Distributed Routing Scheme in Multi-channel Multi-hop Wireless Networks

Mehdi Golestanian,
Faculty of electrical and computer engineering
Birjand University, Birjand, Iran
Mehdi.golestanian@gmail.com

Reza Ghazizadeh
Faculty of electrical and computer engineering
Birjand University, Birjand, Iran
rghazizade@birjand.ac.ir

Mohammadreza Azimi
Department of computer engineering
Shahid Bahonar University, Kerman, Iran
zmmhmmdrz@gmail.com

***Abstract*— In this paper, we propose a new distributed routing protocol designed for multi-channel wireless networks. The proposed routing method consists of two major parts, relay and sub-channel assignment to find the largest spectral efficiency, and relay selection in each hop, using a probability base scheme. The PBS improves the accessibility by reducing the number of hops and traversed distance in the path reaching to destination. Simulation results show proposed scheme reduces the delay of packet transmission and selects the shortest path to destination with the largest spectral efficiency.**

Keywords- Accessibility, Routing, Multi-channel networks, WMN.

I. INTRODUCTION

Distributed routing is a challenging research topic especially, in multi-hop multi-channel networks. Multi-hop multi-channel networks such as Wireless Mesh Networks (WMNs) have been introduced as a promising solution to achieve the extension of the coverage to last mile broadband communication and a solution to overcome the gradation of capacity due to interference problem, by using non-overlapping channels available in IEEE802.11 standard [1]. WMNs interconnect nodes (including hosts and routers) in the network and transmit data to/from clients in a multi-hop manner. Resource allocation [2], frequency assignment and spectrum sharing [3], [4], scheduling [5], [6], and routing are some examples of interesting research topics of this area.

In this paper, we focus on routing schemes in multi-hop multi-channel wireless networks which is one of the most important tasks of the network layer and a challenging issue of WMNs. We propose a new distributed routing scheme in multi-channel multi-hop wireless networks which consider channel condition of the wireless environment and also selects the shortest path reaching to destination.

In general, objective functions in routing schemes can be classified in two groups:

- Objective functions related to throughput and performance of the system such as maximizing total capacity or spectral efficiency [7], power optimization and energy consumption [8], etc.
- Objective functions introduced to maximize the accessibility. Accessibility refers to the probability of successfully finding a route from a source to specific destination [9].

Both of the objectives should be considered in designing a routing protocol, because selecting a route, only based on maximizing the network performance may diverge selected route from destination. Selecting a route with the shortest distance to destination may result to degradation of the network performance. Therefore, an efficient routing method should balance a trade-off between these two objectives.

Two methods, optimal method [10], and table driven method [11], have been introduced in literatures.

In Optimal method, a node finds the shortest path to destination by obtaining the routing information from all nodes in the system and using Bellman-Ford or Dijkstra's algorithm. In table driven method, each node builds a routing table by gathering the information of neighboring nodes. Using the routing table and routing algorithms such as, ad hoc on-demand distance vector routing (AODV) or dynamic source routing (DSR), the optimal path to destination will be discovered. Optimal and table driven methods gather global information of nodes in the networks and based on routing protocols and specific routing metrics can find shortest path to destination which satisfy objectives related to network performance and accessibility. However, both of these methods (optimal and table driven method) sustain the system complexity and signaling overhead to gather information of all nodes in the network. A reasonable and practical solution to this drawback is to design a distributed routing algorithm where each node makes the routing decision only by using local information in a hop-by-hop manner.

Recently, two distributed routing algorithms, geographic and link-state-based method have been proposed in the literatures. Geographic method finds the shortest path with minimum hop number by using geographical location information of neighbor nodes and destination. [12] proposes MFR (Most Forward within Radius) method as a geographic method that selects a node traversing the largest distance toward destination in each hop. The main drawback of the geographic method is ignoring the variable conditions of the channel. Link-state-based method uses signal to noise ratio (SNR) to obtain channel condition and link state of different path reaching to destination. Some examples of distributed routing based on link state methods are [13], [14] which maximize the spectral efficiency and minimize end-to-end outage probability, respectively.

