Directional Relays for Multi-Hop Cooperative Cognitive Radio Networks

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Abstract. *In this paper, we investigate power allocation and beamforming in a relay assisted cognitive radio (CR) network. Our objective is to maximize performance of the CR network while limiting interference in the direction of the primary users (PUs). In order to achieve these goals, we first consider joint power allocation and beamforming for cognitive nodes in direct links. Then, we propose an optimal power allocation strategy for relay nodes in indirect transmissions. Unlike the conventional cooperative relaying networks, the applied relays are equipped with directional antennas to further reduce interference to the PUs and meet the CR network requirements. The proposed approach employs genetic algorithm (GA) to solve the optimization problems. Numerical simulation results illustrate the quality of service (QoS) satisfaction in both primary and secondary networks. These results also show that notable improvements are achieved in the system performance if the conventional omni-directional relays are replaced with directional ones.*

Keywords

Cognitive radio network, cooperative communication, power allocation, beamforming, directional transmission.

1. Introduction

Recently, the increasing number of various wireless services, licensed by conventional fixed spectrum allocation policy, makes the spectrum access a significant problem [1]. Federal Communication Commission (FCC) reports evidence of the claim and show that the spectrum scarcity is not a result of the heavy usage of the spectrum, but it is merely due to the inefficiency of the static frequency allocation [2]. *Cognitive radio* (CR), which was first proposed in late 1990s [3], is a promising approach to overcome the problem. This technique enables much more spectrum efficiency by spectrum sharing between the *primary users* (PUs), to which the spectrum is initially licensed, and the secondary unlicensed users [4]-[6]. The basic concept of the CR networks is to allow *secondary users* (SUs) to use licensed spectrum bands opportunistically as long as they cause no intolerable interference to the PUs [6].

The major challenge of the CR networks is to meet *quality of service* (QoS) requirements of the PUs while trying to maximize throughput of the SUs. Some researchers are focused on the joint optimization of the spectrum sensing and data transmission in CR networks to address this problem [7], [8]. However, they do not consider optimal power allocation for throughput maximization in the CR relay networks. In [9], an optimal power allocation strategy is proposed to maximize the secondary throughput under both sensing performance and total power constraints.

Cooperative communication can effectively tackle the challenges of wireless channels such as multipath fading, shadowing and path loss. Relay nodes are able to create multiple links between a transmitter and a receiver. Consequently, spatial diversity can be achieved by cooperative communication through relays [10], [11]. Furthermore, amplify-and-forward (AF) relaying can be used to improve the sensing performance and increase the throughput [12], [13]. In [14], throughput maximization problem is studied in the CR relay networks where non orthogonal amplify-and-forward (NAF) cooperation protocol is applied. Cooperative transmission of primary traffic by secondary network is also investigated in [15]-[17].

Power control is also an efficient approach to access the spectrum without counteracting transmission of the licensed users. In [18], the authors consider a power control scheme in the CR networks where SUs identify and exploit instantaneous and local spectrum opportunities without causing unacceptable interference to the PUs. A power and channel allocation scheme is investigated in [19] for three kinds of cooperative relay scenarios in CR networks. However, this work assumes that the spectrum bands are ready for use and does not consider the interference power constraint to the PUs. In [20], a joint power and channel allocation scheme is proposed for cooperative relay-assisted CR networks. This scheme is based on the energy pricing for parallel transmission and try to extend the lifetime of the network by considering variant transmit power and spectrum availability. In [21], the SUs can get access to an estimated free channel with the assigned bandwidth and power.

Cooperative communication is also considered in CR networks using directional relays or multiple antennas. In these schemes, beamforming techniques can increase / decrease signal energy in specific directions and improve system performance. In [22], the authors intend to maximize the service probability of the SUs subject to the interference constraints on the PUs. To this end, they devised an iterative algorithm to efficiently obtain the optimal beamforming solution. In [23], a relay-assisted wireless cellular network with multiple-input single-output (MISO) broadcast channel is studied. In this scenario, both the base station and relay are equipped with multiple antennas and employ joint beamforming and power control to minimize total consumed power. The problem of joint power control and beamforming is studied in [24] to minimize total transmission power of the CR network. This problem is solved such that the received interferences at the PUs remain below a threshold level while the *signal to interference plus noise ratio* (SINR) requirements of the SUs who were admitted in the system are guaranteed. In [25], performance of the directional relays is compared to omni-directional ones to exploit a new spectrum opportunity and achieve higher spectrum efficiency.

Recently, we considered joint power allocation and beamforming scheme in relay nodes of a CR network [26]. These nodes were equipped with omni-directional antennas. However, in this paper, we consider directional relays and employ joint power allocation and beamforming in the transmitter and relay nodes of a secondary network. The secondary network applies a scheme consists of two transmission modes: direct mode and indirect (relay) mode. In direct mode, joint power allocation and beamforming scheme is performed in the secondary transmitter. In this mode, the direct links should guarantee QoS requirements of the primary network while trying to maximize total SINR in the SUs. In the later mode, which is activated if QoS requirements are not maintained in at least one SU, directional relays cooperate in transmission process and try to satisfy QoS requirements in both primary and secondary networks. The directional relays and array antenna applied in the network can significantly improve system performance. Both of the transmission modes employ *genetic algorithm* (GA) to determine optimization parameters. The convergence rate of the algorithm is investigated for defined problems by some numerical simulations.

