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Cognitive radio CDMA networking with spectrum sensing

Sanjay Dhar Roy[1,*,†], Sumit Kundu[1], Gianluigi Ferrari[2] and Riccardo Raheli[2]

[1] *Department of Electronics and Communication Engineering, National Institute of Technology, Durgapur, West Bengal, India*
[2] *Department of Information Engineering, University of Parma, Parma, Italy*

SUMMARY

In this paper, the performance of cognitive radio (CR) code division multiple access (CDMA) systems is analyzed. More precisely, CR users belong to a cognitive radio network (CRN), which coexists with a primary radio network (PRN). Both CRN and PRN are CDMA-based, with colocated base stations. Soft hand off and power control are considered in both the CRN and the PRN. Upon the development of an accurate simulator for a representative three-cell cellular scenario, we evaluate the performance of the proposed CR system in terms of outage probability, blocking probability and average data rate of secondary users. Three different spectrum sensing techniques are. Two new schemes, based on interference limit, are proposed and compared with an existing adaptive spectrum sensing scheme. Spectrum activity measurements and spectrum sharing decisions have been considered for evaluating the performance of the three schemes. The paper proposes a new CR-CDMA networking model and a simulation testbed for evaluating performances of secondary users and primary users in terms of outage, blocking, BER and average data rate in the presence of soft hand-off and power control. For comparison purposes, the analysis in the absence of spectrum sensing is also investigated. Copyright © 2012 John Wiley & Sons, Ltd.

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KEY WORDS: cognitive radio; CDMA; spectrum sensing; blocking probability; soft handoff (HO)

1. INTRODUCTION

Measurements on the spectrum usage in the United States have shown that average spectrum occupancy is only 5.5%, with a maximum of 13.1% in urban areas and a minimum of 1% in rural areas [2]. The efficiency in using the available spectral resources has two sides: spectrum efficiency and spectrum occupancy. While spectrum efficiency represents how efficiently a system uses its spectrum (bit/sec/Hz), spectrum occupancy represents the utilization percentage of the overall spectrum over time. These observations have motivated the study of techniques to efficiently exploit the available spectral resources. Among these, cognitive radio (CR) technology, formally defined by Mitola and Maguire in 1999 [3], is an attractive approach.

Cognitive radio systems allow the presence of primary users (PUs) and secondary (or cognitive) users (SUs) [4]. In a CR system, an SU may change its radio parameters on demand. For example, it can adapt its rate when the number of PUs reduces or the interference level lowers [5]. SUs access the channel in an opportunistic way by performing spectrum sensing, that is, detecting the spectrum portions that are not being used by PUs or are being used by SUs with corresponding interference level below a given interference limit. After finding spectrum ‘holes’ or ‘white spaces’ [6], that is, unused spectrum in spatial and/or temporal domains, an SU selects the best available channel: this operation is known as spectrum decision. Other users, either secondary or primary, may utilize the spectrum via spectrum sharing. An SU changes its transmission channel (or frequency)

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*Correspondence to: Sanjay Dhar Roy, ECE Department, NIT Durgapur, M.G. Avenue, Burdwan, WB, India 713209.
†E-mail: s_dharroy@yahoo.com, sanjay.dharroy@ece.nitdgp.ac.in

upon detecting a PU transmitting in the same channel or upon detection of a channel degradation. A scheduled spectrum sensing scheme for spectrum sharing among a group of SUs and a group of PUs is addressed in [7]. Cooperative spectrum sensing has emerged as an interesting research area. A hard decision combining-based cooperative spectrum sensing scheme, in the presence of a feedback error caused by imperfect channel conditions, was proposed in [8].

Cognitive radio technology is mainly used for dynamic spectrum access (DSA), which refers to the opportunistic spectrum usage by SUs. Dynamic spectrum access leads an SU to select the best available channel. SUs can coexist with PUs in two ways: through spectrum underlay or through spectrum overlay [9]. According to the spectrum overlay approach, an SU uses a portion of the spectrum that is not being utilized by the PUs. An SU will have to leave the spectrum whenever a PU asks for it. An SU can also adapt its transmit power or modulation/coding scheme according to the situation [5]. In practice, CR users, and the CR manager (if present) [9], would measure the interference level on the basis of broadcast information from the primary base stations (BSs) and would change their main networking parameters to reduce the interference level at the PU. Code division multiple access (CDMA) based CR networks have been well investigated in recent years. In MultiCarrier CDMA (MC-CDMA) for CR systems, the noncontiguous vacant parts of a certain portion of the spectrum are shared with the users of a primary system. However, the large spectral sidelobes of the Fourier transform-based implementation of MC-CDMA interfere with adjacent primary transmitted signals. To suppress the sidelobes, in [10] a novel complex signature sequence set was proposed for synchronous downlink MC-CDMA-based cognitive radio networking.

In this paper, we consider a heterogeneous network consisting of a cellular CDMA primary radio network (PRN) and a cellular CDMA cognitive radio network (CRN). The PRN and the CRN coexist, in the sense that the spatial cellular topology is the same and, in the centre of each cell, a primary BS (PBS) is colocated with a secondary BS (SBS). In each cell, the PBS and the SBS do not interfere in downlink with each other (e.g., through time division duplexing). We consider a representative three-cell scenario. Multirate CDMA systems use a variable spreading length or a multicode protocol [11]. Both PRN and SRN are multirate CDMA systems. Owing to the use of multirate CDMA, two classes of PUs, with two different data rates, will be considered. PUs in one class (PU_1) transmit at a lower data rate, while PUs in the other class (PU_2) transmit at a higher data rate. This corresponds to assuming the presence of two types of users who need different applications with different bandwidth requirements. In general, higher data rate users are expected to cause higher interference. Our goal is to investigate the impact of spectrum sensing on the system performance. To this end, starting from the spectrum sensing approach originally proposed in [12], we derive two new spectrum sensing techniques. For comparison purposes, the performance is analyzed also in the absence of spectrum sensing.

Spectrum sensing schemes are mainly classified as: (a) methods requiring both source signal and noise power information, (b) methods requiring only noise power information (semi-blind detection), (c) methods requiring no information on source signal or noise power (blind detection) [1]. Likelihood ratio test-based spectrum sensing and matched filtering-based spectrum sensing belong to category (a); wavelet-based spectrum sensing and covariance-based spectrum sensing belong to semi blind detection; eigenvalue-based spectrum sensing belongs to blind detection. The spectrum sensing techniques considered in this paper stem from the covariance-based semi blind spectrum sensing approach followed in [1, 12]. In particular, covariance-based spectrum sensing allows the SBS to know the spectrum activity of SUs. By properly thresholding the autocorrelation function of the received signal, the presence of PUs can be detected [13, 14].

We investigate the impacts of the number of PUs, the number of SUs and of other relevant system parameters (related to both the communication channel and the networking architecture) on the outage probability, the blocking probability and the average data rate. Under the assumption that the PRN and the CRN contain fixed numbers of PUs and SUs, we evaluate the blocking probability experienced by a new SU that attempts to join the system. In each cell, the PBS broadcasts information on the interference level to all PUs and SUs. On the basis of the received information, an SU may decrease its transmit power, may decrease its data rate, or may temporarily stop its transmission [1]. This paper expands upon our preliminary work appearing in [15] and [16]. The present work describes the spectrum sensing methodology and corresponding spectrum access decision criteria as

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used in our model. Specifically, the present work completes [15] and [16] by studying the effects of the data rate of cognitive users on the outage probability of an SU and by clearly discussing detailed procedures for finding the blocking probability in the absence of spectrum sensing.

The major contributions of our paper can be summarized as follows. First, we propose a novel CR-CDMA networking model with coexisting CRN and PRN in the presence of soft hand-off (HO). In this context, two novel spectrum sensing schemes are developed. Performance evaluation of the proposed spectrum sensing schemes is carried out, through a custom MATLAB simulator (We have used MATLAB developed by Mathworks, India.), in terms of outage probability, blocking probability, BER and average data rate of PUs and SUs. The joint impact of multiple antennas and spectrum sensing, in the presence of soft HO, is investigated.