Geographic and link-state-based methods do not ensure that selected route can satisfy both objectives and most of current routing algorithms are designed for single channel systems. Therefore, in this paper, we propose a novel distributed routing scheme considering both system performance and accessibility in multi-channel multi-hop networks. Proposed scheme consists of two major parts. First, we use the idea of relay and sub-channel assignment to select some candidate nodes that are expected to maximize spectral efficiency in each hop. After selecting some candidate nodes, in second step, we use a Probability Based Scheme (PBS) proposed in [9], to select one node as a node in the next hop. According to relative position of each node, respect to the position of the destination and, the PBS selects one of the candidate nodes in each hop to maximize the accessibility to the destination. We will show how PBS provides a trade-off between system performance and accessibility to find a route to destination.

The rest of the paper is organized as follows. In section II, system structure and channel model are described. In section III, problem formulation, relay and sub-channel assignment method are explained. The PBS will be presented in section IV. Section V, includes simulation results and finally, last section concludes the paper.

II. SYSTEM MODEL

A. System Structure

In this section, we explain the structure of the network and channel model used in the proposed distributed routing algorithm.

Fig. 1 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. di (di $\in$ (0, R)) denotes the distance between two nodes in ith hop. θi shows the angle between hop direction and straight line between source and destination (shown by L_{SD}) in hop i, (θi $\in$(-π/2,π/2)). Furthermore, Mp is the number of hop in the path P. Now the distance between transmitter and receiver in hop i (di) can be decomposed to, the distance in the direction of LSD (d_i^x) and the distance perpendicular to the direction of LSD (d_i^y).

$$d_i^x = d_i \cos\theta_i \qquad (1)$$

$$d_i^y = d_i \sin\theta_i \qquad (2)$$

d_i^x is known as information moving distance (IMD), and d_i^y is called information jumping distance (IJD) [12]. 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 Mp hops, if the two following equations are satisfied.

$$\sum_{i=1}^{M_p} d_i^x = D \qquad (3)$$

$$\sum_{i=1}^{M_p} d_i^y = 0 \qquad (4)$$

Equation (3) shows that after Mp hops the route between source and destination should traverse distance D, and Equation (4) means the selected route should converge to L_{SD} line.

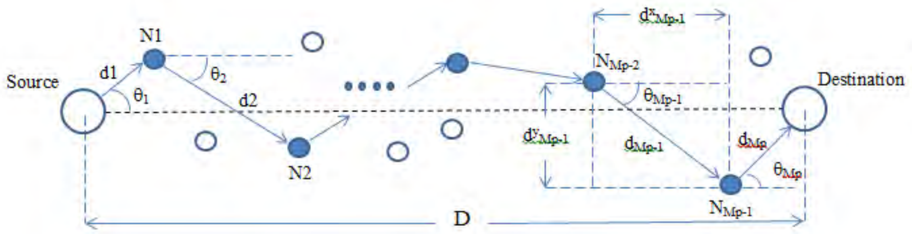


Figure 1. Multi-hop routing scenario

B. *Spectral Efficiency*

Using multi-channel networks is an efficient solution to overcome the degradation of the network capacity. Therefore in this paper, we focus on wireless mesh network with the standard IEEE802.11a which provides 13 orthogonal sub-channels to transmit data packets in a multi-hop manner. Because of the orthogonality between sub-channels there will be no co-channel interference between the links. The channel model is Rayleigh channel, shadowing effect and large scale path loss are ignored. Furthermore, it is assumed that channel variations are slow enough in comparison with the data packet length and all nodes have equal transmission power, P_T.

Spectral efficiency of a link between two nodes, C (bit/s/Hz), is defined as follows

$$C = \log_2\left(1 + \frac{P_T |\alpha|^2}{N}\right) \tag{6}$$

where α is instantaneous channel gain and N represents the variance of additive white Gaussian noise. Each node can gather channel state information of its neighbors, to compute the link capacity. To evaluate the spectral efficiency of selected route, there are two different methods in the literatures.

1) TMBS (throughput maximization bandwidth sharing): in this case it is guaranteed that enough time is allocated to each link, so that, each link can transmit the same amount of data. C_{TMBS} is computed as [15]

$$C_{TMBS} = \frac{1}{\sum_{i=1}^{M_p} \frac{1}{C_i}} \tag{7}$$

where Ci shows the capacity of the selected link in hop i.

