MC/DS-CDMA VERSUS SC/DS-CDMA IN MOBILE RADIO: SPECTRAL EFFICIENCY APPROACH

P.Varzakas

Department of Electronics

Technological Educational Institute of Lamia

3o Km Old Road Lamia-Athens, GR 35100, Lamia

e-mail: pvarzakas@teilam.gr

Abstract—The spectral efficiency of a multicarrier direct-sequence code-division multiple-access (MC/DS-CDMA) cellular system operating in a mobile radio environment with Rayleigh fading, is investigated. In this work, spectral efficiency is evaluated in terms of channel capacity (in the Shannon sense) per user, estimated in an average sense. It is analytically shown that, under normalized conditions and assuming a static model of operation, MC/DS-CDMA spectral efficiency, on downlink, is higher than that of single-carrier direct-sequence code-division multiple-access (SC/DS-CDMA). This result is justified by the combination of path-diversity reception, achieved by a conventional coherent maximal-ratio combining (MRC) RAKE receiver, and physical frequency diversity potential provided, in a fading environment, by frequency-division multiplexing on a set of orthogonal carriers. It is shown that the increase of the carrier frequencies, in the MC/DS-CDMA cellular system, leads to a respective improvement of the spectral efficiency achieved.

Key-Words:-Spectral efficiency, multicarrier modulation, code-division multiple access, cellular systems.

1 Introduction

In the literature, there has been a growing interest in broadband transmission over time-variant channels due to the inherent diversity potential which is provided by the frequency selectivity of such channels, [1]. Then, a variety of modulation and coding schemes are investigated in order to further increase the transmitted data rate for a fixed bit-error-rate (BER) value. However, for a time-variant channel, as it is the case in mobile radio, its capacity, i.e., the maximum rate, at which data can be transmitted with arbitrarily small BER, can be obtained by finding the best distribution of the transmitted signal power as a function of the instantaneous signal-to-noise power ratio (SNR) and then averaging over the SNR distribution, where the maximization is subject to the average power constraint, [2]. For a time-variant channel, its capacity can also be estimated in an average sense while its degradation is anticipated to a certain degree by utilizing some kind of diversity reception technique, [3, 4]. This average channel capacity formula would indeed provide the true channel capacity of the fading channel, when the transmitter adapts to the channel variation using a constant-power variable-rate strategy, [5-8].

Spectral efficiency, defined as the transmitted data rate per unit bandwidth for a specified average transmitted power and fixed BER value, is of primary concern in the design of future wireless communications systems. Orthogonal frequency-division multiplexing (OFDM) is a modulation method designed in the 1970s, [9]. Based on OFDM principle, MC/DS-CDMA proposed recently and investigated in the context of high data rate communication over time-variant channels. Then, in this work, we consider a MC/DS-CDMA system in which a data sequence multiplied by a spreading sequence modulates N orthogonal carriers rather that a single-carrier (SC). Each carrier is spread by the same pseudo-noise (PN) sequence, and each carrier is modulated by the same data symbol; thus this system is analogous to one repetition coding scheme, [10]. This transmission technique has a number of desirable features, including narrow-band interference suppression and a lower chip rate than that of a conventional SC system occupying the same total system's bandwidth, [10]. The lower chip rate is a result of the fact that the entire system's bandwidth is divided equally among N frequency bands. Respectively, at the receiver, maximal-ratio combining (MRC) RAKE reception is employed.

However, one question that arises in considering the previously described MC/DS-CDMA cellular system, is whether or not there is any advantage concerning the spectral efficiency achieved, compared with that of a conventional pure broadband SC/DS-CDMA cellular system. In a conventional SC/DS-CDMA system, each user bit is transmitted in the form of many sequential chips, each of which is of sort duration, thus having a wide bandwidth. Following the methodology described in [11] and [12], in this paper we present a comparison of MC/DS-CDMA and SC/DS-CDMA cellular systems, under normalised conditions, been suitable for providing quantitative results for these multiple-access techniques. Then, we analyze the spectral efficiency achieved by MC/DS-CDMA and SC/DS-CDMA cellular systems operating in an ideal non-fading additive white Gaussian noise (AWGN) and a Rayleigh fading environment. Previous studies in spectral efficiency of cellular systems with frequency reuse were based on a criterion introduced by Hatfied, [13-15], which only measured the traffic loading rather than the throughput intensity. However, in cellular systems, spectral efficiency is usually measured by the overall throughput per cell per sec per Hz. In contrast to these previous works and following the method described in [16-18], here, the spectral efficiency of the considered cellular systems is evaluated in terms of each user's achievable average channel capacity, meaning the normalized average sum data rate per user. Then, here, the achievable rate region (assuming that all users operate at the same data rate and have average transmit powers constraint), under Rayleigh fading conditions, is estimated in an average sense, considering the system's inherent diversity potential. Seen from a multi-user information theory perspective, the assumption that all users share the same rate is only a special case of the rate region, achievable under the respective systems.

The analysis covers the base-to-mobile units link, i.e., the downlink, also called broadcast channel, while a fixed number K of active users per cell, that occupy the radio channel simultaneously (fully loaded cellular systems) is assumed for both multiple-access schemes. However, a variable allocation of users is governed by a birth-death process implying a dynamic channel capacity model, [19]. In addition**,** multiple-access interference (MAI) and co-channel interference (CCI) are considered as gaussian distributed interference, even for small values of number of system's users, [20,21].

