A Multihop Cooperative Routing Algorithm for Minimizing the Number of Hops in Spectrum Sharing Networks

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***Abstract*—In spectrum sharing networks, the farthest neighbor routing (FNR) algorithm [2] has been proposed to find a multihop route when using a single hop transmission is not able to satisfy the quality-of-service (QoS) requirement of the cognitive transmission. However, the large degradation of the end-to-end reliability is caused by the multihop relaying. The end-to-end reliability can be increased by reducing the number of hops. This can be achieved by combining the routing algorithm with the cooperative transmission that can extend the transmission distance. We propose a multihop cooperative routing (MCR) algorithm that extends the lengths of the x axis projections of the hop distances and finds the multihop route that minimizes the number of hops in spectrum sharing networks. The cognitive relay and the cognitive receiver of each hop except the last one are selected by the following procedures. First, the cognitive node that is nearest away from the cognitive sender is selected as the cognitive relay, and let the cognitive destination (CD) be the cognitive receiver. Then, if the participation of the selected cognitive relay can not satisfy the QoS requirement of the cognitive transmission, among the cognitive receiver candidates that satisfy the QoS requirement of the cognitive transmission, the one whose x coordinate has the largest difference from that of the cognitive relay is selected as the cognitive receiver. At the last hop, if the cognitive relay is available, the cooperative transmission is performed. Otherwise, the direct transmission is performed. Simulation results show that the MCR reduces the average number of hops compared to the FNR and outperforms the FNR in terms of the average end-to-end reliability, the average end-to-end throughput, and the average required transmission power.**

I. INTRODUCTION

In cognitive radio networks (CRNs), the cognitive user (CU) dynamically detects the unused spectrum holes released from the primary user (PU) and use them to transmit the data to improve the spectrum efficiency [1]. However, the requirement of the signal detection technique increases the implementation complexity of the CU. Besides, when the traffic load of the PU is heavy, very few unused spectrum holes are available [2].

Another way to implement the cognitive radio (CR) is to let the PU share the spectrum with the CU. In such network, the primary source (PS) and the cognitive source (CS) can transmit the data concurrently if the quality-of-service (QoS) requirements of the primary transmission and the cognitive transmission are both satisfied. The transmission power of the CS must be lower than a certain threshold in order to satisfy the QoS requirement of the primary transmission. Consequently, subject to the QoS requirement of the cognitive transmission, the CS has a maximum transmission distance. If the distance between the CS and the cognitive destination (CD) is longer than the maximum transmission distance of the CS, the QoS requirement of the cognitive transmission can not be satisfied by using a single hop transmission. This problem can be solved by employing the multihop relaying.

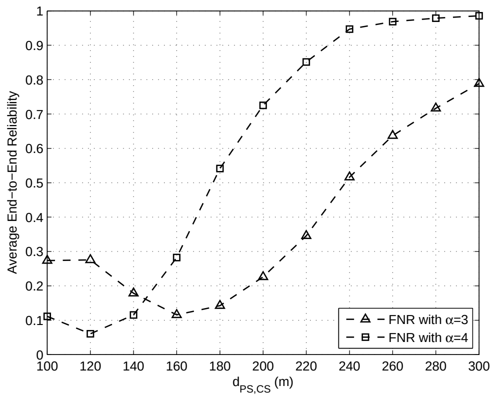

Fig. 1. Average end-to-end reliability versus the distance between the PS and the CS of the FNR with $\alpha = 3$ and $\alpha = 4$.

In [2], the farthest neighbor routing (FNR) algorithm has been proposed to find a multihop route from the CS to the CD. First, the maximum transmission distance of the single hop cognitive transmission interfered by the PS is calculated. Then, among the nodes whose hop distances are less than or equal to the maximum transmission distance calculated in the last step, the node that is farthest away from the congitive sender is selected as the cognitive receiver. The multihop route can be obtained by repeating the above two operations until the found node is the CD, or no node can be found.

