Spectrum-Aware Anypath Routing in Multi-Hop Cognitive Radio Networks

Jie Wang, *Member, IEEE,* Hao Yue, *Member, IEEE,* Long Hai, Yuguang Fang, *Fellow, IEEE*

Abstract—Cognitive radio networks (CRNs) have been emerging as a promising technique to improve the spectrum efficiency of wireless and mobile networks, which form spectrum clouds to provide services for unlicensed users. As spectrum clouds, the performance of multi-hop CRNs heavily depends on the routing protocol. In this paper, taking the newly proposed Cognitive Capacity Harvesting network as an example, we study the routing problem in multi-hop CRNs and propose a spectrum-aware anypath routing (SAAR) scheme with consideration of both the salient spectrum uncertainty feature of CRNs and the unreliable transmission characteristics of wireless medium. A new cognitive anypath routing metric is designed based on channel and link statistics to accurately estimate and evaluate the quality of an anypath under uncertain spectrum availability. A polynomial-time routing algorithm is also developed to find the best channel and the associated optimal forwarding set and compute the least cost anypath. Extensive simulations show that the proposed protocol SAAR significantly increases packet delivery ratio and reduces end-to-end delay with low communication and computation overhead, which makes it suitable and scalable to be used in multi-hop CRNs.

Index Terms—Cognitive radio networks, routing protocol, anypath routing, cognitive capacity harvesting.

1 Introduction

With the remarkable increase of smartphones, many mobile applications, such as mobile social networks, mobile health, online gaming and so on, have been widely developed, resulting in tremendous growth in mobile data traffic. This trend will continue, leading to serious spectrum crisis. Cognitive radio networks (CRNs) have been emerging as a promising technique to improve the spectrum efficiency to meet this increasing mobile traffic demand.

The performance of CRNs heavily depends on routing protocols. On one hand, the routing protocols should be spectrum-aware and consider the spectrum uncertainty feature of CRNs. On the other hand, it should provide reliable performance in unreliable network environment of CRNs due to the unreliable characteristic of wireless medium. As one of the most promising solutions to address unreliable nature of wireless transmission, anypath routing has been well-studied in traditional wireless networks, which achieves significant performance improvement as compared with unicast routing. However, there is not much research devoted to the anypath routing protocol design for CRNs. One of the main challenges is to accurately estimate and evaluate the quality of an anypath under uncertain spectrum availability, which is a salient difference between CRNs and traditional wireless networks and must be carefully considered and modeled in the routing metric. In addition, the computational complexity of existing anypath routing algorithms for CRNs is too high to be implemented in practice. It is also very challenging to develop an efficient routing protocol to compute the optimal anypath in CRNs, since the searching space grows exponentially fast as the number of available channels and the size of the network increase.

To overcome these challenges, in this paper, we propose a novel spectrum-aware anypath routing protocol (SAAR) for multi-hop CRNs. We use a recently proposed network architecture for CRNs, called Cognitive Capacity Harvesting networks (CCHs) [1]–[3], as an example to illustrate our design. CCH consists of a secondary service provider (SSP), cognitive base stations (BSs), cognitive radio routers (CR routers), and secondary users (SUs). The SSP is the operator and manager of CCH, which harvests spectrum resource and allocates it to the network. The CR routers are equipped with cognitive radios, which perform spectrum sensing, collect demand from SUs, and transmit their data around over available licensed spectrum. The BSs are interconnected with high-speed wired links and serve as the gateways of CCH. SUs

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- *J. Wang is with the Faculty of Electronic Information and Electrical Engineering, Dalian University of Technology, Dalian 116023, China. e-mail: wangjie@dlut.edu.cn.*
- *H. Yue is with the Department of Computer Science, San Francisco State University, San Francisco, CA 94132, USA. e-mail: haoyue@sfsu.edu.*
- *L. Hai is with the College of Information Engineering, Shenzhen University, Shenzhen 518060, China. e-mail: hailong@mail.dlut.edu.cn.*
- *Y. Fang is with the Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL 32611, USA. e-mail: fang@ece.ufl.edu.*

include wireless devices using traditional wireless access technologies, and also include wireless devices that are equipped with advanced cognitive radios for communication. CCH forms a spectrum cloud and facilitates the access of SUs with or without cognitive radio capability (See Section 3 for details), which represents a design paradigm shift from individual benefit to collective welfare. Note that the anypath routing protocol SAAR we proposed can be used in any multi-hop CRN with a central node that can perform channel and link information collection and routing table computation, which is not limited to CCHs.