The MC modulation is motivated by Shannon's classical approach of calculating the capacity of a frequency-selective channel by slicing it to infinitesimal bands, but has been considered rather extensively in connection to fading, [22-26]. However, it must be noticed, that the following approach for the MC/DS-CDMA and SC/DS-CDMA cellular systems does not solve the problem of the "capacity region", i.e., the set of information rates at which simultaneously reliable communication of the messages of each user is possible, [27-30], but applies a new method to estimate the channel capacity assigned to each user, in an average sense, considering the system's inherent diversity potential. Finally, the average spectral efficiency estimated here, is not the maximum spectral efficiency achieved over such a channel, [31-33], but average channel capacity represents an optimistic upper bound, in average sense, for applied modulation and coding schemes.

The paper is organized as follows. In sections 2 and 3, MC/DS-CDMA and SC/DS-CDMA cellular systems are examined, respectively. The numerical results and their comparison are given in section 4. Final conclusions are outlined in the last section.

2 The MC/DS-CDMA case

In a pure MC/DS-CDMA system, the same user's data symbol is transmitted in parallel over N orthogonal carriers frequencies (sub-carriers), each multiplied by a different spreading sequence unique to each user. Then, the transmitted signal consists of the sum of the output of these N "branches". The totally allocated system's bandwidth $W_{\mathrm{MC/DS}}$, assuming no guard band between adjacent frequency bands and a strictly band-limited "chip" sequence with bandwidth $W_{\mathrm{mc/ds}}=G_{\mathrm{p,mc/ds}}\cdot W_{\mathrm{s}}$ is as shown in Figure 1, equal to:

$$W_{\mathrm{MC/DS}}=N\cdot W_{\mathrm{mc/ds}}=N\cdot G_{\mathrm{p,mc/ds}}\cdot W_{\mathrm{s}} \qquad (1)$$

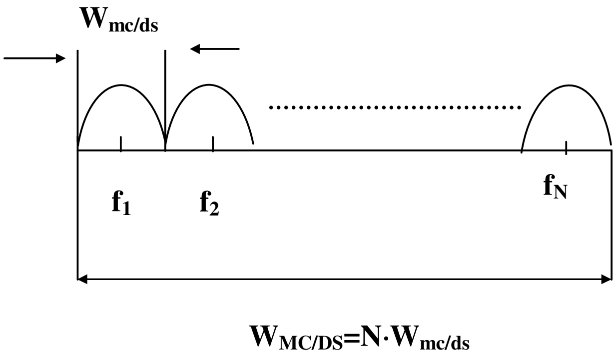

Fig. 1. The spectra of the transmitted signal in a MC/DS-CDMA system.

where $G_{\mathrm{p,mc/ds}}$ is the processing gain (or spreading factor) applied in direct-sequence (DS) transmission, W_{s} is the signal bandwidth and the subscripts 'MC/DS' and 'mc/ds' refer to MC/DS-CDMA system.

In the following, we consider a cellular MC/DS-CDMA system operating in an ideal non-fading AWGN environment with a number K active users per cell. Note that this case is examined here only for theoretical purposes, since it does never appear in practice. Only the average CCI power resulting from the eleven co-channel cells of the first dominant tier is considered significant and all base stations' and mobile units' antennas are assumed omnidirectionals. Clearly, transmission of a user signal (assumed Gaussian at system input) with arbitrarily small BER, depends on MAI and CCI level. Thus, the channel capacity $C_{i,cl,\mathrm{MC/DS}}$ required for errorless transmission of a DS signal of bandwidth $W_{\mathrm{mc/ds}}$, in each of the N disjoint carrier frequencies, is given by the Shannon-Hartley theorem when arbitrarily complex coding and delay is applied, [22,34]:

$$C_{i,cl,\mathrm{MC/DS}} = W_{\mathrm{mc/ds}} \cdot \log_2 (1 + \Gamma_{i,cl,\,\mathrm{MC/DS}}) \qquad (2)$$

where $\Gamma_{i,cl,\mathrm{MC/DS}}$, i=[1,..,12K], is the spread -to-interference plus noise ratio (SINR) received at the mobile unit as it reaches the boundary of a cell, reflecting the lowered signal power spectral density due to spreading and the subscript 'cl' refers to the cellular system. However, in this analysis, we consider the case where the receiver for each user's signal does not know the spreading wave forms of the other users or chooses to ignore them in the demodulation process.

In order to simplify the mathematical description, all hexagon cells of the system, are approximated by circular regions of radius R with the same area. Assuming a fourth power law path loss, the received signal power $P_{i,,cl,\mathrm{MC/DS}}$ at the cell boundary by i-th user, i=[1,..,12K], will then be:

$$P_{i,,cl,\mathrm{MC/DS}}=\alpha R^{-4} \qquad (3)$$

where α is a constant factor, [34]. However, the equal power case is considered, meaning that in the downlink, all mobile units that belong to a certain cell receive equal average signal power from their cell site when an appropriate power control scheme is applied. Therefore, for a cellular MC/DS-CDMA system, $\Gamma_{i,cl,\mathrm{MC/DS}}$ for each mobile unit, can readily be determined considering the average MAI power and average CCI power resulting from the eleven co-channel interfering cells as following, [17],

