# Innovative Chip Waveforms in Microcellular DS/CDMA Packet Mobile Radio

P. I. Dallas and F.-N. Pavlidou

*Abstract*— **The impact of innovative chip waveforms on the performance of a direct sequence code-division multiple-access (DS/CDMA) packet mobile radio network is investigated, assuming either Rayleigh or Nakagami-m frequency selective channels and a differential phase shift keying (DPSK) receiver with selection diversity. A constant improvement of the bit-error rate (BER) and the throughput is presented throughout the study.**

## I. Introduction

CELLULAR networks offer a great number of profits for voice and data transmission due to frequency reuse. In spite of their advantages direct sequence code-division multiple-access (DS/CDMA) systems suffer strongly from the interference due to other users coexisting into the same channel. This interference depends mainly on the correlation properties of the spreading sequences as well as the shape of the chip waveform. Through the literature, only the rectangular and sine pulse chip waveforms have been studied [1]. Recently, Anjaria and Wyrwas [2] presented the raised cosine form as a possible chip waveform pulse.

The model we propose sustains a wide range of alternative chip waveforms, instead of the classic pulse waveforms plus selection diversity, and investigates the performance of a micro-cellular CDMA system in frequency selective channels. The performance criteria are the well-established bit-error rate (BER) as well as a criterion of throughput (the number of successfully received packets per time slot) [3].

The paper is organized as follows. Section II presents the system model. The expressions for throughput and bit error probability for Rayleigh/Nakagami-m are given in Section III. In Section IV, the computational results are presented and discussed. Finally, conclusions are stated in Section V.

## II. System Model

The transmitter model consists of $k$ active simultaneous users transmitting to a central base station using DS/CDMA with differential phase shift keying (DPSK) modulation. The network can support $W$ users, each one using a unique spread-spectrum code. The transmitted signal of the $x$th user $(1 \leq x \leq k)$ is given by $s_x(t) = A\alpha_x(t)b_x(t)\cos(\omega_c t + \theta_x)$ where $\alpha_x(t) = \sum_{j=0}^{N-1} \alpha_x^j p_{T_c}(t - jT_c)$ is the user specific direct sequence code, $\alpha_x^j$ is the $j$th chip of the direct sequence code. $A$ is the amplitude of the transmitted signal, $b_x(t)$ is the data waveform with duration $T_b$. $T_c$ is used to symbolize the duration of the chip waveform and it is assumed that the length of the direct sequence code is $N = T_b/T_c$. Finally, $\omega_c$ is the common angular carrier frequency and $\theta_x$ is the carrier phase of the $x$th user.

Paper approved by D. Kazakos, the Editor for Random Access and Distributed Communications Systems of the IEEE Communications Society. Manuscript received December 15, 1994; revised December 15, 1995.

The authors are with the Telecommunications Division, Department of Electrical and Computer Engineering, Faculty of Technology, Aristotle University of Thessaloniki, 54006 Greece.

Publisher Item Identifier S 0090-6778(96)08587-X.

TABLE I
Parameters for Different Chip Waveforms

| WAVEFORM SHAPE | $m_\psi$ | $m'_\psi$ |
|---|---|---|
| Rectangular | $0.333\,T_c^3$ | $0.166\,T_c^3$ |
| Half-Sine | $0.293\,T_c^3$ | $0.004\,T_c^3$ |
| Raised Cosine | $0.241\,T_c^3$ | $0.009\,T_c^3$ |
| Blackman | $0.207\,T_c^3$ | $0.003\,T_c^3$ |
| Kaiser | $0.195\,T_c^3$ | $0.002\,T_c^3$ |
| Lanczos | $0.099\,T_c^3$ | $0.002\,T_c^3$ |

The pulse $p_{T_c}(t)$ is used to represent any shape of the chip waveform. In this paper, we consider innovative chip waveforms that most of them are well known from the filter theory [4]. The first three have already been used in the literature [1], [2], but the others have not.