The main contributions of this paper can be summarized as follows:

1) We take both the spectrum uncertainty of CRNs and the unreliable transmission characteristics of wireless medium into consideration, and quantify their effects on the cost to transmit a packet from the source node to the destination along an anypath in CRNs in a new routing metric to better estimate the performance of the anypath.
2) We extend the Bellman-Ford algorithm and develop a polynomial-time routing algorithm to find the best channel and the associated optimal forwarding set and compute the least cost anypath with low computation overhead.
3) Extensive simulation results demonstrate that SAAR significantly increases packet delivery ratio and reduces end-to-end delay, which makes it suitable and scalable to be used in practical multi-hop CRNs.

The rest of this paper is organized as follows. We briefly review related work in Section 2. In Section 3, we describe the system architecture of CCH, introduce our system model, and define the problem to be studied. In Section 4, we present the SAAR routing in detail. We evaluate the proposed scheme and present the experimental results in Section 5. Finally, we draw the conclusion in Section 6.

2 Related Work

As an important issue in CRNs, the routing problem has drawn considerable attention. Chowdhury *et al.* [4], [5] and Jin *et al.* [6] develop distributed routing protocols for cognitive radio ad-hoc networks by considering geographic information. Pan *et al.* [7] and Li *et al.* [8] formulate the routing problem in CRNs as a joint routing and link scheduling optimization problem. Ji *et al.* [9] design an effective semi-structure routing scheme to minimize induced latency and energy consumption. It incorporates power control into the routing framework and realizes energy-efficient routing for CRNs. Liang *et al.* [10] investigate the spectrum-mobility-incurred route switching problem in both spatial and frequency domains for CRNs, and address the routing problem with game theory. Ping *et al.* [11] propose a spectrum aggregation-based cooperative routing protocol for cognitive radio ad hoc networks. Chen *et al.* [12] develop a cooperative routing algorithm using mutual-information accumulation for underlay CRNs by dynamically controlling the transmission power of SUs so that its interference to PUs is tolerable. Youssef *et al.* [13] review the routing metrics utilized in CRNs, such as the delay, hop count, routing stability, power consumption, *etc.*, and summarize the generally adopted routing algorithms. The aforementioned works build only one single path from a source to a destination, which is not robust to unreliable wireless links in CRNs. Liu *et al.* [14]–[16] exploit the broadcast nature of the wireless medium and propose an opportunistic routing scheme. They introduce a cognitive transport throughput metric and propose a heuristic algorithm to calculate routing paths. Lin *et al.* [17], [18] analyze the opportunistic routing in CRNs with a traffic model. Zeng *et al.* [19], [20] model the opportunistic routing problem as an optimization problem and introduce a heuristic algorithm to calculate the optimal forwarding set and routing path.

Dubois-Ferriere *et al.* [21], [22] propose the concept of anypath routing. In anypath routing, the path for each packet is determined on-the-fly, depending on which nodes in the forwarding set successfully receive the packet at each hop and their corresponding priorities. Some innovative works have been performed to realize distributed anypath routing [23]–[25], multirate anypath routing [26]–[29], correlation-aware anypath routing [30], latency aware anypath routing [31], and evaluate anypath routing in practical wireless networks [32], [33]. Kim *et al.* [34] propose a two-hop anypath routing protocol for cognitive vehicular networks. Different from the aforementioned works, our proposed SAAR scheme implements anypath routing in multi-hop CRNs. We take the salient nature of multi-hop CRNs, *i.e.*, the uncertain spectrum availability due to the random return of PUs, into consideration while designing optimal anypath routing. Chao et al. propose an anypath routing protocol for multi-hop cognitive radio ad hoc networks in [35], which is designed on top of a multi-channel rendezvous protocol. Here, the multi-channel rendezvous protocol is used to deal with the channel uncertainty in CRNs and find available channels for communication. The anypath routing protocol takes advantage of the neighbor diversity to improve routing efficiency, which is similar to the use of anypath routing in traditional wireless networks. Different from [35], in SAAR, we design a new routing metric, which takes both the channel uncertainty and unreliability of wireless medium into consideration. Based on this routing metric, we also develop an efficient anypth routing algorithm to find the priorities of available channels and the associated forwarding sets at each node.

