SLOW FREQUENCY HOPPING ASSISTED MC DS-CDMA USING LARGE AREA SYNCHRONISED SPREADING SEQUENCES

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ABSTRACT

The family of Multi-Carrier Direct-Sequence CDMA (MC DS-CDMA) systems exhibits numerous attractive properties, which render them attractive candidates for next-generation wireless communications. We demonstrate that spreading codes exhibiting a so-called interference-free window (IFW) are capable of outperforming classic spreading codes, when the interfering multi-user and multipath components arrive within this IFW. The best possible quasi-synchronous timing of the spreading sequences has to be adjusted with the aid of accurate adaptive timing advance control, which has to be significantly more accurate than that used in the lower-bit-rate second-generation GSM system. Firtunately, the IFW duration may be extended with the advent of multi-carrier DS-CDMA proportionately to the number of subcarriers. Hence the resultant MC DS-CDMA system is capable of exhibiting a near-single-user performance without employing a multi-user detector. A deficiency of the resultant system is that the number of spreading codes exhibiting a certain IFW is limited and so is the IFW duration. This contribution sets out to mitigate the above-mentioned shortcomings so that when the users' delays are in the range of the IFW, we separate them with the aid of the unique, user-specific LAS spreading codes. By contrast, when the users roam at a high distance from the base-station and hence their received signal arrive outside the range of the IFW, we separate them using their unique frequency hopping patterns.

1. INTRODUCTION

The concept of slow Frequency Hopping (FH) aided multicarrier DS-CDMA (SFH/MC DS-CDMA) using constant-weight FH patterns activating a fixed number of activated subcarriers during all FH intervals was proposed in [1–3]. This scheme is capable of amalgamating the benefits of slow FH, OFDM [4] and DS-CDMA. This scheme exhibits several advantages, such as supporting flexible multirate and variable rate services, maintaining a high diversity gain, as well as supporting backwards compatibility with the operational 2nd- and 3rd-generation mobile wireless systems, while providing more powerful features for future broadband wireless communication systems. In [2], the authors employed Pseudo-Noise (PN) spreading codes, exhibiting non-zero off-peak auto-correlations and cross-correlations. These correlation properties potentially result in a high Multiple Access Interference (MAI) and limit the achievable capacity of the network. Recently, the attractive family of Large Area Synchronized (LAS) CDMA spreading sequences has been proposed, which is constituted by the combination of the so-called Large Area (LA) codes [5, 6] and Loosely Synchronous (LS) codes [7]. The resultant LAS codes exhibit an Interference Free Window (IFW) [5, 6], where both the off-peak aperiodic autocorrelation values as well as the aperiodic cross-correlation values become zero, resulting in zero Inter-Symbol Interference (ISI) and zero MAI, as long as both the propagation delay-induced and the uncoordinated asynchronous time-offset of the spreading codes is within the IFW. Provided that these conditions are satisfied, a major benefit of the LAS codes is that they are capable of achieving a near-single-user performance without multi-user detectors. More specifically, interference-free CDMA communications become possible, when the total time-offset expressed in terms of the number of chip intervals, which is the sum of the time-offset of the mobile terminals plus the maximum channel-induced delay spread is within the designed IFW.

In order to ensure that the relative time-offsets between the codes are within the IFW, the mobiles are expected to operate in a quasi-synchronous manner. In case of high transmission-delay differences accurate timing-advance control has to be used [8]. Again, a further price that has to be paid in exchange for near-interference-free communications, while dispensing with high-complexity and power-hungry multi-user detection (MUD) is that the system may become 'code-limited' [9]. Hence, in [9] a number of techniques have been proposed for circumventing these limitations.

