An Anypath Routing Protocol for Multi-hop Cognitive Radio Ad Hoc Networks

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***Abstract*—Compared with traditional Wireless Sensor Networks (WSNs), designing a routing protocol in Cognitive Radio Ad Hoc Networks (CRAHNs) is more difficult since issues such as the primary user (PU) occupancy problem and the multi-channel rendezvous problem must be solved. Anypath Routing, a kind of schemes that enables dynamic forwarder selection, seems to be a possible solution to the PU occupancy problem. An anypath routing protocol must combine with a multi-channel rendezvous protocol to become a total solution. To the best of our knowledge, there is no anypath routing protocol designed for CRAHNs. In this paper, we propose an anypath routing scheme in CRAHNs that can be built on top of existing multi-channel rendezvous solutions. The objective of the proposed routing solution is to minimize the number of transmissions to deliver a packet. Simulation results verify that the proposed protocol improves network performance when compared with existing CRAHN routing protocols.**

***Index Terms*—Cognitive Radio Ad Hoc Networks, Dynamic Spectrum Access, Anypath Routing, Channel Hopping, Wireless Multi-hop Networks**

I. Introduction

Although wireless spectrum is a precious resource, a large portion of licensed spectrum is still underutilized and a more intelligent spectrum allocation method is expected to improve spectrum utilization [1]. For this purpose, cognitive radio has received a lot of attention lately because it allows an unlicensed user (secondary user, SU[1]) to access the licensed spectrum not being used by any licensed user (primary user, PU). In cognitive radio ad hoc networks (CRAHNs), SUs are able to recognize spectrum holes and can between them without causing operation interruption of PUs. That is, the available channels for an SU depend on the occupancy condition of its neighboring PUs.

Designing a routing protocol in CRAHNs is more complicated than designing one in traditional wireless networks. In CRAHNs, a PU may occupy a channel at any time which blocks the routes of SUs using the same channel. We refer this to be the PU occupancy problem. Existing CRAHN routing protocols solve the PU occupancy problem in two ways: one tries to avoid the channels with high PU occupancy probability [2][12][15][19][20] and the other uses opportunistic routing which dynamically changes the next hop node for each packet transmission [10][16][17][18]. A limit of both kinds of solutions is that a node can only find a single (one-hop or two-hop) forwarder for each path. The connection between a node and its forwarder is still a vulnerable link. Another kind of routing scheme, anypath routing, enables multiple candidate forwarders to take the responsibility of forwarding the received packet [5][8][11][13][22]. In an anypath routing scheme, a node i multicasts a packet to multiple candidate forwarders (i.e., the forwarding set of node i). Node i's packet can be forwarded if anyone in the forwarding set has received the packet correctly. To avoid redundant transmissions, nodes in the forwarding set have different priorities. A node forwards the received packet only if no higher-priority node has forwarded it. A more detailed review of existing CRAHN routing solutions for the PU occupancy problem and anypath routing schemes can be found in Section II.

Anypath routing may enhance the successful transmission ratio because there are multiple candidate forwarders. It seems to be a promising solution to the PU occupancy problem. However, we do not find any anypth routing protocol that is designed for CRAHNs. To the best of our knowledge, existing anypath routing schemes are all designed for single-channel networks [5][8][11][13][22]. To apply an anypath routing scheme to a CRAHN, the multi-channel rendezvous problem (how two SUs tune to the same channel simultaneously) must be handled. Existing solutions for the multi-channel rendezvous problem can be divided into two categories. Solutions in the first category use a common control channel for nodes to exchange control message needed to achieve rendezvous [2][12][10][17][18][19]. A concern of this kind of solutions is that it is difficult to find a common available channel for all the SUs because different SUs may have different available channels. Even if there exists a globally available channel, it becomes a bottleneck of the network. Solutions in the second category use some kind of channel hopping mechanism where a node follows its channel hopping sequence to switch to different channels at different time [4][7][9][14][21]. Two nodes have a rendezvous when they switch to the same channel at the same time. In general, the channel hopping schemes are considered more practical solutions to the multi-channel rendezvous problem in CRAHNs.

