Cooperative Routing Protocol in Cognitive Radio Ad-Hoc Networks

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Abstract—**Cognitive radio (CR) technology enables the opportunistic use of the vacant licensed frequency bands, thereby improving the spectrum utilization. Therefore, considering end-to-end throughput in CR ad-hoc networks is an important research issue because the availability of local spectrum resources may change frequently with the time and locations. In this paper, we propose a cooperative routing protocol in CR ad-hoc networks. An on-demand routing protocol is used to find an end-to-end minimum cost path between a pair of source and destination. The simulation results show that our proposed cooperative routing protocol not only obtains higher end-to-end throughput, but also reduces the end-to-end delay and the amount of control messages compared to previous work.**

Keywords: ad-hoc networks*; *cognitive radio*; *cooperative routing*; *wireless networks

I. INTRODUCTION

With the advances of wireless technologies, products with wireless communications such as 3G cellular phone, laptop, and tablet PC have been widely used in the world. Therefore, more and more spectrum resources are needed. Within the current spectrum regulatory framework, all of the frequency bands are exclusively allocated to specific services, and violation from unlicensed users is not allowed. The Federal Communications Commission (FCC) has indicated that the percentage of the assigned spectrum that is occupied only from 15 to 85 percent, varying widely in time and places [1]. In order to address the critical problem of spectrum scarcity, the FCC has recently approved the use of unlicensed devices in licensed bands. This new field of research foresees the development of cognitive radio networks (CRNs) to further improve the spectrum efficiency.

A "CR" is a radio that has the sensing ability, and can change its transmitter parameters based on the interaction with environment in which it operates. Thus, CR can exploit the existing wireless spectrum opportunistically. The basic idea of CRNs is that there exist some secondary users (SUs, also called unlicensed users), and they can access the licensed band opportunistically when the primary users (PUs, also called licensed users) are absent, but they need to free the band once the primary user is detected.

Moreover, a technique called cooperative communications (CC) has been proposed [2] to resist the fading effects, and can improve the channel capacity. Authors in [3] shown that CC can brings some benefits in CRNs. For instance, secondary users can relay the traffic of a primary user toward the intended destination or maintaining the signal-to-noise ratio at CR receiver in the situation that CR sender using low transmission power so as to protect the PUs. Since spectrum is valuable resources in CRNs, our objective is to utilize the available resources as many as possible through this cooperative technology that can increase the throughput between SUs. Unfortunately, most of researches considering CC in CRNs are based on single-hop communications. Thus, the considering of end-to-end performance in CR ad-hoc networks is another promising research field.

In this paper, we propose a cooperative routing protocol in CRNs to maximize the end-to-end throughput. Routing in multi-hop CRNs is a challenging research issue because the availability of the spectrum bands is varied with time and places. Traditional ad-hoc routing protocol such as AODV [4] simply flooding route request packet (RREQ) on common control channel (CCC) shared by all SUs for data channel negotiation cannot truly reflect the conditions on the data channels in CRNs. Flooding RREQ in all the data channels also raises concern of scalability. Since a dedicated CCC may not exist or it is just a channel with narrow broadband, table-based routing protocol with large information exchange overhead will jam this narrow channel and lead to low system performance. Therefore, we apply on-demand fashion to broadcast RREQ with calculated accumulation cost that reflects how many transmission opportunities or cooperative benefits along the partial path, and then finally an end-to-end path with minimum cumulated cost can be determined by destination. The proposed metrics used to calculate cost between two nodes take the characteristic of CRNs that the useable bandwidth of a common available channel may be different between CR users into consideration. The simulation results show that our proposed cooperative routing protocol achieves higher end-to-end throughput, smaller end-to-end delay and fewer hop counts than the solutions without considering the characteristics of CRNs.

II. RELATED WORKS

In multi-hop cooperative routing protocols, authors in [5] illustrate the benefits of using CC in multi-hop wireless

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networks by investigating a joint problem of relay node assignment and multi-hop flow routing. Authors in [6] proposed a contention-aware cooperative routing protocol which exploits the benefit of spatial diversity and takes contention relationship among multiple links into consideration, trying to maximize the overall end-to-end throughput of the whole network. However, this routing protocol is implemented based on either link-state routing or distance-vector routing and needs large information exchange to maintain their routing tables.

