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Distributed Cognitive Routing in Multi-channel Multi-hop Networks with Accessibility Consideration

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Abstract Among Cognitive Radio Network (CRN) research topics, routing algorithms especially for multi-channel networks are in the early stages. In this paper, we design a novel cognitive routing scheme for multi-channel multi-hop wireless networks. The main contribution of the proposed routing scheme is the sub-optimal low computational complexity which makes it applicable for distributed network architecture with power constraints. Other important aspect of the proposed routing scheme is considering the objectives related to the network performance, accessibility and efficient spectrum utilization jointly. As the simulation results demonstrate the presented scheme provides a significant improvement in the spectral efficiency and adequate QoS in term of delay propagation and interference in CRN.

Keywords: *Cognitive Radio, routing, multi-channel networks, accessibility, probability based scheme (PBS)*

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1. Introduction

Recently, huge increase of wireless applications causes growth of demand for spectrum access by different groups of organizations and users extensively. Cognitive Radio (CR) has provided an opportunity to overcome the spectral congestion problem by performing some fundamental activities known as cognition cycle [1]. Cognition cycle is the activity performed by CR including observing the wireless environment, adopting itself with the environment conditions by suitable decision making and learning from past behavior of the system [2]. Classifying the users in the CR into two groups of primary users (PUs) and secondary users (SUs) is another benefit of CR. PUs or licensed users have higher priority for spectrum access. SUs are users that are allowed to use spectrum of PUs in an opportunistic and non-interfering manner.

These features of the CR open up the possibility of designing networks with flexible dynamic spectrum access (DSA) strategies. Although a flexible and dynamic spectrum access based on cognition of wireless environment can improve the performance of the network, however, it increases the complexity of communication protocols in different layers. This research focuses on the routing topic in the CR networks with the distributed architecture. The routing protocols in CR networks can be classified in two main classes: 1) routing strategies based on full spectrum knowledge and positioning information of nodes and 2) routing schemes based on local information of spectrum and nodes.

Some distributed cognitive routing schemes leverage routing algorithms based on the power consumption and the interference constraints of the multi-hop networks [3], [4]. In [4], two controlled interference routing strategies, nearest neighbor routing (*NNR*) and farthest neighbor routing (*FNR*), are introduced. The main idea of the proposed routing algorithms are to find relay nodes according to the geometric conditions of the nodes and QoS of the PUs. The *NNR* (*FNR*) method selects the nearest (farthest) neighbor node in a sector with radius of D_{max} in each hop. The D_{max} is determined by positioning and QoS parameters in each hop. Simulation results illustrate that the *FNR* can provide better spectral efficiency and channel utilization than the *NNR*, while the *NNR* method is more efficient in energy consumption.

Some delay based routing metrics have been proposed in the literature [5,6,7,8]. In [5] and [6], two delay metrics delay of switching between frequency bands and back-off delay in the medium access in a specific frequency band have been proposed in the CRNs. In [6], distributed routing algorithm uses summation of the switching delay and back-off delay in each hop as a metric to select the path with the least delay. [7] introduces a delay based cognitive routing method where the main objective of the routing algorithm is to minimize end to end delay of video streaming in the CRN. The routing method uses an Effective Transmission Time (ETT) as a routing metric which shows the delay of the packet transmission from transmitter node on the selected link in the hop i_{th} to receiver node. With a given characteristic of the traffic flow, the SUs in the network communicate with each other to adjust their transmission parameter so that enough QoS for delay sensitive classes can be provided.

Maximizing the throughput of the selected route is the main objective in the proposed routing algorithm in [8]. Authors in [8] introduce a routing protocol based on the spectrum availability in wireless mesh networks. The protocol establishes some candidate nodes according to the Path Spectrum Availability (PSA) metric. After that, among the paths with higher PSA, data packets will be transferred based on the short term spectrum availability and channel conditions. The evaluation of the protocol shows better performance than the popular hop count and the Expected Transmission Time (ETT) metrics.

Designing an efficient routing algorithm requires satisfaction of the routing objectives such as network performance, throughput, delay and efficient usage of the spectrum jointly. In these conditions the problem formulation becomes so complex while in the practical issues, low computational complexity solution is an important factor to algorithm evaluation

In this paper, we design a new interference based distributed routing algorithm for multi-channel cognitive radio networks. The objectives considered in the designing of the routing algorithm are *i*) Maximizing the spectral efficiency of the route by considering required QoS for PUs. *ii*) Maximizing the accessibility which can be equivalent to minimizing the delay of the packet transmission or selecting the shortest path. *iii)* Efficient spectrum utilization which is the main object of the cognitive radio networks. Furthermore, the proposed routing scheme introduces a method with low complexity to solve the optimization problem. We expect that by using multi-channel data transmission, the spectral efficiency of the route is improved in comparison with the single channel data transmission case [9]. Also by utilizing a probabilistic model based on the positioning information of the nodes in the network, the routing scheme can provide less end-to-end delay transmission.

The rest of the paper is organized as follows. Section II presents the system structure of the routing problem. Section III explains the proposed routing scheme. Section IV briefly introduces one of the recent cognitive routing protocols for comparison and evaluation of the proposed routing algorithm. Section V presents the performance evaluation of the proposed method and the last section concludes the paper.

