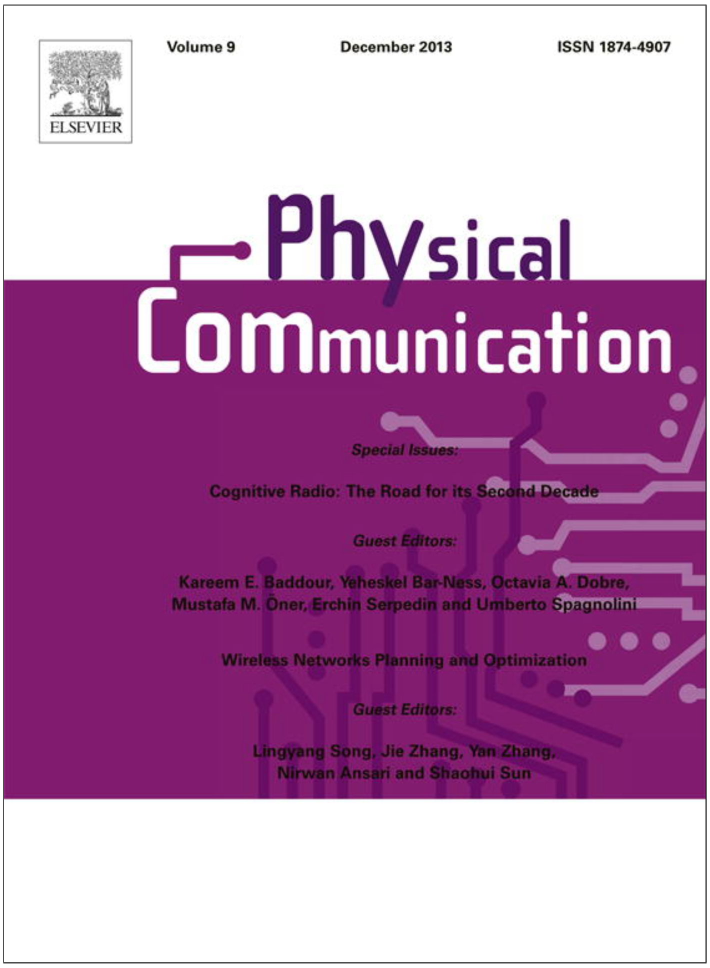
Volume 9
December 2013
ISSN 1874-4907
ELSEVIER
Physical Communication
Special Issues:
Cognitive Radio: The Road for its Second Decade
Guest Editors:
Kareem E. Baddour, Yeheskel Bar-Ness, Octavia A. Dobre,
Mustafa M. Öner, Erchin Serpedin and Umberto Spagnolini
Wireless Networks Planning and Optimization
Guest Editors:
Lingyang Song, Jie Zhang, Yan Zhang,
Nirwan Ansari and Shaohui Sun

Physical Communication 9 (2013) 73–87

Contents lists available at ScienceDirect

Physical Communication

journal homepage: www.elsevier.com/locate/phycom

Full length article

On spectrum sensing in cognitive radio CDMA networks with beamforming

Sanjay Dhar Roy [a,*], Sumit Kundu [a], Gianluigi Ferrari [b], Riccardo Raheli [b]

[a] Department of Electronics & Communication Engineering, NIT Durgapur, Durgapur, Pin-713209, India

[b] Department of Information Engineering, University of Parma, Parma, Italy

ARTICLE INFO

Article history:
Received 23 November 2012
Received in revised form 15 May 2013
Accepted 1 August 2013
Available online 4 September 2013

Keywords:
Cognitive radio (CR)
Code division multiple access (CDMA)
Beamforming
Spectrum sensing
Outage probability
Blocking probability
Soft hand-off (HO)

ABSTRACT

In this paper, the performance of cognitive radio (CR) code division multiple access (CDMA) networks is analyzed in the presence of receive beamforming at the base stations (BSs). More precisely, we analyze, through simulations, the performance achievable by a CR user, with and without spectrum sensing, in a three-cell scenario. Uplink communications are considered. Three different schemes for spectrum sensing with beamforming are presented, together with a scheme without spectrum sensing. CR users belong to a cognitive radio network (CRN) which is coexisting with a primary radio network (PRN). Both the CRN and the PRN are CDMA based. The CRN is assumed to utilize beamforming for its CR users. Soft hand-off (HO) and power control are considered in both the CRN and the PRN. The impact of beamforming on the system performance is analyzed, considering various metrics. In particular, we evaluate the performance of the proposed systems in terms of outage probability, blocking probability, and average data rate of CR users. The results obtained clearly indicate that significant performance improvements can be obtained by CR users with the help of beamforming. The impact of several system parameters on the performance of the three considered spectrum sensing schemes with beamforming is analyzed. Our results, in terms of probability of outage, show that the relative improvement brought by the use of beamforming is higher in the absence of spectrum sensing (reduction of 80%) than in the presence of spectrum sensing (reduction of 42%).

1. Introduction

The term cognitive radio (CR) was first coined by Mitola in 1999 [1]. CR networks allow the presence of primary users (PUs) and secondary users (SUs). An SU may change its radio parameters on demand. For example, it can adapt its data rate when the number of PUs becomes smaller or the interference level is low [2]. SUs access the channel in an opportunistic way. *Spectrum sensing* is related to the identification, by SUs, of unused spectrum portions, i.e., the portions which are not being used by PUs or are being used by SUs with an interference level below a pre-fixed interference limit. After finding spectrum "holes" [3], an SU selects the best available channel: this is known as *spectrum decision*. Other users, either cognitive (secondary) or primary, may utilize the spectrum via *spectrum sharing*. An SU can change its transmission channel or frequency if it detects the presence of a PU in the same channel or if it finds that the channel has worsened. SUs can coexist with PUs in two ways, either through spectrum underlay or spectrum overlay [4]. In practice, CR users, as well as the CR manager (if one exists) [4], 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.

Smart antenna techniques have been used for capacity enhancement in cellular networks [5]. Various types of

* Corresponding author. Tel.: +91 9332107814.
E-mail addresses: s_dharroy@yahoo.com, sanjay.dharroy4@gmail.com (S. Dhar Roy).

1874-4907/$ – see front matter
http://dx.doi.org/10.1016/j.phycom.2013.08.001

beamforming (e.g., fixed, adaptive, flat-top) have been investigated. In [6], the capacity improvement experienced by code division multiple access (CDMA) networks with antenna arrays at the BSs is evaluated for both uplink and downlink communications. In particular, the outage probability is evaluated as a function of cell loading, array parameters, fading, shadowing effects, and voice activity. Different beamforming schemes, based on adaptive algorithms for assigning weights to antennas and on direction-of-arrival estimation methods, have been studied in [7]. The outage probability is also investigated analytically in [8], where a simplified beamforming model is considered. Since beamforming affects the generated interference, it is expected to have a significant impact on the users' performance in the presence of spectrum sensing. Beamforming can be applied at both transmitter and receiver sides. The use of multiple antennas at the mobile stations (MSs) is typically avoided to reduce the system complexity. Hence, receive beamforming (based on the use of multiple antenna elements at the BS) is preferred for uplink communications. Through the use of receive beamforming techniques, the BS can modify the irradiation pattern of the antenna array, in order to create a beam for a specific user, upon calculation of the direction of arrival (DoA) of the electromagnetic wave of the selected user. There are many techniques for DoA estimation, such as spectral estimation methods, the minimum variance distortionless response (MVDR) method, linear prediction methods, the multiple signal classification (MUSIC) algorithm, and the estimation of signal parameters via rotational invariance techniques (ESPRIT) method [7]. DoA is used for steering the beam by changing its orientation angle. More precisely, the main lobe of the antenna array is oriented towards the desired user, while other (interfering) users are associated with nulls of the antenna irradiation pattern.

Beamforming is a standard technique for reducing interference in cellular CDMA networks. In the uplink, near-orthogonal (but not perfectly orthogonal) CDMA spreading codes (such as Gold and Kasami) are typically used. Therefore, even for multirate CDMA networks, the interference in the uplink would be higher. We consider beamforming in the uplink to reduce the interference on the desired SU. It is thus expected that beamforming, in addition to spectrum sensing, will improve the uplink system performance. In the downlink, the use of Walsh Hadamard codes guarantees orthogonality, so the use of beamforming is not crucial.

In this paper, we consider a heterogeneous network consisting of a primary radio network (PRN) and a cognitive radio network (CRN) with underlay spectrum sharing. The PRN and the CRN have separate BSs, and both networks are assumed to be multirate CDMA networks. The CRN employs beamforming at the secondary BS (SBS) for the CR user of interest. We consider beamforming to reduce the interference in the CRN. Even though beamforming may also be applied at a primary BS (PBS), in order to reduce the interference to PUs, we do not consider this case in this paper.

There are mainly three types of spectrum sensing method [9]: (a) methods requiring both source signal and noise power information; (b) methods requiring only noise power information (semi-blind detection); and (c) methods requiring no information on source signal or noise power (blind detection) [9]. The current paper extends the CR-CDMA scenarios presented in [10,11], where several spectrum sensing schemes, in the absence of any beamforming, are considered, in order to encompass the use of beamforming. As beamforming is expected to improve the performance of such spectrum sensing schemes, we incorporate receive beamforming at the SBS and extend the analysis of [11] to estimate the joint impact of spectrum sensing and beamforming on the overall network performance. Apparently, the gain provided by beamforming is not directly related to spectrum sensing, i.e., the gain due to beamforming is independent of the performance improvement associated with any spectrum sensing scheme. However, when combined with spectrum sensing, the overall performance gain is likely to improve significantly. By spectrum sensing, the SBS becomes aware of the presence of PUs and SUs, together with their corresponding data rates. Since beamforming reduces the uplink interference experienced by an SU, the cellular capacity increases: a larger number of SUs is allowed even in the presence of many PUs. This is the major advantage of using beamforming along with spectrum sensing. A capacity increase is feasible owing to the outage probability reduction brought by the use of beamforming. On the other hand, spectrum sensing allows the SBS to know the activity of PUs and other SUs, thus leading to the estimation of the overall interference. After interference estimation, the transmit data rate and power of SUs can then be optimized. Whenever the interference reduces, more SUs (keeping the data rate fixed) are allowed, or the data rate of existing users is increased (keeping the number of SUs fixed); as the interference increases, the number of SUs and/or their data rates are reduced. Therefore, an SU opportunistically increases its data rate in the presence of beamforming. Consequently, the use of beamforming allows the CRN to increase its cellular capacity opportunistically, so an operator can get higher revenue from the secondary network.