$$\begin{aligned}\Gamma_{i,\,cl,\,\mathrm{MC/DS}} &= \frac{\alpha R^{-4}}{N_0 \cdot W_{\mathrm{mc/ds}} + [\,(K-1)\,(\alpha R)^{-4}\,]} + \\ &+ \frac{\alpha R^{-4}}{2Ka R^{-4} + 3K\alpha(2R)^{-4} + 6K\alpha(2.633\,R)^{-4}\,]} = \\ &= \frac{P_{i,cl,\mathrm{MC/DS}}}{N_0 \cdot W_{\mathrm{mc/ds}} + (3.3123\,K-1)\cdot P_{i,cl,\mathrm{MC/DS}}}\end{aligned} \qquad (4)$$

where total interference is considered gaussian and, thus, directly incorporated into Shannon-Hartley formula and N_0 is the power spectral density of the additive white Gaussian noise. However, eq.(4) does not take into account the voice activity cycle, sector-reuse parameterization, lognormal variations and a random location model for the users' positions, as required in describing real commercial systems. In addition, the description of the frequency assignment, in each cell, is beyond the scope of this work. It must be notice, that inter-carrier interference (ICI) occurs because signal components from one sub-carrier cause interference to neighboring sub-carriers. In this paper, the effect of ICI is not considered and, the synchronization, in the reception of the DS signals in MC/DS-CDMA cellular system, is assumed perfect. Thus, for the MC/DS-CDMA cellular system, eq.(4) can equivalently be written in the form:

$$\Gamma_{i,cl,\mathrm{MC/DS}} = \frac{\Gamma}{G_{\mathrm{p,mc/ds}} + (3.3123K - 1)\cdot \Gamma} \quad (5)$$

where $\Gamma = (P_{i,,cl,\mathrm{MC/DS}}/N_0 W_s)$ is the received SNR over the signal bandwidth W_s.

Following eq.(2), the total channel capacity $C_{\mathrm{MC/DS}}$ (in the Shannon sense) for the twelve cells of the cellular MC-DS/CDMA system under consideration, that is, the total channel capacity available to all $12K$ active users, will be given by the sum of the individual rates:

$$C_{\mathrm{MC/DS}} = \sum_{i=1}^{12K} C_{i,cl,\mathrm{MC/DS}} = W_{\mathrm{mc/ds}} \cdot \sum_{i=1}^{12K} \log_2 (1 + \Gamma_{i,cl,\mathrm{MC/DS}}) \quad (6)$$

where $\Gamma_{i,cl,\mathrm{MC/DS}}$ is given by eq.(5). Since, in practice, $\Gamma_{i,cl,\mathrm{MC/DS}}$, i=[1,..,12K], is well below unity (in linear scale) eq.(6) can be approximated by:

$$C_{\mathrm{MC/DS}} = W_{\mathrm{mc/ds}} \cdot \log_2 (1 + 12K \cdot \Gamma_{i,cl,\mathrm{MC/DS}}) \quad (7)$$

We now examine the case of a cellular MC/DS-CDMA system operating in a Rayleigh fading environment. We assume that the physical channel of bandwidth $W_{\mathrm{mc/ds}}$ is greater than the coherence bandwidth W_{coh} of the Rayleigh fading channel. The radio channel is modeled as a slowly fading, time-invariant and discrete multipath channel and, thus, it appears to be frequency-selective to the transmitted DS signals of bandwidth $W_{\mathrm{mc/ds}}$. The maximum number $M_{\mathrm{MC/DS}}$ of uncorrelated resolvable paths ("inherent diversity branches") will be given by, [1]:

$$M_{\mathrm{MC/DS}} = [W_{\mathrm{mc/ds}} \cdot \Delta] + 1 = \left[\frac{W_{\mathrm{mc/ds}}}{W_{\mathrm{coh}}}\right] + 1 \quad (8)$$

where Δ is the maximum delay spread or total multipath spread of the Rayleigh fading channel (assumed known or measurable) and [.] returns the largest integer less than, or equal to, its argument. However, if the bandwidth $W_{\mathrm{mc/ds}}$ is smaller than the coherence bandwidth W_{coh} of the Rayleigh fading channel, there will be no inherent diversity potential, and, if fading reduction is seek through diversity techniques, space diversity or a hybrid scheme shall be used.

The MC transmission calls for a kind of diversity reception since each single data symbol is transmitted, in parallel, in a different carrier frequency. Since, the bandwidth $W_{\mathrm{mc/ds}}$ is assumed greater than the coherence bandwidth W_{coh} of the Rayleigh fading channel, fading will independently affect each of these N orthogonal carrier frequencies, and then physical frequency diversity potential will be obtained. Hence, a N carrier MC/DS-CDMA scheme, with MRC can be seen equivalent to a N-branch space diversity technique. Therefore, the average channel capacity per user $\langle C_i \rangle_{cl,\mathrm{MC/DS,Rayleigh}}$, normalized over the total system's bandwidth $W_{\mathrm{MC/DS}}$, used when the information bit is transmitted, is given by:

$$\frac{\langle C_i \rangle_{cl,\,\mathrm{MC/DS,\,Rayleigh}}}{W_{\mathrm{MC/DS}}} = \int_0^{\infty} \log_2 (1+\gamma') \frac{(\gamma')^{N-1}}{(N-1)! \cdot (\Gamma_{i,cl,\mathrm{MC/DS}})^N} \cdot \exp\left(-\frac{\gamma'}{\Gamma_{i,cl,\mathrm{MC/DS}}}\right) \cdot \mathrm{d}(\gamma') \quad (9)$$

where $\langle . \rangle$ indicates average value, the subscript 'Rayleigh' refers to the Rayleigh fading channel, and $\Gamma_{i,cl,\mathrm{MC/DS}} = \langle \gamma' \rangle$, given by eq.(5), is the average received SINR γ' in each of the N frequencies where the DS signal is transmitted and no correlation between the N fading patterns is assumed.

