Buffer-Aided Relay Selection and Secondary Power Minimization for Two-Way Cognitive Radio Networks

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***Abstract*—In this paper, we consider a cooperative underlay cognitive radio network in which the primary network (PN) consists of a transmitter and receiver and the secondary network (SN) has K bidirectional half-duplex relays. In the SN, two secondary transceivers adopt multiple access broadcast protocol for the secondary data transmission and at each bidirectional relay, there exist two buffers of size L data elements. Hence, each relay can store the incoming secondary data and retransmit it in an appropriate time slot later. We propose a novel buffer-aided bidirectional relay selection policy with secondary power minimization and successive interference cancellation in which the interference between the PN and SN is eliminated. Since buffers are used at the relays, data transmission in the SN is not limited to a predefined schedule. Hence, at each time slot, based on the instantaneous buffer state information of the relays and the instantaneous or statistical channel state information of the involved links, the SN makes a decision. The SN decides optimally when to use one of the relays for the multiple access, use one of the relays for the broadcast mode or be silent provided that the data transmission in both the PN and SN are error free and the secondary power expenditure is minimized. Simulation results show that the proposed scheme minimizes the secondary power expenditure, and achieves up to 40% improvement in the secondary throughput for 6 middle relays compared to the other recently proposed policies without buffer.**

***Index Terms*—Buffer-aided two-way relay network, cognitive radio network, adaptive relay selection, successive interference cancellation, power minimization.**

I. Introduction

Relay-based cooperative communication is a promising strategy to provide broader network coverage, combat the undesirable shadowing and fading effects and achieve a higher transmission reliability. Bidirectional relaying policy has recently emerged as a new relaying technique in a two-way relay network [1]. In such a network, two transceivers exchange independent data through a shared bidirectional relay. In [1], several bidirectional relaying protocols have been proposed for two-way relay network with the half-duplex constraint. The traditional two-way relaying is the simplest bidirectional relaying protocol in which data is exchanged in four successive time slots: transceiver 1-to-relay, relay-to-transceiver 2, transceiver 2-to-relay, and relay-to-transceiver 1. The time division broadcast (TDBC) protocol merges the relay-to-transceiver 1 and relay-to-transceiver 2 phases into one phase, known as the broadcast (BC) phase [1]. In order to further improve the spectral efficiency, the transceiver 1-to-relay and transceiver 2-to-relay phases are merged into one phase, multiple access (MA) phase, in the multiple access broadcast (MABC) protocol [2]. In the MA phase, both the transceivers concurrently transmit to the bidirectional relay which can decode both data of the transceivers.

Recently, relay selection has gained more attention in the cooperative networks because of its implementation simplicity. In other words, the simple relay selection can achieve the similar performance to more complicated cooperative techniques (e.g., distributed space-time codes) [3]. The relay selection scheme for the decode-and-forward relays without buffers is studied in [3] and [4]. This approach is known as the max-min relay selection policy in which the relay with the strongest source to destination path is selected to participate in the data transmission. Subsequently, many relay selection schemes have been proposed for different relay-assisted networks (such as in [5], [6]). Recently, the usage of buffer at the relay level has emerged as a promising technique to improve the performance of a cooperative network. The authors in [7] introduced a buffer-aided relay selection scheme, called max-link relay selection. In their work, a more flexible selection among the existing relays is presented and data transmission schedule of the source and relay is not a priori fixed.

One promising application area for cooperative communications is that of cognitive radio networks. Cognitive radio has received significant attention recently as a means to overcome the scarcity of the radio spectrum resources. In a cognitive radio network, licensed users, known as primary users (PU) share the spectrum with unlicensed, secondary users (SU). In order to improve the performance of the primary network (PN) and secondary network (SN), cooperative communications can be used [8], [9]. In [10], the SN exploits a two-way relay selection scheme along with resource allocation and without buffer to increase the secondary throughput. However in the existing literature, the buffer-aided bidirectional relaying in the cognitive radio network is not investigated. By using buffer-aided bidirectional relay selection scheme, the spectral efficiency of the cognitive radio network can be further optimized.

The main contribution of this paper is to introduce a novel buffer-aided bidirectional relay selection policy along with the secondary power minimization and successive interference cancellation (SIC). That is, by using SIC, both of the PU and SU can use a same spectrum while retaining a tolerated interference between one another. Each relay has two data buffers of size L data elements for storing the data transmitted by two secondary transceivers. At a given time slot, based on the instantaneous buffer state information (BSI) of the relays and the instantaneous or statistical channel state information

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(CSI) of the secondary and interference links, the SN makes a decision. The SN decides optimally when to use one of the relays for the multiple access, use one of the relays for the broadcast mode or be silent under the constraints of an error free data transmission in both the PN and SN and minimum transmit power in the SN. In order to ensure a successful data transmission at both the PN and SN, the induced interference from the SN to the PN should be canceled and the received signal-to-interference-plus-noise (SINR) at the SN should be equal or larger than a desired threshold for the correct decoding. If the instantaneous CSI of the involved links is not available and/or there exists power limitation at the secondary transceivers, the induced interference to the PN cannot be canceled, and therefore, the received SINR at the PN should be equal or larger than a given threshold. Using extensive simulations, we evaluate the performance of our proposed schemes in terms of the secondary throughput, and the secondary power expenditure.

