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Collaborative Multi-hop Routing in Cognitive Wireless Networks

Dingde Jiang[1] · Xu Ying[1] · Yang Han[1] · Zhihan Lv[2]

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Abstract The collaboration of nodes in cognitive wireless networks is a large challenge. This paper studies the collaborative multi-hop routing in cognitive networks. We propose a new algorithm to construct the collaborative routing in multi-hop cognitive networks. Our algorithm takes into account the interference among nodes including primary and secondary users. The clustering and collaboration are exploited to improve the performance of collaborative routing in multi-hop cognitive wireless networks with multiple primary and secondary users. By analyzing the maximum transmission distance, collaborations, transmission angle control and power control, and channel allocation, we propose a new clustering-based collaborative multi-hop cognitive routing algorithm to attain better network performance. Simulation results show that our approach is feasible and effective.

Keywords Cognitive networks · Channel allocation · Node collaboration · Multi-hop wireless communications · Directional antenna

1 Introduction

Current communication network development has a large limitation due to finite network resources, particularly in wireless networks [1–3]. Spectrum resources in wireless networks have received a huge challenge due the contradiction between the lack of existing spectrum resources and the access of a large number of wireless devices [4–6]. Cognitive wireless technologies have been proposed to overcome this problem. Although these technologies have extensive studied so far, their feasibility and applicability to overcome new appearing

✉ Dingde Jiang
jiangdingde@ise.neu.edu.cn

1 College of Information Science and Engineering, Northeastern University, Shenyang 110819, China

2 SIAT, Chinese Academy of Science, Shenzhen, China

situations still face many challenges. Multi-hop wireless cognitive communications with multiple primary and secondary users have been paid extensive attention to in current mobile and wireless applications. We study how to exploit the collaboration to create the effective routing in this paper. However, how to construct the effective and feasible route from source node to destination node is a large challenge.

Cognitive technologies in wireless networks have extensively been studied. Power control optimal game [7] and social relationship [8] were applied to reduce the network interference and reach the optimal channel allocation. The spectrum hole prediction and channel characteristics had been exploited to perform multichannel selection [9]. The contention overhead of relay nodes was studied in multi-hop collaborative relay networks [10]. The linear programming was used to overcome the lifetime optimization in wireless sensor networks and create the cooperative routing [11]. The selection and the prioritization in the cooperative opportunistic routing for multi-hop wireless mesh networks has been studied [12]. To balance energy distribution among nodes, how to select cooperative relay nodes and assign their transmission power was used to construct the appropriate collaborative routing [13]. Unified space–time metrics [14] had been extensively studied. Optimal symmetric strategy with maximum network throughput had been proposed to avoid selfish behaviors of network nodes [15]. Joint cross-layer distributed approach with maximum network throughput was used to build the effective routing and channel allocation in multi-hop and multi-flow mobile ad hoc cognitive networks [16]. However, most of these methods do not investigate the collaborative multi-hop cognitive routing problem for multiple primary and secondary users in wireless networks.

This paper studies the collaborative multi-hop routing in cognitive networks. Different from previous methods, we investigate the multi-hop collaborative routing in cognitive wireless networks with multiple primary and secondary users. In such a case, to create a feasible and effective collaborative cognitive routing is much more difficult due to the intensive inference among nodes including primary users, secondary users, and primary and secondary users. We propose a new algorithm to construct the collaborative routing in multi-hop cognitive networks. We take into account the interference among nodes including primary and secondary users. We use the clustering [17, 18] and collaboration to improve the performance of collaborative routing in the case of multi-hop multiple primary and secondary users. We analyze the maximum transmission distance, collaborations, transmission angle control and power control, and channel allocation in cognitive wireless networks with multiple primary and secondary users. We present a new clustering-based collaborative multi-hop cognitive routing algorithm to attain better network performance. Finally, we conduct a series of numerical experiments to validate our approach. Simulation results show that our approach is promising and effective.

The remainder is organized as follows. Section 2 describes the network model. Section 3 discuss our method. Section 4 conducts the numerical experiments and analysis. We conclude our work in Sect. 5.

2 Network Model

In this section, we discuss the network models and our algorithm including transmission model with directional antenna and network model with multi-hop cooperation.

2.1 Transmission Model with Directional Antenna

In multi-hop wireless cognitive network, the sender of secondary users often know the position of the receiver, so secondary users can make directional transmission to transfer data packets from the source node to the destination node. In this paper, we use the transmission model that sends the message between nodes exploiting directional sending and omni-directional receiving antennas shown in Fig. 1.

In Fig. 1, s_u and s_v denote the sender and receiver of secondary users. s_u uses directional sending mode and main lobe width is θ_u. s_v uses omni-directional receiving mode. When s_u sends data and s_v is in s_u's main lobe, s_v's receiving power gain is:

$$g_{p_{u,v}} = \frac{2\pi}{\theta_{u,v}} \tag{1}$$

The receiving link gain is:

$$g^n_{L_{u,v}} = (d^{S,S}_{u,v})^{-\delta^n} \tag{2}$$

If there are r times transmitting power inside the main lobe, i.e. $(1 - r)$ times radiate to the environment, then the total receiving gain of the receiving end $g^n_{s_u,s_v}$ is:

$$g^n_{s_u,s_v} = r \times g_{L_{u,v}} \times g_{p_{u,v}} \tag{3}$$

Formula (3) indicates that when secondary users' receiving end lies within the main lobe of the sending end, it can gain good receiving gain. According to formula (3), the receiving power of the secondary user is:

$$P^{n,t}_{s_u,s_v} = P^{n,t}_{s_u} \times g^n_{s_u,s_v} \tag{4}$$

Only when the Signal Interference Noise Ratio (SINR) of the receiving end exceeds the threshold value, receiving end can receive signal properly, i.e.:

$$\Theta_{s_v} \le \frac{P^{n,t}_{s_u,s_v}}{N_{s_v} + W^{n,t}_{s_v}} \tag{5}$$

where Θ_{s_v} denotes the threshold value of SINR. N_{s_v} is the noise, and $W^{n,t}_{s_v}$ denotes the interference power. Combining with formula (4), we can get the following minimum transmitting power using the directional transmitting antenna at node s_u [19]:

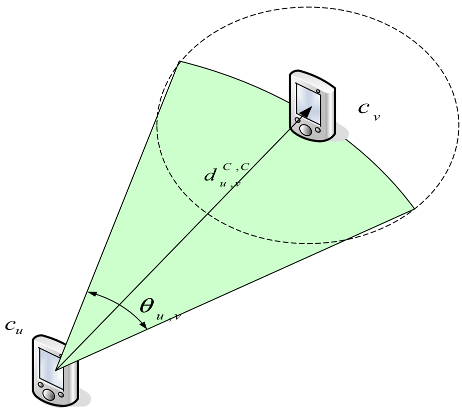


Fig. 1 Directional antenna transmission model

$$P_{s_u}^{n,t} \geq \frac{\Theta_{s_v} \times (N_{s_v} + W_{s_v}^{n,t})}{g_{s_u,s_v}^{n}} \tag{6}$$

2.2 Multi-hop Collaborative Communication Model

In this paper, we discuss multi-hop collaborative communication between multiple primary users and multiple secondary users. The network model of multi-hop collaborative communications is shown in Fig. 2. In this network model, multiple primary users send message through a base station while multiple secondary users conduct multi-hop collaborative communications through multiple middle secondary user (cognitive user) nodes. Supposing that in multi-hop wireless network, primary users are $P = \{p_1, p_2, \ldots, p_N, p_d\}$ and p_d denotes base station. Secondary users are $s = \{s_1, s_2, \ldots, s_K\}$ and there are N available channels. Each channel is divided into I time slots. Communication between different secondary users causes interference to the corresponding primary users, and communication between different primary users have the same effect on the secondary users too. In this network model, we should consider how to maximize spectrum efficiency under the situation that secondary users have no impact on primary users' normal communication, and how to provide reliable communication and improve spectrum utilization between secondary users by mutual cooperating between secondary users.

