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Research Article

Distributed Routing and Spectrum Allocation Algorithm with Cooperation in Cognitive Wireless Mesh Networks

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Routing and spectrum allocation is an important challenge in cognitive wireless mesh networks. A distributed routing and spectrum allocation algorithm with cooperation (DRSAC-W) in cognitive wireless mesh networks is proposed in this paper. In order to show the decrease of the average end-to-end delay with cooperation in DRSAC-W, a distributed routing and spectrum allocation algorithm without cooperation (DRSAC-WO) is proposed in this paper. Minimizing the average end-to-end delay is the objective of DRSAC-W and DRSAC-WO. Simulation results show that the proposed algorithm DRSAC-W with cooperation can alleviate the high delay due to the heterogeneity of available channels of different nodes and achieve low average end-to-end delay.

1. Introduction

The scarcity of spectrum resource is often thought to be a bottleneck in wireless mobile communications. Cognitive radio (CR) is intelligent revolutionary spectrum (channel) sharing technology and the most important new wireless technology today. The core function of CR is that it can sense the vacancy spectrum resources and share these unused spectrum resources [1]. Secondary users (SU) can use the authorized spectrum which primary users (PU) did not use [2, 3].

A cognitive wireless mesh network (CWMN) is a wireless mesh network which integrates CR technology [4, 5]. A CR-Mesh node (such as a CR-Mesh gateway, a CR-Mesh router, or a CR-Mesh client), which integrates CR technology, can sense the spectrum which PU are not using and access the vacancy spectrum resource.

Wireless mesh networks (WMN) are a type of next generation broadband wireless access networks. There are many challenge problems in wireless mesh networks. Recently, there are some research results about routing and channel allocation [6–10]. However, research results of routing and channel allocation in WMN cannot be applied to CWMN directly, because the problem of routing and channel allocation in a CWMN has the following characteristics. (1) The routing protocol of WMN uses static channel, while the routing protocol of a CWMN must utilize dynamic channels. (2) The CR-Mesh node uses the allocated spectrum which the PU did not use; hence, the CR-Mesh node must ensure that it does not interfere with the communication of the PU. (3) The channels available to a CR-Mesh node are a subset of all available channels, and this subset changes over time in a CWMN. (4) There are heterogeneity available channel sets among different CR-Mesh nodes in a CWMN. (5) There are differences among the different channels, due to the activity of PU.

At present, the research about CWMNs is at an early stage. There are many open challenges [11] in CWMN. Although for the routing and spectrum allocation problems, there are already some research results [12–19].

An improved layered AODV route protocol in cognitive wireless mesh networks was proposed by Tingrui et al. [12]. An AODV-COG route protocol based on AODV protocol was proposed by Sun et al. The objective of AODV-COG is to increase the throughput of a CWMN [13]. An economic framework for adaptation and control of the network resources with the final goal of the network profit maximization was proposed by Amini and Dziong [14]. A multisource video on-demand application over a multiinterface cognitive wireless mesh networks was studied by Yong Ding with the objective of maximizing the number of sessions of the network. A distributed multipath routing and spectrum allocation algorithm (DRCA) and a centralized multi-path routing and spectrum allocation algorithm (CRCA) were proposed by Ding and Xiao [15]. Lee et al. aim at solving the problem of coexistence of CWMN and other wireless networks, in order to share spectrum among multiple wireless networks. A route and spectrum allocation algorithm with the objective of minimizing the used spectrum was proposed [16].

With the optimization of average throughput and average delay, a distributed routing and channel allocation was proposed by Zhang et al. [17]. A multi-path routing and channel allocation strategy was proposed by Gu et al., with the goal of optimizing average throughput and average delay [18]. A dynamic layered-graph routing model and routing policy for CWMN were proposed by Li et al. [19].

The problem of routing and spectrum allocation with node cooperation is studied in this paper. We aim to minimize the end-to-end average delay.

This paper offers the following innovations when compared to existing research. (1) The effect among multiple wireless requests is taken into account, in order to minimize the average end-to-end delay. (2) The different wireless channels have different transmission characteristics, with delay being one of the most important of these characteristics. (3) DRSAC-WO, a distributed routing and spectrum allocation algorithm without cooperation, and DRSAC-W, a distributed routing and spectrum allocation algorithm with cooperation, are proposed in this paper.

The remainder of the paper is organized as follows. We discuss the network model and problem description in Section 2. In Section 3, we describe the proposed DRSAC-WO and DRSAC-W algorithms. Simulations comparing the performance of the proposed algorithms are presented in Section 4. Section 5 concludes the paper and outlines our future work.