2. System Structure

We consider a CR network scenario with two PUs and N_S SUs distributed uniformly in a D×D square area. Each PU is characterized by an on-off pattern which is modeled by a binary sequence based on the statistical behavior of the PUs. To transmit the data packets from a source to destination, SUs can play the role of relay nodes which decode and forward data packets to the next node. An OFDM-based single antenna for CR system is assumed and the complete spectrum sensing has been performed. Furthermore, instantaneous OFDM channel gains are available. The power optimization is relaxed and equal transmission power is allocated to all the SUs in the network.

As Figure 1 shows, h^l_{SP} and h^l_{KP} represent channel gain between a transmitter node and l_{th} PU $(l \in \{1,2\})$, and between k_{th} relay and l_{th} PU, respectively. h^i_{sk} denotes the channel gain between transmitter and k_{th} relay in i_{th} sub-channel.

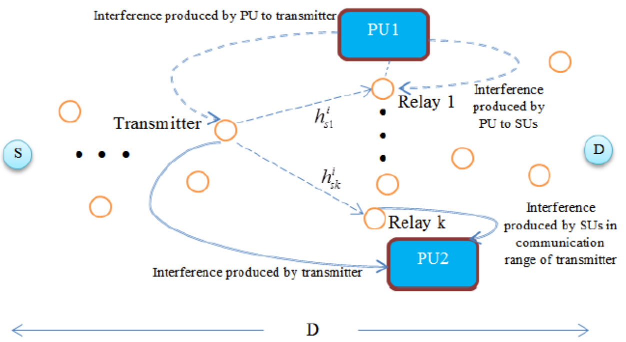


Figure 1. Configuration of the assumed CR network

An optimal routing scheme should be able to consider both channel conditions and positioning information to select a short path with high spectral efficiency. To find an optimal route between source and destination, it is assumed that position of source and destination is known and SUs are able to identify their position in the network based on geographical information of source, destination and other SUs. The geographical information including the traversed distance and its direction in each hop can be attached to header of data packets.

3. Proposed Routing Scheme for Multi-Channel Crns

In this section, the proposed routing scheme is explained. Table 1 shows the procedure of proposed routing algorithm in three steps.

Table 1. Steps of the Proposed Routing Scheme

Step I: predicting the channel status (PU activity) and determining the number of available channels.
Step II: selecting candidate relays and related sub-channels to maximize spectral efficiency considering the interference that PUs can tolerate and conditions achieved from *step I*.
Step III: using the PBS algorithm to select a relay and sub-channel in each hop from the candidate nodes determined in *step II* to improve the spectral efficiency of route and accessibility to destination jointly

Before explaining the details of the steps, it is important to mention that we consider several objectives in the steps of the proposed routing scheme. The first step provides the opportunity for efficient spectrum access in a multi-channel network. In other steps, we aim at introducing methods for solving a multi-objective optimization. The objectives in the proposed scheme are related to network performance in term of spectral efficiency (investigated in step II) and objective related to QoS of the network in term of delay and selecting the shortest path to destination (investigated in step III). It is obvious that while solving a multi-objective problem, satisfying an objective might be in conflict of other goals. Therefore, a comprehensive solution for multi-objective optimization should be able to balance a trade-off between objectives. We also investigate this point in step III. In the following the details of the proposed scheme is explained.

STEP I: as the proposed scheme is designed for the multi-channel CRN, the information of channels such as the number of available channels, the presence or the absence of the PUs in the frequency bands plays an important role. In the absence of the PUs, the SUs are allowed to use the frequency bands of the PUs for the data transmission. In order to determine the availability of PUs bandwidth, spectrum sensing is the most important function for SUs. Accurate and constant spectrum sensing consumes the energy of SUs significantly. Employing predictive techniques to discover spectrum holes in absence of PUs, is one of the solutions to reduce the consuming energy of SUs for spectrum sensing. There are several proposed machine learning techniques in the literature to predict the spectrum holes in absence of PUs using statistical behavior of PUs bandwidth usage [10-15]. In order to model the on-off behavior of the PUs, we use an automata model with simple structure and acceptable prediction rate [13]. Each SU is equipped with a predictive system so that before data transmission the presence or the absence of a PU can be predicted and the number of available sub-channels can be determined. Figure 2 illustrates an example of the increasing channel numbers in the absence of the PUs.

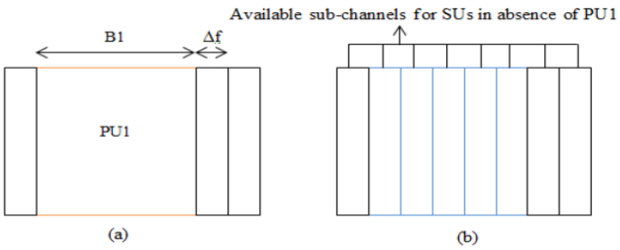


Figure 2. The available number of channels in (a) presence and (b) absence of the PU1

Increasing the number of available sub-channels and using OFDM based data transmission can improve the spectral efficiency of the network by reducing the interference between users in the network. After determining the number of available sub-channels in the next step the routing scheme finds candidate nodes and sub-channels to transmit data packets in each hop.