II. System Model

Consider a cooperative cognitive radio network in which the PN consists of a transmitter and receiver and the SN has two secondary transceivers and K bidirectional half-duplex relays. In the SN, no direct transmission link between the two transceivers exists, and data is exchanged between the two transceivers only through the bidirectional relays using the MABC protocol [4]. We consider a cognitive underlay network in which both the PU and SU transmit concurrently. The PU owns the licensed spectrum, but it allows the SU to use the licensed spectrum provided that the SN can limit its interference to the PN below a pre-specified limit. Our goal is to mitigate the interference between the SU and PU in the buffer-aided bidirectional relay selection scheme while minimizing the power consumption in the secondary network.

In the underlay cognitive radio network, because of the interference constraint, the SN is not always allowed to send information. Therefore, each bidirectional relays in the SN needs two buffers to prevent data loss of the secondary transceivers. In addition, by exploiting buffers at the relays, the secondary data transmission is not limited to a predefined schedule and at each time slot, all the available secondary links and relays can be selected to participate in the secondary data transmission. Hence, each relay R_k, has two data buffers Q_{2k-1} and Q_{2k} of size L data elements for storing the secondary data transmitted by two transceivers. We assume that the primary source and two secondary transceivers have a continuous stream of data to transmit. Time is considered to be slotted. All wireless links are impaired by zero mean additive white Gaussian noise (AWGN) and Rayleigh block fading, i.e., the channel gains are fixed during one time slot and change independently from one time slot to another. Let g_{ij} denotes the squared channel gain between two nodes i and j which is exponentially distributed. $P_{S_{pn}}$, P_{R_k} and $P_{T_{sn}}$ are the transmit power of the primary source (S_{pn}), the relay R_k, and the secondary transceivers (T_{sn1}, T_{sn2}), respectively. Because of energy limitations in the network, maximum transmit power of node j is denoted by P_j^{max}. In addition, ν_j is the noise variance at the receiver j.

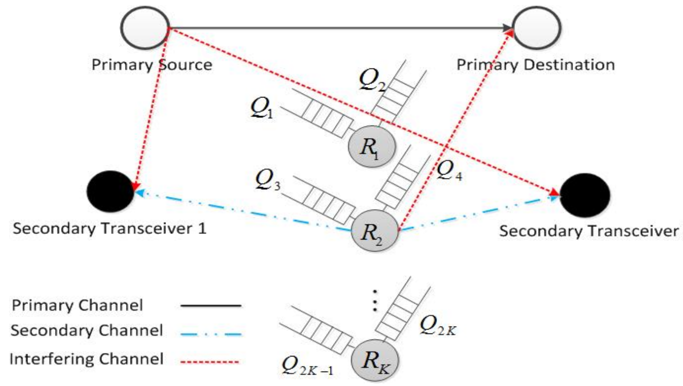

Fig. 1. The broadcast mode, in which the relay R_2 is selected to broadcast secondary data to two secondary transceivers.

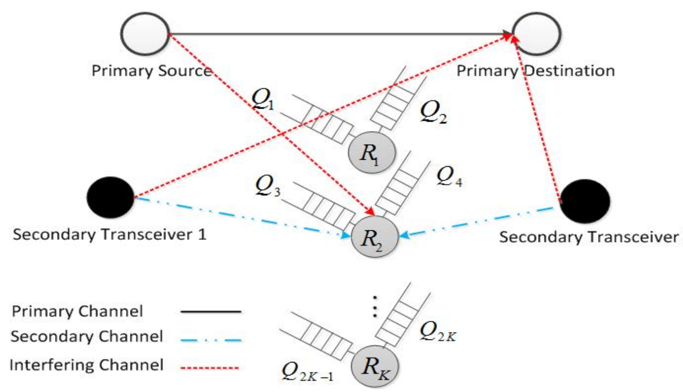

Fig. 2. The multiple access mode, in which the relay R_2 is selected to receive secondary data from two secondary transceivers.

At each time slot, based on the BSI of the relays and CSI of the secondary and interference links between the PN and SN, the SN makes decision either to transmit or be silent. If the SN decides to transmit, it selects one of the middle bidirectional relays either for the broadcast or multiple access mode. If a certain relay R_j is selected for the broadcast mode, it sends secondary data to both transceivers, and therefore, there exists one interference signal at the primary destination (D_{pn}) and one interference signal from primary source at each secondary transceiver. On the other hand, if the relay R_j is selected for the multiple access mode, it receives secondary data from both the transceivers, and thus, there exist two interference signals at the primary receiver and one interference signal at the selected relay from the PN. SIC can be used to mitigate the interference between the PN and SN while ensuring the quality-of-service (QoS) of the primary and secondary data transmission. To achieve the required QoS at the primary and secondary receivers, the received SINR should be greater or equal to a desired threshold λ_{pn} and λ_{sn}, respectively. These thresholds depend on the channel characteristics of the cognitive radio network.

