

Buffer-Aided Relay Selection with Interference Cancellation and Secondary Power Minimization for Cognitive Radio Networks

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Abstract—In this paper, we consider a cooperative underlay cognitive radio network with K half-duplex decode-and-forward relays that are used by the source-destination pairs of both the primary network (PN) and secondary network (SN). The SN exploits buffers with size of L data elements at relays to store the incoming secondary information and retransmit it later. We propose a novel buffer-aided relay selection scheme with successive interference cancellation and optimal SN power allocation that allows to mitigate the mutual interference between PN and SN. Using extensive simulations, we investigate performance of the proposed scheme in terms of the secondary throughput and power expenditure. Our results show that the proposed policy manages the interference between PN and SN efficiently, minimizes secondary power consumption and achieves higher secondary throughput compared to the recently proposed policy.

Index Terms—Cognitive radio network, buffer-aided relaying, relay selection, interference cancellation, power allocation.

I. INTRODUCTION

Cooperative communication is seen a promising way to extend the coverage of wireless systems and reduce the effects of fading and shadowing while achieving a higher transmission reliability. The basic idea of cooperative communications is to rely on helper, relay node that assist a source node in its data transmission [1]. Reaping the benefits of cooperative communications requires overcoming major technical challenges. In particular, there is a need to develop suitable approaches for relay selection [2].

In [3], max-min relay selection policy is proposed in which the relay with the strongest end-to-end path between the source and the destination is selected for data transmission. More recently, the use of buffering at the relay has attracted attention as a means to further improve the network performance [4]. An interesting relay selection is proposed in [5], in which buffers are used at the relays to enable selection of the relay with best source-relay (S-R) link for data reception and the relay with best relay-destination (R-D) link for data transmission.

In parallel to the development of cooperative communications, cognitive radio has emerged as a promising technique for optimizing spectral efficiency. In a cognitive radio network, licensed, primary users (PU) can share their spectrum band with unlicensed, secondary users (SU). This spectrum sharing between PU and SU is allowed as long as the interference induced to PU is maintained below a certain threshold [6].

Recently, it has been shown that, by using cooperative techniques in a cognitive radio network, the performance of both the primary network (PN) and secondary network (SN) can be improved. In [7], secondary throughput is improved by using relay selection without buffer in the SN.

The main contribution of this paper is to develop a novel buffer-aided relay selection algorithm with successive interference cancellation (SIC) and power allocation (PA) at the SN. In particular, by using SIC, both PU and SU can transmit concurrently while maintaining a tolerable mutual interference level. In the proposed approach, both PN and SN use the same set of half-duplex relays. Each relay has a buffer with size of L data elements for storing the secondary data. Relays with full and empty secondary buffer are candidate only for data transmission and data reception, respectively. At each time slot, the SN selects one of the idle relays with the minimum transmit power either for data transmission or reception provided that both the primary and secondary data transmissions are error free. In particular, in the proposed algorithm, the interference between PN and SN is canceled and the secondary power expenditure is minimized. Simulation results assess the performance of our proposed schemes in terms of secondary throughput and power consumption. Our results show that the proposed policy minimizes secondary power expenditure and achieves higher secondary throughput compared to the recently proposed relay selection policy for cognitive radio in [7].

II. SYSTEM MODEL

Consider a cooperative cognitive radio network with one pair of primary nodes, one pair of secondary nodes and a cluster \mathcal{C} of K decode-and-forward half-duplex relays, i.e., $R_k \in \mathcal{C}$, ($1 \leq k \leq K$). In both PN and SN, no direct link exists between the source and the destination and communication can be established only via intermediary relays. Thus, we ignore the interference from the primary source to the secondary destination and also from the secondary source to the primary destination. Here, we adopt a cognitive underlay network model in which PU and SU transmit simultaneously as long as SU maintains its interference to the PU below a certain threshold.