The paper is classified as below. In Section 2, the system model is described. The optimization problems are formulated in both transmission modes in Section 3. In Section 4, a GA procedure is applied to solve defined problems. Then, in Section 5, numerical simulation results are presented to investigate performance of the proposed scheme. Finally, the paper is concluded in Section 6.

2. System Model

A primary broadcasting network, consisting of one transmitter (PTx) and K receivers, is considered. We also consider that a cognitive wireless relay network consists of one transmitter (STx), L receivers and N relay nodes, coexists with the primary network in the same geographical area. The secondary transmitter is equipped with a linear array of M uniformly spaced omni-directional antenna elements. All secondary receivers are also equipped with omni-directional antennas. Each relay node has directional transmitting and omni-directional receiving abilities. This directional transmission increases signal energy toward the desired area and reduces interference in other directions. This property improves the probability of successful communications in the CR network and mitigates the harmful interference to the PUs. Furthermore, relay nodes are grouped into L clusters based on their geographical proximity. Each cluster is responsible to forward the message signal from the secondary transmitter to the corresponding cognitive receiver. This system model is depicted in Fig. 1.

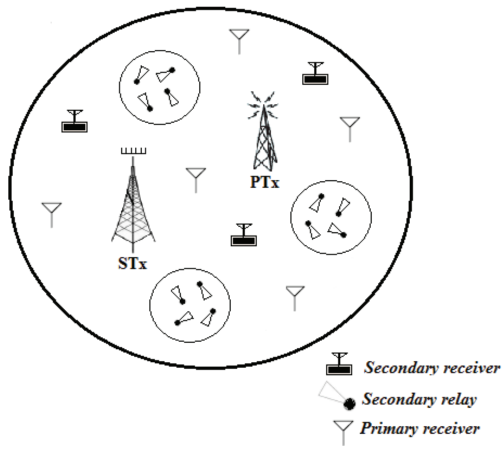

Fig. 1. System model.

In cognitive network, joint power allocation and beamforming scheme is performed at the secondary transmitter. It is assumed that the secondary transmitter has perfect knowledge about all channel gains of the system. Actually, channel estimation is an important subject in the considered scenario. But, as the main focus of this paper is on employing directional relays for multi-hop cooperative CR networks, we apply this simplifying assumption. Some good approaches recommended in [27] may be used to estimate the channel gains. The secondary transmitter array response in the direction of departure, θ, is defined by [28]:

$$\mathbf{v}(\theta)=\left[1,e^{-j2\pi/\lambda_c d\sin(\theta)},\ldots,e^{-j2\pi/\lambda_c d(M-1)\sin(\theta)}\right]^{\mathrm{T}} \tag{1}$$

where d is the separation distance between two antenna elements, λ_c is the carrier wavelength of the message signal and $(.)^{\mathrm{T}}$ denotes the transpose operations. We also consider slow flat fading channels in which the channel responses are constant over each symbol period. Furthermore, we denote channel loss from the STx to the lth SU, kth PU, and the rth relay node by $g_l^{(s)}$, $g_k'^{(s)}$, and $g_r''^{(s)}$, respectively. Similarly, $g_l^{(p)}$, $g_k'^{(p)}$, and $g_r''^{(p)}$ indicate the channel loss from PTx to the lth SU, kth PU, and the rth relay node, respectively, where $l \in [1, L]$, $k \in [1, K]$, and $r \in [1, N]$. The channel response from the cognitive transmitter to the

lth SU, kth PU, and the rth relay node are respectively shown by the following M-component vectors:

$$\begin{aligned} \mathbf{h}_l &= \sqrt{g_l^{(s)}}\mathbf{v}(\theta_l)\ \forall l \in [1, L], \\ \mathbf{h}'_k &= \sqrt{g_k'^{(s)}}\mathbf{v}(\theta'_k)\ \forall k \in [1, K], \\ \mathbf{h}''_r &= \sqrt{g_r''^{(s)}}\mathbf{v}(\theta''_r)\ \forall r \in [1, N] \end{aligned} \tag{2}$$

where θ_l, θ'_k, and θ''_r are direction of departure from the secondary transmitter to the lth SU, kth PU, and rth relay node, respectively.

3. Problem Formulation

The process of signal transmission from the secondary transmitter to the SUs consists of two different transmission modes: direct mode and indirect (relay) mode. Indirect mode takes place when the direct links between the transmitter and cognitive receivers failed due to some problems such as multipath fading, shadowing, and path loss and thus QoS requirements are not satisfied in the secondary network. Under such conditions, relaying process begins and directional relays are responsible to forward the message signal from the secondary transmitter to the SUs. This cooperative communication method helps to overcome the mentioned problem and tries to guarantee the desired QoS in both primary and secondary networks.