Fig. 1 shows the proposed system model in which the SN selects one of the relays for the broadcast mode. In this figure, the PU and SU are shown in white and black, respectively. As this figure shows, at a given time slot the relay R_2 is selected to broadcast secondary data from its secondary buffers to both the secondary transceivers. The interference links between the PN and SN are shown in red. In addition, Fig. 2 illustrates the proposed system model in which the SN selects the relay R_2

for the multiple access mode.

In our proposed policy, there exists a central node with full CSI. The central node determines the status of the secondary relays whether to transmit data, receive packets or be silent during the data transmission period of the PN. All of the secondary relays can be candidate to act as a central node. The central node needs to have the BSI and the CSI of the involved secondary links, the primary links and the interference links between the PN and SN. The BSI can be easily known at the central node by counting the packets in the buffers of the secondary relays. The CSI of the secondary links can be easily achieved by sending the pilot signals by the secondary transceivers and estimating the received pilot signals at the central node. Thus, in our proposed policy, it is assumed that the CSI of the secondary links are available. Furthermore, in the LTE-Advanced cellular communication, for the cognitive radio application, the primary base station sends the pilot signals and the CSI of the primary link to the secondary users. Hence, the secondary users can estimate the CSI of the primary link and the interference links from the PN to the SN. However, in the proposed policy, two cases of having instantaneous CSI and statistical CSI of the primary link and the interference links between the PN and SN are investigated.

III. Proposed Policy

In this section, we propose a novel buffer-aided bidirectional relay selection scheme along with secondary power minimization and SIC in which the interference signals between the PN and SN are mitigated. In the SN, data can be transmitted either between the secondary transceivers and the relay cluster (multiple access mode) or between the relay cluster and the secondary transceivers (broadcast mode), respectively. In the proposed policy, at each time slot, the SN decides optimally whether to use broadcast mode, use multiple access mode or be silent. In the following subsections, we investigate all the two possible cases for the data transmission in the considered cognitive radio network.

A. Secondary Network Uses Multiple Access Mode

Suppose that, at the i-th time slot in the SN, a relay R_j is selected to receive the secondary data from both the secondary transceivers. Thus, both secondary transceivers will cause interference at the primary receiver during the primary data transmission. In addition, the primary source induces interference at the selected relay R_j in the secondary data transmission. Our aim is to cancel the interference from the SN to PN and to ensure that the SINR at the relay R_j is equal or greater than λ_{sn}. The primary data is successfully received at the primary destination if the received SINR is greater than or equal to the threshold λ_{pn}:

$$\frac{g_{S_{pn}D_{pn}}P_{S_{pn}}}{(I_1+I_2)\Psi(T_{sn},D_{pn})+\nu_{D_{pn}}} \geq \lambda_{pn}, \tag{1}$$

where I_1 and I_2 are the interference signals from the secondary transceiver 1 and 2 to the primary destination and are equal to $I_1 = g_{T_{sn1}D_{pn}}P_{T_{sn}}$ and $I_2 = g_{T_{sn2}D_{pn}}P_{T_{sn}}$, respectively. $\Psi(T_{sn}, D_{pn}))$ is a factor indicating whether the interference from secondary transceivers to the primary destination can be canceled via SIC approach or not. It is given by:

$$\Psi(T_{sn},D_{pn}) = \begin{cases} 0, & \text{if } \frac{I_1+I_2}{g_{S_{pn}D_{pn}}P_{S_{pn}}+\nu_{D_{pn}}} \geq \lambda_{sn}, \\ 1, & \text{otherwise.} \end{cases} \tag{2}$$

In addition, the relay R_j successfully receives the secondary data, if the received SINR is greater than or equal to the threshold λ_{sn}:

$$\frac{P_{T_{sn}}(g_{T_{sn1}R_j}+g_{T_{sn2}R_j})}{g_{S_{pn}R_j}P_{S_{pn}}+\nu_{R_j}} \geq \lambda_{sn}. \tag{3}$$

Because of the battery limitation at the secondary transceivers, they have a maximum transmit power denoted by $P_{T_{sn}}^{max}$. For SIC to be feasible at the primary destination, $\Psi(T_{sn}, D_{pn})$ in (2) should be zero. Hence, by some mathematical manipulation we get:

$$P_{T_{sn}}^{max} \geq \frac{\lambda_{sn}(g_{S_{pn}D_{pn}}P_{S_{pn}}+\nu_{D_{pn}})}{g_{T_{sn1}D_{pn}}+g_{T_{sn2}D_{pn}}}. \tag{4}$$

Therefore, SIC in Subsection III-A is feasible if and only if (4) is satisfied, and the instantaneous CSI of the primary link and the interference links between the PN and the SN is available. In the next proposition, the minimum transmit power of the secondary transceivers are derived under the conditions that the interference from the SN to the PN can be canceled via SIC approach and the secondary data transmission is error free.