In general, the multipath-intensity profile (MIP) in an urban Rayleigh fading environment is exponential, but, here, MIP is assumed discrete and constant, so that the "resolvable" path model can be considered to have equal path strengths on the average. Furthermore, if path-diversity reception, provided by a MRC RAKE receiver, is also applied to the MC/DS-CDMA system, in each carrier frequency, then additional diversity will be achieved. Hence, the average SINR after path-diversity applied, in each of the N carrier frequencies, $\Gamma_{i,\mathrm{pt},cl,\mathrm{MC/DS}}$, will be given by, [36]:

$$\Gamma_{i,\mathrm{pt},cl,\mathrm{MC/DS}} = M_{\mathrm{MC/DS}} \cdot \Gamma_{i,cl,\mathrm{MC/DS}} = = M_{\mathrm{MC/DS}} \cdot \left[\frac{\Gamma}{G_{\mathrm{p,mc/ds}} + (3.3123\ K - 1) \cdot \Gamma} \right] \tag{10}$$

where the new suffice 'pt' refers to the path-diversity reception applied. Then, the spectral efficiency $SE_{cl,\mathrm{MC/DS,Rayleigh}}$ achieved by the cellular MC/DS-CDMA system operating in a Rayleigh fading environment and expressed in (bits/sec/Hz) over the total available system's bandwidth $W_{\mathrm{MC/DS}}$, is found to be:

$$SE_{cl,\mathrm{MC/DS,\ Rayleigh}} = \frac{\langle C_i \rangle_{cl,\mathrm{MC/DS,\ Rayleigh}}}{W_{\mathrm{MC/DS}}} = = \int_0^{\infty} \log_2 (1 + \gamma') \cdot \frac{(\gamma')^{N-1}}{(N-1)! \cdot (\Gamma_{i,\mathrm{pt},cl,\mathrm{MC/DS}})^N} \cdot \cdot \exp\left(- \frac{\gamma'}{\Gamma_{i,\mathrm{pt},cl,\ \mathrm{MC/DS}}} \right) \cdot \mathrm{d}(\gamma') \tag{11}$$

where $\Gamma_{i,cl,\mathrm{MC/DS}}$, used in eq.(9), has been changed now to $\Gamma_{i,\mathrm{pt},cl,\mathrm{MC/DS}}$.

3 The SC/DS-CDMA case

In a pure cellular SC/DS-CDMA system, the available radio channel of bandwidth $W_{\mathrm{SC/DS}}=G_{\mathrm{p,sc/ds}} \cdot W_{\mathrm{s}}$ (where $G_{\mathrm{p,sc/ds}}$ is the proceessing gain applied) is reused in all neighboring cells, while different code sequences use the same radio channel to carry different traffic channels in each of these cells. In this case, the channel capacity (in the Shannon sense) required for errorless transmission of a spread signal of bandwidth $W_{\mathrm{SC/DS}}$ will be given by, [17]:

$$C_{i,cl,\mathrm{SC/DS}} = W_{\mathrm{SC/DS}} \cdot \log_2 (1 + \Gamma_{i,cl,\mathrm{SC/DS}}) \tag{12}$$

where $\Gamma_{i,cl,\mathrm{SC/DS}}$, i=[1,..,12K], is the spread SINR received at the mobile unit as it reaches the boundary of a cell, and determined by considering, also in this case, the average received CCI power, as following:

$$\Gamma_{i,cl,\mathrm{SC/DS}} = \frac{\alpha R^{-4}}{N_0 \cdot W_{\mathrm{SC/DS}} + [\,(K-1)(\alpha R)^{-4}\,]} + + \frac{\alpha R^{-4}}{N_0 \cdot W_{\mathrm{SC/DS}} + [\,2K\alpha\alpha^{-4} + 3K\alpha(2R)^{-4} + 6K\alpha(2.633\,R)^{-4}\,]} = = \frac{P_{i,cl,\mathrm{SC/DS}}}{N_0 \cdot W_{\mathrm{SC/DS}} + (3.3123\ K - 1) \cdot P_{i,cl,\mathrm{SC/DS}}} \tag{13}$$

where it is assumed that $P_{\mathrm{i,cl,SC/DS}}=P_{\mathrm{i,,cl,MC/DS}}=\alpha R^{-4}$ is the user's average received signal power and the new subscripts 'SC/DS' and 'sc/ds' refer to SC/DS-CDMA cellular system. Eq.(13) can equivalently be written in the form:

$$\Gamma_{i,cl,\mathrm{SC/DS}} = \frac{\Gamma}{G_{\mathrm{p,sc/ds}} + (3.3123\,K - 1) \cdot \Gamma} \tag{14}$$

where $\Gamma=(P_{i,,cl,\mathrm{SC/DS}}/N_0 W_{\mathrm{s}})$ is the received SNR over signal bandwidth W_{s}.