3.1 Direct Mode-Joint Power Allocation and Beamforming Scheme

In direct mode, transmission process starts by establishing direct links between the cognitive transmitter and receivers. A joint power allocation and beamforming scheme is performed at the secondary transmitter to establish these links and keep the induced interference to the PUs below an acceptable level.

The secondary transmitter creates L data streams each carrying an independent message signal to one of the SUs. Each of these signals is multiplied by the beamforming vector assigned to the corresponding SU and transmitted toward this user. At the same time, primary transmitter, which employs time division duplex (TDD) method, transmits a continuous signal with power p_0. Consequently, the received signal at each of the SUs can be expressed by:

$$y_l = \sum_{i=1}^{L}\sqrt{p_i}\mathbf{w}_l^H\mathbf{h}_i s_i(t-\tau_i) + \sqrt{g_l^{(p)}p_0}s_0(t-\tau_0^l) + n_l(t); \quad l = 1,\ldots,L \tag{3}$$

where, p_i is transmission power of the secondary transmitter to the ith SU, subject to its maximum power constraints, $\bar{p}_i$, $\mathbf{w}_l = [w_l^{(1)}, \ldots, w_l^{(M)}]^T$, $\forall l \in [1, L]$ is a M-component complex weight vector for the lth SU, $\mathbf{h}_i$ is the channel response from the cognitive transmitter to the ith SU, and $(.)^H$ is the Hermitian transpose. Also, $s_i(t)$ is the message signal transmitted by the secondary transmitter received at the ith SU with delay τ_i. In (3), $s_0(t)$ is a message signal transmitted by the primary transmitter. This message signal has unit energy and arrives to the lth SU with delay τ_0^l. It is assumed that the message signals have unit energy. This means that $E\{|s_i(t)|^2\}=1$. The $E\{.\}$ and $|.|$ denote the statistical expectation and amplitude of a complex number, respectively. The additive noise $n_l(t)$ is circularly symmetric complex Gaussian (CSCG) random sequence at the input of the lth SU, with zero mean and variance of $E\{|n_l(t)|^2\}=\sigma^2$ (which is identical for all cognitive nodes).

Similarly, the received signals at each of the PUs and relay nodes can be expressed respectively, as follows:

$$\begin{aligned} y'_k &= \sqrt{g_k'^{(p)}p_0}s_0(t-\tau_0'^k) \\ &+ \sum_{l=1}^{L}\sqrt{p_l}\mathbf{w}_l^H\mathbf{h}'_k s_l(t-\tau'_l) + n'_k(t); \quad k = 1,\ldots,K, \end{aligned} \tag{4}$$

$$\begin{aligned} y''_r &= \sum_{l=1}^{L}\sqrt{p_l}\mathbf{w}_l^H\mathbf{h}''_r s_l(t-\tau''_l) \\ &+ \sqrt{g_r''^{(p)}p_0}s_0(t-\tau_0''^r) + n''_r(t); \quad r = 1,\ldots,N \end{aligned} \tag{5}$$

where, τ'_l and τ''_l are time delays of the message signals received from the secondary transmitter at the kth PU and the rth relay, respectively. Similarly, $\tau_0'^k$ and $\tau_0''^r$ indicate the time delays of the message signals received from the primary transmitter at the kth PU and the rth relay node, respectively. The terms of $n'_k(t)$ and $n''_r(t)$ are CSCG noise at the kth PU and the rth relay node, respectively.

We define an optimization problem to find beamforming weights and transmission power values in order to maximize the total SINR in the SUs while QoS is satisfied for each PU. This optimization problem can be formulated as follows:

$$\max_{\mathbf{p_s},\mathbf{w_s}} \mathrm{SINR}_{\mathrm{total}} = \sum_{l=1}^{L}\mathrm{SINR}_l \tag{6}$$

subject to:

$$\eta_k \le \eta_0; \quad k = 1,\ldots,K,$$
$$\mathbf{p_s} \le \bar{\mathbf{p}}_\mathbf{s}$$

where, η_0 is maximum tolerable interference to the PUs. Also, SINR_l and η_k are the amount of SINR at the lth SU and interference power experienced by the kth PU, respectively, which can be defined by:

$$\mathrm{SINR}_l = \frac{\left|\mathbf{w}_l^H\mathbf{h}_l\right|^2 p_l}{\sum_{\substack{i=1\\i\ne l}}^{L}\left|\mathbf{w}_l^H\mathbf{h}_i\right|^2 p_i + \sigma^2 + g_l^{(p)}p_0}; \quad l = 1,\ldots,L, \tag{7}$$

$$\eta_k = \sum_{l=1}^{L}\left|\mathbf{w}_l^H\mathbf{h}'_k\right|^2 p_l; \quad k = 1,\ldots,K. \tag{8}$$