2) ETBS (equal time bandwidth sharing): ETBS allocates equal time duration to each link to transmit data packets [7]. ETBS has some advantages to TMBS which make it a better choice for ad-hoc networks.

As mentioned, TMBS assigns enough time duration to transmit the data packet. Therefore, for channels with deep fade and bad channel condition, the time assigned to data transmission will increase and results to high energy consumption. However, ETBS allocates equal time to link between nodes to transmit data which results to energy saving and becomes a better option for ad-hoc networks and WMNs. C_{ETBS} can be computed as

$$C_{ETBS} = \frac{1}{M_p} \min C_i \qquad i=1,2,\ldots Mp \tag{8}$$

Ci indicates spectral efficiency of link in hop i.

In this paper, we use C_{ETBS} to evaluate the spectral efficiency of a selected route, because of its favorable properties for ad-hoc networks and WMNs. The distributed routing scheme selects a receiver node for next hop based on spectral efficiency (Ci) and a probability based scheme to increase the network performance and accessibility to destination.

III. PROBLEM FORMULATION

To design the routing scheme, we consider the network performance as a routing strategy. Therefore, paths which can maximize the total capacity of the network are selected. Moreover, we propose a method to satisfy accessibility introduced in (3) and (4). Consequently, the problem formulation of proposed routing scheme can be modeled as follows.

$$\max \; C_{tot} \tag{9}$$

$$s.t. \quad \sum_{i=1}^{M_P} d_i^x = D$$
$$\sum_{i=1}^{M_P} d_i^y = 0$$

where Ctot can be computed using C_{TMBS} or C_{ETBS}. Now to provide a routing scheme, we use the following equation in ith hop as follows and consider effect of the number of sub-channels and their conditions.

$$C_i = \max \left(\sum_{n=1}^{N} \sum_{k=1}^{K} \log_2(1+\rho_k^n \gamma_k^n)\right) \quad (10)$$

where ρ_k^n is time-sharing parameter for kth relay and nth sub-channel. ρ_k^n can be set to zero or one. ρ_k^n=1 means relay k and sub-channel n are selected as the next node and relative sub-channel to data packets transmission. While ρ_k^n=0 shows that relay k and sub-channel n are not selected. Therefore, in a relay and sub-channel which maximize the link capacity ρ_k^n should set to one. γ_k^n denotes the link SNR between transmitter and kth relay on sub-channel n which is defined as

$$\gamma_k^n = \frac{\left|\alpha_k^n\right|^2 P_T}{N} \quad (11)$$

where α_k^n is the channel gain between transmitter and relay k on sub-channel n, which follows Rayleigh distribution. PT is the transmission power and it is assumed that PT is the same for all nodes in the network. N is the variance of additive white Gaussian noise. Finally, to select the best node, transmitter finds a relay and a sub-channel with the largest channel gain. Parameter ρ_k^n for this sub-channel and relay will be set to one and others will be set to zero.

In the next section, the PBS and its effect on network performance and accessibility is evaluated.

IV. Probability Based Scheme (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 the hops. Accessibility can be achieved by satisfaction of Equations (3) and (4). It is obvious that if the routing scheme chooses relay nodes in the direction toward the destination, (3) will be satisfied. Therefore, the main issue of accessibility is satisfaction of the Equation (4) 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 paragraph, we explain how PBS can improve the accessibility in the proposed distributed routing scheme.

Now, suppose that N_{up} and N_{down} denote nodes with the largest link capacity in the A_{up} and A_{down} areas shown in Fig. 1, respectively. Aup is the area toward the destination with $\theta i \in (0,\pi/2)$ and Adown is the area below the line of L_{SD} with $\theta i \in (-\pi/2,0)$. Selection of the nodes was explained in the previous section. After selection of N_{up} and N_{down} nodes, the PBS selects the best node, N_{best}, with probability of δ, ($\delta \in (0,1)$) among N_{up} and N_{down} nodes 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^{y0} are defined as IMD and IJD of the best node N_{best} in each hop. Also, $d_i^{x,so}$ and $d_i^{y,s0}$ are IMD and IJD of other nodes, respectively. Fig. 2 shows these parameters where the best node is located in the A_{up} region.