The rest of the paper is organized as follows. In Section 2, the system model is introduced. In Section 3, the considered simulation model is described. In Section 4, numerical results are presented and discussed. Finally, Section 5 concludes the paper.

2. SYSTEM MODEL

In this section, we describe the network model and explain spectrum sensing schemes used in the present work. In Section 2.1, the system model is discussed while spectrum sensing techniques are described in Section 2.2. The major contributions of our paper have also been noted in Section 2.3.

2.1. Three-cell cognitive radio scenario

In Figure 1, the reference three-cell CR system is shown. As previously mentioned, in each cell a PRN and an SRN (or cognitive radio network, CRN) coexist. We also assume that the interference because of the activity of PUs and SUs is available at the SBSs via fluctuations of correlation function, as described in [12]. Soft HO is considered in each cellular network (either primary or

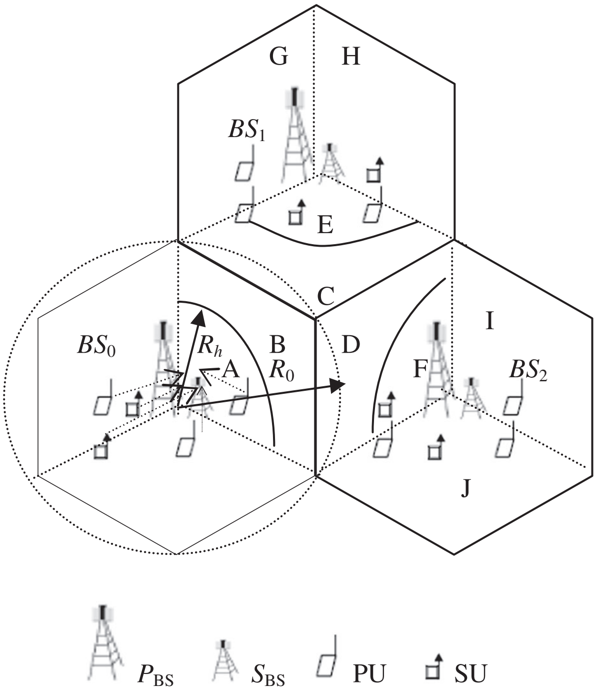

Figure 1. Hexagonal multicellular (three-cell) model with three BSs labelled as 0, 1, 2. A, E, F are non-HO regions and B, C, D are soft HO regions of BS_0, BS_1 and BS_2 respectively. Primary BSs and secondary BSs are colocated at the centre of the cells. R_0 is the radius of a cell. R_h is the radius of hard HO zone, in other words, R_h indicates soft HO boundary. We assume the SU of interest is inside the hard handoff zone of cell #0.

secondary). Soft HO requires a 'make-before-break' handover procedure [17], that is, a mobile station (MS) in a low signal zone under its current BS may already receive the signals sent from other neighboring BSs and, therefore, can be virtually connected to (and power-controlled by) more than one BS. To carry out a soft HO, the gains of all links between the MS and the connected BSs are evaluated and, then, a decision on power control is taken. Moreover, when carrying out the HO, a user may need to change its current pseudonoise (PN) code issued by the old BS to a new PN code issued by the new BS. Each cell in Figure 1 is divided into three sectors, with the same number of data users per sector. Each sector is further divided into two regions, denoted as soft HO and non-HO. In each cell, there are then three soft HO regions (denoted as B, C, D) and three non-HO regions (denoted as A, E, F). The analysis in the remainder refers to uplink communications. The soft HO region is defined on the basis of the distance from the BS, as shown in Figure 1. The three cells are numbered as 0, 1 and 2. In each cell, the PBS and SBS are colocated, and PUs and SUs are power-controlled by their respective BSs. An MS, either an SU or a PU, placed outside the HO boundary (R_{h}) (defined as the distance of the circular region within which there is no HO) is considered to be under soft HO with the three BSs associated to the three neighboring cells. A PU interferes at the SBS of its cell. Both the SBS and the SU are assumed to receive, from the PBS, information on the usage capacity percentage (u_{cp}) of the cell, defined as the ratio between the number of active PUs in the cell and the maximum number of sustainable users (including both PUs and SUs) in the system. In the case of the PRN, a PU is assumed to transmit at a higher rate, given by $m r_{\mathrm{d}}$, where m is an integer depending on the spreading length of PN codes for transmissions in the multirate CDMA system and r_{d} is the basic data rate. Two classes of PUs are then considered, depending on the used transmit rate: PU_1 denotes the first group of PUs, using the basic rate r_{d}; PU_2 denotes the second group of PUs, using a data rate equal to $2r_{\mathrm{d}}$. In the absence of spectrum sensing, all SUs are assumed to transmit at the same rate $4r_{\mathrm{d}}$.

Under the above assumptions, the total interference power at an SBS, because of SUs and PUs, can be written as follows:

$$I_{S_{\mathrm{BS}}}^{\mathrm{UL}} = I_{\mathrm{SU}} + I_{\mathrm{PU}_1} + I_{\mathrm{PU}_2}, \tag{1}$$

where the first term at the right-hand side of the equation corresponds to the interference power because of all SUs active in the uplink, whereas the other two terms correspond to the interference powers because of PU_1 and PU_2, respectively. All these powers will be evaluated through the simulator described in Section 3. The received power of each user (either a PU or a SU) is normalized to 1 at its BS — this is consistent with the assumption of power control.

2.2. *Spectrum sensing techniques*

As described in the previous section, we assume the presence of three types of users with three different data rates. The number (and, obviously, the presence) of each type of user and the interference caused by each of them can be obtained using the fluctuations of estimated autocorrelation function as explained subsequently [13, 14].

At the SBS of the cell of interest, the interference from all SUs, but the desired SU, is computed according to the previously introduced (spectrum sensing) method. Obviously, all PUs will also interfere at the SBS and this interference contribution can be estimated as well using fluctuations of the correlation estimator. Because the SUs and PUs have different rates, their autocorrelation fluctuations will be different. Here, the choice of the value of the threshold used to detect the fluctuations of the autocorrelation function depends on the data rate (which, in turn, depends on the spreading length). In other words, a particular class of users is typically detected using a threshold different from that of another class of users. Different thresholds should be considered for different classes of users because a lower threshold value for a particular class of users may lead to the (erroneous) detection of users of other class, which requires higher threshold. With a proper choice of the detection threshold, a user is detected if the fluctuations of the correlation estimator exceed the threshold [1]. In our CR-CDMA networks, the presence of users and their created interference at the SBS are determined in the same way. The threshold value is selected on the basis of the fluctuations of the autocorrelation function in the absence of the signal, that is, only in the presence of noise [13, 14].

The received signal is divided into M temporal windows, each of duration T. The fluctuations of autocorrelation are estimated at each window. Using M windows, second-order moment of estimated correlation is found as follows [13, 14]: $\varphi(\tau) = \frac{1}{M}\sum_{n=1}^{M-1}\left|R_{yy}^{n}(\tau)\right|^{2}$; where $R_{yy}^{n}(\tau)$ is the estimated correlation of received signal at n-th window.

This fluctuation will exceed a predefined threshold level if signal is present along with noise. The threshold level is selected on the basis of noise power.

Thus, the covariance method uses the fluctuations of autocorrelation of the received signal at different times, that is, $\phi(\tau)$ at different values of τ. In an ideal situation, the correlations of noise samples taken at different times should be zero if an AWGN channel is assumed. However, the correlation of the signal samples taken at different times would be larger than zero if the time separations are smaller than the data symbol duration [18].

2.2.1. Scheme 0 ('Ghavami SS'). This is the spectrum sensing scheme proposed by Ghavami and Abolhassani in [12]. SUs are prevented from transmitting (upon positive spectrum sensing) if $\sqrt{\beta} + 1 > (1/u_{\mathrm{cp}})$ is satisfied, where $\beta = I_{\mathrm{SU}}^{2}/I_{\mathrm{PU}}^{2}$. I_{SU} is the received interference power from SUs, and I_{PU} is the received interference power from PUs. The usage capacity percentage u_{cp} is defined as the percentage of the cell capacity used by the primary network. The PBS broadcasts the value of u_{cp} in the control channel. The SUs and the SBS listen to the control channel to obtain u_{cp} and take consequential decision(s) about spectrum access. Therefore, we are implicitly assuming some kind of cooperation between PBS and SBS. On the basis of the required QoS, the total number of sustainable users in a CDMA network may be determined. At any particular time, all PUs are not likely to be simultaneously active, so that SUs can transmit without hampering the QoS of PUs. Because the PBS knows the number of active PUs, it computes and broadcasts u_{cp} as the ratio between active PUs and total sustainable users in the network.