Also, $\mathbf{p}_s = [p_1, \ldots, p_L]$ and $\mathbf{W}_s = [\mathbf{w}_1, \ldots, \mathbf{w}_L]$ are optimization parameters. These vectors consist of transmission power values and beamforming weights of the secondary transmitter. Transmission power values are limited by maximum power constraint, $\bar{\mathbf{p}}_\mathbf{s}$. In (7), σ^2 is the noise variance which is identical for all cognitive nodes. This is a simplified, but acceptable hypothesis. A GA procedure is applied to solve the optimization problem. Then, the amount of SINR should be checked in each of the SUs:

$$\mathrm{SINR}_l \geq \mathrm{SINR}_{\mathrm{target}}\,; \quad l = 1, \ldots, L. \tag{9}$$

If (9) is not satisfied in each of the SUs, it means that the indirect transmission through the directional relays must be activated for that user.

3.2 Indirect Mode-Relays Equipped with Directional Antenna

In the previous section, we have seen that if any of the direct links does not maintain the target SINR, the indirect mode is activated for its corresponding user. In this case, directional relays of a cluster assigned to that SU are responsible to forward the transmitted message signal. But first, it is necessary to determine those relays in the corresponding cluster that decode the source message without any error. To this end, the achieved SINR of these relays are compared with a predefined threshold. Those relays that their SINRs are greater than or equal to this threshold value, are selected to participate at the second step of the scheme:

$$\mathrm{SINR}_r^{(l)} \geq \mathrm{SINR}_{\mathrm{th}_r}\,; \ \forall l \in L'\left(L' \subseteq \{1, \ldots, L\}\right) \tag{10}$$

where $\mathrm{SINR}_{\mathrm{thr}}$ is the threshold value and $\mathrm{SINR}_r^{(l)}$ denotes the SINR value at the rth relay node of the lth cluster and is defined by:

$$\mathrm{SINR}_r^{(l)} = \frac{\left|\mathbf{w}_l^{\mathrm{H}} \mathbf{h}_l''\right|^2 p_l}{\sum_{\substack{i=1\\ i\neq l}}^{L} \left|\mathbf{w}_l^{\mathrm{H}} \mathbf{h}_i''\right|^2 p_i + \sigma^2 + g_r''^{(p)} p_0}; \tag{11}$$
$$\forall l \in L'\left(L' \subseteq \{1, \ldots, L\}\right), \quad r = 1, \ldots, N_{(l)}.$$

In (11), $N_{(l)}$ is the number of relays in the lth cluster and L' denotes the set of SUs that their required SINR values are not satisfied by direct transmission.

In fact**,** secondary relays are considered as some nodes that have two capabilities. In the first stage, they act as secondary receivers to receive the message signal transmitted by the cognitive transmitter and in the next stages, they are intermediate transmitters to forward the message signal to the main cognitive receivers (SUs).

After determining those relays that can participate in the indirect transmission mode, the relaying phase starts to meet the QoS at those SUs which cannot decode the message signal in the first transmission mode. The QoS constraints of these SUs should be investigated after each relaying phase to determine if they can receive their message signals in proper manner. If the required QoS requirements do not maintained in any of the SUs, the relaying process is repeated until all relays participate in the relaying process or a predefined maximum number of relaying phases, $N_{\max}$, is achieved.

Both transmit and receive processes at the cognitive nodes are executed based on data buffering. Consequently, after each phase of the relaying process, the SINR values at inactive relays of each cluster are increased and these relays may participate in the next phase of the relaying process.

The data buffering and iterative relaying processes reduce the throughput of the CR network. This reduction is proportional to the number of relaying phases. This is the cost that is incurred by the CR network to meet the whole system requirements.

In the nnth phase of the indirect transmission, the received signal at the lth SU can be expressed as:

$$y_l^{(nn)} = \sum_{r,\forall r\in R^{(nn)}} \sqrt{g_l^{(r)} p_r^{(nn)}}\, F_r(\theta_l) s_r(t - \tilde{\tau}_r^{\,l}) + \sqrt{g_l^{(p)} p_0}\, s_0(t - \tau_0^l) + n_l(t); \quad \forall l \in L'^{(nn)} \tag{12}$$

where $R^{(nn)}$ denotes the set of selected relays in the nnth relaying phase and $L'^{(nn)}$ denotes the set of SUs that cannot correctly decode the message signal of the secondary transmitter up to this phase. Also, $g_l^{(r)}$ and $g_l^{(p)}$ are the channel losses between the rth relay and the lth SU, and between the PTx and the lth SU, respectively. The parameters, $p_r^{(nn)}$ and $s_r(t)$ indicate transmission power and message signal of the rth selected relay in the nnth relaying phase. A message signal has unit energy ($\mathrm{E}\{|s_r(t)|^2\}=1$) and is received at the lth SU with delay $\tilde{\tau}_r^{\,l}$. Furthermore, transmitted signal of the primary transmitter is received at the lth SU with delay τ_0^l. The term $n_l(t)$ is CSCG noise at the lth SU. Also, $F_r(\theta_l)$ represents the radiation pattern of the rth relay in the direction of the lth SU. The radiation pattern of the rth relay is defined by:

$$F_r(\theta) = \begin{cases} 1; & \theta_r^1 \leq \theta \leq \theta_r^2 \\ 0; & \text{otherwise} \end{cases}; \quad r = 1, \ldots, N. \tag{13}$$