Cooperative routing protocols at mobile ad-hoc networks are also proposed in [7, 8]. They concern more about the stability of relay nodes which are selected at routing phase. Relay node selection algorithm is designed in order to let the selected relay nodes stay connected between the sender and receiver as long as possible to achieve the benefit of cooperative routing and to avoid the overhead caused by frequent relay nodes reselection.

The above cooperative routing protocols do not concern any factors such as activity of primary users or channel availability in CRNs. Authors in [9] presented many routing protocols in CRNs and illustrate that conducting the spectrum and path selection jointly can ensure that the route remains connected during the network operation as each link has a different set of feasible spectrum bands. As we mentioned before, table-driven routing protocols such as link-state routing or distant-vector routing is not suitable in CRNs. Thus, we find that many on-demand routing protocols [10-14] are proposed.

In COOP [15], the authors proposed a distributed algorithm for joint dynamic routing, relay selection, and spectrum allocation in cognitive and cooperative ad-hoc networks. This paper goes one step further and addresses techniques to leverage the spatial diversity that characterizes the wireless channel in CR ad-hoc networks. The joint routing and relay selection algorithm select a forwarder from a set of feasible next-hop nodes according to the utility function. However, the utility function is defined as link capacity multiply maximum differential backlog on link, and the link capacity is only relevant to signal-to-interference-plus-noise power ratios (SINR). Thus, the decision of relay, next hop forwarding node and spectrum selection is independent of some features of CRNs. Moreover, the knowledge of feasible next hops with positive advance towards the destination for a sender means that this algorithm needs topology control and collects global information of each node. This kind of routing method will easily result in long end-to-end latency and accompanied by congestion at CCC.

III. COOPERATIVE ROUTING IN CR AD-HOC NETWORKS

Our proposed routing protocol is on-demand based. When a source node has data for a destination node, it broadcasts a RREQ on the CCC. Each intermediate node receiving a RREQ can calculate the accumulated cost from the source to itself. The accumulated cost is then placed into RREQ. Through rebroadcasted the RREQ by intermediate nodes, many RREQs finally reach destination. Destination will choose the path which has the minimum end-to-end path cost and then reply a route reply packet (RREP) to the source. In the following, the terms of node and CR user are interchangeable.

A. System Model

We consider a cooperative CR ad-hoc network that primary users are located in different regions and have different spectrum utilizations of their own spectrums. The same group of primary users act in the same primary users region, and operate at the same spectrum or channel. Secondary users are non-infrastructure based and spread over all these regions. The available channels are assumed to be organized in two separate channels. A CCC is used by all secondary users for spectrum access negotiations. The data channels are used for data communications. The data channels consist of a set of discrete mini-bands identified by a discrete index. Each user that has packets to send will contend the spectrum access on the fixed CCC. We assume that a CR user only has one transceiver to operate in either CCC or data channel at the same time. For example, there are three regions of primary users in Fig. 1, labeled as PU_1, PU_2 and PU_3. We assume there are three available data channels. Thus, the available channel set of a CR user located at PU_1 may be {2, 3} when it detect the existence of primary users at channel 1. When two nodes want to communicate with each other, they should select a common available channel in both available channel set. Therefore, each source can build a suitable path to destination with different selected channels at each hop, and can find some relay nodes to do cooperative transmission among the path if possible.

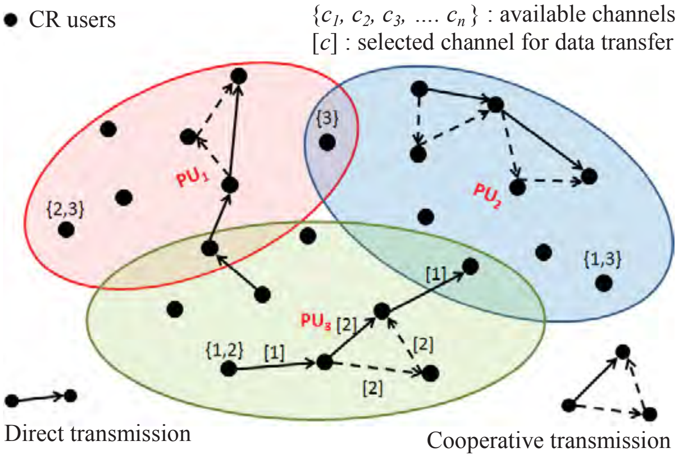
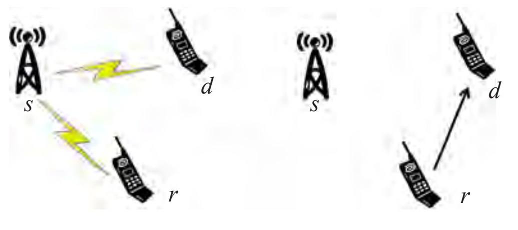