The spectrum sensing technique of reference is the covariance-based semi-blind spectrum sensing approach originally proposed in [12,13]. In particular, covariance-based spectrum sensing allows the secondary BS (SBS) to know the spectrum activity of the SUs. By properly thresholding the autocorrelation function of the received signal, the presence of PUs can be detected [14,15]. We assume that the PRN and the CRN contain fixed numbers of PUs and CRs, respectively, and that the PBS broadcasts information on the usage capacity percentage (UCP) 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, to all PUs, to the SBS, and to all SUs. A PU interferes at the SBS of its cell. The SUs and the SBS listen to the control channel to obtain UCP and take any consequent decision(s) about spectrum access. Therefore, we are implicitly assuming some kind of cooperation between the PBS and the SBS. At any particular time, all PUs are not likely to be simultaneously active, so SUs can transmit without hampering the quality of service

(QoS) of the PUs. At the SBS, the presence of PUs and other SUs is detected, and the total interference from currently active PUs and SUs is also measured using fluctuations of correlation estimators. This sensing approach is followed by the SBS in order to estimate the available resources for an SU. The levels of interference caused by PUs and SUs are compared with respect to chosen thresholds. The procedure for interference estimation will be characterized at system level, and its implementation in the simulation model will be detailed.

After incorporating receive beamforming at the SBS, we analyze the joint impact of spectrum sensing and beamforming on the overall system performance. The impact of the number of antenna elements and of other parameters on the outage probability is evaluated. In this scenario, we also evaluate the blocking probability of a new SU attempting to access the CRN. The performance improvement due to beamforming, with respect to that of equivalent schemes without beamforming [11], is investigated both qualitatively and quantitatively through our extensive simulations.

The major contributions of this paper can be summarized as follows.

- We develop a CR-CDMA networking model with beamforming and spectrum sensing at the SBS.
- We evaluate the impact of beamforming for various numbers of antenna elements.
- We carry out a quantitative analysis of the relative improvements, brought by the use of beamforming at the SBS, with and without spectrum sensing.
- We develop a novel simulation framework for the considered CR-CDMA networking model with beamforming.
- The three spectrum sensing schemes proposed in [11] are extended with the incorporation of beamforming (to reduce interference at the SBS) and their performances are analyzed in a comparative way.
- We investigate the trade-off between the probability of blocking and the probability of outage for an SU, considering the three spectrum sensing schemes with beamforming already mentioned.
- We analyze the trade-off between the cost of including multiple antennas and the performance improvement using beamforming.
- We evaluate performance of the SU of interest in terms of outage probability in the presence of higher load (large number of users) in the networking model.

The rest of this paper is organized as follows. In Section 2, the reference system model is accurately described. In Section 3, we describe our simulation model. In Section 4, numerical results are presented. Finally, Section 5 concludes the paper.

2. System model

2.1. Network model

The basic networking model (in the absence of beamforming) is same of that considered in [11], which we briefly recall here (the interested reader is referred to [11] for more details). The three-cell network model under study is shown in Fig. 1a. We assume coexistence of the PRN and the CRN. We also assume that the information regarding interference due to the activity of PUs and SUs is available to the SBS via measurement of autocorrelation fluctuations as described in [13]. Moreover, we consider two other modified schemes, denoted Scheme 1 and Scheme 2, respectively, for data transmission permission for SUs. In the absence of spectrum sensing, the PRN is a multirate CDMA network with spreading codes with variable spreading length, allowing two fixed data rates (r_d and $2r_d$) for the PUs. The SUs in the CRN use a fixed data rate equal to $4r_d$. As in any CR set up with underlay spectrum sharing, PUs and SUs can coexist as long as the interference experienced by the PRN is kept below an interference threshold. In the absence of spectrum sensing, assuming that the interference limit is not crossed, the SUs can transmit at a data rate higher than that of a PU. In practice, however, whenever the SBS finds that the total interference is above the predefined interference threshold, some SUs are asked to reduce their rates—the PUs are priority users and may need higher rates than the SUs. These aspects may be captured by slightly extending our general model. More precisely, we assume here that PUs do not need high data rates for some specific application. On the basis of the spectrum sensing carried out by the SBS, the SBS knows the interference caused by PUs and the interference caused by SUs; and on the basis of some beacon information, i.e., the UCP information sent by the PBS, the SBS can estimate how much SU interference is allowed at a specific time. The CRN then carries out appropriate power and rate adjustments to reduce the SU interference. Furthermore, we consider the presence of soft HO in our three-cell cellular model. Under soft HO, an MS may have simultaneous traffic channel communications with more than one BS and may be power controlled by a BS different from the BS of its current cell. The link gains of all links between the MS and BSs involved in soft HO are evaluated, and a power control decision is taken in favor of the BS which has the highest link gain. Moreover, while undergoing the HO, a user may need to change its current pseudo noise (PN) spreading code (used with the old BS) to a new PN spreading code issued by the new BS. As anticipated in Section 1, in the present study, we focus on uplink communication.

Each cell is divided into three sectors. Each sector is divided into two groups of regions: soft HO regions (denoted B, C, D) and non-HO regions (denoted A, E, F). Each cell is divided into three sectors with the same number of data users ($N_d = N_{\mathrm{PU}} + N_{\mathrm{SU}}$) per sector. The soft HO region is defined on the basis of the distance from the BS, as shown in Figs. 1a and 1b. BS_0 indicates the location of both the primary and the secondary BSs, denoted P_{BS0} and S_{BS0}, in cell #0. We assume receive beamforming at S_{BS0} to improve the performance of an SU of interest. More precisely, we assume that a sectorized antenna is used to cover all the SUs (in a particular sector) for paging, synchronization, and call set up. Adaptive beamforming is then used for managing voice (or data) traffic, i.e., after the call setup. During the call, the desired user is tracked with a specific beam in order to optimize system performance. In the CRN, the SBS knows the positions of all SUs, and

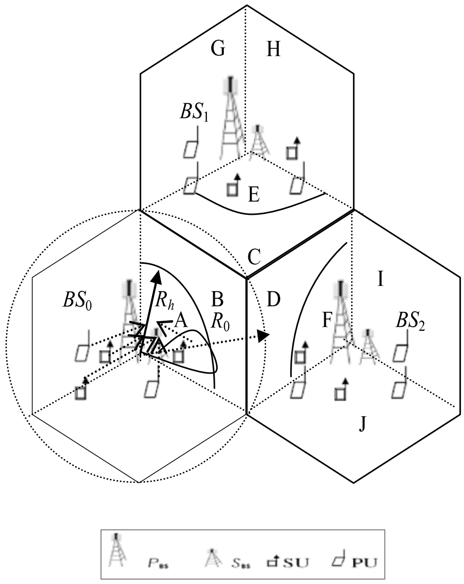

Fig. 1a. A three-cell CR-CDMA networking model.

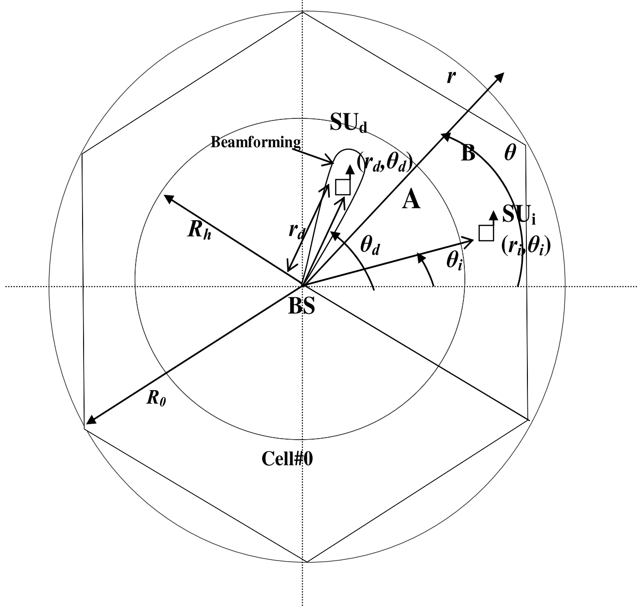

Fig. 1b. Cell of interest, cell #0, with SU of interest ($\mathbf{r}_d$, $\boldsymbol{\theta}_d$), and corresponding positions of an interfering user, ($\mathbf{r}_i$, $\boldsymbol{\theta}_i$).

carries out beamforming for the desired user whenever needed. When the SBS becomes aware that an SU is requesting resources (e.g., he/she is making a call), it steers the beam towards this user and the interference from other users gets reduced. In fact, both PU interference and SU interference are reduced if they are outside the beam. As we consider that the desired user is tracked by an antenna beam from SBS, it is implicitly assumed that the number of users simultaneously tracked by the SBS is not very large. However, should the SBS want to track a larger number of users, a larger number of sharp beams should be formed, thus increasing the complexity of the beamforming network due to increased number of antennas in the array along with additional complex hardware and processing. In order to keep the analysis tractable, in the current work we assume a single desired SU, which requires a single beam from the SBS: this makes the beamforming network simple. In the case of multiple desired users, the analysis needs to be modified. If, with a given set of used data rates and transmit powers, the interference on the PRN is above the interference threshold, power and rate adjustment on the SUs are then carried out.

Beamforming at the SBS and spectrum sensing act together to improve the performance of the CRN. However, spectrum sensing information is not required for implementing beamforming. Beamforming can be carried out with users' location information, regardless of the spectrum occupancy. PUs and SUs are power controlled by their corresponding BSs. With reference to the three-cell model shown in Fig. 1a, this applies to the two BSs of the other two cells, i.e., BS_1 and BS_2. An MS (either an SU or a PU) located outside the HO boundary R_h is considered to be under soft HO with three neighboring BSs. A PU would interfere at the SBS, since the PBS and the SBS are co-located. Both the SBS and the SU know the UCP of the cell, transmitted by P_{BS} and 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 cell. In the case of the PRN, a PU is assumed to transmit at a rate given by mr_d, where m is dependent on the spreading length of the PN code in the multirate CDMA system and r_d is the basic data rate. In contrast, all SUs are assumed to transmit at the same rate $4r_d$ in the absence of spectrum sensing in the CRN. Two classes of PU are considered: PU_1 denotes the first group of PUs using the basic rate r_d, while PU_2 denotes the second group of PUs using a data rate equal to $2r_d$. A justification of the use of these types of rate will be given in Section 3.

