SOME EXTENSIONS TO SYNCHRONOUS O/O SYSTEMS

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Abstract- We discuss some extensions to the conventional OCDMA/OCDMA (O/O) system. First of all, synchronous O/O, defined for spreading gain N = 2^n is extended to any spreading gain that is a multiple of 4. In a second step, we consider the performance of O/O systems, where the signatures of the two orthogonal sets are displaced with respect to each other. It is found that this displacement can result in a significant performance improvement.

I. INTRODUCTION

Many aspects of time-alignable Code-Division Multiple Access (CDMA) systems have been studied extensively in literature. This time-alignment can easily be realized in the downlink, since all user signals originate from the same base station. For the uplink, however, strict time alignment requires an unrealistically stringent synchronization of the users. Nevertheless, with multicarrier-CDMA, the signal alignment can be maintained for much weaker synchronization requirements, by application of an appropriate cyclic prefix and single-tap equalization [1]. This makes the study of CDMA systems with time aligned signatures justified both for uplink and downlink transmission.

For undersaturated systems (i.e. the number of users K ≤ spreading gain N) that can be aligned in time, one can eliminate the interference between the users by making the users symbol-synchronous, combined with the assignment of orthogonal signatures (OCDMA) to the users. If K exceeds N, one can extend the set of N orthogonal signatures by means of another set of M (≤ N) orthogonal signatures, resulting in the OCDMA/OCDMA (O/O) system [2-4]. This system has the advantage over other signature sets (e.g. random spreading [5]) that the interference levels among the users are drastically reduced. Indeed, since the first N users (‘set 1 users’) are assigned orthogonal signatures, they will suffer exclusively from interference of the remaining set of M users (‘set 2 users’). At the other hand, also the set 2 users are orthogonal, so that they suffer from interference of the set 1 users only. In addition to this, thanks to the lower interference levels of the set 1 users, interference cancellation is favored where the set 1 users are detected prior to the set 2 users at each stage of the iteration process [3].

Under the restriction of binary chips, binary O/O was defined in [2-4] for N = 2^n, where the signatures were built up from the Walsh-Hadamard vectors \(\text{WH}_N^{(i)}\) (i = 1,…,N) of order N [6]. The signatures of the set 1 and set 2 users are these Walsh-Hadamard vectors, overlaid by means of a set-specific scrambling sequence. Depending on the nature of these scrambling sequences, two particular types of O/O are the ‘Quasi-Orthogonal Sequences’ (QOS) [7] and ‘random O/O’ [3]. For QOS, the scrambling sequence of the set 1 users is absent, while the scrambling sequence of the set 2 users is a fixed bent sequence. For random O/O, both scrambling sequences take one value of \(\{1,-1\}^N\) with equal probability in every symbol interval.

Complete binary orthogonal Hadamard signature sets are known to exist for all spreading gains that are a multiple of 4 (< 428). Hence, we can easily extend random O/O to any spreading factor N = 4k. In addition to this, one can extend these O/O systems to more general ones, by allowing the signatures of the users of different sets to be displaced with respect to each other. In this way, we have an additional degree of freedom at our disposition to manipulate the crosscorrelation between the users. In section II and III, we discuss the system model and the MUltiuser Detector (MUD) [8], respectively. Section IV presents the simulation results, and the paper is concluded by section V.

II. SYSTEM MODEL

In O/O systems, the set 1 users are assigned orthogonal sequences, so that they have to be perfectly aligned in time in order to preserve their orthogonality. The same requirement holds for the set 2 users. Although conventional O/O systems align all signatures perfectly in time, there is actually no need to align the signatures of the set 1 and set 2 users in order to preserve the orthogonality within the two sets. Hence, the displacement \(\tau\) of the set 2 signatures with respect to the set 1 signatures is a degree of freedom that has been overlooked in the conventional system. In this paper, we will restrict our attention to chip-synchronous systems, so that all chip pulses are aligned in time, while the symbol intervals of different sets are allowed to be unaligned.