STEP II: In this step, the proposed cognitive routing scheme employs the relay and sub-channel assignment scheme considering the constraints of the interference that PUs can tolerate. Before the problem formulation we need to present a metric to evaluate the spectral efficiency of the route.

In order to evaluate the spectral efficiency of selected route via M_P hops, we use C_{ETBS} [16]. In C_{ETBS}, equal time duration is allocated to each link between the nodes in the network to transmit the data packets. This assumption provides fairness in the power consumption for the channels with deep fade and bad conditions. The C_{ETBS} is defined as follows.

$$C_{ETBS} = \frac{1}{M_p} \min(C_i), i = 1, 2, ..., M_p \qquad (1)$$

where C_i is the link capacity in i_{th} hop and M_P is the number of hops in the path reaching to destination.

Note that in (1) the parameter C_{ETBS} depends on both of link capacity (Ci) and number of hops (MP) or the length of the path. Therefore, maximizing the can be expressed as maximizing the C_{ETBS} spectral efficiency of links of the path and minimizing its lengths. In this step (step II), we introduce a method to maximize the spectral efficiency of links considering the interference that PUs can tolerate. Therefore, the overall form of optimization problem for the proposed routing scheme can be presented as follows.

$$\max C_{ETBS}, s.t. \text{ The total interference} \le I_{th} \qquad (2)$$

Where I_{th} is the maximum acceptable interference to PUs.

In C_{ETBS} the link capacity between nodes m and n (C_i) is defined as

$$C_{mn} = \log_2\left(1 + \frac{P_T |h_{mn}|^2}{\sigma^2 + \sum_{l=1}^{L} J_{mn}^l}\right), \qquad (3)$$

where P_T, is the transmission power, h_{mn} is the channel gain between nodes m and n, σ^2 is the variance of the AWGN noise and J_{mn}^l is the interference produced by l_{th} PU to the link between node m and n. The interference produced by node S to PU for an OFDM-based data transmission in a CRN with L PUs and N sub-channels for SUs can be calculated as follows [17],

$$I_{SP} = |h_{SP}|^2 P_T T_S G_i^l, 1 \le i \le N \text{ and } 1 \le l \le L \qquad (4)$$

where T_s is the symbol duration, h_{SP} is the channel gain between node S (transmitter in each hop) and node P (PU) and G_i^l is the density of interference between orthogonal sub-channels [17],

$$G_i^l = \int_{d_{il} - \frac{B_l}{2}}^{d_{il} + \frac{B_l}{2}} \left(\frac{\sin \pi f T_s}{\pi f T_s}\right), \qquad (5)$$

In (5), d_{il} shows the spectral distance between l_{th} PU band and i_{th} SU band and B_l is the bandwidth of l_{th} PU.

Now in the rest of procedure, we introduce a method to select the path with the highest spectral efficiency in each link and in STEP III, we present a method which reduces the number of hops (M_P) in a route and selects the shortest path. Consequently, the C_{ETBS} will be maximized by maximizing the spectral efficiency of each link and selecting the shortest path jointly. The optimization problem in distributed form to maximize the capacity of each link (C_i) between nodes S (transmitter) and k_{th} relay in communication range of the transmitter can be expressed in (6).

$$\begin{aligned} &\max\left(\rho_k^i \log_2\left(1 + \frac{|h_{Sk}|^2 P_T}{\sigma_k^2 + \sum_{l=1}^{L} J_{Sk}^l}\right)\right) \\ &\textit{Subject to}: \\ &I_{SPU} + I_{KPU} \le I_{th} \\ &I_{SPU} = \sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{k \in K}\left(\rho_k^i \left|h_{Sl}^{(i)}\right|^2 P_T T_S G_i^l\right) \\ &I_{kPU} = \sum_{l=1}^{L}\sum_{i=1}^{N}\sum_{k \in K'}\left(\rho_k^i \left|h_{kl}^{(i)}\right|^2 P_T T_S G_i^l\right) \\ &\rho_k^i \in \{0,1\}, \sum_{i=1}^{N}\sum_{k \in K} \rho_k^i = 1. \end{aligned} \qquad (6)$$

In (6) ρ_k^i is the binary decision parameter. ρ_k^i =1, means that k_{th} relay and i_{th} sub-channel are selected as a node in next hop and related sub-channel, respectively. K is the set of all SUs in the whole network and K' is the set of SUs in communication range of the transmitter in each hop. $h_{kl}^{(i)}$ is the channel gain between k_{th} relay and l_{th} PUs on i_{th} sub-channel and $h_{Sl}^{(i)}$ is the channel gain between transmitter and l_{th} PU on i_{th} sub-channel. Furthermore, shows the interference produced by transmitter to PUs on ith sub-channel. I_{kPU} is a matrix which shows the interference produced by SUs to PUs.

Therefore, the optimization problem in distributed form can be expressed as finding the two variables i and k showing the i_{th} sub-channel and k_{th} relay, respectively which maximize the spectral efficiency of the link in each hop. Consequently, the spectral efficiency of the selected route is evaluated using (1).

