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This is the accepted version of a paper presented at *2013 IEEE 77th Vehicular Technology Conference, VTC Spring 2013; Dresden; Germany; 2 June 2013 through 5 June 2013*.

Citation for the original published paper:

Shalmashi, S., Slimane, B. (2013)

On Secondary User Transmission Schemes in Relay-Assisted Cognitive Radio Networks.

In: *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)* (pp. 6692665-). IEEE

IEEE Vehicular Technology Conference Proceedings

<http://dx.doi.org/10.1109/VTCSpring.2013.6692665>

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-116589>

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IEEE Vehicular Technology Conference (VTC Spring), Dresden, Germany, June 2013

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On Secondary User Transmission Schemes in Relay-Assisted Cognitive Radio Networks

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Abstract—We consider a cooperative cognitive radio network with one primary user and many secondary users. In each transmission frame, one secondary user is selected to act as a relay for the primary user and also transmits its own data. Three different schemes for the secondary user's transmission is studied, namely, *time-splitting*, *superposition coding*, and a *combined* scheme that takes advantages of both time-splitting and superposition coding schemes. We formulate the relay selection problem for each scheme with the objective of maximizing the secondary user's data rate while satisfying a pre-defined gain threshold for the primary user. This constraint provides an incentive for the primary user when allowing the secondary user access its licensed band. We obtain the optimal solution for this problem in each scheme, on which the relay selection is based on. Finally, we compare the performance of different schemes using Monte-Carlo simulations.

I. INTRODUCTION AND RELATED WORK

Cognitive radio increases the flexibility in spectrum usage by allowing unlicensed (secondary) users to access the spectrum of licensed (primary) users [1]. We address the *overlay* cognitive radio network where secondary users (SUs) overhear the primary user (PU) and facilitate its transmission by cooperation [2]. In this context, cooperation refers to the cooperative communication that exploits path diversity in order to achieve higher data rate and communication reliability [3]. As the cooperative strategy, *decode-and-forward* relaying is considered in the half-duplex mode. That is, when a cooperation is formed, the primary transmitter (PT) broadcasts its message in the first transmission phase, and the secondary transmitter (ST) relays the primary's message and also transmits its own message in the second phase. We study three schemes for the SU's transmission, namely, *time-splitting*, *superposition coding*, and a *combined* scheme that takes advantages of both time-splitting and superposition coding schemes.

Cooperative spectrum sharing with time-splitting was modeled in [4] as a hierarchical game. In this model, the PU selects an ad-hoc group of SUs as well as the transmission length with the objective of maximizing its rate. SUs in the selected group divide their transmission time into two parts, one for relaying the PU's message, and the other for communicating with their corresponding receivers in the interference channel which is formed among them. In order to obtain the optimal solution, an exhaustive search over different number of ad-hoc users is needed. Thus, a sub-optimal solution is presented in [4]. This work was extended by [5] and [6] with different objectives for both primary and secondary networks.

Authors in [7] and [8] considered cooperative spectrum sharing with superposition coding. They studied a scenario with one PU and one SU. However, the ST uses superposition coding and allocates some of its power to transmit the primary's message and uses the rest for its own message. In [7], the authors define the primary network's priority in terms of outage probability. They show that if the ST is located in a certain distance from the PT, there always exists a fraction of the power that the ST is able to allocate for the PT's message and achieve a lower outage probability compared to the direct link transmission without cooperation. This problem was extended in [9] to include many SUs with the goal of selecting one ST, which minimizes the primary's outage probability, as the relay. However, [9] does not take into account the secondary's outage probability. In [8], the time slot duration and the fraction of the power that the ST allocates for primary's data transmission is optimized with the objective of maximizing the SU's rate. However, in the optimal solution of the formulated problem in [8], the PU only achieves the direct link rate which is the rate that it can obtain without any cooperation, and therefore, there would be no benefit in cooperation for the PU.