Figure 1 shows the average end-to-end reliability versus the distance between the PS and the CS of the FNR with $\alpha = 3$ and $\alpha = 4$, where α denotes the path loss exponent. The end-to-end reliability is defined as the probability of successful reception of a packet at all cognitive receivers of all hops and can be given by

$$\rho = \prod_{i=1}^{K} \beta_c^{(i)}, \tag{1}$$

where K denotes the number of hops of the multihop route between the CS and the CD, and $\beta_c^{(i)}$ represents the probability of successful reception of a packet at the cognitive receiver of the ith hop. From Fig. 1, we can observe that the end-to-end reliability degrades significantly.

To increase the end-to-end reliability, the number of hops should be reduced. As we know, the cooperative transmission is able to prolong the transmission distance. Therefore, combining the routing algorithm with the cooperative transmission can reduce the number of hops. Although the research of the cooperative routing in wireless networks has been done in [4]-[8], none of them address the issues of taking the interferences from other networks into account and minimizing the number of hops. As a result, in the CRN where the cognitive sender and the cognitive relay have their own transmission power constraints and are interfered by the PS, we propose a multihop cooperative routing (MCR) algorithm that extends the lengths of the x axis projections of the hop distances and finds the multihop route that minimizes the number of hops. The selection procedures of the cognitive relay and the cognitive receiver of each hop except the last one are described as follows. First, the node that is closest to the cognitive sender is selected as the cognitive relay, and let the CD be the cognitive receiver. Then, check if the QoS requirement of the cognitive transmission is satisfied by the participation of the selected cognitive relay. If not, among the cognitive receivers whose x coordinates are larger than the x coordinate of the cognitive relay and probabilities of the successful reception of a packet are larger or equal to the QoS threshold of the cognitive transmission, the one whose x coordinate has the largest difference from that of the cognitive relay is selected as the cognitive receiver. At the last hop, if the cognitive relay is available, the cooperative transmission is employed. Otherwise, the direct transmission is employed. The difference between the MCR and the FNR is that in addition to the cognitive receiver, a cognitive relay is selected, and when the cognitive recevier fails to decode the data transmitted from the cognitive sender, the selected cognitive relay retransmits the data overheard from the cognitive sender to the cognitive receiver. Finally, we conduct the computer simulations to investigate the average numbers of hops of the FNR and the MCR and the performances of the FNR and the MCR in terms of the average end-to-end reliability, the average end-to-end throughput, and the average required transmission power.

II. MULTIHOP COOPERATIVE ROUTING (MCR)

A. System Model

We consider the network scenario illustrated in Fig. 2. There are a primary network (PN) and a CRN in the scenario. The PN consists of the PS and the primary destination (PD). The CRN consists of many cognitive nodes including the CS and the CD. The CS and the CD are on a line that is parallel to the x axis. Let M represent the number of hops of the multihop route $\{\text{CS}, A_1, ..., A_{M-1}, \text{CD}\}$. Let A_i denote the cognitive receiver of the cognitive cooperative transmission performed in the ith hop, where $i = 1, ..., M-1$. Let B_j represent the cognitive relay of the cognitive cooperative transmission performed in the jth hop, where $j = 1, ..., M$. We consider that the multihop relaying is performed without concurrency. Two or more than two cognitive cooperative transmissions will not occur simultaneously. As a result, at any time, the PD will be interfered by the cognitive sender or the cognitve relay of only one hop. Due to size and power constraints, we assume that each node is equipped with a single antenna. The channel of each link is characterized by the short term Rayleigh fading. We use the probability of successful reception of a packet as the QoS metric. If the signal-to-interference-plus-noise ratio (SINR) is higher than a certain predefined threshold, the receiver can receive the packet successfully. Under the Rayleigh fading channel, the author in [3] demonstrated that the probability of the successful reception of a packet can be written as