Proposition 1. Under a global CSI assumption, for each relay R_j, in order to have $\Psi(T_{sn}, D_{pn}) = 0$ and $SINR_{T_{sn}R_j} \geq \lambda_{sn}$, the minimum transmit power of the secondary transceivers can be found as

$$P_{T_{sn}}^{\min} = \lambda_{sn} \max\left(\frac{(g_{S_{pn}D_{pn}}P_{S_{pn}}+\nu_{D_{pn}})}{g_{T_{sn1}D_{pn}}+g_{T_{sn2}D_{pn}}}, \frac{(g_{S_{pn}R_j}P_{S_{pn}}+\nu_{R_j})}{g_{T_{sn1}R_j}+g_{T_{sn2}R_j}}\right). \tag{5}$$

Proof. To have SIC feasibility, $\Psi(T_{sn}, D_{pn}) = 0$ should be satisfied. Therefore, we have

$$P_{T_{sn}} \geq \frac{\lambda_{sn}(g_{S_{pn}D_{pn}}P_{S_{pn}}+\nu_{D_{pn}})}{g_{T_{sn1}D_{pn}}+g_{T_{sn2}D_{pn}}}. \tag{6}$$

For data transmission between the secondary transceivers and the relay R_j to be received successfully, according to (3) we have

$$P_{T_{sn}} \geq \frac{\lambda_{sn}(g_{S_{pn}R_j}P_{S_{pn}}+\nu_{R_j})}{g_{T_{sn1}R_j}+g_{T_{sn2}R_j}}. \tag{7}$$

Hence, when (6) and (7) hold, the minimum transmit power of the secondary transceivers is given in (5). □

Due to the energy limitation at the secondary transceivers, SIC may be infeasible. In the next proposition, under a global CSI assumption, we find the minimum transmit power of the secondary transceivers provided that: a) The cancellation of the interference from the SN to the PN is infeasible due to energy limitation, and b) The primary and secondary data transmission are error free.

Proposition 2. Assume that global CSI is available, and due to the energy limitation at the secondary transceivers, the SIC condition in (4) is not satisfied and $\frac{\lambda_{sn}(g_{S_{pn}R_j}P_{S_{pn}}+\nu_{R_j})}{g_{T_{sn1}R_j}+g_{T_{sn2}R_j}} \leq$

$\frac{g_{S_{pn}D_{pn}}P_{S_{pn}}-\lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn}(g_{T_{sn1}R_j}+g_{T_{sn2}R_j})}$ holds. In order for each relay R_j to have a successful data transmission in both of the PN and SN, the minimum transmit power of the secondary transceivers is

$$\bar{P}_{T_{sn}}^{\min} = \frac{\lambda_{sn}(g_{S_{pn}R_j}P_{S_{pn}} + \nu_{R_j})}{g_{T_{sn1}R_j} + g_{T_{sn2}R_j}}. \tag{8}$$

Proof. For correct decoding at both the PN and SN, (1) and (3) should be fulfilled, respectively. In addition, $\Psi(T_{sn}, D_{pn})$ in (2) is equal to 1. By some mathematical manipulation we reach to the following equations:

$$P_{T_{sn}} \leq \frac{g_{S_{pn}D_{pn}}P_{S_{pn}} - \lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn}(g_{T_{sn1}R_j} + g_{T_{sn2}R_j})}, \tag{9}$$

$$P_{T_{sn}} \geq \frac{\lambda_{sn}(g_{S_{pn}R_j}P_{S_{pn}} + \nu_{R_j})}{g_{T_{sn1}R_j} + g_{T_{sn2}R_j}}. \tag{10}$$

Thus, if $\frac{\lambda_{sn}(g_{S_{pn}R_j}P_{S_{pn}}+\nu_{R_j})}{g_{T_{sn1}R_j}+g_{T_{sn2}R_j}} \leq \frac{g_{S_{pn}D_{pn}}P_{S_{pn}}-\lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn}(g_{T_{sn1}R_j}+g_{T_{sn2}R_j})}$ holds, the minimum transmit power of the secondary transceivers for SIC infeasibility is given in (8). In contrast, if we have SIC infeasibility and $\frac{\lambda_{sn}(g_{S_{pn}R_j}P_{S_{pn}}+\nu_{R_j})}{g_{T_{sn1}R_j}+g_{T_{sn2}R_j}} > \frac{g_{S_{pn}D_{pn}}P_{S_{pn}}-\lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn}(g_{T_{sn1}R_j}+g_{T_{sn2}R_j})}$, the secondary transceivers should not transmit data at the i-th time slot and have to remain silent. □

If the instantaneous CSI of the primary link and the interference links between the PN and the SN is not available, SIC cannot be applied and the secondary interference has to be treated as noise at the primary receiver. In the next proposition, we find the minimum transmit power of the secondary transceivers provided that: a) The instantaneous CSI of the primary link and the interference links between the PN and the SN is not known, and b) The primary and secondary data transmission are error free.

