Cognitive radio based on Cooperative spectrum sharing with imperfect CSI

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Abstract—Cognitive radio is an emerging technology that aims for efficient spectrum usage. Cognitive radios have been proposed as a solution to the spectrum underutilization problem and have been proven to increase spectrum efficiency. However, in this we are analyzing the performance of the cognitive radio based on cooperative spectrum sharing. Here we propose a two-phase spectrum sharing protocol which supports relaying functionality, it take the advantage of situation when primary system is fails to achieve its target rate due to weak channel situations the secondary system allocates some of its transmitters for helping the primary system to achieve its target rate by acting as decode–forward relay. As a reward the secondary system gains spectrum access by using remaining transmitters to transmit its own signal. Analytic and simulation results confirm the efficiency of the proposed spectrum sharing protocol. We show that the both primary and secondary are able to achieve better outage performance with increasing the secondary transmitters. And also it is shown that primary user’s interference probability is always equal to 0.75 when CSI of interference links is imperfect.

Keywords—Cooperative spectrum sharing, selection of relay, imperfect CSI, outage probability.

I. INTRODUCTION

The growths of wireless applications and increasing demands for higher quality of services have led to a perceived lack of available radio bandwidth. Dynamic spectrum sharing models [1]–[4] have been shown to be effective in achieving more efficient utilization of spectrum resources.

Along with the conventional “detect-and-avoid” type of interweave protocols [5], a number of Spectrum sharing models for secondary spectrum access have come up in literature as spectrum regulatory policies develop gradually [6], [7]. In cognitive radios the role of cooperative transmission has been studied in [8],[9]. In spectrum leasing protocol based on cooperative transmission, the spectrum sharing process is totally controlled by the primary system. Particularly, the primary system determines whether to lease a some part of its own time to the secondary system. In return, the secondary system has to spare a bit of the leased time to assist relay the primary transmission [10].

Spectrum sharing protocols based on cooperative amplify-forward and DF relaying were proposed in [11] and [12] respectively. In [12] the primary system consists of a transmitter-receiver pair and only one transmitter acts partially as a DF relay for the primary system to attain secondary spectrum access together with the primary system. In [13], the spectrum sharing protocol based on DF was extended to a multi-user situation. A corresponding two-step distributed secondary user selection plan was offered. While [8],[9] provided the Information theoretic upper bounds for cooperative spectrum access based on non-causal information, the cooperative spectrum sharing problem was considered in [11]–[13].

In this paper, we extend the work in [14] by considering a more general scenario where (i) the primary system is a two-phase selective relaying network [14],[15] and (ii) transmitters in the secondary system may either acts as relay in the primary system or serve as secondary access transmitters. Under this abstraction, the notable difference between [13] and this work are as follows. Firstly, with the selective relaying primary system considered in this paper, the secondary system can always try for an opportunity to access the spectrum, whereas in [13] the secondary system is eligible to try only when the primary system requests for help from the neighbouring nodes. Secondly, in [13] all the secondary transmitters try for both relaying and spectrum access opportunities, but the secondary systems in this paper can designate its transmitters as either possible candidates for relaying the primary signal or secondary spectrum access. Thirdly, in this paper the secondary system is capable to take advantage of the failures of primary relay selection and access the spectrum without any interference constraint, but in [13] when the primary relay selection fails no secondary access is possible. So, with the proposed protocol in this paper, the secondary system is capable to attain more flexibility in managing the performance of the both primary and secondary systems.

Under proposed spectrum sharing protocol, we analyse the performance of the primary and secondary systems and derive closed-form expressions for the outage probabilities. We show that the secondary system is capable to access the spectrum band without reducing the outage performance of the primary system and also it improves the outage performance of the primary system by designating an appropriate number of its transmitters as primary relays. We show that the number of secondary users increases the outage performances of the both primary and secondary systems increases. And it is shown that the primary system’s interference probability is always equals to 0.75 when the channel state information of interference links is imperfect.
II. SYSTEM MODEL AND PROTOCOL DESCRIPTION

A. System Model

The system architecture is shown in the Fig.1. The primary system consists of primary transmitter (PT) and primary receiver (PR) as well as M relays R_i, i ∈ {1, 2, ..., M} and its supports the selective relaying functionality. Without secondary access, one primary transmission from PT to PR is accomplished over two transmission phases by the assistance of suitable relay R_p, p ∈ {1,2,...,M}, which is selected from M candidates [14],[15]. The secondary system is a multi-user system, whereby N Transmitters R_s, s ∈ {M+1,M+2, ..., M+N}, try to communicate in a time orthogonal fashion with a common receiver SR on a secondary basis in this spectrum band [10] with the restraint that its operation does not degrade the performance of the primary system. Transmitters R_s, s ∈ {M+1,M+2, ..., M+N}, try to communicate in a time orthogonal fashion with a common receiver SR on a secondary basis in this spectrum band [10] with the restraint that its operation does not degrade the performance of the primary system.