In the following we consider a cellular SC/DS-CDMA system operating in a Rayleigh fading environment. If the bandwidth $W_{\mathrm{SC/DS}}$ is greater than the coherence bandwidth W_{coh} of the Rayleigh fading channel, the maximum number $M_{\mathrm{SC/DS}}$ of uncorrelated resolvable paths will be given by, [1]:

$$M_{\mathrm{SC/DS}} = [W_{\mathrm{SC/DS}} \cdot \Delta] + 1 = \left[\frac{W_{\mathrm{SC/DS}}}{W_{\mathrm{coh}}} \right] + 1 \tag{15}$$

Although the number of resolvable paths $M_{\mathrm{SC/DS}}$ may be a random number, it is bounded by eq.(15). We now estimate the average channel capacity per user in a SC/DS-CDMA cellular system, as affected by the inherent diversity potential of the DS transmission. In addition, we assume that all users of the system equally share the average capacity provided by the entire physical channel of bandwidth $W_{SC/DS}$ and that all users in all cells operate under similar Rayleigh fading conditions. Thus, we write:

$$\left\langle C_i \right\rangle_{cl,\mathrm{SC/DS,Rayleigh}} = \frac{1}{12K} \cdot \left\langle C \right\rangle_{cl,\mathrm{SC/DS,Rayleigh}} \qquad (16)$$

where $\langle C_i \rangle_{cl,\mathrm{SC/DS,Rayleigh}}$ is the i-th user's portion of the totally available average capacity $\langle C \rangle_{cl,\mathrm{SC/DS,Rayleigh}}$ of the channel $W_{SC/DS}$. Then, considering, a conventional coherent MRC RAKE receiver, the output's decision variable is identical to the decision variable which corresponds to the output of a M-branch space diversity MRC technique, with M=$M_{SC/DS}$, [1]. Consequently, the maximal-ratio coherently combining reception of DS spread signals, achieved by the considered RAKE receiver, is equivalent to a M-branch space diversity MRC technique and is the optimal diversity scheme as it provides the maximum output SINR, [36]. Therefore, the probability density function (p.d.f.) of the combined instantaneous SINR $\gamma_{\mathrm{m,t}}$ of the spread DS signal over the bandwidth $W_{SC/DS}$, with no correlation among the $M_{SC/DS}$ "branches", will follow the Erlang distribution, [37], i.e.,

$$\mathrm{p}^{M_{\mathrm{SC/DS}}}(\gamma_{\mathrm{m,sc/ds,t}}) = \frac{1}{(M_{\mathrm{SC/DS}}-1)!} \cdot \frac{\left(\gamma_{\mathrm{m,sc/ds,t}}\right)^{M_{\mathrm{SC/DS}}-1}}{\left(\Gamma_{\mathrm{m,sc/ds,t}}\right)^{M_{\mathrm{SC/DS}}}} \cdot \cdot \exp\left(-\frac{\gamma_{\mathrm{m,sc/ds,t}}}{\Gamma_{\mathrm{m,sc/ds,t}}}\right) \qquad (17)$$

where $\Gamma_{\mathrm{m,sc/ds,t}}$=$\langle \gamma_{\mathrm{m,sc/ds,t}} \rangle$ is the totally received average spread SINR value in the m-th, m=[1,…,$M_{SC/DS}$], diversity branch from all 12K users, $M_{SC/DS}$ is obtained from eq.(15) and the subscripts 't' and 'm' refer to the totally received average spread SINR from all users and to the m-th diversity branch, respectively. Thus, an expression for the average capacity $\left\langle C \right\rangle_{cl,\mathrm{SC/DS,Rayleigh}}$ of the channel $W_{SC/DS}$ can be written as:

$$\left\langle C \right\rangle_{cl,\mathrm{SC/DS,\ Rayleigh}} = W_{\mathrm{SC/DS}} \int_0^\infty \log_2\left(1+\gamma_{\mathrm{m,sc/ds,t}}\right) \frac{\left(\gamma_{\mathrm{m,sc/ds,t}}\right)^{M_{\mathrm{MC/DS}}-1}}{\left(M_{\mathrm{MC/DS}}-1\right)! \left(\Gamma_{\mathrm{m,sc/ds,t}}\right)^{M_{\mathrm{MC/DS}}}} \cdot \cdot \exp\left(-\frac{\gamma_{\mathrm{m,sc/ds,t}}}{\Gamma_{\mathrm{m,sc/ds,t}}}\right) \cdot \mathrm{d}(\gamma_{\mathrm{m,sc/ds,t}}) \qquad (18)$$

Clearly, this channel capacity estimation, is based on the equivalence described above and indicates the average total channel capacity that appears at the MRC RAKE receiver output in the form of the average best recovered data rate from all 12K users. However, in general, the performance of the coherent MRC RAKE receiver depends on the number of the employed taps and the Rayleigh fading channel estimation. If the number of employed taps is less than the resolvable paths' number, the receiver performance will substantially be degraded because the power of the remaining "branches" will appear at the receiver output as self-noise power. In this work, we consider the optimum operation of the coherent MRC RAKE receiver where the number of taps employed is equal to the number $M_{SC/DS}$ of resolvable paths as given by eq.(15) and Rayleigh fading channel is perfectly estimated.

