



# Hybrid Duplex Relay Selection in Cognitive Radio Network

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**Abstract.** The existing cognitive single relay selection technology is lack of a full-duplex/half-duplex mode switching criteria, and only maximizes the system performance of secondary users in the single-duplex mode relay selection process, which result in a single relay mode and the overall performance of single primary networks and secondary networks is not optimal. To tackle these problems, the criteria for switching the hybrid duplex mode of the relay node is first derived. In the case of adopting the amplify-and-forward (AF) and decode-forward (DF) protocols, each candidate relay terminal selects the optimal duplex mode according to the signal-to-noise ratio (SNR) of the self-interference channel and the critical point of self-interference. Then propose a low interference hybrid duplex relay selection algorithm, the relay node uses the comprehensive performance loss of the primary network performance and the performance gain of the secondary network user as the indicator to optimize the relay selection, which maximizes the sacrifice value of the primary network. The simulation results show that the proposed algorithm can significantly improve the performance of the primary network system and the whole system. Furthermore, the performance of the secondary network is slightly reduced (or even improved).

**Keywords:** Cognitive network · Relay selection · Hybrid duplex mode · Low-interference

## 1 Introduction

With the development of mobile communication, the demand for spectrum resources has increased dramatically. Due to limited spectrum resources, the shortage of spectrum resources becomes serious [1–3].

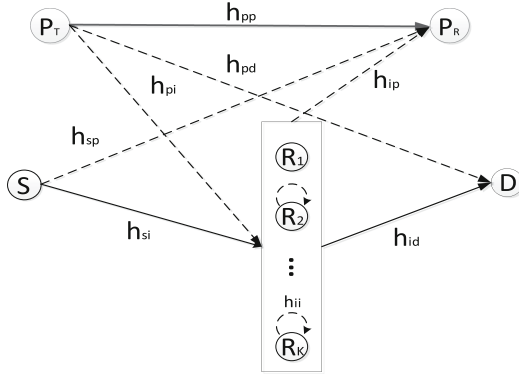
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Cognitive relay selection technology has been widely studied for future communication development [4]. It enables secondary users to effectively use licensed spectrum to complete their own communications while ensuring the quality of primary users communication. The full-duplex relay technology can simultaneously receive and transmit signals of the same frequency [5]. Therefore, cognitive relay technology combines the two technologies to improve spectrum utilization. There are many alternative candidate relays in cognitive relay networks. When different nodes are selected as relays, different performance will be brought to the system [6]. It is very meaningful to study how to effectively select the appropriate node as the communication relay.

In the Underlay mode cognitive relay network, optimizing the secondary network performance indicators as the target of selecting relay nodes. Most of the existing cognitive relay selection schemes follow a principle: when the interference caused by the secondary user to the primary user satisfies the interference temperature, the relay selection scheme can be used to increase the capacity of the system or reduce the probability of interruption. Traditional max-min relay selection (MMRS) relay selection method is applied to cognitive half-duplex relay networks to maximize secondary system capacity [7–9]. Based on the interrupt performance of the orthogonal frequency division multiplexing network, within each subcarrier, the relay network adopts a full-duplex AF relay protocol and the relay selection mode follows the MMRS criterion [10]. Research on optimal relay selection (ORS) mode in cognitive relay network based on imperfect channel information imperfection (CII), as the number of candidate relays increases, the system performance of the secondary network will increase significantly [11]. The cognitive full-duplex relay selection method is studied in detail to optimize the performance of the secondary user network [12–15]. However, in the Underlay mode cognitive network, even if the secondary users can meet the strict interference temperature limit, user networks also sacrifice their performance or power to tolerate additional interference from secondary user network access. In addition, the existing works does not involve the hybrid duplex mode switching problem of cognitive relay networks. This paper in Underlay mode cognitive relay network based on AF protocol and DF protocol respectively, proposing a low-interference hybrid duplex relay selection algorithm to maximize the primary user's sacrifice value for full/half duplex mode switching and optimal relay selection.

## 2 System Model

Relay selection model for cognitive relay network, including a primary network base station  $P_T$ , a primary user destination terminal  $P_R$ , a secondary network base station  $S$ ,  $K$  secondary candidate relays  $R(R_1, R_2 \dots R_K)$ , and a secondary destination terminal  $D$ . Considering that each relay equips with two antennas, one of which is used to receive signals and the other is used to transmitting signals, moreover, each antenna can communicate both in half-duplex mode and full-duplex mode. Figure 1 shows the system model considered in this paper.