2. Network Model and Problem Description

2.1. Network Model. We adopt a simple undirected graph $G = (V, E)$ model of the CWMN, which consists of CR-Mesh router and CR-Mesh gateways. V represents the set of CR-Mesh routers and CR-Mesh gateways. $\mathrm{GW}(\mathrm{GW} \subset V)$ represents the set of CR-Mesh gateways. E represents the set of wireless links. Each node $v_i \in V$ has an available channel set K_i which has been sensed. Each node $v_i \in V$ has I_i cognitive radio interfaces (CRIs). T_R and I_R represent the communications distance and interference distance, respectively, and $I_R = 2 \times T_R$. The physics distance between node v_i and node v_j is represented by $d(v_i, v_j)$. Two CR-Mesh nodes which can communicate with each other must satisfy the following conditions. (1) There are common available channels, $K_i \cap K_j \neq \Phi$. (2) There are unoccupied CRIs for each node. (3) The nodes must satisfy the restriction of distance, $d(v_i, v_j) \leq T_R$. (4) The nodes must satisfy the restriction of interference.

There is interference between wireless links (u_1, v_1) and (u_2, v_2) which must satisfy the following condition.

Table 1: Symbol implication.

Symbol	Implication
V	Sets of nodes $\|V\| = n$
E	Set of edges $\|E\| = m$
Δ	Set of wireless requests
K	Set of available channels
T_R	Communications distance
I_R	Interference distance
I_i	Available number of cognitive radio interfaces of node i
K_i	Available channel set of node i
D^k	Delay of channel k
$x(u, v)$	Allocation channel of wireless link (u, v)

(1) $d(u_1, u_2) \leq I_R$ or $d(u_1, v_2) \leq I_R$ or $d(v_1, u_2) \leq I_R$ or $d(v_1, v_2) \leq I_R$, and (2) the same channel must have been allocated to two wireless links, $x(u_1, v_1) = x(u_2, v_2)$.

$H(u, g_i)$ represents the hop count from CR-Mesh route node u to the CR-Mesh gateway node $g_i (g_i \in \mathrm{GW})$.

$X = \{x(u, v)\}_{n*n}$, $x(u, v) = k$ that represents the wireless link (u, v) is allocated channel k. $x(u, v) = 0$ that represents the wireless link (u, v) is not allocated any channel. Every wireless link either is allocated only one channel or is not allocated a channel.

D^k represents the delay of the channel k $(k \in K, k \geq 1)$, in units of *ms*. Different channels have different delays, that is, different channels i and j lead to $D^i \neq D^j$. In order to describe the proposed algorithm, we assume that there is channel 0. The delay of channel 0 is $D^0 = \infty$. The meaning of other symbols are summarized in the Table 1.

2.2. Problem Description. We study the problem under the condition of heterogeneous available channels, and the route from source node to destination node is constructed distributedly. We aim to minimize the average end-to-end delay.

$\Delta = \{\delta_i = (s_i, d_i)\}$ represent the set of wireless requests, s_i and d_i represents the source node and destination node of wireless request $\delta_i \cdot \mathrm{Path}(s_i, d_i)$ represents the path from source node s_i to destination node $d_i \cdot \mathrm{Delay}(s_i, d_i)$ represents the average end-to-end delay of $\mathrm{Path}(s_i, d_i)$, as computed with the following:

$$\mathrm{Delay}(s_i, d_i) = \sum_{(u,v) \in \mathrm{Path}(s_i, d_i)} D^k x(u, v) = k. \tag{1}$$

AvgDelay (Δ) represents the average end-to-end delay. Minimizing the average end-to-end delay is the goal and is formulated as follows:

$$\begin{gathered} \mathrm{Min} \quad \mathrm{AvgDelay}(\Delta), \\ \mathrm{AvgDelay}(\Delta) = \frac{1}{|\Delta|} \sum_{\delta_i \in \Delta} \mathrm{Delay}(s_i, d_i). \end{gathered} \tag{2}$$

A simple topology is considered. This topology is shown in Figure 1. There are 2 CR-Mesh gateways, and 10 CR-Mesh router nodes. CR-MR4 $\{1, 2, 3, 4, 5\}/3$ represents that the node CR-MR4 has the available channel set $\{1, 2, 3, 4, 5\}$,