2.2.2. Proposed spectrum sensing schemes.

Scheme 1: In this scheme, in the absence of SUs a fixed number of PUs in each sector is assumed. In the remainder, we will consider 30 PUs, equally divided into the two groups PU_1 and PU_2, and a basic data rate $r_{\mathrm{d}} = 10$ kb/s. The maximum interference generated by all PUs, denoted as $I_{\max}$, will be evaluated with this constraint. At any time, the total interference caused by SUs and PUs must be lower than this interference limit.

Scheme 2: In this scheme, we assume that the PRN can tolerate some interference from SUs, even when all PUs are present in the system, up to the limit $I_{\max}/u_{\mathrm{cp}}$. At any time, the total interference caused by SUs and PUs must be lower than this interference limit.

We now provide more details on the proposed spectrum sensing schemes. As anticipated in Section 1, both schemes are based on the covariance-based spectrum sensing as mentioned in [1, 12]. However, in our spectrum sensing schemes we also consider spectrum sharing condition/permission for SUs. For example, the spectrum is first sensed, using covariance-based spectrum sensing, to infer about the presence of PUs. Because we are assuming multirate CDMA transmissions [12], we can distinguish between the presence of SUs and of the two types of PUs. Once the spectrum activity (by all present users) is known, spectrum sharing permission might be given to an SU who requests resources. By spectrum sensing, the overall interference created by currently active SUs in the system is also known.

After measurement of the spectrum activity, there can be the two following possibilities:

(1) The total interference, because of active SUs and PUs, is higher than the maximum tolerable level. If the total interference is found to be more than the interference limit, then an SU (already active in the network) will be asked to stop transmitting to reduce spectrum activity. In this context, spectrum sensing thus indicates spectrum activity measurement and spectrum sharing decision for SUs. Note that we slightly modify the spectrum sensing scheme proposed in [1]. More precisely, we predetermine a fixed interference limit rather than considering an adaptive interference limit based on the activity level of PUs (as used in [12]).

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(2) If the overall interference caused by all active users is lower than the allowed limit, a new SU may thus be allowed.

In a nutshell, we consider spectrum sensing as a combination of spectrum activity measurement and spectrum sharing decision for new SUs. Spectrum activity measurement is needed to find the presence of PUs and of existing interfering SUs. In any case, the total amount of interference generated by all users should not exceed the preset interference level of a fully loaded CDMA cell [12]. The condition for a positive spectrum sharing decision (i.e., to allow a new SU to transmit data) is derived using the proposed algorithm, which relies on proper observations of the fluctuations output by the correlation estimator.

There is another significant difference with other spectrum sensing schemes. In general, the presence of a PU is determined by traditional spectrum sensing techniques such as, for example, energy detection-based sensing, matched filtering-based sensing, etc. In a CDMA cellular network, an MS is identified by a PN code. A user's signal is modulated twice: first, it is modulated with a high frequency signal (the PN sequence or chip signal), which converts the user signal into a wideband signal; then, the latter signal is modulated with an RF carrier signal and transmitted through the antenna. Any user in a CDMA environment is an interferer to every other user. In particular, our system considers coexistence of SUs and PUs in one coverage area. Both types of users are present inside the CDMA network; however, SUs are served by an SBS while PUs are served by a PBS. At the SBS, the presence of PUs is detected and the total interference from currently active PUs is also measured using fluctuations of correlation estimators. The levels of interference caused by PUs and SUs are compared with respect to chosen thresholds, which are selected as explained in the previous section.

Traditional spectrum sensing schemes only find the presence of a PU. If a PU is found using spectrum sensing, an SU is not allowed to use the spectrum. A CDMA network is interference-limited and the number of users may be increased using many PN codes with graceful QoS degradation. Energy detectors are not used to detect CDMA signals, because the energy of the signal is almost the same as that of the noise. Thus, CDMA signals are not easily detectable using energy detectors or other popular spectrum-sensing schemes. CDMA signals are detected with the help of fluctuations of correlation estimators.

We assume the same threshold for all spectrum sensing schemes studied in this paper, it is expected that similar probability of detection will be obtained in all three cases of sensing algorithms for our three-cell model. The reference SBS detects the presence of CDMA signals generated by PU_1, PU_2 and SUs in the same manner as mentioned in [12, 14]. Interference from all interferers at the SBS is estimated in the presence of noise as in [14]. However, to properly select a threshold in our model, the following considerations are crucial. If we choose a too high threshold value, the probability of false alarm will be reduced, but the probability of missed detection will increase because some signals giving low fluctuations will not be detected. With the same threshold, the probability of detection seems to be lower than in the case when only one BS scenario (i.e., one PBS and one SBS) is considered.

The spectrum sensing method proposed in [1] has been used, in our work, in a three-cell CR-CDMA network considering soft HO and power control. Although we consider only three cells, the analysis presented here can be applied to a generic scenario with more than three cells as well. Furthermore, our approach can be appropriately modified if the PBS and the SBS are not colocated. However, this extension, currently under investigation, is not straightforward and goes beyond the scope of this paper.

As previously mentioned, the interference powers I_{SU}, I_{PU_1} and I_{PU_2} will be evaluated via simulations in Section 3. The PRN and CRN are colocated, with the corresponding BSs PBS and SBS positioned at the centre of each cell. We evaluate interference at SBS considering the (two classes of) PUs and the SUs separately.

The propagation radio channel is modeled as in [19]. More precisely, the link gain for a user at location (r, θ) in polar coordinates, with respect to BS_i, $i \in \{0, 1, 2\}$, is

$$G_i(r, \theta) = d_i(r, \theta)^{-\alpha_p} 10^{\xi_S/10}, \tag{2}$$

where $d_i(r,\theta)$ is the distance between the MS and BS_i, α_{p} is the path loss exponent and $10^{\xi_s/10}$ is the log-normal component with ξ_s normally distributed with zero mean and variance σ_s^2. The shadow fading at i-th BS is [19]

$$\xi_{s,i} = a\zeta + b\zeta_i, \tag{3}$$

where $a^2 + b^2 = 1$, ζ and ζ_i are independent Gaussian random variables with zero mean and variance σ_s^2 [20]. The out-cell interference consists of the interference because of MSs from regions E, C, G, H of cell #1 and from regions D, F, I, J of cell #2. MSs in the farthest sectors (G, H, I, J) are assumed to be power controlled by the respective BSs. The reference user is located in the non-HO region of the reference sector, that is, in region 'A'. The total in-cell interference in cell # 0 is

$$I_{\mathrm{in}} = I_1 + I_2, \tag{4}$$

where I_1 is due to all MSs in A and those in B connected to BS_0, I_2 is due to MSs in B but connected to BS_1 and BS_2. The out-cell interference is

$$I_{\mathrm{out}} = 2\left(I_{\mathrm{E}} + I_{\mathrm{c1}} + I_{\mathrm{c2}} + I_{co} + I_{\mathrm{G}} + I_{\mathrm{H}}\right) \quad , \tag{5}$$

where I_{E} is the interference power because of MSs in region E and connected to BS_1 (note that SUs would be connected to S_{BS1} and PUs would be connected to P_{BS1}); I_{c1} and I_{c2} are the interference powers because of MSs in region C and power controlled by BS_1 and BS_2, respectively; I_{co} is due to the MSs in region C and controlled by BS_0; I_{G} and I_{H} are the interference powers because of MSs in regions G and H. As previously mentioned, MSs in these farthest sectors are assumed to be power controlled by the corresponding BS, that is, BS_1. A multiplication factor equal to 2 is used in (5) to take into account the (same) interference contribution from cell #2. The actual received power from the desired SU is $U = S_R e^S$, where S is a Gaussian random variable with zero mean and variance $\sigma_S^2 = \sigma_e^2$. Thus, σ_e can be interpreted as a power control error (PCE). The desired SU is assumed to be in the non-HO region, that is, in region 'A'.