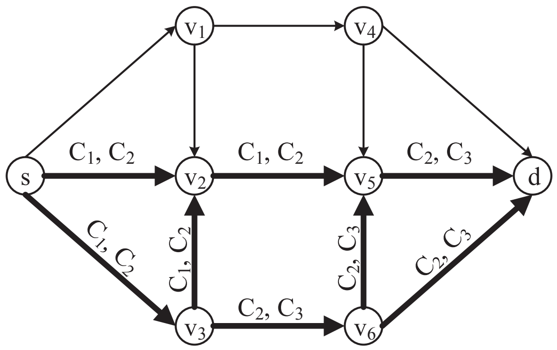

Fig. 1 Illustration of an anypath routing for CRNs.

TABLE 1 Summary of Notations

Symbol	Definition
N_B	number of BSs
N_R	number of CR routers
N	number of nodes ($N = N_B + N_R$)
M	number of channels
p_{ij}^m	delivery probability from node i to j on channel m
$\mathbf{J}_i^m$	forwarding set of node i on channel m
$p_{i\mathbf{J}}^m$	hyperlink delivery probability on channel m
q_i^m	channel quality of node i on channel m
$D_{i\mathbf{J}}^m$	hyperlink cost on channel m
$D_{\mathbf{J}}^m$	remaining anypath cost from $\mathbf{J}_i^m$ to the destination
D_i^m	anypath cost of node i on channel m
D_i	anypath cost of node i
$N_{\mathbf{d}}$	number of nodes in the destination node set
s	source node
$\mathbf{d}$	destination node set

3 Motivation

Fig. 1 illustrates a small CRNs consisting of 8 nodes. The link labels indicate the available channels for the links, *e.g.*, node s can communicate with node v_2 using channels C_1 and C_2. Taking the routing from node s to node d as an example, traditional routing protocols always pre-determine a path from node s to node d before data transmission, e.g., $s - v_2 - v_5 - d$. Then, at each hop, the sender selects a channel and transmits data over the channel when it is available to the receiver. The sender retransmits any data to the receiver if it is lost during the transmission, until the receiver successfully receives it. Later, motivated by [36], some works [34], [35] propose to use anypath routing to improve the routing performance in CRNs. In [34], [35], each node is associated with a forwarding set, which is a subset of its neighboring nodes. When a sender transmits a packet, it chooses one available channel and broadcasts the packet to all the nodes in the forwarding set. As long as it is received by at least one node in the forwarding set, the packet will be further forwarded. Different from [34], [35] where channel selection and route selection are addressed separately, in this work, we consider both of them in anypath routing and propose a novel spectrum-aware anypath routing protocol, called SAAR, for multi-hop CRNs. We take both the spectrum uncertainty of CRNs and the unreliable transmission characteristics of wireless medium into consideration, and quantify their effects on the cost to transmit a packet from the source node to the destination along an anypath in CRNs in a new routing metric to better estimate the performance of the anypath. In addition, we extend the Bellman-Ford algorithm [27] and develop a polynomial-time routing algorithm to find the best channels and the associated optimal forwarding sets with low computational overhead, which makes SAAR suitable and scalable to be deployed in real-world CRNs. Fig. 1 depicts the anypath from source node s to destination node d derived by using SAAR, which is shown in bold arrows. The forwarding sets for nodes s, v_2, v_3, v_5, and v_6 are $\{C_1 : v_2, v_3; C_2 : v_2, v_3\}$, $\{C_1 : v_5; C_2 : v_5\}$, $\{C_1 : v_2; C_2 : v_2, v_6; C_3 : v_6\}$, $\{C_2 : d; C_3 : d\}$, and $\{C_2 : v_5, d; C_3 : v_5, d\}$, respectively.