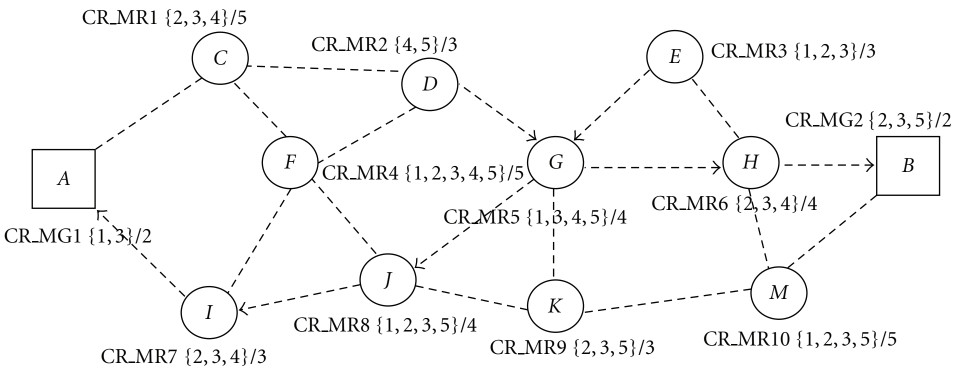


Figure 1: Cognitive wireless mesh network topology.

with five CRIs, $K_2 = 5$, and $I_2 = 5$. There are 5 available channels in wireless network, $K = \{1, 2, 3, 4, 5\}$, the delay of each of these is $D = \{3, 5, 6, 9, 2\}$.

$\delta_1 = (E, A)$ and $\delta_2 = (D, B)$ are two wireless requests in the network environment. Table 2 shows the constructed paths and spectrum allocations without cooperation. $\text{Path}(E, A) = E \xrightarrow{1} G \xrightarrow{5} J \xrightarrow{2} I \xrightarrow{3} A$ represents the constructed path of wireless request δ_1. It means that the allocated channel from node E to node G is channel 1, the allocated channel from G to node J is channel 5, the allocated channel from J to node I is channel 2, and the allocated channel from I to node A is channel 3. We can compute the $\text{Delay}(E, A) = 16$ and $\text{Delay}(D, B) = 20$ using (1). The following computes the average end-to-end delay:

$$\text{AvgDelay}(\Delta) = \frac{(\text{Delay}(E, A) + \text{Delay}(D, B))}{2} = 18. \quad (3)$$

Table 3 shows the constructed paths and allocated spectrum with cooperation. The delays are $\text{Delay}(E, A) = 20$ and $\text{Delay}(D, B) = 13$, and the average end-to-end delay is

$$\text{AvgDelay}(\Delta) = \frac{(\text{Delay}(E, A) + \text{Delay}(D, B))}{2} = 16.5. \quad (4)$$

The wireless request δ_1 arrives before wireless request δ_2. Without cooperation, the fundamental of spectrum allocated is channel with the lowest delay. When the wireless request δ_2 arrives, the wireless link $G \rightarrow J$ has been allocated channel 5. The wireless link $D \rightarrow G$ only can be allocated channel 4.

With cooperation, the channel allocated to the wireless link $G \rightarrow J$ is changed to channel 3, and the channel of the wireless link $G \rightarrow J$ is changed to channel 5. Although the $\text{Delay}(E, A)$ increases, the $\text{Delay}(D, B)$ decreases with cooperation. Additionally, the decrease in $\text{Delay}(D, B)$ is more than the increase in $\text{Delay}(E, A)$, thus, the overall average end-to-end delay decreases.

The claim of this paper is that making these types of choices will minimize the average end-to-end delays for all requests in the network.

Table 2: Path and delay without cooperation.

	$\text{Path}(s_i, d_i)$	$\text{Delay}(s_i, d_i)$
δ_1	$E \xrightarrow{1} G \xrightarrow{5} J \xrightarrow{2} I \xrightarrow{3} A$	16
δ_2	$D \xrightarrow{4} G \xrightarrow{3} H \xrightarrow{2} B$	20

Table 3: Path and delay with cooperation.

	$\text{Path}(s_i, d_i)$	$\text{Delay}(s_i, d_i)$
δ_1	$E \xrightarrow{1} G \xrightarrow{3} J \xrightarrow{2} I \xrightarrow{3} A$	20
δ_2	$D \xrightarrow{5} G \xrightarrow{3} H \xrightarrow{2} B$	13

3. Distributed Routing and Spectrum Allocation Algorithm

DRSAC-WO, a distributed routing and spectrum allocation algorithm without cooperation, and DRSAC-W, a distributed routing and spectrum allocation algorithm with cooperation, are proposed in this paper. In order to show the decrease in average end-to-end delay when there is node cooperation, we compare the two algorithms. The InitCRNode algorithm is common to both DRSAC-WO and DRSAC-W algorithms.