Similar to method introduced in [18], the optimization problem in (6) can be solved as a convex optimization by relaxing the integrality constraint on ρ_k^i which means ρ can have any real value between 0 and 1. However, solving convex optimization problems requires numerical calculation techniques which results in much computations due to the recursive entity of these techniques. The order of computational complexity of the optimization problem as a convex problem is $O\left(K^3N^3\right)$ [18]. Therefore, for the systems with computational power constraints, sub-optimal algorithms with less computational complexity are preferred. In the following, we will use a low complexity method to solve the problem. In this way, the parameter η_k^i is defined.

$$\eta_k^i = \frac{SINR_{Sk}^i}{I_{SPU} + I_{KPU}} \tag{7}$$

$$SINR_{Sk}^i = \frac{\left|h_{Sk}^i\right|^2 P_T}{\sigma_k^2 + \sum_{l=1}^{L} J_{Sk}^l} \tag{8}$$

η_k^i represents the ratio of SINR between transmitter (S) and k_{th} relay, to the total interference imposed to PUs on i_{th} sub-channel. As it is assumed that the transmission power of all nodes is the same, the maximum value of η_k^i can determine the relay and sub-channel with the highest link capacity and minimum interference to PUs. Therefore, relay and sub-channel will be selected as

$$k(i) = \arg\max_k \left(\eta_k^i\right), \tag{9}$$

In fact by using the formula in (7) and (9), we search for the best relay node with the highest SINR and the least interference to PUs. Please note that the power optimization is relaxed and it is assumed that all SUs have the same power. For such scenario the proposed solution finds the best existing node and sub-channel. Furthermore, the computational complexity of the proposed scheme is *O(KN)* [19] which provides a low complexity in the system implementation. After selecting a relay and sub-channel the routing scheme selects the shortest path reaching to the destination using a probabilistic model which is explained in the *STEP III*.

STEP III: To reduce hops in path and also balancing the trade-off between two objectives (network performance and accessibility) a Probability Based Scheme (PBS) introduced by [20] is utilized. In continue, we will explain the details of the PBS.

Probability Based Scheme (PBS) is a probabilistic model to improve the accessibility and it can help to find a path with less number of hops. In order to explain the PBS algorithm consider the following multi-hop network shown in Figure 3.

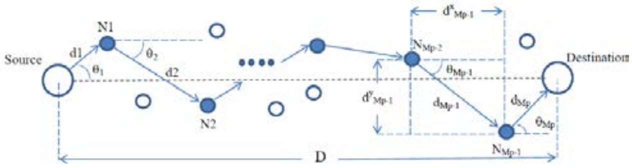


Figure 3. the structure of a multi-hop network

Figure 3 shows an example of multi-hop wireless network including source, destination and some relay nodes to transmit data in a multi-hop manner. It is assumed that the geographical position of both source and destination are known and each node can calculate its relative position to the destination. Now suppose that D shows the distance between source and destination and communication range of each node is R. The parameter $d_i (d_i \in (0, \mathrm{R}))$ denotes the distance between two nodes in i_{th} hop. θi shows the angle between hop direction and straight line between source and destination (shown by L_{SD}) in hop i, $(\theta i \in (-\pi/2, \pi/2))$. Furthermore, M_p is the number of hop in the path P. Now the distance between transmitter and receiver in hop i (d_i) can be decomposed to, the distance in the direction of $\mathrm{L_{SD}}(d_i^x)$ and the distance perpendicular to the direction of $\mathrm{L_{SD}}(d_i^y)$.

$$d_i^x = d_i \cos\alpha \tag{10}$$

$$d_i^y = d_i \sin\alpha \tag{11}$$

d_i^x is known as information moving distance (IMD), and d_i^y is called information jumping distance (IJD) [17]. Two parameters d_i^x (IMD) and d_i^y (IJD) are used to model accessibility objective. It is obvious that a route can reach to the destination by M_p hops, if the two following equations are satisfied.

$$\sum_{i=1}^{M_p} d_i^x = D \tag{12}$$

$$\sum_{i=1}^{M_p} d_i^y = 0 \tag{13}$$

Equation (12) shows that after Mp hops the route between source and destination should traverse distance D, and Equation (13) means the selected route should converge to L_{SD} line. Accessibility can be achieved by satisfaction of Equations (12) and (13). It is obvious that if the routing scheme chooses relay nodes in the direction toward the destination, (12) will be satisfied. Therefore, the main issue of accessibility is satisfaction of the Equation (13) converging selected route to destination in perpendicular direction of line L_{SD}. In this way, distributed routing scheme introduces some constraints to optimize trade-off between accessibility and network performance. In the following, we explain how the PBS can improve the accessibility and balance a trade-off between objectives of network performance and accessibility in the proposed distributed routing scheme.

Suppose that N_{up} and N_{down} denote nodes with the largest link capacity (selected based on method introduced in *step II*) in the A_{up} and A_{down} areas shown in Figure 4, respectively. The reason of selecting two nodes with the highest link capacity in A_{up} and A_{down} is to provide some candidate nodes with high spectral efficiency but with different accessibility status. A_{up} is the area toward the destination with $\theta i \in (0, \pi/2)$ and Adown is the area below the line of LSD with $\theta i \in \left(-\pi/2, 0\right)$. After selection of N_{up} and N_{down} nodes, the PBS selects the node with the highest link capacity (N_{best}) with probability of δ, $(\delta \in (0,1))$ to reach to the destination. The most important part in the PBS is determining the probability of δ in each hop. To determine δ parameter, suppose in hop i, $D_{i-1}^{y} = \sum_{j=1}^{i-1} d_j^y$ is defined as the summation of the IJDs in i-1 previous hops. Parameters d_i^{xo} and d_i^{yo} are defined as IMD and IJD of the best node N_{best} in each hop. Also, $d_i^{x,so}$ and $d_i^{y,so}$ are *IMD* and *IJD* of other nodes, respectively. Figure 4 shows these parameters where the best node is located in the A_{up} region.