Consider such a chip-synchronous random O/O system with \(K (= N+M)\) users and spreading factor \(N\), where the set 2 users are displaced over \(n\) chip intervals of length \(T_c\) with respect to the set 1 users. We assume that the databits \(a_k(i)\) of each user \(k\) (\(k = 1,...,K\)) are transmitted in bursts \(a_k = (a_k(1), ..., a_k(L))\) of length \(L\). The signal of interest for one burst is then

\[
S(t) = \sum_{k=1}^{N} s_k(t) + \sum_{k=N+1}^{K} s_k(t-nT_c) + w(t)
\]  

(1)
where signal $s_k(t)$ of user $k$ is given by

$$s_k(t) = \sum_{i=1}^{L} a_k(i) \left[ \sum_{j=1}^{K} \beta_k^{(i)}(j)\cdot p_j(t - i, NT_c - jT_c) \right]$$

(2)

In these expressions,

- $\beta_k^{(i)} = \left[ \beta_k^{(i)}(0), ..., \beta_k^{(i)}(N-1) \right] \in \{1/N, -1/N \}^N$ is the binary signature sequence of user $k$ in symbol interval $i$.
- The signatures of the set 1 and set 2 users are obtained by overlaying a set of Hadamard vectors $H_N^{(i)}$ ($i = 1, ..., N$) of order $N$ by means of the scrambling sequences $\Phi^{(i)}$ and $\Phi^{(i)}$, respectively:

$$\beta_k^{(i)} = \text{diag}(\Phi^{(i)}(0), ..., \Phi^{(i)}(N-1)), H_N^{(i)} \quad k = 1, ..., N$$

(3)

$$\beta_k^{(i)} = \text{diag}(\Phi^{(i)}(0), ..., \Phi^{(i)}(N-1)), H_N^{(i)} \quad k = N+1, ..., K$$

Both scrambling sequences are independent and take one of the values of $\{1, -1 \}^N$ with equal probability in every symbol interval.

- $p_j(t)$ is a unit-energy chip pulse with chip duration $T_c$.
- The associated pulse $\phi_j(t)$, obtained after matched filtering of $p_j(t)$, is assumed to be a Nyquist pulse, i.e., $\phi_j(tT_c) = \delta_\tau$.
- $w(t)$ is real-valued white Gaussian noise with spectral density $\sigma^2$.

In order to obtain observables $y_k = (y_k(1), ..., y_k(L))$ for the detection of $a_k$ ($k = 1, ..., K$), $S(t)$ is first applied to the matched filter $p_j(-t)$, sampled at the time instants $(iN+j)T_c$ (set 1 users) or $(iN+j+n)T_c$ (set 2 users), followed by a correlation with signature $\beta_k^{(i)}$ for $i = 1, ..., L$. This yields for $y_k(i)$:

$$y_k(i) = \begin{cases} a_k(i) + \sum_{j=1}^{K} Y_j^{(i)}[a_j(i) - 1], & k \leq N \\ a_k(i) + \sum_{j=N+1}^{K} Y_j^{(i)}[a_j(i) + 1], & k > N \end{cases}$$

(4)

where $w(t)$ is a Gaussian noise sample with variance $\sigma^2$, and $Y_j^{(i)}$ is the contribution of user $j$ on $y_k(i)$:

$$Y_j^{(i)}[a_j(i) - 1] = a_j(i - 1), \rho^{(i)}(0, N-n) + a_j(i), \rho^{(i)}(0, n)$$

(5)

$$Y_j^{(i)}[a_j(i) + 1] = a_j(i), \rho^{(i)}(0, N-n) + a_j(i - 1), \rho^{(i)}(0, n)$$

In expression (5), $a_j(0)$ and $a_j(L+1)$ have to be put to zero for all $j$, and

$$\rho^{(i)}(m, \Delta_1, \Delta_2) = \sum_{m=0}^{\min\{N-1, \Delta_1 \}} \sum_{n=0}^{\min\{N-1, \Delta_2 \}} b_k^{(m+\Delta_1)}(m+\Delta_2)$$

(6)

III. INTERFERENCE CANCELLATION

Thanks to the special nature of the interference levels of O/O systems, the set 1 users suffer from less MUltiuser Interference (MUI) than the set 2 users, as long as $M < N$. As a consequence, a sensible way to detect the users is by means of an interference canceller [8], where the set 1 users are detected in parallel prior to the parallel detection of the set 2 users at each stage of the cancellation.