Next, we consider receive beamforming at S_{BS0}. The distance between the antenna elements of the linear equally spaced (LES) array (shown in Fig. 1c) is assumed to be 0.5λ, where λ is the carrier wavelength (in meters). In the LES array system, a combining network, which combines outputs of an array of low-gain antenna elements, generates an ideal antenna pattern. Beamforming is achieved by power combining of individual low-gain antenna signals. The combining network can generate an antenna pattern with the following gain [5]:

$$G(\varphi,\theta)=\left|\frac{\sin\left(0.5M_r\,\pi\,(\sin\theta-\sin\varphi)\right)}{M_r\sin\left(0.5\pi\,(\sin\theta-\sin\varphi)\right)}\right|^2, \tag{1}$$

where M_r is the number of antenna elements and θ is a variable. The beam can be steered to a desired direction φ by varying θ [5].

The antenna gain is shown in Figs. 1d and 1e. In this paper, we will use the antenna pattern specified in [5] to evaluate the impact of beamforming on the CDMA uplink capacity. The desired SU is in region A and is identified by a specific pair (r_d,θ_d). The interference power of another user, identified by an angle θ_i with respect to the BS in cell #0, will be multiplied by the following antenna gain $G(\theta_i,\theta_d)$:

$$G(\theta_i,\theta_d)=\left|\frac{\sin\left(0.5M_r\,\pi\,(\sin\theta_i-\sin\theta_d)\right)}{M_r\sin\left(0.5\pi\,(\sin\theta_i-\sin\theta_d)\right)}\right|^2. \tag{2}$$

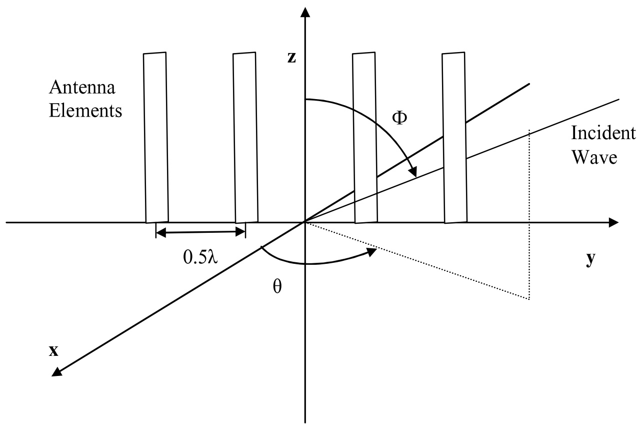

Fig. 1c. A standard linear equally spaced (LES) array.

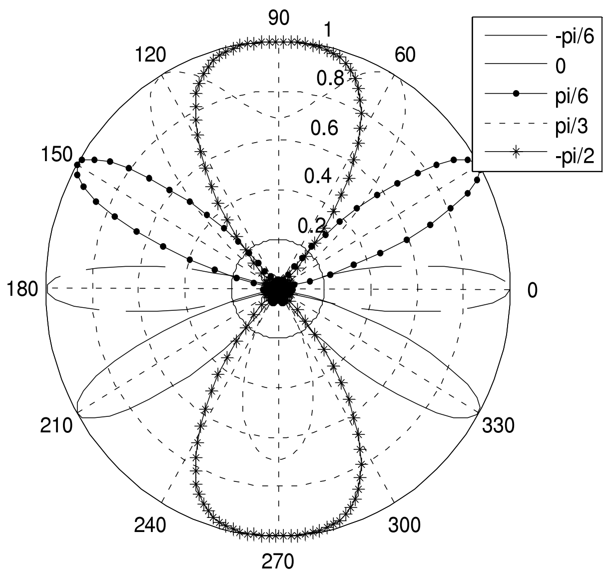

Fig. 1d. Beamforming gain, $G(\varphi, \theta)$ vs. θ.

The beamforming gain in (2) is much lower than that given by (1) for a small difference between two angles, and it decreases further for increasing values of the difference between θ_i and θ_d. This is shown in Figs. 1d and 1e. In general, θ_i and θ_d differ significantly as θ_d is the desired angle, whereas θ_i is a direction towards the null of the antenna radiation diagram. Moreover, $G(\theta_i, \theta_d)$ could be reduced further by increasing the number (M_r) of array elements (Fig. 1e). Consequently, the interference can be reduced further. The interference model in the presence of beamforming gain will be described in Section 2.3, whereas the performance will be investigated in Section 3.1.

The number of each type of user and the interference caused by each of them is obtained subsequently by using fluctuations of estimated autocorrelation as in [14,15]. At the SBS of the cell of interest, the interference caused by all SUs except the desired SU is computed following the spectrum sensing method proposed in [11]. The interference contributions of all PUs can also be estimated as in the case of SUs, i.e., following the method based on the fluctuations of the estimated autocorrelation. Since PUs and SUs have different data rates, the fluctuations of their corresponding autocorrelation functions will be different.

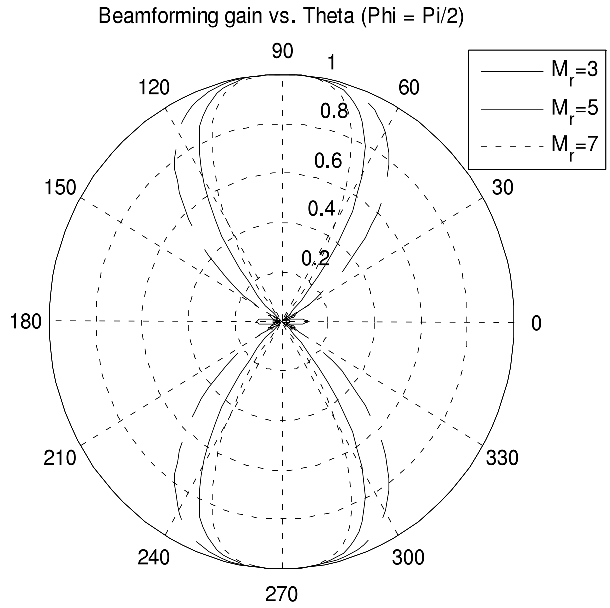

Fig. 1e. Effects of the number of array elements. Beamforming gain, $G(\varphi, \theta)$ versus $\boxed{\theta}$ with $\boxed{\varphi = \frac{\pi}{2}}$ with respect to Eq. (1); $\boxed{\theta = \theta_i}$, $\boxed{\varphi = \theta_d}$.

Therefore, the thresholds used to detect autocorrelation fluctuations are chosen separately depending on the data rate of the user, i.e., depending on the spreading code length used. A user is detected whenever the fluctuations of the estimated autocorrelation exceed the chosen threshold for that class of users [14]. The number of active CDMA users (both SUs and PUs) present in the network is indicated by the number of times the threshold is exceeded by the autocorrelation fluctuations. Similarly, the numbers of users (both SUs and PUs) present in the network and their interference at the SBS are estimated in the same manner as above in the present CR-CDMA networks. The received signal is divided into M temporal windows, each of duration T. The fluctuations of the autocorrelation function are estimated at each window. Using these M windows, the second-order moment of the estimated autocorrelation function can be found as follows [14,15]: $\varphi(\tau) = \frac{1}{M}\sum_{n=1}^{M-1} \left|R_{yy}^{n}(\tau)\right|^2$, where $R_{yy}^{n}(\tau)$ is the estimated correlation of the received signal at nth window. This fluctuation will exceed a predefined threshold level if the signal is present along with noise as the threshold level has been selected on the basis of the noise power.

2.2. Spectrum sensing schemes

The spectrum sensing schemes in the absence of beamforming, denoted Scheme 0, Scheme 1, and Scheme 2, are discussed in detail in [11]. In this subsection, we only recall their main features (for more details, the reader is referred to [11]).

Scheme 0 ("*Ghavami SS*"): This is the spectrum sensing scheme as proposed by Ghavami et al. in [12]. SUs are prevented from transmitting (upon positive spectrum sensing) when the condition $\sqrt{\beta} + 1 > \frac{1}{u_{cp}}$ is satisfied, where $\beta = \frac{I_{\mathrm{SU}}^2}{I_{\mathrm{PU}}^2}$. I_{SU} is the received interference power from SUs, and I_{PU} is the received interference power from PUs. As introduced previously, UCP (u_{cp}) corresponds to the percentage of the cell capacity used by the primary network. The PBS broadcasts u_{cp} in the control channel while the SUs and the SBS listen to the control channel to obtain u_{cp} and take any consequential decision(s) about spectrum access. Thus some kind of cooperation between the PBS and the SBS is implicitly assumed. The total number of sustainable users in a CDMA network may be determined on the basis of quality of service (QoS) requirements. The SUs can transmit without hampering the QoS of PUs, as all PUs are not likely to be simultaneously active at any particular time. Since the PBS knows the number of active PUs, it computes and broadcasts u_{cp} as the ratio between active PUs and total number of sustainable users in the network.

Scheme 1: In this scheme, in the absence of SUs, a fixed number of PUs in each sector is assumed. In what follows, we will consider 30 PUs, equally divided into the two groups PU_1 and PU_2, and a basic data rate $r_d = 10$ kbps. The maximum interference generated by all PUs, denoted $I_{\max}$, 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 $\frac{I_{\max}}{u_{cp}}$. At any time, the total interference caused by SUs and PUs must be lower than this interference limit.

The sensing schemes introduced above are now extended in order to incorporate beamforming for the desired user. Using beamforming, the interference is reduced regardless of the specific spectrum sensing scheme under use. In the present work, all schemes are based on covariance-based spectrum sensing [12,13], in the presence of beamforming for a desired SU. We also consider spectrum sharing condition/permission for SUs. Through spectrum sensing, the overall interference created by currently active SUs in the system can be measured. After measuring the spectrum activity, there can be the two following possibilities.

(1) A number of SUs are asked to stop transmitting when the total interference is more than the allowed interference limit. Actually, SUs are asked to lower the data rate and the transmit power before stopping the transmission completely.

(2) A new SU is allowed into the network if the total interference is lower than the allowed interference limit.

In this paper, we consider spectrum sensing as a combination of spectrum activity measurement and spectrum sharing decision for new SUs in the presence of beamforming for an SU. Spectrum activity measurement is needed to find the presence of PUs and of existing interfering SUs.