In the nnth phase of indirect mode, transmitted signals of the relays introduce some interference values to the PUs. Applying relay nodes equipped with directional antennas can be further reduced the interference and increase the QoS in the primary network. In the nnth phase of the relaying process,the received signal at each of the PUs is given by:

$$y_k'^{(nn)} = \sqrt{g_k'^{(p)} p_0}\, s_0(t - \tau_0'^k) + \sum_{r,\forall r\in R^{(nn)}} \sqrt{g_k'^{(r)} p_r^{(nn)}}\, F_r(\theta_k') s_r(t - \tilde{\tau}_r') + n_k'(t); \quad k = 1, \ldots, K \tag{14}$$

where $g_k'^{(p)}$ and $g_k'^{(r)}$ are the channel losses from PTx to the kth PU and from the rth relay to the kth PU, respectively. Also, $\tau_0'^k$ and τ_r' indicate the time delay experienced by the signal transmitted from PTx to the kth PU and from the rth relay to the kth PU, respectively. The angle θ_k' is direction of departure from the rth relay to the kth PU, and finally, $n_k'(t)$ is CSCG noise at the input of the kth PU.

Similarly, the received signal in the rth relay is:

$$y''^{(nn)}_r = \sum_{\substack{r',\forall r' \in R^{(nn)},\\ r' \neq r}} \sqrt{g''^{(r')}_r p^{(nn)}_{r'}} F_{r'}(\theta''_r) s_{r'}\left(t - \tilde{\tau}''_{r'}\right) + \sqrt{g''^{(p)}_r p_0} s_0(t - \tau''^{r}_0) + n''_r(t); \quad r = 1,\ldots,\left(N - N_s^{(nn)-1}\right) \tag{15}$$

where, $g''^{(r')}_r$ and $g''^{(p)}_r$ are the channel losses from the r'th relay to the rth relay and from PTx to the rth relay, respectively. Also, $\tilde{\tau}''_{r'}$ and τ''^{r}_0 indicate the time delay of the signal transmitted by the r'th selected relay and PTx to the rth relay, respectively. The angle θ''_r is direction of departure from the r'th relay to the rth relay and $N_s^{(nn)-1}$ denotes the number of selected relays up to (nn-1)th relaying phase.

The relaying phases in the indirect transmission mode are terminated if the required QoS is maintained in the secondary network:

$$\mathrm{SINR}_l^{(nn)} \geq \mathrm{SINR}_{\mathrm{target}} - \mathrm{SINR}_l - \sum_{i=1}^{(nn)-1} \mathrm{SINR}_l^{(i)}. \tag{16}$$

Otherwise, the process is continued until all relays have participated in the relaying process or a predefined maximum number of relaying phases is achieved. If it is necessary to continue the relaying phase, the relays that participate in the next phase are determined through their new SINR values. The SINR value of each relay is:

$$\mathrm{SINR}_{r,(l)}^{(nn)} = \frac{\sum_{r',\forall r' \in R_l^{(nn)}, r' \neq r} g''^{(r')}_r p^{(nn)}_{r'} \left|F_{r'}(\theta''_r)\right|^2}{\sum_{r',\forall r' \in \left\{R^{(nn)} - R_l^{(nn)}\right\}} g''^{(r')}_r p^{(nn)}_{r'} \left|F_{r'}(\theta''_r)\right|^2 + g''^{(p)}_r p_0}; \quad r = 1,\ldots,\left(N - N_s^{(nn)-1}\right), \forall l \in L'^{(nn)} \tag{17}$$

where $R_l^{(nn)}$ denotes the set of relays located in the lth cluster which have participated in the nnth relaying phase. Therefore, the relay that its total SINR exceeds the activation threshold level can participate in the next phase of relaying.

We defined a new optimization problem to find optimum transmission power values of the relays participate in the indirect mode. The objective is minimization of the total power consumption of those relays that participate in each phase. This is done under QoS constraints of both primary and secondary networks, taking into account their maximum transmission power constraints:

$$\min_{p_r} P_{\mathrm{total}} = \sum_{r,\forall r \in R^{(nn)}} p_r$$

subject to:

$$\mathrm{SINR}_l^{(nn)} \geq \mathrm{SINR}_{\mathrm{target}} - \mathrm{SINR}_l - \sum_{i=1}^{(nn)-1} \mathrm{SINR}_l^{(i)}, \tag{18}$$

$$\eta_k^{(nn)} \leq \eta_0,$$
$$p_r^{(nn)} \leq \bar{p}_r^{(nn)},$$
$$\text{for } l \in L'^{(nn)}, k = 1,\ldots,K,\ r \in R^{(nn)}$$