3.1. InitCRNode Algorithm. InitCRNode algorithm initializes all CR-Mesh nodes of the CWMN. The initialization constructs the neighbor node list, available channels of each neighbor node, and the hop count to CR-Mesh gateway node.

We must do some parts of this computation with a centralized algorithm rather than a distributed algorithm However, the choice of path to the gateway is based upon local information. $L(u)$ represents the information at node u and the neighbor information of node u. $L(u) \cdot \text{Set}$ represents the set of neighbor nodes of CR-Mesh router node u. Other related information is listed in Table 4.

The following formulas show how to compute $L(u) \cdot ax(u)$ and $L(u) \cdot AC(v)$:

$$L(u) \cdot ax(u) = K_u - L(u) \cdot x(u), \quad (5)$$

$$L(u) \cdot AC(v) = L(u) \cdot C(v) - L(u) \cdot UC(v). \quad (6)$$

Input: $ICM(v)$
Output: $ICM(u)$, $L(u)$
1. $L(u) \cdot \text{Set} \leftarrow \Phi \quad T_s \leftarrow 0$
2. if u is GW node {
3. $ICM(u) \cdot H(u,u) \leftarrow 0$
4. $ICM(u) \cdot Ch \leftarrow K_u$
5. Broadcast $ICM(u)$
6. Exit }
7. else if u is MR node {
8. $H(u,g_i) \leftarrow \infty \quad \forall g_i \in GW$;
9. While $(GetCurrTime() \leq T_s$ or $L(u) \cdot Set = \Phi)$ {
10. if (u *receives* $ICM(v)$){
11. $L(u) \cdot \text{Set} \leftarrow L(u) \cdot \text{Set} \bigcup \{v\}$
12. $L(u) \cdot C(v) \leftarrow ICM(v) \cdot C$
13. $L(u) \cdot UC(v) \leftarrow \Phi$
14. $L(u) \cdot x(u) \leftarrow \Phi$
15. $L(u) \cdot x(u,v) \leftarrow 0$
16. if $|L(u) \cdot \text{Set}| = 1$ {
17. Init Timer T_s; }}// end if
18. }// end while
19. $L(u) \cdot H(u,g_i) \leftarrow$
$\text{Min}\{\text{Min}_{v \in L(u) \cdot \text{Set}}\{H(v,g_i)\} + 1,\ H(u,g_i)\} \quad \forall g_i \in GW$;
20. $ICM(u) \cdot H(u,g_i) \leftarrow L(u) \cdot H(u,g_i)$
21. $ICM(u) \cdot C \leftarrow K_u$;
22. Boardcast $ICM(u)$; }// end else if

Algorithm 1: InitCRNode algorithm.

Table 4: Information $L(u)$ of node u.

ID	Name	Description
1	$x(u)$	Set of used channel of node u
2	K_u	Set of available channel of node u
3	$ax(u)$	Set of allocable channel of node u
4	$H(u,g_i)$	Hop from node u to gateway node g_i
5	$x(u,v)$	Allocated channel for wireless link (u,v)
6	$C(v)$	Set of available channel of neighbor node v
7	$UC(v)$	Set of used channel of neighbor node v
8	$AC(v)$	Set of allocable channel of neighbor node v

$ICM(u)$ represents the initialization control information of node u.

$ICM(u) \cdot C = K_u$ represents the available channel set of node u.

$ICM(u) \cdot H(u,g_i) = H(u,g_i)$ represents the minimum hop count from node u to gateway node g_i. See Algorithm 1.

3.2. DRSAC-WO Algorithm. DRSAC-WO is a distributed routing and spectrum allocation algorithm without cooperation.

$UCM(u)$ represents the update control information of node u. $UCM(u)$ is sent when the allocated channel of node u changed.

$UCM(u) \cdot UC$ represents the set of channels used by node u. The choice of the next hop is that, the node which has the lowest delay channel in common with node u is chosen as the next hop node from the neighbor node set. If more than one neighbor has the same lowest delay common channel, then the node with the lowest hop count is chosen as the next hop node. The DRSAC-WO algorithm is shown below.