Figure 1. A cooperative CR ad-hoc network

In our proposed cooperative routing protocol, time is divided into k frames. Each frame consists of control phase and data transmission phase. Secondary users operate at CCC in control phase, and operate at data channel in data transmission phase. In control phase, there is a spectrum sensing process executed at physical layer to scan all spectrums, so secondary users can obtain the available channel set and active information of primary users periodically. Each secondary user can broadcast its updated information to neighbors during the information exchange period. If any secondary user has data packet to send, they can send out some negotiation messages in order to communicate with a specific receiver at a designed channel in data transmission frame.

In data transmission phase, CR users can adopt either direct communications or CC to forwarding packet. Fig. 2 is a simple three-node network for CC. In time slot t as shown in Fig. 2 (a), source s sends a packet to destination d, which is also overheard by relay r. In the second time slot $t+1$ as shown in Fig. 2 (b), relay node r forwards the data received in the time slot t to destination d. Destination d can now apply any diversity combining technique [16] on the two copies of the data from two different paths, thereby achieving higher capacity gains.



(a) time slot t (b) time slot $t+1$

Figure 2. CC in a simple three-node network.

Assuming the relay can fully decode the source message, the capacity (bps) of using CC between s and d with relay r on a channel is given by [16, 17],

$$C_{coop}(s,r,d) = B/2 \quad \min\{\log_2(1+SNR_{sr}), \log_2(1+SNR_{sd}+SNR_{rd})\}, \tag{1}$$

where SNR_{sr}, SNR_{sd}, and SNR_{rd} are the signal-to-noise power ratios (SNRs) of links (s, r), (s, d), and (r, d), respectively, and B is the bandwidth of the channel. The capacity of using direct communication at link (s, d) on the same channel is:

$$C_{dirc}(s,d) = B\log_2(1+SNR_{sd}). \tag{2}$$

Note that, the capacity of CC may be lower than that of the corresponding direct communication.

B. Cooperative Routing Protocol

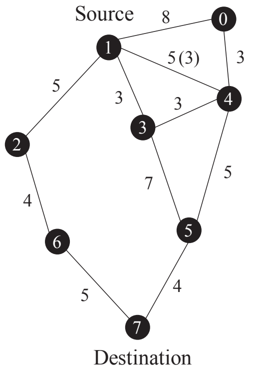
1) Route Discovery

We will describe our on-demand routing protocol including route request phase and route reply phase. In route request phase, a source node s broadcasts a route request packet (RREQ) on the CCC in order to find an end-to-end minimum cost path to destination d. Each RREQ packet includes the cumulated path cost from source to the current receiving node. We can define the spectrum and cooperative aware cost between any two nodes i and j as:

$$\mathrm{cost}_{i,j} = 1/C^*_{i,j}, \tag{3}$$

where $C^*_{i,j}$ is the maximal achievable capacity between node i and j. With such cost, if two nodes have more transmission opportunities, better channel quality, or cooperative benefit, smaller transmission cost between the two nodes is possible. A node j receiving a RREQ from node i will setup reverse path in its routing table and rebroadcast the RREQ. The fields of reverse path include the source *id* of RREQ, *id* of node i, cost cumulated from source to node j through node i, the selected data channel and selected relay node if CC is used. Through the reverse path, the RREP packet can route backward to the source along the end-to-end minimum cost path. Any intermediate node receiving more than one RREQ from the same source node s will update its reverse path and rebroadcast the RREQ when the cumulated path cost of current received RREQ is smaller than the one at its routing table. If any intermediate node has a fresh enough path to destination in its routing table, the node will generate a RREP and send it to source immediately. This can reduce the latency of finding a path from source to destination. In addition, in route request phase, RREQ is rebroadcasted only when node finds the other path with lower cost, the RREQ flooding overhead is mitigated.