In this paper, in addition to overcome the PU occupancy problem and the multi-channel rendezvous problem, we design an anypath routing scheme for CRAHNs with the minimum

[1]In this paper, the terms SU and node may be used interchangeably to represent a secondary user.

cost. The cost is defined as the minimum number of transmissions to deliver a packet. Built on top of an existing channel hopping scheme, we propose an anypath routing scheme, denoted as AP_CR. AN_CR is not limited to a specific channel hopping scheme. A node running AP_CR can efficiently select its transmission schedule and forwarding set such that the cost is minimized. Simulation results verify that AP_CR performs better than two existing representative schemes CWH [15] and CNOR [16].

The contribution of the paper can be summarized as follows.

1) Define the minimum-cost CRAHN anypath routing problem (Section III).
2) Design an efficient anypath routing scheme for CRAHNs without using a CCC (Section IV).
3) Provide simulation results to verify the performance of the proposed routing scheme (Section V).

II. Related Works

First we review some solutions that solve the PU occupancy problem by avoiding the channels with high PU occupancy probability [2][12][15][19][20]. CWH is a typical routing scheme in this kind [15]. The availability of the path from source to destination is the product of the link available probabilities of the links that constitute the path. Nodes running CWH exchange link availability probability information through the CCC. A source selects multiple disjoint paths for data delivery where each of the paths has an availability no less than a predefined threshold P_m. Besides avoiding the links that likely being occupied by PUs, RASR also considers the number of available channels between the sender and the destination [12]. A sender running RASR first uses the AODV scheme to find several paths to the destination through the CCC. The path that has the highest stability, which is in proportional to the number of available channels between the source and the destination, will be selected for data transmissions. YHSLB avoids the channels with high PU occupancy probability and malicious nodes at the same time [20]. A malicious node intends to fail any transmission passing it by selecting a link with high PU occupancy probability as its next hop. A malicious-node-avoiding mechanism is provided in YHSLB. A node running CRQ-routing avoids the link with high PU occupancy probability by selecting the node with the least required time from the candidate forwarders to deliver the packet to the destination [2]. That is, the link availability is transferred to the time required to deliver a packet to the destination. In LCR, the authors observed that a node closer to a PU has higher probability to be blocked than a node that is far from any PU [19]. Thus, nodes running LCR estimate the locations of nearby PUs based on history information of PUs' occurrences. The PU location information is exchanged among nodes through the CCC. A node selects its next hop node among candidate nodes by comparing their distances to the nearest PU and the one that has the longest distance will be selected.

Some other solutions use opportunistic routing which dynamically changes the next hop node for each packet transmission to solve the PU occupancy problem [10][16][17][18]. In CNOR, when a node i has a packet to send, it broadcasts an RTS packet on a randomly selected available channel to all the candidate forwarders tuned to that channel [16]. The candidate forwarders contend to act as node i's forwarder where a candidate forwarder that is closer to the destination has higher priority. The first one that successfully replies a CTS packet will be the forwarder of node i. Because each of the candidate forwarders may act as the next hop node, CNOR provide some kind of robustness in route selection. Similar to CNOR, a node running OCR also finds its next hop node dynamically [10]. The difference is that a sender running OCR will first announce the data channel to be used, the location information of its own and that of the destination through CCC. The RTS and CTS packets will be exchanged between the sender and its candidate forwarders at the announced data channel. In GGPF, instead of only selects next hop node, a node selects both one-hop and two-hop nodes [17]. Specifically, if the destination is one hop away, a sender will send the packet directly. Otherwise, a sender i will first select the two-hop neighbor j that is closest to the destination as its two-hop node. Then, node i uses an anypath routing to forward packets to node j.

To the best of our knowledge, all the existing anypath routing protocols regard the number of transmissions to deliver a packet as the cost and try to find the minimum-cost path for packet transmissions. The cost of an anypath routing scheme consists of two parts: the first one is cost from the sender to its forwarding set and the other one is from the forwarding set to the destination. Different anypath schemes consider different issues when calculating the cost. In LDK, the cost for a node is simply calculated from the quality of the links involved in its packet transmissions [8]. LDK is designed for a network where different links have different transmission rates. The cost calculation of LDK is typical in anypath cost calculation and we applied it in AP_CR. A detailed description of the cost calculation of LDK will be presented in Section IV. Considering the distance changes between the sending and receiving vehicles in cost calculation, LLA can be applied to a vehicular ad-hoc network [13]. M-LCR is a multicast anypath routing scheme where the cost calculation considers the number of destinations that can be reached by each candidate forwarder node [5][11]. ZX considers the networks where malicious node exist [22]. A malicious node broadcasts fake cost information such that it is included in each node's forwarding set. When receiving packets to be forwarded, a malicious node discards all of them. ZX proposes a way to identify and avoid the malicious nodes.