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 A_{down} area while the transmitter is located above the line L_{SD}. Fig. 3-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.

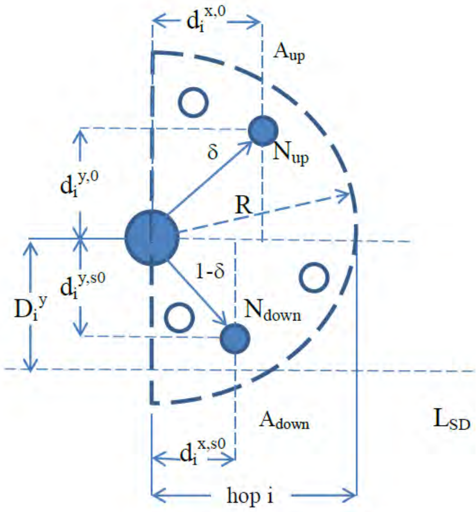


Figure 2. N_{up} and N_{down} are selected nodes among all nodes in the A_{up} and A_{down} area, respectively and N_{up} is selected with probability of δ as a receiver in the next hop.

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 Nbest 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, Nbest is located in Aup, and transmitter node is above the line L_{SD}. As shown in Fig. 3-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:

$$\overline{D_i^{x-}} = \sum_{j=1}^{i-1} d_j^x + \delta d_i^{x,0} + (1-\delta) d_i^{x,s0} \quad (12)$$

$$\overline{D_i^{y-}} = D_{i-1}^{y-} + \delta d_i^{y,0} + (1-\delta) d_i^{y,s0} \quad (13)$$

According to the equations (3) and (4), 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.

$$\sum_{j=i+1}^{M} d_j^x = D - \overline{D_i^{x-}} \quad (14)$$

$$\sum_{j=i+1}^{M} d_j^y = -\overline{D_i^{y-}} \quad (15)$$

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 $\overline{d_x}$ [9]. However, IJD of optimal nodes in A_{up} and A_{down} follows two different distributions with the average value $\overline{d_U^y}$ and $\overline{d_D^y}$ ($\overline{d_U^y}$ = -$\overline{d_D^y}$), respectively. For more details refer to [9]. Now in each hop, the average IJD after ith hop is:

$$\overline{d_y} = \delta \overline{d_U^y} + (1-\delta)\overline{d_D^y} = (1-2\delta)\overline{d_D^y} \quad (16)$$

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

$$\overline{M_i} = \frac{\sum_{j=i+1}^{M} d_j^x}{\overline{d_x}} \quad (17)$$

$$\overline{M_i} = \frac{\sum_{j=i+1}^{M} d_j^y}{\overline{d_y}} \quad (18)$$

Then, it is obvious that

$$\frac{\sum_{j=i+1}^{M} d_j^y}{\overline{d_y}} = \frac{\sum_{j=i+1}^{M} d_j^x}{\overline{d_x}} \quad (19)$$

By substituting (12)-(16) into (19) a quadratic equation with parameter δ will be achieved:

$$A\delta^2 + B\delta + C = 0 \qquad (20)$$

where

$$A = 2(d_i^{x,0} + d_i^{x,s0}) \qquad (21)$$

$$B = \frac{\overline{d_x}}{\overline{d_D^y}}(d_i^{y,0} - d_i^{y,s0}) - 2(D - \sum_{j=1}^{i-1} d_j^x) + 3d_i^{x,s0} - d_i^{x,s0} \qquad (22)$$

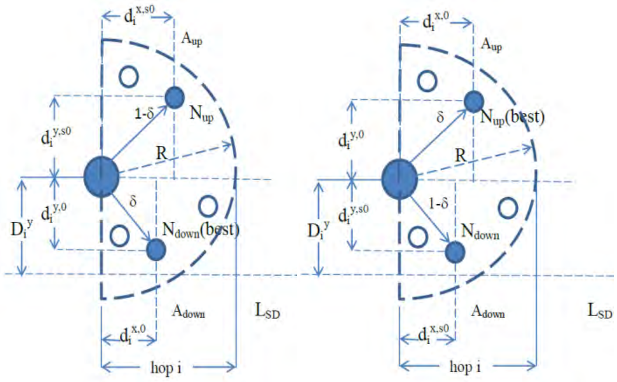
$$C = \frac{\overline{d_x}}{\overline{d_D^y}}(\sum_{j=1}^{i-1} d_j^y + d_i^{y,s0}) + (D - \sum_{j=1}^{i-1} d_j^x - d_i^{x,s0}) \qquad (23)$$