If we assume that the signal to each user appears at the receiver input with the same average spread SINR $\Gamma_{i,cl,\mathrm{SC/DS}}$, then the totally received spread SINR power ratio from all 12K active users will be equal to $12K \cdot \Gamma_{i,cl,\mathrm{SC/DS}}$, and $\Gamma_{\mathrm{m,sc/ds,t}}$ can be written as:

$$\Gamma_{\mathrm{m,sc/ds,t}} = 12\mathrm{K} \cdot \Gamma_{i,cl,\mathrm{SC/DS}} \qquad (19)$$

Thus, following eq.(14),

$$\Gamma_{\mathrm{m,\,sc/ds,\,t}} = \frac{12\,K\Gamma}{G_{\mathrm{p,\,sc/ds}} + (3.3123\mathrm{K} - 1) \cdot \Gamma} \qquad (20)$$

Then, combining eqs (16) and (18), the spectral efficiency $SE_{cl,\mathrm{SC/DS,Rayleigh}}$ achieved by a cellular SC/DS-CDMA system operating in a Rayleigh fading environment and measured in (bits/sec/Hz) over the total system's bandwidth $W_{SC/DS}$, is found to be:

$$SE_{cl,\text{SC/DS, Rayleigh}} = \frac{\langle C_i \rangle_{cl,\text{SC/DS, Rayleigh}}}{W_{\text{SC/DS}}} = \\ = \frac{1}{12K\left(M_{\text{SC/DS}}-1\right)!\left(\Gamma_{\text{m,sc/ds, t}}\right)^{M_{\text{SC/DS}}}} \cdot \\ \cdot \int_0^\infty \log_2(1+\gamma)\cdot\gamma^{M_{\text{SC/DS}}-1}\cdot\exp\left(-\frac{\gamma}{\Gamma_{\text{m.sc/ds, t}}}\right)\cdot d\gamma \tag{21}$$

where the notation for the combined instantaneous SINR $\gamma_{\text{m,sc/ds,t}}$, used in eq.(18), has been changed to γ and the SINR value $\Gamma_{\text{m,sc/ds,t}}$ is given by eq.(20). However, the so derived $SE_{cl,\text{SC/DS,Rayleigh}}$ value represents an average value following the average channel capacity per user $<C_i>_{cl,\text{SC/DS,Rayleigh}}$ and reflects the average best value achieved in the considered Rayleigh fading environment.

4 Comparison of MC/DS-CDMA and SC/DS-CDMA cellular systems-normalized conditions

We use eqs (11) and (21) to compare, the performance of a MC/DS-CDMA and a SC/DS-CDMA cellular systems in terms of spectral efficiency achieved. In particular, considering that both cellular systems operate in a Rayleigh fading environment with $W_{\text{MC/DS}}= W_{\text{SC/DS}}$ =10MHz, $W_{\text{mc/ds}}$=1.25MHz and assuming the following values:

(i) signal bandwidth: W_s=30KHz,
(ii) number of users per cell for both cellular systems: K=10,
(iii) total multipath spread of the urban Rayleigh fading channel: Δ=3μsec,
(iv) number of "inherent diversity branches" of MC/DS-CDMA cellular system: $M_{\text{MC/DS}} = [W_{\text{mc/ds}} \cdot \Delta]+1$=4,
(v) number of "inherent diversity branches" of SC/DS-CDMA cellular system: $M_{\text{SC/DS}} = [W_{\text{SC/DS}} \cdot \Delta]+1$=31, and
(vi) number of carrier frequencies in cellular MC/DS-CDMA system: N=8 (so that $W_{\text{MC/DS}}=N\cdot W_{\text{mc/ds}}$).

Note that all integrals are calculated numerically, as they can not be expressed in closed form. Furthermore, considering K=10 as an indicative value (in real cellular systems the actual number K of users per cell is of the order of 50). Then, the spectral efficiencies achieved on the downlink, $SE_{cl,\text{MC/DS,Rayleigh}}$ and $SE_{cl,\text{SC/DS,Rayleigh}}$ (given by eqs (11) and (21) respectively) in a Rayleigh fading environment are plotted against Γ (expressed in dB) in Figure 2. As it can readily be seen, for cellular operation in a Rayleigh fading environment and under normalized conditions, MC/DS-CDMA offers always higher spectral efficiency, expressed in (bits/sec/Hz), than that of a cellular SC/DS-CDMA system. In addition, one must notice that, in all cases plotted in Figure 2, as Γ increases to infinity, the spectral efficiency of each of the considered cellular systems under discussion asymptotically tends to an upper limit value, indicating that there is no way to increase its spectral efficiency by increasing the power of the transmitted signals.

The greatly increased spectral efficiency of the cellular MC/DS-CDMA system is directly related to the number N of orthogonal carrier frequencies used and to the additional diversity that results after path-diversity reception is applied to each of the N frequencies.

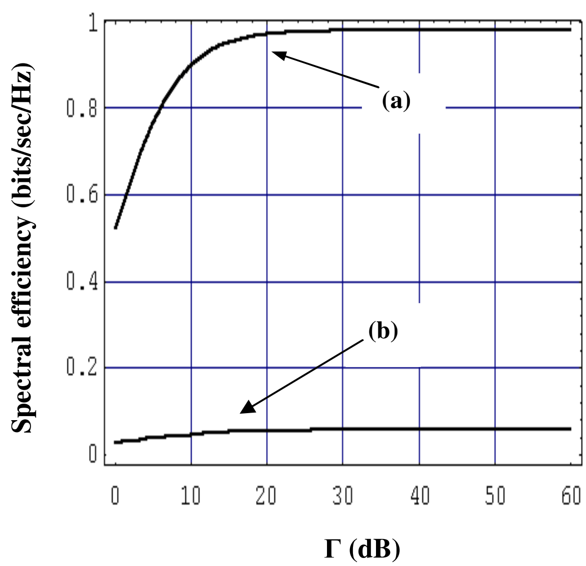

Fig 2. Spectral efficiency in (bits/sec/Hz) on downlink in a Rayleigh fading environment: (a) cellular MC/DS-CDMA system, (b) cellular SC/DS-CDMA system.