III. System Model and Problem Definition

A. System model

In this paper, we consider a multi-hop CRAHN, denoted as $G(V, E)$ where V is the set of SUs in the CRAHN and E is the set of links connecting SUs. There are M PUs and C licensed channels in the CRAHN. A SU is equipped with one cognitive radio and periodically monitors C channels. Each node keeps track of the occupancy condition of all the channels to estimate the availability probability of them. The channel availability probability is periodically updated and remains unchanged between two updates. A PU uses a fixed licensed channel. The link availability between two SUs is defined as the probability that the channel is not being occupied by a PU [15]. We assume that time is divided into a series of equal-sized time slots. Each node i has a unique channel hopping sequence, CHS_i, which determines the channel node i to be switched to in each time slot. As mentioned in Section I, the proposed AP_CR is not limited to use a specific channel hopping mechanism. In this paper, we assume that each node generates its channel hopping sequence by the same random number generator with the ID of the node as the seed. A node is aware of the IDs of its neighbor nodes and thus can obtain their channel hopping sequences. An SU can send multiple data packets in a time slot while its receiver replies an ACK for each correctly received data packet.

B. Problem definition

We intend to design a distributed anypath routing scheme for a CRAHN with the minimum cost in this paper. The proposed scheme must provide rendezvous among SUs in a multi-channel network and overcome the PU occupancy issue. The delay issue should also be addressed in designing a CRAHN routing solution. In this paper, we consider a constraint, transmission delay bound, which represents the maximum transmission delay of a packet from the source to the destination. This constraint is actually application-dependent. If transmission delay is a concern, the transmission delay bound can be set as required. If not, the transmission delay bound can be set to infinity. The purpose of the scheme is to minimize the number of transmissions to deliver a packet in a CRAHN under the predefined transmission delay bound. The problem to be solved can be formally defined as follows.

Definition 1. Minimum-Cost CRAHN Anypath problem

Given a CRAHN $G(V, E)$ and a transmission delay bound B, find an anypath routing scheme with the minimum cost. That is, find an anypath routing scheme such that $\sum_{i\in V} D_i$ is minimized with the constraint $TD_i \leq B, \forall i \in V$ where D_i is the cost of node i and TD_i is the transmission delay of node i.

IV. Proposed Protocol

To solve the Minimum-Cost CRAHN Anypath problem, we propose an anypath protocol, AP_CR. AP_CR builds on top of a channel hopping scheme and works in a multi-hop CRAHN. AP_CR extends the cost calculation scheme used in LDK [8] (which will be introduced in Section IV-A) and dynamically finds minimum-cost paths for each sender within the transmission delay bound. In the following, we describe the operation of AP_CR in detail.

A. Cost calculation of LDK

The cost calculation of LDK is applied backward from the one-hop neighbors of the destination to all the nodes in the network. The calculation order of nodes having the same hop count to the destination is determined randomly. The cost of a node i (D_i) is given by

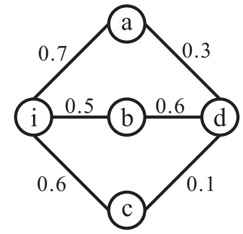


Fig. 1. An example of anypath cost calculation

$$D_i = d_{iJ} + D_J \tag{1}$$

where d_{iJ} is the reciprocal of the probability of at least one member in J that successfully receives the packet. The value of D_J is given by

$$D_J = \sum_{j\in J} w_{ij} \cdot D_j \tag{2}$$

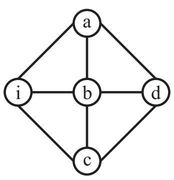
where w_{ij} is the ratio of delivering the packet contributed by node j out of the set J. Specifically,

$$w_{ij} = \frac{p_{ij} \cdot \prod_{k=1}^{j-1}(1 - p_{ik})}{1 - \prod_{j\in J}(1 - p_{ij})} \tag{3}$$

