Analysis of CDMA Systems with Variable Spreading Factors

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Abstract: We present an analytical model that extends previous analyses of CDMA systems in practical multipath environments where users can operate at different bit rates. This scenario is of interest for the Wideband CDMA strategy employed in UMTS, and the model permits to compare performances of classic and more innovative spreading signals.

Key-Words: DS-SS, WCDMA, Spreading Sequences, Multipath, Bit Error Rate

1 Introduction

The introduction of the Wideband CDMA (WCDMA) technique in the mobile radio third generation standard (3G-UMTS) [1] has given new impetus to the development of analytical models able to predict the effect of multi-user interference (MUI) in a multipath environment. One peculiar feature of WCDMA is the possibility, it offers, to operate with different values of the bit rate R_b, even variable with time, while maintaining constant the chip rate R_c, and therefore the bandwidth occupancy. This facility permits to manage efficiently different services (High/Medium quality video, Mobile office/Internet graphics, Internet text, Voice, Messaging/SMS), that are intrinsically characterized by different user data rate requirements. Previous classic formulas for performance evaluation of CDMA systems must be suitably adapted for taking into account this new scenario, where interfering bits with different time duration can coexist.

Another interesting issue concerns the choice of the spreading sequences. 3G-UMTS uses Orthogonal Variable Spreading Factor (OVSF) codes for channeling and Gold codes and S(2) codes for scrambling, actually achieving generally good performance. Anyway, discussion is in progress about the opportunity to change the spreading sequences in the next (fourth) generation of mobile communications [2]. An attractive opportunity, in this sense, consists in the usage of chaotic signals.

The object of this paper is to present a general approach which permits to take into account either variable bit rates or “non-canonical” spreading codes. Error rate analyses for multirate CDMA schemes have been already reported in previous literature [3]-[5]. Most of these studies, however, used the standard Gaussian approximation, that is known to provide, in many cases, much more optimistic results than the true bit error rate. Moreover, some of them were limited to the analysis in presence of thermal noise only, which is unrealistic for the considered applications, and/or were focused on the systems using multicode rather than variable spreading gain. At the best of our knowledge, only in [6] an analytical model was first presented with the aim to take into account the true interference distributions, removing the Gaussian approximation and providing a more realistic evaluation of the bit error rate. A performance comparison was also developed between multicode and variable spreading transmissions.

Our study has similarities with the work in [6], but also shows important differences, in regard to either the methodology used or the considered scenario. First of all, following [7], that provides a classic model for the analytical evaluation of the performance of a direct-sequence CDMA system with single rate, we prefer to use the characteristic function method, that permits to operate with products of, suitably identified, functions of independent random variables. No specific assumption is made on the features of the interference contributions. In particular, the proposed model applies to a general scenario where each user may have a number of interfering users with lower bit rate and a number with higher bit rate, each with its own ensemble of multipath terms. Either the uplink or the downlink transmissions are considered. Moreover, reference is done to specific (not ideal) spreading sequences, thus emphasizing differences in performance for various operation conditions. As regards the multipath channel, it is modeled in accordance with the ITU-R M.1225 Recommendation [8] which provides environment descriptions (indoor office, outdoor to indoor and pedestrian, vehicular) significant enough for practical applications. On the other hand, the generality of the model does not preclude its usage for different channel models.

A first series of results is presented. We show that chaotic signals may compete with the most classic solutions in some operation conditions, while their large number of degrees of freedom promises margins for design optimization.

The organization of the paper is as follows. In Section 2 we provide the model parameters. In Section 3 we give a brief overview of the considered spreading signals. In Section 4 the analytical formula for performance evaluation is presented and, in Section 5, some numerical examples are discussed. Finally Section 6 concludes the paper.

2 Model Parameters

The key parameter for the model is the spreading factor *SF* which is defined as the ratio between the chip rate R_c and the bit rate R_b. When using chaotic signals, the spreading factor can assume any integer value. On the other hand, the spreading factors adopted in WCDMA, that employs OVSF sequences, are always a power of two. For this reason, the values SF = 32, 64 and 128 will be chosen for the subsequent numerical evaluation (in the case of Gold sequences, these numbers must be reduced by one). As $T_c = 1/R_c = 0.26$ µs by definition, the corresponding bit time will be $T_b = 1/R_b = 8.3$ µs, 16.6 µs and 33.3 µs, respectively.