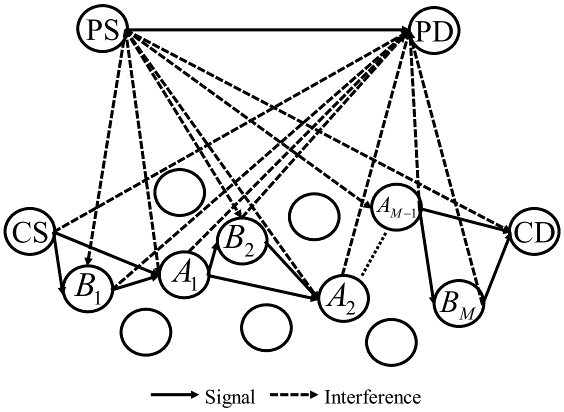

Fig. 2. The primary transmission coexists with the multihop cognitive cooperative transmission.

$$\begin{aligned}\beta &= \Pr(\text{SINR} \geq \gamma) \\ &= \exp\left(-\frac{\gamma N_0}{P_0 d_0^{-\alpha}}\right) \times \prod_{i=1}^{L} \frac{1}{1+\gamma\frac{P_i}{P_0}\left(\frac{d_0}{d_i}\right)^{\alpha}},\end{aligned} \tag{2}$$

where γ denotes the SNIR threshold, N_0 represents the noise variance, P_0 is the sender transmission power, d_0 denotes the distance between the sender and the receiver, L represents the number of interferers, P_i is the transmission power of the ith interferer, and d_i denotes the distance between the ith interferer and the receiver.

B. Transmission Power of the Cognitive Sender and the Cognitive Relay

When the primary transmission coexists with the cognitive cooperative transmission, in order to satisfy the QoS requirement of the primary transmission, the transmission power of the cognitive sender and the cognitive relay must be less than their own certain threhsolds. Figure 3 depicts

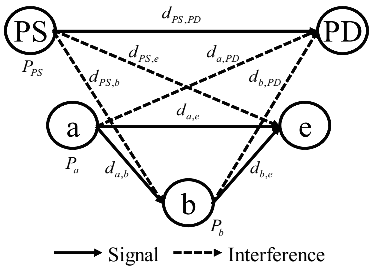

Fig. 3. The primary transmission coexists with the cognitive cooperative transmission.

the network scenario that the primary transmission coexists with the cognitive cooperative transmission. Node a, node b, and node e denote the cognitive sender, the cognitive relay, and the cognitive receiver, respectively. We derive the transmission power constraints of the cognitive sender and the cognitive relay as follows. The QoS requirement of the primary transmission can be written as

$$\Pr(\text{SINR at the PD} \geq \gamma_p) \geq \delta_p, \tag{3}$$

where γ_p denotes the predefined SINR threshold of the primary transmission, and δ_p represents the QoS threshold of the primary transmission interfered by the cognitive sender. From (2), when the PD is interfered by the cognitive sender, the probability of the successful reception of a packet at the PD can be given by

$$\Pr(\text{SINR at the PD} \geq \gamma_p) = \frac{\exp\left(-\frac{\gamma_p N_0}{P_{PS} d_{PS,PD}^{-\alpha}}\right)}{1 + \gamma_p \frac{P_a}{P_{PS}} \left(\frac{d_{PS,PD}}{d_{a,PD}}\right)^{\alpha}}, \tag{4}$$

where P_{PS} and P_a denote the transmission power of the PS and the cognitive sender, respectively, and $d_{PS,PD}$ and $d_{a,PD}$ represent the distances between the PS and the PD and between the cognitive sender and the PD, respectively. By substituting (4) into (3), we can get

$$P_a \leq \frac{\beta_{SNR} - \delta_p}{\delta_p \gamma_p} \left(\frac{d_{a,PD}}{d_{PS,PD}}\right)^{\alpha} P_{PS}, \tag{5}$$

where

$$\beta_{SNR} = \exp\left(-\frac{\gamma_p N_0}{P_{PS} d_{PS,PD}^{-\alpha}}\right). \tag{6}$$