where p_{ij} is the probability that node j successfully receives the packet from node i. The denominator of equ.(3) is the probability that at least a member of i's forwarding set has successfully received the packet. The numerator of equ.(3) is the probability that node j has received the packet and all the nodes with higher priorities than j do not receive the packet. The destination has an initial cost value of zero while all other nodes have an initial cost value of infinity. Node i will build its forwarding set by checking its neighbors sequentially from the one with the lowest cost to the one with the highest cost (random selection is used to break ties). A neighbor of i will be inserted into node i's forwarding set if doing so reduces the cost of i's forwarding set, D_J. This process is repeated until all neighbors are in the forwarding set or the first neighbor that cannot be inserted into D_J is found.

Fig. 1 is an example of cost calculation in LDK where node d is the destination. The number associated with each link is the available probability of the link. When building the forwarding set of node a, because node d has the smallest cost (=0) in a's neighbors, node d is first tested if it should be inserted into node a's forwarding set. The cost of a with d as the only member of a's forwarding set is given by $D_a = d_{aJ} + D_J = \frac{1}{0.3} + \frac{0.3}{1\times 0.3} \times 0 = 3.3$ which is smaller than a's current cost (=∞) and node d should be inserted into a's forwarding set. The cost of a with nodes d and i as the members of a's forwarding set is given by $D_a = \frac{1}{1-(1-0.3)\times(1-0.7)} + \frac{1\times 0.3\times 0+(1-0.3)\times 0.7\times\infty}{1-(1-0.3)\times(1-0.7)} = \infty$ which is larger than a's current cost and thus node i will not be a member of node a's forwarding set. Similar forwarding set building process is applied for nodes b and c. The forwarding set of nodes b and c are the same as that of node a: node d is the only member of their forwarding set. The cost of nodes b and c is thus equal to $D_b = d_{bJ} + D_J = \frac{1}{0.6} + \frac{1\times0.6}{0.6} \times 0 = 1.6$ and $D_c = d_{cJ} + D_J = \frac{1}{0.1} + \frac{1\times0.1}{0.1} \times 0 = 10$, respectively. When building the forwarding set of node i, the cost of inserting node b to i's forwarding set is calculated first because node b has the smallest cost in i's neighbors. The cost of node i with b as the only member of i's forwarding set is $D_i = d_{iJ} + D_J = \frac{1}{0.5} + \frac{1\times0.5}{0.5} \times 1.6 = 3.6$ which is smaller than i's cost and node a should be in node i's forwarding set. The cost of i with the forwarding set consisting of nodes a and b is $D_i = 3.4$. This means node b should also be inserted into node i's forwarding set. Because the cost of i with a forwarding set consisting of nodes a, b, and c is $D_i = 4.2$ which is larger than i's current cost, node c will not be included in i's forwarding set. That is, the forwarding set of node i consists of nodes a and b and the cost of node i is 3.4.

B. Cost calculation of AP_CR



(a)

slot / node	0	1	2	3	4	5	6	7	8
i	1	1	3	2	3	3	1	1	2
a	1	3	2	1	2	1	1	3	2
b	1	1	3	2	2	1	2	1	3
c	2	1	1	2	2	3	1	2	1
d	3	1	3	2	2	1	2	3	2

•••

(b)

Fig. 2. An example of rendezvous condition with (a) network topology and (b) the associated channel hopping sequences for different nodes

The cost calculation of AP_CR is similar to that of LDK. The difference is that a sender running AP_CR may have a rendezvous with different sets of nodes (and thus different forwarding sets and cost values) at different time slots since the AP_CR protocol works on top of a channel hopping scheme. For example, consider the topology shown in Fig. 2(a) and each node's channel hopping sequence (with three available channels in the network) shown in Fig. 2(b), the set of nodes having a rendezvous with node i at time slots 0 and 1 is $\{a, b\}$ and $\{b, c\}$, respectively. The cost calculation of AP_CR at a time slot is the same as that of LDK.