Proposition 3. Assume that only the statistical CSI of the primary link and the interference links between the PN and the SN is known, and $\frac{\lambda_{sn}(\Omega_{S_{pn}R_j}P_{S_{pn}}+\nu_{R_j})}{g_{T_{sn1}R_j}+g_{T_{sn2}R_j}} \leq \frac{\Omega_{S_{pn}D_{pn}}P_{S_{pn}}-\lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn}(g_{T_{sn1}R_j}+g_{T_{sn2}R_j})}$ holds. In order for each relay R_j to have a successful data transmission in both of the PN and SN, the minimum transmit power of the secondary transceivers is

$$\bar{P}_{T_{sn}}^{\min} = \frac{\lambda_{sn}(\Omega_{S_{pn}R_j}P_{S_{pn}} + \nu_{R_j})}{g_{T_{sn1}R_j} + g_{T_{sn2}R_j}}, \tag{11}$$

where $\Omega_{S_{pn}R_j} = \mathbb{E}\{g_{S_{pn}R_j}\}$, $\Omega_{S_{pn}D_{pn}} = \mathbb{E}\{g_{S_{pn}D_{pn}}\}$, and $\mathbb{E}\{\cdot\}$ denotes expectation.

Proof. The proof is analogous to that of Proposition. 2, by replacing $\Omega_{S_{pn}R_j}$ and $\Omega_{S_{pn}D_{pn}}$ with $g_{S_{pn}R_j}$ and $g_{S_{pn}D_{pn}}$, respectively. Furthermore, if only the statistical CSI of the primary link and the interference links between the PN and the SN is known, and $\frac{\lambda_{sn}(\Omega_{S_{pn}R_j}P_{S_{pn}}+\nu_{R_j})}{g_{T_{sn1}R_j}+g_{T_{sn2}R_j}} > \frac{\Omega_{S_{pn}D_{pn}}P_{S_{pn}}-\lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn}(g_{T_{sn1}R_j}+g_{T_{sn2}R_j})}$, the secondary transceivers should not transmit data at the i-th time slot and have to remain silent. □

B. Secondary Network Uses Broadcast Mode

Assume that, at the i-th time slot in the SN, the relay R_j is selected to transmit the secondary data to both the secondary transceivers. Thus, the secondary relay R_j causes interference at the primary receiver during the primary data transmission. In addition, the primary source induces interference at both the secondary transceivers in the secondary data transmission. Our aim is to cancel the interference from the SN to PN via SIC approach and to ensure that the SINR at both the secondary transceivers are equal or greater than λ_{sn}. The primary data is successfully received at the primary destination if the received SINR is greater than or equal to a desired threshold λ_{pn}:

$$\frac{g_{S_{pn}D_{pn}}P_{S_{pn}}}{g_{R_jD_{pn}}P_{R_j}\Psi(R_j, D_{pn}) + \nu_{D_{pn}}} \geq \lambda_{pn}, \tag{12}$$

where $\Psi(R_j, D_{pn})$ is a factor indicating whether the interference from secondary relay R_j to the primary destination can be canceled with the help of SIC scheme or not, with

$$\Psi(R_j, D_{pn}) = \begin{cases} 0 & \text{if } \frac{g_{R_jD_{pn}}P_{R_j}}{g_{S_{pn}D_{pn}}P_{S_{pn}}+\nu_{D_{pn}}} \geq \lambda_{sn}, \\ 1 & \text{otherwise.} \end{cases} \tag{13}$$

Furthermore, both the secondary transceivers successfully receive the secondary data, if the received SINRs are greater than or equal to a threshold λ_{sn}:

$$\frac{P_{R_j}g_{R_jT_{sn1}}}{g_{S_{pn}T_{sn1}}P_{S_{pn}} + \nu_{T_{sn1}}} \geq \lambda_{sn}, \tag{14}$$

$$\frac{P_{R_j}g_{R_jT_{sn2}}}{g_{S_{pn}T_{sn2}}P_{S_{pn}} + \nu_{T_{sn2}}} \geq \lambda_{sn}. \tag{15}$$

Due to the battery limitation, the secondary relay R_j has a maximum transmitting power denoted by $P_{R_j}^{\max}$. For canceling the interference from the SN to PN, $\Psi(R_j, D_{Pn})$ in (13) should be equal to 0. Thus, by some mathematical manipulation we have

$$P_{R_j}^{\max} \geq \frac{\lambda_{sn}(g_{S_{pn}D_{pn}}P_{S_{pn}} + \nu_{D_{pn}})}{g_{R_jD_{pn}}}. \tag{16}$$

Therefore, SIC in Subsection III-B is feasible if and only if (16) is fulfilled, and the instantaneous CSI of the primary link and the interference links between the PN and the SN is available. In the next proposition, we find the minimum transmit power of the secondary relay R_j under the conditions that the interference from the SN to the PN can be canceled via SIC policy and the secondary data transmission is error free.