The schematic of the system is shown in Fig. 1; the modulation used is 2-PSK. For the k-th user, $1 \le k \le K$:

- $b_k(t)$ is the information signal, given by a random sequence of bits $b_l^k \in \{+1,-1\}$, with duration T_k;
- $a_k(t)$ is the spreading signal, with chip duration T_c;
- θ_k is the phase of the local oscillator;
- τ_k is a random delay taking into account possible asynchronism among transmissions.

Moreover, ω_c is the common value of the carrier circular frequency, whose amplitude has been denoted by A; setting $\phi_k = \theta_k - \omega_c \tau_k$ we have:

$$s_k(t-\tau_k) = Aa_k(t-\tau_k)b_k(t-\tau_k)\cos(\omega_c t + \phi_k) \quad (1)$$

The multipath channel is described according with the ITU-R M.1225 Recommendation [8]; the corresponding model is a tapped-delay line like that shown in Fig. 2. Because of multipath, the k-th signal consists of a direct path and $R-1$ replicas, each one characterized by an attenuation A_r^k and an excess delay τ_r^k, with $2 \le r \le R$.

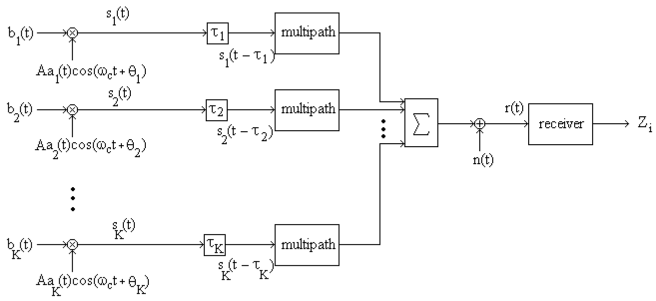

Fig. 1. Block diagram of the considered WCDMA system (uplink).

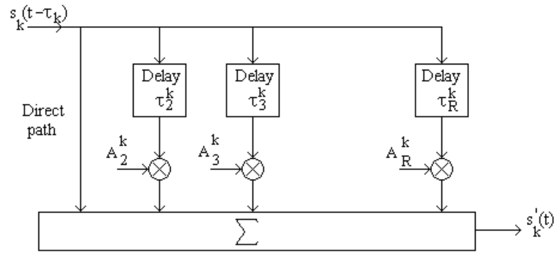

Fig. 2. Multipath channel model.

We suppose that $A_r^k = A_r^h$ and $\tau_r^k = \tau_r^h$, $\forall k \neq h$, i.e., all users exhibit, for each path, the same attenuation and delay. This assumption is congruent with the tapped delay line model in [8], where these values are given by averaging "worst" and "best" conditions. In particular, each environment exhibits a delay spread variability, that cannot be captured using a single tapped delay line. Therefore, up to two multipath channels are defined for each environment (indoor office, outdoor to indoor and pedestrian, vehicular); each of these two channels is expected to be encountered for some percentage of time in a given test. These percentages, together with the values of A_r^k and τ_r^k are specified in [8] and have been used in our numerical evaluation. Examples will be given in Section 5. Looking at Fig. 1, on the basis of Fig. 2, the k-th signal at the output of the multipath channel is:

$$s'_k(t) = \sum_{r=1}^{R} AA_r^k a_k(t-\tau_k-\tau_r^k) b_k(t-\tau_k-\tau_r^k) \cdot \cos(\omega_c t + \phi_k - \omega_c \tau_r^k) \quad (2)$$

Summing the contributions of all users and taking into account the presence of the thermal noise n(t), the signal at the receiver input is

$$r(t)=\sum_{k=1}^{K}\sum_{r=1}^{R}AA_r^k a_k(t-\tau_k-\tau_r^k)b_k(t-\tau_k-\tau_r^k) \cdot\cos(\omega_c t+\phi_k-\omega_c\tau_r^k)+n(t) \quad (3)$$