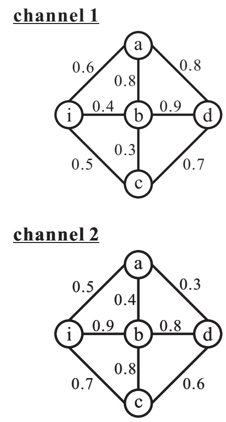
Now we are ready to define the cost calculation of AP_CR. A node running AP_CR has different costs at different time slots. The cost of node i running AP_CR at time slot t, denoted as $D_{i,t}$, is given by

$$D_{i,t} = d_{i,J,t} + D_{J,t} \tag{4}$$

where $d_{i,J,t}$ is the cost of node i delivering a packet to its forwarding set J at time slot t and $D_{J,t}$ is the cost of delivering a packet from the forwarding set J to the destination at time slot t. The calculation of $d_{i,J,t}$ is the same as that in TDK while the value of $D_{J,t}$ is given by

$$D_{J,t} = \sum_{j\in J} (w_{i,j} \cdot min_{t+1\leq s\leq t+b_i} D_{j,s}) \tag{5}$$

where $w_{i,j}$ is the ratio of delivering the packet contributed by node j out of the set J and b_i is the one-hop delay bound of node i. The one-hop delay bound is derived from the end-to-end transmission delay bound B. For simplicity purposes, in this paper, we assume $b_i = B/h_i$ where h_i is the hop count distance between node i and the destination. Note that each node uses the smallest cost within the one-hop delay bound in $D_{J,t}$ calculation. Node i builds a cost table containing its costs of all time slots before one-hop delay bound and broadcasts the cost table to all its neighbors[2]. Neighbors of nodes i should update their own cost tables if necessary.



(a)

slot / node	0	1	2	3	4
a	∞	∞	∞	∞	3.3

•••

(b)

b	∞	1.1	1.6	1.2	1.2

•••

(c)

c	∞	1.4	∞	1.6	1.6

•••

(d)

i	2.4	3.6	3.1	2.1	∞

•••

(e)

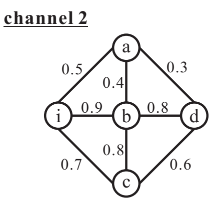
Fig. 3. A cost calculation example of AP_CR with (a) topology and link quality in channel 1, 2 and (b)(c)(d)(e) each node's cost table

Fig. 3 is an example of AP_CR cost calculation with three available channels where node d is the destination. The topology and link quality of the example network can be found in Fig. 3(a) where the number associated with each link is the available probability of the link. Each node's channel hopping sequence, the same as the previous example, is shown in Fig. 2(b). The initial cost table of each node is as the follows: the destination has a cost table of all 0's and all other nodes have a cost table with all infinities. At time slot 0, since node a have a rendezvous with nodes b and i (at channel 1, refer to Fig. 2(b)) and both nodes have the same cost (=∞), we assume node b is considered first when building the forwarding set of node a. The cost of node a at time slot 0 with b as the only member of a's forwarding set is $D_{a,0} = d_{a,J,0} + D_{J,0} = \frac{1}{0.8} + \frac{1\times0.8}{0.8} \times \infty = \infty$ which is no smaller than a's current cost and thus node b will not be a member of node a's forwarding set. Similar forwarding set building process is applied for node a from time slots 1 to 3. When building the forwarding set of node a at time slot 4, node a can meet nodes b, and d. The cost of inserting node d to a's forwarding set is calculated first because node d has the smallest cost (=0). The cost of node a with d as the only member of a's forwarding set is $D_{a,4} = d_{a,J,4} + D_{J,4} = \frac{1}{0.3} + \frac{1\times0.3}{0.3} \times 0 = 3.3$ which is smaller than a's cost and thus node d will be a member of node a's forwarding set. The cost of a with nodes

[2]There exist broadcast schemes in CRAHNs without using a common control channel [7].

d and b as the members of a's forwarding set is given by $D_{a,4} = d_{a,J,4} + D_{J,4} = \infty$ which is larger than a's current cost and thus node b will not be inserted into node a's forwarding set. The obtained cost table of node a, shown in Fig. 3(b), will be broadcast to all its neighbors. Similar process will be applied to all the nodes (except node d) to calculate their cost tables. For example, receiving node a's cost table, node b's cost table will be updated as shown in Fig. 3(c). Receiving node b's cost table, node c's cost table will be updated as shown in Fig. 3(d). Finally, receiving the cost tables of nodes a, b, and c, node i's cost table is updated as shown in Fig. 3(e).