Destination node d will set a timeout period when it receives the first arrival RREQ from the same RREQ source. There may be several RREQs finally arriving at the destination node d along different paths within this timeout period. Destination d can simply choose the one with the minimum path cost. After timeout period, a RREP is sent back from destination to the source along the reverse path. The main intention of replying RREP is to confirm the channels or relay nodes which are used at the routing path from source to destination. Thus, a node i receiving a RREP packet from node j can confirm the next hop to route to destination and the corresponding channel and relay node for data communication with node j. For example in Fig. 3, we assume that destination node 7 replies a minimum cost path to source node 1 through intermediate nodes 5 and 4. The numbers nearby edges are the minimum transmission cost between two nodes. And the number inside bracket is the minimum transmission cost with cooperative benefit. Note that, the minimum cost from source node to intermediate node 4 is through relay node 3 as shown in node 4's routing table.



Node 4 routing table					
Dst.	Previous node	Cost	Ch.	Relay node	Relay Ch.
1	1	3	1	3	2

Node 5 routing table					
Dst.	Previous node	Cost	Ch.	Relay node	Relay Ch.
1	4	8	1	-	-

Node 7 routing table					
Dst	Previous node	Cost	Ch.	Relay node	Relay Ch.
1	5	12	1	-	-

Figure 3. An example of routing path from destination to source.

2) Cooperative and Cognitive Aware Metrics

We present the performance metric to find the maximal achievable capacity at link (i, j). In general ad-hoc networks, there are many routing metrics for routing protocol to estimate whether a path is good or not. For instance, numbers of hop counts, expected transmission time, or expected transmission count [18] is most common metrics. However, these traditional metrics are not applicable to a network that each node has channel heterogeneity. Moreover, relay selection should solve together with path selection. Therefore, we need to define a new link cost metric in order to adapt this new cooperative and cognitive environment.

As mentioned before, the available channels of each secondary user depend on the location of the secondary user and activity of the surrounding primary users. Therefore, each accessible channel may be occupied by primary users in a specific percentage within a time period. Thus, we define the channel utilization U_i^c as the ratio of the total air time consumed by primary users in a given time interval of channel *c* at node *i*. We assume the channel utilization can be obtained from MAC layer. This information can also be explicitly obtained by message exchanges among neighbors on the CCC. Channel utilization shows how often the primary users occupy the channels. In other words, this information indicates that how many opportunities a secondary user can access the data channels. Therefore, the channel with lower utilization is more suitable for CR nodes to use because transmission at this channel has less interference with primary users.

In CR ad-hoc networks, CR users borrow the data channels from primary users. We define the potential bandwidth B_i^c as the amount of usable bandwidth in a given time interval of channel *c* at node *i*. We can express the potential bandwidth B_i^c as

$$B_i^c = w^c \cdot (1 - U_i^c), \tag{4}$$

where w^c represents the bandwidth of channel *c*. Thus, if the channel utilization of a channel is 1, it means that the potential bandwidth of the channel is 0. So far, the potential bandwidth just represents the available bandwidth of a node at a channel but not available bandwidth of a link between two nodes. Let $B_{i,j}^c$ denote the potential bandwidth of a link (*i, j*) at channel *c*. Then we have

$$B_{i,j}^c = w^c \cdot (1 - U_i^c)(1 - U_j^c). \tag{5}$$

Formula (5) represents that we should select a channel which is available for both sender and receiver simultaneously. We should note that nodes are located in different regions and are suffered to different activity of surrounding primary users. Thus, the utilization of a channel may low at some nodes but high at others. Through the calculation of the potential bandwidth for each common channel, we can calculate the capacity between two nodes. In (1) and (2), we have shown the capacity of direct link and cooperative link in traditional networks. Considering multiple channels and potential bandwidth, we can express the capacity of using direct transmission of link (*i, j*), $C_{dirc}^c(i, j)$, at channel *c* as

$$C_{dirc}^c(i, j) = B_{i,j}^c \log_2(1 + SNR_{i,j}^c), \tag{6}$$

where $SNR_{i,j}^c$ is the signal to noise ratio of link (*i, j*) at channel *c*. The capacity of using CC between node *i* and node *j* with relay node *r* at channel *c* can be presented as

$$\begin{aligned} C_{coop}^c(i, r, j) = \frac{1}{2} \min\{B_{i,j}^c, B_{r,j}^c, B_{i,r}^c\} \text{ x} \\ \min\{\log_2(1 + SNR_{i,r}^c), \log_2(1 + SNR_{i,j}^c + SNR_{r,j}^c)\}. \end{aligned} \tag{7}$$