However, this holds only for small values of N, because, for increased values of N, the system's spectral efficiency is limited by the total interference power. Then, the relationship between the spectral efficiency $SE_{cl,\mathrm{MC/DS,Rayleigh}}$ on downlink of cellular MC/DS-CDMA system, as given by eq.(11), and the number N of carrier frequencies, is shown in Figure 3, for W_s=30KHz, K=10, Δ=3μsec, Γ=15dB (keeping in all cases $W_{MC/DS}$=10MHz since $W_{MC/DS}=N\cdot G_{p,mc/ds}\cdot W_s$).

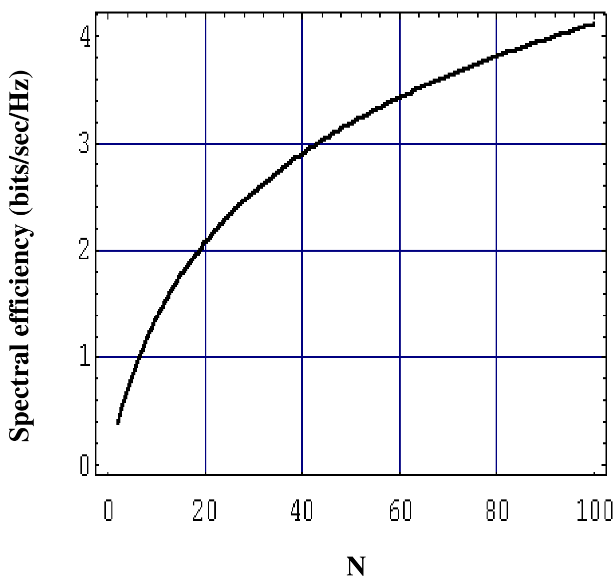

Fig. 3. Spectral efficiency in (bits/sec/Hz) on downlink of cellular MC/DS-CDMA system in a Rayleigh fading environment against the number N of carrier frequencies.

As it can be seen directly from Figure 3, the spectral efficiency achieved by a cellular MC/DS-CDMA is increased as the number N of carrier frequencies increases. However, the increase of carrier frequencies in a cellular MC/DS-CDMA system, adds complexity to the system.

5 Conclusion

In this paper, we compared MC/DS-CDMA and SC/DS-CDMA cellular systems in terms of spectral efficiency, expressed in (bits/sec/Hz), achieved under normalized conditions. Then, here, spectral efficiency is evaluated in terms of the theoretically Shannon channel capacity available to each system's user, in the downlink transmission, for Rayleigh fading operation and considering the diversity potential that each scheme provides as a physical means for fading mitigation. The results show that, cellular MC/DS-CDMA system with path-diversity reception provided by a MRC RAKE receiver, has always an advantage in spectral efficiency over cellular SC/DS-CDMA, especially, when a large number of carrier frequencies are used. Consequently, the cellular MC/DS-CDMA system is shown to be another good alternative in the situation of the cellular network evolution from the cellular SC/DS-CDMA to an advanced CDMA system. However, the increased number of carrier frequencies and path-diversity applied in each of them, in MC/DS-CDMA, adds serious complexity to the system. Finally, a simulation process must be described analytically, in order to compare with the theoretical results of this paper. We are still working on this, for a future paper, but results are not yet derived due to complicated system's parameters.

References:

[1] J.G. Proakis and M.Salehi, '*Digital Communications'*, *5rd Edit*., McGraw-Hill, 2008.

[2] A.J. Goldsmith, The Capacity of Downlink Fading Channels with Variable Rate and Power, *IEEE Trans. on Veh. Technology*, vol.46, 1997, pp. 569-580.

[3] W.C.Y. Lee, Estimate of Channel Capacity in Rayleigh Fading Environment, *IEEE Trans. on Veh. Technology*, vol.39, no.3, 1990, pp. 187-189.

[4] M.K. Simon and M.S. Alouini, *Digital Communication over Fading Channels: A Unified Approach to Performance Analysis*, New York: John Wiley, 2000.

[5] L.H. Ozarow, S. Shamai and A.D. Wyner, Information theoretic considerations for cellular mobile radio, *IEEE Trans. on Veh. Technology*, vol.VT-43, no.2, 1994, pp. 359-378.

[6] A.J. Goldsmith and P. Varaiya, Capacity of fading channels with channel side information, *IEEE Trans. on Inform. Theory*, vol.43, no.6, 1997, pp.1986-1992.

[7] G. Kaplan and S. Shamai, Achievable performance over the correlated Rician channel, *IEEE Trans. on Communications*, vol. 42, no.11, 1994, pp. 2967-2978.

[8] T. Ericson, A Gaussian channel with slow fading, *IEEE Trans. on Inform. Theory*, vol. IT-16, 1970, pp. 353-355.

[9] J.P. Linnartz and S. Hara, Special issue on multi-carrier communications, *Wireless Personal Commun.,*, vol.2, no.1,2, 1995, pp. 1-7.

[10] S. Kondo and L.B. Milstein, Performance of multicarrier DS CDMA systems, *IEEE Trans. on Communications*, vol.44, 1996, pp. 238-246.

[11] P. Varzakas and G.S. Tombras, Spectral efficiency of a cellular MC/DS-CDMA system in Rayleigh fading, *Int. Journal of Communication Systems,* vol.18, no.8, 2005, pp. 795-781.

[12] P. Varzakas and G.S. Tombras, Spectral Efficiency of a Single Cell Multi-Carrier DS-CDMA System in Rayleigh Fading*, Journal of the Franklin Institute-Engineering and Applied Mathematics* vol. 343, no.3, 2006, pp.295-300.