Each relay R_k , holds a data buffer Q_k having a *maximum size of L* data elements for storing the secondary data. The communication of the PU is based on an arbitrary relay selection policy. Based on the kind of relay selection scheme used by PN, the relays might have or might not have buffers for the primary system. Time is considered to be slotted. All

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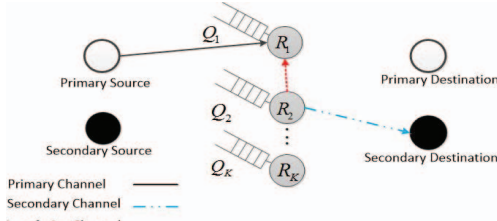


Fig. 1. The system model, in which primary source and SU at R_2 are selected for data transmission simultaneously.

wireless links in the cognitive radio network undergo zero mean Additive White Gaussian Noise (AWGN) and Rayleigh block fading. Thus, the fading coefficients are constant during one time slot and vary independently from one time slot to another. The squared channel gain between the nodes i and j is denoted by g_{ij} and is exponentially distributed. The primary source (S_{pn}), the relay R_k and the secondary source (S_{sn}) transmit with powers P_{pn} , P_{R_k} and P_{sn} , respectively. Due to energy limitation, each transmitting node j in the network has a maximum power P_j^{max} . The noise variance at the receiver j is denoted by ν_j . In the proposed policy, to achieve the required quality-of-service (QoS) at the PN and SN, the received SNR (or SINR) should be greater or equal to a threshold λ_{pn} and λ_{sn} , respectively. These thresholds depend on the channel characteristics in the network.

Fig. 1 illustrates the proposed system model. In this figure, at one arbitrary time slot the primary source and the relay R_1 are selected for primary data transmission. Simultaneously, relay R_2 is selected to transmit secondary data from its secondary buffer to the secondary destination. Thus, there are two incoming signals at R_1 , i.e., inter-relay interference occurs. Given such a model, our goal is to propose a novel buffer-aided relay selection scheme with SIC and secondary PA under a global Channel State Information (CSI) assumption.

III. PROPOSED POLICY

In this section, we propose a novel buffer-aided relay selection scheme with SIC and PA in SN. Without loss of generality, we assume that the PN uses an arbitrary relay selection policy. In PN and SN, data can be transmitted either through S-R links or through R-D links. Thus, in what follows, we investigate all the four possible cases for transmission data in PN and SN. Through the remaining parts of the paper, we assume that the PN and SN use relays R_j and R_k , ($R_k \neq R_j$), respectively.

A. PN uses S-R Link and SN exploits R-D Link

Consider that, at the i -th time slot, in the PN, the relay R_j is selected to receive a data packet from the primary source. Furthermore, in the SN, the relay R_k , ($R_k \neq R_j$) is selected to transmit data to the secondary destination (D_{sn}). Thus, SN causes inter-relay interference at the relay R_j during the primary data transmission. The secondary data is successfully transmitted if the received SNR is greater than or equal to a threshold λ_{sn} , i.e.,

$$\frac{g_{R_k D_{sn}} P_{R_k}}{\nu_{D_{sn}}} \geq \lambda_{sn}. \quad (1)$$

On the other hand, the primary data is successfully received at the relay R_j , if the received SINR is greater than or equal to the threshold λ_{pn} , i.e.,

$$\frac{g_{S_{pn} R_j} P_{S_{pn}}}{g_{R_k R_j} P_{R_k} \Psi(R_k, R_j) + \nu_{R_j}} \geq \lambda_{pn}, \quad (2)$$

in which Ψ is an indicator that denotes whether the inter-relay successive interference cancellation (IRSIC) is feasible or not. This indicator is given by

$$\Psi(R_k, R_j) = \begin{cases} 0 & \text{if } \frac{g_{R_k R_j} P_{R_k}}{g_{S_{pn} R_j} P_{S_{pn}} + \nu_{R_j}} \geq \lambda_{sn}, \\ 1 & \text{otherwise.} \end{cases} \quad (3)$$

In the following two propositions, we find the minimum transmit power of the relay R_k in the SN for two cases of feasible and infeasible IRSIC, provided that the primary and secondary data transmissions are error free.