**Fig. 1.** Relay selection model in cognitive wireless networks.

In Underlay mode, the primary user allows the secondary user to access the licensed spectrum while satisfying the interference temperature  $I_{th}$  and treats the signals of the secondary user as background noise. It is supposed that in the cognitive relay network, S and D cannot communicate directly, because of the secondary user's transmit power is limited. The data interaction between S and D need to be completed with the assistance of the relay terminal, so the direct transmission path between S and D can be ignored. Assuming that the transmit powers of  $P_p$ ,  $P_s$ , and  $P_i$  of  $P_T$ , D, and  $i$  are constants. In the Fig. 1, the solid line indicates the transmission link of the useful signal and the dotted line indicates the interference link. In addition, we presume that the noise at each node obeys an additive white Gaussian noise with a mean of zero and a variance of  $N_0$ .

### 3 Performance Analysis of Secondary Network and Primary Network

In the Underlay mode cognitive relay network, the relay node can work in both half-duplex and full-duplex modes. The two modes will bring different gains to the capacity of the secondary network [16]. The capacity of the secondary network in the two modes will be analyzed separately.

#### 3.1 Full Duplex Mode

In the Underlay mode cognitive relay network, when the relay node adopts the full-duplex relay mode, the relay node can simultaneously receive and retransmit signals at the same frequency. Therefore, the signal transmission will cause self-interference to the signal reception. The received signals at the secondary candidate relay node  $i$  and the secondary destination node D are

$$y_i = \sqrt{P_s}h_{si}x_s + \sqrt{P_i}h_{ii}x_i + \sqrt{P_p}h_{pi}x_p + n_i \quad (1)$$

$$y_d = \sqrt{P_i}h_{id}x_i + \sqrt{P_p}h_{pd}x_p + n_d \quad (2)$$

where  $x_s$ ,  $x_i$ ,  $x_p$ ,  $n_i$ , and  $n_d$  denote the transmitting signal of the secondary network base station S, the retransmitted signal of secondary relay  $i$ , the transmission signal of the primary network base station P<sub>T</sub>, the background noise of secondary relay  $i$ , and the background noise of secondary destination terminal D, respectively.

The instantaneous received powers at the secondary candidate relay  $i$  and the secondary destination terminal D are

$$\varepsilon\{|y_i|^2\} = P_s|h_{si}|^2 + P_i|h_{ii}|^2 + P_p|h_{pi}|^2 + N_0 \quad (3)$$

$$\varepsilon\{|y_d|^2\} = P_i|h_{id}|^2 + P_p|h_{pd}|^2 + N_0 \quad (4)$$

When the secondary relay network adopts the AF protocol, the relay node directly amplifies the received signal, and the amplification factor  $\beta_1$  is defined as

$$\beta_1 = \sqrt{\frac{P_i}{P_s|h_{si}|^2 + P_p|h_{pi}|^2 + P_i|h_{ii}|^2 + N_0}} \quad (5)$$

When the secondary relay network adopts the DF protocol, the relay node decodes the received signal first and then re-encodes for forwarding. Therefore, the resending signal of the relay node can be expressed as

$$x_i = \begin{cases} \beta_1 y_i, & \text{with AF} \\ \sqrt{\frac{P_i}{P_s}} x_s, & \text{with DF} \end{cases} \quad (6)$$

where  $h_{pi}$ ,  $h_{ii}$ , and  $h_{si}$  are the channel coefficients of P<sub>T</sub> to  $i$ ,  $i$  to  $i$  and S to  $i$  respectively, when node  $i$  is selected as the relay. In the cognitive full-duplex relay network, the Signal to Interference Plus Noise Ratio (SINR) in the hops of  $i$  and D can be defined as

$$\gamma_i^{FD} = \frac{P_s^2|h_{si}|^2}{P_p^2|h_{pi}|^2 + P_i^2|h_{ii}|^2 + N_0} \quad (7)$$

$$\gamma_{d-i}^{FD} = \frac{P_i^2|h_{id}|^2}{P_p^2|h_{pd}|^2 + N_0} \quad (8)$$

The end-to-end SINR of secondary networks in cognitive half-duplex relay mode can be defined as

$$\gamma_{CFD-i} = \begin{cases} \frac{\gamma_i^{FD}\gamma_{d-i}^{FD}}{\gamma_i^{FD} + \gamma_{d-i}^{FD} + 1}, & \text{with AF} \\ \min(\gamma_i^{FD}, \gamma_{d-i}^{FD}), & \text{with DF} \end{cases} \quad (9)$$