C. Transmission Schedule of AP_CR



(a)

slot / node	0	1	2	3	4	5	6	7	8
i	2.4	3.6	3.1	2.1	∞	3.0	2.8	3.6	5.3
a	∞	∞	∞	∞	3.3	1.2	∞	2	3.3
b	∞	1.1	1.6	1.2	1.2	1.1	1.2	1.6	∞
c	∞	1.4	∞	1.6	1.6	∞	∞	∞	∞

•••

(b)

Fig. 4. A cost calculation example of AP_CR with (a) topology and link quality in channel 2 and (b) each node's cost table

When a packet arrives at node i at time slot t, node i will transmit the packet at the time slot s ($s \geq t$). The time slot s is within one-hop delay bound and has the minimum cost for node i. Because a node knows the costs of its neighbors, a sender is able to determine the priority of its forwarding set at time slot s. The priority of a neighbor node j is determined according to the minimum cost of j within one-hop delay bound. That is, the priority of node j is determined by $min_{s+1 \leq r \leq s+b_i} D_{j,r}$. A node with a smaller cost has a higher priority. The priority information is attached to each packet to notify each member of the forwarding set. Receiving the packet, a member of the forwarding set replies an ACK packet based on its priority: the node with highest priority replies the first, the node with the second highest priority replies the second, and so on.

In traditional anypath mechanisms, a forwarder transmits only when higher priority nodes fail to do so. However, in CRAHNs where nodes running a channel hopping protocol, such as transmit-only-when-necessary mechanism does not work. This is because when a forwarder j forwards at a particular time slot r, the other forwarders may not have a rendezvous with node j at time slot r. That is, forwarders other than j are not sure whether the packet has been forwarded not. To solve this problem, in AP_CR, the probability for the highest-priority forwarder to forward the packet is set to one. The other forwarders forward the packet with a probability that the higher-priority nodes fail to forward the packet. Specifically, the probability for a forwarder with the j-th highest priority to forward the received packet is $p_{ij} \cdot \prod_{k=1}^{j-1}(1-p_{if(k)})$ where $f(k)$ is a function that returns the node ID of the k-th highest priority node in the forwarding set. Note that the forwarding probability mentioned above works when a forwarder overhears an ACK packet from a higher-priority forwarder. If no ACK packet from higher-priority forwarder is received, to enhance reliability, a forwarder will forward the packet with a probability of one.

Fig. 4 is an example of AP_CR transmission schedule where node d is the destination. The topology and link quality of the example network can be found in Fig. 4(a). Again, the number associated with each link is the link available probability of the link. Each node's channel hopping sequence is shown in Fig. 2(b). Fig. 4(b) shows each node's cost table. The one-hop delay bound is assumed to be 5 in this example. Consider the situation that node i wants to deliver a packet at time slot 0. First node i schedules its transmission at the minimum-cost time slot (time slot 3). The forwarding set of node i at time slot 3 contains nodes b and c. Because $min_{3+1 \leq r \leq 3+5} D_{b,r} = 1.1$ and $min_{3+1 \leq r \leq 3+5} D_{c,r} = 1.6$, node b will have higher priority and has a forwarding probability of one. The probability of node c to forward the packet is $1 - p_{ib} = 1 - 0.9 = 0.1$ if node c overhears node b's ACK. If no ACK packet has been overheard by c, c will also forward the received packet.

V. Simulation

We have implemented a simulator using C++ to evaluate the performance of the proposed AP_CR protocol. Two representative existing routing protocols in CRAHNs, CWH [15] and CNOR [16] were also implemented for comparison purposes. In the simulations, nodes are uniformly deployed in an area of 500 m× 500 m. The source node is selected from the upper left corner while the destination is select from the lower right corner. Each node is equipped with one CR transceiver which can be switched to any channel. The transmission range is 150 meters while the interference range is 300 meters. A time slot is set to 1 s and the capacity of a channel is 11 Mbps. The packet size is set to 512 bytes. For each simulation, the source node sends 100 packets to the destination. The PU occupancy probability of each time slot is uniformly distributed between 0.01 and 0.5 for each channel [15]. Each point in the figures is an average of 10 simulations with each simulating 2000 time slots. The network topology and source-destination pairs are regenerated in each simulation run. The duration of transmission delay bound is set to 25 s.

In the following, observations are made from three aspects.