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

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

If Δ = 0, and 0 < δ < 1, δ is the answer, otherwise δ is set to zero.

If Δ > 0, equation has two answers, if δ1 and δ2 are in the interval [0,1], the larger value will be accepted. Larger value of δ improve the network performance. If none of δ1 and δ2 is in the [0,1], δ will be set to zero, because there is no reasonable solution for it.



(a) (b)

Figure 3-a) D_{i-1}^{y-} > 0 and $d_i^y < 0$. b) D_{i-1}^{y-} > 0 and $d_i^y > 0$.

Case 4. D_{i-1}^{y-} < 0 and $d_i^y < 0$. In this case transmitter is below the LSD line and the best node is in the Adown area. According to the discussion in the previous case, δ can be achieved by solving (20). Note that the Equation (16) have to change to the following equation.

$$\overline{d_y} = \delta\overline{d_D^y} + (1-\delta)\overline{d_U^y} = (1-2\delta)\overline{d_U^y} \qquad (24)$$

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 (20) 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:

$$\overline{d_x} = \frac{1}{3}(\overline{d_{pre}^x} + d_{i,up}^x + d_{i,down}^x) \qquad (25)$$

$$\overline{d_D^y} = \frac{1}{2}(\overline{d_{D,pre}^y} + d_{i,down}^y) \qquad (26)$$

$$\overline{d_U^y} = \frac{1}{2}(\overline{d_{U,pre}^y} + d_{i,up}^y) \quad (27)$$

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. $d_{i,up}^x$, $d_{i,down}^x$, $d_{i,up}^y$ and $d_{i,down}^y$ are the IMD and IJD of two candidate nodes selected to maximize network spectral efficiency in the A_{up} and A_{down} areas, respectively.

As a brief review, the proposed distributed routing scheme at the first step, according to sub-channel information (based on IEEE802.11a, 13 non-overlapping channels) finds relay nodes and sub-channels which maximize the network capacity. Two nodes will be selected in this step, one from A_{up} and the other from A_{down} region. After that, using the PBS, one of the nodes which can improve the accessibility to destination is selected. To make the adequate decision, the PBS, using the information of the transmitter and its neighbors in each hop selects one node. It is expected that, this routing method can balance the trade-off between network performance and accessibility by reducing number of hops in multi-channel multi-hop networks.

V. SIMULATION AND EXPERIMENTAL RESULTS

To model a multi-hop network, an area with the dimension of $D \times D$ is assumed. The source and destination nodes are placed in (0,D/2) and (D,D/2) respectively. Relay nodes are placed randomly, with uniform distribution in this area. Communication range of each node (R) is assumed 2 Km. Furthermore, it is supposed that each node has at least one neighbor to transmit data packets. The channel model is Rayleigh with mean power gain -10 dB. P_T, the transmission power of all nodes in the network, is 10^{-3} W. The variance of additive white Gaussian noise is set to 10^{-3} W. We assume that the source node transmits data packet to destination using relay nodes in multi-hop manner. According to channel conditions, each node selects two relay nodes with larger channel gain, and then by using the PBS scheme, one node is selected as a receiver in the next hop. This process continues until the packet reaches to destination. We run the simulation 200 iterations to evaluate the proposed routing scheme.

Fig. 4 shows the effect of the PBS on the number of hops from source to destination. The distance between source and destination increases from 4 to 10 Km. As it is illustrated the probabilistic model reduces the number of hops and find a shorter path to destination.