The system rate is

$$R_{CFD-i} = W \log_2(1 + \gamma_{CFD-i}) \quad (10)$$

When the secondary user does not access the spectrum of the primary user, the SNR of the primary network communication can be defined as

$$\gamma_{pp} = P_p |h_{pp}|^2 / N_0 \quad (11)$$

If the secondary user accesses the spectrum of the primary user in the full duplex relay mode, the secondary network base station S and the relay node  $i$  work simultaneously, which commonly causing interference to the primary user receiver PD is

$$I_{CFD-i} = P_s |h_{sp}|^2 + P_i |h_{ip}|^2 \quad (12)$$

The SNR of the primary network is

$$\gamma_{pp-i}^{FD} = \frac{P_p^2 |h_{pp}|^2}{P_s^2 |h_{sp}|^2 + P_i^2 |h_{ip}|^2 + N_0} \quad (13)$$

The primary system rate is

$$R_{pp-i}^{FD} = W \log_2(1 + \gamma_{pp-i}^{FD}) \quad (14)$$

where  $h_{id}$ ,  $h_{pd}$ ,  $h_{pp}$ ,  $h_{sp}$ , and  $h_{ip}$  are the channel coefficients of  $i$  to D, P<sub>T</sub> to D, P<sub>T</sub> to P<sub>R</sub>, S to P<sub>T</sub> and  $i$  to P<sub>T</sub>, respectively.  $W$  is the system bandwidth.

### 3.2 Half Duplex Mode

When a relay node adopts the half-duplex relay mode, it operates in two orthogonal time slots or frequencies (this is assumed to be a time slot). The received signals at the secondary candidate relay node  $i$  and the secondary destination node D are

$$y_i = \sqrt{P_s} h_{si} x_s + \sqrt{P_p} h_{pi} x_{p1} + n_i \quad (15)$$

$$y_d = \sqrt{P_i} h_{id} x_i + \sqrt{P_p} h_{pd} x_{p2} + n_d \quad (16)$$

The retransmit signal of the relay node  $d$  is expressed as

$$x_i = \begin{cases} \beta_2 y_i, & \text{with AF} \\ \sqrt{\frac{P_i}{P_s}} x_s, & \text{with DF} \end{cases} \quad (17)$$

The amplification factor  $\beta_2$  of the AF protocol is

$$\beta_2 = \sqrt{\frac{P_i}{P_s |h_{si}|^2 + P_p |h_{pi}|^2 + N_0}} \quad (18)$$

The instantaneous received signal power of the secondary candidate relay and the secondary destination terminal D are expressed as (19) and (4), respectively

$$\varepsilon\{|y_i|^2\} = P_s |h_{si}|^2 + P_p |h_{pi}|^2 + N_0 \quad (19)$$

The SINR of  $i$  and D hops can be expressed as

$$\gamma_i^{HD} = \frac{P_s^2 |h_{si}|^2}{P_p^2 |h_{pi}|^2 + N_0} \quad (20)$$

$$\gamma_{d-i}^{HD} = \frac{P_i^2 |h_{id}|^2}{P_p^2 |h_{pd}|^2 + N_0} \quad (21)$$

The end-to-end SINR of secondary networks in cognitive half-duplex relay mode is expressed as

$$\gamma_{CHD-i} = \begin{cases} \frac{\gamma_i^{HD} \gamma_d^{HD}}{\gamma_i^{HD} + \gamma_d^{HD} + 1}, & \text{with AF} \\ \min(\gamma_i^{HD}, \gamma_d^{HD}), & \text{with DF} \end{cases} \quad (22)$$

The system rate is

$$R_{CHD-i} = W \log_2(1 + \overline{\gamma_{CHD}}) \quad (23)$$

When the secondary user accesses the spectrum of the primary user in the half-duplex relay mode, the interference caused to the primary is expressed as

$$I_{CHD-i} = \max(P_s |h_{sp}|^2, P_i |h_{ip}|^2) \quad (24)$$

The SNR of the primary network is

$$\gamma_{pp-i}^{HD} = \min\left(\frac{P_p \gamma_{pp}}{P_s \gamma_{sp} + 1}, \frac{P_p \gamma_{pp}}{P_i \gamma_{ip} + 1}\right) \quad (25)$$