3.3. DRSAC-W Algorithm. DRSAC-W is a distributed routing and spectrum allocation algorithm with cooperation. The difference between the DRSAC-W and DRSAC-WO is (1) adding a cooperation request strategy to Algorithm 2 between line 16 and line 17 to DRSAC-W and (2) adding the cooperation response strategy for the neighbor node of node u to DRSAC-W.

$RCM(u)$ represents the information contained in the cooperation request from node u.

$RCM(u) \cdot x(u,v)$ represents the allocated channel of wireless link (u,v). The fundament of cooperation in DRSAC-W algorithm is that, node u sending the request cooperation control information to find the lower delay wireless link for wireless link (u,v). It must ensure that the sum of delays is lower than the sum of the earlier delays. Minimizing the average end-to-end delay is the goal.

$REM(v)$ represents the response information which is sent from node v to node u.

$REM(v) \cdot x(u,v)$ represents the allocated channel for wireless link (u,v).

Algorithm 3 shows the cooperation request strategy of node u, while Algorithm 4 shows the cooperation response strategy of node v which is the neighbor of node u.

Input: $\delta_i = (s_i, d_i)$, u
Output: $x(u, v)$
1. $j \leftarrow 0 \quad k \leftarrow 0$
2. if (u *receives* $UCM(x)$) {
3. $L(u) \cdot UC(x) \leftarrow UCM(x) \cdot UC$}
4. if $L(u) \cdot x(u) \geq I_u$ exit
5. Compute $L(u) \cdot ax(u)$ according to (5)
6. for each $y \in L(u) \cdot \text{Set}$\{
7. if $L(u) \cdot UC(y) \geq I_y$ continue
8. Compute $L(u) \cdot AC(y)$ according to (6)
9. $K(u, y) = L(u) \cdot ax(u) \bigcap L(u) \cdot AC(y)$
9. $j = \arg \text{Min}\{D^m\} \quad m \in K(u, y)$
10 if $(D^k > D^j)$\{
11. $k \leftarrow j \quad v \leftarrow y$
12. } else if $(D^k = D^j)$ {
13. if $L(v) \cdot H(v, d_i) > L(y) \cdot H(y, d_i)$\{
14. $k \leftarrow j \quad v \leftarrow y$}}
15. }//end for
16. $x(u, v) \leftarrow k$
17. $L(u) \cdot x(u) \leftarrow L(u) \cdot x(u) \bigcup \{x(u, v)\}$
18. $UCM(u) \cdot UC \leftarrow L(u) \cdot x(u)$
19. Boardcast $UCM(u)$

Algorithm 2: DRSAC-WO algorithm.

Input: $\delta_i = (s_i, d_i, \tau_i)$, u, $x(u, v) = k$
Output: $x(u, v) = k'$
1. Send $RCM(u)$
2. Init Timer T_w
3. while ($GetCurrTime() \leq T_w$)\{
4. if (u *receives* $REM(v)$ from z) {
5. Cancel timer T_w
6. Boardcast $FBM(u)$
7. $k' \leftarrow REM(v) \cdot x(u, v)$
8. $L(u) \cdot x(u) \leftarrow L(u) \cdot x(u) - \{x(u, v)\}$
9. $x(u, v) \leftarrow k'$
10. }// end while

Algorithm 3: Cooperation request strategy of node u.

Input: (u, v), $RCM(u)$
Output: $x(u, v)$
1. if (v *receives* $RCM(u)$ from u) {
2. Compute $L(v) \cdot ax(v)$ according to (5)
3. Compute $L(v) \cdot AC(u)$ according to (6)
4. $k1 \leftarrow RCM(u) \cdot x(u, v)$
5. $K(v, u) \leftarrow L(v) \cdot ax(v) \bigcap L(v) \cdot AC(u)$
6. for each $k2$
$k2 \in K(v, u) and (D^{k2} < D^{k1})$)\{
7. For each $y \in L(v) \cdot Set$\{
8. if $x(v, y) = k2$
9. Compute $L(v) \cdot AC(y)$ according to (6)
10. $K(v, y) \leftarrow L(v) \cdot ax(v) \bigcap L(v) \cdot AC(y)$
11. $k3 = \text{argMin}\{D^m\} \quad m \in K(v, y)$
$st \cdot D^{k3} < D^{k1}$.
12. $\beta \leftarrow D^{k1} - D^{k3}$
13. if $\alpha < \beta$\{
14. $\alpha \leftarrow \beta \quad k4 \leftarrow k3 \quad w \leftarrow y$}
15. } }// end for
16. $x(v, w) \leftarrow k4$
17. $REM(v) \cdot x(u, v) \leftarrow k2$
18. Send $REM(v)$
19. $L(v) \cdot x(v) \leftrightarrow L(v) \cdot x(v) \bigcup \{k4\} - \{k1\}$
20. $UCM(v) \cdot UC \leftarrow L(v) \cdot x(v)$

Algorithm 4: Cooperation response strategy of node v which is the neighbor node of node u.