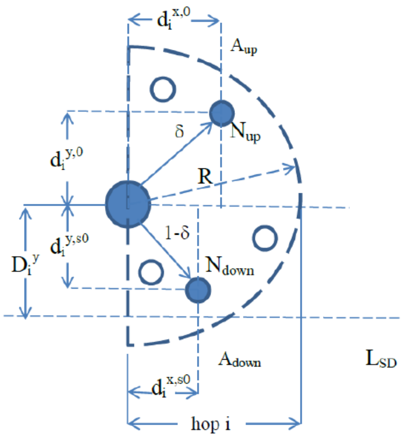
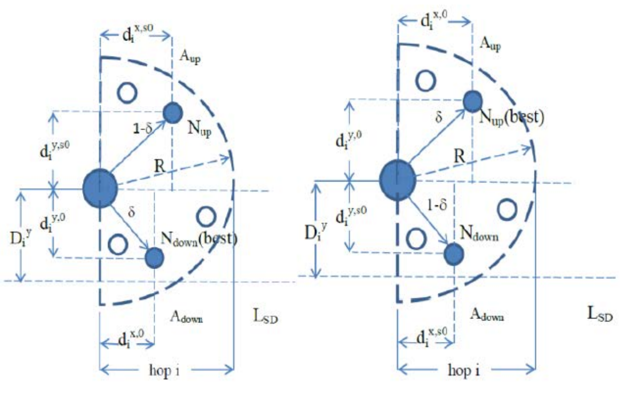


Figure 4. N_{up} and N_{down} are selected nodes among all nodes in the A_{up} and A_{down} area, respectively and N_{up} (N_{best}) is selected with probability of δ as a receiver in the next hop



(a) (b)

Figure 5. a) $D_{i-1}^{y} > 0$ and $d_i^y < 0$. b) $D_{i-1}^{y} > 0$ and $d_i^y > 0$

Based on the location of the transmitter and position of N_{up} and N_{down} determining δ parameter can be classified in four different cases.

Case 1. $D_{i-1}^{y} > 0$ and $d_i^y < 0$ show that the best receiver is located in Adown area while the transmitter is located above the line L_{SD}. Figure 5-a, illustrates such a scenario. In this case, the probability δ is set to 1, because this node with the largest link capacity improves the accessibility to destination.

Case 2. $D_{i-1}^{y} < 0$ and $d_i^y > 0$. Similar to previous case, δ is set to 1. Because selection of the N_{best} as a receiver in next hop improves both accessibility and network capacity.

Case 3. $D_{i-1}^{y} > 0$ and $d_i^y > 0$. In this case, N_{best} is located in A_{up}, and transmitter node is above the line L_{SD}. As shown in Figure 5-b it is more possible that the route diverges from the destination. Therefore, N_{best} is selected with the probability of δ. Hence, the average total IMD and IJD after *i* hops will be:

$$\overline{D_i^{x-}} = \sum_{j=1}^{i-1} d_j^x + \delta d_i^{x,0} + (1-\delta) d_i^{x,s0} \tag{14}$$

$$\overline{D_i^{y-}} = D_{i-1}^{y-} + \delta d_i^{y,0} + (1-\delta) d_i^{y,s0} \tag{15}$$

According to the equations (12) and (13), to model accessibility, the routing procedure should satisfy following equations in the rest of the route. Note, a route is a path to destination via *M* hops.

$$\sum_{j=i+1}^{M} d_j^x = D - \overline{D_i^{x-}} \tag{16}$$

$$\sum_{j=i+1}^{M} d_j^y = -\overline{D_i^{y-}} \tag{17}$$

In a homogeneous network with the uniform distribution for nodes position, IMD of optimal nodes in A_{up} and A_{down} has the same distribution with the average of $\overline{d_x}$ [20]. However, IJD of optimal nodes in A_{up} and A_{down} follows two different distributions with the average value $\overline{d_U^y}$ and $\overline{d_D^y}\left(\overline{d_U^y} = -\overline{d_D^y}\right)$, respectively. Now in each hop, the average IJD after i_{th} hop is:

$$\overline{d_y} = \delta \overline{d_U^y} + (1-\delta)\overline{d_D^y} = (1-2\delta)\overline{d_D^y} \tag{18}$$

The average number of hops to destination based on $\overline{d_x}$ and $\overline{d_y}$ can be written as:

$$\overline{M_i} = \frac{\sum_{j=i+1}^{M} d_j^x}{\overline{d_x}} \tag{19}$$

$$\overline{M_i} = \frac{\sum_{j=i+1}^{M} d_j^y}{\overline{d_y}} \tag{20}$$

Then, it is obvious that

$$\frac{\sum_{j=i+1}^{M} d_j^y}{\overline{d_y}} = \frac{\sum_{j=i+1}^{M} d_j^x}{\overline{d_x}} \tag{21}$$