By using the same method, we can also obtain

$$P_b \leq \frac{\beta_{SNR} - \delta_p}{\delta_p \gamma_p} \left(\frac{d_{b,PD}}{d_{PS,PD}}\right)^{\alpha} P_{PS}, \tag{7}$$

where P_b denotes the transmission power of the cognitive relay, and $d_{b,PD}$ represents the distance between the cognitive relay and the PD. In order to maximize the lengths of the x axis projections of the hop distances, the transmission power of the cognitive sender and the cognitive relay is given by

$$P_a = \frac{\beta_{SNR} - \delta_p}{\delta_p \gamma_p} \left(\frac{d_{a,PD}}{d_{PS,PD}}\right)^{\alpha} P_{PS} \tag{8}$$

and

$$P_b = \frac{\beta_{SNR} - \delta_p}{\delta_p \gamma_p} \left(\frac{d_{b,PD}}{d_{PS,PD}}\right)^{\alpha} P_{PS} \tag{9}$$

respectively.

C. Cognitive Cooperative Transmission Interfered by the PS

We adopt the decode-and-forward incremental relaying protocol proposed in [9]. In the cooperative transmission, the transmission time is seperated into two time slots. In the first time slot, the cognitive sender transmits the data to the cognitive receiver. Due to the broadcast nature of the wireless channel, the cognitive relay can also receive the data. Let $n_{i,j}$ denote the additive noise measured at node j when node i is the sender and can be modeled as zero mean complex Gaussian random variable with variance N_0. The received signal at the cognitive receiver and the cognitive relay in the first time slot can be expressed as

$$y_{e,1} = \sqrt{P_a d_{a,e}^{-\alpha}} h_{a,e} s_a + \sqrt{P_{PS} d_{PS,e}^{-\alpha}} h_{PS,e} s_{PS} + n_{a,e} \tag{10}$$

and

$$y_b = \sqrt{P_a d_{a,b}^{-\alpha}} h_{a,b} s_a + \sqrt{P_{PS} d_{PS,b}^{-\alpha}} h_{PS,b} s_{PS} + n_{a,b}, \tag{11}$$

respectively, where $d_{a,e}$, $d_{a,b}$, $d_{PS,e}$, and $d_{PS,b}$ denote the distances between the cognitive sender and the cognitive receiver, between the cognitive sender and the cognitive relay, between the PS and the cognitive receiver, and between the PS and the cognitive relay, respectively, $h_{a,e}$, $h_{a,b}$, $h_{PS,e}$, and $h_{PS,b}$ represent the Rayleigh fading coefficients of the channels between the cognitive sender and the cognitive receiver, between the cognitive sender and the cognitive relay, between the PS and the cognitive receiver, and between the PS and the cognitive relay, respectively, and s_a and s_{PS} are the data signals transmitted by the cognitive sender and the PS, respectively. The cognitive receiver decodes the data after the data is received. The decoding is correct if the SINR measured at the cognitive receiver is higher than a certain threshold. If the decoding is correct, the cognitive receiver informs the cognitive sender that the decoding is correct. Otherwise, the cognitive receiver informs the cognitive relay that the decoding is failed. Then, in the second time slot, the cognitive relay sends the data to the cognitive receiver if the decoding of the data received from the cognitive sender at the cognitive relay is correct. In the second time slot, the received signal at the cognitive receiver can be written as

$$y_{e,2} = \sqrt{P_b d_{b,e}^{-\alpha}} h_{b,e} s_b + \sqrt{P_{PS} d_{PS,e}^{-\alpha}} h_{PS,e} s_{PS} + n_{b,e}, \tag{12}$$

where $d_{b,e}$ denotes the distance between the cognitive relay and the cognitive reciever, $h_{b,e}$ represents the Rayleigh fading coefficient of the channel between the cognitive relay and the cognitive receiver, and s_b is the data signal transmitted by the cognitive relay.