The primary network rate is

$$R_{pp-i}^{HD} = W \log_2(1 + \gamma_{pp}^{HD}) \quad (26)$$

## 4 Mode Switching

The difference between the half-duplex relay mode and the full-duplex relay mode is reflected in the presence or absence of self-interference, so the SNR  $\gamma_{ii}$  of the self-interference channel is a key factor in mode switching. The necessary and sufficient condition for the full-duplex mode to be better than the half-duplex mode is that  $\gamma_{ii}$  is lower than the critical point  $\gamma_{ii}^{th}$  of self-interference. In this scenario, it is assumed that the secondary network base station S is farther away from the primary destination terminal than the secondary candidate relay, that is,  $i$  is more disturbing to the primary user than S. Therefore, the secondary network uses the half duplex to cause interference to the primary user is  $I_{CHD-i} = P_i |h_{ip}|^2$ .

**Lemma 1:** When the secondary relay network adopts the AF protocol, if (27) is established, the performance of the relay node in full-duplex mode is better than that in the half-duplex mode. Otherwise, the half-duplex mode is adopted, which the performance is better than performance in full-duplex mode.

$$\gamma_{ii} < \gamma_{ii-AF}^{th} = \frac{P_s \gamma_{si} (\gamma_{d-i} - \overline{\gamma_{CHD-i}} - P_s \gamma_{sp})}{P_i (\overline{\gamma_{CHD-i}} + \gamma_{sp}) (\gamma_{d-i} + 1)} - \frac{P_p \gamma_{pi} + 1}{P_i} \quad (27)$$

**Lemma 2:** When the secondary network adopts the DF protocol, if the formula (28) is established, the performance of the relay node in the half-duplex mode is better than that in the full-duplex mode. If the Eq. (29) is established, then the performance of the relay node in full-duplex mode is better than that in half-duplex mode.

$$\gamma_{d-i}^{FD} < \overline{\gamma_{CHD-i}} + P_s \gamma_{sp} = (1 + \gamma_{CHD-i})^{1/2} - 1 + P_s \gamma_{sp} \quad (28)$$

$$\gamma_{ii} < \gamma_{ii-DF}^{th} = \frac{P_s \gamma_{si}}{P_i (\overline{\gamma_{CHD-i}} + P_s \gamma_{sp})} - \frac{P_p \gamma_{pi} + 1}{P_i} \quad (29)$$

When the secondary relay network adopts the AF protocol, each secondary candidate relay node performs mode selection according to Lemma 1. When the secondary network adopts the DF protocol, each secondary candidate relay node performs mode selection according to Lemma 2. Ensuring that the sacrifices made by the primary are more valuable optimizes the performance of the entire network, including the secondary user network and the primary network.

## 5 Low Interference Mode Switching Relay Selection Algorithm

A low-interference hybrid duplex mode switch relay selection (HDMSRS) algorithm is proposed. In this section, aiming to optimize the mode switching and relay selection of the whole network. The utility function can be defined as

$$C_i = \arg \max_{i=1 \sim n} (\gamma_{ete}^i - \gamma_{s \rightarrow p}^i) \quad (30)$$

where  $\gamma_{ete}^i$  is the revenue function of the entire system

$$\gamma_{ete}^i = \begin{cases} \overline{\gamma_{CHD-i}} & \text{with HD} \\ \gamma_{CFD-i} & \text{with FD} \end{cases} \quad (31)$$

$\gamma_{s \rightarrow p}^i$  is the cost function of the entire system

$$\gamma_{s \rightarrow p}^i = \begin{cases} \max \left( \frac{P_s |h_{sp}|^2}{N_0}, \frac{P_i |h_{ip}|^2}{N_0} \right) & \text{with HD} \\ \frac{P_s |h_{sp}|^2 + P_i |h_{ip}|^2}{N_0} & \text{with FD} \end{cases} \quad (32)$$

In order to maximize the overall performance of both secondary and primary systems, a hybrid relay mode is proposed to switch the appropriate mode according to the instantaneous CSI. The utility function for each candidate relay is

$$C_{Hybrid} = \max (C_{i-HD}, C_{i-FD}) \quad (33)$$

where  $C_{i-HD}$  is the utility function of candidate relay nodes operating in half-duplex mode;  $C_{i-FD}$  is the utility function of candidate relay nodes operating in full-duplex mode.