Since the capacity of CC in (7) is related to the potential bandwidth of the link, the bandwidth *B* in (1) is replaced by $\min\{B_{i,j}^c, B_{r,j}^c, B_{i,r}^c\}$ in (7). This is because that the channel bandwidth of each link is diverse in CRNs. Thus, considering the potential bandwidth of links, the capacity of cooperative link should be bounded in the minimum potential bandwidth of the three direct links $B_{i,j}^c, B_{r,j}^c, B_{i,r}^c$. To put it simply, if the potential bandwidth $B_{i,r}^c$ and $B_{r,j}^c$ is larger than $B_{i,j}^c$, we can treat the potential bandwidth of link (*i, r*) and link (*r, j*) equal to link (*i, j*), and (7) is equivalent to (1). If the potential bandwidth $B_{r,j}^c$ or $B_{i,j}^c$ is smaller than $B_{i,r}^c$, it means that there is more interference from primary users at link (*i, r*) or link (*r, j*) compared with link (*i, j*).

Once again, we note that the capacity of a cooperative link may be lower than that of the corresponding direct link. Therefore, if $C_{coop}^c(i, r, j) > C_{dirc}^c(i, j)$, it gets throughput improvement via relay node *r*. It indicates that sender can use a higher modulation rate and relay also can fully decode the packet. Finally, receiver can receive the packet transmitted from relay and apply diversity combining technique to improve the channel capacity. If $C_{coop}^c(i, r, j) \le C_{dirc}^c(i, j)$, there is no any cooperative benefit via relay node *r*. It indicates that relay node may not fully decode the signal correctly in this situation. Therefore, we do not adapt CC via relay node *r*.

Since a relay node is not always available when we need it to relay packets, we use the relay availability to indicate how often a relay is available and can help other nodes to relay packets. There is no simple way to know the relay availability of a relay node in advance. One approach is to predict its value according to its previous availabilities. Let I_r^k be the relay availability of relay *r* at *k*-th frame. The predicted availability of relay *r* at next frame *k*+1 is generally evaluated as an exponential average of the measured availability of its previous periods. Let τ_r^{k+1} be our predicted availability of relay *r* at period *k*+1. For $0 \le \alpha \le 1$, we have

$$\tau_r^{k+1} = \alpha I_r^k + (1 - \alpha)\tau_r^k, \quad \text{for} \quad 0 \le I_r^k \le 1. \tag{8}$$

The value of I_r^k contains our most recent information; τ_r^k stores the past history.

Given those cooperative and spectrum aware metrics, an intermediate node *j* receiving a RREQ from node *i* can now select the most suitable channel and relay to maximize the achievable capacity between node *i* and *j*. The selection process is divided into three steps. In step 1, node *j* finds the optimal common channel *c** that maximizes the capacity of using direct transmission of link (*i, j*) according to formula (6). In step 2, we can find the optimal common channel *c'* that maximizes the capacity of using CC between node *i* and *j* via candidate relay node *r* according to formula (7). In step 3, if the capacity of using CC via candidate relay node *r* is larger than the capacity of using direct transmission, we can calculate the achievable capacity between node *i* and *j* with relay node *r* using relay availability. We can express the achievable capacity as:

$$\begin{aligned} C_{i,j} = (1 - \tau_r^{k+1}) \cdot C_{dirc}^{c*}(i, j) + \tau_r^{k+1} \cdot C_{coop}^{c'}(i, r, j), \\ for \quad C_{coop}^{c'}(i, r, j) > C_{dirc}^{c*}(i, j). \end{aligned} \tag{9}$$

If more than one relay has cooperative benefit, we select the one with maximum achievable capacity. Achievable capacity between nodes *i* and *j* includes the benefit getting from CC. If τ_r^{k+1} is equal to 1, this is a special case that we select an idle node as a cooperative relay node, and the achievable capacity between node *i* and *j* is totally equal to the capacity using CC between node *i* and node *j* with relay node *r*.

Otherwise, this achievable capacity between node i and j indicates that, we only have a throughput improvement in partial of time when relay is idle.