The receiver elaborates this signal according with a classic correlation scheme (omitted in Fig. 1 for saving space) and produces the decision variable

$$Z_i=\int_0^{T_i} r(t)a_i(t)\cos(\omega_c t)dt \quad (4)$$

which determines the bit error rate (BER). In (4) we have set $\tau_i=0$ and $\phi_i=0$ as usual and possible once having identified the signal to detect (τ_k and ϕ_k have therefore the meaning of relative delay and phase). Elaboration of the decision variable, in order to obtain an explicit formula for the BER, is the key point of the analysis. This will be addressed in Section 4, stressing implications of the coexistence of users at different bit rates. In the next section, instead, we will define the spreading sequences adopted.

3 Spreading Signals

In this paper, three different kinds of spreading signals have been considered: OVSF sequences, Gold sequences, and chaotic signals. OVSF sequences and Gold sequences are well known; the procedures for their design and features can be found in the literature (see [9]-[10], for example). As we are interested to emphasize their correlation properties, we limit to remind that:

- The correlation properties of OVSF codes are very good on condition: a) to control synchronism between the sequences and, b) to limit the number of sequences required. Condition a) is necessary since orthogonality is usually lost when the sequences suffer a relative delay; this makes the use of OVSF as spreading signals mostly attractive in the downlink, and much less attractive in the uplink. Condition b) is imposed by the observation that the number of orthogonal sequences for a given *SF* is small. Also their auto-correlation properties are far from ideality, generally showing rather high out-of-phase peaks. The last observation justifies, in particular, the limited immunity that OVSF codes show against multipaths. As a matter of fact, these codes can be outperformed even in downlink, if the delay spread is high. Examples in this sense will be given in Section 5.
- Gold sequences, of length $N = 2^m - 1$, exhibit a three-valued cross-correlation function with values $\{-1, -t(m), t(m) - 2\}$, being $t(m) = 2^{(m+1)/2} + 1$, in the case of odd m, or $t(m) = 2^{(m+2)/2} + 1$, in the case of even m. They show good auto- and cross-correlation properties, particularly for increasing values of m. They can be used (and really they are in WCDMA) either in uplink or in downlink.

Chaotic signals have been valued in CDMA systems, because of their favorable correlation properties [11]-[13]. Among the options to generate chaotic signals, we consider the classic solution of the following nonlinear system:

$$\begin{aligned} du/dt &= \sigma\cdot(v-u) \\ dv/dt &= r\cdot u - v - 20\cdot u\cdot w \\ dw/dt &= 5\cdot u\cdot v - b\cdot w \end{aligned} \quad (5)$$

resulting in the so-called “Lorenz chaotic signal”. In this system, σ, r and b are suitably fixed parameters (a typical choice assumes $\sigma = 16$, $r = 45.6$ and $b = 4$) while $u(t)$, $v(t)$ and $w(t)$ are the system states: each state variable can be used for providing time evolution of a chaotic spreading signal.

System (5) is solved starting from assigned initial conditions (for example $u(0) = 0.82$, $v(0) = 0.63$ and $w(0) = 0.74$); the result is an unpredictable set of aperiodic functions, each one showing features very similar to white noise and therefore with excellent correlation properties.

For a given set of initial conditions, different chaotic spreading signals can be obtained by producing a long chaotic evolution and then dividing it in a desired number of segments (each segment providing a spreading signal). This is the option used in the present paper; as an alternative, one can construct different spreading signals by solving system (5) with different initial conditions.

The solutions of the Lorenz system are real functions. In this sense they can be seen as multilevel signals. Their amplitudes can be quantized in order to obtain a fully digital sequence. As an alternative, one can obtain chaotic sequences directly in binary form [14]. Such a solution may have advantages from the implementation point of view, minimizing some practical difficulties that often make the usage of chaotic maps hardly repeatable. Anyway, the performances achievable with the two systems in the considered multipath/multi-user environment are very similar [15], so that the conclusions we will draw for the

Lorenz signals hold, with good approximation, for the binary chaotic sequences, too.