where $\mathrm{SINR}_l^{(nn)}$ and $\eta_k^{(nn)}$ are the amounts of SINR at the lth SU and interference power experienced by the kth PU in the nnth phase of the relaying mode, respectively which are defined by:

$$\mathrm{SINR}_l^{(nn)} = \frac{\sum_{r,\forall r \in R_l^{(nn)}} g_l^{(r)} p_r^{(nn)} \left|F_r(\theta_l)\right|^2}{\sum_{r,\forall r \in \left\{R^{(nn)} - R_l^{(nn)}\right\}} g_l^{(r)} p_r^{(nn)} \left|F_r(\theta_l)\right|^2 + g_l^{(p)} p_0 + \sigma^2}, \quad \forall l \in L'^{(nn)} \tag{19}$$

$$\eta_k^{(nn)} = \sum_{r,\forall r \in R^{(nn)}} g'^{(r)}_k p_r^{(nn)} \left|F_r(\theta'_k)\right|^2, \quad k = 1,\ldots,K. \tag{20}$$

If (18) does not have a feasible solution, i.e., the target SINR cannot be achieved within the current relaying phase, it is necessary to follow another optimization problem in order to maximize total SINR of the SUs under QoS constraints of the PUs:

$$\max_{p_r} \mathrm{SINR}_{\mathrm{total}}^{(nn)} = \sum_{l,\forall l \in L'^{(nn)}} \mathrm{SINR}_l^{(nn)} \tag{21}$$

subject to:

$$\eta_k^{(nn)} \leq \eta_0,$$
$$p_r^{(nn)} \leq \bar{p}_r^{(nn)},$$
$$\text{for } l \in L'^{(nn)},\ k = 1,\ldots,K,\ r \in R^{(nn)}.$$

The optimization parameters in each of the above defined problems are found so that the QoS constraints in both primary and secondary networks are satisfied.

4. Using Genetic Algorithm to Solve Problems

Genetic algorithm is one of the recent optimization methods that mostly used in complicated and nonlinear problems [29]. This algorithm has attracted much attention because of its ability to solve global optimization problems, flexibility against complicated sets, and simple implementation. This algorithm maintains a population of potential solutions and applies an iterative selection process based on the fitness of individuals to find the optimum solution in the search space.

Here we use GA to solve the optimization problems defined in the previous sections. The population size of each generation is set to 10 times of the number of optimization parameters. The optimization parameters in (6) and (18) are a row vector of size $L(2M + 1)$ and $N_s^{(nn)}$, respectively. In (6), this vector includes transmission power values and beamforming weights of the secondary transmitter assigned to each SUs:

$$\mathbf{X} = \left[\mathbf{P}_s, Am(\mathbf{w}_1^T),\ldots, Am(\mathbf{w}_\mathrm{L}^\mathrm{T}), Ph(\mathbf{w}_1^\mathrm{T}),\ldots, Ph\left(\mathbf{w}_\mathrm{L}^\mathrm{T}\right)\right] \tag{22}$$

In (18), $\mathbf{X}$ is transmission power of the relays that participate in the indirect mode of transmission:

$$\mathbf{X} = \left[P_{r_i}\right]^T; \quad i \in R^{(nn)}. \tag{23}$$

where $Am(\mathbf{w}_l^\mathrm{T})$ and $Ph(\mathbf{w}_l^\mathrm{T})$ are M-component vectors indicating amplitudes and phases of $\mathbf{w}_l$'s, respectively. Also, P_{ri} is transmission power of the ith relay participates in the indirect transmission mode and $N_s^{(nn)}$ is the number of the selected relays in the nnth relaying phase of this transmission mode.

We rewrite the defined optimization problems in the following form:

$$\min_X F(\mathbf{X})$$

subject to:

$$\begin{aligned} &\mathbf{C}_E(\mathbf{X})=0; && \mathbf{C}_E=\left[C_E^{(1)},\ldots,C_E^{(P)}\right]^{\mathrm{T}},\\ &\mathbf{C}_I(\mathbf{X})\le 0; && \mathbf{C}_I=\left[C_I^{(1)},\ldots,C_I^{(Q)}\right]^{\mathrm{T}},\\ &\mathbf{Lb}\le\mathbf{X}\le\mathbf{Ub}; && \mathbf{Lb}=\left[Lb_1,\ldots,Lb_J\right]^{\mathrm{T}},\\ & && \mathbf{Ub}=\left[Ub_1,\ldots,Ub_J\right]^{\mathrm{T}} \end{aligned} \tag{24}$$

where F is the objective function, $\mathbf{C}_E$ is a vector containing P equality constraints, $\mathbf{C}_I$ is a vector containing Q inequality constraints, and **Lb** and **Ub** are the lower and upper bound vectors for the optimization parameters, respectively.