[13] D.N. Hatfield, Measure of spectral efficiency in land mobile radio, *IEEE Trans. Electromagn. Compat*., vol. EMC-19, 1997, pp. 266-268.

[14] W.C.Y. Lee, Spectrum efficiency in cellular, *IEEE Trans. on Veh. Technology*, vol. 38, 1989, pp. 69-75.

[15] R. Prasad and A. Kegel, Effects of Rician faded and lognormal shadowed signals on spectrum efficiency in microcellular radio, *IEEE Trans. on Veh. Technology*, vol.42, 1993, pp. 274-280.

[16] P. Varzakas, Optimum processing gain for a hybrid direct sequence/slow frequency hopping code division multiple access cellular system over Rayleigh fading channels: the direct sequence/slow frequency hopping code division multiple access case, *Int. Journal of Communication Systems,* vol. 25, no.8, 2012, pp.1034-1043.

[17] P. Varzakas, Channel Capacity per user in a Power and Rate Adaptive Hybrid DS/FFH-CDMA Cellular System over Rayleigh Fading Channels, *Int. Journal of Communication Systems*, vol. 25, no. 7, 2012, pp. 943-952.

[18] P. Varzakas and G.S. Tombras, Spectral efficiency for a hybrid DS/FH CDMA system in cellular mobile radio, *IEEE Trans. on Veh. Technology,* vol.50, no.6, 2001, pp.1321-1327.

[19] M.S. Alencar and I.F. Blake, The capacity for a discrete-state Code Division Multiple Access Channel, *IEEE J. Select. Areas Commun*., vol. 12, no. 5, 1994, pp.925-937.

[20] S.V. Hanly, *Information capacity of radio networks*, Ph.D. dissertation, Cambridge University, Aug. 1993.

[21] K.S.Gilhousen, I.M. Jacobs, R. Padovani, A. Viterbi, L.A. Weaver and C.E. Wheatley, On the capacity of a cellular CDMA system, *IEEE Trans. on Veh. Technology*, vol.40,n1991, pp.303-312.

[22] C.E. Shannon, Communication in the presence of noise, *Proc. IRE*, vol.37, no.1, 1949, pp.10-21.

[23] S.N. Diggavi, Analysis of multicarrier transmission in time-varying channels, in *Proc. 1997 IEEE Int. Conf. Communications (ICC' 97),* Montreal, Que., Canada*,* June 8-12, 1997, pp.1091-1095.

[24] D. Goeckel and W. Stark, Throughput optimization in faded multicarrier systems, in *Proc. Allerton Conf. Communication and Computers*, Monticello, IL, Allerton House, Oct. 4-6, 1995, pp.815-825.

[25] E. Biglieri, J.Proakis and S.Shamai, Fading channels: Information-theoretic and communications aspects, *IEEE Trans. on Inform. Theory*, vol. 44, no.6, 1998, pp. 2619-2692.

[26] J.P. Linnartz, Performance Analysis of Synchronous MC-CDMA in Mobile Rayleigh Channel With Both Delay and Doppler Spreads, *IEEE Trans. on Veh. Technology,* vol. 50, no.6, 2001, pp.1375-1387.

[27] S. Verdu, The Capacity Region of the Symbol-Asynchronous Gaussian Multiple-Access Channel, *IEEE Trans. on Inform. Theory*, vol.35, no.4, 1989, pp.733-751.

[28] J.Y.N. Hui and P.A. Humblet, The Capacity Region of the Totally Asynchronous Multiple-Access Channel, *IEEE Trans. on Inform. Theory*, vol.IT-31, no.2, 1985, pp. 207-216.

[29] S. Shamai and A.D. Wyner, Information-Theoretic Considerations for Symmetric, Cellular, Multiple-Access Fading Channels-Part I-II, *IEEE Trans. on Inform. Theory*, vol.43, no.6, 1997, pp. 1877-1911.

[30] A.D. Wyner, Shannon-Theoretic Approach to a Gaussian Cellular Multiple-Access Channel, *IEEE Trans. on Inform. Theory*, vol. 40, no. 6, 1994, pp. 1713-1727.

[31] S. Verdu and S. Shamai (Shitz), Spectral efficiency of CDMA with Random Spreading, *IEEE Trans. on Inform. Theory*, vol.45, no.2, 1999, pp. 622-640.

[32] L. Chang, He Miao and X. Wei, "An Optimal Gain Control Scheme for Digital On-Channel Repeater with Feedback Interference Canceller in Digital Terrestrial Television Broadcasting Networks", *WSEAS TRANSACTIONS on COMMUNICATIONS*, Issue 5, vol. 10, 2011, pp.147-154.

[33] S.Shamai and S.Verdu, "The impact of frequency-flat fading on the spectral efficiency of CDMA", *IEEE Trans. on Inform. Theory*, vol. 45, no.4, 2001, pp. 1302-1327.

[34] R.G. Gallager, *Information Theory and Reliable Communication*, John Wiley & Sons, 1968.

[35] W.C.Y. Lee, *Mobile Communications Design Fundamentals,* New York, Wiley, 2nd Edit., 1993.
[36] Y. Murata, R. Esmailzadeh, K. Takakusaki, E.Sourour and M.Nakagawa, Path diversity for FFH/PSK spread-spectrum communication systems, *IEEE J. Sel. Areas in Commun*., vol.12, no.5, 1994, pp.970-975.
[37] W.C. Jakes*, Microwave Mobile Communications,* 1st Edit, New York*:* Wiley, 1974.