Each candidate relay  $C_i$  selects a duplex mode according to its own utility to optimize overall performance.

The specific HDMSRS algorithm flow is described in Algorithm 1.

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**Algorithm 1.** The HDMSRS algorithm flow is as follows

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**Step1** Initializing secondary candidate half-duplex and full-duplex relay terminal sets H and F in the secondary network base station S, then send relay request information by broadcast.

**Step2** The secondary network base station S and each candidate relay terminal i that receives the relay request, estimate channel state information of itself to the primary destination terminal D first, determine whether the interference temperature limit can be met when i works in half-duplex mode and full-duplex mode respectively:

**Step2.1** If only the work is satisfied in the half-duplex (full-duplex) mode, the half-duplex (full-duplex) relay mode is adopted directly;

**Step2.2** If the work is not satisfied in the half duplex mode and the full duplex mode, the candidate relay terminal cannot communicate as a relay;

**Step2.3** If the work is satisfied in both the half-duplex mode and the full-duplex mode, mode selection is performed by Lemma 1 or Lemma 2.

**Step3** Calculate its own utility value according to equation (30) and feed it back to the F and H sets at S.

**Step3.1** If i selects half-duplex mode, add this node to the set H.

**Step3.2** If i selects full-duplex mode, add this node to the set F.

**Step4** Select the maximum value according to equation (34) and equation (35) in the H and F sets at S.

$$C_i^{FD*} = \max (C_1^{FD}, C_2^{FD} \dots C_n^{FD}) \quad (34)$$

$$C_i^{FD*} = \max (C_1^{FD}, C_2^{FD} \dots C_n^{FD}) \quad (35)$$

**Step5** Compare the utility values corresponding to the two candidate relay terminals selected in **Step4** according to the formula (36), and the larger one is selected as the relay node.

$$U_i^* = \max (C_i^{HD*}, C_i^{FD*}) \quad (36)$$

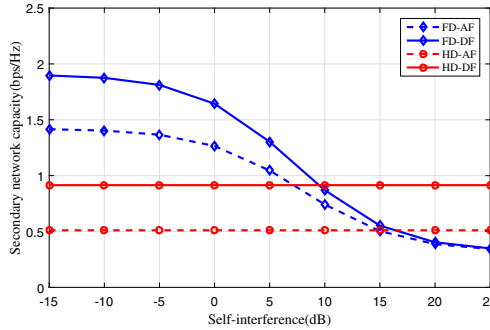

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## 6 Simulation and Performance Analysis

The simulation results of the proposed mode switching and relay selection in cognitive hybrid duplex network will be discussed in this section. The system simulation is run on Matlab. Considering one primary network base station, one PN terminal, one secondary network base station, secondary network terminal

**Table 1.** Main simulation parameters

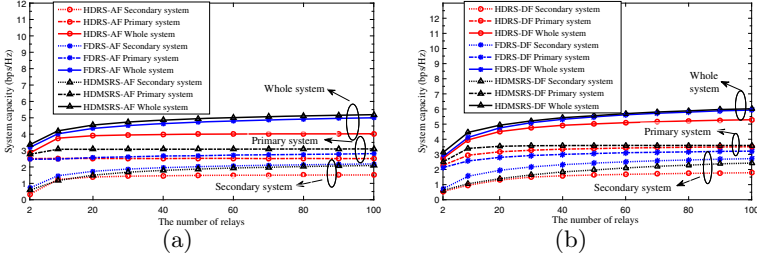
Parameter	Values
Transmission power of $P_P$	1 dB
Interference temperature $I_{th}$	3 dB
Road loss index $\eta$	3
System bandwidth W	1 MHz
Additive Gauss white noise variance $N_0$	1
Channel coefficient expression	$h_{m,n} = k * d_{m,n}^{-\eta}$

**Fig. 2.** The relationship between self-interference and secondary network system capacity under different duplex mode and relay protocol.

in the simulation scenario. There are many secondary candidate relay nodes uniformly distributed within the SN BS and SN DT. Assuming that the channel coefficients between each node can be expressed as  $h_{m,n} = k * d_{m,n}^{-\eta}$ , where  $k$  denotes the attenuation factor, which obeys a complex Gaussian distribution with a mean of zero and a variance of one,  $d_{m,n}$  denotes the distance from node to node  $n$ , and  $\eta$  is the path loss index. The main simulation parameters are detailed in Table 1.