Proposition 4. Under a global CSI assumption, for each relay R_j, in order to have $\Psi(R_j, D_{pn}) = 0$ and $SINR_{R_jT_{sn}} \geq \lambda_{sn}$, the minimum transmit power of the relay R_j can be found as

$$P_{R_j}^{\min} = \lambda_{sn} \max\Big(\frac{(g_{S_{pn}D_{pn}}P_{S_{pn}} + \nu_{D_{pn}})}{g_{R_jD_{pn}}}, \frac{(g_{S_{pn}T_{sn1}}P_{S_{pn}} + \nu_{T_{sn1}})}{g_{R_jT_{sn1}}}, \frac{(g_{S_{pn}T_{sn2}}P_{S_{pn}} + \nu_{T_{sn2}})}{g_{R_jT_{sn2}}}\Big). \tag{17}$$

Proof. To have SIC feasibility, $\Psi(R_j, D_{pn}) = 0$ should be satisfied. Thus, we have

$$P_{R_j} \geq \frac{\lambda_{sn}(g_{S_{pn}D_{pn}}P_{S_{pn}} + \nu_{D_{pn}})}{g_{R_jD_{pn}}}. \tag{18}$$

For data transmission between the relay R_j and the secondary transceivers to be received correctly, according to (14) and (15) we have

$$P_{R_j} \geq \frac{\lambda_{sn}(g_{S_{pn}T_{sn1}}P_{S_{pn}} + \nu_{T_{sn1}})}{g_{R_jT_{sn1}}}, \quad (19)$$

$$P_{R_j} \geq \frac{\lambda_{sn}(g_{S_{pn}T_{sn2}}P_{S_{pn}} + \nu_{T_{sn2}})}{g_{R_jT_{sn2}}}. \quad (20)$$

When (18), (19) and (20) hold, the minimum transmit power of the secondary relay R_j is given in (17). $\square$

The energy limitations at the relays can make it impossible to achieve SIC. In the next proposition, under a global CSI assumption, we find the minimum transmit power of the secondary relay R_j provided that: a) The cancellation of the interference from the SN to the PN is infeasible due to energy limitation, and b) The primary and secondary data transmission are error free.

Proposition 5. Assume that global CSI is available, and because of the battery limitation at the secondary bidirectional relays, the SIC condition in (16) is not satisfied and $\lambda_{sn} \max\big(\frac{(g_{S_{pn}T_{sn1}}P_{S_{pn}}+\nu_{T_{sn1}})}{g_{R_jT_{sn1}}}, \frac{(g_{S_{pn}T_{sn2}}P_{S_{pn}}+\nu_{T_{sn2}})}{g_{R_jT_{sn2}}}\big) \leq \frac{g_{S_{pn}D_{pn}}P_{S_{pn}}-\lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn}g_{R_jD_{pn}}}$ holds. In order for each relay R_j to have successful data transmission in both of the PN and SN, the minimum transmit power of the secondary relay R_j is

$$\bar{P}_{R_j}^{\min} = \max\big(\frac{\lambda_{sn}(g_{S_{pn}T_{sn1}}P_{S_{pn}} + \nu_{T_{sn1}})}{g_{R_jT_{sn1}}}, \frac{\lambda_{sn}(g_{S_{pn}T_{sn2}}P_{S_{pn}} + \nu_{T_{sn2}})}{g_{R_jT_{sn2}}}\big). \quad (21)$$

Proof. For correct decoding in both of the PN and SN, (12), (14) and (15) should be fulfilled, respectively. In addition, $\Psi(R_j, D_{pn})$ in (14) is equal to 1. By some mathematical manipulation we reach to the following equations

$$P_{R_j} \leq \frac{g_{S_{pn}D_{pn}}P_{S_{pn}} - \lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn}g_{R_jD_{pn}}}, \quad (22)$$

$$P_{R_j} \geq \frac{\lambda_{sn}(g_{S_{pn}T_{sn1}}P_{S_{pn}} + \nu_{T_{sn1}})}{g_{R_jT_{sn1}}}, \quad (23)$$

$$P_{R_j} \geq \frac{\lambda_{sn}(g_{S_{pn}T_{sn2}}P_{S_{pn}} + \nu_{T_{sn2}})}{g_{R_jT_{sn2}}}. \quad (24)$$

If $\lambda_{sn}\cdot\max\big(\frac{(g_{S_{pn}T_{sn1}}P_{S_{pn}}+\nu_{T_{sn1}})}{g_{R_jT_{sn1}}}, \frac{(g_{S_{pn}T_{sn2}}P_{S_{pn}}+\nu_{T_{sn2}})}{g_{R_jT_{sn2}}}\big) \leq \frac{g_{S_{pn}D_{pn}}P_{S_{pn}}-\lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn}g_{R_jD_{pn}}}$ holds, the minimum transmit power of the secondary relay R_j for SIC infeasibility is given in (21). On the other hand, if we have SIC infeasibility and $\lambda_{sn} \cdot \max\big(\frac{(g_{S_{pn}T_{sn1}}P_{S_{pn}}+\nu_{T_{sn1}})}{g_{R_jT_{sn1}}}, \frac{(g_{S_{pn}T_{sn2}}P_{S_{pn}}+\nu_{T_{sn2}})}{g_{R_jT_{sn2}}}\big) > \frac{g_{S_{pn}D_{pn}}P_{S_{pn}}-\lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn}g_{R_jD_{pn}}}$, the secondary relays should not transmit data at the i-th time slot and have to be silent. $\square$