The following formula shows the sum of delays for all edges in the network:

$$\Im = \sum_{x(u,v)=k} D^k \quad (u, v) \in E. \tag{7}$$

Before adjusting the channel, $x(u, v) = k1$, $x(v, w) = k2$, after adjusting the channel, $x(u, v) = k2$, $x(v, w) = k4$. α represents the delay difference of channel $k4$ and $k1$. The larger the value of α, the lower the average end-to-end delay.

4. Simulation and Results

In order to validate the efficiency of the algorithms proposed in this paper, we implemented the DRSAC-W, DRSAC-WO, and DRCA [15] algorithms using NS-2 [20].

The network topology that was simulated corresponds to the wireless access network of a university. There are some available channels in 2000 m × 2000 m area. The PU uses the channel stochastically with $T_R = 50$ m and $I_R = 100$ m.

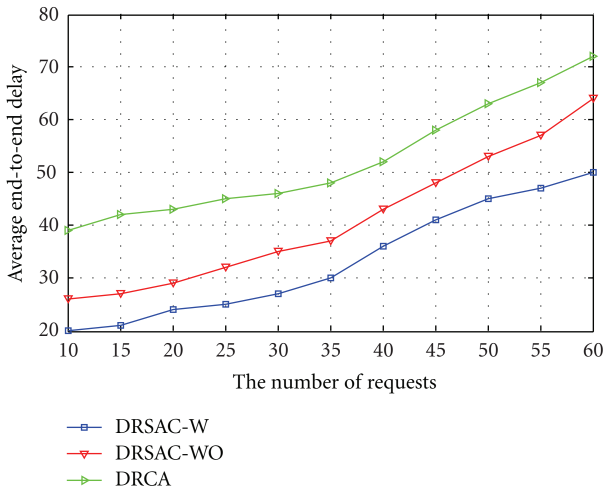
There are two network topologies with different numbers of nodes: $n = 25$ and $n = 50$. Two nodes are chosen randomly as the gateway nodes.The available number of channels for $n = 25$ and $n = 50$ are $|K| = 6$ and $|K| = 9$. The duration in seconds of each wireless request is randomly selected from the interval $[1, 10]$. The rate of wireless requests is 2 Mb/s. The delay in ms of each channel is a random value in the range $[1, 10]$. The simulated time is 200 s.

The simulation results that we report are the average of 500 simulation runs. The performance parameters that we report are the average end-to-end delay and average throughput.

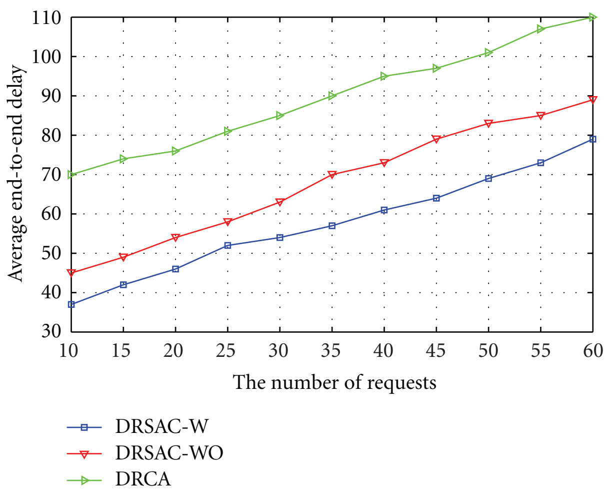
The simulation considers the following two aspects (1) Analyzing the performance of DRSAC-WO, DRSAC-W and DRCA with different numbers of requests. (2) Analyzing the performance of DRSAC-WO, DRSAC-W and DRCA with different numbers of available channels.

4.1. The Performance Comparison with Different Numbers of Requests. We analyse the performance of algorithms with different numbers of wireless requests. Figures 2 and 3 show the simulation results.

We can see from Figure 2, as the number of requests increases the average end-to-end delay increases for all three algorithms. This is because the available network resources do not change despite the increased number of wireless requests. Therefore, the average end-to-end delays increase.