2.3. *Contribution of the paper*

Now we highlight the major contributions of our paper:

- We propose a CR-CDMA networking model with coexisting CRN and PRN in the presence of soft HO.
- Two new spectrum sensing schemes have been developed.
- Performance evaluation of spectrum sensing schemes (Scheme 0, Scheme 1, Scheme 2) has been carried out in terms of outage, blocking probability, BER and average data rate of PU and SU.
- A simulation testbed, as described below, has been developed to evaluate the performance of the spectrum sensing schemes.

In the next section, we show the simulation model and subsequently show some interesting results.

3. SIMULATION MODEL

The simulations are carried out in MATLAB with the following main input parameters: the degree of soft HO (denoted as $P_{R_{\mathrm{h}}}$), the shadowing correlation (denoted as a^2), the PCE (denoted as σ_e) and the number of PUs and SUs. The soft HO region boundary R_{h} is given as $R_{\mathrm{h}} = R_0\sqrt{1 - P_{R_{\mathrm{h}}}}$, where R_0 is the radius (normalized to unity for ease of implementation) of the circular cell which approximates the hexagonal cell.

3.1. *Generation of user locations and interference powers*

In each cell, users are assumed to be uniformly distributed and continuously active [21]. The generation of the users' locations and the interference powers is carried out considering the following steps:

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(1) A fixed number of users ($N_\mathrm{d} = N_\mathrm{PU} + N_\mathrm{SU}$) is generated. N_d denotes the total number of users. This number includes all PUs (N_PU) and SUs (N_SU).

(2) The locations (in the (r, θ) coordinate system) of all N_d SUs and PUs are generated and users are divided into non-HO and soft HO regions on the basis of their locations. We denote N_h and N_s as the number of users in the non-HO and soft HO regions, respectively. Assuming that the desired SU is in the non-HO region, the remaining interfering (primary and secondary) users in the non-HO region are $N_\mathrm{h} - 1$. The number of users in the soft HO region is thus $N_\mathrm{s} = N_\mathrm{d} - N_\mathrm{h}$.

(3) For each of the N_s users in soft HO region, the link gains to the three BSs of the three cells (either SBSs, for an SU, or PBSs, for a PU) interested in the soft-HO are generated as $G_i(r,\theta) = r_i^{-\alpha_p} e^{\xi_i}, i = 0, 1, 2$, where ξ_i is a Gaussian random variable with zero mean and variance $b^2\sigma_s^2$; and r_i is the distance from the i-th BS [15, 16]. Each user (either primary or secondary) is power controlled by the BS to which the link gain is maximum (if G_i is maximum, from the BS in the i-th cell).

(4) The interference power received at the reference i-th SBS (the same amount of interference would be at the PBS) is

$$I = S_\mathrm{R} \cdot \exp(r_n) \frac{G_0}{G_i} m, \tag{6}$$

where: $G_i = d_i^{-\alpha_p} 10^{\frac{\xi}{10}} |h_i|^2$; h_i is the fading coefficient; r_n is a normal random variable with zero mean and standard deviation σ_e; and S_R is the required received power (normalized to unity in the simulations, as the signal-to-interference ratio (SIR), is unaffected by this normalization). The data rate of any user is $m \cdot r_\mathrm{d}$ where m is equal to: 1 for PU_1; 2 for PU_2; and 4 for SUs (in the absence of spectrum sensing).

We do not consider the presence of fading in deciding to which BS (either BS_0, BS_1, or BS_2) an MS is connected. This is justified because the HO decision is based on the average received signal strength and not on the instantaneous random fluctuations caused by multipath fading. However, after making the decision regarding the BS to which the MS will be connected, we consider multipath fading in our interference estimation model. This interference modeling jointly takes into account path loss, shadowing and Rayleigh fading. With this interference modeling, we then evaluate the BER and the probability of outage for the PU and the SU of interest, respectively. The BER and probability of outage are also evaluated in the absence of fading to highlight its impact.

(5) The next interference contribution is due to $N_\mathrm{h} - 1$ users in non-HO region of the reference cell and to interferences from $N_{\mathrm{B}0}$ users in region 'B', which are power controlled by the BS of the reference cell. Assuming that each MS present in non-HO region is power controlled by the BS of the 0-th cell, the interference power becomes

$$I_1 = S_\mathrm{R} \sum_{i=1}^{N_\mathrm{h}-1} e^{r_{n,i}} m + S_\mathrm{R} \sum_{i=1}^{N_{\mathrm{B}0}} e^{r_{n,i}} m. \tag{7}$$

(6) The next interference contribution is due to $N_{\mathrm{B}1}$ and $N_{\mathrm{B}2}$ users in region 'B'. These users are power controlled by BS_1 and BS_2, respectively, and the corresponding interference powers are

$$I_2 = S_\mathrm{R} \sum_{i=1}^{N_{\mathrm{B}1}} e^{r_{n,i}} \frac{G_0}{G_1} m + S_\mathrm{R} \sum_{i=1}^{N_{\mathrm{B}2}} e^{r_{n,i}} \frac{G_0}{G_2} m. \tag{8}$$

(7) The interference contributions because of PUs and SUs in adjacent sectors (i.e. regions E, C, D and F) of first and second cells can be found in a similar manner. The number of MSs in each of the regions E and F is $N_\mathrm{d} - N_\mathrm{s}$. Therefore, it follows that $I_3 = I_\mathrm{E} + I_\mathrm{C}$ and $I_4 = I_\mathrm{D} + I_\mathrm{F}$.

(8) The interference powers from MSs in regions G, H, I and J are then generated. Let $I_5 = I_{\mathrm{G}} + I_{\mathrm{H}}$ and $I_6 = I_{\mathrm{I}} + I_{\mathrm{J}}$. I_{I} and I_{J} are the interference powers because of MSs in regions I and J.

(9) The total interference power can then be computed as

$$I = \sum_{k=1}^{6} I_k. \tag{9}$$

(10) The useful signal from the desired SU is then $U = S_d e^x$, where x is a Gaussian random variable with zero mean and variance σ_e^2. The corresponding SIR is U/I.

3.2. Probability of outage without spectrum sensing

The probability of outage for a user is defined as the probability that the SIR at the user falls below a predefined SIR threshold. If this happens, then the link quality and other QoS indicators would be degraded. Therefore, the probability of outage provides a measure of the acceptable user QoS level.

The following steps are considered for the evaluation of the probability of outage:

(1) The users (either PUs or SUs) are assumed to be continuously active, that is, the users are characterized by an activity factor equal to 1.

(2) For a desired SU, the SIR is generated as shown in the previous section and is compared with a threshold value given by $\gamma_{\mathrm{th}}^{/} = \gamma_{\mathrm{th}}/G_{\mathrm{p}}$, where G_{p} indicates the processing gain and the SIR threshold is denoted as γ_{th}.

(3) If the SIR falls below $\gamma_{\mathrm{th}}^{/}$, an outage counter ($outage_{\mathrm{count}}$) is incremented.

(4) Steps (2) and (3) are repeated a large number of times ($N_t >> 1$) to yield an accurate estimate of the probability of outage P_{out} as $outage_{\mathrm{count}}/N_t$.

3.3. Probability of outage with spectrum sensing

The following steps are considered for the evaluation of the probability of outage in this scenario:

(1) As in the absence of spectrum sensing, a fixed number of users (N_{PU} and N_{SU}) is considered. The interference contributions by PUs (PU_1 and PU_2) are obtained as described in Section 3.1. The interference caused by SUs can be similarly calculated. The interference powers from SUs and PUs are calculated on the basis of the number of PUs and SUs currently active in the system.

(2) $\sqrt{\beta} = I_{\mathrm{SU}}/I_{\mathrm{PU}}$, that is, the ratio between the interference power because of SUs' activity and the interference power because of PUs' activity, is evaluated at the SBS.