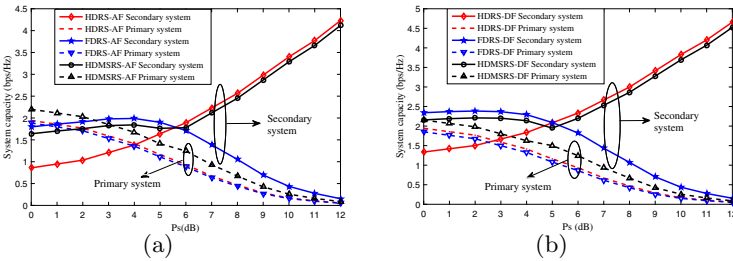
In Fig. 2 showing the relationship between the change in self-interference value and the capacity of the secondary network system when the secondary relay network adopts different duplex modes and relay protocols. The transmit power of the secondary network base station and the secondary relay are both  $P_s = P_i = 1$  dB. When the half-duplex relay mode is adopted, there is no self-interference at the relay node. The system capacity of the relay network is independent of the change of the self-interference value, and the relationship is expressed as a straight line. When the secondary relay network accesses the spectrum of the primary user in full-duplex mode, whether it adopts AF protocol or DF protocol, the system capacity of the secondary network decreases as the self-interference value increases. It can be seen from the figure that the necessary and sufficient condition for the performance of the full-duplex relay mode is superior to the half-duplex mode is that the self-interference value  $\gamma_{ii}$  is less

than the two intersection points, i.e. the self-interference thresholds  $\gamma_{ii-DF}^{th}$  and  $\gamma_{ii-AF}^{th}$ .



**Fig. 3.** The relationship between transmit power and system capacity under different algorithms under two protocols.

Figure 3 show that the relationship between transmit power and system capacity under different algorithms in AF and DF protocols. Setting the number of relays  $n = 4$  in this scene,  $P_s = P_i$ . The HDMSRS algorithm proposed in this paper can achieve the best mode selection in the relay selection process. In order to optimize the performance of the secondary relay network, the relay will transmit in full-duplex mode with small  $P_i$ . As the  $P_i$  increases, the self-interference is large, and the relay will switch to half-duplex mode for transmission. In addition, the algorithm proposed in this paper can be significantly improved the primary system capacity while lightly reducing (or even enhancing) the capacity of the secondary system with the comparison of the HDRS and FDRS algorithms based on MMRS criteria. For example, when  $P_s = 6$  dB, the capacity of the secondary system, is reduced by 8.3% compared with the DRS algorithm, while increasing by 3.1% compared with the FDRS algorithm. For the capacity of the primary system, the proposed HDMSRS algorithm is improved by 38.9% compared with the HDRS algorithm, and is increased by 41.1% compared with the FDRS algorithm.



**Fig. 4.** The relationship between the capacity of system and the number of candidate relays under two protocols.

Figure 4 examine the relationship between the capacity of system and the number of candidate relays. Setting  $P_s = P_i = 1$  dB, what is more, in order to distinguish the capacity curve of the secondary user and the primary user, let  $P_p = 2$  dB. As can be seen from the above figures, the HDMSRS algorithm proposed in this paper can significantly improve the system capacity of the primary user and improve the whole system capacity under the condition of slightly reducing the capacity of the secondary system. For example, when the number of relay is 60, the capacity of the secondary system of the proposed HDMSRS algorithm is improved by 26.7% compared with the HDRS algorithm, while compared with the FDRS algorithm is reduced by 10.5%. For the capacity of the primary system, the proposed HDMSRS algorithm is improved by 26.5% compared with the HDRS algorithm, compared with the FDRS algorithm, the proposed algorithm is improved by 14.8%. For the capacity of the whole system, the HDMSRS algorithm can be increased by 31.6% and 13.1% compared with the HDRS algorithm and the FDRS algorithm, respectively.

## 7 Conclusion

In this paper, to solve the single duplex mode of the relay node, the criteria of full-duplex/half-duplex mode switching has been derived. Moreover, the proposed a low interference hybrid duplex relay selection algorithm which chooses optimal relay based on the combined performance of primary network performance loss and secondary network user performance gains, has improved the performance of the primary network system and the entire system. The simulation results have been performed to verify the superiority of the algorithm on performance improvement of primary network system and the whole system while the performance of secondary user network is slightly decreased (or even promoted).

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