In this network model, the sending end of secondary users uses directional antenna to send signals and the receiving end uses omni-directional receiving antenna to receives signals. Thus the transmission model between primary users for sending message can be expressed as follows:

$$\frac{P_{p_u}^{b} G_{p_u,p_d}^{b}}{R_{p_d}} \geq \sum_{\substack{n \in N \\ n \neq u}} P_{p_n}^{b} G_{p_n,p_d}^{b} + \sum_{k \in K} P_{s_k}^{b} G_{s_k,p_d}^{b} + N_{p_d} \tag{7}$$

where N_{p_d} denotes thermal (and/or ambient) noise. b denotes the channel that primary users use, $P_{p_u}^{b}$ denotes primary users' sending power, G_{p_u,p_d}^{b} denotes the receiving power gain of

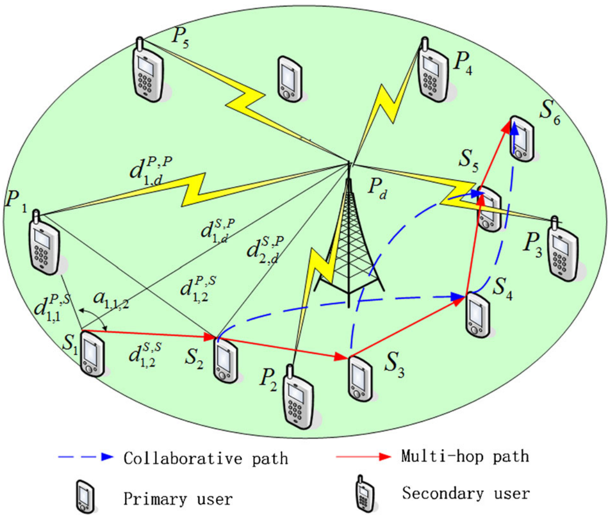


Fig. 2 Multi-hop collaborative communication network model

sending end p_u in receiving end p_d, R_{p_d} denotes SIR of the primary receiving end p_d, $P^b_{p_n}$ denotes other primary users' transmitting power which use the same channel b, $G^b_{p_n,p_d}$ denotes receiving power gain of the sending end p_n under the same channel $b$in primary receiving end p_d, $P^b_{s_k}$ denotes transmitting power of other secondary users s_k under the same channel b, and $G^b_{s_k,p_d}$ denotes the receiving power gain of secondary user sending end s_k under the same channel $b$in primary receiving end p_d. Formula (7) denotes the normal transmitting model between primary users p_u and base station p_d.

Likewise, the message transmission model between secondary users can be expressed as follows:

$$\frac{P^c_{s_u} G^c_{s_u,s_v}}{R_{s_v}} \geq \sum\nolimits_{\substack{n \in K \\ n \neq u}} P^c_{s_n} G^c_{s_n,s_v} + \sum\nolimits_{k \in N} P^c_{p_k} G^c_{p_k,s_v} + N_{s_v} \tag{8}$$

where N_{s_v} denotes thermal (and/or ambient) noise, c denotes the channel that secondary users use, $P^c_{s_u}$ denotes transmitting power of secondary users, $G^c_{s_u,s_v}$ denotes receiving power gain of the sending end s_u in the receiving end s_v of secondary users, $P^c_{p_k}$ denotes transmitting power of other primary users p_k under the same channel c, and $G^c_{p_k,s_v}$ denotes receiving power gain of primary users sending end p_K under the same channel c in secondary users' receiving end s_v. Formula (8) denotes the normal transmitting model between secondary users s_u and s_v.

In this network model, proper channel allocation is needed to guarantee reliable communication between the primary and secondary users and to avoid secondary users affecting normal communication of primary users. In this paper, we exploit graph coloring model to allocate proper channels for multiple secondary users in the multi-hop cognitive collaborative transmission process. The available matrix, channel interference matrix and channel utility matrix are used to achieve this goal. The detailed allocation process is to formulate in the following Sect. 3.4. Additionally, to effectively avoid the impact of secondary users on normal communication of primary users, in the channel allocation process, channel interference matrix and channel utility matrix are utilized to implement it. At the same time, the directional antenna, clustering and node collaboration are also exploited to overcome this impact. The corresponding derivation can found in Sect. 3. Meanwhile, reliable cooperation should be done between secondary users to ensure information transmission between secondary users. The following discuss are all based on the two models above i.e. directional antenna transmission model and multi-hop collaborative communication network model. In the next section, we will introduce our proposed cognitive multi-hop collaboration algorithm.

3 Cognitive Multi-hop Collaboration Algorithm

In the cognitive collaborative multi-hop communication network based on directional antenna, the transmission radius that different secondary users use different channels is often not the same. When we construct multi-hop paths, the paths will change while sending message because the channels which users use are not constant. To decrease the algorithm complexity, we firstly use omni-directional antenna to construct multi-hop collaborative paths, and then change it into directional antenna by adjust antenna main lobe and sending angle. According to the different transmitting radius that different channels users use, each user who participate in communication are assigned to certain channel. In this section, we will discuss the maximum transmission radius, collaborative multi-hop transmission paths, sending angle, transmitting power control, channel allocation strategy and cognitive collaborative multi-hop algorithm of secondary users.

3.1 Maximum Transmission Radius

When secondary users use omni-directional antenna, the maximum transmission radius of secondary users concerns with the state of primary users and the inference between secondary users. When primary users don't use channels, the maximum transmission radiuses are all maximum values no matter secondary users use omni-directional antenna or directional antenna. But the sending angle of secondary users is different, the former is 360°, the latter is θ.

According to Fig. 2, in the directional antenna transmission model of our paper, when secondary user s_u use directional antenna, its transmission angle faces receiving end s_v, and if secondary user s_n is out of the range of the main lobe, then the receiving power of secondary user s_n is:

$$P^{n,t}_{s_u,s_n} = P^{n,t}_{s_u} \times (d^{S,S}_{u,n})^{-\delta} \times (1-r) \tag{9}$$

Because r is often very large, secondary user's sending end don't produce any interference to other secondary users. When secondary user s_n is inside the main lobe range, s_n participates in the cooperation of node s_v. The receiving power of s_n is calculated according to formula (4). Thereby, when the sending angle of secondary users is settled, secondary user makes no effect on the users that don't joint in the communication. That is to say, the maximum transmission radius of secondary user depends on itself. The formula is shown as follow:

$$d^{S,S}_{u,v} \leq \left(\frac{P^{n,t}_{s_u}}{\Theta_{s_v}(N_{s_v} + W^{n,t}_{s_v})} \frac{2\pi}{\theta_{u,v}} r \right)^{\frac{1}{\delta^n}} \tag{10}$$

In conclusion, when primary user doesn't use the channel, secondary users calculate maximum transmission radius according to formula (10). When primary user uses the channel, secondary users calculate maximum transmission radius according to the below formula:

$$\begin{cases} d^{S,S}_{u,v} \leq \left(\frac{P^{n,t}_{s_u}}{\Theta_{s_v}(N_{s_v} + W^{n,t}_{s_v})} \frac{2\pi}{\theta_{u,v}} r \right)^{\frac{1}{\delta^n}} \\ s.t. \frac{P^b_{p_u} G^b_{p_u,p_d}}{R_{p_d}} \geq \sum_{\substack{n \in N \\ n \neq u}} P^b_{p_n} G^b_{p_n,p_d} + \\ P^b_{s_u} G^b_{s_u,p_d} + N_{p_d} \end{cases} \tag{11}$$

where Θ_{s_v} denotes SNR's threshold value of secondary user s_v at maximum transmission radius, $P^{n,t}_{s_u}$ denotes transmitting power of secondary user s_u, $\theta_{u,v}$ denotes the directional sending angle when s_v sends the message to s_v, and r denotes the power ratio of s_u in main lobe.