2.3. Interference modeling

The interference model in the absence beamforming is discussed in detail in [11] and is briefly recalled here. We assume that the total interference at S_{BS}, due to SUs and PUs, can be written as follows:

$$I_{S_{\mathrm{BS}}}^{UL} = I_{\mathrm{SU}} + I_{\mathrm{PU}_1} + I_{\mathrm{PU}_2}, \tag{3}$$

where the first term on the right-hand side of the equation relates to the interference due to all active SUs in uplink, whereas the other two terms are associated with the interferences due to PU_1 and PU_2, respectively, and will be evaluated through the simulator described in Section 3. As beamforming for the desired SU is considered, the interference caused by PUs and other SUs needs to be appropriately modified considering the geometrical parameter of the scenario, shown in Fig. 1b. The beamforming gain, given by Eq. (2), is included in the received power expression at the SBS from all PUs and SUs. The received power of each user (either a PU or an SU) is normalized to 1 at their corresponding BSs. As previously mentioned, the interference powers I_{SU}, I_{PU_1}, and I_{PU_2} will be evaluated via simulations as described in Section 3. The PRN and the CRN are co-located, with the corresponding BSs P_{BS} and S_{BS} positioned at the center of each cell. We evaluate the interference at S_{BS} considering the two classes of PUs and SUs separately. The propagation radio channel is modeled as in [16]. More precisely, the link gain for a user at location (r, θ), with respect to BS_i, $i \in \{0, 1, 2\}$, is

$$G_i(r, \theta) = d_i(r, \theta)^{-\alpha_p} 10^{\xi_S/10}, \tag{4}$$

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 fading coefficient, with ξ_s normally distributed with zero mean and variance σ_s^2. More precisely, the exponential normal fading coefficient at ith BS can be written as [16]

$$\xi_{s,i} = a\zeta + b\zeta_i, \tag{5}$$

where $a^2 + b^2 = 1$, and ζ and ζ_i are independent Gaussian random variables (rvs) with zero mean and variance σ_s^2. The out-cell interference consists of the interference due to MSs from regions E, C, G, H of cell #1 and from regions D, F, I, J of cell #2. The 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 reference sector, i.e., in region A. The total in-cell interference in cell # 0 is [16].

$$I_{\mathrm{in}} = I_1 + I_2, \tag{6}$$

where I_1 is due to all MSs in A and those in B connected to BS_0, and I_2 is due to MSs in B but connected to BS_1 and BS_2. The out-cell interference is [17]

$$I_{\mathrm{out}} = 2(I_E + I_{C1} + I_{C2} + I_{CO} + I_G + I_H), \tag{7}$$

where the I_i $(i = E, C1, C2, CO, G, H)$ are the interference terms due to MSs in different regions such as E, C, G, H. Explicit expressions for these terms can be found in [11].

The effectively received power from the desired SU can be expressed as

$$\boxed{U = S_R e^S}, \tag{8}$$

where S is a Gaussian random variable with zero mean and variance equal to σ_e^2. Therefore, σ_e can be interpreted as the power control error (PCE). The desired SU is assumed to be in the non-HO region, i.e., in region A.

The interference model derived above, which extends the one proposed in [11] taking into account the presence of beamforming, is considered in the developed simulator, outlined in the following section.

3. Simulation model

The simulator has been developed with MATLAB, and it takes the following parameters at its input: the degree of soft HO (PR_h), the shadowing correlation (a^2), the PCE (σ_e), and the numbers of PUs and SUs. As far as beamforming is concerned, we assume that the desired user is tracked by an antenna beam. The beamforming is carried out with the use of (M_r) antenna array elements. Some typical values of M_r, such as 3, 5, and 7, are considered in our analysis. The soft HO region boundary R_h is given as $R_h = R_0\sqrt{1-\mathrm{PR}_h}$, where R_0 is the radius, normalized to unity, of the circular cell which approximates the hexagonal cell. Users are assumed to be uniformly distributed over the cells. We formulate the spectrum sharing problem in the reference CDMA network of Fig. 1a by considering the value of m depending on the spreading length. In our work, we consider fixed values of rates and integer values for m. This simplifies the management, by our MATLAB simulator, of rate adjustment in order to account for arbitrary (even non-integer) values of m; our simulation algorithm should be properly extended. However, we remark that in principle any value of m can be considered. The extension of our analysis is in this direction is the subject of our future research activity. The simulation model for the network in the absence of beamforming is the same as that presented in [11]. For the sake of clarity, we recall the main characteristics of this simulator (for more details, the reader is referred to [11]), in order to make the extension to the presence of beamforming clear.

3.1. Uplink signal-to-interference ratio estimation with beamforming

I. A number of PUs $\boxed{(N_{\mathrm{PU}})}$ and a number of SUs $\boxed{(N_{\mathrm{SU}})}$ are generated.

II. The locations (in the (r,θ) coordinate system) of all SUs and PUs (N_d) are generated, and users are divided into non-HO(N_h) and soft HO (N_s) regions on the basis of their locations. The desired SU is assumed to be in the non-HO region; the number of remaining interfering users, considering all PUs and other SUs in the non-HO region, is $N_h - 1$. The number of users in the soft HO region is $N_s = N_d - N_h$.

III. For each of the N_s users in the soft HO region, the link gains corresponding to each of the three BSs (either the SBSs for the SUs, or the PBSs for the PUs) involved in the soft HO are generated as $G_i(r,\theta) = r_i^{-\alpha_p} e^{\xi_i}$, $i = 0, 1, 2$, where 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 [11]. The correlation of shadow fading has been considered following [16,11]. The PUs and SUs are power controlled by their corresponding BSs, for which the link gain is maximum, i.e., a PU or SU is power controlled by BS_i if G_i is maximum.

IV. The ideal (i.e., perfect) beamforming gain for each user is generated according to (2); i.e.

$$G(\theta_i,\theta_d) = \left|\frac{\sin\left(0.5M\pi\,(\sin\theta_i - \sin\theta_d)\right)}{M\sin\left(0.5\pi\,(\sin\theta_i - \sin\theta_d)\right)}\right|^2.$$

The interference received at the reference BS can be expressed as follows [17]:

$$I = S_R \exp(r_n)\left(\frac{G_0}{G_{i_0}}\right) mG\left(\theta_i,\theta_d\right). \tag{9}$$

Due to the incorporation of soft HO, any SU can be power controlled by any one of the three BSs (i.e. BS_i, $i = 1, 2, 3$). If the interfering node is connected to BS_{i_0}, here $i_0 = 0, 1, 2$. Where r_n is a normal random variable with zero mean and standard deviation σ_e, and S_R is the required received power at the corresponding BS (normalized to unity in the simulation, since the signal-to-interference ratio, SIR, is unaffected by assigning $S_R = 1$). The data rate of any user is mr_d, where m is the spreading length of a CDMA user.

V. The interference due to the MSs, in the non-HO region (A) of the reference cell, power controlled by BS_0, can be expressed as

$$I_2 = S_R mG\left(\theta_i,\theta_d\right)\sum_{i=1}^{N_h-1} e^{r_{n,i}}. \tag{10}$$

Next, we consider the interference caused by users in regions E, C, D, and F of cell #1 and cell #2. The interference by these users may be found in similar manner following Eqs. (9) and (10). The number of MSs in each of the regions E and F is $(N_d - N_s)$. Denote $I_3 = I_E + I_C$ and $I_4 = I_D + I_F$.

VI. The interference from MSs in regions G, H, I, and J is then generated using our simulator. We estimate the interference as in the case of Eq. (9). Denote $I_5 = I_G + I_H$ and $I_6 = I_I + I_J$.

VII. The total interference, caused by interfering users at different regions, can be written as

$$I = \sum_{k=1}^{6} I_k. \tag{11}$$

VIII. The signal-to-interference ratio at the reference BS for the desired user can be expressed as

$$\mathrm{SIR} = \frac{U}{I}, \tag{12}$$

where U is the received (useful) power from the desired user at the reference BS, given by (8), and I is the total interference power at the reference BS for the desired user.

3.2. Outage probability in the absence of spectrum sensing

The outage probability is computed through the following steps.

I. All users are considered to be continuously active.

II. The uplink SIR for a desired SU at the reference BS is generated as shown in the previous subsection and compared with a threshold value given by $\gamma^{\mathrm{th}} = \gamma_{\mathrm{th}}/pg$, where pg indicates the processing gain and $\boxed{\gamma_{\mathrm{th}}}$ is the SIR threshold. The beamforming gains are considered while estimating the total interference at the reference BS. In [11], the beamforming factor is not considered.

III. If the SIR falls below γ^{th}, an outage counter ($\text{outage}_{\text{count}}$) is incremented.
IV. Steps (II) and (III) are repeated a large ($N_t \gg 1$) number of times to yield an accurate estimate of the probability of outage as $P_{\text{out}} = \text{outage}_{\text{count}}/N_t$.

3.3. Probability of outage with spectrum sensing and beamforming

The following steps are followed.

I. The interference power from SUs and the interference power from PUs are estimated following the steps in Section 3.1.
II. The condition $\sqrt{\beta}+1 > \frac{1}{u_{cp}}$ (or the conditions imposed by Schemes 1 and 2 described in Section 2) needs (need) to be satisfied at the reference SBS.
III. If the condition at the previous point is not met, then SUs are removed one by one, initially from the non-HO region of BS_0 (region '*A*') and then from other zones, i.e., regions '*B*', '*C*', '*D*', '*E*', '*F*', '*G*', or '*H*'. After each removal, the condition is again checked. As we consider beamforming at the SBS, the overall interference at the SBS would be small. Therefore, the SU of interest would not be in outage in many iterations of the simulation run. Once the condition is satisfied or all SUs are removed, the probability of outage is evaluated as shown in Section 3.2, i.e., as $P_{\text{out}} = \text{outage}_{\text{count}}/N_t$. The beamforming factor helps to reduce the outage probability by reducing the overall interference for the desired user.

3.4. Blocking probability with spectrum sensing

One SU is assumed as the desired user, and all other SUs and PUs are considered as interfering users. The PBS broadcasts the UCP information. On the basis of the UCP information and the spectrum sensing information, the admissibility of a new SU is considered at the SBS. The overall interference at the SBS in the presence of beamforming would be much lower than that in the case without beamforming. This leads to rare blocking of the SU of interest. Therefore, depending on beamforming, we anticipate very low probability of blocking for the SU of interest, and this will be confirmed in Section 4 by our simulation results.

The following cases may occur when a new SU wants to make an active connection with the SBS.

