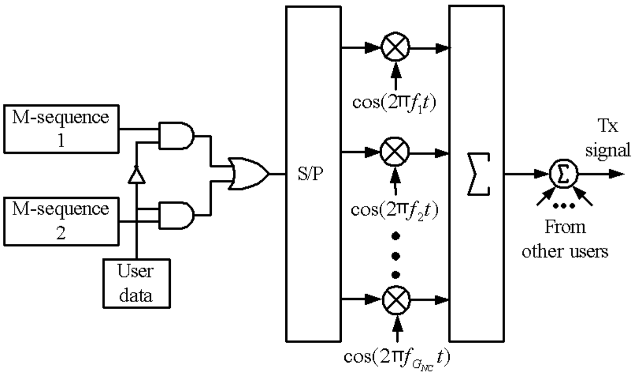

Figure 2 – DC-MC-CDMA transmitter at the base-station

The receiver structure for the proposed DC-MC-CDMA system is presented in Figure 3. The received signal is first coherently down-converted to base-band and multiplied by the equalization coefficients. A chip-by-chip frequency de-spreading operation is performed by each of the user-specific pair of spreading codes, C_j and C'_j, and the resulting signals are added to form the variables y_1 and y_2. The final decision variable is calculated by subtracting y_2 from y_1, integrating the result and sampling at the end of the integration interval. To estimate the transmitted symbol, the final decision variable is compared to zero.

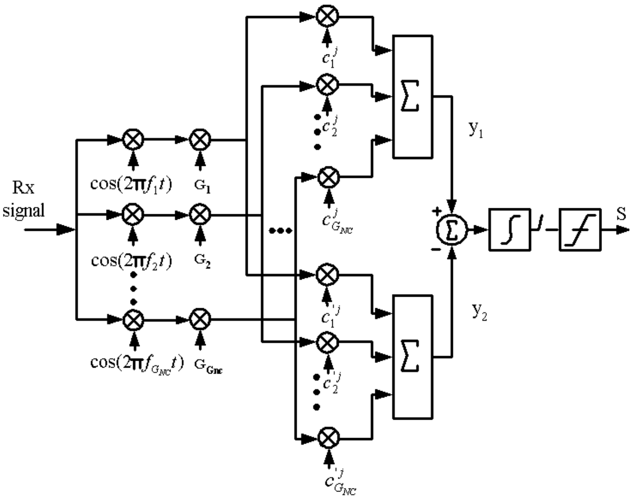

Figure 3 – The DC-MC-CDMA receiver

Since the DC-MC-CDMA employs frequency diversity, some diversity combining technique must be used. It is well-known that, for single user detection systems, Maximum Ratio Combining (MRC) is the optimum choice. However, determining the equalization coefficients according to this technique leads to an orthogonality loss among carriers, favoring the presence of MAI. The equalization coefficients can also be determined via the Zero Forcing (ZF) criteria, also known by Orthogonality Restoring Combining (ORC). This technique can totally eliminate the multi-path interference by inverting the channel response at the receiver side. In this case, the equalization coefficients are given by [3]:

$$G_l = \frac{1}{H_l} \qquad l = 1, 2, \ldots, G_{nc} \tag*{10)}$$

where H_l is the channel response in the frequency domain for the l-th carrier. A negative aspect of this equalization scheme is the noise enhancement for small values of H_l. Better results can be achieved by using other combining schemes, like the MMSE (Minimum Mean Square Error) equalization. The objective of this scheme is to reduce the mean square error between the transmitted and the equalized signals. The equalization coefficients are given in this case by [3]:

$$G_l = \frac{H_l^*}{|H_l|^2 + 1/\gamma_c} \tag{11}$$

where γ_c is the signal-to-noise ratio (SNR) per carrier. One should note that MMSE equalization is equal to the ZF equalization when $\gamma_c \to \infty$. Also, it should be noted that the MMSE scheme is more complex than ZF, since it requires current SNR estimation per carrier, although suboptimal MMSE schemes can be easily derived [3], aiming at simplifying the implementation.

5 - Simulation Results

A precise mathematical analysis of the DC-MC-CDMA system was considered to be beyond of the scope of this work, and represents itself an opportunity for future contributions. Like in Zare's case, in our system MAI analysis cannot recall the Central Limit Theorem, but instead, is strongly dependent on partial cross-correlation properties [4] of the spreading sequences. An extensive validation process was then previously conducted to guarantee the reliability of our simulation results and the conclusions drawn from these results.

Figure 4 presents the performance results of our multi-carrier system (denoted simply by MC in this figure) in comparison to the single-carrier one proposed in [1] (denoted by SC in Figure 4), as seen by one reference user in the downlink. As in [1], it was considered here a fully loaded synchronous CDMA system, with m-sequences of length 127, allowing a maximum of 63 subscribers. The channels are three-tap time-invariant ones, having gain coefficients and path delays determined according to Table 1. The MC system uses MMSE equalization. Other considerations are the same as those adopted in [1].