By substituting (14)-(18) into (21) a quadratic equation with parameter δ will be achieved:

$$A\delta^2 + B\delta + C = 0 \tag{22}$$

where

$$A = 2\left(d_i^{x,0} + d_i^{x,s0}\right) \tag{23}$$

$$B = \frac{\overline{d_x}}{\overline{d_D^y}}\left(d_i^{y,0} - d_i^{y,s0}\right) - 2\left(D - \sum_{j=1}^{i-1} d_j^x\right) + 3d_i^{x,s0} - d_i^{x,s0} \tag{24}$$

$$C = \frac{\overline{d_x}}{\overline{d_D^y}}\left(\sum_{j=1}^{i-1} d_j^y + d_i^{y,s0}\right) + \left(D - \sum_{j=1}^{i-1} d_j^x - d_i^{x,s0}\right) \tag{25}$$

Based on $\Delta = B^2 - 4AC$:

If $\Delta < 0$, there is no solution for quadratic equation, and δ sets to zero.

If $\Delta = 0$, and $0 < \delta <$, δ is the answer, otherwise δ is set to zero.

If $\Delta > 0$, equation has two answers, if $\delta 1$ and $\delta 2$ are in the interval [0,1], the larger value will be accepted. Larger value of δ improve the network performance. If none of $\delta 1$ and $\delta 2$ is in the [0,1], δ will be set to zero, because there is no reasonable solution for it.

Case 4. $D_{i-1}^y < 0$ and $d_i^y < 0$. In this case transmitter is below the L_{SD} line and the best node is in the Adown area. According to the discussion in the previous case, δ can be achieved by solving (22). Note that the Equation (18) have to change to the following equation.

$$\overline{d_y} = \delta \overline{d_D^y} + (1-\delta)\overline{d_U^y} = (1-2\delta)\overline{d_U^y} \tag{26}$$

For δ calculation last two cases require parameters, $\overline{d_x}$, $\overline{d_U^y}$ and $\overline{d_D^y}$. These parameters depend on the channel and link conditions and network topology. Therefore, a closed form solution for (22) may not be derived. However, as the proposed routing scheme is a distributed fashion, and calculating the parameters $\overline{d_x}$, $\overline{d_U^y}$ and $\overline{d_D^y}$ needs only global information, an approximation of these parameters requiring the previous hops information can be utilized. A reasonable solution in practical conditions, required information can be transmitted in piggybacking manner, so that each node can compute δ and select a node for the next hop. The approximation of $\overline{d_x}$, $\overline{d_U^y}$ and $\overline{d_D^y}$ are proposed as:

$$\overline{d_x} = \frac{1}{3}\left(\overline{d_{pre}^x} + d_{i,up}^x + d_{i,down}^x\right) \tag{27}$$

$$\overline{d_D^y} = \frac{1}{2}\left(\overline{d_{D,pre}^x} + d_{i,down}^y\right) \tag{28}$$

$$\overline{d_U^y} = \frac{1}{2}\left(\overline{d_{U,pre}^y} + d_{i,up}^y\right) \tag{29}$$

Where $\overline{d_{pre}^x}$, $\overline{d_{pre}^y}$ and $\overline{d_{U,pre}^y}$ are received approximation of $\overline{d_x}$, $\overline{d_U^y}$ and $\overline{d_D^y}$, respectively. $d_{i,down}^x$, $d_{i,up}^y$, $d_{i,down}^y$ and are the IMD and IJD of two candidate nodes selected to maximize network spectral efficiency in the A_{up} and A_{down} areas, respectively. Using the PBS the routing scheme finds a path with less number of hops, less traversed distance and less delay which improves the QoS in delay sensitive services.

The main reason of using the PBS scheme except reducing number of hops and length of route is to balance a trade-off between objective related to spectral efficiency and transmission delay. The PBS by selecting two nodes (in two regions A_{up} and A_{down}) with the highest link capacity considering the interference constraints improves the objective related to spectral efficiency of the routing problem. After that the PBS balances a trade-off between network performance and accessibility objectives. Therefore, if selecting a node with the highest link capacity might increase the probability of diverging the route from the destination, the routing algorithm selects node with less link capacity but improves the accessibility. It is clear that if a node can improve both spectral efficiency and accessibility the routing scheme selects the node in each hop.

Before evaluation of the proposed routing scheme, in next section, we overview one of the recent distributed cognitive routing algorithm and then compare the performance of routing algorithms in section V.