D. Probability of the Successful Reception of a Packet of the Cognitive Receiver of the Cognitive Cooperative Transmission Interfered by the PS

By using the method in [10], we derive the probability of successful reception of a packet at the cognitive receiver of the cognitive cooperative transmission interfered by the PS. The outage probability of receiving a packet at the cognitive receiver can be given by

$$p_e^O = \Pr(\text{Outage}|\text{SINR}_{e,1} < \gamma_c)\Pr(\text{SINR}_{e,1} < \gamma_c), \quad (13)$$

where $\text{SINR}_{e,1}$ denotes the SINR measured at the cognitive receiver after the data transmitted from the cognitive sender is received at the cognitive receiver, and γ_c represents the predefined SINR threshold of the cognitive transmission. The conditional outage probability in (13) can be expressed as

$$\begin{aligned}\Pr(\text{Outage}|\text{SINR}_{e,1} < \gamma_c) &= \Pr(\text{SINR}_b < \gamma_c)\\ &+ \Pr(\text{SINR}_b \geq \gamma_c)\Pr(\text{SINR}_{e,2} < \gamma_c|\text{SINR}_{e,1} < \gamma_c),\end{aligned} \quad (14)$$

where SINR_b denotes the SINR measured at the cognitive relay after the data transmitted from the cognitive sender is received at the cognitive relay, and $\text{SINR}_{e,2}$ represents the SINR measured at the cognitive receiver after the data transmitted from the cognitive relay is received at the cognitive receiver. Because the event $\text{SINR}_{e,2} < \gamma_c$ and the event $\text{SINR}_{e,1} < \gamma_c$ are independent, (14) can be rewritten as

$$\begin{aligned}\Pr(\text{Outage}|\text{SINR}_{e,1} < \gamma_c) &= \Pr(\text{SINR}_b < \gamma_c)\\ &+ \Pr(\text{SINR}_b \geq \gamma_c)\Pr(\text{SINR}_{e,2} < \gamma_c).\end{aligned} \quad (15)$$

By substituting (15) into (13), we can obtain

$$\begin{aligned}p_e^O &= \Pr(\text{SINR}_b < \gamma_c)\Pr(\text{SINR}_{e,1} < \gamma_c)\\ &+ \Pr(\text{SINR}_b \geq \gamma_c)\Pr(\text{SINR}_{e,2} < \gamma_c)\Pr(\text{SINR}_{e,1} < \gamma_c).\end{aligned} \quad (16)$$

Let p_e^S denote the probability of successful reception of a packet at the cognitive receiver. By substituting $p_e^O = 1 - p_e^S$ into (16) and using $\Pr(X < f) = 1 - \Pr(X \geq f)$, we can get

$$\begin{aligned}p_e^S &= \Pr(\text{SINR}_{e,1} \geq \gamma_c)\\ &+ \Pr(\text{SINR}_b \geq \gamma_c)\Pr(\text{SINR}_{e,2} \geq \gamma_c)\\ &- \Pr(\text{SINR}_b \geq \gamma_c)\Pr(\text{SINR}_{e,2} \geq \gamma_c)\Pr(\text{SINR}_{e,1} \geq \gamma_c),\end{aligned} \quad (17)$$

where

$$\Pr(\text{SINR}_{e,1} \geq \gamma_c) = \frac{\exp\left(-\frac{\gamma_c N_0}{P_a d_{a,e}^{-\alpha}}\right)}{1 + \gamma_c \frac{P_{PS}}{P_a}\left(\frac{d_{a,e}}{d_{PS,e}}\right)^{\alpha}}, \quad (18)$$

$$\Pr(\text{SINR}_b \geq \gamma_c) = \frac{\exp\left(-\frac{\gamma_c N_0}{P_a d_{a,b}^{-\alpha}}\right)}{1 + \gamma_c \frac{P_{PS}}{P_a}\left(\frac{d_{a,b}}{d_{PS,b}}\right)^{\alpha}}, \quad (19)$$

and

$$\Pr(\text{SINR}_{e,2} \geq \gamma_c) = \frac{\exp\left(-\frac{\gamma_c N_0}{P_b d_{b,e}^{-\alpha}}\right)}{1 + \gamma_c \frac{P_{PS}}{P_b}\left(\frac{d_{b,e}}{d_{PS,e}}\right)^{\alpha}}. \quad (20)$$