Cooperative Routing Algorithm

```
Initially, source node $s$ broadcasts a RREQ at CCC.
When Any node $j$ receiving a RREQ with cumulated cost $<s,i>$ from node $i$ do
    According to (6), node $j$ finds the common data channel $c^*$ that maximizes the capacity of using direct transmission at link $(i, j)$.
    According to (7), node $j$ finds the common data channel $c'$ that maximizes the capacity of using cooperative transmission via relay node $r$.
    According to (9), node $j$ calculates the achievable capacity $C_{i,j}$ between node $i$ and $j$ with relay node $r$.
    For multiple candidate relay, selecting the one $r^*$ has the maximum achievable capacity $C^*_{i,j}$.
    According to (3), node $j$ calculates the cumulated cost$<s, j>$ = cost$_{i,j}$ + cumulated cost$<s, i>$.
    If the cumulated cost is smaller than the one in the routing table do
        update node $j$'s routing table
        If node $j$ is an intermediate node do
            rebroadcasts RREQ with the cumulated cost$<s, j>$
    End if
    If node $j$ is a destination do waits a timeout period and replies a RREP to the source node along the reverse path.
End when
```

IV. SIMULATIONS

We have implemented our cooperative routing protocol in ns-2 2.31 with Cognitive Radio Cognitive Network Simulator [19]. First, we evaluate the average end-to-end throughput for the network with increasing the number of source-destination pairs. We randomly generate 50 nodes in a 1000m × 1000m area. All source-destination pairs are constant bit rate (CBR) flows with 512-byte-length packets, and the packet arrival interval is default setting with 0.05s. The source of CBR flow and destination is assigned randomly. In Fig. 4, we can see that AODV has the worst performance although we select the best common available channel between each two nodes along the path. Our proposed cooperative routing protocol has a throughput improvement compared to the same protocol without CC. Our protocol also has a better end-to-end throughput compared to the routing protocol COOP [15]. The routing protocol COOP selects a forwarding node from a set of feasible next hop of a sender. The advantage of this routing protocol is that the routing path discovery latency is almost equal to zero. However, the knowledge of feasible next hop means this algorithm needs topology control and collects global information of each node. Moreover, the decision of relay and next hop forwarding node is dependent to the SNR value of links. Therefore, the performance of COOP declines earlier than our routing protocol because it does not guarantee an end-to-end shortest path and out of consideration of the characteristics of CRNs.

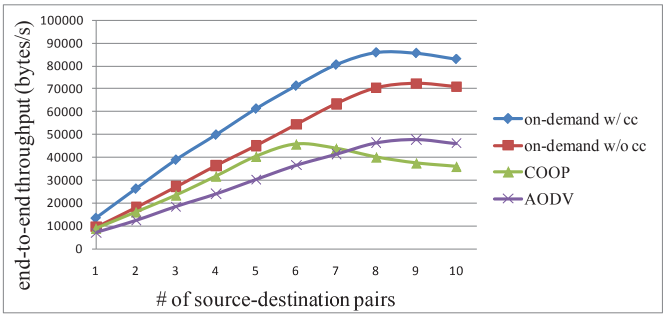


Figure 4. End-to-end throughput vs. number of communication pairs

After that, we evaluate the average end-to-end delay time for the CRNs with increasing the number of hop counts. In this simulation, we calculate the end-to-end delay time of the corresponding hop count as shown in Fig. 5. We can see that the average end-to-end delay of our routing protocol with CC is lower than without CC, AODV and COOP. Note that, the strategy of next hop and relay selection of COOP is lack of consideration of channel utilization. Therefore, the average end-to-end delay time of COOP is longer than our protocol.

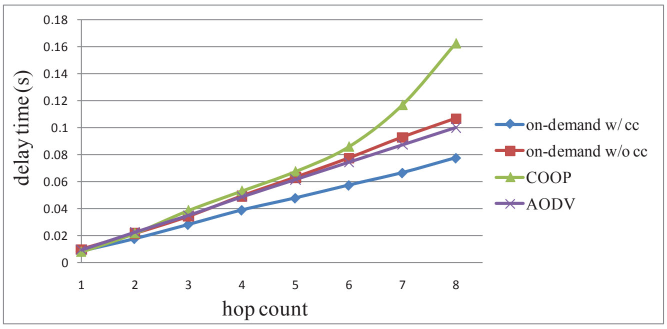


Figure 5. End-to-end delay time vs. number of hop counts

As mentioned before, the performance of COOP is worse than ours because it does not guarantee an end-to-end shortest path. Thus, we evaluate the end-to-end hop count of both cooperative routing protocols with increasing of distance between source-destination pair. As shown in Fig. 6, with increasing the end-to-end distance, the simulation result of our protocol without CC has the same hop count as with CC and AODV. The COOP routing protocol needs more hop count than ours.