We separate the total (M+N) terminals of primary relays and secondary transmitters into two groups R_r, i ∈ M_1 = {1, 2, ..., M+Q} and R_r,i' ∈ M_2 = { M+Q+1, M+Q+2, ..., M+N }, where 0 ≤ Q< N is an arbitrary integer. Particularly, R_r, i ∈ M_1 are assigned as possible relay candidates for helping the primary system during the time that the remaining secondary transmitters R_s, s ∈ M_2 are selected as possible candidates for secondary spectrum access. In this paper, we assume that the secondary system has intelligence to imitate the radio protocols of the primary system [3].

The direct link of primary system PT→PR is assumed to be weak due to fading or/and shadowing and is thus neglected for data transmission [15]. Note that this assumption is not restrict the application to the situation where there exists a direct link of the proposed spectrum sharing protocol. The channels over links PT→R_s, R_i→ PR, and R_i→SR are modeled to be Rayleigh flat fading with channel coefficients denoted by h_{1i}, h_{2i}, h_{3i} respectively, where i ∈ M = {1,2,...,M + N}, we have h_{ki} ~ C\{0,\Omega_{ki}\}, where k=1,2,3 and \Omega_{ki} is the average channel gain between the corresponding transmitters and receivers. And P_1 and P_2 are the transmit powers of PT and R_s, i ∈ M respectively.

B. Distributed Secondary User Selections

To optimize the performance for the secondary system, we propose a distributed relay-secondary user selection scheme without degrading the performance of the primary system. This scheme consists of two steps. In the first step, one relay R_p, P ∈ M_1 is selected to help (relay) the primary transmission in achieving a request target rate (if possible). When in the case of selection of R_p succeeds, by the relay assistance from R_p, the primary system is then able to overcome interference lower than a certain threshold in the relaying phase, without compromising its outage performance.

Accordingly, a secondary transmitter R_s, s ∈ M_2 is then selected to access the spectrum simultaneously with R_p in the relaying phase (if possible). Note that Rs has to obey to an interference restriction to ensure that the outage performance of the primary system is not decrease as compared to the situation where there is no secondary spectrum access. On the other case, if the selection of R_p fails in the first step, in the two transmission phases the primary system will remain silent and hence there will be no interference constraint for secondary spectrum access. In this case, R_s’, s’ ∈ M_2 which minimizes the outage probability of the secondary system is selected to the spectrum access.

III. OUTAGE PERFORMANCE ANALYSIS

A. Outage Probability Of Primary System

An outage for the primary system occurs when the selection of R_p fails. Then the outage probability for the primary system with request target rate lpt is given by

\[ P_{out}^p = (1 - p_1 p_2)^{M+Q} \]

Where \[ p_1 = e^{-\Omega_1^{-1} \frac{Z_1^2}{\rho_1 \rho_p}} \] and \[ p_2 = e^{-\Omega_2^{-1} \frac{Z_2^2}{\rho_1 \rho_p}} \]

| TABLE I
| RELAY SELECTION AND CORRESPONDING OPERATION |

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B. Outage probability of secondary system

We denote the event that an outage occurs for the primary system as $P_o$, and the outage probability of the secondary system with target rate $I_{st}$ is given by

$$P_{out}^S = Pr(I_{3s} < I_{3t}|O_p)P_{out}^P + Pr(I_{3s} < I_{3t}|\bar{O}_p)(1 - P_{out}^P)$$

Where $I_{3s}$ denotes the achievable rate between Rs' and SR, and $I_{3s}$ denotes the achievable rate between Rs and SR, respectively. It can be derived that

$$P_{out}^S = (1 - p_1P_2)^{H+Q} \left[ -e^{-\Omega_1^{-1}\frac{\zeta^2}{\rho_o}} \right]^{I_{st}-Q} + (1 - p_1P_2)^{H+Q} \sum_{j=1}^{I_{st}-Q} \left[ \sum_{i=0}^{f-1} \left( -P_2 \right)^{j-i} \right]^{(H+Q) - \bar{I}_st}$$

Where,

$$T_1(j) = P_2(1 - P_2)^j(1 - P_{out}) \sum_{i=0}^{f-1} \left( -P_2 \right)^{j-i} \rho_o^{-i}$$

$$T_2(j) = \left( \begin{array}{c} H+Q \\ j \\ \end{array} \right) \sum_{i=0}^{f-1} \left( -P_2 \right)^{j-i} \rho_o^{-i}$$

$$C_{\eta-2-n}^{H-2-n} f^{\eta-2-n} \frac{\Omega_1^{-1}\frac{\zeta^2}{\rho_o}}{(-1)^{-j+n+\eta+\zeta+1}}$$

$$T_3(j) = \frac{1}{1 - P_{out}} \left( \frac{M + Q}{f} \right) (P_2P_1)^{H+Q-f}$$

IV. INTERFERENCE PROBABILITY OF THE PRIMARY USER

When the perfect CSI of interference links is obtained at the SU, the interference from the SU is regulated below the interference threshold $Q$. When the CSI of interference links is imperfect, the SU may adjust the transmit power incorrectly and cause an interference higher than the interference threshold $Q$. Thus, in order to quantitify the impact of imperfect CSI of the interference links on the PU, we present a performance metric termed as interference probability, $P_I$, which is defined as the probability that the interference from the SU is higher than the interference threshold $Q$. Since we adopt the two time-slots AF partial relay selection protocol, the interference event occurs if and only if one of the two cases below occurs:

Case One: In the first time slot, SU source adjusts the transmit power Ps incorrectly and causes an interference higher than the interference threshold.