By contrast, in this contribution, we will consider SFH and code hopping (CH) assisted MC DS-CDMA (SFH-CH MC DS-CDMA) to circumvent this potential synchronization problem associated with the limited-duration-IFW as well as with the limited number of LAS codes. The principle of the proposed SFH-CH MC DS-CDMA is that when the users' delays are in the range of the IFW, we separate

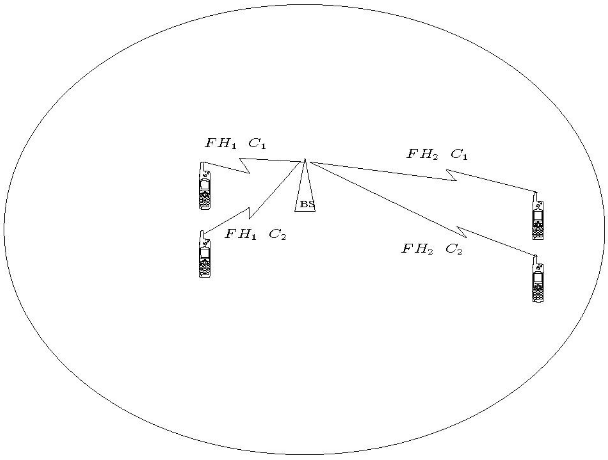

Figure 1: The cellular scenario considered

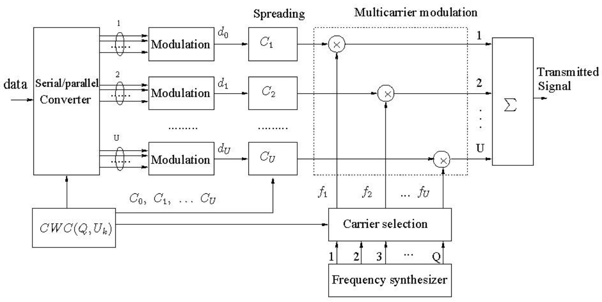

Figure 2: The proposed transmitter

them with the aid of the unique, user-specific LAS spreading codes. By contrast, when the users roam at a high distance from the Base-Station (BS) and hence their received signals arrive outside the range of the IFW, we separate them using their unique frequency hopping patterns. As shown in Figure 1, the two users at the left are close to the BS and hence their associated delays are within the range of the IFW, therefore we separate them using the LAS spreading codes C_1 and C_2. By contrast, the delay-induced timing-offset between the users at the left and those at the right exceeds the zero-range of the IFW, hence we have to separate them with the aid of their unique, user-specific frequency hopping patterns FH_1 and FH_2. Hence, the proposed FH-CH MC DS-CDMA system will enable us to suppress the effects of MAI.

The organization of this paper is as follows. Section 2 describes our system model, Section 3 characterizes the achievable performance of the proposed system, while Section 4 provides our performance study. Finally, Section 5 offers our conclusions.

2. SYSTEM MODEL

The model of the transmitter and the multiple access channel used in the analysis of the SFH/MC DS-CDMA system is depicted in Fig. 2. In the figure, CWC(U, U_k) represents a Constant-Weight Code (CWC) of user k having U_k number of '1's and $(U - U_k)$ number of '0's, where the presence of a logical '1' indicates an activated subcarrier frequency. Hence, the Hamming-weight of CWC(U, U_k) is U_k. This code is read from a so-called CWC book [3], which represents the frequency-hopping patterns. Theoretically, the size of the CWC book is given by $\binom{U}{U_k} = U!/U_k!(U-U_k)!$. To elaborate a little further, the CWC(U, U_k) plays two different roles. *Its first role* is that its weight - namely U_k - determines the number of activated subcarriers invoked, while *its second function* is that the positions of the U_k number of binary '1's determine the selection of a set of U_k number of activated subcarrier frequencies from the U number of frequency synthesizer outputs. At the transmitter of the kth user seen in Fig. 2 the bit stream having a bit duration of T_b is first serial-to-parallel (S-P) converted, yielding U_k parallel streams, which are mapped to the subcarriers activated by the CWC(U, U_k). Following the Serial-to-Parallel (SP) conversion stage, the symbol duration of the SFH/MC DS-CDMA signal is extended and becomes $T_s = U_k T_b$. Recall that as a second benefit of the proposed CWC, multi-rate transmission can be supported by controlling the weight of the code CWC(U, U_k). As seen in Fig. 2, after serial-to-parallel conversion each stream is DS spread. Each of the K users in the proposed system will be assigned a unique, user-specific LAS spreading code $c_k(t)$, specifically selected according to its delay. In this contribution, the family of LS(4,32,4) [5,6] codes is invoked, which includes four groups of LS codes. The spreading codes in the same group will exhibit an IFW width of $\iota = 3$ chips, while the spreading codes from different groups will have an IFW of $\iota = 0$ chips, *i.e.* they are orthogonal only in case of perfect synchronization. Finally, the transmitted signal of the kth user can be expressed as:

$$s_k(t) = \sum_{u=0}^{U_k-1} \sqrt{2P} b_{ku}(t) c_k(t) \cos\left(2\pi f_u^{(k)} t + \varphi_u^{(k)}\right), \tag{1}$$

where P represents the transmitted power per carrier, while U_k indicates the weight of the CWC currently employed by the kth user. Furthermore, $b_{ku}(t)$ represents the current data stream's waveform, $c_k(t)$ denotes the kth user's DS spreading waveforms, while $\left\{f_u^{(k)}\right\}$ and $\left\{\varphi_u^{(k)}\right\}$ represent the current subcarrier frequency set and modulation phase set, respectively.

The conventional matched filter based RAKE receiver using Maximum Ratio Combining (MRC) can be invoked for detection, as shown in Fig. 2, where we assume that L number of diversity paths are available. In contrast to the transmitter side, where only U_k out of U activated subcarriers are transmitted by user k, at the receiver all U subcarriers are always tentatively demodulated. Specifically, if the receiver has the explicit knowledge of the FH patterns and the spreading code $c_k(t)$, the information bits conveyed by different subcarriers can be detected.

3. PERFORMANCE ANALYSIS

The conventional matched filter based RAKE receiver using MRC may be invoked for detection, where we assume that the RAKE receiver is capable of combining only L_r of the L_p number of resolvable diversity paths, since only a limited detection complexity is affordable. We assume that we have established time synchronization and that we benefit from perfect estimates of both the channel and perfect knowledge of the FH patterns employed by the different users. The individual matched filter outputs are appropriately delayed, in order to coherently combine the L_r number of signal paths processed by the RAKE combiner. Without loss of generality, our analysis focused on considering the first subcarrier, which is activated by K_h number of users. More explicitly, the number of frequency hopping hits [10] at this subcarrier was K_h. For convenience, we ignore the subscript of this subcarrier. Hence, the lth RAKE combiner finger's output Z_{kl} is sampled at $t = T + lT_c + \tau_k$, in order to detect the kth user's symbol $b_k[0]$ transmitted on the first subcarrier, which is expressed as:

$$Z_{kl} = D_{kl} + I_{kl}, \tag{2}$$

where D_{kl} represents the desired signal component, which can be expressed as:

$$D_{kl} = \sqrt{2P}T_s b_k[0] h_{kl}^2. \tag{3}$$

In Equation 3 $b_k[0]$ is the first bit transmitted by the kth user, where we have $b_k[0] \in \{+1, -1\}$. Hence, the interference plus noise term I_{kl} in Equation 2 can be expressed as:

$$I_{kl} = I_{kl}[S] + I_{kl}[M] + N_k, \tag{4}$$

where $I_{kl}[S]$ represents the Multipath Interference (MPI) imposed by the user-of-interest, which can be formulated as:

$$\begin{aligned} I_{kl}[S] &= \sqrt{2P}T_s h_{kl} \sum_{\substack{l_p=0 \\ l_p \neq l}}^{L_p-1} \frac{h_{kl_p} \cos\theta_{kl_p}}{T_s} \\ &\times \int_0^{T_s} b_k[t-(l_p-l)T_c] \cdot c_k[t-(l_p-l)T_c] c_k[t] dt. \end{aligned} \tag{5}$$

Furthermore, $I_{kl}[M]$ represents the MAI inflicted by the $K-1$ number of interfering signals, which can be expressed as:

$$\begin{aligned} I_{kl}[M] &= \sqrt{2P}T_s h_{kl} \sum_{\substack{k'=1 \\ k' \neq k}}^{K_h} \sum_{l_p=0}^{L_p-1} \frac{h_{k'l_p} \cos\theta_{k'l_p}}{T_s} \\ &\cdot \int_0^{T_s} b_{k'}[t-(l_p-l)T_c-(\tau_{k'}-\tau_k)] \times \\ &c_{k'}[t-(l_p-l)T_c-(\tau_{k'}-\tau_k)] c_k[t] dt. \end{aligned} \tag{6}$$