(3) The condition $\sqrt{\beta} + 1 \leqslant (1/u_{\mathrm{cp}})$ (or the conditions imposed by Schemes 1 and 2 described in Section 2) is checked at the SBS.

(4) If the condition is not satisfied, then SUs are removed one by one, initially from the non-HO region of the 0-th cell (region 'A') and then from other zones, that is, regions B, C, D, E, F, G or H. Once the condition is satisfied or all SUs are removed, then the probability of outage is evaluated as shown in Section 3.3., that is, $P_{\mathrm{out}} = outage_{\mathrm{count}}/N_t$.

Because our three-cell model is an extension of the one-cell model in [1], we expect similar effects, if the PBS and SBS are not colocated, to those mentioned in [1]. In this situation, all received power must be appropriately modified, at the SBS, in the uplink, because the distances are now different. Localization modules, such as GPS, are expedient to find the distances and angles associated with each of SUs and PUs. On the opposite, when PBS and SBS are colocated, the same received power at the PBS and the SBS can be considered. In this situation, the power received from a PU at the PBS is different from the interference caused by the same PU at the SBS. Intuitively, this might lead to increase in interference level.

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3.4. Probability of blocking without spectrum sensing

When a user wants to make a call to another user in the network, the user may get a connection if some of the channels (radio resources, such as frequency bands and spreading codes) are free. However, if all the channels are occupied, then the user will be denied a connection. The probability of blocking indicates the probability of a denied connection. In a network, the probability of blocking should be as small as possible, because it physically relates to the satisfaction of a user requesting a connection.

A new user, attempting to join the network and violating the condition described in Section 3.3 at point 3, will be denied access to the network, that is, will be blocked. The probability of blocking can then be computed considering the following steps:

(1) We consider an SIR threshold that guarantees a sufficient QoS level to continue a call.
(2) Next, we consider a new user generating a call. We evaluate the instantaneous SIR at the SBS considering a fixed number of PUs and a fixed number of SUs (including the new user).
(3) If the instantaneous SIR at the SBS is lower than $\gamma_{\text{th}}^{/} = \gamma_{\text{th}}/G_{\text{p}}$, then the call is blocked.

The above steps are repeated a number of times sufficiently large to allow the evaluation of the probability of blocking as follows: $P_{\text{blk}} = No.of\ blocked\ calls/No.of\ calls.$

3.5. Probability of blocking with spectrum sensing

In this case, we consider one SU of interest and all other SUs as interferers. After spectrum sensing, u_{cp} information is made available to the SBS, which can then decide to admit or not the SU. More precisely, when a new SU tries to join the system (i.e. it makes a call) the following cases can occur:

Case 1. The SU may be allowed to join the system with its current profile, that is, with its desired data rate and current transmit power, because it fulfils the necessary constraints.
Case 2. The SU may be allowed to join the system with reduced data rate and/or transmit power values, because its current profile does not fulfil the necessary constraints. If this is the case, the transmit power is reduced in steps according to the rule $P_{\text{next}} = P_{\text{currnt}} - \alpha.P_{\text{current}}$. The transmit power is reduced up to a minimum value fixed to 50% of the original transmit power. When the interference remains higher than the allowed maximum tolerable level, even after the transmit power reduction described above, then the data rate is reduced. The data rate of the SU is reduced from $4r_{\text{d}}$ to r_{d}, in steps of r_{d}, until the condition on the maximum tolerable interference level is fulfilled, at which point the SU is allowed into the network. If the condition cannot be satisfied, even after data rate reduction to r_{d}, then the SU is blocked.
Case 3. When the condition on the maximum tolerable interference cannot be fulfilled, regardless of power control and data rate reduction, the call is blocked.

3.6. Average data rate with spectrum sensing

In the presence of spectrum sensing, the average data rate is evaluated together with the blocking probability. In each simulation run, the data rate of an allowed SU can vary between $4r_{\text{d}}$ and 0, as described earlier. Therefore, over a large number of consecutive simulation runs the data rates of the desired SUs are collected and the average data rate is then obtained as the following arithmetic average:

$$Avg.\,data\ rate = \frac{summation\ of\ data\ rates}{no.\,of\ iterations}.$$

3.7. Bit error rate analysis

The BER of a PU is estimated in our three-cell CR-CDMA networking model from the signal-to-interference plus noise ratio expression that takes into account also the signal-to-noise ratio (SNR) because of AWGN. However, for other results, multiple access interference (MAI) will only be considered, because our scenario is interference-dominated. We compare the BER performance of our model with that of Ref. [1]. The signal-to-interference plus noise ratio expression given by Equation (9) in [22] has been used to determine, analytically, the BER in one-cell coexistence model of [12]. However, in our three-cell scenario the BER is evaluated using our simulation testbed, the only difference, with respect to the evaluation of the other performance indicators, being the fact that the AWGN is taken into account following the approach in [22–24]. We also consider the presence of Rayleigh fading in the evaluation of the BER, to evaluate its impact on the performance of a PU.

4. RESULTS AND DISCUSSIONS

The main parameters of the analytical framework are set as follows: the standard deviation of the shadow fading is $\sigma_s = 6$ dB; the distance between BSs is $D = 2000$ m; the spreading bandwidth is $W = 5.0$ MHz; the chip rate is $R_{\text{ch}} = 5.0$ Mcps; the PCE is $\sigma = 2$ dB; the SIR threshold is $\gamma_{\text{th}} = 6$ dB; the path loss exponent is $\alpha_{\text{p}} = 4$; the shadowing correlation is characterized by $a^2 = 0.3$ and $P_{R_{\text{h}}} = 0.3$; the basic data rate r_{d} is set to 7 kb/s, if not otherwise explicitly stated; finally, the processing gain is defined as $G_{\text{p}} = R_{\text{ch}}/r_{\text{d}}$.

In Figure 2, the probability of outage for an SU is shown as a function of the number of SUs. The number of PUs of type 1 and type 2 are fixed to 5 in both cases. It can be observed that the probability of outage increases for increasing values of the number of cognitive users. This is due

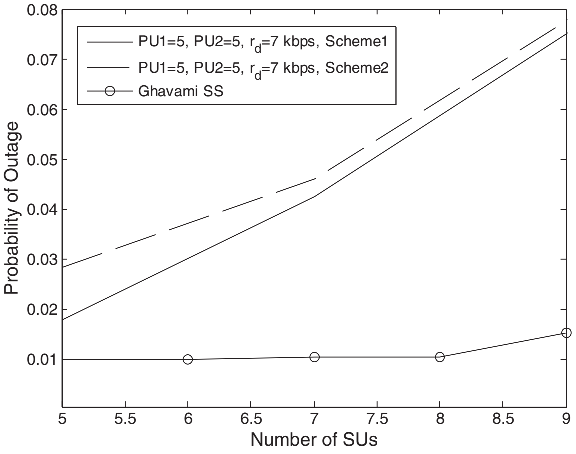

Figure 2. Probability of outage for a SU as a function of the number of SUs. The number of PUs is fixed to 10 and the basic data rate is set to 7 kb/s.