(a) The new SU may be allowed with its current data rate and transmit power.
(b) The SU may be allowed with reduced power. The transmit power is reduced in steps according to the rule $P_{\text{next}} = P_{\text{current}} - \alpha P_{\text{current}}$, where $\alpha \in (0, 1)$. The transmit power is reduced up to $P_{\min}$ (fixed to 50% of the original transmit power). The data rate of the new SU may need to be reduced from $4r_d$ to r_d in steps of r_d if the power reduction does not make interference reduction to the sustainable limit. The new SU is blocked if the interference condition is not met even after power and data rate reduction.
(c) The new SU is blocked if the present overall interference is above the threshold limit.

3.5. Mean data rate with spectrum sensing and beamforming

In the absence of spectrum sensing, the average data rate of an SU corresponds to the chosen data rate of the desired SU. However, the data rate of the new SU varies from $4r_d$ to 0 when we consider call blocking with spectrum sensing and beamforming. The data rate of the SU is obtained as the arithmetic average of data rates in different simulation runs. We expect the support of a high data rate for the SU of interest, as with beamforming the SU of interest will be blocked a smaller number of times. This will be confirmed by simulation results in Section 4, where a considerable increase of the average data rate will be observed in the presence of beamforming.

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 of adjacent cells is $D = 2000$ m; the spread bandwidth is $W = 5.0$ MHz; the chip rate is $R_{ch} = 5.0$ Mcps; the PCE is $\sigma_e = 2$ dB; the SIR threshold is $\gamma_{\text{th}} = 6$ dB; the path loss exponent is 4; the shadowing correlation is characterized by $a^2 = 0.3$ and $PR_h = 0.3$; three values of M_r (namely 3, 5, and 7) are considered; the basic data rate r_d is set to 7 kbps, if not otherwise explicitly stated; finally, the processing gain is defined as $pg = R_{ch}/r_d$. In Schemes 1 and 2, $r_d = 10$ kbps, the numbers of PU_1 and PU_2 are each set to 15, only at the beginning, to evaluate $I_{\max}$. In order to highlight the impact of beamforming, the performance of the proposed spectrum sensing schemes with beamforming will be analyzed with direct comparisons to the corresponding schemes without spectrum sensing.

In Fig. 2, the probability of outage for an SU is shown as a function of the number of SUs. It can be observed that the probability of outage increases for increasing values of the number of SUs [11]. This is due to a corresponding increase of the multiple access interference (MAI) caused by SUs. Obviously, the probability of outage reduces when spectrum sensing is considered. It can be observed that the probability of outage is lowest when beamforming is considered in the case of Ghavami spectrum sensing (SS). In this case, in fact, the allowed interference for SUs is determined on the basis of the number of currently active PUs. The reason for the superior performance of Ghavami SS is explained in detail in [11]. The percentages of decrease of the outage probability with five antenna elements (beamforming) and spectrum sensing are found to be 46% and 55% for values of the number of SUs fixed at 7 and 9, respectively.

In Fig. 3, the blocking probability of an SU is shown as a function of the number of SUs, considering Scheme 1 with beamforming. As in the absence of beamforming, the blocking probability is an increasing function of the number of SUs in the system. However, the relative increasing rate of the probability of outage reduces significantly when the number M_r of antenna elements increases from 3 to 5. On the other hand, a minor performance improvement is observed when M_r is increased beyond 5.

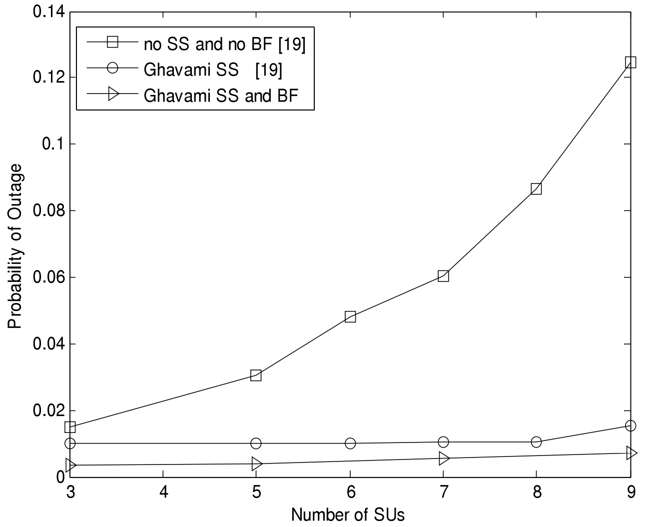

Fig. 2. Probability of outage for SUs as a function of the number of SUs, with fixed numbers of PUs and fixed value of the SUs' data rate. Beamforming is considered only with Ghavami SS.

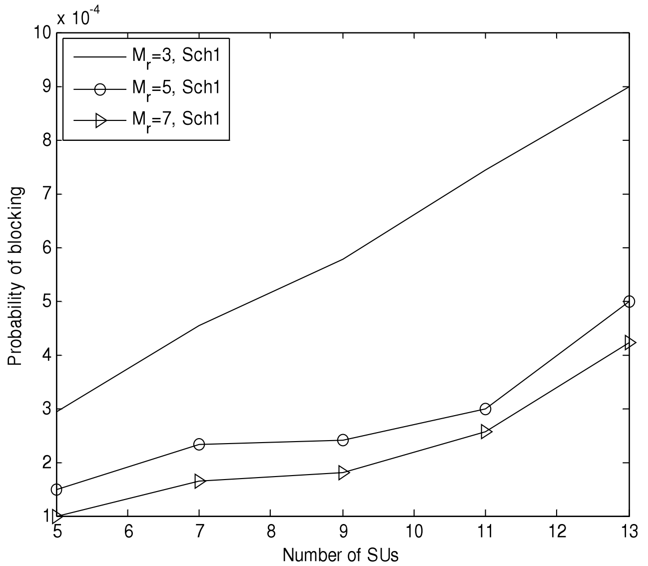

Fig. 3. Blocking probability for SUs as a function of the number of SUs, with fixed number of PUs and fixed value of SUs' data rate. Beamforming is considered.

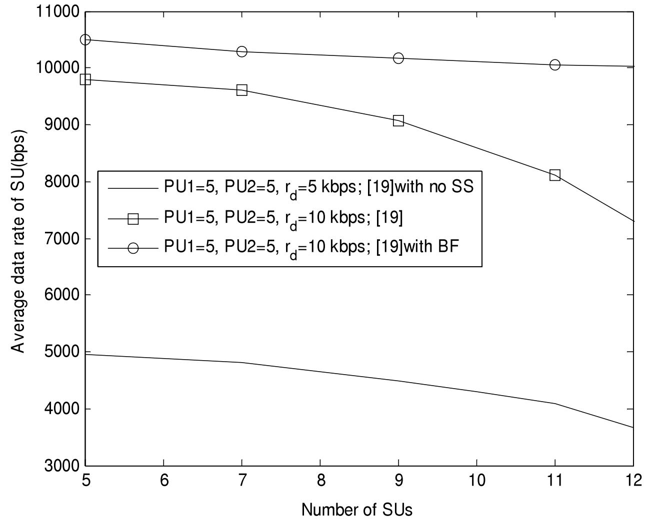

Fig. 4. Average data rate of SUs as a function of the number of SUs, with fixed numbers of PUs and various values of SUs' data rate. Spectrum sensing is considered.

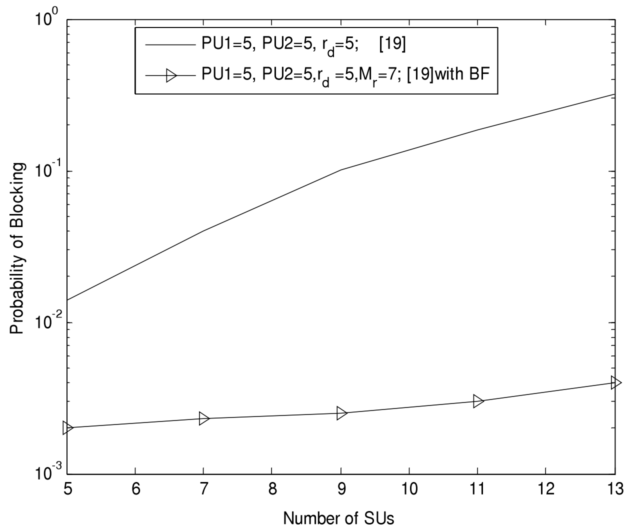

Fig. 5. Probability of blocking for SUs as a function of the number of SUs, with fixed numbers of PUs and fixed value of SUs' data rate, in the presence of beamforming. Ghavami SS is considered.

In Fig. 4, 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, as the interference is an increasing function of the number of users. 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 data rate would vary from $4r_d$ 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 the data rate. The data rate of an SU increases significantly if beamforming is applied at the secondary BS for the desired CR user. Moreover, the achievable data rate remains almost constant (at a high value) if the number of SUs increases from 5 to 12. In the presence of beamforming, the average data rate increases, with respect to the case without beamforming [11], by 7.3%, 12%, and 53% for values of the number of SUs set to 5, 9, and 13, respectively. It can be observed that, in the presence of beamforming, the data rate increases faster (than in the case without beamforming) for increasing values of the network load.

In Fig. 5, the blocking probability for an SU is shown as a function of the number of SUs, considering the Ghavami SS scheme and beamforming. It can be observed that the probability of blocking reduces significantly in the presence of beamforming. In the presence of beamforming, the blocking probability is reduced by 86%, 97%, and 99%, with respect to that the corresponding cases without beamforming [11], when the number of SUs is set to 5, 9, and 13, respectively; the remaining system parameters are set to the same values.

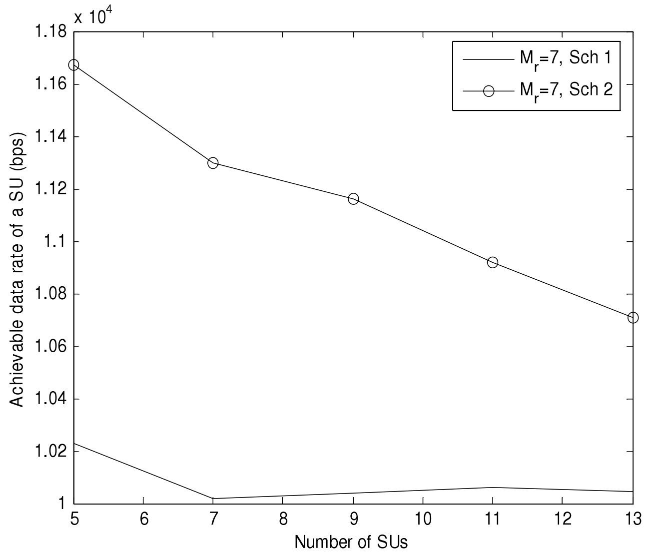

Fig. 6. Achievable data rate for SUs as a function of the number of SUs, with fixed numbers of PUs, in the presence of beamforming.