In this paper, a cooperative cognitive radio network with one PU and many SUs is considered. The PU can allow one SU to use its spectrum and act as a relay for the PT. The relay selection problem is formulated for different transmission schemes. The objective is to maximize the SU's data rate while satisfying a pre-defined gain threshold for the PU. The gain requirement provides the PU with an incentive to allow the SU access its licensed band. We obtain the optimal solution for this problem in each scheme.

II. SYSTEM MODEL

A cognitive radio network is considered with a single PT-PR pair, and multiple secondary transmitters ST_i and receivers SR_i , $i \in \mathcal{M} \triangleq \{1, \dots, M\}$. Since the PU is the owner of the spectrum, the SUs are willing to cooperate with the PU in order to access its spectrum. In case of cooperation between a secondary and the primary user, the ST_i should act as a relay to help the PU's transmission, while transmitting its own data. We assume that, in each transmission frame, at most one SU is allowed to transmit and cooperate with the PU.

The medium access is based on the time division multiple access (TDMA) scheme, where the PU accesses the channel in an assigned transmission frame with length T . When the

PU is willing to cooperate with one of the secondary users, ST_i , the transmission frame is divided into two time slots with durations $\delta_i T$ and $(1 - \delta_i)T$, with $0 \leq \delta_i \leq 1$, as depicted in Fig. 1. The first time slot is dedicated to the PU's transmission and the second one to the SU's. Throughout the rest of the paper, we assume a unit-time frame length, i.e., $T = 1$.

The channel model consists of path-loss and Rayleigh block fading components, in which the channel is constant during one frame, but varies over different frames. Furthermore, the channel is assumed to be known at both primary and secondary transmitters. Note that transmitted signals are assumed to be zero-mean and uncorrelated with normalized power, i.e., $E[x_{s,i}] = E[x_p] = 0$ and $E[|x_{s,i}|^2] = E[|x_p|^2] = 1$.

Fig. 1. Transmission frame structure.

III. SECONDARY TRANSMISSION SCHEMES

We consider three schemes for the secondary user's transmission, namely, *time-splitting*, *superposition coding*, and a *combined* scheme. In the following, we discuss each of these schemes in detail, and formulate the corresponding problem.

A. Time-splitting scheme

If a cooperation is formed between the PT and the ST_i , $i \in \mathcal{M}$, (i.e., $\delta_i \neq 1$), the PT broadcasts in the first time slot of length δ_i . In the time-splitting scheme, the cooperative ST_i who acts as a relay for the PT, divides its assigned transmission time slot of length $(1 - \delta_i)$ into two different sub-time slots, as shown in Fig. 2. It transmits the PU's data in the first sub-time slot with length $(1 - \delta_i)(1 - \beta_i)$, where $0 \leq \beta_i \leq 1$, and uses the second sub-time slot with duration $(1 - \delta_i)\beta_i$ for communicating to the SR_i . Note that the ST_i uses its total power for transmissions in both sub-time slots.

Let R_{dir} denote the achievable rate, with normalized bandwidth, for the PU when it transmits during the whole frame duration with no cooperation (i.e., $\delta_i = 1$, for all $i \in \mathcal{M}$). We have

$$R_{\text{dir}} = \log_2(1 + \Gamma_{\text{dir}}),$$

where $\Gamma_{\text{dir}} \triangleq \Gamma_{pt,pr}$, and $\Gamma_{k,j}$ is the received signal-to-noise ratio (SNR) from transmitter k to receiver j where $k, j \in \{pt, pr, st_i, sr_i\}$.