If the instantaneous CSI of the primary link and the interference links between the PN and the SN is not available, SIC cannot be applied and the secondary interference has to be treated as noise at the primary receiver. In the next proposition, we find the minimum transmit power of the secondary transceivers provided that: a) Only the statistical CSI of the primary link and the interference links between the PN and the SN is known, and b) The primary and secondary data transmission are error free.

Proposition 6. Assume that only the statistical CSI of the primary link and the interference links between the PN and the SN is known, and $\lambda_{sn} \max\big(\frac{(\Omega_{S_{pn}T_{sn1}}P_{S_{pn}}+\nu_{T_{sn1}})}{g_{R_jT_{sn1}}}, \frac{(\Omega_{S_{pn}T_{sn2}}P_{S_{pn}}+\nu_{T_{sn2}})}{g_{R_jT_{sn2}}}\big) \leq \frac{\Omega_{pn}D_{pn}P_{S_{pn}}-\lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn}g_{R_jD_{pn}}}$ holds. In order for each relay R_j to have successful data transmission in both of the PN and SN, the minimum transmit power of the secondary relay R_j is

$$\bar{P}_{R_j}^{\min} = \max\big(\frac{\lambda_{sn}(\Omega_{S_{pn}T_{sn1}}P_{S_{pn}} + \nu_{T_{sn1}})}{g_{R_jT_{sn1}}}, \frac{\lambda_{sn}(\Omega_{S_{pn}T_{sn2}}P_{S_{pn}} + \nu_{T_{sn2}})}{g_{R_jT_{sn2}}}\big), \quad (25)$$

where $\Omega_{S_{pn}T_{sn1}} = \mathbb{E}\{g_{S_{pn}T_{sn1}}\}$, $\Omega_{S_{pn}T_{sn2}} = \mathbb{E}\{g_{S_{pn}T_{sn2}}\}$.

Proof. The proof is analogous to that of Proposition. 5. If only the statistical CSI of the primary link and the interference links between the PN and the SN is known, and $\lambda_{sn} \cdot \max\big(\frac{(\Omega_{S_{pn}T_{sn1}}P_{S_{pn}}+\nu_{T_{sn1}})}{g_{R_jT_{sn1}}}, \frac{(\Omega_{S_{pn}T_{sn2}}P_{S_{pn}}+\nu_{T_{sn2}})}{g_{R_jT_{sn2}}}\big) > \frac{\Omega_{S_{pn}D_{pn}}P_{S_{pn}}-\lambda_{pn}\nu_{D_{pn}}}{\lambda_{pn}g_{R_jD_{pn}}}$, the secondary transceivers should not transmit data at the i-th time slot and have to remain silent. $\square$

C. Proposed Buffer-Aided Bidirectional Relay Selection Policy

In the proposed scheme, in the SN, the bidirectional relays with full and empty buffers are candidate only for the broadcast mode and multiple access mode, respectively. If the buffers of all the bidirectional relays are full, none of them can receive the secondary data. In this case, transmission at the secondary transceivers are suspended until one of the relay has non-full buffers. In addition, if the buffers of all the bidirectional relays are empty, none of them can transmit the secondary data. In this case, the relays do not transmit secondary data until one of the secondary relay has non-empty buffers. Under global CSI assumption, by using Table 1, the central node decides optimally when to use one of the non-full relays for the multiple access, use one of the non-empty relays for the broadcast mode or be silent such that the data transmission in both the PN and SN are error free and the transmit power in the SN is minimized.

IV. Simulation Results and Analysis

In this section, we evaluate the performance of the proposed scheme in terms of the secondary throughput and secondary power consumption via simulation and numerical results. We assume transmit power of 7 dB at the primary source and Rayleigh block fading with unit variance. Fig. 3 illustrates the average throughput of the SN, measured in bps/Hz, versus the secondary maximum transmit SNR for instantaneous and statistical CSI of interference links between the PN and the SN. The maximum transmission rate of the secondary transceivers are 1 bps/Hz. Hence, the maximum achievable average throughput of the SN reaches to 1 bps/Hz. In this figure, we can clearly see that by increasing L, K and the maximum secondary transmit SNR, the average secondary

TABLE I

BUFFER-AIDED BIDIRECTIONAL RELAY SELECTION ALGORITHM (UNDER GLOBAL CSI ASSUMPTION)

i) For each relay R_j, we check the SIC feasibility for multiple access mode through (4).