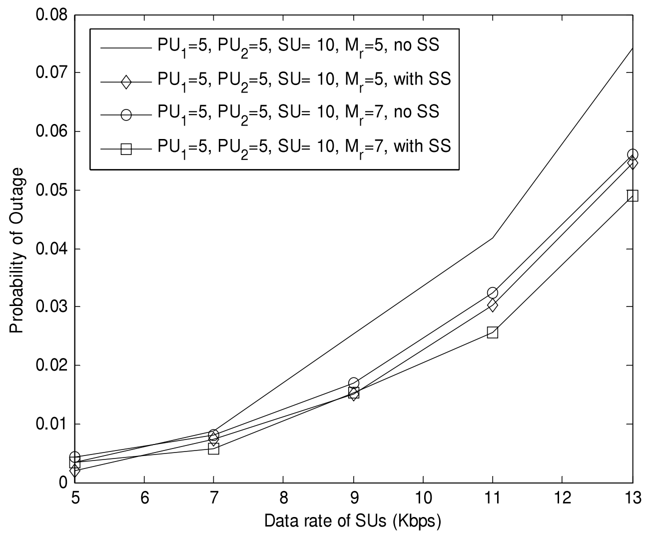

Fig. 7. Probability of outage for SUs as a function of basic data rate, with fixed numbers of PUs and SUs. Beamforming is considered in all cases.

In Fig. 6, the achievable data rate for an SU, in the presence of beamforming, is shown as a function of the number of SUs, considering Schemes 1 and 2. It can be observed that the achievable data rate of an SU with Scheme 2 is higher than that achievable with Scheme 1. In fact, the interference level allowed by Scheme 2 is almost twice that allowed by Scheme 1. Therefore, it is expected that the blocking probability of an SU in the case of Scheme 2 will be small with respect to that with Scheme 1. Hence, the achievable data rate with Scheme 2 will be higher.

In Fig. 7, the probability of outage for an SU is shown as a function of data rate of SUs, with fixed numbers of PUs and SUs. Two different values of M_r are considered, and both the presence and the absence of spectrum sensing are investigated. The probability of outage increases when number of antenna elements reduces from 7 to 5, both in the absence and in the presence of spectrum sensing.

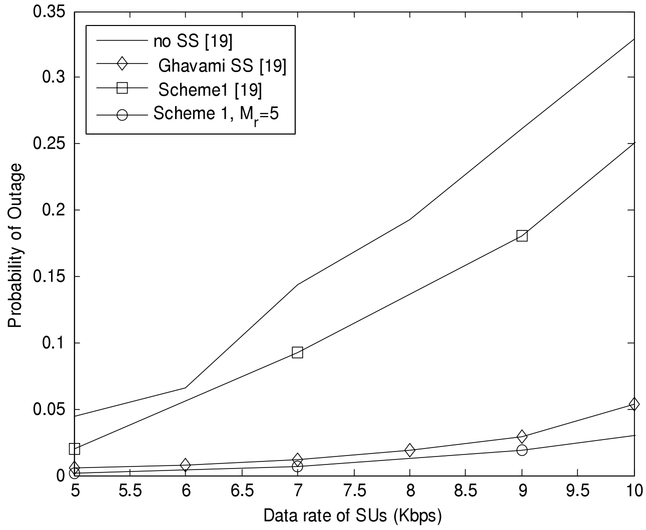

Fig. 8. Probability of outage for SUs as a function of data rate of SUs with fixed numbers of PUs and fixed value of SUs' data rate.

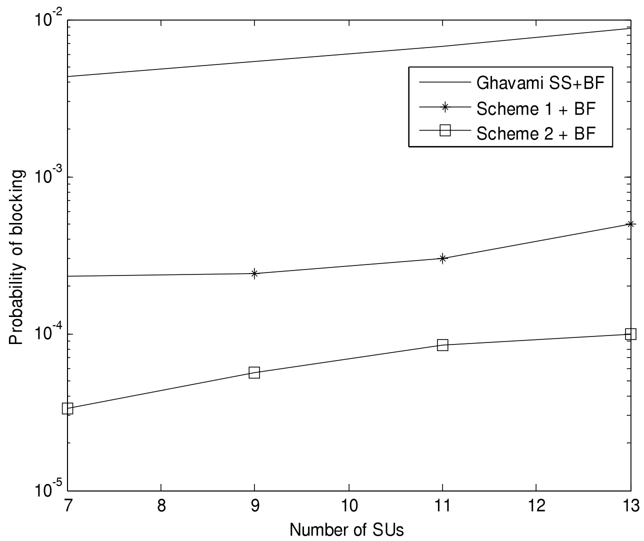

Fig. 9. Comparison of blocking probability for the three spectrum sensing schemes in the presence of beamforming.

However, note that the increase is more limited in the case of spectrum sensing.

In Fig. 8, the probability of outage for SUs is shown as a function of the data rate of SUs, with fixed numbers of PUs and SUs. The number of PU_1 and PU_2 is considered as 5 and 5, respectively. The number of SUs is considered as 10 for all the curves here. The effects of beamforming on the outage probability, in the case of Scheme 1, are investigated and compared with those of other schemes. The outage probability is reduced in the presence of beamforming by 94.3%, 89%, and 85%, with respect to that of [11] when Scheme 1 is considered for N_{su} fixed at 7, 9, and 13, respectively. The probability of outage with $N_{su} = 13$ is not shown in this figure.

In Fig. 9, the probability of blocking is shown as a function of the number of SUs. The performance of all three spectrum sensing schemes has been evaluated. The number of both types of PU is fixed at 5 for Ghavami SS (due to the predefined threshold the number of PUs is

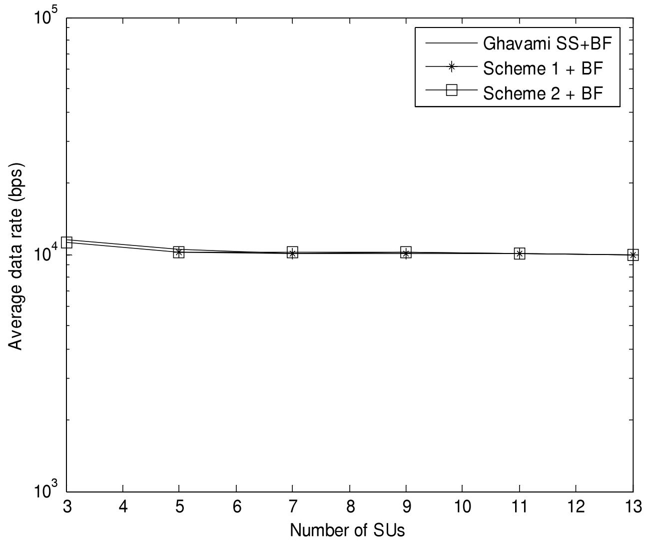

Fig. 10. Comparison of the average data rate for the three spectrum sensing schemes in the presence of beamforming.

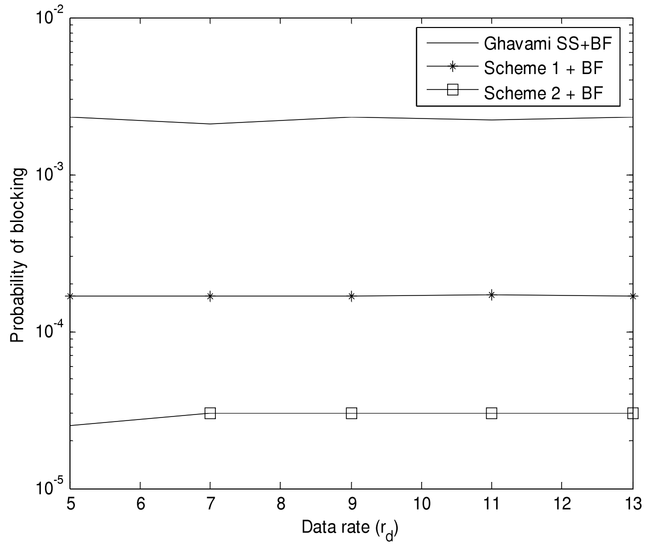

Fig. 11. Comparison of the blocking probability for the three spectrum sensing schemes with respect to the basic data rate.

fixed at 15 for Schemes 1 and 2). The blocking probability for Schemes 1 and 2 is less as the allowable interference threshold is high for Schemes 1 and 2 in the presence of beamforming. The number of antenna elements is $M_r = 5$.

In Fig. 10, the average data rate of an SU is shown as a function of the number of SUs. A comparative performance evaluation of all three spectrum sensing schemes has been depicted in this figure. The number of both types of PU is fixed at 5 for Ghavami SS and, as already mentioned, due to the predefined threshold, the number of PUs is fixed at 15 for Schemes 1 and 2. Still, the average data rate for Schemes 1 and 2 is almost the same as for Ghavami SS in the presence of beamforming (BF). Even in the presence of a number of PUs larger than that considered in the Ghavami SS scheme, Schemes 1 and 2 allow one to increase the threshold level by using beamforming, and they can thus support the same data rate as that of the Ghavami SS scheme.

In Fig. 11, the blocking probability is shown as a function of the basic data rate. The performances of all three spectrum sensing schemes, in the presence of beamforming, are compared. The number of PUs is set to 5 for the Ghavami SS and to 15 for Schemes 1 and 2 by considering the fixed interference threshold. The blocking probability for Schemes 1 and 2 is lower than that with the Ghavami SS scheme, as the allowed interference threshold is high for the latter scheme. The probability of blocking for Scheme 2 is the lowest, being in the order of 10^{-5} with the number of antenna elements set to 5.

In Fig. 12, the average data rate is shown as a function of the basic data rate, i.e., the data rate of an SU. The performance of all three spectrum sensing schemes, in the presence of beamforming, has been investigated. The numbers of both types of PU and SU are the same as considered for Fig. 12. The average data rate for Schemes 1 and 2 is almost the same as in case of Ghavami SS in the presence of beamforming. In the presence of beamforming, the performance of all three schemes is almost same.