Moreover, the end-to-end achievable rate for the PU $R_{p,i}$, when it cooperates with the ST_i ($\delta_i \neq 1$), is limited by the minimum rate in the two transmission phases [3], i.e.,

$$R_{p,i} = \min\{R_{p,i}^{(1)}, R_{p,i}^{(2)}\}, \quad i \in \mathcal{M}, \quad (1)$$

where $R_{p,i}^{(1)}$ is the rate between the PT and the ST_i in the first time slot, and $R_{p,i}^{(2)}$ is the rate at which the ST_i relays the PU's message to the PR in the first sub-time slot of the second transmission phase. These rates are given by

$$R_{p,i}^{(1)} = \delta_i \log_2(1 + \Gamma_{pt,st_i}), \quad (2)$$

$$R_{p,i}^{(2)} = (1 - \delta_i)(1 - \beta_i) \log_2(1 + \Gamma_{st_i,pr}). \quad (3)$$

Fig. 2. Frame structure in the time-splitting scheme.

The PU's gain that is achieved by cooperating with the ST_i is considered as the performance metric for the primary network. This gain is defined as

$$G_{p,i} = \frac{R_{p,i} - R_{\text{dir}}}{R_{\text{dir}}}. \quad (4)$$

The PU allows a secondary access to the spectrum if at least a pre-defined gain, G^{th} , is achieved through cooperation, i.e.,

$$G_{p,i} \geq G^{\text{th}}. \quad (5)$$

By substituting (4) in (5), we obtain the following constraint for any relay candidates among the SUs:

$$R_{p,i} \geq R_{\text{dir}}(1 + G^{\text{th}}). \quad (6)$$

In every frame, each SU tries to optimize the parameters δ_i and β_i to maximize its transmission rate while satisfying the PU's gain requirement. Let $R_{s,i}$ be the i th SU rate, i.e.,

$$R_{s,i} = (1 - \delta_i)\beta_i \log_2(1 + \Gamma_{st_i,sr_i}), \quad i \in \mathcal{M}. \quad (7)$$

Then, the optimization problem per frame for each SU is

$$\max_{\delta_i, \beta_i} R_{s,i} \quad (8)$$

$$\text{s.t. } R_{p,i} \geq R_{\text{dir}}(1 + G^{\text{th}}), \quad (9a)$$

$$0 \leq \delta_i \leq 1, \quad (9b)$$

$$0 \leq \beta_i \leq 1. \quad (9c)$$

Note that the objective function in (8) is a decreasing function in δ_i , but an increasing function in β_i . The SUs should find these parameters in such a way that the constraints in (9) are fulfilled.

We denote the set of the SUs which can satisfy the constraints in (9), and therefore, obtain a feasible solution for the problem in (8)–(9), by $\mathcal{M}_R \subset \mathcal{M}$. This set is the set of all relay candidates among which the one that achieves the maximum rate is selected to act as a relay for the PU and also transmit its own data. That is,

$$r = \arg \max_{i \in \mathcal{M}_R} R_{s,i}, \quad (10)$$

where r is the index of the SU that is chosen as the relay.

Now, to solve the optimization problem (8)–(9), we note from (1)–(3) that for a given δ_i , only the second term in $R_{p,i}$, i.e., $R_{p,i}^{(2)}$, is dependent on the parameter β_i . In fact, $R_{p,i}^{(2)}$ is a decreasing function in β_i . Since $R_{p,i}$ is the minimum of the two rates, for a given δ_i , the maximum $R_{p,i}$ that can be achieved is when the two rates in (1) are equal [4], [8], i.e.,

$$R_{p,i}^{(1)} = R_{p,i}^{(2)}. \quad (11)$$

Solving (11) for a given δ_i ($\delta_i \neq 1$), we obtain the optimal β_i

as

$$\beta_i(\delta_i) = 1 - \frac{\delta_i \log_2(1 + \Gamma_{pt,st_i})}{(1 - \delta_i) \log_2(1 + \Gamma_{st_i,pr})}. \quad (12)$$