3.2 Collaborative Multi-hop Transmission Paths

In the process of cognitive collaborative multi-hop communication, secondary users can not disturb the normal communication of primary users. What is more, the interference between secondary users should be as small as possible so that primary and secondary users can both communicate reliably. Secondary users will act as none authoritative users and sense the channels that authoritative users don't use. Multiple secondary users perform the cooperation. To realize the above purpose and build collaborative multi-hop transmission paths from source node to destination node of secondary users, we propose a maximum receiving power set algorithm based on clustering collaboration. According to the limited maximum transmission radius of secondary users, we take the nodes that can be covered by the radius of sending node as a cluster. The head of the cluster is the sending node. Only the nodes inside the cluster can participate in cooperation and the nodes out of the cluster must take the message inside the cluster as noise and abandon it. Besides, we use achievable rate to guarantee the possibly maximum transmitting power while power is limited. As mentioned in [20], the achievable rate of the receiving signal of node s_r is:

$$V_{s_r}(\mu_{s_r}) = \frac{1}{2}\log(1 + \mu_{s_r}) = \frac{1}{2}\log(1 + \frac{Pr_{s_r}}{N_{s_r}}) \tag{12}$$

where μ_{s_r} denotes SNR, N_{s_r} expresses noise, and Pr_{s_r} stands for transmitting power of the secondary user.

If we define paths set $L_j^{s_i} = \{s_1, \varphi, c_d\}$, then the achievable rate of the jth path L_j can be denoted as:

$$V_{L_j} = mean\{V_{s_r}\}, \quad s_r \in L_j \backslash s_1 \tag{13}$$

The achievable rate of the path indicates the average achievable rate value of other secondary users' nodes except node s_1 in the path L_j.

The transmission radius of different channels that different users use is different too, that is to say, the clusters are different. So, we define collaboration matrix A_n^t as follows:

$$A_n^t = \begin{pmatrix} a_{s_1,s_1}^{n,t} & a_{s_1,s_2}^{n,t} & \cdots & a_{s_1,s_{K-1}}^{n,t} & a_{s_1,s_K}^{n,t} \\ a_{s_2,s_1}^{n,t} & a_{s_2,s_2}^{n,t} & \cdots & a_{s_2,s_{K-1}}^{n,t} & a_{s_2,s_K}^{n,t} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ a_{s_{K-1},s_1}^{n,t} & a_{s_{K-1},s_2}^{n,t} & \cdots & a_{s_{K-1},s_{K-1}}^{n,t} & a_{s_{K-1},s_K}^{n,t} \\ a_{s_K,s_1}^{n,t} & a_{s_K,s_2}^{n,t} & \cdots & a_{s_K,s_{K-1}}^{n,t} & a_{s_K,s_K}^{n,t} \end{pmatrix} \tag{14}$$

where A_n^t denotes if the data that one secondary user uses channel n to send can be received properly by another secondary user at time t. What's more, the following formula holds:

$$a_{s_i,s_j}^{n,t} = \begin{cases} 1, & d_{i,j}^{S,S} \leq Tr_{s_i}^{n,t} \\ 0, & other \end{cases}, \quad i,j \in \{1,2,\ldots,K\} \tag{15}$$

where $Tr_{s_i}^{n,t}$ is the transmission radius of secondary users.

When transmission path L_j is known, the node receiving power in that path can be expressed as follows:

$$\begin{cases} Pr_{s_r}^{n,t} = \sum\limits_{i=1}^{i=r} a_{s_i,s_r}^{n,t} \times P_{s_i,s_r}^{n,t} \quad i \in L_j \\ L_j = \{s_1, s_2, \ldots, s_r, \ldots, s_d\} \end{cases} \tag{16}$$

We can calculate the achievable rate of collaborative multi-hop path L_j according to formulas (12) and (13).

We define achievable node set as $U^t = [U^t_{s_1}, U^t_{s_2}, \ldots, U^t_{s_K}]$. From formulas (14) and (15), we know that the message sent from secondary user s_i can not be received by each user in the network. If $a^{n,t}_{s_i,s_j} > 0$, then node s_j is the achievable node of node s_i. $U^t_{s_i} = [u_1, u_2, \ldots, u_T], \forall a^{n,t}_{s_i,u_j} > 0$, $\exists n > 0$, $t > 0$. Set U^t has nothing to do with the paths.

We define neighbor node set as $B^t = [B^t_{s_1}, B^t_{s_2}, \ldots, B^t_{s_K}]$. The neighbor node set of secondary user s_i at time t is $B^t_{s_i} = \{b^t_1, b^t_2, \ldots, b^t_{|M|}\}$ which means the range of new nodes selected at time t. At first, $B^t_{c_i} = U^t_{c_i}$. After one link is constructed, we update $B^t_{s_i} = B^t_{s_i} \backslash L^t_k, s_i \in L^t_k$. When $Pr_{b_j} > Pr_{b^*_j}, \forall b^*_j \in \{B^t_{s_i} \backslash b_j\}, L^t_k = \{s_1, s_2, \ldots, s_i, b_j\}$, secondary user b_j is the next hop node of s_i and the path is updated as $L^t_k = L^t_k \cup b_j$.

The steps of the maximum receiving power set algorithm based on clustering collaboration can be denoted as follows.

Algorithm1:

Step1: Let time $t = 1$ and initialize the maximum T.

Step2: Initialize the neighbor node set matrix B^t of each secondary user.

Step3: Choose source node s_1, and initialize $L_1 = \{s_1\}$, $m = 1$.

Step4: Construct all possible paths from source node to destination node and calculate the total path number M.

Step5: Choose path L_i and let $m = m + 1$.

Step6: Choose the largest receiving power node from $U^t_{s_j}$ as the next hop of node c_j and label as s_t.

Step7: If s_t does not exist, update $B^t_{s_j}$. Or otherwise let $j = j + 1$ and go back to Step 6.

Step8: If s_j is the last node of path L_i, let $L_i = L_i \cup s_t$. Or otherwise build a new path as follows:

$$L_j = \left\{s_1, \ldots, s_j\right\} \cup s_t, \left\{s_1, \ldots, s_j\right\} \in L_i.$$

Step9: Let $i = i + 1$. If $m < M$, go back to Step 5.

Step10: If $B^t_{s_j}$ is updated, go back to Step 4.

Step11: Update all the paths sets and delete repeated paths.