4 System Model and Problem Formulation

4.1 System Architecture of CCH

The architecture of CCH [1]–[3] is shown in Fig. 2. It consists of four types of network entities: an SSP, a few number of BSs, and a large number of CR routers and SUs. We assume that SSP has its own spectrum (called basic band) and its deployed network facilities (BSs and CR routers) can use the basic band to provide basic reliable services. The BSs and CR routers are equipped with multiple cognitive radios, which can tune to any basic band or harvested band for communication. With cooperation of BSs and CR routers, the SSP harvests spectrum resource and allocates it on demand. The SSP, BSs, and CR routers form a spectrum cloud and could provide service for SUs with or without cognitive capability. In this spectrum cloud, the SSP is the manager, the BSs act as gateways of the cloud and further connect to Internet or other data networks, and the CR routers and BSs are the access points which facilitate SUs to access the CCH. The SUs can be any wireless device using any accessing technique (*e.g.*, Laptops, tablets, or desktop computers using WiFi, cell phones using GSM/GPRS, smart phones using 3G/4G/NxtG, *etc.*). If a SU has cognitive capability, it could communicate with CR routers and BSs over both harvested bands and basic band. Otherwise, it could only communicate over the basic band. As a spectrum cloud, the performance of CCH heavily depends on the routing protocol, which needs to provide optimal and reliable routing between any two nodes (two CR routers, two BSs, or one CR router and one BS) for internal communication in the CCH domain, or a node (CR router) and multiple gateways (BSs) for external communication. We will present the design of spectrum-aware anypath routing for CCH in detail in the following Sections. Mainly used notations are listed in Table 1 for easy reference.

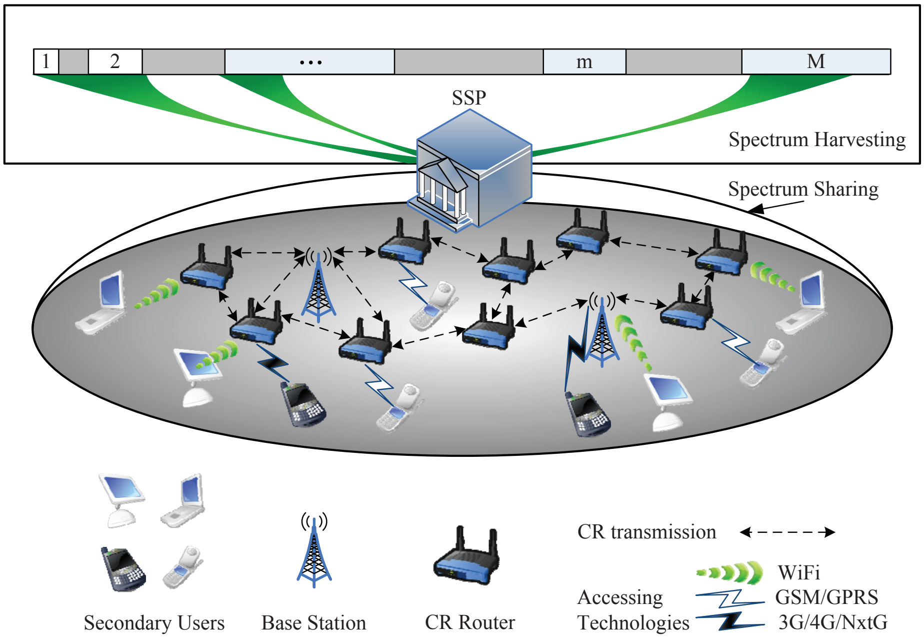

Fig. 2 System architecture of CCH.