i) Rectangular:

$$p_{T_c}(t) = u(t)$$

ii) Half-Sine:

$$p_{T_c}(t) = \sqrt{2}\,\sin\left(\frac{\pi t}{T_c}\right)u(t)$$

iii) Raised Cosine:

$$p_{T_c}(t) = \sqrt{\frac{2}{3}}\left[1 - \cos\left(\frac{2\pi t}{T_c}\right)\right]u(t)$$

iv) Blackman:

$$p_{T_c}(t) = c_1\left[0.42 - 0.5\cos\left(\frac{2\pi t}{T_c}\right) + 0.08\cos\left(\frac{4\pi t}{T_c}\right)\right]u(t)$$

v) Kaiser:

$$p_{T_c}(t) = c_2 \frac{I_0\left\{\beta\pi\sqrt{1 - \left[\dfrac{t - \frac{T_c}{2}}{T_c}\right]^2}\right\}}{I_0(\beta\pi)}u(t)$$

where $\beta > 0$ can be any real positive number.

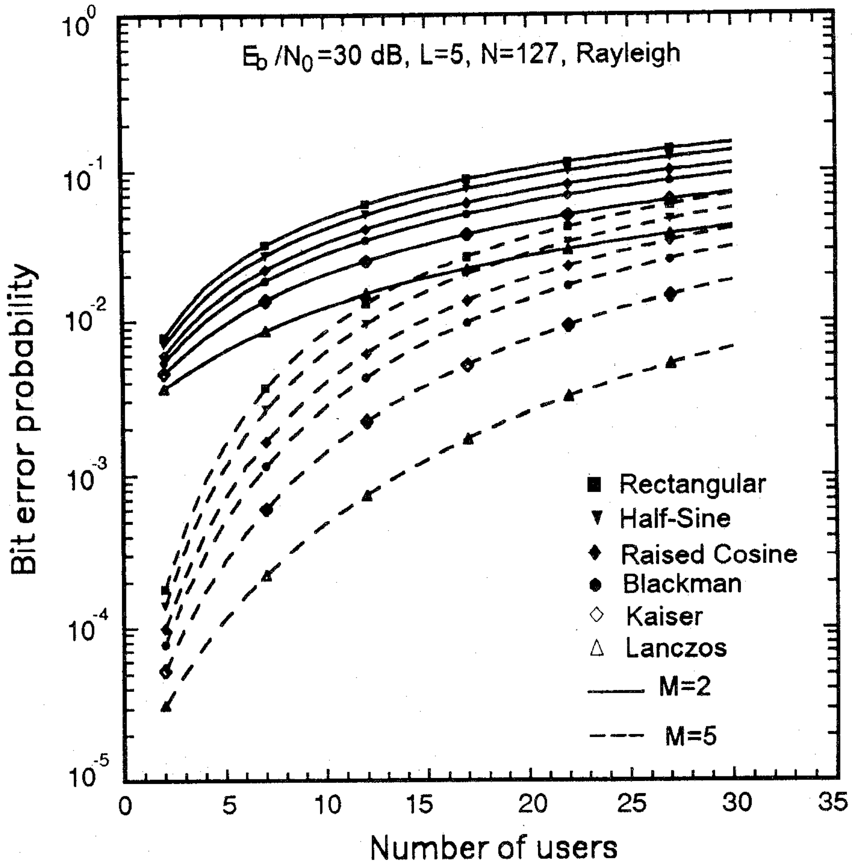


Fig. 1. *Rayleigh Model:* Bit error probability as a function of simultaneous users for different order of explicit diversity.

vi) Lanczos:

$$p_{T_c}(t) = c_3\left[\frac{\sin(2\pi t)}{2\pi t}\right]^2 u(t) \tag{1}$$

$c_i(i = 1, 2, 3)$ are constants used for the purpose of satisfying the normalization condition $\int_0^{T_c} p_{T_c}^2(t) = 1$. $I_0(\cdot)$ is the modified Bessel function of the first kind and zeroth order. $u(t)$ is the step function and implies that the chip waveform is restricted to the duration $T_c$.

The lowpass equivalent impulse response of the channel is the well known formula that is given by $h_x(t) = \sum_{l=1}^{L} \beta_{lx}\delta(t - \tau_{lx}) \exp(j\varphi_{lx})$ where $L$ is the number of resolvable paths. $\tau_{lx}$, $\varphi_{lx}$ are the path delay and the path phase, respectively, referred to the $l$th path of the $x$th user. Both of them are random variables uniformly distributed. The path gain $\beta_{lx}$ is also an independent random variable distributed either Rayleigh [5] or Nakagami-m [6].