Step12: Save the path information.

Step13: Let $t = t + 1$. If $t > T$, save the results to the file and exit. Or otherwise go back to Step 2.

According to Algorithm 1, we can get a series of paths from source node to destination node, i.e. $\Pi(L)$. The optimal path is the one whose achievable rate is the largest.

To optimize the path sets obtained in Algorithm, we perform the shortest optimal route set process for the path sets. Then we can get the path with maximum achievable rate and minimum hops through this process.

We define the shortest optimal route candidate set Q^{short}_{opt}, which satisfies three conditions:

- $Q^{short}_{opt} \subseteq Q_{opt}$;
- $L^{short}_{opt} \in Q^{short}_{opt}, \left|L^{short}_{opt}\right| = min[\Pi(|L|)]$, $|L|$ denotes the node number of L;
- $V_{L^{short}_{opt}} = \max(V_{\Pi(L)})$.

If $L_1 \subseteq L_2$ for two random routes L_1, L_2, this means L_1 is the subset of L_2, and the order of nodes in L_2 is the same as that in L_1. If $L_2 = L^{short}_{opt}$ and the achievable rate of its subset L_1 is $V_{L_1} = V_{L^{short}_{opt}}$, then L_1 is the shortest optimal route and we let $L^{short}_{opt} = L_1$.

3.3 Control of Transmission Angle and Power

We can confirm the maximum transmission radius of secondary users from formulas (11) and (12). According to the directional antenna transmission model shown in Fig. 2 and formulas (11) and (12), for sending node s_u whose transmission radius is $d_{u,v}^{S,S}$, when primary user doesn't use the channel, its cover area S_u is:

$$\begin{cases} S_u = \dfrac{\theta_{u,v}}{2}(d_{u,v}^{S,S})^2 \\ s.t.\, d_{u,v}^{S,S} \le \left(\dfrac{P_{s_u}^{n,t}}{\Theta_{s_v}(N_{s_v} + W_{s_v}^{n,t})} \dfrac{2\pi}{\theta_{u,v}} r \right)^{\frac{1}{\delta^n}} \end{cases} \tag{17}$$

When primary user uses the channel, its cover area S_u can be denoted as:

$$\begin{cases} S_u = \frac{\theta_{u,v}}{2}(d_{u,v}^{S,S})^2 \\ s.t.\, d_{u,v}^{S,S} \le \left(\frac{P_{s_u}^{n,t}}{\Theta_{s_v}(N_{s_v} + W_{s_v}^{n,t})} \frac{2\pi}{\theta_{u,v}} r \right)^{\frac{1}{\delta^n}} \\ \frac{P_{pu}^{b} G_{pu,pd}^{b}}{R_{pd}} \ge \sum_{\substack{n\in N \\ n\neq u}} P_{pn}^{b} G_{pn,pd}^{b} + \\ \quad P_{s_u}^{b} G_{s_u,pd}^{b} + N_{pd} \end{cases} \tag{18}$$

In Eqs. (17) and (18), s_u and s_v are arbitrary sending and receiving secondary users, respectively. Moreover, Eqs. (17) and (18) are correct for any sending secondary user s_u and receiving secondary user s_v. Accordingly, without loss of generality, we can attain the maximum transmission radius of secondary sending user s_u as follows:

$$d_{\text{max,u,v}}^{S,S} = \left(\frac{P_{s_u}^{n,t}}{\Theta_{s_v}(N_{s_v} + W_{s_v}^{n,t})} \frac{2\pi}{\theta_{u,v}} r \right)^{\frac{1}{\delta^n}} \tag{19}$$

Thus the maximum cover area of secondary user s_u is:

$$\begin{aligned} S_{\text{max,u}} &= \frac{\theta_{u,v}}{2}(d_{\text{max,u,v}}^{S,S})^2 \\ &= \frac{\theta_{u,v}}{2}\left(\frac{P_{s_u}^{n,t}}{\Theta_{s_v}(N_{s_v} + W_{s_v}^{n,t})} \frac{2\pi}{\theta_{u,v}} r \right)^{2\frac{1}{\delta^n}} \\ &= \frac{1}{2}\left(\frac{2\pi P_{s_u}^{n,t}}{\Theta_{s_v}(N_{s_v} + W_{s_v}^{n,t})} r \right)^{2\frac{1}{\delta^n}} (\theta_{u,v})^{1-2\frac{1}{\delta^n}} \end{aligned} \tag{20}$$

According to formulas (19) and (20), we find that the maximum transmission radius and the maximum cover area of the secondary sending node are closely related to the sending angle. When the transmitting power of the secondary user sending node is certain, the maximum transmission radius of the secondary user is inversely proportional to the angle's $\frac{1}{\delta^n}$ power $(\theta_{u,v})^{\frac{1}{\delta^n}}$, and its cover area is in proportional to the angle's $(1 - 2\frac{1}{\delta^n})$ power $\left(\theta_{u,v}\right)^{1-2\frac{1}{\delta^n}}$. Similarly, from formulas (19) and (20), we find that the maximum transmission radius and the maximum cover area of the secondary user sending node are also very closely related to the sending power. When the sending angle of the secondary user sending node is certain, the maximum transmission radius of the secondary user is in proportional to the transmitting power's $\frac{1}{\delta^n}$ power $(P_{s_u}^{n,t})^{\frac{1}{\delta^n}}$, and its cover area is in proportional to the transmitting power's $2\frac{1}{\delta^n}$ power $\left(P_{s_u}^{n,t}\right)^{2\frac{1}{\delta^n}}$. It can be seen that the secondary user will get different maximum transmission radius and maximum cover area under different sending angles and sending powers. What's more, the different receiving nodes being covered will lead to different collaborative nodes to participate collaborations.

To conduct reliable cognitive multi-hop collaborative communications, we take the following strategies to control the sending angle and transmitting power of the secondary sending node.

Strategy 1 After cognitive multi-hop paths based on the omni-directional antenna is constructed, if there exists the node inside the coverage area of the secondary user and the nodes in the path except the receiving end are in the cluster taking sending end as cluster head, then this node is the collaborative node when the below formulas holds:

$$\{s_v, s_t\} \in S_{s_u}, \{s_u, s_v, s_t\} \in L_i \tag{21}$$

where s_u, s_v, and s_t denote sending end, receiving end and collaborative user, L_i and S_{s_u} express the path and the cluster. The secondary user s_t satisfied with formula (21) is the collaborative user. The sending angle is $\theta_u = \max[\angle(s_v, s_u, s_t)]$. The transmission radius of the secondary user changes into $Tr_{s_u}^{n,t} = \max(d_{u,v}^{S,S}, d_{u,t}^{S,S})$.

Strategy 2 When there does not exists the collaborative node inside the coverage area of the secondary user or the nodes in the path do not meet formula (21), i.e. there are no collaborative node, then the sending angle is $\theta_u = \min\ (\theta)$ and the transmission radius of the secondary user changes into $Tr_{s_u}^{n,t} = d_{u,v}^{S,S}$, where θ is the minimum sending angle defined in advance. We can calculate the transmitting power of the secondary user sending end according to formula (6).

The collaborations of cognitive nodes (secondary user nodes) is shown in Fig. 3.

3.4 Channel Allocation

In the process of cognitive multi-hop collaborative transmission, to ensure normal communication of all primary and secondary users, we need to allocate proper transmission channels to the corresponding secondary users. As mentioned in [21], we utilize graph coloring model to allocate multi-hop cognitive collaborative transmission channels for multiple secondary users. We define available matrix V, channel interference matrix I and channel utility matrix U to make proper channel allocation.