In Fig. 13, the probability of outage is shown as a function of the number of SUs, considering various numbers

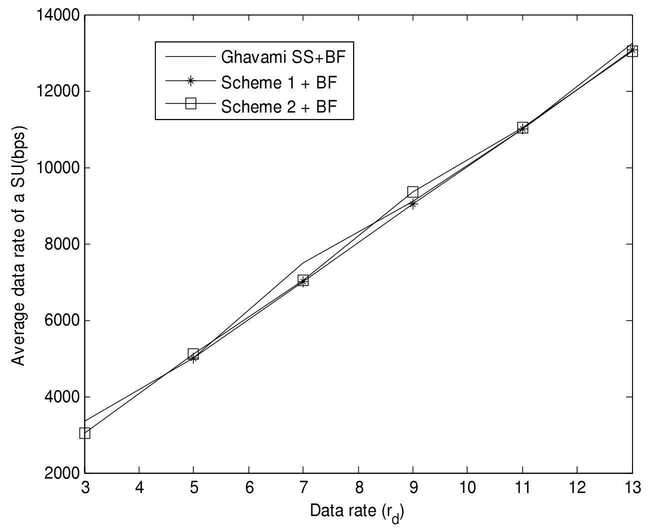

Fig. 12. Comparison of the average data rate for the three spectrum sensing schemes in the presence of beamforming.

of antenna elements, in the absence of spectrum sensing. Three different values of the number of antenna elements are considered, namely 3, 5, and 7. In particular, we consider the effects of only beamforming on the performance of an SU in our three-cell CR CDMA networking model. For comparison purposes, two more curves are added: one curve, relative to a scenario with spectrum sensing and beamforming, and another curve, which is representative of the impact of soft hand-off on the CRN. As we consider a higher degree of soft HO, a larger number of SUs would be present in the soft HO region, thus reducing the uplink interference for the SU of interest. A performance improvement, with respect to the case with $PR_h = 0.3$, can be observed—note that, unless otherwise stated, for all curves PR_h is set to 0.3. As can be observed from the figure, the probability of outage of an SU reduces significantly if spectrum sensing, together with beamforming, is considered. The effect is more pronounced when the cell is moderately loaded with SUs, i.e., a larger number of SUs is present. We

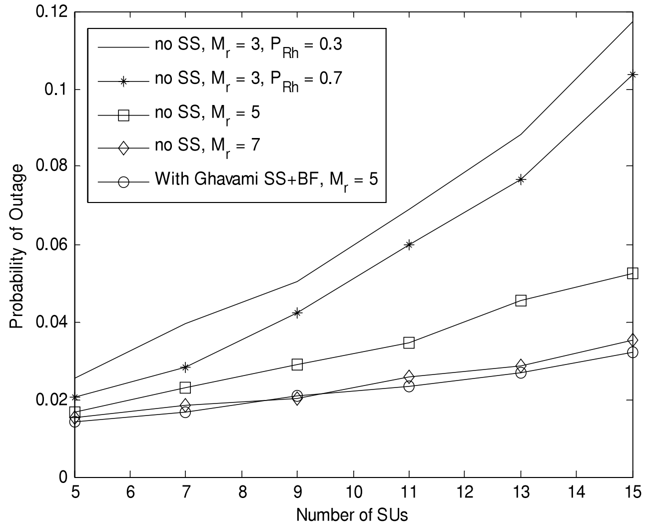

Fig. 13. Probability of outage as a function of the number of SUs in the presence of beamforming.

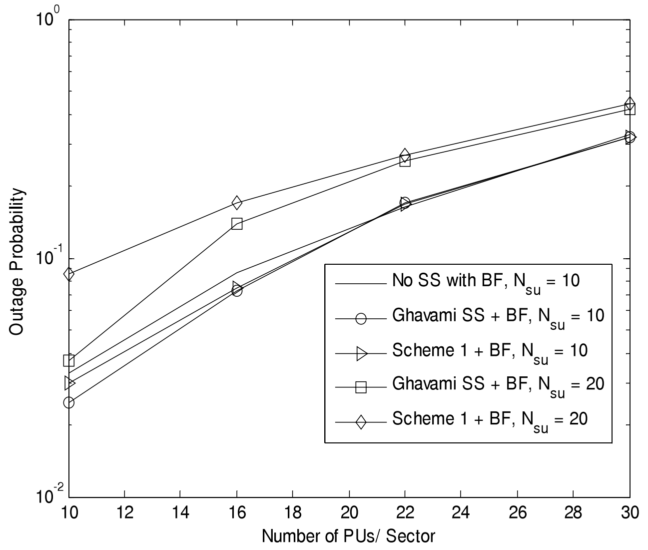

Fig. 14. Outage probability as a function of the number of PUs per sector.

can observe the same behavior also for the case with $M_r = 5$. Another important observation can be made from the results in this figure. A similar performance can be achieved either with $M_r = 7$ in the absence of spectrum sensing or with $M_r = 5$ in the presence of spectrum sensing. In other words, spectrum sensing may not be essential for an SU to achieve a relevant performance gain in the presence of beamforming, provided that the number of antenna elements is sufficiently large. In the presence of spectrum sensing with beamforming, the same level of performance achievable with only beamforming can instead be achieved with a smaller number of antenna elements. Therefore, spectrum sensing, when used jointly with beamforming, requires a smaller number of antenna elements to reach a given performance level, i.e., a reduction of the complexity of the beamforming system is allowed. On the other hand, in the CR setup considered, spectrum sensing is essential, as the interference on the PRN needs to be kept below the interference threshold. The outage probability of an SU decreases by 67.7% as M_r increases from 3 to 7 with the number of SUs fixed at 13—all other parameters being fixed as in the previous cases considered. An increase of PR_h from 0.3 to 0.7, in the CRN only, decreases the outage probability by 16% when the number of SUs is fixed at 13 and all other parameters are kept fixed. When the number of antenna elements is set to 5 and the number of SUs is fixed at 11, the outage probability decreases by 32%, in the presence of spectrum sensing, with respect to the case with beamforming only. All other parameters are fixed at the same values for both cases.

In Fig. 14, the outage probability of an SU is shown as a function of the number of PUs per sector—note that in all previous results the total number of users has been considered in the same manner. In particular, we evaluate the effects of a higher load on the performance of an SU. The number of PUs per sector is varied from 10 to 30, with the latter value being considerably high. The number of SUs is set to either 10 or 20. From the results presented in this figure, two observations can be made. As the number of PUs is increased beyond a specific value, i.e., for large numbers of PUs, the outage probability degrades even in the presence of spectrum sensing and beamforming. For smaller values of the number of PUs, the effects are similar to those observed in the previous figures. The best performance is obtained with the Ghavami SS scheme in the presence of beamforming. It can also be noticed that, when the number of PUs per sector increases beyond a critical value, the performance mainly depends on the number of SUs. All curves converge to a single one for a fixed number of SUs. If the system is heavily loaded with 30 PUs, the outage probability in the case of Ghavami SS is only 3% lower than that in the absence of spectrum sensing. However, in the same scenario, the outage probability in the case of Ghavami SS is only 1% lower than that in the case of Scheme 1. As the number of PUs is increased from 22 to 30 with 10 SUs, the outage probability for Ghavami SS increases from 0.17 to 0.319, whereas the outage probability for Scheme 1 increases from 0.17 to 0.3225. As already observed in Fig. 13, the improvement will be more significant in the case of a heavily loaded system up to a moderate level of traffic load (in correspondence to which the number of PUs is 10 and the number of SUs is 10). In other words, the combined use of spectrum sensing and beamforming outperforms the use of beamforming only. However, as the load is increased to a very high value, as in Fig. 14, the outage probability of both schemes reaches a very high level (nearly a saturation value) because of the heavy interference increase in both cases. The use of beamforming for the SUs not only reduces the interference from SUs but also the interference from the active PUs. In fact, the SU of interest is under the principal beam of the antenna while all other users (both PUs and SUs) come under the null of the antenna beam. Therefore, the uplink interference from all PUs in the same geographical area is also mitigated. In particular, the probability of outage reduces significantly, with joint beamforming and cognition, in the presence of a moderate number of SUs. However, in very high load conditions, we do not find significant gains either from beamforming or from spectrum sensing. In the case of a heavily loaded system, a saturation effect is instead observed. It can thus be concluded that

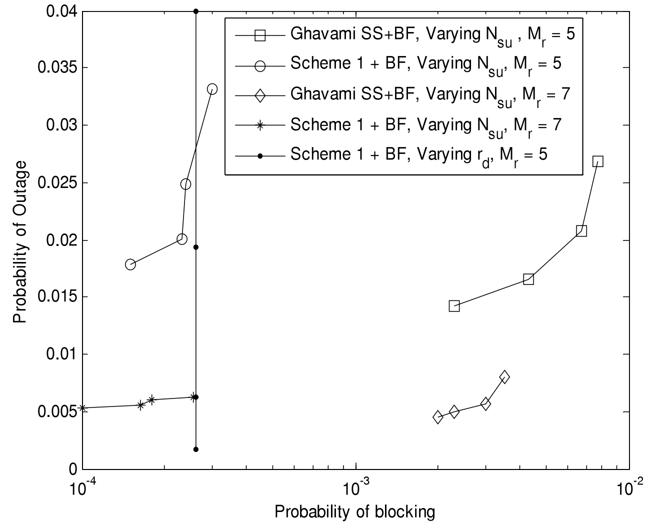

Fig. 15. Probability of outage as a function of the probability of blocking.

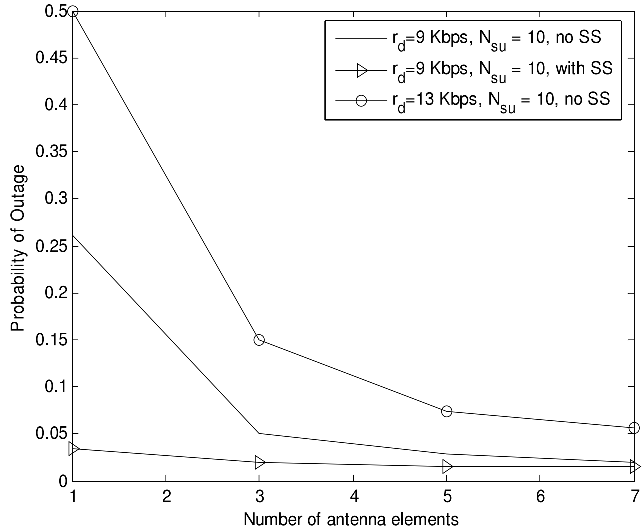

Fig. 16. Probability of outage as a function of the number of antenna elements.

cognition plays a crucial role in improving the performance at moderate traffic loads.