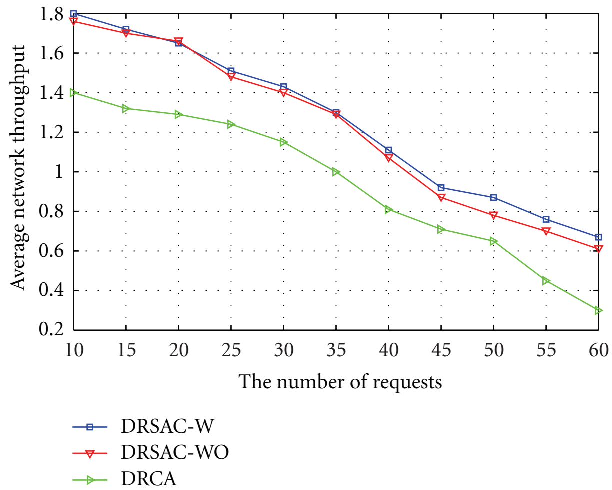


(a) $n = 25$

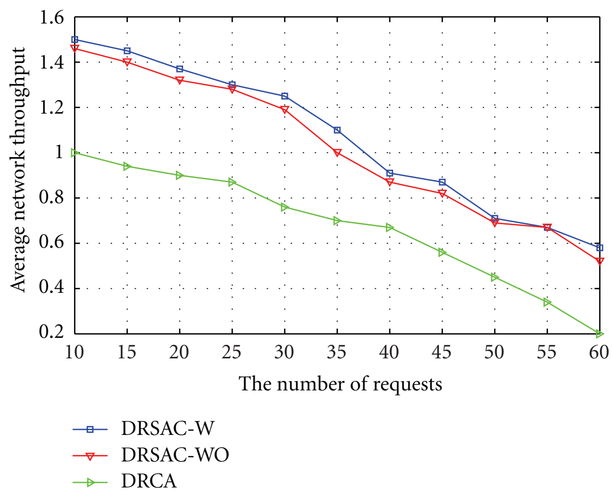


(b) $n = 50$

FIGURE 2: Average end-to-end delay with different numbers of requests.



(a) $n = 25$



(b) $n = 50$

FIGURE 3: Average throughput with different numbers of requests.

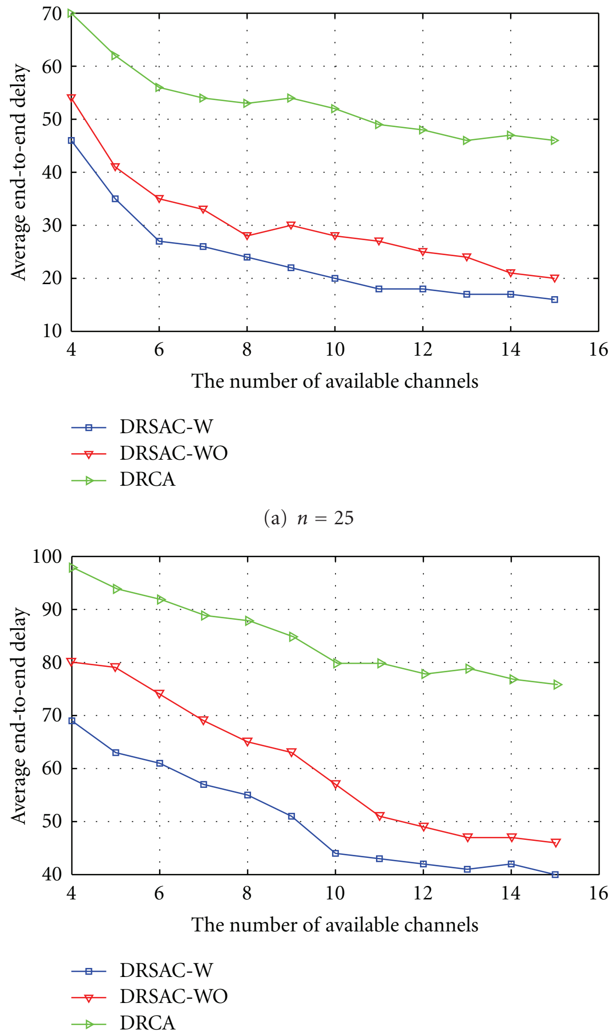
The average end-to-end delay of DRSAC-W and DRSAC-WO algorithm are less than for the DRCA algorithm. This is because DRSAC-W and DRSAC-WO algorithms choose the node, which has the lowest delay common channel as the next hop. Unlike our goal of minimizing the average end-to-end delay, minimizing the sum of bandwidths of each session is the goal of DRCA algorithm. Furthermore, the average end-to-end delay of DRSAC-W is less than that of the DRSAC-WO. This is because that the DRSAC-W algorithm reduces the average end-to-end delay due to node cooperation.