Because secondary users use directional antenna and the sending angle is not constant, it will only affect the primary or secondary user in a certain direction. Thus, we mainly discuss the interference between primary and secondary users and between secondary and secondary users under directional antennas.

When secondary user s_u uses directional antenna to send data to secondary user s_v, another secondary user s_r is affected by secondary user s_u only if the following formula holds:

- $d_{u,r}^{S,S} \le Tr_{s_u}^{m,t}$;
- $\theta_u = \angle(s_r, s_u, s_v) + \angle(s_r, s_u, s_t)$ or $\frac{\theta}{2} \ge \angle(s_r, s_u, s_v)$

The first formula in the condition above is the situation of collaborative node existing in the path while the second formula is the situation of no collaborative nodes. We use the set Ω to denote both conditions above.

There exists interference only if both two conditions above are satisfied. This can be denoted as:

$$I_{s_i,s_j}^{m,t} = \begin{cases} 1, & \Omega \ holds \\ 0, & \Omega \ does \ not \ hold \end{cases} \tag{22}$$

where $I_{s_i,s_j}^{m,t} = 1$ denotes that there is interference among nodes and $I_{s_i,s_j}^{m,t} = 0$ indicates that there does not exist the interference. In the allocation process, we allocate the channel without interference to secondary users, namely consider the case $I_{s_i,s_j}^{m,t} = 0$.

When calculating the channel available matrix, we suppose that the maximum transmission radiuses of secondary users using different channels depends on formula (10) and we ignore the influence of the primary users. Thus, when we allocate channels, we must consider whether the channel m that the secondary user use will influence the primary user. Channel available matrix V can be built as:

$$V_{s_i}^{m,t} = T_t^m \times V_{1s_i}^{m,t} \times I_{s_i,p_m}^{m,t} \tag{23}$$

$$V_{1s_i}^{m,t} = \begin{cases} 1, & a_{s_i,s_j}^{m,t} = 1 \\ 0, & a_{s_i,s_j}^{m,t} = 0 \end{cases} \tag{24}$$

where $a_{s_i,s_j}^{m,t}$ is defined in formula (15) and denotes whether the message from secondary user s_i to secondary user s_j can be received properly, 1 denotes correct receipt, and 0 denotes incorrect receipt.

As mentioned as above, when secondary users use the channel not used by primary users, they can exploit the maximum transmission distance to send data and can obtain the maximum utility for this channel. Moreover, some channels cannot be used by primary users for a long time and thus secondary users should use this kind of channel first to avoid excessive channel switch and the frequent change of network topology. In addition, when secondary users choose channels, they should choose the channels far from primary users to avoid influence on primary users as possible. The channel utility matrix is related with the transmission distance of the secondary user, usage time of the primary user and the distance between primary and secondary users. This relation can be denoted as:

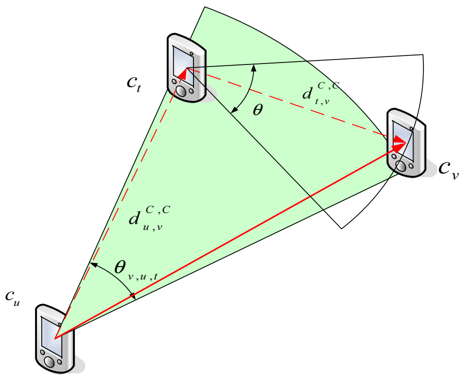


Fig. 3 Collaborations of cognitive nodes

$$U_{s_i}^{m.t} = Tr^2 \times num \times D = (Tr_{s_i}^{m.t})^2 \times \sum_t T_t^m \times d_{i,m}^{S,P} \quad (25)$$

where Tr denotes the transmission distance of the secondary user while using channel m, num denotes the total number of times that the primary user dot not use channel m, D indicates the physical distance between primary and secondary users, T_t^m denotes if the primary user uses channel m at time t, and 0 denotes using it while 1 denotes not using it.

Thereby, according to channel available matrix V, channel interference matrix I and channel utility matrix U, we can allocate proper transmission channel for all secondary users.

3.5 Algorithm

Our algorithm exploits the clustering idea and node collaborations to perform the multi-hop collaborative cognitive routing. By such a way, we can effectively reduce the transmission power of sending nodes while can obtain the maximum receiving power through collaborations. Our algorithm is called as the Clustering-based Collaborative Cognitive Routing algorithm (CCCR). The detailed steps of CCCR is as follows:

Step1: Initialize maximum transmission radius of secondary users using different channels at different time.

Step2: Judge the idle status information of primary users and learn the situation that the primary users use the channels at different times.

Step3: Let $t = 1$ and initialize the maximum T.

Step4: Conduct all possible paths from source cognitive node to destination cognitive node according to Algorithm. Calculate the achievable rate of all paths V^t.

Step5: Conduct the shortest optimal route set process for all the path sets and get the shortest optimal path.

Step6: Analyze each path and judge whether there exist collaborative nodes in each link.

Step7: Calculate sending angle and transmitting power of each sending cognitive user, respectively.

Step8: Save the resulting paths information.

Step9: Conduct the channel allocations according to the channel allocation strategy.

Step9: Let $t = t + 1$.

Step10: If $t$is larger than T, then exit. Or otherwise go back to Step 4.

4 Simulation Results and Analysis

In this section, we are to conduct a series of test to validate our algorithm. Our simulation scenario is a 50 $\times$ 50 square area, including multiple sending primary users (called primary users), one receiving primary user (called base station), and multiple secondary users. The number of primary users is corresponding to the number of channels. We randomly create the positions of primary users, base station, and secondary users. The number of secondary users is 10, 15, and 25. The maximum transmission radius of each secondary user is 10, 15, and 25.

4.1 Multi-hop Forwarding Path

Next, we discuss the multi-hop forwarding path construction from source node to destination node in cognitive wireless networks built according to our algorithm. Figure 4 shows the multi-hop path construction process with directional antennas, where source and destination nodes are 1 and 4, respectively. According to our algorithm, node 16 can receive the signal that node 1 sends to node 18, while node 7 can receive the signal that node 18 sends to node 16. Similarly, node 11 can obtain the signal that node 16 forwards to node 7. Node 8 can obtain the signal that node 7 transmits to node 11. Node 4 can get the signal that node 11 sends to node 13 and node 13 forwards to node 8. Likewise, node 3 can obtain the signal that node 1 sends to node 11 and node 15 can capture the signal that node 8 transmits to node 4. It is clear that using the omni-directional antennas we can built the path from source node 1 to destination node 4 while there exists the larger inference among network nodes. Thereby, our algorithm further uses the directional antennas to optimize the path performance. Then we can obtain the multi-hop path with directional antennas, where the path is constructed by $L = \{1, 18, 16, 7, 11, 13, 8, 4\}$ indicated in Fig. 5. According to our algorithm, we further analyze the path L to find the collaborative nodes 3 and 15. Collaborative nodes 3 and 15 cooperate the links from node 7 to node 11 and from node 8 to node 4, respectively. Finally, we obtain the multi-hope collaborative path according to our algorithm shown in Fig. 6.