Case Two: In the first time slot, SU source does not interfere with the PU; however, in the second time slot, the selected relay adjusts the transmit power Prk incorrectly and causes an interference higher than the interference threshold. Therefore, according to the total probability law, the interference probability can be expressed as

$$P_I = Pr(P_s|\bar{h}_{sv}|2 > Q) + Pr(P_s|\bar{h}_{sv}|2 \leq Q)Pr(Prk|hrkv|2 > Q)$$

where $rk$ denotes the selected relay. When the CSI of interference links is perfect, the transmit powers of the SU source and the selected relay satisfy the interference constraints, i.e. $P_s = Q|h_{sv}|2$ and $Prk = Q|hrkv|2$, so it is obvious that $P_I$ is always equal to zero. When the CSI of interference links is imperfect, $P_s = Q|h_{sv}|2$ and $Prk = Q|hrkv|2$. Since $|h_{ij}| = |h_{ji}|$ and $|h_{ij}| = |h_{ji}|$, the PU’s interference probability is not always equal to zero anymore.

It is important to note that the PU’s interference probability is always equal to 0.75 when the CSI of interference links is imperfect. Therefore, in order to guarantee that the PU’s interference probability is below an acceptable value, we adopt a back-off transmit power control mechanism, i.e. the SU selects a reduced transmit power as the actual one: $P_s = \eta P_s$ and $Prk = \eta Prk$, where $\eta$ denotes the back-off power control coefficient ($0 \leq \eta \leq 1$). Finally, using the same rationale, the PU’s interference probability by adopting the back-off power control is given by

$$P_I' = \left( 1 + \frac{\eta^{-1}}{\sqrt{\eta^{-1} - 2 - 2\eta^{-1}}\eta^{-1}} \right)^{\frac{\eta^{-1}}{2} - \frac{\eta^{-1}}{4}}$$
Under proposed spectrum sharing protocol, we show the simulation and analytical results for the outage probability of primary system in Fig.1. Here SNR varies from 5 dB to 20 dB. Three cases of Q where Q=0, Q=5 and Q=10 are considered.

It can be observed from Fig.2 indicating that the primary system is able to achieve the same outage performance as a conventional schema, even when no secondary transmitter is assigned for helping the primary system. So a higher diversity gain is obtained by the primary system with an increasing Q. This represents that with the proposed spectrum sharing protocol, the secondary system is capable to maintain or improve the outage performance of the primary system by certain desired margin by simply varying 0≤Q<N.

In Fig.3, we show the analytical results of the outage probability for the secondary system with different values of Q. Here the Q varies from 0 to N. Three cases of SNR where SNR=5, 15 and 25 dB. From Fig.3 it can be observed that, when SNR is small, secondary system should assign all of its transmitters for spectrum access to optimize its performance. And when SNR is high, it acting selfishly, i.e. assigning all of its available transmitters for spectrum access and none for helping the primary system.

In Fig.4, we show the analytical results for outage probability for the secondary system with the different values of N. We can observed from Fig.4 that due to an increased multi-user diversity gain for both the primary and secondary systems, secondary outage probability decreases with increasing N. \( P_{out}^{s} \) is also decreases with a decreasing \( I_{st} \). because with a smaller request target rate , the primary system is able to tolerate a larger interference power which allows more secondary transmitters in \( M_{2} \) to participate in the selection for spectrum access, and it gives a larger multi-user diversity gain for the secondary system. And finally, \( P_{out}^{s} \) decreases with decreasing \( I_{st} \).

The analytical results of the outage probability for the primary system with different values of N are shown in Fig.5. It can be observed that primary outage probability decreases with increasing N, representing that increased multi-user diversity gain.

Comparing Fig.4 and Fig.5, we note that both the primary and secondary systems are able to benefit from an increasing number of secondary transmitters N.
In this paper, we propose a two-phase spectrum sharing protocol which supports relaying functionality, it take the advantage of situation when primary system is fails to achieve its target rate due to weak channel situations the secondary system allocates some of its transmitters for helping the primary system to achieve its target rate by acting as decode–and-forward relay. As a reward the secondary system gains spectrum access by using remaining transmitters to transmit its own signal. Analytic and simulation results confirm the efficiency of the proposed spectrum sharing protocol. We show that the both primary and secondary are able to achieve better outage performance with increasing the secondary transmitters. And also it is shown that primary user’s interference probability is always equal to 0.75 when CSI of interference links is imperfect. Thus, in order to guarantee the PU’s interference probability below an acceptable value, we adopt the back-off power control mechanism and derive the exact outage probability of partial AF relay selection in underlay cognitive relay networks.

REFERENCES