Substituting (12) in the constraint (9c), we obtain

$$\delta_i \leq \frac{\log_2(1 + \Gamma_{st_i,pr})}{\log_2(1 + \Gamma_{st_i,pr}) + \log_2(1 + \Gamma_{pt,st_i})} \triangleq \delta_i^{ub}, \quad (13)$$

where δ_i^{ub} is the upper bound for the δ_i which satisfies the constraint (9b) as well. Using (1), (11), and the rate constraint in (9a), we have

$$R_{p,i}^{(1)} \geq R_{dir}(1 + G^{th}). \quad (14)$$

Substituting (2) in (14), we obtain a lower bound on δ_i as

$$\delta_i \geq \frac{R_{dir}(1 + G^{th})}{\log_2(1 + \Gamma_{pt,st_i})} \triangleq \delta_i^{lb}. \quad (15)$$

If $\delta_i^{ub} \geq \delta_i^{lb}$ for the i th SU, the optimization problem (8)–(9) admits a feasible solution for this user, and it would be included in the set $\mathcal{M}_R$ of the relay candidates. The objective in (8) is a decreasing function in δ_i and an increasing function in β_i . From (12), β_i , itself, is a decreasing function in δ_i . Hence, the objective, for all $i \in \mathcal{M}_R$, is maximized by setting

$$\delta_i^{opt} = \delta_i^{lb}, \quad \text{and} \quad \beta_i^{opt} = \beta_i(\delta_i^{lb}). \quad (16)$$

Substituting the optimum values (16) in (7) results in the maximum achievable rate for each relay candidate while satisfying the gain requirement of the PU. Note that the optimal solution satisfies the constraint (9a) with equality. Finally, among the relay candidates, the one with the highest rate is allowed to access the spectrum.

B. Superposition coding scheme

In the superposition coding scheme, transmission in the first time slot is similar to the previous scheme discussed in Sec. III-A. However, in the second time slot, in case of cooperation (i.e., $\delta_i \neq 1$), instead of splitting the time slot, the ST_i allocates the fraction ν_i of its total transmit power to the PU's message and the fraction $1 - \nu_i$ to its own message, and uses the whole duration of the second time slot to transmit a linear combination of the two messages. We assume that the SRs have the capability to cancel the interference caused by the PU, if they can decode the received primary message.

In this scheme, based on the achievable rates derived in [10, Sec. III], the optimization problem per frame for each SU is

$$\max_{\delta_i, \nu_i} R_{s,i}^{sc} \quad (17)$$

$$\text{s.t. } R_{p,i} \geq R_{dir}(1 + G^{th}), \quad (18a)$$

$$0 \leq \delta_i \leq 1, \quad (18b)$$

$$0 \leq \nu_i \leq 1. \quad (18c)$$

The optimization problem (17)–(18) is a slightly modified version of the problem studied in [8]. Solving (11) for a given δ_i ($\delta_i \neq 1$), we have

$$\nu_i(\delta_i) = \frac{(\gamma(\delta_i) - 1)(1 + \Gamma_{st_i,pr})}{\gamma(\delta_i)\Gamma_{st_i,pr}}, \quad (19)$$

Fig. 3. Avg. SU's rate vs. $\bar{\Gamma}_{dir}$, with $G^{th} = 40\%$ and $M = 15$.

where $\gamma(\delta_i) = (1 + \Gamma_{pt,st_i})^{\frac{\delta_i}{1-\delta_i}}$. The optimal values of ν_i and δ_i for this problem can be obtained using a similar approach as in Sec. III-A and considering the fact that the objective in (17) is a decreasing function of ν_i and δ_i . Therefore, the objective is maximized, for all $i \in \mathcal{M}_R^{sc}$, by setting [8]

$$\delta_i^{opt} = \delta_i^{lb}, \quad \text{and} \quad \nu_i^{opt} = \nu_i(\delta_i^{lb}). \quad (20)$$