Proposition 1. For each pair of relays R_j and R_k , in order to have feasible IRSIC ($\Psi(R_k, R_j) = 0$) and $SNR_{R_k D_{sn}} \geq \lambda_{sn}$, the minimum transmit power of the relay R_k in SN can be given by

$$P_{R_k}^{\min} = \max \left(\frac{\lambda_{sn} (g_{S_{pn} R_j} P_{S_{pn}} + \nu_{R_j})}{g_{R_k R_j}}, \frac{\lambda_{sn} \nu_{D_{sn}}}{g_{R_k D_{sn}}} \right). \quad (4)$$

Proof: In order to have the SIC feasibility, the function Ψ defined in (3), should be zero. Thus, we have

$$P_{R_k} \geq \frac{\lambda_{sn} (g_{S_{pn} R_j} P_{S_{pn}} + \nu_{R_j})}{g_{R_k R_j}}. \quad (5)$$

For the secondary data transmission to be decoded correctly, according to (1), we have

$$P_{R_k} \geq \frac{\lambda_{sn} \nu_{D_{sn}}}{g_{R_k D_{sn}}}. \quad (6)$$

Therefore, when (5) and (6) hold, the minimum transmit power of the relay R_k is given by (4). ■

Proposition 2. Assume that, due to the power limitation at the relay R_k , the SIC condition in (5) is not satisfied. For each pair of relays R_j and R_k , in order to have successful data transmission in both of PN and SN, if $\frac{\lambda_{sn} \nu_{D_{sn}}}{g_{R_k D_{sn}}} \leq \frac{g_{S_{pn} R_j} P_{S_{pn}} - \lambda_{pn} \nu_{R_j}}{\lambda_{pn} g_{R_k R_j}}$ holds, the minimum transmit power of the relay R_k is

$$\bar{P}_{R_k}^{\min} = \frac{\lambda_{sn} \nu_{D_{sn}}}{g_{R_k D_{sn}}}. \quad (7)$$

Proof: In order to have correct decoding for both PN and SN, (2) and (6) should be satisfied, respectively. Furthermore, Ψ in (2) must be equal to one. Hence, the condition of the correct data transmission in the PN is

$$P_{R_k} \leq \frac{g_{S_{pn} R_j} P_{S_{pn}} - \lambda_{pn} \nu_{R_j}}{\lambda_{pn} g_{R_k R_j}}. \quad (8)$$

Thus, if $\frac{\lambda_{sn} \nu_{D_{sn}}}{g_{R_k D_{sn}}} \leq \frac{g_{S_{pn} R_j} P_{S_{pn}} - \lambda_{pn} \nu_{R_j}}{\lambda_{pn} g_{R_k R_j}}$ holds, the minimum transmit power of the relay R_k in the case of IRSIC infeasibility is $\bar{P}_{R_k}^{\min} = \frac{\lambda_{sn} \nu_{D_{sn}}}{g_{R_k D_{sn}}}$. On the other hand, if we have

$\frac{\lambda_{sn}\nu_{D_{sn}}}{g_{R_k D_{sn}}} > \frac{g_{S_{pn} R_j} P_{S_{pn}} - \lambda_{pn}\nu_{R_j}}{\lambda_{pn} g_{R_k R_j}}$ and the IRSIC is not feasible, the relays should not transmit secondary data at the i -th time slot and have to be silent. ■

B. PN uses R-D Link and SN exploits S-R Link

In this subsection, the PN causes inter-relay interference at the relay R_k during the secondary data transmission. The primary data is successfully received at the primary destination (D_{pn}), if the received SNR is greater than or equal to the threshold λ_{pn} , i.e.,

$$\frac{g_{R_j D_{pn}} P_{R_j}}{\nu_{D_{pn}}} \geq \lambda_{pn}. \quad (9)$$

Also, the secondary data is transmitted correctly if the received SINR is greater than or equal to the threshold λ_{sn} , i.e.,

$$\frac{g_{S_{sn} R_k} P_{S_{sn}}}{g_{R_j R_k} P_{R_j} \Psi(R_j, R_k) + \nu_{R_k}} \geq \lambda_{sn}. \quad (10)$$