4.2 System Model

Suppose there are N_B BSs and N_R CR routers equipped with multiple cognitive radios in our CCH. Let N denote the total number of nodes in the CCH, *i.e.*, $N = N_B + N_R$. With cooperation of BSs and CR routers, the SSP has the statistical knowledge about every channel at every location. A channel in the basic band is used as the common control channel (CCC) for signaling exchange, and there are M orthogonal channels that can be used for transmitting packets. We model the network as a hypergraph $\mathbf{G} = (\mathbf{V}, \mathbf{E})$, where $\mathbf{V}$ is the set of BSs and CR routers, and $\mathbf{E}$ represents a set of hyperedges or hyperlinks. For each link from node i to j, there is a packet delivery probability p_{ij}^m for each channel $m = 1, \ldots, M$. A hyperlink is an ordered pair $(i, \mathbf{J}_i^m) \in \mathbf{E}$, where $i \in \mathbf{V}$ and $\mathbf{J}_i^m$ is the forwarding set of node i on channel m. The hyperlink delivery probability $p_{i\mathbf{J}}^m$ on channel m is defined as the probability that a packet transmitted by node i is successfully received by at least one node in $\mathbf{J}_i^m$. Since the loss of a packet at different receivers occurs independently in practice [26], [27], the hyperlink delivery probability $p_{i\mathbf{J}}^m$ can be calculated as

$$p_{i\mathbf{J}}^m = 1 - \prod_{j \in \mathbf{J}_i^m} (1 - p_{ij}^m). \tag{1}$$

Due to the randomness of the transmission activities of PUs, we model the occupation of PUs in each channel as an independently and identically distributed alternation between two states, *i.e.*, ON state when PU is active and OFF state when PU is inactive. We can measure the expected channel OFF time $E[T_{off}^m]$ and channel ON time $E[T_{on}^m]$ by periodic sensing. Then, taking both the channel availability and the expected channel OFF time into consideration, we define the channel quality q_i^m of node i on channel m as follows

$$q_i^m = \frac{E[T_{off}^m]}{E[T_{off}^m] + E[T_{on}^m]} \times \frac{E[T_{off}^m]}{\max\limits_{k=1,\ldots,M} E[T_{off}^k]}, \tag{2}$$

where $\max\limits_{k=1,\ldots,M} E[T_{off}^k]$ indicates the maximum expected channel OFF time on all feasible channels.

A larger channel quality q_i^m indicates that channel m is better and more suitable for transmitting packets. The knowledge about packet delivery probability p_{ij}^m and channel quality q_i^m can be acquired by the SSP with the cooperation of BSs and CR routers. Based on p_{ij}^m and q_i^m, we define a new routing metric, called the expected cognitive anypath transmissions (ECATX), as follows:

$$ECATX(i, \mathbf{J}_i^m) = \frac{1}{p_{i\mathbf{J}}^m \times q_i^m}. \tag{3}$$

We are interested in calculating the anypath cost D_i from a node i to a given destination via a forwarding set. The anypath cost D_i^m on channel m is defined as the summation of the hyperlink cost, *i.e.*, the forwarding cost $D_{i\mathbf{J}}^m$, and the remaining anypath cost $D_{\mathbf{J}}^m$ from set $\mathbf{J}_i^m$ to the destination, which can be represented as follows:

$$D_i^m = D_{i\mathbf{J}}^m + D_{\mathbf{J}}^m. \tag{4}$$

Here the hyperlink cost $D_{i\mathbf{J}}^m$ is defined as the ECATX metric, *i.e.*,

$$D_{i\mathbf{J}}^m = ECATX(i, \mathbf{J}_i^m), \tag{5}$$

and the remaining anypath cost $D_{\mathbf{J}}^m$ is defined as the weighted average of the anypath cost of the nodes in the forwarding set $\mathbf{J}_i^m$ to the destination, *i.e.*,