C. Combined scheme

Finally, in the last scheme, which we refer to as the combined scheme, it is assumed that the SU has the possibility to adapt either the time-splitting scheme or the superposition coding scheme, and therefore, the scheme that can achieve a higher rate for the SU is the one which would be employed.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the three schemes described in Sec. III by means of Monte-Carlo simulations. We assume a circular cell with radius $R = 200$ m. The PT is located in the center of the cell and the PR at the cell edge. In each realization, M secondary transmitters are generated randomly with uniform distribution over the cell area with radius $0.1R \leq d_{pt,st_i} \leq 0.5R$ from the PT. The lower bound on the distance of the STs are enforced so that the path-loss model is valid. SRs are generated uniformly over the area with radius $0.1R \leq d_{st_i, sr_i} \leq 0.5R$ from their corresponding transmitters. The path-loss exponent is considered to be $\alpha = 4$, and the fading component of the channel is generated randomly in each realization. We assume the total transmit power of each transmitter is 1 W, and $\sigma^2 = 10^{-9}$ W. The number of Monte-Carlo simulation runs is set to 10000. The results are shown for $G^{th} = 40\%$ and $M = 15$ unless stated otherwise.

Fig. 3 shows the average data rate of the SU as a function of PU's direct link average SNR ($\bar{\Gamma}_{dir}$). Note that the average is taken over all Monte-Carlo runs which include the instances that none of the STs are selected as a relay, since they cannot meet the gain constraint of the PU, and thus, $R_{s,i} = 0$. As expected, when $\bar{\Gamma}_{dir}$ is high, the opportunities of relaying decreases and therefore, the secondary's average rate has a decreasing behavior. Consequently, the cooperation is more beneficial when the direct link is weak. This result is also inline with the findings in [10], [11].

Fig. 4. Avg. SU's rate vs. different nr. of available SUs, with $G^{\text{th}} = 40\%$, and $\bar{\Gamma}_{\text{dir}} = 2$ dB.

Fig. 5. CDF of SU's rate for $M = 15, 50$, with $G^{\text{th}} = 40\%$ and $\bar{\Gamma}_{\text{dir}} = 2$ dB.

We fix $\bar{\Gamma}_{\text{dir}} = 2$ dB in the remaining part of this section. Now, for a specific gain requirement of the PU, we vary the number of SUs that are available in the cell area (M). We can see in Fig. 4 that the average SU's rate increases in general as the number of SUs in the cell increases. However, it can be observed that, when M is large, the average SU rate achieved in the superposition coding scheme approaches the average rate in the time-splitting scheme. From [10, Eq. (9)], it is obvious that the superposition coding scheme results in a higher SU rate when it is possible for the SR to cancel the interference. Therefore, the ST can assign a higher power to its own message, i.e., a smaller ν_i . With higher number of SUs in the cell, there is a higher probability that the PU can find a helpful relay which can meet the gain requirement and also cancel the interference and require a smaller ν_i . This effect is also shown in Fig. 5 which depicts the CDF of the SU's rate for $M = 15$ and $M = 50$. It can be seen that when the number of SUs is $M = 50$, the gap between the time-splitting and the superposition coding schemes is smaller compared to the case where $M = 15$.

Fig. 6 depicts the average SU's rate for the different schemes versus different values of PU's gain requirement. It can be observed that the average SU rate is a decreasing function of the PU's gain requirement, which is due to the fact that there exists less opportunities for relaying when the gain requirement is high. Furthermore, in the combined scheme, where the SU has the opportunity to choose its transmission scheme, it achieves higher rates.

Now, we study the combined scheme in more details in Fig. 7. The figure shows the preference percentage, for different available schemes, in the combined approach. That is, the percentage of the Monte-Carlo realizations where no relaying is used (i.e., no cooperation is formed), or the relay employs the time-splitting, or the superposition coding scheme. This usage percentages is depicted for three values of the PU's gain requirements. We can observe that when the value of G^{th} is increased, the number of realizations in which the PU uses the direct link transmission is also increased, i.e., no cooperations are formed. Moreover, the figure shows that in the combined scheme, in most instances, the relay chooses the time-splitting approach as its transmission scheme.