In Equations 5 and 6 the $\cos(\cdot)$ terms are contributed by the phase differences between the incoming carrier and the locally generated carrier used by the demodulator. Finally, the noise term in Equation 4 can be expressed as:

$$N_{kl} = h_{kl} \int_0^{T_s} n(t) c_k[t] \cos(2\pi f_c t + \theta_{kl}) dt, \tag{7}$$

which is a Gaussian random variable having a zero mean and a variance of $N_0 T_s h_{kl}^2$, where $\{h_{kl}\}$ represents the path attenuations.

The MRC's decision variable Z_k, which is given by the sum of all the RAKE fingers' outputs, can be expressed as:

$$Z_k = \sum_{l=0}^{L_r-1} Z_{kl}. \tag{8}$$

Following a similar procedure to that described in [11] and a range of arduous, but fairly standard calculations, the corresponding Bit Error Ratio (BER) formula becomes:

$$\begin{aligned} P_b(E) &= Q\left(\sqrt{\frac{(\mathrm{E}[Z_k])^2}{\mathrm{Var}[Z_k]}}\right) & (9) \\ &= \frac{1}{\pi} \int_0^{\pi/2} \prod_{l=0}^{L_r-1} \left(\frac{m \sin^2\theta}{\overline{\gamma}_l + m\sin^2\theta}\right)^m d\theta, & (10) \end{aligned}$$

where $\overline{\gamma}_l = \gamma_c e^{-\eta l}$ $l = 0, 1, \ldots, L_r - 1$, represents the negative exponentially decaying channel impulse response (CIR). For a random spreading code the corresponding expression of γ_c is given by [11]:

$$\gamma_c = \left[\frac{K_h q(L_p, \eta)}{G} + \frac{q(L_p, \eta) - 1}{G} + \left(\frac{\Omega E_b}{N_0}\right)^{-1}\right]^{-1}, \tag{11}$$

while for the LAS CDMA system advocated, we have [11]:

$$\gamma_c = \left[\frac{\Upsilon_S(l)}{G} + \frac{K_h \Upsilon_M(l)}{G} + \left(\frac{\Omega_0 E_b}{N_0}\right)^{-1}\right]^{-1}. \tag{12}$$

As we can observe in Eq.(12), the performance of the proposed SFH/CH LAS MC DS-CDMA is dependent on the number of frequency hopping hits K_h, on the E_b/N_0 value encountered and on the MAI factors $\Upsilon_M(l)$, $\Upsilon_s(l)$. Hence the CWC-based frequency hopping and code hopping scheme is expected to minimize the average product of $K_h \Upsilon_M(l)$, because it can be shown that it is the MAI, which dominates the total interference encountered by the system, which hence predetermines the attainable BER.

Here we continue our discourse by proposing a low-complexity technique of selecting the optimum frequency hopping and code hopping pattern. Without loss of generality, we assume that the users' delays $\tau_1 \leq \tau_2 \leq \ldots \tau_K$. As illustrated in [11], the factors $\Upsilon_S(l)$ and $\Upsilon_M(l)$ are relatively low, when the users' delays are within the range of the IFW. Hence, we partitioned the total number of users K into four different groups according to the users' delay. Each group had the same number of $K/4$ users. Then we selected four different CWC(Q, U) FH codes for these four groups of users, where these FH codes have the maximum possible Hamming distance [10]. In each group, every user will be assigned to a unique, user-specific LAS spreading code. Hence the total number of users supported becomes the product of the number of LAS codes and the number of CWCs. Therefore, given the indices of both the LAS code and of the CWC, the corresponding user index is uniquely identified.

4. NUMERICAL RESULTS

In our investigations we compared a traditional and a LAS-code based SFH MC DS-CDMA system. The associated system parameters are summarized in Table 1.