E. Routing Algorithm

First, the cognitive node that is nearest away from the cognitive sender is selected as the cognitive relay. Let the cognitive receiver be the CD. Check if the participation of the selected cognitive relay can satisfy the QoS requirement of the cognitive transmission $p_e^S \geq \delta_c$, where δ_c denotes the QoS threhsold of the cognitive transmission. If so, the algorithm terminates. Otherwise, calculate the probability of the successful reception of a packet of each cognitive receiver candidate whose x coordinate is lareger than that of the cognitive relay. Then, among the cognitive receiver candidates that satisfy the QoS requirement of the cognitive transmission, the one whose x coordinate has the largest difference from that of the cognitive relay is selected as the cognitive receiver. The multihop route can be established by repeating the procedures stated above until the selected cognitive receiver has the largest x coordinate among all the cognitive nodes except the CD. The detail algorithm is presented as follows:

1) Set $i = 0$, $j = 1$, $k = 0$, and $A_0 = CS$.
2) Let E_g denote the set of nodes whose x coordinates are larger than the x coordinate of node g except the CD.
3) Among E_{A_i}, select the cognitive node that is nearest away from A_i as the cognitive relay B_j.
4) Let $a = A_i$, $b = B_j$, and $e = CD$ and use (17) to calculate p_e^S. If $p_e^S \geq \delta_c$, or B_j has the largest x coordinate among all the cognitive node except the CD, let $k = 1$ and go to 7). Otherwise, go to the next step.
5) For each cognitive receiver candidate in E_{B_j}, let e be the cognitive receiver candidate and use (17) to calculate p_e^S.
6) Among the candidate cognitive receivers whose p_e^S's are equal to or larger than δ_c, select the one whose x coordinate has the largest difference from that of B_j as A_{i+1}. If A_{i+1} has the largest x coordinate among all the cognitive nodes except the CD, let $k = 1$.
7) If $k = 0$, let $i = i+1$, $j = j+1$, and go to 3). Otherwise, terminate.

III. PERFORMANCE EVALUATION

The computer simulations are conducted to investigate the average numbers of hops of the FNR and the MCR and the performances of the FNR and the MCR in terms of the average end-to-end relaibility, the average end-to-end throughput, and the average required transmission power. Table 1 lists the simulation parameters. The coordinates of the PS, the PD, the CS, and the CD are $(0, d_{PS,CS}+50)$, $(d_{PS,PD}, d_{PS,CS}+50)$, $(0, d_{CS,CD}/2)$, and $(d_{CS,CD}, d_{CS,CD}/2)$, respectively. The other cognitive nodes are randomly distributed in a square area. The cooridates of the vertices of the square are $(0, 0)$,

TABLE I
SIMULATION PARAMETERS.

parameter	value
SINR thresholds γ_p and γ_c	3
noise power N_0	-70 dBm
distances $d_{PS,PD}$ and $d_{CS,CD}$	100m
QoS threshold δ	0.95
QoS thresholds δ_p and δ_c	0.9
number of the cognitive nodes excluding the CS and the CD	50
transmission rate R of the direct transmission	2 b/s/Hz

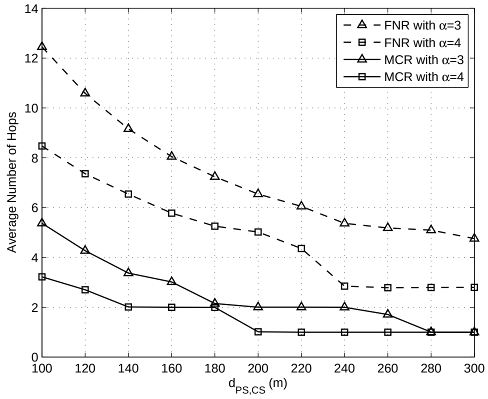

Fig. 4. Average number of hops versus the distance between the PS and the CS of the FNR and the MCR with $\alpha = 3$ and $\alpha = 4$.

