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Spectral efficiency of a single-cell multi-carrier DS-CDMA system in Rayleigh fading

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Abstract

The spectral efficiency of a multi-carrier direct-sequence code-division multiple-access (MC/DS-CDMA) system operating in a Rayleigh fading environment is investigated and evaluated in terms of the theoretically achievable channel capacity (in the Shannon sense) per user, estimated in an average sense. This short paper covers operation of the considered system over broadcast communication randomly time-varying channels as applicable to wireless radio networks and single-cell indoor mobile systems and leads to the derivation of a closed-form expression for the achieved spectral efficiency. Furthermore, the relation between the number of the employed sub-carriers and the achieved spectral efficiency is revealed.

Keywords: Spectral efficiency; Channel capacity; Multi-carrier modulation; Code-division multiple access; Rayleigh fading

1. Introduction

Based on orthogonal frequency-division multiplexing (OFDM), multi-carrier direct-sequence code-division multiple-access (MC/DS-CDMA) has been proposed and investigated in the context of high data rate communication over time-variant channels [1]. In such a MC/DS-CDMA system, the data sequence, multiplied by a spreading sequence, modulates a set of N orthogonal frequency carriers rather than a single one, as it is the case in conventional DS-CDMA. In this paper, we consider the operation of

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a single-cell MC/DS-CDMA system in a Rayleigh fading environment and evaluate its spectral efficiency in terms of the theoretically achievable channel capacity (in the Shannon sense) per user, on the condition that this is estimated in an average sense. Such an approach is justified by the fact that the spectral efficiency achieved by any multiple access communication system depends on the physical model of the fading radio environment, i.e., on what is known about the particular fading channels. For example, if nothing is known for the fading statistics of a channel then its countable capacity (in bits/s) will be dictated by the minimum fade signal-to-noise ratio (SNR), $\gamma_{\min}$, and will, thus, tend to zero as $\gamma_{\min} \rightarrow 0$. On the other hand, if fading statistics is known, then an "average" capacity formula can be derived after the distribution of the fading SNR γ for a fixed transmission rate [2–4].

The presented analysis refers to the downlink transmission (broadcast channel) for a fixed number K of simultaneous users, reflecting a static model of operation. Then, following the method described in [5–7], channel capacity is estimated assuming an equal power case, meaning that all users receive equal average signal power when an appropriate power control scheme is applied, in combination to the path-diversity achieved by a conventional coherent maximal-ratio combining (MRC) RAKE receiver and the physical frequency diversity potential provided by frequency-division multiplexing on a set of orthogonal carriers. However, this approach does not deal with the problem of the "capacity region", i.e., the set of information rates at which simultaneously reliable communication of each user messages is possible [8,9]; it is merely based on estimating the average channel capacity per user, considering the system's inherent diversity potential in conjunction to the path-diversity obtained by MRC RAKE reception. Hence, the derived spectral efficiency expression does not indicate the system's maximum value in (bits/s/Hz), but it represents an optimistic upper bound, in average sense, for practical modulation and coding schemes [5–7].

2. System description and channel capacity per user

In MC/DS-CDMA, each user's data symbol is transmitted in parallel over N orthogonal carrier frequencies (sub-carriers), multiplied by a spreading sequence unique to each user. Then, the received signal will be the output sum of all these N "branches", while the totally allocated system bandwidth, $W_{\mathrm{MC/DS}}$, assuming no guard band between adjacent frequency bands and a strictly band-limited "chip" sequence with bandwidth $W_{\mathrm{mc/ds}} = G_{\mathrm{p,mc/ds}} W$, will be equal to

$$W_{\mathrm{MC/DS}} = N W_{\mathrm{mc/ds}} = N G_{\mathrm{p,mc/ds}} W, \tag{1}$$

where $G_{\mathrm{p,mc/ds}}$ is the processing gain applied for direct-sequence (DS) spread transmission and W is the user unspread signal bandwidth.

However, reliable transmission of each user signal over each of the N sub-carriers clearly depends on the level of cooperation among the K users of the system, i.e., the multiple-access interference (MAI) power, while inter-carrier interference (ICI) is considered minimum. Thus, the nth channel capacity per user, $C_{i,n}$, i.e. each user's i $(1 \leqslant i \leqslant K)$ conditional channel capacity (in the Shannon sense) over the nth sub-carrier, $(1 \leqslant n \leqslant N)$, will be given by the Shannon–Hartley theorem when arbitrarily complex coding and delay is applied and the total MAI power, caused by even a small number of interfering users, tends to be Gaussian distributed [10]. In this respect, considering the profound