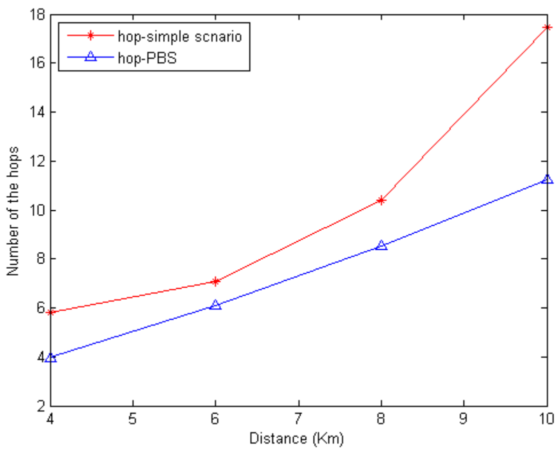


Figure 4. Effect of the PBS on the average number of the hops.

As mentioned, the PBS, in the procedure of selecting relays in a path, balances the trade-off between accessibility and performance of the network. Therefore, in order to evaluate the network performance, we use C_{ETBS} as a metric for spectral efficiency and network performance, because both of the parameters, link capacity and the number of the hops are considered in (8). Fig. 5 shows C_{ETBS} of network using the PBS.

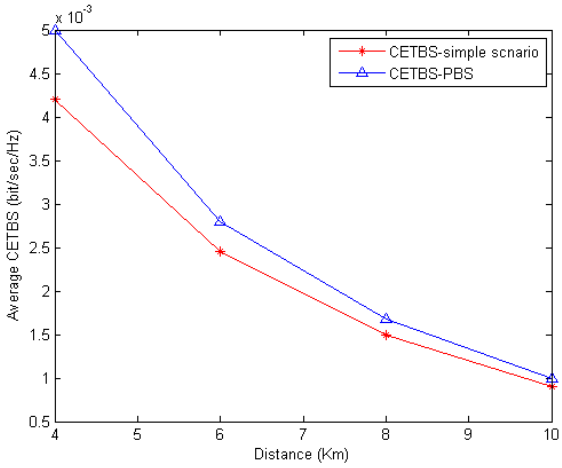


Figure 5. Network performance of the proposed routing scheme.

Fig. 6, evaluates the performance of proposed routing scheme in term of packet transmission delay. In this simulation, equal transmission time is allocated to each node for packet transmission. The PBS scheme reduces the delay between source and destination by reducing the number of the hops to reach to destination. Less delay transmission improves the QoS in delay sensitive services. Furthermore, it can improve the probability of successful data packet delivering. Table I shows the probability of accessibility. We assume that lifetime of packets are 5×10^{-5} seconds in the network. Therefore the packet experiencing more delay will be dropped.

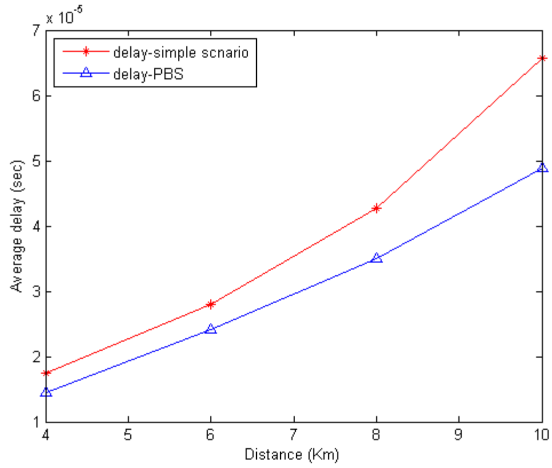


Figure 6. The average delay to transmit data packets.

Table I. the probability of successful transmission

The probability of successful data transmission	
Simple scenario	Using the PBS
0.36	0.88

Conclusion

In this paper, we used the idea of relay and sub-channel assignment as a method for distributed routing in multi-channel multi-hop wireless networks. In the proposed distributed routing scheme, each node, selects a relay and sub-channel which maximizes the network spectral efficiency by only local information of its one-hop neighbors. The PBS controls the procedure of relay selection so that, the path can converge to destination with less the number of the hop. As this routing method is a distributed, C_{ETBS} is used to evaluate the routing scheme.

As the results show, using the PBS can improve C_{ETBS} and also reduce the number of the hops and transmission delay in the path reaching to destination.

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