$(0, d_{CS,CD})$, $(d_{CS,CD}, 0)$, and $(d_{CS,CD}, d_{CS,CD})$. The transmission power of the PS is given by

$$P_{PS} = -\frac{\gamma_p N_0}{d_{PS,PD}^{-\alpha} \log \delta}, \tag{21}$$

where δ denotes the QoS threshold of the interference-free primary transmission. The simulation results are averaged over 10000 network scenarios.

Figure 4 shows the average number of hops versus the distance between the PS and the CS of the FNR and the MCR with $\alpha = 3$ and $\alpha = 4$. From Fig. 4, we can observe that the average number of hops decreases or remains almost constant or remains constant when the distance between the PS and the CS increases. The reason of the decrease of the average number of hops is explained as follows. When the distance between the PS and the CS becomes larger, the cognitive nodes suffer from less interference from the PS, and according to (8) and (9), the transmission power of the cognitive sender and the cognitive relay increases. Therefore, subject to the same QoS requirement, each hop distance of FNR and the lengths of the x axis projections of the hop distances of MCR both become longer. The average numbers of hops are reduced due to the longer hop distances and the longer lengths of the x axis projections of the hop distances. Figure 4 also reveals that at $\alpha = 3$ and $\alpha = 4$, the average number of hops of the MCR is less than that of the FNR because the cooperative transmission increases the the lengths of the x axis projections of the hop distances.

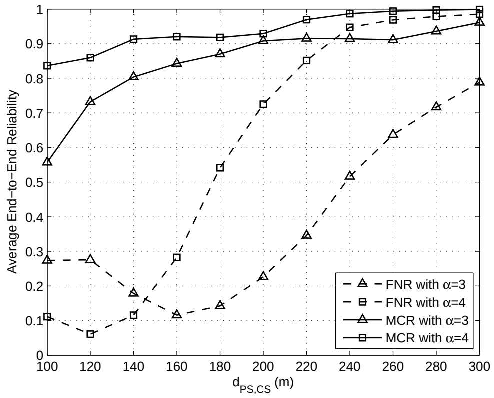

Fig. 5. Average end-to-end reliability versus the distance between the PS and the CS of the FNR and the MCR with $\alpha = 3$ and $\alpha = 4$.

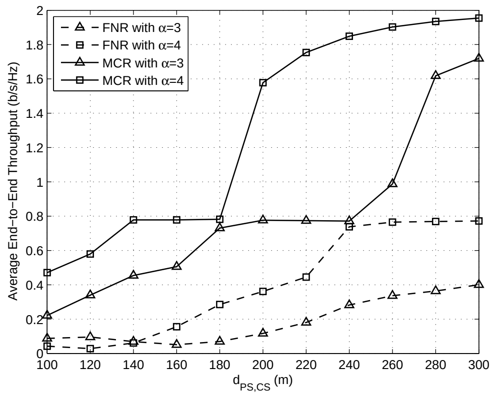

Fig. 6. Average end-to-end throughput versus the distance between the PS and the CS of the FNR and the MCR with $\alpha = 3$ and $\alpha = 4$.

Figure 5 shows the average end-to-end reliability versus the distance between the PS and the CS of the FNR and the MCR with $\alpha = 3$ and $\alpha = 4$. At $\alpha = 3$ and $\alpha = 4$, compared to the FNR, the MCR increases the average end-to-end reliability. This is caused by that the MCR reduces the average number of hops compared to the FNR.