Finally, we evaluate the packet overhead of our proposed routing protocol with increasing the size of topology. Let the number of *hello* messages and *routing* messages as the indicator of packet overhead. The role of hello messages is used to exchange channel information and the neighbor list of a node. Through the hello messages, nodes can get the knowledge of channel utilization and their neighbors. The routing messages include RREQ and RREP. We randomly generate 5 to 50 nodes in a 1000m × 1000m area. The number of CBR flow is fixed at 4 sessions. Fig. 7 shows the packets overhead of our proposed protocol, AODV and COOP. AODV has the least control overhead. The proposed routing protocol with CC has more control overhead than the protocol without CC because we need the information of finding out the common neighbors between two nodes. Since COOP needs topology control, each node in COOP has to broadcast control messages periodically to get the knowledge of feasible next hop. Therefore, the COOP has the most control overhead.

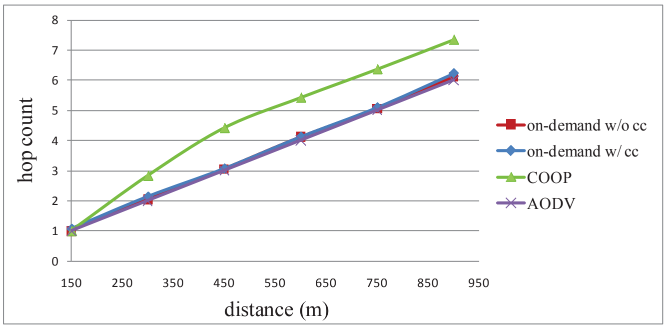


Figure 6. End-to-end hop counts vs. distance between source-destination pair

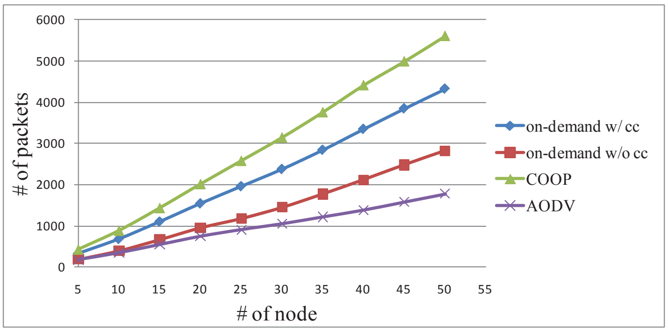


Figure 7. Number of control packets vs. number of nodes

V. CONCLUSIONS

In this paper, we proposed a cooperative routing protocol in CR ad-hoc networks that addresses the concern of end-to-end CR performance over multiple hops. We adopt an on-demand based routing style which is more suitable in CRNs to find the end-to-end minimum cost path. We first define the channel utilization, and then the potential bandwidth for a link at a specific channel. Through combining the potential bandwidth and the channel quality, we can calculate the capacity of direct transmission or cooperative transmission at a specific channel with relay. Finally, we define the relay availability that indicates how often the relay can help for transmission. With these performance metrics, we can calculate the maximum achievable capacity with cooperative benefit between two adjacent nodes and evaluate the cost we used in routing discovery. Therefore, by using this CC technology, we can go one step further to leverage the available recourses in CRNs so as to improve their performance.

REFERENCES

[1] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, S. Mohanty, “Next Generation Dynamic Spectrum Access Cognitive Radio Wireless Networks: A Survey,” *The International Journal of Computer and Telecommunications Networking*, Vol. 50, Issue 13, pp. 2127 - 2159, Sep. 2006

[2] A. Nosratinia, A. Hedayat, “Cooperative Communication in Wireless Networks,” *IEEE Communication Magazine*, Vol. 42, No.10, pp. 74 - 80, Oct. 2004.