4.2 Path Achievable Rate and Collaborations

Now we discuss the path achievable rate and collaborations of our algorithm. When the transmission radius of secondary users becomes large, we can obtain the larger path achievable rate shown in Fig. 7, where N denotes the number of secondary users. This is because the larger the transmission radius is, the more the collaborative nodes are. Thereby one can obtain the larger path achievable rate. Likewise, when the number of secondary users increases, we also get the higher path achievable rate. It is clear that the more secondary users is, the larger the density of nodes. In a result, there are more nodes able to

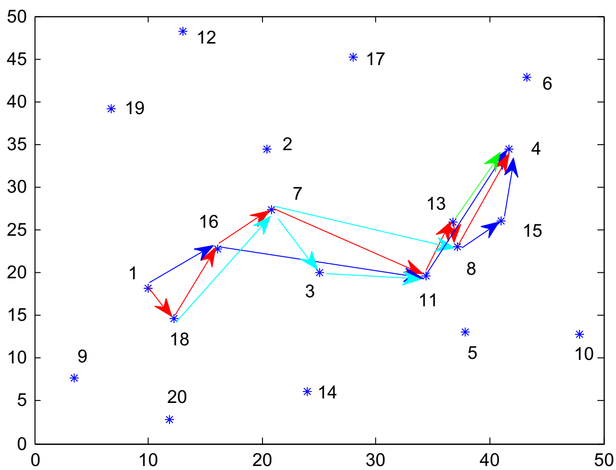


Fig. 4 Multi-hop path construction with omni-directional antennas

Fig. 5 Multi-hop path construction with directional antennas

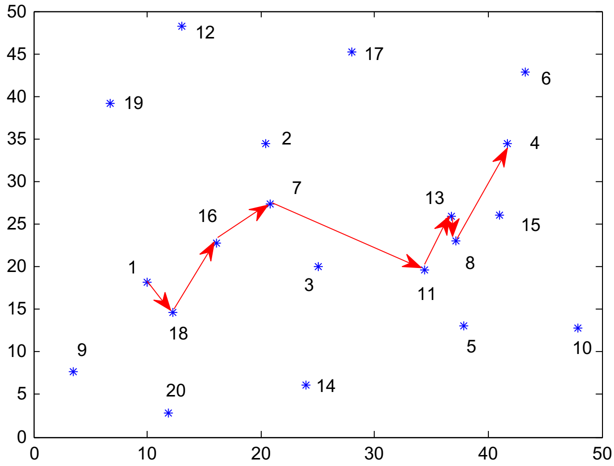
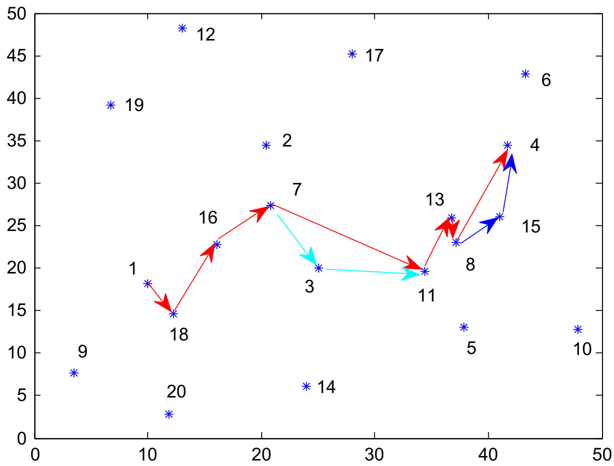


Fig. 6 Multi-hop path with collaborations



take part in the collaborative process and the path achievable rate is raised. Figure 8 plots the impact of transmission radius on the number of collaborative nodes. We can see that the larger transmission radius and secondary users' number lead to more node to participate the collaborations among nodes. However, we also notice that when the transmission radius is 25, there are less collaborative nodes in the case of 25 secondary users that that of 15 ones. According to our algorithm, this case can lead to the larger interference and thus our algorithm only let less nodes participate the collaborations to avoid the interference. This shows that our algorithm holds the better performance.

Next, to further validate our algorithm, we compare CCCR with the Shortest-Path-based Cognitive Routing algorithm (SPCR). We analysis the path achievable rate and collaborations of both algorithms. We can clearly see that CCCR holds the larger path achievable rate than SPCR shown in Fig. 9. However, the different sizes of secondary users have lower affection on the path achievable rate of SPCR while they produce the larger impact on that of CCCR, this is because CCCR can select the optimal routing according to the

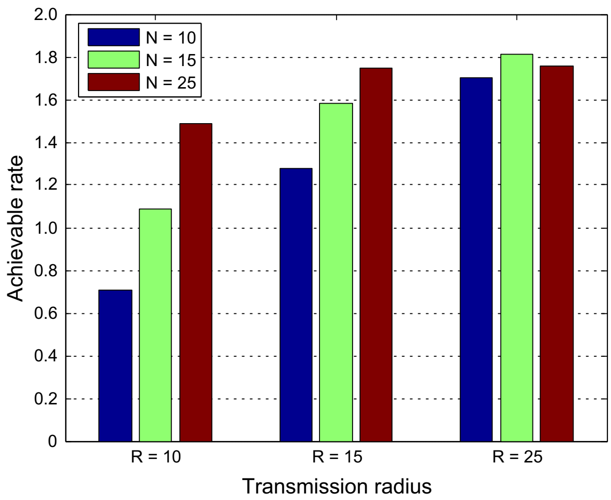


Fig. 7 Impact of transmission radius on achievable rate

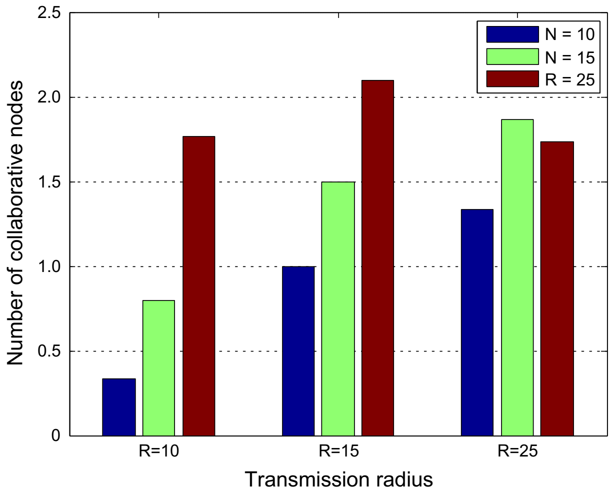


Fig. 8 Impact of transmission radius on number of collaborative nodes

proposed strategies and approach. Moreover, from Fig. 9, we can see that when the number of secondary users is 10, 15, 25, the improve ratios of CCCR's achievable rate to SPCR's one are, respectively, 8.9, 13.9, and 14.1 %. This indicates that CCCR obtain the better network performance. Figure 10 indicates the number of nodes taking part in the collaboration process for both algorithms. For CCCR, different scales of secondary users have the larger impact on the number of collaborative nodes than SPCR. In addition, from Fig. 10, we also see that for both algorithms, when we add secondary users, we can generally obtain the more collaborative nodes. This is because both algorithms always takes into account as many nodes as possible to perform the node collaborations. In such a case, we always expect the more network nodes to achieve the higher path rate. In contrast to SPCR, CCCR can dynamic choose the collaborative nodes according to the network