A) The produced overhead: First of all, we investigate the overhead produced by each protocol in a network with different number nodes or different number of channels. Nodes running CWH broadcast their routing tables and the cost for each link periodically to their neighbors. Nodes running AP_CR have to broadcast their cost tables to their neighbors. For CNOR, the overhead comes from the control packets (RTS/CTS) exchanged before each data transmission. The produced overhead for different number of nodes can be found in Fig. 5(a). As expected, for all three protocols, the produced overhead increases as more nodes are in the network while AP_CR produces the least overhead. As shown in Fig. 5(b), AP_CR also produces the least overhead for different number of channels. Both CWH and AP_CR produce higher overhead

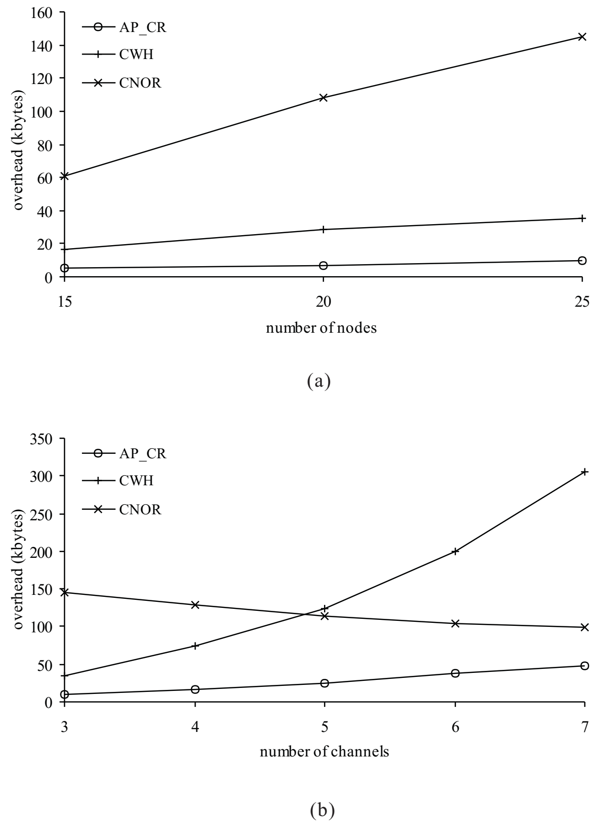


Fig. 5. Produced overhead with (a) different number of nodes and (b) different number of channels

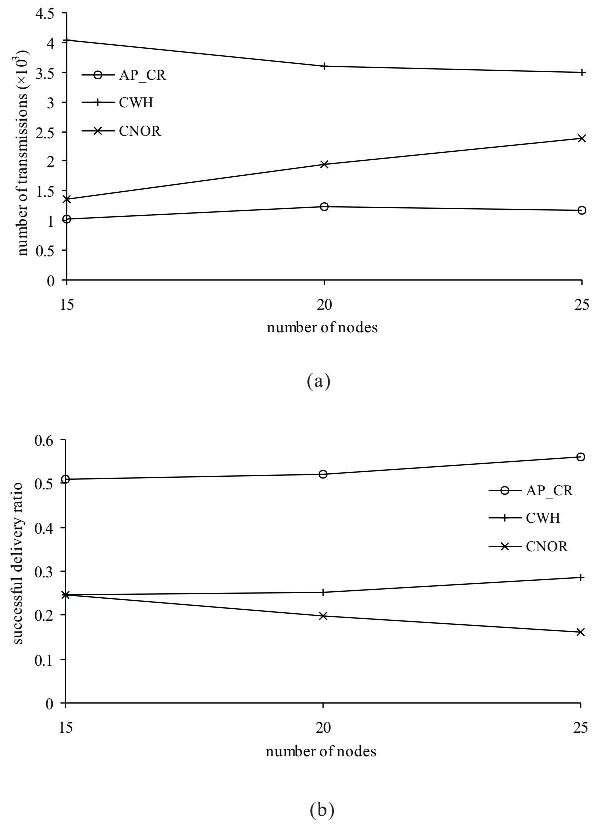
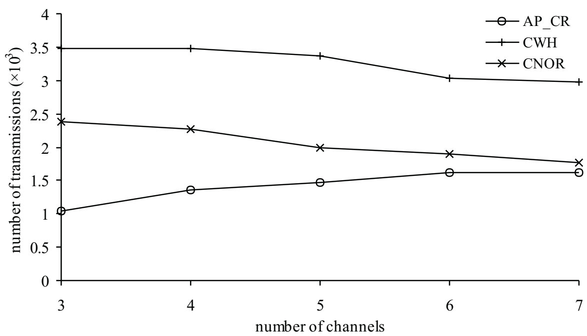