The lower bound vector in both problems is an all-zero row vector. The upper bound vectors are defined as follows for direct and relay modes, respectively:

$$Ub_i=\begin{cases}\overline{\mathbf{P}}_S; & \forall i\in[1,L],\\ 1; & \forall i\in[L+1,L\times(M+1)],\\ 2\pi; & \forall i\in[L\times(M+1)+1,L\times(2M+1)],\end{cases} \tag{25}$$

$$Ub_i=\overline{P}_r;\ \forall r\in R^{(nn)}. \tag{26}$$

If (18) does not have any feasible solution, the same procedure is applied to solve the optimization problem defined in (21).

Various conditions have been suggested to terminate GA searching process. At the best condition, GA is stopped when the best solution is found. Otherwise, a predefined time limitation is applied to terminate the searching process. Genetic algorithm can also stop if a predefined maximum number of iterations or error values are achieved [29].

5. Numerical Results

In order to evaluate performance of the proposed approach, we consider the system shown in Fig. 2. In this system, a rectangular area with a size of *1500 m × 1500 m* is considered as the coverage area of a primary network with one transmitter and two receivers. A CR network, consists of one transmitter and two receivers are located in this area and eight relays which are grouped in 2 clusters, are responsible to forward the message signal from STx to the cognitive receiver assigned to their clusters.

The channel energy associated with a certain link $X\rightarrow Y$ is modelled according to $\alpha_{X,Y} = L_0(d_0/d_{X,Y})^{\beta}$, where $d_{X,Y}$ is the distance between node X and node Y, L_0 is the reference attenuation for a reference distance of $d_0 = 1$ m and β is the path loss exponent. In the simulations, L_0 and β are set to -30 dB and 2, respectively. Transmission power of the primary transmitter is set to 100 mW and maximum transmission power of the secondary transmitter and relay nodes are assumed to be 17 mW and 37 mW, respectively. The maximum tolerable interference to the PUs and the target SINR of the SUs are set to -40 dBm and 5 dB, respectively. For all secondary nodes, σ_n^2 is set to -60 dBm. In each of the problems, the population size of the GA is set to 10 times of the number of optimization parameters.

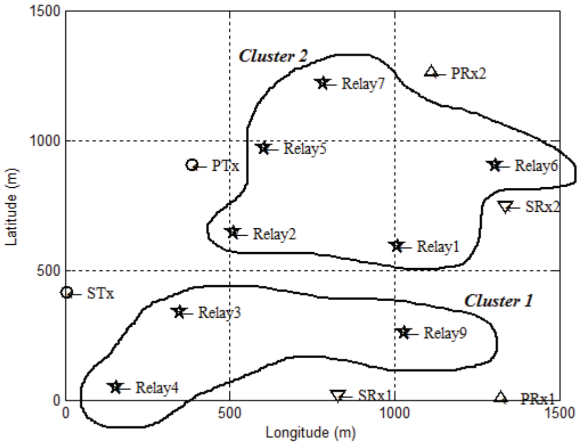

Fig. 2. Configuration of the considered system.

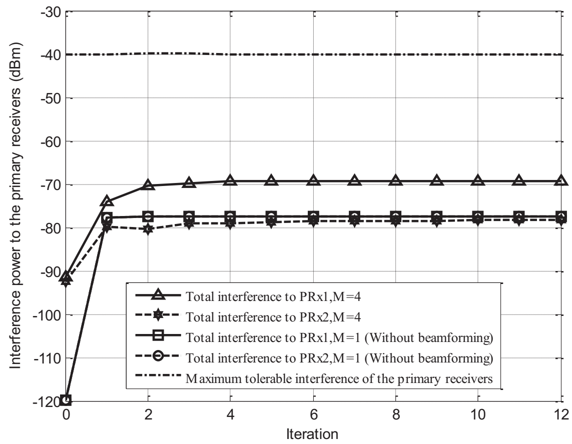

Fig. 3. Total interference to the PUs in the direct mode.

In the following subsections, performance of the system is evaluated in both modes of transmission.

5.1 Direct Mode

In the direct mode, joint power allocation and beamforming scheme is employed in the secondary transmitter. For this purpose, the secondary transmitter is equipped with a linear array of uniformly spaced omni-directional antennas with an antenna separation distance equal to half of the operating frequency wavelength.

The interference power experienced by each primary receiver is shown in Fig. 3. These results show that the first mode of the proposed scheme satisfied the QoS requirements of the PUs. Figure 4 shows convergence of

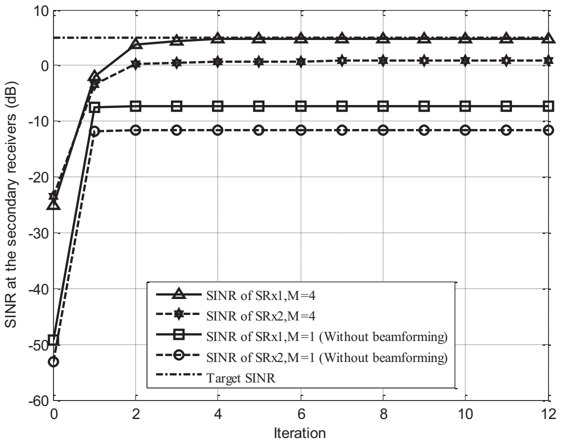

Fig. 4. Convergence of SINR at the SUs in the direct mode.

the SINR at the SUs when secondary transmitter is equipped with a linear array of 4 elements. These results are compared to the case where the cognitive transmitter equipped with single antenna. According to expectations, array antennas can increase the SINR values at the SUs. However, the achieved SINR values do not maintain the desired QoS in the users. This leads to employing directional relays in the indirect transmission mode.