So far, we have discussed the results related to the average SU's rate using different transmission schemes. However, it is valuable to investigate how much each scheme costs in terms of energy consumption for relaying the PU's message. Let E^{sc} , E^{ts} , and E^{comb} be the energy that the selected secondary transmitter ST_r spends to relay the PT's message. We have

$$E^{\text{ts}} = (1 - \delta_r^{\text{opt}})(1 - \beta_r^{\text{opt}})P_{st_r}, \quad (21)$$

$$E^{\text{sc}} = (1 - \delta_r^{\text{opt}})\nu_r^{\text{opt}}P_{st_r}. \quad (22)$$

For calculation of E^{comb} , in each instance that the time-splitting is used the energy cost is calculated from (21), and if the superposition coding scheme is employed, (22) is used. Note that in cases of the direct link transmission (i.e., no relaying), the energy cost is zero. These cases are excluded from averaging. Fig. 8 shows the average energy cost for the three schemes versus PU's gain requirement. It is observed that the cost of relaying is slowly increased when the primary's gain is increased. We note that the optimum value of the time slot parameter, i.e., δ_r^{opt} , is equal to the value of the lower bound in all the schemes (cf. (16) and (20)). In addition, the value of the lower bound in (15) is proportional to the gain of the PU. Consequently, by increasing the PU's gain requirement, every SU that meets the conditions of the transmission, needs to assign a longer time slot duration to the PU (i.e., a larger δ_r^{opt}). At the same time, if the SU is using the superposition coding scheme, it should increase the value of ν_r^{opt} in order to reach the required G^{th} , and if it is using the time-splitting scheme, it should decrease the value of the β_r^{opt} . However, it is observed that the superposition coding scheme consumes more energy on average compared to the other schemes. Looking at (21)–(22), we see that the only terms that define the relation between the average energy costs of the two schemes are the values of the parameters ν_r^{opt} and $1 - \beta_r^{\text{opt}}$.

In Fig. 9, the CDF of the optimal parameters ν_r^{opt} and $1 - \beta_r^{\text{opt}}$ of the selected relay is shown for $G^{\text{th}} = 40\%$ and $G^{\text{th}} = 90\%$. It can be observed that the values of the assigned power for relaying in the superposition coding scheme is always higher than the values of the allocated time for relaying in the time-splitting scheme. Therefore, on average, the superposition coding scheme leads to a higher energy cost than the time-splitting scheme, as can be seen in Fig. 8. The combined

Fig. 6. Avg. SU's rate vs. G^{th} , with $M = 15$ and $\bar{\Gamma}_{\text{dir}} = 2$ dB.

Fig. 7. Usage per scheme for a SU when the combined scheme is used, with $M = 15$ and $\bar{\Gamma}_{\text{dir}} = 2$ dB.

scheme, which takes advantage of the other two schemes, leads to energy costs less than the superposition coding scheme and higher than the time-splitting scheme.

V. CONCLUSIONS

In this paper, different transmission schemes for the secondary users, in a cooperative cognitive radio network, are studied. The goal is to select a secondary user to act as a relay and satisfy a pre-determined gain requirement for the primary user. For each scheme, the optimization problem, with the objective of maximizing the secondary user rate while meeting the primary user gain constraint, is formulated. The corresponding optimal solutions are obtained.

Performance of the three schemes are evaluated by means of Monte-Carlo simulations. It is observed that, in terms of secondary user's rate, the combined scheme results in a better performance than the time-splitting scheme which, in turn, provides higher rates than the superposition coding scheme. In terms of relaying energy cost, the time-splitting scheme leads to the lowest, and the superposition coding scheme to the highest cost. The results also show that the cooperation is beneficial when the primary's direct link is weak and there exists enough secondary users to select from.

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Fig. 8. Avg. relaying energy cost vs. G^{th} , with $M = 15$, and $\bar{\Gamma}_{\text{dir}} = 2$ dB.

Fig. 9. CDF of ν_r^{opt} and $1 - \beta_r^{\text{opt}}$, for the time-splitting and superposition coding schemes, with $M = 15$, and $\bar{\Gamma}_{\text{dir}} = 2$ dB.

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