To obtain a tentative decision $\hat{a}_k(i)$ of the set 1 user $k$ ($k = 1, ..., N$) at iteration $I$, we cancel the MUI of the set 2 users on the set 1 users, based on the tentative decisions for the databits of the set 2 users, obtained at iteration $1(I)$:

$$\hat{a}_k^{(I)}(i) = \Phi_{ao} \left[ y_k(i) - \sum_{j=N+1}^{K} Y_j^{(i)}(\hat{a}_j^{(I)}(i-1), \hat{a}_j^{(I)}(i)) \right]$$

(7)

where $\Phi_{ao}(x)$ is given by

$$\Phi_{ao}(x) = \begin{cases} \text{sign}(x) & |x| > \omega \\ x & |x| \leq \omega \end{cases}$$

(8)

Note that $\hat{a}_j^{(I)} = 0$ ($j = 1, ..., K$). Parameter $\omega \in [0,1]$ is selected by means of computer simulations in order to optimize the performance. Its value is typically about 0.7.

Likewise, the tentative decisions $\hat{a}_k^{(I)}$ for the set 2 users $k$ ($k = N+1, ..., K$) at iteration stage 1 are obtained by a cancellation of the MUI caused by the set 1 users, based on the tentative decisions of the set 1 users that have previously been obtained at that iteration stage:

$$\hat{a}_k^{(I)}(i) = \Phi_{ao} \left[ y_k(i) - \sum_{j=1}^{N} Y_j^{(i)}(\hat{a}_j^{(I)}(i), \hat{a}_j^{(I)}(i+1)) \right]$$

(9)

IV. SIMULATION RESULTS

For all simulations, the system performance is evaluated by means of the critical overload. We define the critical overload as the maximum achievable channel overload $\beta_{max} = (K_{max} - N)/N$ with interference cancellation, so that the required SNR ($= 1/\sigma^2$) for an average BER $= 10^{-5}$ is less than 0.35 dB above the required SNR of a single user system that achieves the same BER. It is a measure for the maximum acceptable channel overload, so that the system performance is degraded only slightly as compared to the single user performance.

Simulations have been performed for system (1) with random O/O for all spreading factors, varying from $N = 16$ up to 200, that are a multiple of 4. For $N = 16, 32, 64$ and 128, we have selected the well-known Walsh-Hadamard vectors of order $N$ [6] as the Hadamard vectors (see (3)). The length of the databursts is taken as $L = 100$, and the number of iterations in the interference canceller has been restricted to 10.

In figure 1, the critical overload is shown for $N = 32, 64$ and 128 and shifts $n/N$ varying from 0 to 0.5. We notice that...
the conventional random O/O system (i.e. n = 0) has the worst performance of all possible time-shifted random O/O systems. For \( N = 32, 64 \) and 128, we see that the optimal performance is obtained for a displacement \( n = N/2 \), allowing for a critical overload that is more than respectively 8, 4 and 2 times higher than that of the corresponding conventional random O/O system.

![Critical overload as a function of n/N.](image1)

Figure 1: Critical overload as a function of n/N.

Figure 2 compares the critical overload for 1) the conventional O/O system, 2) improved O/O where n takes a random value of \([0, \ldots, N-1]\), and 3) improved O/O with \( n = N/2 \). It can be observed for every system that the critical overload has the trend to increase with increasing spreading factor. Nevertheless, the critical overload is degraded severely for all systems at the spreading factors \( N = 32, 64 \) and 128, where Walsh-Hadamard sequences are used to build up the system. This implies that the use of Walsh-Hadamard vectors results in an inferior performance as compared to other Hadamard vectors. This inferiority is most pronounced for the conventional O/O system.

Another observation from figure 2 is that the critical overload can be increased as compared to the conventional O/O systems, for all spreading factors, by allowing n to take on any random value. Moreover, fixing n to N/2 results for (almost) all spreading factors in a superior performance as compared to systems with random n. In this way, critical overloads of about 64% can be achieved.

V. CONCLUSION

In this paper, we extended the conventional O/O system to an improved O/O system where the signature sequences of the two different orthogonal sets are displaced in time with respect to each other. In addition to this, binary improved systems can be constructed for any spreading factor that is a multiple of 4. With interference cancellation, we found that

- A random displacement of the signatures results in a significantly better performance of the O/O system.
- For any system, the allowable channel load has the trend to increase with increasing spreading factor.
- An even higher critical load can be achieved by selecting a time shift that equals N/2. This is the best choice for N = 32, 64 and 128. In this way, critical overloads up to 64% can be realized.
- The choice of Walsh-Hadamard sequences for the O/O system at \( N = 2^k \) turns out to result in an inferior performance as compared to the performance with Hadamard vectors of about the same dimension.

![Critical overload for three different O/O systems.](image2)

Fig. 2: Critical overload for three different O/O systems.

REFERENCES