The receiver consists of a matched filter, a DPSK demodulator, and a selection diversity component of order $M(1 \leq M \leq L)$. The decision is based on the largest peak of the $M$ received correlated peaks (corresponding to the path with the largest path gain).

## III. Performance Analysis

*1) Rayleigh Channel:* The average bit error probability, after the referred system model and carrying out some mathematical manipulations [7], is given by

$$P_{er}(k) = M \sum_{i=0}^{M-1} \binom{M-1}{i} \frac{(-1)^i}{i+1} \frac{1}{2\left[1 + \dfrac{\gamma_c}{i+1}\right]}. \tag{2}$$

*2) Nakagami-m Channel:* In the case of Nakagami-m channel, the analytical solution is very difficult to be found and the BER probability will originate from the solution of the integral below

$$P_{er}(k) = \int_0^\infty \tfrac{1}{2}\exp(-\gamma_b)\Bigg\{ M \sum_{i=0}^{M-1} \binom{M-1}{i} (-1)^i \times \exp\left(-\frac{mi\gamma_b}{\overline{\gamma}_c}\right)\left[\sum_{p=0}^{m-1} \frac{\left(\dfrac{m\gamma_b}{\overline{\gamma}_c}\right)^p}{p!}\right]^i \times \exp\left(-\frac{m}{\overline{\gamma}_c}\gamma_b\right)\left[\sum_{j=0}^{m-1}\left(\frac{m}{\overline{\gamma}_c}\right)^{j+1}\frac{\gamma_b^j}{j!} - \sum_{j=0}^{m-1}\left(\frac{m}{\overline{\gamma}_c}\right)^j \frac{j\gamma_b^{j-1}}{j!}\right]\Bigg\} d\gamma_b \tag{3}$$

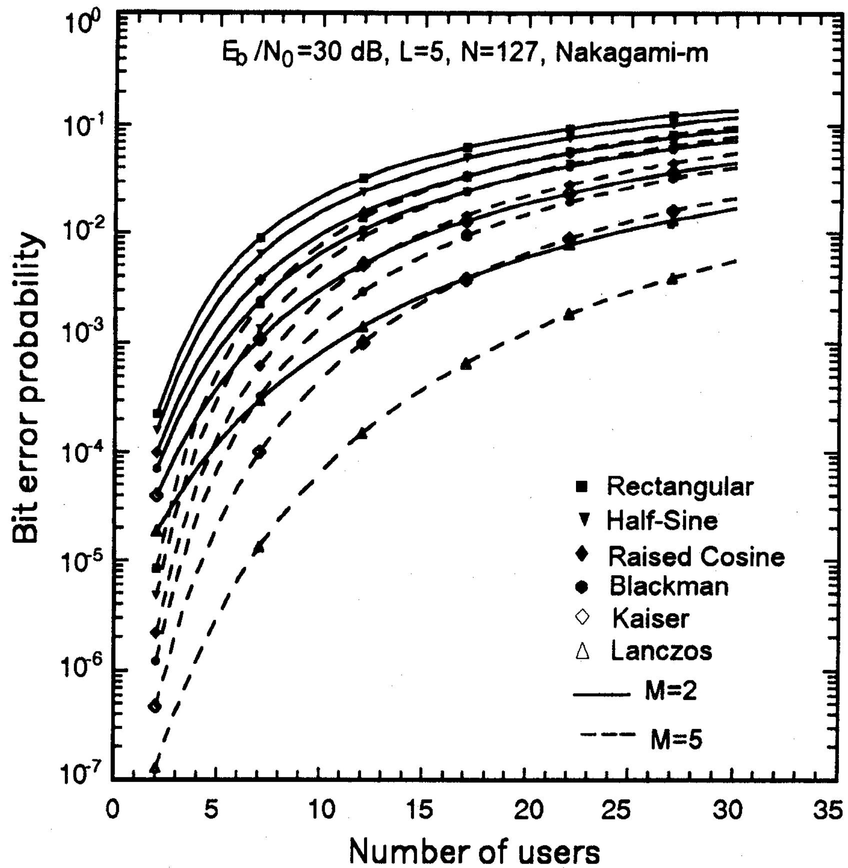


Fig. 2. *Nakagmi-m Model:* Bit error probability as a function of simultaneous users for different order of explicit diversity.