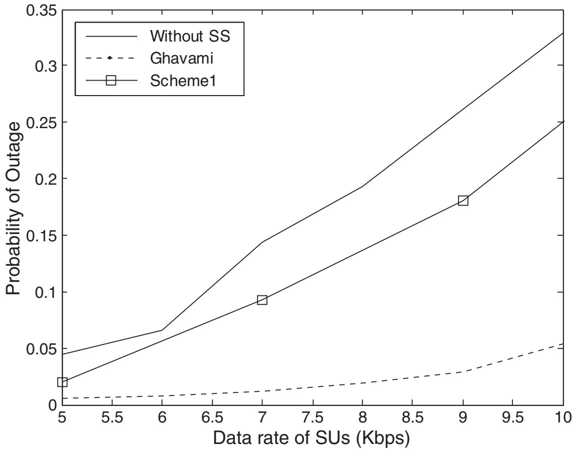

Figure 3. Probability of outage for a SU as a function of the admissible data rate of a SU. The numbers of PUs of type 1, of PUs of type 2 and of SUs are 5, 5 and 10, respectively.

to a corresponding increase of the MAI caused by SUs. Three curves are shown in this figure: two are associated with the two schemes proposed in our paper, whereas the remaining one is associated with the scheme with spectrum sensing proposed in [12] (the curves are labeled as 'Ghavami'). In particular, three different approaches to spectrum sensing are directly compared: Scheme 1, Scheme 2 and the scheme proposed in [12] ('Ghavami SS'). The probability of outage is lowest when spectrum sensing is performed jointly with the algorithm proposed in [12]. In this case, in fact, the allowed interference for SUs is determined on the basis of the actual number of PUs currently active. More precisely, if at any given time the active PUs cause an interference power I_{PU}, then the interference tolerable by SBS caused from SUs would be equal to $\sqrt{\beta}\, I_{\text{PU}}$. Thus, the tolerable interference caused at SBS because of SUs would change *adaptively* according to the PUs' activity. On the opposite, Schemes 1 and 2 consider a *fixed* interference limit because of the overall number of PUs and SUs in the system, regardless of their specific activity levels. The allowed interference limit is lower with less number of PUs. In this figure, the interference limit is set by considering the number of PUs to 10 (5 each) in the absence of SUs. However, the maximum tolerable interference limit in Scheme 1 is lower than the corresponding one in Scheme 2, so that the probability of outage is slightly better for Scheme 1. Therefore, it is expected that the performance with the adaptive spectrum sensing algorithm proposed in [12] is the best among all three schemes.

In Figure 3, the probability of outage for a cognitive user is shown as a function of the number of SUs for different values of the data rate. As one can see, the probability of outage increases when

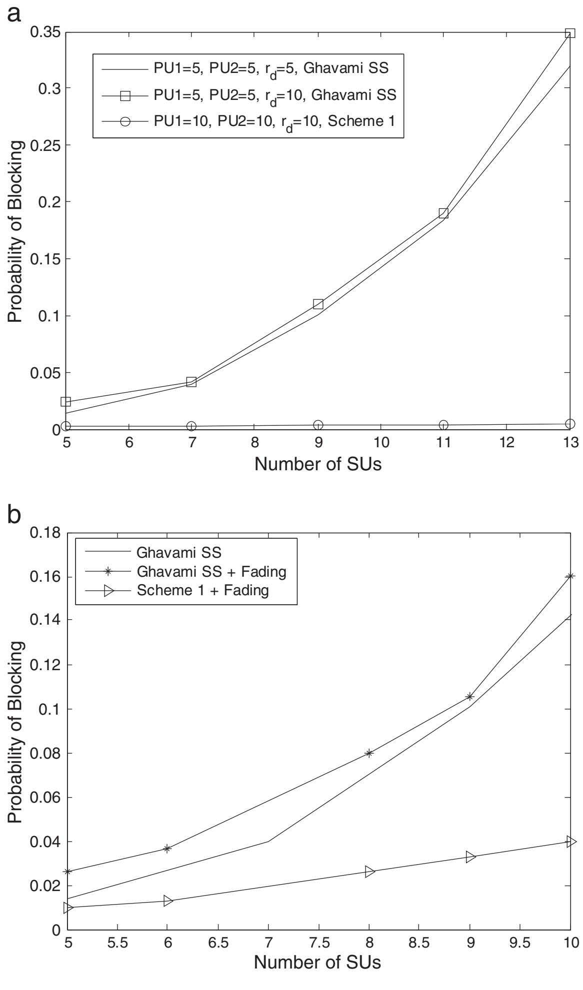

Figure 4. (a) Probability of blocking of a SU as a function of the number of SUs. The number of PUs is set to 10 and two different values of data rate are considered. (b) Probability of blocking of a SU as a function of the number of SUs. Comparison of Ghavami SS with Scheme 1 in the presence of Rayleigh fading.

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the data rate increases. This is expected, because a higher data rate increases the interference in a multirate CDMA system. The three curves in the figure refer to the three spectrum sensing schemes and correspond to fixed number of both types of PUs (5 PUs for each type) and a fixed number of SUs (10 SUs). The probability of outage is lowest when spectrum sensing is carried out using the 'Ghavami SS' scheme. P_{R_h} is set to 0.3; however, the probability of outage is likely to reduce, regardless of the spectrum sensing scheme, when higher degrees of soft HO (e.g. $P_{R_\mathrm{h}} = 0.7$) are considered [20].

In Figure 4(a), the blocking probability for a SU is shown as a function of the number of SUs, while the number of PUs is kept fixed. Two different values of the data rate of SUs are considered. The blocking probability is evaluated in the presence of spectrum sensing. Regardless of the value of the basic data-rate, the blocking probability is an increasing function of the number of SUs. It can be observed that the basic data-rate has a limited impact on the blocking probability. Scheme 1 performs better than 'Ghavami SS' in terms of blocking probability. In Figure 4(a), the blocking probability, in case of Scheme 1, is increasing at a low rate (almost a constant for the chosen range of number of SUs) because the maximum interference threshold is set by considering a higher number of PUs (i.e. at 10 (each)). Because the allowed interference level is set higher by considering larger number of PUs, the increase in blocking probability of an SU is not significant. In Figure 4(b), we

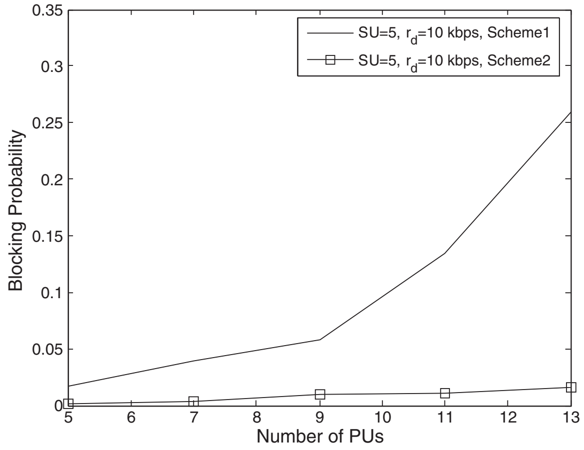

Figure 5. Probability of blocking of a SU as a function of the number of PUs (equally split between the two different types). The number of SUs is set to 5 and the basic data rate is set to 10 kb/s.

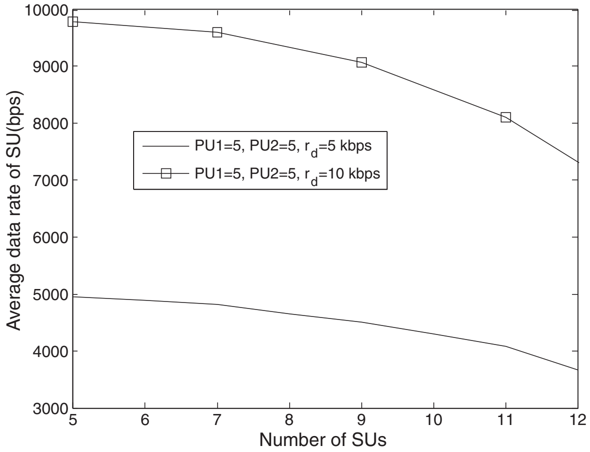

Figure 6. Average data rate of a SU as a function of the number of SUs, in the presence of spectrum sensing. The number of PUs is fixed and two possible values for the basic data-rate are considered.

compare the performance of Ghavami SS with Scheme 1 in the presence of Rayleigh fading under the same scenario. In Figure 4(b), in the case of Scheme 1, the maximum interference threshold is set with the number of PUs to five (5) each. The number of PUs is the same as in the case of Ghavami SS. Because the blocking here is based on the maximum interference threshold, the performance of Scheme 1 is slightly better than Ghavami SS. We did not consider the cooperation amongst users for performance evaluation of a SU as considered in [1]. It is expected that the performance of Ghavami SS with cooperation among users will be better in comparison to Scheme 1. However, the outage probability is significantly less in the case of Ghavami SS under the same number of PUs.