4 BER Formula

According with the most classic theory for the analysis of CDMA systems, an explicit formula for the BER is derived by means of the characteristic function method [7]. By elaborating expression (4), the decision variable Z_i can be rewritten as:

$$Z_i = \eta_i + \frac{1}{2} A T_i b_0^i C + \sum_{r=2}^{Q} \frac{1}{2} A A_r^i b_{-1}^i R_{i,i}(\tau_r^i)\cos(\omega_C \tau_r^i)$$
$$+ \sum_{r=Q+1}^{R} \frac{1}{2} A A_r^i [b_{-i(r)}^i R_{i,i}(\tau_r^i) + b_{-i(r)+1}^i \hat{R}_{i,i}(\tau_r^i)]\cos(\omega_C \tau_r^i)$$
$$+ \sum_{\substack{k=1\\k\neq i}}^{K} \frac{1}{2} A \int_0^{T_i} b_k(t-\tau_k) a_k(t-\tau_k) a_i(t)\cos(\phi_k)dt \quad (6)$$
$$+ \sum_{\substack{k=1\\k\neq i}}^{K} \sum_{r=2}^{R} \frac{1}{2} A A_r^k \int_0^{T_i} b_k(t-\tau_k-\tau_r^k) a_k(t-\tau_k-\tau_r^k)$$
$$\cdot a_i(t)\cos(\phi_k - \omega_C \tau_r^k)dt$$

where $i(r)$ is a positive integer depending on the delay τ_r^i and

$$R_{a,b}(\tau) = \int_0^{\tau} a_a(t-\tau) a_b(t)dt$$
$$\hat{R}_{a,b}(\tau) = \int_{\tau}^{T_i} a_a(t-\tau) a_b(t)dt \quad (7)$$

with $0 \le \tau \le T_i$, are the continuous time partial cross-correlation functions; the values of $R_{a,b}(\tau)$ and $\hat{R}_{a,b}(\tau)$ depend on the spreading sequences adopted, but can be easily computed for all signals presented in Section 3. In (6), the first term:

$$\eta_i = \int_0^{T_i} n(t) a_i(t)\cos(\omega_C t)dt \quad (8)$$

is due to the thermal noise $n(t)$. The second term includes the useful bit b_0^i that is due to the direct path but also to the Q – 1 replicas of the useful signal whose delays $\tau_2^i < \tau_3^i < ... < \tau_Q^i$ yield $i(r) = 1$. The latter contribution is explicitly taken into account in the second part of factor C defined as:

$$C = 1 + \sum_{r=2}^{Q} \frac{A_r^i}{T_i} \hat{R}_{i,i}(\tau_r^i)\cos(\omega_c \tau_r^i) \quad (9)$$

The third term in (6) is due to the interfering contributions (bit b_{-1}^i) of these Q replicas, while the fourth term is due to the remaining R – Q replicas (that do not contain b_0^i). Finally, the fifth and sixth terms express the MUI contributions.

The main difficulty of the analysis consists in enucleating, and taking into account, the various possible cases: the k-th MUI contribution, in fact, is characterized by its own bit duration T_k that may be equal, greater or smaller than the bit duration of the useful signal T_i. This is because, as stressed, different transmissions can require different bit rates. As the bit durations assume a finite set of values, we can collect interfering contributions of the same type. Thus, we denote by E the number of interfering signals with $T_i = T_k$, by P the number of interfering signals with $T_i > T_k$, and by G the number of interfering signals with $T_i < T_k$.