Ψ indicates whether IRSIC can take place or not. It is given by

$$\Psi(R_j, R_k) = \begin{cases} 0 & \text{if } \frac{g_{R_j R_k} P_{R_j}}{g_{S_{sn} R_k} P_{S_{sn}} + \nu_{R_k}} \geq \lambda_{pn}, \\ 1 & \text{otherwise.} \end{cases} \quad (11)$$

For feasible IRSIC, Ψ should be zero. Therefore, we have

$$P_{S_{sn}} \leq \frac{g_{R_j R_k} P_{R_j} - \lambda_{pn}\nu_{R_k}}{\lambda_{pn} g_{S_{sn} R_k}}. \quad (12)$$

In the following two propositions, we find the minimum transmit power of the secondary source for two cases of feasible and infeasible IRSIC, provided that the primary and secondary data transmissions are error free.

Proposition 3. For each pair of relays R_j and R_k , in order to satisfy the IRSIC condition and have successful data transmission in both of PN and SN, if $\frac{\lambda_{sn}\nu_{R_k}}{g_{S_{sn} R_k}} \leq \frac{g_{R_j R_k} P_{R_j} - \lambda_{pn}\nu_{R_k}}{\lambda_{pn} g_{S_{sn} R_k}}$ holds, minimum transmit power of the secondary source is

$$P_{S_{sn}}^{\min} = \frac{\lambda_{sn}\nu_{R_k}}{g_{S_{sn} R_k}}. \quad (13)$$

Proof: The proof is analogous to that of Proposition. 2. ■

Proposition 4. Assume that IRSIC is infeasible. For each pair of relays R_j and R_k , in order to have successful data transmission in both of PN and SN, the minimum transmit power of the secondary source is

$$\bar{P}_{S_{sn}}^{\min} = \frac{\lambda_{sn}(g_{R_j R_k} P_{R_j} + \nu_{R_k})}{g_{S_{sn} R_k}}. \quad (14)$$

Proof: For the correct transmission of the secondary data, (10) should be satisfied. Since the IRSIC cannot take place, Ψ in (10) must be one. Consequently, via algebraic manipulation the proposition can be proved. If the IRSIC is not feasible and $P_{S_{sn}}^{max} < \bar{P}_{S_{sn}}^{\min}$ holds, the secondary source cannot transmit at the i -th time slot and should be silent. ■

Unlike the previous two subsections, next, we consider two interfering signals simultaneously. In such cases, our aim is to cancel the interference from the SN to PN and to ensure that the SINR at the D_{sn} is equal or greater than λ_{sn} .

C. Both PN and SN use the S-R Link

In the following two propositions, we find the minimum transmit power of the secondary source for two cases of feasible and infeasible cancellation of secondary interference to PU, provided that the primary and secondary data transmissions are error free.

Proposition 5. For each pair of relays R_j and R_k , in order to have SIC feasibility ($\Psi(S_{sn}, R_j) = 0$) and $SINR_{S_{sn} R_k} \geq \lambda_{sn}$, the minimum transmit power of the secondary source is

$$P_{S_{sn}}^{\min} = \max\left(\frac{\lambda_{sn}(g_{S_{pn} R_j} P_{S_{pn}} + \nu_{R_j})}{g_{S_{sn} R_j}}, \frac{\lambda_{sn}(g_{S_{pn} R_k} P_{S_{pn}} + \nu_{R_k})}{g_{S_{sn} R_k}}\right). \quad (15)$$

Proof: The proof is analogous to that of Proposition. 1. However, here, for successfully received secondary data, the received SINR should be greater than or equal to λ_{sn} . ■