where $m$ is the fading parameter of Nakagami-m distribution, $\overline{\gamma}_c$ is the average signal to noise ratio and is given by $\overline{\gamma}_c = [N_0/E_b\rho+(kL-1)\varepsilon_k^2]^{-1}$, assuming that the interference is Gaussian. $E_b$ is the energy per bit while $N_0$ represents the additive white Gaussian noise (AWGN) with two sided spectral density $N_0/2$ and $\rho = (1/2)E[\beta^2]$ is the half average power per path. The quantity $\varepsilon_k^2 = 2\{(1/T^3)[\mu_{k1}(0)m_\psi + \mu_{k1}(1)m'_\psi]\}$ is an interference parameter [1] and denotes physically, the amount of interference to the current bit, caused by the preceding and the succeeding bits. The parameters $\mu_{k1}(0)$, $\mu_{k1}(1)$ are defined in [1] and can be computed easily from the aperiodic crosscorrelation functions of the spreading sequences. The values of $m_\psi$ and $m'_\psi$ depend on the shape of the chip waveform and are given in Table I.

The packet success probability $P_{cor}(k)$ is the probability to transmit correctly a packet that consists of $N_d$ data bits, and is given by [3]

$$P_{cor}(k) = [1 - P_{er}(k)]^{N_d}. \tag{4}$$

The normalized throughput $S$ is defined as the average number of successfully received packets per time slot, normalized by the system capacity, and it is given by

$$S = \frac{1}{W}\sum_{k=1}^{W} kP_kP_{cor}(k) \tag{5}$$

where $P_k$ is the probability of having $k$ simultaneous users by transmitted packets. Assuming a Binomial arrival distribution of offered traffic with rate $G$ (since the number of the simultaneously active users is finite) the above parameter is given by

$$P_k = \binom{W}{k}\left[\frac{G}{W}\right]^k\left[1-\frac{G}{W}\right]^{W-k}. \tag{6}$$

The ratio $G/W$ denotes naturally the system utilization.

## IV. Computational Results and Discussion

In this section, some computational results are presented. All the results have been taken out considering the well known random Gold sequences with lengths $N = 127$.

In Figs. 1 and 2, we present the error probability as a function of the active users for the two types of channel (Rayleigh and Nakagami-m). The parameter $M$ indicates the order of the selection diversity. We apply two cases, $M = 2$ and $M = 5$. In the $M = 5$, we notice that either with Kaiser or with Lanczos shapes we approach or overcome the currently used limit for voice quality $10^{-3}$. Of course a large number of antennas lead to a great order of complexity, but the benefits are very attractive and the decrease of the error probability is significant. If the requirements are very strict for low complexity, the newly introduced chip waveforms give the solution, e.g., in the Rayleigh model, using Lanczos shape and

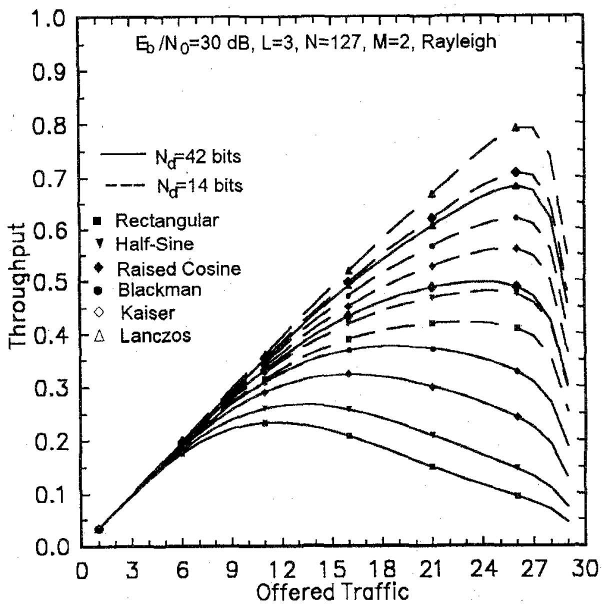


Fig. 3. *Rayleigh Model:* The influence of different packet lengths on the normalized throughput.