As it can be noted from Figure 4, MAI is practically eliminated by both systems, but our DC-MC-CDMA system can significantly outperform the one proposed in

[1] in all situations shown. Furthermore, our system is less sensitive to the variation in the channel gain coefficients. This superior performance is justified by the high order of the frequency diversity: even for the fixed channel, its frequency selectivity is enough for a diversity gain, since the bit energy is spread over 127 carriers.

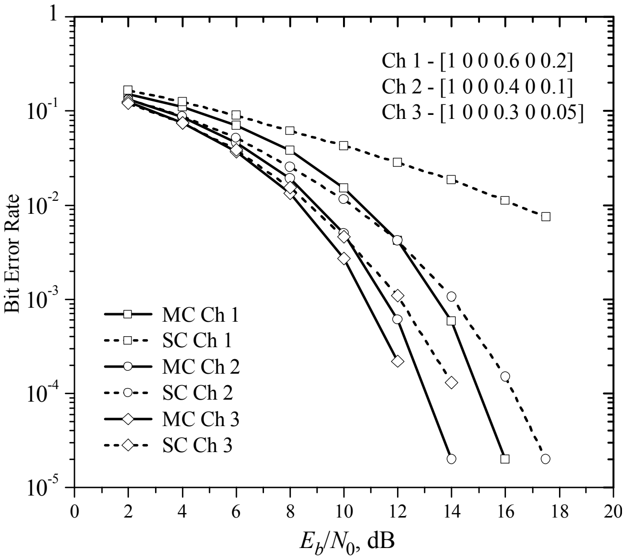

Figure 4 - Performance comparison between the DC-MC-CDMA (denoted as MC) and the system proposed in [1] (denoted as SC), on fixed multi-path channels.

Figure 5 shows the performance results of the DC-MC-CDMA system in comparison to the single-carrier one proposed in [1], as seen by a reference user in the downlink. It was also considered here a fully loaded system with length 127 *m*-sequences (maximum of 63 users). The channels are three-tap, time-varying channels with gain coefficients and path delays also determined according to Table 1. The fading is Rayleigh distributed, constant during one symbol interval, independent from symbol to symbol and correlated among carriers, this correlation being determined by the channel multi-path delay profile. As in the case of a fixed channel, the multi-carrier system uses MMSE equalization. Other considerations are the same as those adopted in [1].

Name	Path gains	Path delays	Fading model
Ch 1	1, 0.60, 0.20	0, $3T_c$, $5T_c$	Fixed for the results in Figure 4. Rayleigh for the results in Figure 5
Ch 2	1, 0.40, 0.10	0, $3T_c$, $5T_c$	
Ch 3	1, 0.30, 0.05	0, $3T_c$, $5T_c$	

Table 1 – Channel parameters considered in Figs. 4 and 5

As it can be noted in Figure 5, the system proposed by H. Zare and D. Liu in [1] is not able to cope with the channel time-varying nature, and almost all MAI are still present. On the other hand, the DC-MC-CDMA system proposed here is still able to almost eliminate the MAI.

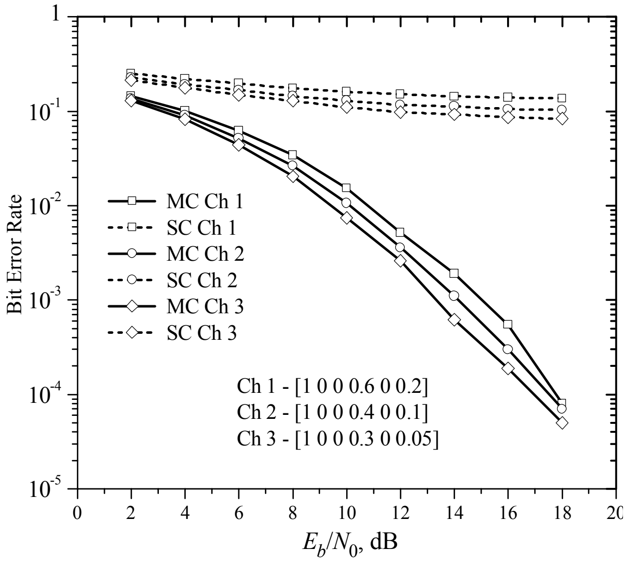

Figure 5 - Performance comparison between the DC-MC-CDMA (denoted as MC) and the system proposed in [1] (denoted as SC), on time varying multi-path channels.

6 - Conclusion

A technique was proposed here to reduce the influence of the Multiple Access Interference on the downlink of a Multi-Carrier, Code-Division Multiple Access system, without resorting to a Multi-User Detection strategy. The technique is adapted from the idea suggested in [1], and is based on the use of a spreading sequences pair for each subscriber. Although the limiting factor to the system capacity is that the maximum number of active users is halved, as compared to the case in which a single spreading code per user is adopted, MAI can be almost eliminated for both fixed and time-varying, frequency selective, multi-path fading channels.

It was also verified that in the case of a small number of users, the sensitivity of the suggested system by changing the user of reference is lower than that achieved by the system proposed in [1]. In a fully loaded situation, the sensitivity of both systems is roughly the same. If the channel is time varying, our system is even less sensitive.

References

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