In the LAS-CDMA 2000 system [12] the LA(2552,136,17) and LS(4,32,4) codes are combined. More explicitly, the total length of the LS(N, P, W_0) =LS(4,32,4) code is $L_s = NP + 2W_0 = 136$ chips, which is incorporated into the LA(L_A, M, K) = LA(2552,136,17) code, as detailed in [6]. Although the length of this LS code is $L_S = NP + 2W_0 = 136$ chips, the effective spreading gain of the LAS code is identical to that of its constituent LS codes, namely $G_{\text{LAS}} = G_{\text{LS}} = 128$, because the zero-valued section of the spreading code does not increase the attainable spreading factor. By contrast, a traditional random code based CDMA system having the same $L_A = 2552$ number of chips would have a higher spreading gain, since it does not have any zero-valued gaps, and therefore has no IFW. Hence the corresponding equivalent spreading gain becomes $G_{\text{Random}} = 2552/17 = 151$. Furthermore, we assume that the channel's maximum delay spread was $\tau_{ch} = 3\mu s$, hence the number of resolvable paths became $L_p = \lfloor \frac{\tau_{ch}}{T_c} \rfloor + 1$ [3]. The width of the IFW was $\iota = 3T_c$ and the maximum delay difference of the users was $\tau_{max} = 15\mu s$, which corresponds to a cell radius of 4.5km, while the negative exponential MIP's decay factor was $\eta = 0.2$.

Fig. 3 portrays the BER performance of the proposed SFH/CH LAS MC DS-CDMA when each subcarrier experienced independent narrow-band Rayleigh fading. More explicitly, the chip duration T_c of each subcarrier was higher than the channel's delay spread τ_{ch}, which hence results in $L_p = 1$ resolvable path. Here the chip rate of each of the $Q = 8$ subcarriers was $320k$chips/s, which was a factor of $Q = 8$ lower than that of an identical-bandwidth single-carrier CDMA system. Hence the MC-CDMA system's IFW was extend by an identical factor, allowing for commensurate cell-size extension. Observe in Fig. 3 that SFH/CH LAS MC DS-CDMA invoking the proposed LAS codes and orthogonal CWC-based frequency hopping is capable of approaching the single-user performance. Furthermore, the performance of the proposed frequency hopping

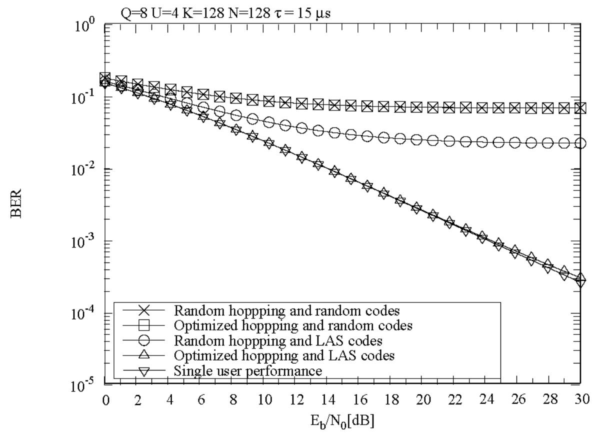

Figure 3: BER versus E_b/N_0 performance of SFH/CH MC LAS DS-CDMA, when each subcarrier is subjected to independent narrow-band Rayleigh fading. The system parameters were summarized in Table 1.

scheme described in Section 3 was significantly better performance than that of the traditional random codes combined with random FH.

Fig. 4 characterizes the attainable performance of the SFH/CH LAS MC DS-CDMA system, when the chip rate of each subcarrier is $1.2288M$chips, which is similar to that of the Chinese Time-Division Duplex (TDD) CDMA system [13]. Hence the number of resolvable paths is $L_p = \lfloor \frac{\tau_{ch}}{T_c} \rfloor + 1 = 4$. For simplicity's sake, we assume that all paths have the same Nakagami fading parameter [3], *i.e.* we have $m_l = m$, $l = 0, \ldots, L_r - 1$, and the negative exponential MIP's decay factor was $\eta = 0.2$. We observe in Fig. 4 that the performance of SFH/CH LAS MC DS-CDMA invoking the LAS codes combined with CWC-based frequency hopping now exhibited a 4dB E_b/N_0 performance degradation in comparison to the single-user performance at a BER of 10^{-3}, although it remained significantly better than that of the traditional random codes combined with random FH.