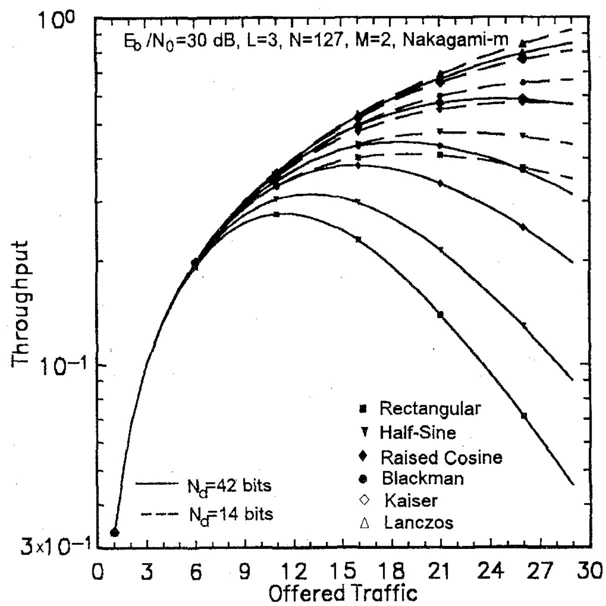


Fig. 4. *Nakagami-m Model:* The influence of different packet lengths on the normalized throughput.

$M = 2$, we could accommodate more users than in the cases of rectangular, half-sine, and raised cosine pulses with $M = 5$.

In Figs. 3 and 4, the other performance parameter is depicted, the throughput versus the packet length. We note that shorter packet length enhances the performance. Short packet lengths means that the number of correctly received packets becomes higher. Indeed, the errors occur in bursts, so decreasing the packet length, we aid the system to pass the packets unaffected from errors. With short packet lengths, the innovative chip waveforms are very close to each other and the throughput of the network is very high. The degradation in the saturation state is also slightly smaller in case of short packet length, because although the network is overloaded, it can manipulate more easily short packet lengths than larger ones.

An overview of the preceding analysis leads us to the conclusion that the introduction of new chip waveforms into the DS/CDMA model can only prove to be beneficial.

## V. Conclusion

In this study, innovative chip waveforms have been applied in DS/CDMA systems. Two performance criteria have been used, BER and throughput. In both cases, the impact of the innovative chip waveforms on the performance of the system was very positive. Especially, the Kaiser and Lanczos shapes gave distinguished results enlarging the capacity of the system.

## References

[1] M. B. Pursley, "Spread spectrum multiple-access communications," in *Multi-User Communication Systems,* G. Longo, Ed. New York: Springer-Verlag, 1981, pp. 139–199.
[2] R. Anjaria and R. Wyrwas, "The effect of chip waveform on the performance of CDMA systems in multipath, fading, noisy channels," in *Proc. 42nd VTS Conf.,* Denver, 1992, pp. 672–675.
[3] C. A. F. J. Wijfells, H. S. Misser, and R. Prasad, "A micro-cellular CDMA system over slow and fast Rician fading radio channels with forward error correcting coding and diversity," *IEEE Trans. Veh. Technol.,* vol. 42, no. 4, pp. 570–580, Nov. 1993.
[4] N. K. Bose, *Digital Filters: Theory and Applications.* New York: North-Holland, 1985.
[5] K. Pahlavan and M. Chase, "Spread-spectrum multiple access performance of orthogonal codes for indoor radio communication," *IEEE Trans. Commun.,* vol. 38, no. 5, pp. 574–577, May 1990.
[6] N. C. Beaulieu and A. Abu-Dayya, "Analysis of equal gain diversity on Nakagami fading channels," *IEEE Trans. Commun.,* vol. 39, no. 2, pp. 225–234, Feb. 1991.
[7] I. Gradshteyn and I. M. Ryzhic, *Tables of Integrals, Series, and Products.* New York: Academic, 1980.