ii) If successive interference cancellation is feasible, then

ii-a) If SIC took place, $P_{T_{sn}}^{\min}$ is given in (5).

ii-b) If SIC did not take place, $\bar{P}_{T_{sn}}^{\min}$ is given in (8).

ii-c) At the i-th time slot, the minimum transmit power of the secondary transceivers is $\min(P_{T_{sn}}^{\min}, \bar{P}_{T_{sn}}^{\min})$.

iii) Assuming that SIC condition in (4) is not satisfied then only the case (b) of step ii is used.

iv) For each relay R_j, we check the SIC feasibility for broadcast mode through (16).

v) If successive interference cancellation can take place, then

v-a) If SIC took place, $P_{R_j}^{\min}$ is given in (17).

v-b) If SIC did not take place, $\bar{P}_{R_j}^{\min}$ is given in (21).

v-c) At the i-th time slot, the minimum transmit power of the relay R_j is $\min(P_{R_j}^{\min}, \bar{P}_{R_j}^{\min})$.

vi) Assuming that SIC is infeasible, then only case (b) of step v is used.

vii) We compare the minimum transmit power of each relay R_j and the secondary transceivers and choose the minimum of them.

viii) If no relays can be found to send or receive the secondary data, the secondary network should be silent.

throughput is increased. By using our proposed policy in Section III, in each time slot, the SN examines at most $2 \times K$ links to see whether or not interference between the PN and SN can be canceled. Thus, if L and K are increased, the number of candidate relays which can be selected is increased, resulting in the increase of the secondary throughput. In addition, in Fig. 3, our proposed scheme is compared with the relay selection policy in [10] in terms of the secondary throughput. This figure shows that the proposed policy achieves higher average secondary throughput in comparison with the scheme in [10]. There exist up to 20% and 40% increase in the average secondary throughput for $K = 12$ and $K = 6$, respectively, compared with [10].

Fig. 4 shows amount of the secondary power consumption that is saved by the proposed policy and the policy in [10]. The relay selection without secondary power allocation is exploited in the relay selection procedure as a reference policy to calculate the secondary power reduction. Therefore, at each time slot, the SN in the reference policy transmits with the maximum available power. The y-axis in this figure is equal to the secondary power of the proposed policy and policy in [10] minus the secondary power of the reference policy. As Fig. 4 shows, by increasing K, the probability of finding the appropriate relay is increased, resulting in the decrease of the secondary power consumption. Moreover, the proposed policy saves more secondary power compared with the scheme in [10]. As it can be seen from the Fig. 3 and Fig. 4, when the buffer size is increased, the secondary throughput is increased and the secondary power consumption is decreased. Thus, using buffers causes more secondary throughput and less secondary power expenditure.

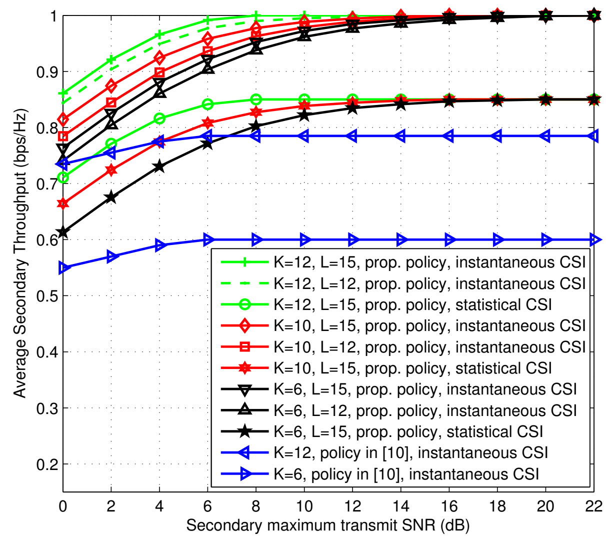

Fig. 3. The average secondary throughput by increasing the secondary maximum transmit SNR for varying K and L.

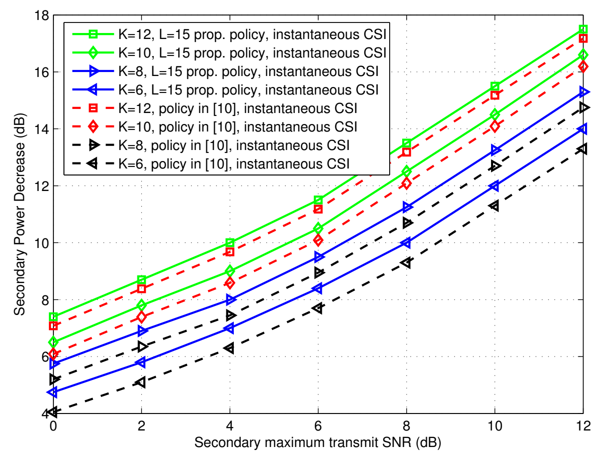

Fig. 4. The power reduction by increasing the secondary maximum transmit SNR for varying K and $L = 15$.

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