Proposition 6. Assume that, due to the power limitation at the secondary source, SIC is not feasible. For each pair of relays R_j and R_k , for having successful data transmission in both of PN and SN, if $\frac{\lambda_{sn}(g_{S_{pn} R_k} P_{S_{pn}} + \nu_{R_k})}{g_{S_{sn} R_k}} \leq \frac{g_{S_{pn} R_j} P_{S_{pn}} - \lambda_{pn}\nu_{R_j}}{\lambda_{pn} g_{S_{sn} R_j}}$ holds, the minimum transmit power of the secondary source is

$$\bar{P}_{S_{sn}}^{\min} = \frac{\lambda_{sn}(g_{S_{pn} R_k} P_{S_{pn}} + \nu_{R_k})}{g_{S_{sn} R_k}}. \quad (16)$$

Proof: This proof is in line with that of Proposition. 2. However, we must account for the fact that, for successfully received secondary data, the received SINR should be greater than or equal to λ_{sn} . ■

If we have SIC infeasibility and $\frac{\lambda_{sn}(g_{S_{pn} R_k} P_{S_{pn}} + \nu_{R_k})}{g_{S_{sn} R_k}} > \frac{g_{S_{pn} R_j} P_{S_{pn}} - \lambda_{pn}\nu_{R_j}}{\lambda_{pn} g_{S_{sn} R_j}}$, the secondary source should not transmit data at the i -th time slot and must remain silent.

D. Both PN and SN use the R-D Link

The case of using the R-D link by both of PN and SN is exactly similar to Subsection III-C.

Proposition 7. For each pair of relays R_j and R_k , in order to have $\Psi(R_k, D_{pn}) = 0$ and $SINR_{R_k D_{sn}} \geq \lambda_{sn}$, the minimum transmit power of the secondary source can be found as

$$P_{R_k}^{\min} = \max\left(\frac{\lambda_{sn}(g_{R_j D_{pn}} P_{R_j} + \nu_{D_{pn}})}{g_{R_k D_{pn}}}, \frac{\lambda_{sn}(g_{R_j D_{sn}} P_{R_j} + \nu_{D_{sn}})}{g_{R_k D_{sn}}}\right). \quad (17)$$

Proposition 8. Assume that because of the power limitation at the relay R_k , the SIC condition is not satisfied. For each pair of relays R_j and R_k , in order to have successful data transmission in both of PN and SN, if $\frac{\lambda_{sn}(g_{R_j D_{sn}} P_{R_j} + \nu_{D_{sn}})}{g_{R_k D_{sn}}} \leq \frac{g_{R_j D_{pn}} P_{R_j} - \lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn} g_{R_k D_{pn}}}$ holds, the minimum transmit power of the secondary source is

$$\bar{P}_{R_k}^{\min} = \frac{\lambda_{sn}(g_{R_j D_{sn}} P_{R_j} + \nu_{D_{sn}})}{g_{R_k D_{sn}}}. \quad (18)$$

TABLE I
BUFFER-AIDED RELAY SELECTION ALGORITHM

- i) For each of R_k - D_{sn} link, we check SIC feasibility.
- ii) If successive interference cancellation is feasible, then
 - ii-a) If SIC took place, $P_{R_k}^{\min}$ is given in (4), (17).
 - ii-b) If SIC did not take place, $\bar{P}_{R_k}^{\min}$ is given in (7), (18).
 - ii-c) At the i -th time slot, the minimum secondary transmit power of the relay R_k is $\min(P_{R_k}^{\min}, \bar{P}_{R_k}^{\min})$.
- iii) Assuming that SIC is not feasible, then only case (b) of step ii is used.
- iv) For each of S_{sn} - R_k link, we check SIC feasibility.
- v) If successive interference cancellation can take place, then
 - v-a) If SIC took place, $P_{S_{sn}}^{\min}$ is given in (15), (13).
 - v-b) If SIC did not take place, $\bar{P}_{S_{sn}}^{\min}$ is given in (16), (14).
 - v-c) At the i -th time slot, the minimum transmit power of the secondary source is $\min(P_{S_{sn}}^{\min}, \bar{P}_{S_{sn}}^{\min})$.
- vi) Assuming that SIC is not feasible, then only case (b) of step v is used.
- vii) We compare the minimum secondary transmit power of each relay R_k and the secondary source and choose the minimum of them.
- viii) If any relays can not be found to send or receive the secondary data, SN should be silent.