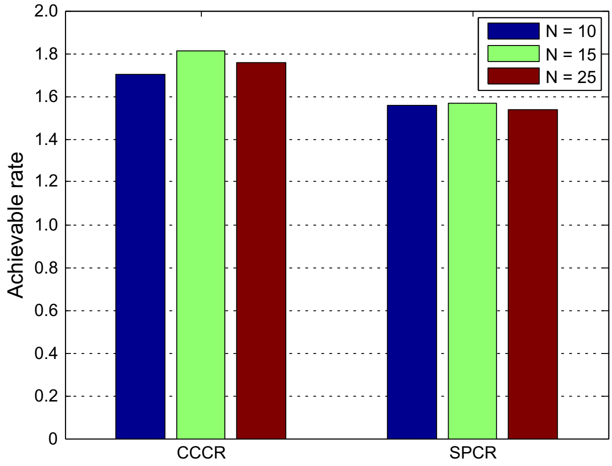
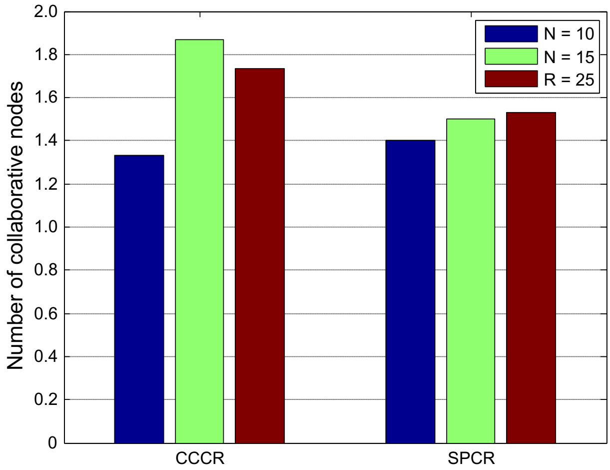


Fig. 9 Impact of different strategies on achievable rate

Fig. 10 Impact of different strategies on number of collaborative nodes



situations. Thereby, CCCR holds the different sizes of collaborative nodes for different scales of secondary users. This further indicates that CCCR hold the better performance.

4.3 Energy Consumption

In this subsection, we analyze the total energy consumption of networks for both algorithms. Figure 11 plots the total energy consumption of networks for SPCR. It is interesting that when the transmission radius is 10, its total transmission power increases with the growth of secondary users, while it decreases when the transmission radius is 25. When the transmission radius is 15, its total transmission power is nearly the same for secondary user with the size by 10 and 15. For 25 secondary users, this exhibits the growth. More importantly, from Fig. 11, we can clear see that for different transmission and sizes of

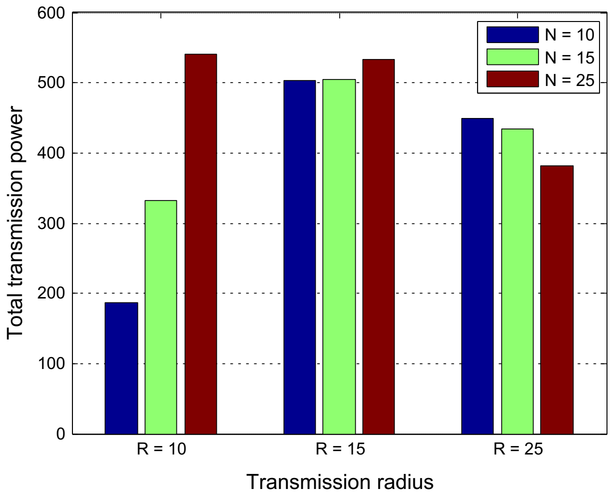


Fig. 11 Total energy consumption of networks for SPCR

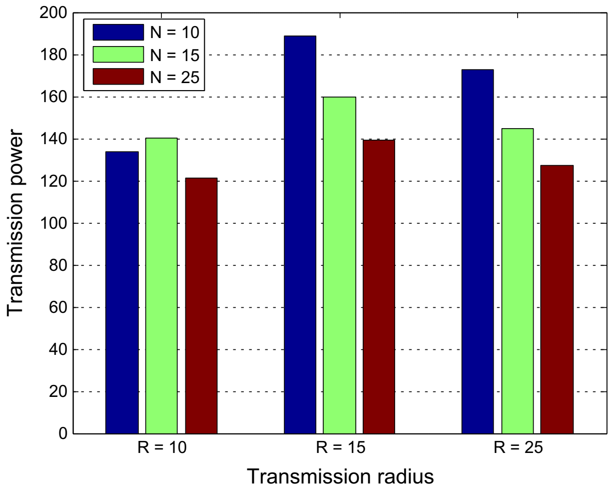


Fig. 12 Energy consumption of networks for CCCR

secondary users, the total transmission power is bigger than 190 and the average total transmission power is about 350. This is a fairly large transmission power. In contrast to SPCR, CCCR hold much lower transmission power shown in Fig. 12. From Fig. 12, we can see that the total energy consumption of CCCR decreases with the addition of the number of secondary users. However, when the transmission radius is 10, the total energy consumption of networks with 15 secondary users is larger than that with 10 and 25 secondary users. In such a case, the total energy consumption of CCCR still decreases with the growth of secondary users. Moreover, Fig. 12 tells us that the total energy consumption of CCCR changes from about 120 to 189 for different transmission radiuses and the different scales of secondary users. This is much lower than the energy consumption of SPCR in Fig. 11. Thereby, CCCR further exhibits the better performance.

4.4 Channel Utility and Network Connectivity

Next, we discuss the channel utility and network connectivity about our algorithm. Figure 13 plots the channel utility of cognitive networks according to our algorithm. When adding the secondary users, we can obtain the increasing channel utility for different transmission radiuses. Moreover, when the transmission radius is 10, we get the maximum channel utility by about 13.2 and the minimum channel utility by about 5. In contrast to the transmission radiuses with 10 and 15, that with 25 has much lower impact on the channel utility. On the whole, the total channel utility of our algorithm is higher. To further the channel utility performance of our algorithm, we calculate the average channel utility of each nodes in the path in Fig. 14. It is clear that when adding the transmission radius and

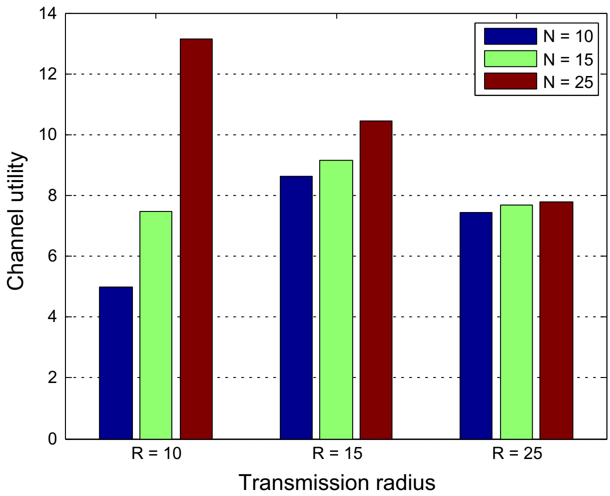


Fig. 13 Channel utility of cognitive networks

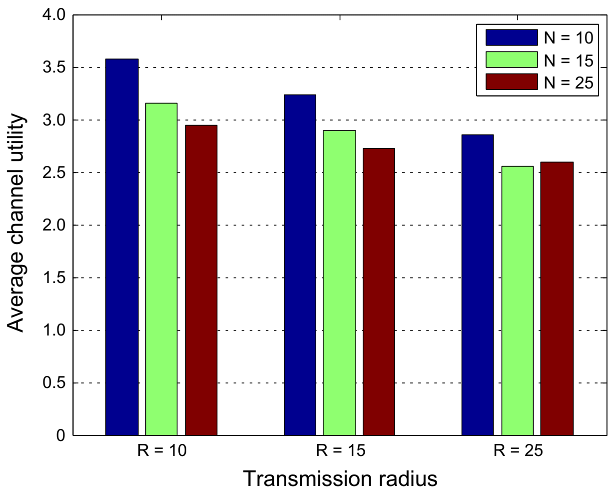


Fig. 14 Average channel utility of each node in cognitive networks

the number of secondary users, we can obtain the larger average channel utility. For different transmission radiuses and the number of secondary users, the average channel utility of each node changes between 2.6 and 3.6, this shows that our algorithm holds the better channel utility.