For the MUI of the first type (*i.e.*, $T_i = T_k$), the last term in (6) can be written as

$$\sum_{e=1}^{E}\sum_{r=2}^{R} \frac{1}{2} A A_r^e [b_{-e(r)}^e R_{e,i}(\tau_e + \tau_r^e) + b_{-e(r)+1}^e \hat{R}_{e,i}(\tau_e + \tau_r^e)]$$
$$\cdot \cos(\phi_e - \omega_C \tau_r^e) \quad (10)$$

When $T_i > T_k$, noting by N_k the ratio T_i/T_k, there are, in general, $N_k + 1$ interfering bits (from the k-th user) for each bit of the useful signal. Correspondingly, the last term in (6) can be written as

$$\sum_{p=1}^{P}\sum_{r=2}^{R} \Bigg[\frac{1}{2} A A_r^p [b_{-p(r)}^p R_{p,i}(\tau_p + \tau_r^p) + \sum_{j=0}^{N_p-2} b_{-p(r)+1+j}^p$$
$$\cdot \int_{jT_p+(\tau_p+\tau_r^p)}^{(j+1)T_p+(\tau_p+\tau_r^p)} a_p(t-(jT_p+\tau_p+\tau_r^p)) \cdot a_i(t)dt + b_{-p(r)+N_p}^p$$
$$\cdot \hat{R}_{p,i}((N_p-1)T_p + (\tau_p+\tau_r^p))] \cdot \cos(\phi_p - \omega_C \tau_r^p) \Bigg] \quad (11)$$

Finally, when $T_i < T_k$, we must distinguish between the case $(\tau_k + \tau_r^k)$ mod $T_k > T_i$ (when interference involves only one bit) and the case $(\tau_k + \tau_r^k)$ mod $T_k < T_i$ (when interference involves two bits). So, the last term in (6) can be written as:

$$\sum_{g=1}^{G}\sum_{r=2}^{R} \frac{1}{2} A A_r^g \begin{Bmatrix} b_{-g(r)}^g R_{g,i}(\tau_g + \tau_r^g) + b_{-g(r)+1}^g \hat{R}_{g,i}(\tau_g + \tau_r^g) \\ \text{when } 0 < \tau_g + \tau_r^g < T_i \\ b_{-g(r)}^g \int_0^{T_i} a_g(t-(\tau_g+\tau_r^g)) a_i(t)dt \\ \text{when } T_i < \tau_g + \tau_r^g < T_g \end{Bmatrix}$$
$$\cdot \cos(\phi_g - \omega_C \tau_r^g) \quad (12)$$

Expressions (10)-(12) can be also used to compute the fifth term in (6), which expresses the direct path contributions of MUI, simply by including, in the inner sum, the term with $r = 1$ and setting $A_1^e = A_1^p = A_1^g = 1$ and $\tau_1^e = \tau_1^p = \tau_1^g = 0$, for any k. Starting from these expressions and applying the characteristic function method, with tedious but simple algebra, the average bit error probability $\overline{P}_{e,i}$ can be determined in explicit form. Omitting details for saving space, we obtain

$$\overline{P}_{e,i} = \frac{1}{2}\mathrm{erfc}\left(C\sqrt{\frac{E_b}{N_0}} \right) + \frac{1}{\pi}\int_0^\infty \frac{\sin(Cu)}{u}\left[1-\Phi_1(u)\right]\Phi_2(u)du \tag{13}$$

where E_b/N_0 is the signal-to-noise ratio,

$$\Phi_2(u) = \exp\left(-\frac{N_0}{4E_b}\cdot u^2 \right) \tag{14}$$

and

$$\Phi_1(u) = \Phi_{\xi 1}(u)\cdot\Phi_{\xi 2}(u)\cdot\Phi_{\xi 3}(u)\cdot\Phi_{\xi 4}(u) \tag{15}$$

In (15), $\Phi_{\xi 1}(u)$ is the characteristic function for the sum of the third and fourth terms at the right hand side of (6) (multipaths of the useful signal); $\Phi_{\xi 2}(u)$, $\Phi_{\xi 3}(u)$ and $\Phi_{\xi 4}(u)$ are the characteristic functions of (10), (11) and (12), respectively, where the inner sum starts from r = 1 for taking into account the direct path of the other users. The product of the $\Phi_{\xi j}$'s permits to collect the various kinds of MUI contributions. All these functions can be expressed in analytical form and, replaced in (13), they allow to compute the average BER without the need to resort to long Monte-Carlo like simulations. The complete $\Phi_{\xi j}$'s expressions are omitted here, and will be reported in [16].