In Fig. 15, we investigate the trade-off between probability of outage and probability of blocking, by evaluating the probability of outage as a function of the blocking probability. For given traffic load and network conditions, the probability of outage and the probability of blocking are evaluated in the presence of beamforming and spectrum sensing: the sequence of pairs of probabilities values lead to "trade-off curves". In particular, we consider two different spectrum sensing schemes with beamforming. As the number of antenna elements is fixed to 5 or 7 and the number of SUs varies from 5 to 11, the probability of blocking and the probability of outage are evaluated. With higher values of M_r, the obtained trade-off indicates that the performance with Scheme 1 with beamforming is better. However, for $M_r = 5$ it can be observed that the blocking probability of a SU is lower for the case of Scheme 1 with beamforming than for the case with Ghavami SS with beamforming, and that the outage probability of an SU is higher for the case of Scheme 1 with beamforming than for the case of Ghavami SS with beamforming. In the same figure, one curve with varying data rate is also shown. The outage probability increases as the data rate is increased from 5 to 11 kbps, but the blocking probability remains the same for Scheme 1 in the presence of beamforming. This is expected, as the change in the basic data rate does not change the blocking probability. Let us now quantify this trade-off. In the case with $M_r = 7$ and Scheme 1, if the number of SUs is changed from 5 to 7, then the blocking probability increases by 63%, while the outage probability increases by only 4%. In the case of Ghavami SS, for the same setting, the blocking probability increases by 15%, whereas the outage probability increases by 11%. As the number of SUs increases from 5 to 7 with $M_r = 5$ and $r_d = 10$ kbps, the probability of blocking increases from 2.3e−3 to 4.3e−3, while the outage probability increases from 0.0142 to 0.0166 for Ghavami SS with beamforming. Again for the same setting, the blocking probability increases from 1.5e−4 to 2.333e−4, while the outage probability increases from 0.0178 to 0.0201 for Scheme 1 with beamforming.

In Fig. 16, the trade-off between the performance improvement brought by beamforming and the number of antenna elements is investigated, by evaluating the probability of outage as a function of the number of antenna elements. The performance improvement in the presence of beamforming is significantly large when the number of antenna elements is set to 5. More precisely, the decreasing rate of the outage probability, when the number of antenna elements is increased from 5 to 7, is lower than that observed when the number of antenna elements increases from 3 to 5 (i.e., a diminishing returns behavior is observed). The outage probability decreases by 81% when the number of antenna elements is increased from 1 to 3. The outage probability decreases by 42% when the number of antenna elements increases from 3 to 5, but it increases further by only 30% when the number of antenna elements varies from 5 to 7. All previous results are obtained setting the data rate to 9 kbps and the number of SUs to 10, but no significant change in performance increase is expected if the number of antenna elements are to be set beyond 7.

5. Conclusions

In this paper, we have analyzed the performance of a cognitive (secondary) user in a CR-CDMA cellular system considering beamforming at secondary BSs. A simulation model for a three-cell representative scenario, incorporating soft HO, has been developed to assess the performance of an SU, considering three possible spectrum sensing schemes. In particular, the proposed simulation model allows fast performance evaluation of a CR-CDMA system and allows one to jointly evaluate the effects of spectrum sensing and beamforming. More precisely, the outage and blocking probabilities of the above three schemes have been compared in the presence of beamforming. With regard to earlier work [11], significant performance improvements, in terms of outage and blocking probabilities, are brought by the use of beamforming, and this is especially significant in the presence of moderate traffic load. In the presence of spectrum sensing, the percentage decrease, in terms of outage probability, with 5 antenna elements is 46% and 55%, in correspondence to numbers of SUs set to 7 and 9, respectively.

All the schemes with spectrum sensing perform better than any scheme with no spectrum sensing. The SU performance, in terms of outage and blocking probabilities, improves if the data rate of the SUs decreases. Finally, a larger number of SUs degrades the performance of an SU of interest, in terms of outage and blocking probabilities, for a fixed number of PUs. In all cases, receive beamforming at secondary BSs improves the performance of an SU. Beamforming, together with spectrum sensing, dramatically improves the performance of an SU. The blocking probability is reduced in the presence of beamforming by 86%, 97%, and 99% with respect to that of [11] for the number of SUs fixed at 5, 9, and 13, respectively, keeping all other parameter values set as in [11].

Acknowledgment

The activities of G. Ferrari are carried out within the framework of the COST Action IC0902: "Cognitive Radio and Networking for Cooperative Coexistence of Heterogeneous Wireless Networks" (http://newyork.ing.uniroma1.it/IC0902/).

References

[1] J. Mitola III, G.Q. Maguire Jr., Cognitive radio: making software radios more personal, IEEE Personal Communications Magazine 6 (4) (1999) 13–18.
[2] S. Haykin, Cognitive radio: brain-empowered wireless communications, IEEE Journal on Selected Areas in Communications 3 (2) (2005) 201–220.
[3] Ian F. Akyildiz, Won-Yeol Lee, Mehmet C. Varun, Shantidev Mohanty, A survey on spectrum management in cognitive radio networks, IEEE Communications Magazine 46 (4) (2008) 40–48.
[4] Dong In Kim, Long Bao Le, E. Hossain, Joint rate and power allocation for cognitive radios in dynamic spectrum access environment, IEEE Transactions on Wireless Communications 7 (12) (2008) 5517–5527.
[5] J.C. Liberti, T.S. Rappaport, Smart Antennas for Wireless Communications: IS-95 and Third Generation CDMA Applications, Prentice Hall, NJ, USA, 1999.
[6] Lal C. Godara, Application of antenna arrays to mobile communications—part II: beam-forming and direction-of-arrival considerations, Proceedings of the IEEE 85 (8) (1997) 1195–1245.
[7] Hanyu Li, Yu-Dong Yao, Jin Yu, Outage probabilities of wireless systems with imperfect beamforming, IEEE Transactions on Vehicular Technology 55 (5) (2006) 1503–1515.
[8] A.F. Naguib, A. Paulraj, T. Kailath, Capacity improvement with base-station antenna arrays in cellular CDMA, IEEE Transactions on Vehicular Technology 43 (3) (1994) 691–698.
[9] Y. Zeng, Y.C. Liang, A.T. Hoang, R. Zhang, A review on spectrum sensing for cognitive radio: challenges and solutions, EURASIP Journal on Advances in Signal Processing 2010 (2010) 1–15. Article ID 381465.
[10] S. Dhar Roy, S. Kundu, G. Ferrari, R. Raheli, Performance evaluation of cognitive radio CDMA networks with and without spectrum sensing, in: IEEE Int. Conf. on Communications, ICC 2010, Workshop on Cognitive Radio Interfaces and Signal Processing, CRISP, Cape Town, South Africa, May 2010.
[11] S.D. Roy, S. Kundu, G. Ferrari, R. Raheli, Cognitive radio CDMA networking with spectrum sensing, International Journal of Communication Systems (2012) http://dx.doi.org/10.1002/dac.2421.
[12] S. Ghavami, B. Abolhassani, Opportunistic communications in Multi-Rate CDMA systems for cell capacity improvement using cognitive radio, in: International Symposium on Telecommunications, IST 2008, Tehran, Iran, August 2008, pp. 193–198.
[13] S. Ghavami, B. Abolhassani, Spectrum sensing and power/rate control for CDMA cognitive radio networks, International Journal of Communication Systems (2011) John Wiley & Sons Publication.
[14] Nzéza C. Nsiala, R. Gautier, G. Burel, Blind multiuser detection in multirate CDMA transmissions using fluctuations of correlation estimators, in: Proceeding of IEEE Globe COM, November 2006, pp. 1–5.
[15] G. Burel, Detection of spread spectrum transmissions using fluctuations of correlation estimators, in: The Proceeding of IEEE-ISPACS'2000, Honolulu, HI, November 2000.
[16] J.Y. Kim, G.L. Stuber, CDMA soft HO analysis in the presence of power control error and shadowing correlation, IEEE Transactions on Wireless Communications 1 (2) (2002) 245–255.
[17] Sanjay Dhar Roy, Sumit Kundu, Performance of data services in Cellular CDMA in presence of soft handoff and beamforming, in: Third International Conference on Industrial and Information Systems, ICIIS2008, IIT Kharagpur, India, pp. 1–6, December 2008.

Sanjay Dhar Roy received his B.E. (Hons.) degree in Electronics and Telecommunication Engineering in 1997 from Jadavpur University, Kolkata, India, and his M.Tech. degree in Telecommunication Engineering in 2008 from NIT Durgapur. He received his Ph. D. degree from NIT 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 he is currently an Assistant Professor there.

His research interests include radio resource management, hand-off, and cognitive radio networks. As of today, he has published 60 research papers in various journals and conference proceedings. 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. Dr. Dhar Roy has also reviewed for IEEE GlobeCom, IEEE PIMRC, IEEE VTC, etc.

Sumit Kundu received his B.E. (Hons.) degree in Electronics and Communication Engineering in 1991 from NIT, Durgapur, India, and his M.Tech. degree in Telecommunication Systems Engineering and Ph.D. in Wireless Communication Engineering from IIT Kharagpur, India, respectively.

He has been a faculty member in the Department of ECE, National Institute of Technology, Durgapur since 1995, and is currently a Professor there. His research interests include radio resource management in wireless networks, cognitive radio network, wireless sensor network and co-operative communication and wireless ad hoc and sensor networks.

He is a senior 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 of 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 conference proceedings, and more than 10 book chapters. He is coauthor of seven 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.

Prof. 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; and 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 his Dr. Ing. degree (Laurea) in Electrical Engineering "summa cum laude" from the University of Pisa in 1983, his Master of Science degree in Electrical and Computer Engineering with full marks from the University of Massachusetts at Amherst, USA, in 1986, and his 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 the Scientific Committee of CNIT (Consorzio Nazionale Interuniversitario per le Telecomunicazioni) from 2000 to 2005.

He has also been a Member of the Executive Committee of CNIT since 2008 and a 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 towards systems for communication, processing, and storage of information. His research has led to numerous international publications in journals and conference proceedings, as well as 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), and European Signal Processing Conf. (EUSIPCO).