In our proposed policy, at each time slot, SN selects one of the idle relays with the minimum transmit power either for data transmission or reception provided that both the primary and secondary data transmissions are error free. The relays with full secondary buffer, can be selected only for data transmission and the relays with empty secondary buffer are candidate only for data reception. If PN transmits data between the primary source and the relay R_j , SN can use the scheme in Table I with equation number in *italic* to select from the remaining relays. Moreover, if the PN transmits data between the relay R_j and the primary destination, the SN adopts the procedure in Table I with equation number in **bold** to select from the remaining relays.

IV. SIMULATION RESULTS AND ANALYSIS

In this section, we investigate our proposed policy in terms of the secondary throughput and secondary power expenditure. We consider Rayleigh block fading with unit variance and primary transmit power of 8 dB. Fig. 2 shows the average secondary throughput, measured in bps/Hz. Transmission rate equals to 1 bps/Hz. Thus, the maximum average secondary throughput equals to 1 bps/Hz. As this figure shows, by increasing L , K and maximum secondary transmit power, the secondary throughput is enhanced. By increasing the number of relays and buffer size, the number of possible candidates for relay selection is increased, result in improvement of secondary throughput. Moreover, Fig. 2 compares the average secondary throughput of our proposed policy with relay selection scheme in [7]. It can be seen that proposed scheme achieves higher average secondary throughput compared with policy in [7]. The improvement reaches up to 25% and 45% for $K = 10$ and $K = 4$, respectively, relative to [7].

Fig. 3 depicts the secondary power reduction achieved by the proposed policy. We use the buffer-aided relay selection scheme without secondary PA in the selection process as a reference policy to calculate the power reduction. Fig. 3 shows that, as K increases, the reduction in secondary power increases, thus yielding additional power saving.

V. CONCLUSION

In this paper, we have proposed a novel buffer-aided relay selection policy with SIC and PA in SN. In this proposed

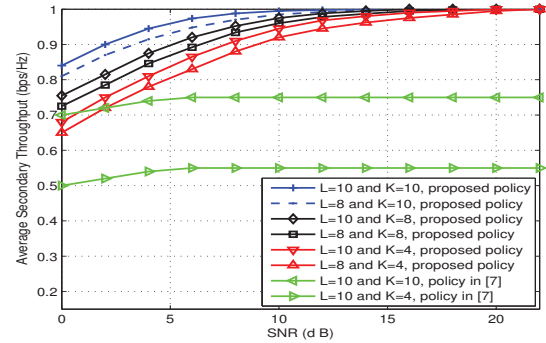


Fig. 2. Average secondary throughput versus maximum secondary transmit SNR for varying K and L , when $\lambda_{pn} = \lambda_{sn}$.

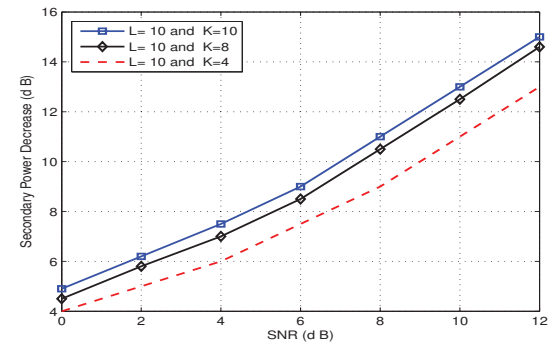


Fig. 3. Power reduction versus maximum secondary transmit SNR for varying K and $L = 10$, when $\lambda_{pn} = \lambda_{sn}$.

approach, if the PN selects a certain relay to transmit its information, the SN can select one of the remaining relays either for data transmission or reception. In this respect, we have shown that our proposed approach can mitigate the ensuing interference between PN and SN. In addition, we have investigated the performance of the proposed scheme in terms of the secondary throughput and the secondary power consumption via extensive simulations.

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