5 Examples

As an example of application of the proposed theory, we consider a simplified scenario where a useful signal with SF^i = 64 is disturbed by six interfering signals, two with SF^p = 32, two with SF^e = 64 and two with SF^g = 128. The simplified scenario permits to obtain acceptable performance without the need to use FEC (Forward Error Correcting) schemes, that are necessary to reduce the BER when the number of users is higher, and which are not the object of the present paper.

The three operation environments proposed in the ITU-R M.1225 Recommendation are separately considered with their own model parameters. More specifically, we have numbered the simulations as follows:

1. Indoor office
2. Outdoor to indoor and pedestrian
3. Vehicular

Such a notation is also used in Fig. 3, relative to the downlink, and in Fig. 4, relative to the uplink.

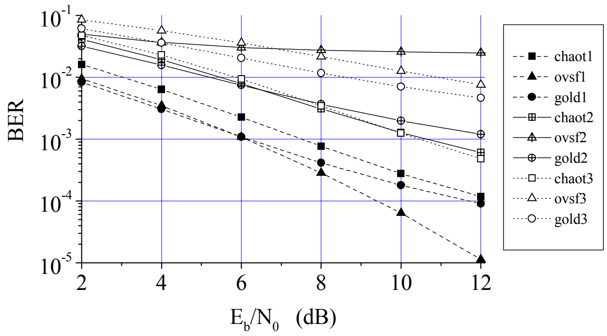

Fig. 3. Example of performance evaluation for the downlink.

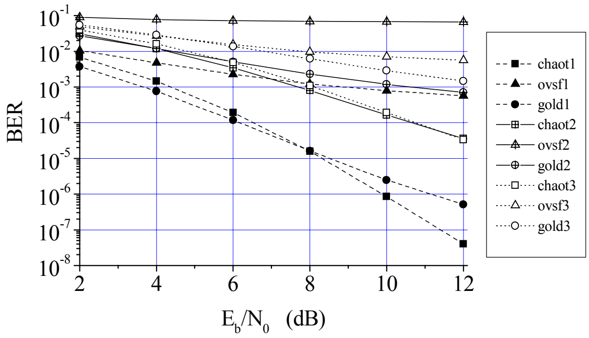

Fig. 4. Example of performance evaluation for the uplink.

For each environment, the analysis has been repeated by using OVSF sequences (ovsf), Gold sequences (gold) and Lorenz chaotic signal (chaot). Thus, chaot$x$, for example, means chaotic signal in environment x (with x = 1, 2, 3); similarly for the other notation. From the figures we can see that, except for the case of downlink indoor office, the OVSF sequences show, in any test environment, the worst performance. This can been explained, qualitatively, with their bad out-of phase correlation properties, that make such sequences very vulnerable to the multipath effects. Such a behavior is mitigated in the case of the indoor office because of the reduced root mean square delay spread characterizing this environment, but only for downlink, where transmissions are synchronized. The case of downlink indoor office is also the only one where Gold sequences outperform chaotic (signals) everywhere in the explored region of E_b/N_0 values. In all the other situations, instead, the performance offered by the chaotic signals is better than that of the OVSF sequences and of the Gold sequences as well (the latter, at least for signal-to-noise ratios sufficiently high). We have repeated the analysis for many other configurations (for example changing the spreading factor of the useful signal) always achieving similar conclusions. Thus it seems correct to say that, in this kind of applications, chaotic signals have a great potentiality, to the point to be considered, in our opinion, for designing new spreading sequences in the fourth generation of mobile communications. Even more if we consider that results like those shown in Figs. 3 and 4 have been obtained by assuming non optimized chaotic signals, so that further improvements could be expected by exploiting better the degrees of freedom these signals offer.