In Figure 5, the blocking probability for a SU is shown as a function of the number of PUs, considering both Schemes 1 and 2. It can be observed that the blocking probability increases for increasing numbers of PUs in the system. This is due to the corresponding increase in the interference caused by a large number of users. Scheme 2, however, performs significantly better than Scheme 1 because the maximum tolerable interference limit (related to the maximum number of supported PUs) is considerably higher.

In Figure 6, the average data rate of an SU is shown as a function of the number of SUs, considering two possible values of the basic data rate. It can be observed that the average data rate of an SU reduces for increasing values of the number of SUs. This is expected because the interference is

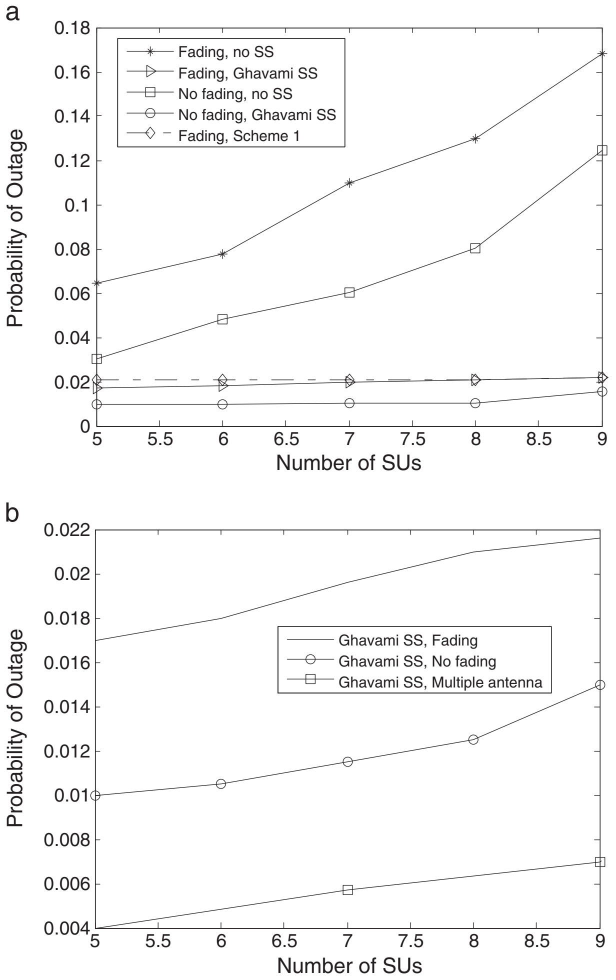

Figure 7. (a) The probability of outage for a SU as a function of the number of SUs, in presence of spectrum sensing and Rayleigh fading. The number of PUs is fixed to 10 and the basic data rate is set to 10 kb/s. (b) The probability of outage for a SU as a function of the number of SUs with multiple antennas with five antenna elements at the SBS.

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an increasing function of the number of SUs. Furthermore, the number of users to be blocked would be larger when the interference increases. Assuming that the data rate of a blocked user is zero, then the admissible data rate would vary from $4r_{\mathrm{d}}$ to zero. For both considered values of the data rate, the average data rate of SUs is a decreasing function of the number of cognitive users. Note, however, that the decrease is relatively faster for higher values of r_{d}. In this figure, the data rate of PUs is kept constant to evaluate the effects of spectrum sensing scheme, 'Ghavami SS', on the achievable data rate of a SU.

In Figure 7(a), the probability of outage for an SU is shown, as a function of the number of SUs, in the presence of Rayleigh fading. No SS and 'Ghavami SS' schemes are considered. In all cases, the outage probability is an increasing function of the number of SUs. The probability of outage versus the number of SUs plots for Schemes 1 and 2, in the absence of fading, is already shown in Figure 2. The effect of fading on Scheme 1 is similar as in case of 'Ghavami SS'. However, in Figure 7(a), the allowed interference limit is set higher in comparison to that of Figure 2. The allowed interference limit in the present case is found by considering the number of PUs to 30 (15 each) in the absence of SUs. The figure clearly indicates that the probability of outage increases significantly, for no SS case, in the presence of Rayleigh fading.

In Figure 7(b), the probability of outage for an SU is shown, as a function of the number of SUs, in the presence of Rayleigh fading and multiple antennas. The number of antenna elements is assumed to be five (5). The received signals from different antennas are assumed to be independent. We compare the performance of 'Ghavami SS' scheme for three different cases, that is, with fading, without fading and using multiple antennas. Multiple antennas are considered in the uplink at the SBS for the SU of interest. Multiple antenna forms a beam for the desired user and other users come under the null of the beam. Thus, the total uplink interference at the SBS decreases and the outage probability of the SU of interest decreases to a large extent as evident from the figure.

In Figure 8, the BER of a PU is shown as a function of the SNR, defined as the ratio between signal and AWGN powers. In the legend of Figure 8, 'our model' indicates our three-cell model with soft handoff and power control and 'Ghavami' indicates one-cell model of [12]. Our three-cell model with soft handoff and power control is compared with Ghavami's one-cell model with spectrum sensing. Spectrum sensing algorithm, 'Ghavami SS' is considered here. As anticipated in Section 3.7, the BER is analytically evaluated for the one-cell model of Ghavami using Equation (8) in [22]. For low SNR values (SNR$\leqslant$2 dB), the effect of AWGN is stronger than that of MAI. The BER is evaluated via simulation for our three-cell model. We find that the BER of a PU for our case closely follows that of Ghavami's model, although our model accounts for three cells and, consequently, for a more significant interference than that of the one-cell model in [12]. For low values of the SNR, our model closely matches the one-cell model. However, for high SNR, that is, when the noise is low, the effect of MAI is dominant and this justifies the performance difference

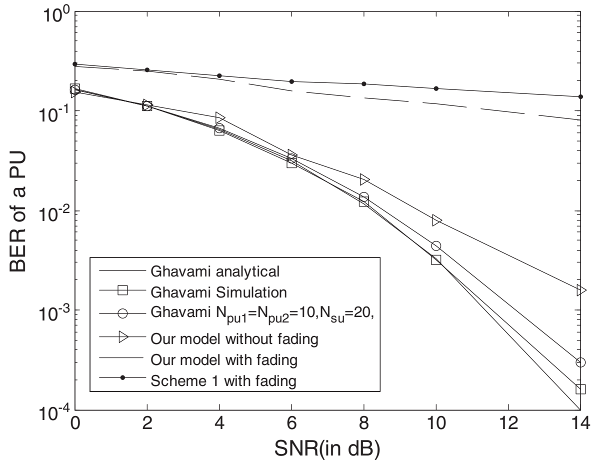

Figure 8. BER of a PU as function of SNR (in dB) in the presence of fading. Both analytical and simulation results are shown. The number of PUs is fixed to 10 and the basic data rate is set to 10 kb/s.

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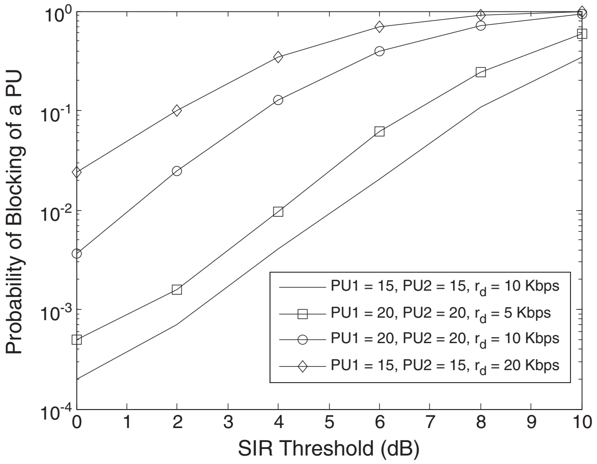

Figure 9. Probability of blocking of a PU as a function of SIR threshold (in dB).

between our three-cell model and one-cell model of [12]. Furthermore, a significant performance degradation can be observed in the presence of fading. Performance of Scheme 1 in the presence of fading has also been shown here. The performance of Scheme 1 is slightly worse than that of 'Ghavami SS' in the presence of fading.