5.2 Indirect Mode

In the indirect mode, signal transmission to the cognitive receivers is performed by cooperation of the relays equipped with directional antennas. The beamwidth of each relay is set to 0.7854 radian.

Total transmission power of the relays is shown in Fig. 5 and compared to the case where relays are equipped with omni-directional antenna. This figure shows that applying directional antennas can significantly reduce power consumption in the CR network. Also, performance of the proposed scheme is investigated by checking the QoS in the primary and secondary networks. The achieved SINR at the SUs is shown in Fig. 6. It is seen that cooperative transmission improves the QoS at the SUs. The SINR values are converged to the target value in a reasonably low number of iterations. Total interference experienced by each of the PUs is shown in Fig. 7. According to this figure, directional transmissions protect PUs from harmful interference and guarantee QoS of these users.

Above results show that the proposed scheme by applying directional relays, can tackle challenges faced in the practical implementation of the CR networks.

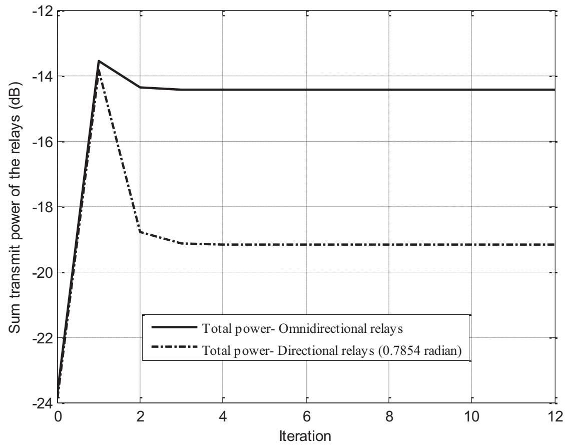

Fig. 5. Total transmission power of the relays.

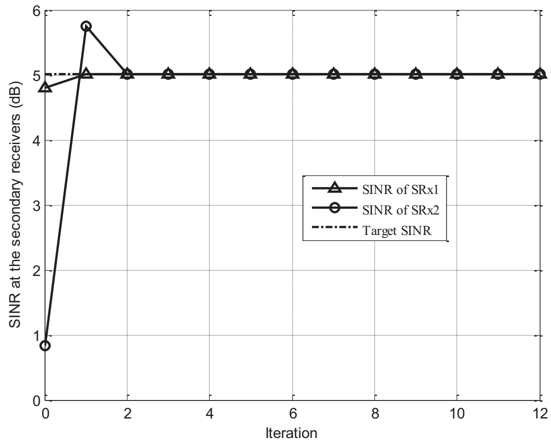

Fig. 6. Convergence of SINR at the SUs in the indirect mode of transmission.

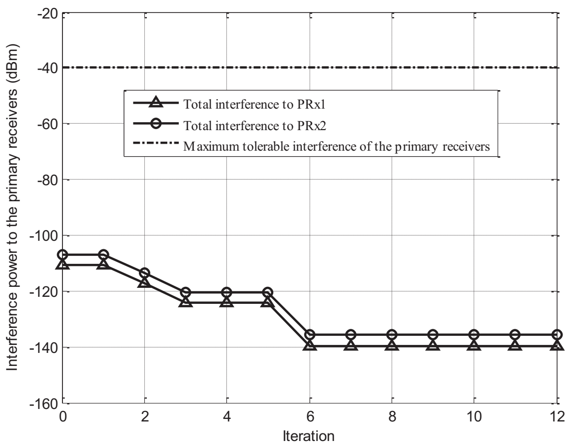

Fig. 7. Total interference to the PUs in the indirect mode of transmission.

6. Conclusions

Generally, coexistence of the primary and secondary networks is faced with some challenges. Some advanced techniques, such as cooperative relaying and directional transmissions are used to overcome these challenges. In this paper, the joint power allocation and beamforming scheme was applied in the secondary transmitter with employing directional relays. Two different transmission modes were formed: direct mode from secondary transmitter to SUs and indirect mode via directional relays. These transmission modes were implemented by employing GA as an optimization technique for solving the nonlinear problems. Their performances were investigated to meet the QoS of both primary and secondary networks. The simulation results showed that cooperative communication through directional relays can significantly improve the system quality against conventional techniques employ omni-directional ones.

Acknowledgments

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