Finally, Fig. 5 displays the performance of the proposed system, when supporting multi-rate services, where the chip-rate of each subcarrier is $1.2288M$chips. Hence we assume that U_k is uniformly distributed in the interval $[1, Q]$ between activating a single carrier and all the carriers. From Fig.5 we observe that the system's performance becomes inferior in comparison to the fixed rate scenario associated with $U_k = U, k = 1, \ldots, K$ when supporting multi-rate services, since the randomly activated subcarriers of multi-rate service increase the "hit" probability [10]. Nonetheless, the system's performance still remains superior in comparison to that of the traditional random code based system.

5. CONCLUSIONS

In this paper we investigated the performance of a novel SFH LAS MC DS-CDMA system, which is capable of cir-

Parameters	Values
Channel	Nakagami-m
Negative exponential MIP decay factor	$\eta = 0.2$
Channel's delay spread	$\tau_{ch} = 3\mu s$
Asynchronous delay difference of uplink	$\tau_{max} = 5,\ 15\mu s$
Number of resolvable path L_p	$\lfloor \tau_{ch}/T_c \rfloor + 1$
LAS spreading code	LA(2552,136,17)+ LS(4,32,4) [6]
Q	8
U	4

Table 1: Parameters of the proposed SFH MC DS-CDMA system.

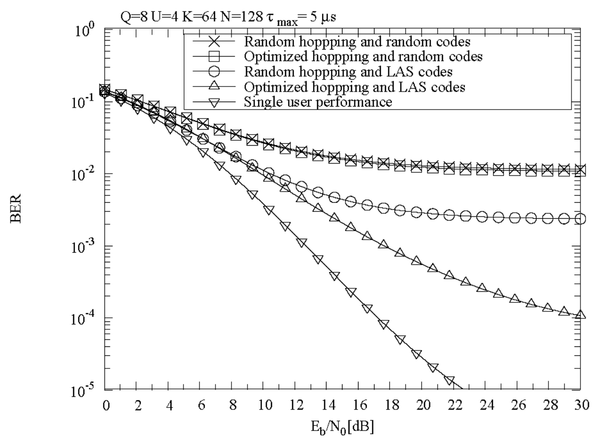

Figure 4: BER versus E_b/N_0 performance of SFH/CH MC LAS DS-CDMA when the chip rate of each subcarrier was $1.2288M$chips. The system parameters were summarized in Table 1.

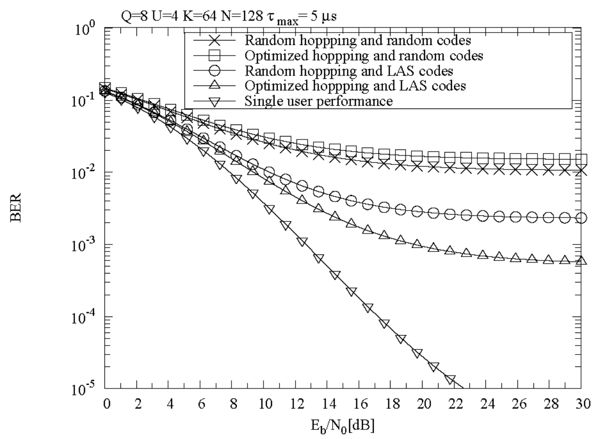

Figure 5: BER versus E_b/N_0 performance of SFH/CH MC LAS DS-CDMA when the chip rate of each subcarrier is $1.2288M$chips and the multi-rate services we supported by activating a various number of subcarriers ranging between one and Q. The system parameters were summarized in Table 1.

cumventing the strict timing advance control requirement of an identical system dispensing with SFH. As a benefit, the proposed system becomes capable of approaching the single-user-performance, while dispensing with the employment of MUDs. Furthermore, the system advocated exhibited a high flexibility in terms of supporting multirate services.

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