6 Conclusions

Performance evaluation in WCDMA systems is an involved task because of the coexistence of different causes for degradation, *i.e.*, thermal noise, MUI and multipath, in conjunction with variable spreading factors among the users. For this reason, most evaluations are made via Monte-Carlo like simulations. In this paper we have shown that an analytical approach can be conceived that, extending previous classic analyses of CDMA, allows to find an explicit formula for the BER also in such a more complex case. The proposed theory can be applied for any kind of spreading signal, the trick being in the proper evaluation of the correlation properties. In this sense, our analysis has permitted to confirm that: i) the OVSF sequences are not good for most cases and, ii) chaotic signals, for example obtained through a Lorenz generator, could be a valid alternative in future applications.

References:

[1] 3rd Generation Partnership Project, "Multiplexing and Channel Coding (FDD)", 3G TS 25.212 (2000-03), March 2000.

[2] Special Issue on "Innovative Signal Transmission and Detection Techniques for Next Generation Cellular CDMA Systems", Eurasip Journal on Wireless Communications and Networking, Vol. 2004, Aug. 2004.

[3] T. Ottosson, A. Svensson, "Multi-rate performance in DS/CDMA systems", Chalmers University of Technology, Goteborg, Sweden, 1995.

[4] S. J. Lee, H. W. Lee, D. K. Sung, "Capacities of single-code and multi-code DS-CDMA systems accommodating multiclass services", *IEEE Trans. Veh. Technol.*, Vol. 48, March 1999, pp. 376-384.

[5] R. Zhang, T. Thiung, H. Zhang, P. He, "BER performance comparison of single code and multicode DS/CDMA channelization schemes for high rate data transmission", *IEEE Commun. Lett.*, Vol. 5, Feb. 2001, pp. 67-69.

[6] M. Fan, C. Hoffmann, K.-Y. Siu, "Error-rate analysis for multirate DS-CDMA transmission schemes", *IEEE Trans. Commun.*, Vol. 51, Nov. 2003, pp. 1897-1909.

[7] E. A. Geraniotis, M. B. Pursley, "Error probability for direct-sequence spread-spectrum multiple-access communications-part II: approximations", *IEEE Trans. Commun.*, Vol. 30, May 1982, pp. 985-995.

[8] Recommendation ITU-R M.1225, "Guidelines for Evaluation of Radio Transmission Technologies for IMT-2000", Feb. 1997.

[9] M. Nilsson, "Efficient ASIC implementation of a WCDMA rake receiver", Master's thesis, Luleå Univ. of Technology, Sweden, April 2002.

[10] J. G. Proakis, *"Digital Communications*", McGraw-Hill, 1995, p. 727.

[11] F. Chiaraluce, E. Gambi, R. Garello, P. Pierleoni, "Performance of DCSK in multipath environments: a comparison with systems using Gold sequences", *IEICE Trans. Fundamentals of Electronics, Communications and Computer Sciences*, Vol. E85-A, Oct. 2002, pp. 2354-2363.

[12] G. Setti, R. Rovatti, G. Mazzini, "Performance of chaos-based asynchronous DS-CDMA with different pulse shapes", *IEEE Commun. Lett.*, Vol. 8, July 2004, pp. 416-418.

[13] R. Rovatti, G. Mazzini, G. Setti, "On the ultimate limits of chaos-based asynchronous DS-CDMA – I: basic definitions and results", *IEEE Trans. Circuit Systems - I*, Vol. 51, July 2004, pp. 1336-1347.

[14] D. Lèon, S. Balkir, M. W. Hoffman, L.C. Pèrez, "Robust chaotic PN sequence generation techniques", *Proc. IEEE ISCAS 2001*, Vol. 4, Sydney, Australia, May 2001, pp. 53-56.

[15] F. Biondi, F. Chiaraluce, E. Gambi, "On the performance of chaotic sequences in multiple access systems with variable spreading factor", *Proc. Int. Symp. Inf. Theory and its Appls.* (*ISITA 2004*), Parma, Italy, 10-13 Oct. 2004, pp. 388-392.

[16] F. Chiaraluce, E. Gambi, G. Righi, "A general model for performance evaluation in DS/CDMA systems with variable spreading factors", *in preparation*.