$$D_{\mathbf{J}}^m = \sum_{j \in \mathbf{J}_i^m} \omega_{ij}^m D_j, \tag{6}$$

where D_j represents the anypath cost of node j to the destination, and weight ω_{ij}^m is the probability of node j being the actual forwarding node. Without loss of generality, let $\mathbf{J}_i^m = \{1, \ldots, j, \ldots, J\}$ with anypath cost $D_1 \leq \ldots \leq D_j \leq \ldots \leq D_J$. Since a node with lower anypath cost will have a higher priority to forward the packet, node 1 has the highest priority to forward the packet, followed by node 2, and node n has the lowest priority. Node j will be the forwarding node only when it receives the packet and none of the nodes with higher priority receives it, which happens with probability $p_{ij}^m \prod_{k=1}^{j-1}(1 - p_{ik}^m)$. Then, the weight ω_{ij}^m is defined as

$$\omega_{ij}^m = \frac{p_{ij}^m \prod_{k=1}^{j-1}(1 - p_{ik}^m)}{1 - \prod_{k \in \mathbf{J}_i^m}(1 - p_{ik}^m)}, \tag{7}$$

where $\prod_{k=1}^{0}(1 - p_{ik}^m) = 1$, and the denominator is the normalizing constant.

The anypath cost D_i from node i to a given destination is defined as the weighted average of the anypath cost D_i^m on every available channel and can be calculated as

$$D_i = \sum_{m=1}^{M} \alpha_i^m D_i^m, \tag{8}$$

where α_i^m represents the probability that channel m is the selected channel to transmit the packet over. Suppose the channel quality follow $q_i^1 \geq \ldots \geq q_i^m \geq \ldots \geq q_i^M$. Since a channel with higher availability probability will have a higher priority to be selected, channel 1 has the highest priority, and channel M has the lowest priority. Channel m will be selected only when it is available and none of the channels with higher priority is available, which happens with probability $q_i^m \prod_{k=1}^{m-1}(1 - q_i^k)$. Thus, α_i^m is defined by

$$\alpha_i^m = \frac{q_i^m \prod_{k=1}^{m-1}(1 - q_i^k)}{1 - \prod_{k=1}^{M}(1 - q_i^k)}, \tag{9}$$

where $\prod_{k=1}^{0}(1 - q_i^k) = 1$.

As an example, consider the network depicted in Fig. 3. Suppose we have two channels, and the forwarding sets of the two channels are the same. The forwarding sets of the nodes s, v_2, v_3, v_5, and v_6 are $\{v_2, v_3\}$, $\{v_5\}$, $\{v_6, v_2\}$, $\{d\}$, and $\{d, v_5\}$, respectively. Link labels show the delivery probability p_{ij}^m, with a format of $\{p_{ij}^1, p_{ij}^2\}$, and node labels show the channel quality q_i^m, with a format of $\begin{pmatrix} q_i^1 \\ q_i^2 \end{pmatrix}$. The anypath cost of the destination node d is $D_d = 0$.

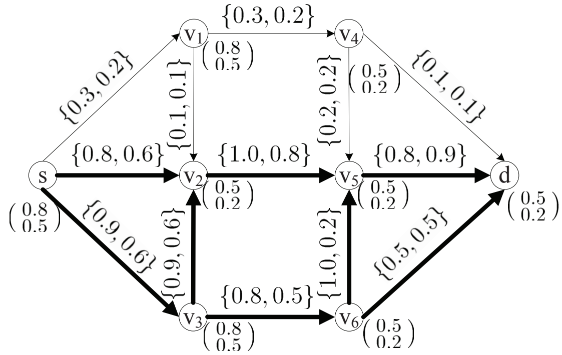

Fig. 3 An example to illustrate the calculation of anypath cost.