In Figure 9, the probability of blocking of a PU is shown as a function of the SIR threshold. In this case, we assume that all SUs are already blocked. This is justified because a PU can be blocked only when all SUs are blocked already to decrease the total interference at the PBS. Furthermore, the blocking of a PU is considered on the basis of received SIR at the corresponding PBS. The effects of increasing the number of users and increasing the basic data rate are investigated in this figure. As the number of users is increased, the total interference at the PBS increases, and as a result, the SIR of the PU of interest decreases and finally the probability of blocking of the PU increases. A PU is blocked if the uplink SIR at the PBS is less than the SIR threshold. The probability of blocking of a PU increases as the basic data rate increases. It may be noted that the increase in data rate leads to decrease in processing gain. The corresponding SIR of the PU of interest at PBS also reduces as the processing gain decreases. Hence, the blocking probability of the PU of interest increases.

5. CONCLUSIONS

In this paper, we have analyzed the performance of a cognitive (secondary) user in a CR-CDMA system. A simulation model has been developed to assess the performance of an SU considering, as a reference, the spectrum sensing scheme proposed in [12]. Starting from this scheme, two new spectrum sensing schemes for a three-cell cellular scenario, incorporating soft HO, have been developed. In particular, the proposed simulation model allows fast performance evaluation of a CR-CDMA system. More precisely, the outage and blocking probabilities of the above three spectrum sensing schemes have been compared. All these schemes with spectrum sensing perform better than any scheme with no spectrum sensing. Moreover, Scheme 2 outperforms Scheme 1 in terms of SU blocking probability for any given fixed number of SUs and this improvement is more pronounced for large numbers of PUs. The SU performance, in terms of outage and blocking probabilities, improves if the data rate of SUs decreases. Finally, a larger number of cognitive users degrade the SU performance, in terms of outage and blocking probabilities, for fixed number of PUs.

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AUTHORS' BIOGRAPHIES

Sanjay Dhar Roy received his BE (Hons.) degree in Electronics and Telecommunication Engineering in 1997 from Jadavpur University, Kolkata, India and M.Tech. degree in Telecommunication Engineering in 2008 from National Institute of Technology Durgapur. He received his Ph.D. degree from National Institute of Technology Durgapur in 2011. He worked for Koshika Telecom Ltd. from 1997 to 2000. After that he joined the Department of Electronics and Communication Engineering, National Institute of Technology Durgapur as a Lecturer in 2000 and is currently an Assistant Professor there. His research interests include radio resource management, handoff, and cognitive radio networks. As of today, he has published 50 research papers in various journals and conferences. Dr. Dhar Roy is a member of IEEE (Communication Society) and is a reviewer of IET Communications, Electronics Letters and Journal of PIER, IJCS, Wiley, International Journal of Electronics, Taylor & Francis.

Sumit Kundu received his BE (Hons.) degree in Electronics and Communication Engineering in 1991 from NIT, Durgapur, India and M.Tech. degree in Telecommunication Systems Engineering and Ph.D. in Wireless Communication Engineering from IIT Kharagpur, India respectively. He has been a member of the faculty of the Department of ECE, National Institute of Technology, Durgapur since 1995 and is currently an Associate Professor there. His research interests include radio resource management in wireless networks, cognitive radio networks, wireless Ad Hoc and sensor networks. He is a member of IEEE (Communication Society) and is a reviewer of several IEEE journals.

Gianluigi Ferrari was born in Parma, Italy, in 1974. He received his 'Laurea' and Ph.D. degrees from the University of Parma, Italy, in 1998 and 2002, respectively. Since 2002, he has been with the University Parma, where he currently is an Associate Professor of Telecommunications. He was a visiting researcher at USC (Los Angeles, CA, USA, 2000–2001), CMU (Pittsburgh, PA, USA, 2002–2004), KMITL (Bangkok, Thailand, 2007), and ULB (Brussels, Belgium, 2010). Since 2006, he has been the Coordinator of the Wireless Ad-hoc and Sensor Networks (WASN) Lab (http://wasnlab.tlc.unipr.it/) in the Department of Information Engineering of the University of Parma. As of today he has published more than 160 papers in leading international journals and conferences, and more than 10 book chapters. He is coauthor of 7 books, including 'Detection Algorithms for Wireless Communications, with Applications to Wired and Storage Systems' (Wiley: 2004), 'Ad Hoc Wireless Networks: A Communication-Theoretic Perspective' (Wiley: 2006-technical best seller), 'LDPC Coded Modulations' (Springer: 2009), and 'Sensor Networks with IEEE 802.15.4 Systems: Distributed Processing, MAC, and Connectivity' (Springer: 2011). He edited the book 'Sensor Networks: where Theory Meets Practice' (Springer: 2010). His research interests include digital communication systems analysis and design, wireless ad hoc and sensor networking, and adaptive digital signal processing. He participates in several research projects funded by public and private bodies. Professor Ferrari is a co-recipient of: a best student paper award at IWWAN'06; a best paper award at EMERGING'10; an award for the outstanding technical contributions at ITST-2011; the best paper award at SENSORNETS 2012. The WASNLab team won the first Body Sensor Network (BSN) contest, held in conjunction with BSN 2011. He acts as a frequent reviewer for many international journals and conferences. He acts also as a technical program member for many international conferences. He currently serves on the Editorial Boards of several international journals. He was a Guest Editor of the 2010 EURASIP JWCN Special Issue on 'Dynamic Spectrum Access: From the Concept to the Implementation'.

Riccardo Raheli received the Dr. Ing. degree (Laurea) in Electrical Engineering 'summa cum laude' from the University of Pisa in 1983, the Master of Science degree in Electrical and Computer Engineering with full marks from the University of Massachusetts at Amherst, USA, in 1986, and the Doctoral degree (Perfezionamento) in Electrical Engineering 'summa cum laude' from the Scuola Superiore S. Anna, Pisa, in 1987. From 1986 to 1988 he was a Project Engineer with Siemens Telecomunicazioni, Milan. From 1988 to 1991, he was a Research Professor at the Scuola Superiore S. Anna, Pisa. In 1990, he was a Visiting Assistant Professor at the University of Southern California, Los Angeles, USA. Since 1991, he has been with the University of Parma, as a Research Professor, Associate Professor since 1998 and Full Professor since 2001. In this role, he was Chairman of the Communication Engineering Program Committee from 2002 to 2010 and Member of

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the Scientific Committee of CNIT (Consorzio Nazionale Interuniversitario per le Telecomunicazioni) from 2000 to 2005. He has also been Member of the Executive Committee of CNIT since 2008 and Member of the Scientific Committee of the Doctoral School in Engineering and Architecture since 2011. His scientific interests are in the general area of Information and Communication Technology, with special attention toward systems for communication, processing and storage of information. His research has lead to numerous international publications in journals, conference proceedings, and a few industrial patents. He is coauthor of a few scientific monographs such as 'Detection Algorithms for Wireless Communications, with Applications to Wired and Storage Systems' (John Wiley & Sons, 2004) and 'LDPC Coded Modulations' (Springer, 2009). He is supervising coauthor of the paper which received the '2006 Best Student Paper Award in Signal Processing & Coding for Data Storage' from the Communications Society of the Institute of Electrical and Electronics Engineers (IEEE). He served on the Editorial Board of the IEEE Transactions on Communications from 1999 to 2003. He was Guest Editor of a special issue of the IEEE Journal on Selected Areas in Communications (JSAC) published in 2005. He served on the Editorial Board of the European Transactions on Telecommunications (ETT) from 2003 to 2008. He was Guest Editor of a special issue of the IEEE Journal of Selected Topics in Signal Processing (JSTSP) published in 2011. He served as Co-Chair of the General Symposium on Selected Areas in Communications at the International Communications Conference (ICC 2010), Cape Town, South Africa, and the Communication Theory Symposium at the Global Communications Conference (GLOBECOM 2011), Houston, Texas, USA. He has also served on the Technical Program Committee of many international conferences such as ICC, GLOBECOM, IEEE Intern. Symp. Power-Line Commun. and its Appl. (ISPLC), European Signal Processing Conf. (EUSIPCO) and others.

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