Figure 15 indicates the impact of the transmission radius and the number of secondary users on the number of available channels. For different transmission radiuses, when the number of secondary users changes larger, we can obtain the more available channels. Furthermore, the number of available channels varies between 5 and 13. To further the performance of our algorithm in the available channels, we computer the average number of available channels for each node in Fig. 16. Figure 16 shows that when adding the transmission radius and the number of secondary users, we can get the larger number of available channels for each node on average. Moreover, the average number of available

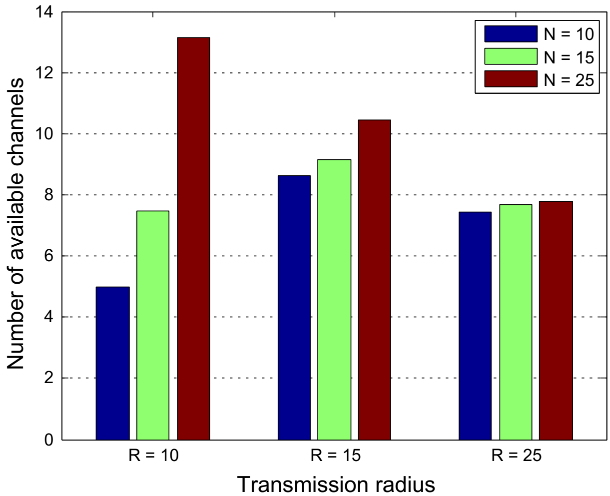


Fig. 15 Number of available channels for different transmission radiuses

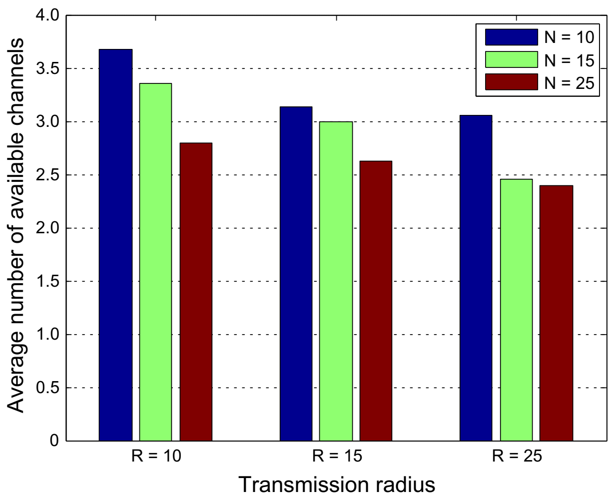


Fig. 16 Number of average available channels for different transmission radiuses

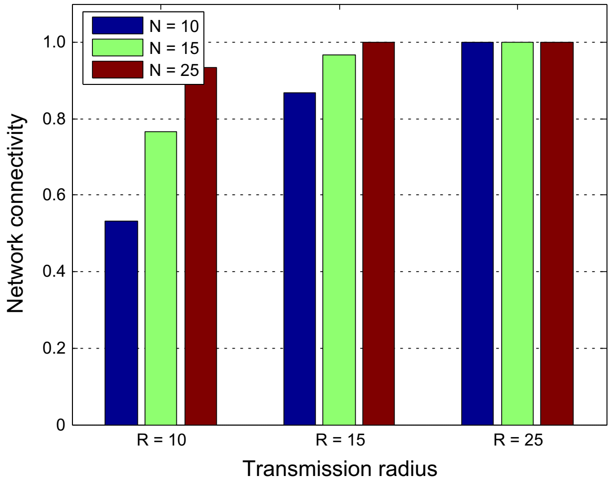


Fig. 17 Network connectivity for different transmission radiuses

channels changes between 2.4 and 3.7. This illustrates that our algorithm holds the larger available channels on average.

Figure 17 shows the impact of different transmission radiuses and different sizes of secondary users on network connectivity. We use the network connection probability to denote the network connectivity. From Fig. 17, we can clearly see when the transmission radius is 10, the connection probability of networks increases from 0.55 to 0.92 with the number of secondary users changing from 10 to 25, while for the transmission radius by 15, it grows from 0.85 to 1 with the number of secondary users increasing. For the transmission radius by 25, we can network connection probability by 1 when adding the secondary users. This further indicates the better performance of our algorithm.

5 Conclusion

This paper propose a new algorithm to construct the collaborative routing in multi-hop cognitive networks with multiple primary and secondary users. Our approach considers the interference between primary users and secondary users. We take into account the interference between secondary users. After analyzing the maximum transmission distance, collaborations, transmission angle control and power control, and channel allocation, we propose a new clustering-based collaborative multi-hop cognitive routing algorithm. By a series of simulation tests, we find that if there exist more secondary users and larger transmission radius, we can let more nodes take part in the collaboration process and attain larger achievable rate. Moreover, we also see that our approach holds lower network energy consumption. Simulation results show that our approach is promising.

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Dingde Jiang received the Ph.D. degree in communication and information systems from School of Communication and Information Engineering, University of Electronic Science and Technology of China, Chengdu, China, in 2009. He is an Professor in College of Information Science and Engineering, Northeastern University, Shenyang, China. His research interests include energy-efficient networks, cognitive networks, network measurement, network security, Internet traffic engineering, and performance analysis. Dr. Jiang is a member of IEEE and IEICE.

Xu Ying received B.Sc. in College of Electronic and Information Engineering, Northeastern University at Qinhuangdao, China, in 2011. He is currently a Master in Communication and Information System, Northeastern University, China. His research interests include energy-effient networks.

Yang Han received B.Sc. in College of Information Science and Engineering, Hainan University, Hainan, China, in 2010. He is currently a Master in Communication and Information System, Northeastern University, China. His research interests include cognitive radio network and cooperation communication.

Zhihan Lv is an engineer and researcher of virtual/augmented reality and multimedia major in mathematics and computer science, having plenty of work experience on virtual reality and augmented reality projects, engage in application of computer visualization and computer vision. His research application fields widely range from everyday life to traditional research fields (i.e. geography, biology, medicine). During the past years, he has finished several projects successfully on PC, Website, Smartphone and Smartglasses. In 2012, he was granted PhD. degree in Computer applied technology from Ocean university of China (2006–2012). Before that, he has enjoyed sixteen months full-time research experience at Centre national de la recherche scientifique (CNRS)-UPR9080 in Paris (2010–2011). After then, he has fulfilled two-year postdoc research experience at Umea university and a short invited teaching experience at KTH Royal Institute of Technology in Sweden. Since 2012, he has held an assistant professor position at Chinese Academy of Science.