[3] Q. Zhang, J.-C. Jia, and J. Zhang, “Cooperative Relay to Improve Diversity in Cognitive Radio Networks,” *IEEE Communications Magazine*, Vol. 47, Issue. 2, pp. 111 - 117, Feb. 2009

[4] C. E. Perkins and E. M. Royer, “Ad-hoc On-Demand Distance Vector Routing,” *Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*, pp.90–100, Feb. 1999

[5] S. Sharma, Y. Shi, Y. T. Hou, H. D. Sherali, S. Kompella “Cooperative Communications in Multi-hop Wireless Networks: Joint Flow Routing and Relay Node Assignment,” *Proceedings of IEEE International Conference on Computer Communications* (INFOCOM), pp. 1 - 9, San Diego, CA, USA, Mar. 2010

[6] J. Zhang, Q. Zhang, “Contention-Aware Cooperative Routing in Wireless Mesh Networks,” *Proceedings of IEEE International Conference on Communications* (ICC), pp. 1 - 5, Dresden, Germany, June. 2009

[7] W.-H. Chen, S.-C. Hu, A.-C. Pang, C.-T. Fan Chiang, “Cross-layer Cooperative Routing for Vehicular Networks,” *Proceedings of IEEE International Computer Symposium* (ICS), pp. 67 - 72, Tainan, Taiwan, Dec. 2010

[8] B. An, T. T. Duy, “A Cooperative Routing in Mobile Ad-Hoc Wireless Sensor Networks with Rayleigh Fading Environments,” *Proceedings of International Symposium on Computer Communication Control and Automation* (3CA), pp. 22 - 25, Tainan, Taiwan, May. 2010

[9] I. F. Akyildiz, W.-Y. Lee, K. R. Chowdhury, “CRAHNs: Cognitive Radio Ad Hoc Networks,” *Ad Hoc Networks*, Vol. 7, Issue 5, pp. 810 - 836, July. 2009

[10] G.-M. Zhu, I. F. Akyildiz, G.-S. Kuo, “STOD-RP: A Spectrum-Tree Based On-Demand Routing Protocol for Multi-Hop Cognitive Radio Networks,” *Proceedings of Proceedings of IEEE* Global Telecommunications Conference (GLOBECOM), pp. 1 - 5, New Orleans, LA, USA, Nov. 2008

[11] A. Sampath, L. Yang, L.-L. Cao, H. Zheng, B. Y. Zhao, “High Throughput Spectrum-aware Routing for Cognitive Radio Networks,” *Proceedings of Proceedings of the International Conference on Cognitive Radio Oriented Wireless Networks and Communications* (CROWNCOM), pp. 1 - 5, Singapore, May. 2008

[12] C.-W. Pyo, M. Hasegawa, “Minimum Weight Routing based on a Common Link Control Radio for Cognitive Wireless Ad hoc Networks,” *Proceedings of the International Conference on Wireless Communications and Mobile Computing* (IWCMC), pp. 399 - 404, Honolulu, Hawaii, Aug. 2007

[13] K. R. Chowdhury, I. F. Akyildiz, “CRP: A Routing Protocol for Cognitive Radio Ad Hoc Networks,” *IEEE Journal on Selected Areas in Communications*, Vol. 29 , Issue: 4 , pp. 794 - 804, Apr. 2011

[14] H.-S. Ma, L.-L. Zheng, X. Ma, Y.-J. Luo, “Spectrum Aware Routing for Multi-Hop Cognitive Radio Networks with a Single Transceiver,” *Proceedings of the Cognitive Radio Oriented Wireless Networks and Communications* (CrownCom), pp. 1 - 6, Singapore, May. 2008

[15] L. Ding, T. Melodia, S. N. Batalama, J.D. Matyjas, “Distributed Routing, Relay Selection, and Spectrum Allocation in Cognitive and Cooperative Ad Hoc Networks,” *Proceedings of IEEE Communications Society Conference on Sensor Mesh and Ad Hoc Communications and Networks* (SECON), pp. 1–9, Boston, Massachusetts, June. 2010

[16] K. J. Ray Liu, A. K. Sadek, W.-F. Su and A. Kwasinski, “Cooperative Communications and Networking”, Cambridge Univ Pr, January 2009

[17] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, “Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior,” *IEEE Transactions on Information Theory*, Vol. 50, No. 12, pp. 3062 - 3080, Dec. 2004.

[18] D. S. J. De Couto, D. Aguayo, J. C. Bicket, and R. Morris, “A High-Throughput Path Metric for Multi-Hop Wireless Routing,” *Proceedings of the 9th annual international conference on Mobile computing and networking* (MobiCom), pp. 134-146, New York, USA, 2003.

[19] “Cognitive Radio Cognitive Network Simulator” http://stuweb.ee.mtu.edu/~ljialian