4. Overview of Nnr and Fnr Routing Algorithms

In order to evaluate the performance of the proposed routing algorithm, in this section, we review a distributed routing algorithm in cognitive radio networks. Similar to our proposed method, the proposed routing scheme introduced in [4], is based on the interference constraints of PUs and positioning information of the nodes in the network. Authors investigate the multi-hop data transmission strategies called nearest neighbor routing (*NNR*) and farthest neighbor routing (FNR) via SUs deriving geometric conditions and required QoS for PUs. *NNR* (*FNR*) strategy searches the nearest (farthest) node in area with radius D_{max} as a relaying node to transmit data packet from source to destination. The parameter D_{max} is defined based on the interference constraints and positioning parameters in the specific area. If the transmitter node in hop i, is far from the PU, then D_{max} selects larger value and if the transmitter is close to the PUs then D_{max} gets smaller values. Other important parameter to compute D_{max} is required QoS for the PU. If maximum interference that the PU can tolerate decreases, then D_{max} decreases so that nearer neighbor nodes that require less power transmission with less interference to PU is selected in each hop. Analysis of *NNR* and *FNR* algorithms show that *FNR* has better end to end channel utilization and reliability and less transmission delay than *NNR* method. However, *NNR* method has better energy efficiency. Due to limitation of the number of the pages you can find the details of two routing protocols in [4].

Although NNR and FNR methods consider both interference and positioning information of nodes in the network however, the route selection procedure does not consider network performance and accessibility jointly. Furthermore, these methods do not exploit benefits of multi-channel data transmission. In the next section we evaluate the NNR and FNR methods with our proposed routing algorithm on a same network scenario.

5. Simulation and Experimental Results

In order to evaluate the performance of the proposed routing scheme, we simulate a CRN with dimension of D×D with the configuration shown in Figure 1. The source and destination are located at *(0, D/2)* and *(D, D/2)* respectively. Two PUs are randomly placed between source and destination and also The SUs are deployed randomly with the density of 10 (*node/Km*^{2}) in the network. *B1*, *B2* and Δf are the bandwidth of *PU1*, *PU2* and *SUs* which are assumed 2 MHz, 1 MHz and 0.2 MHz, respectively. The variance of the additive white Gaussian noise is assumed 10^{-3} *W*. Transmission power for all SUs is 10^{-2} W. The mean power gain of the Rayleigh fading is considered -10 dB for all channels and the threshold value for PUs interference and interference produced by PUs to the nodes (J_{ik}^{l}) is assumed 10^{-6} W. Two routing *NNR* and *FNR* are also implemented on the same network with following parameters. The parameter Θ_c that shows the threshold value of SINR for activation of SUs is considered 10 dB. The threshold value for successful data transmission for PUs is Θ_p which is also considered 10 dB. ε_c and ε_{p} are the outage probability for activation of SUs and PUs respectively which are both assumed 0.9 and parameter μ is the rate of successful packet transmission by PUs which is considered 0.9. The performance of proposed method in comparison with the *NNR*, *FNR* and simple scenario is evaluated in term of spectral efficiency, number of hops and packet delay. In the simple scenario the PBS is eliminated and route selection is only based on maximizing the spectral efficiency of the route.

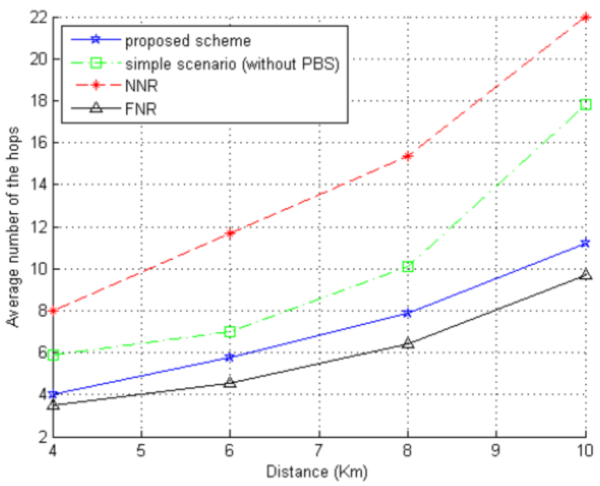


Figure 6. The number of hops versus distance

Figure 6 shows the comparison of the proposed routing method with three other scenarios in term of the average number of hops versus variable distance between source and destination. As can be seen the *FNR* method by choosing the farthest node in each hop can find routes with less hop number. However, there is an important point in evaluation of routing schemes and that is the difference between path length and number of hops.

In Figure 7 we illustrate a scenario to show the difference between path length and number of hops in evaluation of the route. In Figure 7, route 1 consists of two hops and route 2 is made of three hops. However, as can be seen route 2 is so near to the direct line between source and destination which means that the length of the path is shorter than route 1. Selecting the short path reaching to destination, results in reduction of transmission delay and this is one of the main advantages of using the PBS in route selection. The PBS by selecting node which converge the route to the direct line between source and destination (L_{SD}) reduce the packet delay. The result of comparison of the proposed routing scheme and other scenarios for transmission delay is presented in Figure 8.

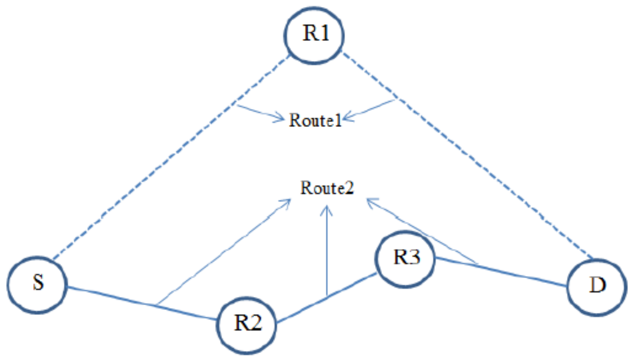


Figure 7. The difference between evaluation of route in term of number of hops and length of route

As Figure 8 demonstrates the proposed method by using the PBS can improve the delay of packet delivering.