Fig. 6. Impact of number of nodes

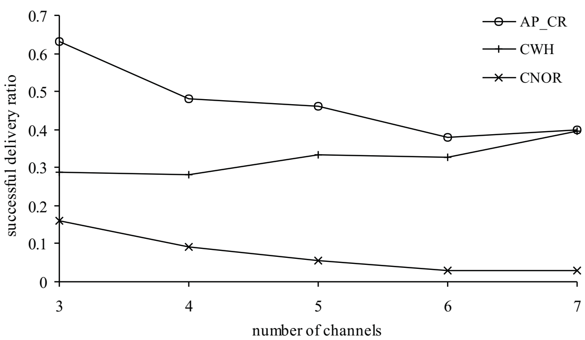
when more channels are utilized. This is because, when more channels are available in a network, the number of broadcasts needed is increased since the neighbors are distributed in more channels. For CNOR, the produced overhead decreases as the number of available channels increases. This results from the reduced RTS/CTS exchanges because of the reduced contending nodes in each channel.

B) Impact of number of nodes: In this experiment, the number nodes is changed to observe its impact on number of transmissions and successful delivery ratio. The former is defined as the total number of transmissions of all the senders (including the source and the forwarders) to deliver 100 packets from the source to the destination. The latter is defined as the ratio that packets can be delivered to the destination within the transmission delay bound. As shown in Fig. 6(a), AP_CR and CNOR have similar performance and perform better than CWH. We believe it is because both AP_CR and CNOR schemes allow a node to select next hop forwarder for each transmission. Such a mechanism reduces the effect of PU occupancy. For CWH, the number of transmissions is larger than the other two protocols because a node running CWH uses a fixed route for all the 100 packets. If any of the links along the route is occupied by a PU, the transmission is blocked and retransmission is needed. The number of transmissions for CWH reduces as the number of nodes increases since more candidate forwarders are available and thus has a higher chance for the sender to find a better route. The results of successful delivery ratio can be found in Fig. 6(b). Having a whole forwarding set to help forward the packet, AP_CR has the highest successful delivery ratio as expected. The CNOR achieves the lowest successful delivery ratio because its forwarder selection scheme only considers the distance to the destination. Without considering the link quality, it takes a longer time for a sender to establish a connection to its forwarder. Therefore, the total transmission delay becomes longer and cannot meet the delay requirement.

C) Impact of number of channels: The effect of different numbers of available channels are investigated in this experiment. For the number of transmissions, as shown in Fig. 7(a), AP_CR and CNOR perform much better than the CWH. Note that the number of transmissions for CWH reduces as the number of channels increases because of a higher chance for the sender to find a better route. The number of transmissions for CNOR also reduces slightly as the number of channels increases because of reduced RTS/CTS exchanges. For the successful delivery ratio, AP_CR still outperforms the other two protocols, as shown in Fig 7(b). Note that the successful delivery ratio of AP_CR and CNOR decreases as the number of channels increases. This is because when more channels are utilized, the number of rendezvous is reduced. This implies a sender takes a longer time to have a rendezvous with its forwarder and thus has a lower chance to meet the transmission delay requirement. For CWH, due to a higher chance for the sender to find a better route with more channels, the successful delivery ratio increases as more channels are available.



(a)



(b)

Fig. 7. Impact of number of channels

VI. Conclusions

Existing anypath protocols cannot be applied in a CRAHN that operates on multiple channels and each of which can be occupied by a PU at any time. In this paper, we design an anypath routing scheme that works efficiently in CRAHNs. In addition to being capable of working on top of existing multi-channel rendezvous solutions, the proposed AP_CR protocol enabling a sender to efficiently select its transmission schedule and forwarding set such that the transmission cost is minimized. Simulation results verify that AP_CR outperforms two existing representative CRAHN routing protocols, CWH and CNOR, in terms of number of transmissions and delivery ratio.

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