We can see from Figure 3, as the number of requests increases, the average throughput of all three algorithms deceases. This is because the available network resource does not change despite the number of wireless requests increasing. Additionally, the average throughput of DRSAC-W and DRSAC-WO algorithms is greater than is DRCA algorithm. The average throughput of DRSAC-W and DRSAC-WO iss the same. This is because that the difference between DRSAC-W and DRSAC-WO is that DRSAC-W algorithm adopt the node cooperation in order to decease end-to-end average delay.

4.2. The Performance Comparison with Different Numbers of Available Channels. We analyse the performance of the three algorithms with different numbers of available channels via simulation. Figures 4 and 5 are the result of averaging the result of 500 simulations, when the number of wireless requests in each 200 second simulation run was 30.

We can see from Figure 4, as the number of available channels increases, the average end-to-end delay of all three algorithms decreases. This is because that the number of wireless requests did not change while the number of available channels increased. The average end-to-end delay of DRSAC-W and DRSAC-WO algorithms was less than for the DRCA algorithm.

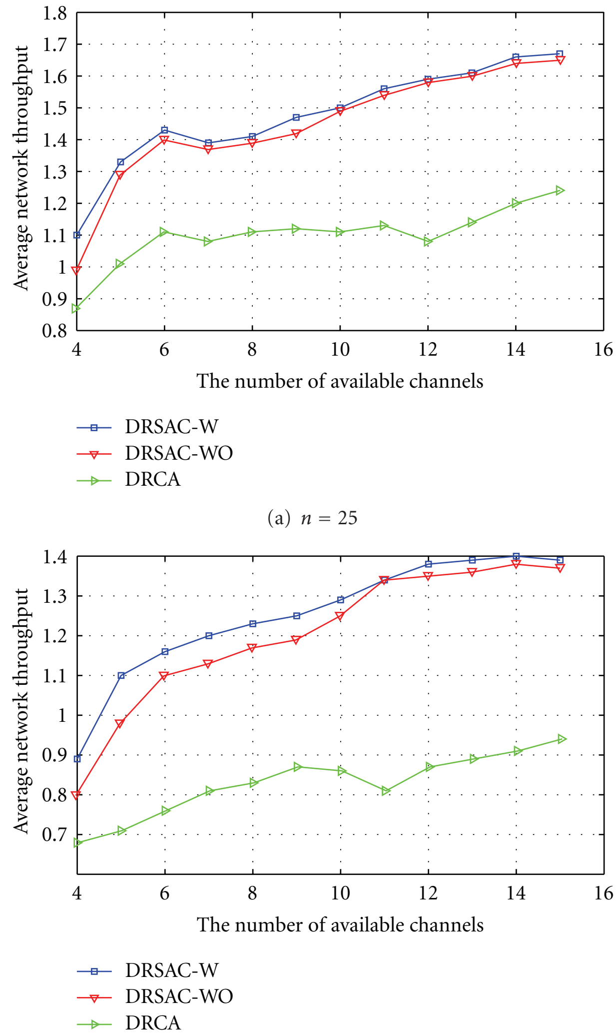
We can see from Figure 5, as the number of available channels increase, the average throughput of all three



(a) $n = 25$

(b) $n = 50$

Figure 4: Average end-to-end delay with different numbers of available channels.



(a) $n = 25$

(b) $n = 50$

Figure 5: Average throughput with different numbers of available channels.

algorithms increases. Although, the average throughput of the DRSAC-W and DRSAC-WO algorithm is greater than for the DRCA algorithm. There is no difference between the DRSAC-W and DSRAC-WO algorithms.

5. Conclusion

The problem of routing and spectrum allocation with the goal of minimizing end-to-end average delay is researched in this paper. A distributed routing and spectrum allocation algorithm without cooperation and a distributed routing and spectrum allocation algorithm with cooperation are proposed in this paper. Simulation results show that DRSAC-W and DRSAC-WO algorithms can achieve low average end-to-end delay and high average throughput. The average end-to-end delay of DRSAC-W is less than DRSAC-WO, showing that the average end-to-end delay deceases with node cooperation. The problem of load balanced of routing and spectrum allocation will be addressed in our future work.

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