Figure 6 shows the average end-to-end throughput versus the distance between the PS and the CS of the FNR and the MCR with $\alpha = 3$ and $\alpha = 4$. The throughput of the ith hop, where $i = 1, ..., M$, is defined as

$$t_c^{(i)} = R^{(i)} \times \beta_c^{(i)}, \tag{22}$$

where $R^{(i)}$ denotes the transmission rate of the ith hop. We know that the end-to-end throughput equals to the minimum of the throughputs of all hops. Besides, because the transmission occurs at only one hop at any time, the end-to-end throughput is reduced by the factor of M. The end-to-end throughput can be expressed as

$$T = \min_{i=1,...,M} \frac{t_c^{(i)}}{M}. \tag{23}$$

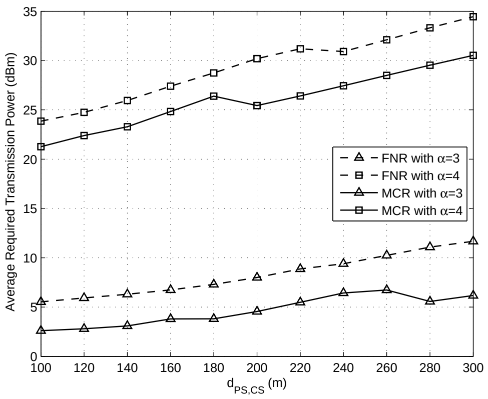

Fig. 7. Average required transmission power versus the distance between the PS and the CS of the FNR and the MCR with $\alpha = 3$ and $\alpha = 4$.

Figure 6 also reveals that at $\alpha = 3$ and $\alpha = 4$, the MCR increases the aveage end-to-end throughput compared to the FNR. This is also caused by that the MCR reduces the average number of hops compared to the FNR.

Figure 7 shows the average required transmission power versus the distance between the PS and the CS of the FNR and the MCR with $\alpha = 3$ and $\alpha = 4$. The required transmission power can be written as

$$P = \sum_{i=1}^{M} P_c^{(i)}, \tag{24}$$

where $P_c^{(i)}$ represents the required cognitive transmission power of the ith hop. From Fig. 7, we can observe the following phenomena. The average required transmission power of the FNR with $\alpha = 3$ increases when the distance between the PS and the CS increases. The average transmission power of the FNR with $\alpha = 4$ and the MCR with $\alpha = 4$ decreases when the distance between the PS and the CS increases from 220m to 240m and from 180m to 200m, respectively. Except when the distance between the PS and the CS is between 220m and 240m and between 180m and 200m, the average transmission power of the FNR with $\alpha = 4$ and the MCR with $\alpha = 4$ increases, respectively, when the distance between the PS and the CS increases. The average required transmission power of the MCR with $\alpha = 3$ remains almost constant and decreases when the distance between the PS and the CS is between 160m and 180m and increases from 260m to 280m, resepctively. Except those ranges, the average required tranmission power of the MCR with $\alpha = 3$ increases when the distance between the PS and the CS increases. The reasons of the increase, the decrease, and remaining almost constant of the average required transmission power are described as follows. When the distance between the PS and the CS increases, the distances between the cognitive sender and the PD and between the cognitive relay and the PD also increase. Consequently, according to (8) and (9), the transmission power of the cognitive sender and the cognitive relay increases. When the distance between the PS and the CS increases, although the average number of hops decreases, the total average required transmission power increases due to the increase of the transmission power of the cognitive sender and the congnitive relay. On the other hand, when the distance between the PS and the CS increases, although the required transmission power of the cognitive sender and the cognitive relay increases, the total average required transmission power decreases or remains almost constant because of the decrease of the number of hops. Figure 7 also reveals that at $\alpha = 3$ and $\alpha = 4$, the required transmission power of MCR is less than that of the FNR.

IV. CONCLUSION

In the FNR, the multihop relaying causes the large degradation of the end-to-end relaibility. To reduce the number of hops, we have proposed a MCR algorithm that prolongs the lengths of the x axis projections of the hop distances and finds the multihop route that minimizes the number of hops. Simulation results show that the average number of hops of the MCR is less than that of the FNR, and the MCR outperfoms the FNR in terms of the average end-to-end reliability, the average end-to-end throughput, and the average required transmission power.

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