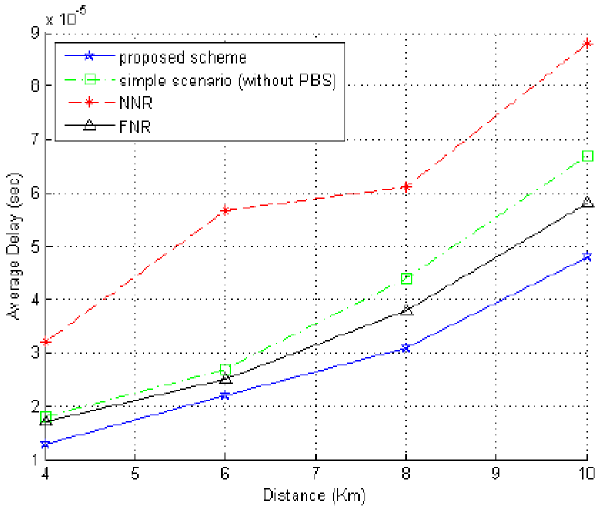


Figure 8. The average packet delay in different distance between source and destination

Figure 9 presents the spectral efficiency of the selected routes using C_{ETBS} for different routing methods. As Figure 9 shows there is significant improvement in the spectral efficiency of the selected route respect to the *NNR* and *FNR* methods. The reason is that the proposed routing method is designed for multi-channel data transmission while *NNR* and *FNR* methods are designed for single channel networks. Furthermore, the proposed predictive model provides more available channels in the absence of PUs which improves the performance of the network more than other methods.

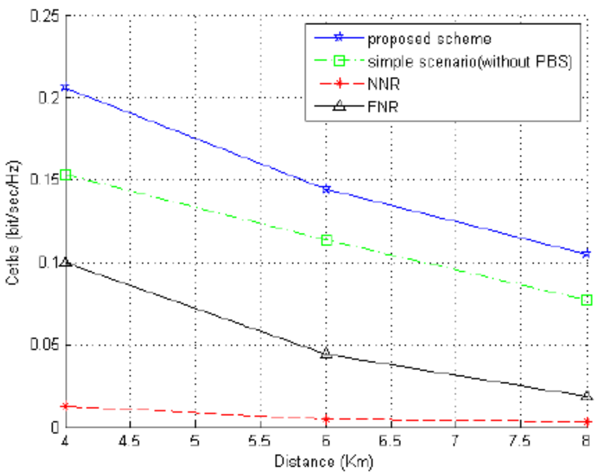


Figure 9. The spectral efficiency of the routing schemes

Using OFDM-based data transmission is another reason of the improvement in the spectral efficiency of the selected route (C_{ETBS}). Furthermore, it provides better QoS for PUs in concurrent activity of PUs and SUs which is the main problem in *NNR* and *FNR* methods.

Finally in Figure 10, the effect of interference produced by PUs on the network performance is investigated. As it is obvious using the proposed scheme, PUs can increase their transmission power and their guard zone without degradation in the performance of SUs.

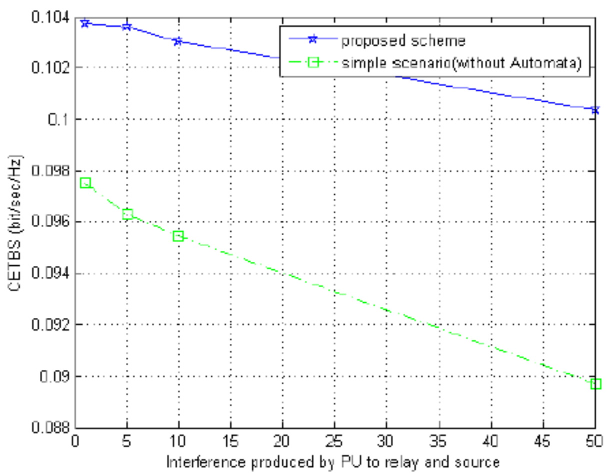


Figure 10. The effect of interference (with scale of 10^{-6} watt) produced by PUs on the network performance

6. Conclusion

In this paper, we introduced a novel cognitive routing method in the multi-channel multi-hop wireless network. The constraints of the interference that PUs can tolerate, is at the basis of designing the proposed routing strategy. Moreover, the proposed method considers objectives related to spectral efficiency, end to end delay and efficient spectrum utilization in the procedure of route selection. An important feature of proposed scheme is low complexity and applicable for practical implementations in distributed architecture. Using OFDM based data transmission in multi-channel networks is one of the most important principals to improve the spectral efficiency of the selected route in the routing strategy. The simulation results confirm that the proposed scheme improves the network performance by using several orthogonal channels. Other important aspect of routing problem that is considered in the proposed scheme is reducing the end to end transmission delay. The proposed scheme utilized a well-defined probability based scheme (PBS) to guide the procedure of route selection to select shortest path using geographic information of nodes in the network. Joint satisfaction of routing objectives results that the proposed routing scheme can provide adequate QoS for users in the network in term of transmission delay and tolerable interference for PUs while the frequency bands are used efficiently.

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