As the forwarding sets of node v_5 are $\mathbf{J}_5^1 = \mathbf{J}_5^2 = \{d\}$, the anypath cost D_5 can be calculated as follows:

$$\begin{aligned}
D_5 &= \tfrac{q_5^1}{1-(1-q_5^1)(1-q_5^2)} D_5^1 + \tfrac{q_5^2(1-q_5^1)}{1-(1-q_5^1)(1-q_5^2)} D_5^2 \\
&= \tfrac{q_5^1}{1-(1-q_5^1)(1-q_5^2)} \left(\tfrac{1}{p_{5d}^1 \times q_5^1} + \tfrac{p_{5d}^1 \times D_d}{p_{5d}^1} \right) \\
&\quad + \tfrac{q_5^2(1-q_5^1)}{1-(1-q_5^1)(1-q_5^2)} \left(\tfrac{1}{p_{5d}^2 \times q_5^2} + \tfrac{p_{5d}^2 \times D_d}{p_{5d}^2} \right) \\
&= \tfrac{0.5}{1-(1-0.5)(1-0.2)} \left(\tfrac{1}{0.8 \times 0.5} + \tfrac{0.8 \times 0}{0.8} \right) \\
&\quad + \tfrac{0.2(1-0.5)}{1-(1-0.5)(1-0.2)} \left(\tfrac{1}{0.9 \times 0.2} + \tfrac{0.9 \times 0}{0.9} \right) \\
&= 3.
\end{aligned} \tag{10}$$

Since the forwarding set of node v_6 is $\{d, v_5\}$, with anypath cost D_5 and D_d, the anypath cost of node v_6 can be calculated as follows:

$$\begin{aligned}
&D_6 \\
&= \tfrac{q_6^1}{1-(1-q_6^1)(1-q_6^2)} D_6^1 + \tfrac{q_6^2(1-q_6^1)}{1-(1-q_6^1)(1-q_6^2)} D_6^2 \\
&= \tfrac{q_6^1}{1-(1-q_6^1)(1-q_6^2)} \left(\tfrac{1}{(1-(1-p_{6d}^1)(1-p_{65}^1)) \times q_6^1} + \tfrac{p_{6d}^1 \times D_d + p_{65}^1(1-p_{6d}^1) \times D_5}{1-(1-p_{6d}^1)(1-p_{65}^1)} \right) \\
&\quad + \tfrac{q_6^2(1-q_6^1)}{1-(1-q_6^1)(1-q_6^2)} \left(\tfrac{1}{(1-(1-p_{6d}^2)(1-p_{65}^2)) \times q_6^2} + \tfrac{p_{6d}^2 \times D_d + p_{65}^2(1-p_{6d}^2) \times D_5}{1-(1-p_{6d}^2)(1-p_{65}^2)} \right) \\
&= \tfrac{0.5}{1-(1-0.5)(1-0.2)} \left(\tfrac{1}{(1-(1-0.5)(1-1)) \times 0.5} + \tfrac{0.5 \times 0 + 1 \times (1-0.5) \times 3}{1-(1-0.5)(1-1)} \right) \\
&\quad + \tfrac{0.2(1-0.5)}{1-(1-0.5)(1-0.2)} \left(\tfrac{1}{(1-(1-0.5)(1-0.2)) \times 0.2} + \tfrac{0.5 \times 0 + 0.2 \times (1-0.5) \times 3}{1-(1-0.5)(1-0.2)} \right) \\
&= 4.39.
\end{aligned} \tag{11}$$

Continuing the above process, we can compute $D_2 = 5.71$, $D_3 = 6.07$, and $D_s = 7.18$.

4.3 Problem Definition

Based on the definition of the anypath cost, we are ready to find the least cost anypath between a pair of nodes (two BSs, two CR routers, or one BS and one CR router) for routing within CCH, or between a source node (CR router) and one of multiple gateways (BSs) to route data to a destination outside CCH. In addition, we need to find the forwarding set on every channel for every node, together with the priorities of different channels and nodes within a forwarding set. Thus, our SAAR problem is formally defined as follows:

Definition 1: SAAR($\mathbf{G}, q_i^m, p_{ij}^m, s, \mathbf{d}$): **Instance:** A hypergraph $\mathbf{G} = (\mathbf{V}, \mathbf{E})$, with channel quality q_i^m and packet delivery probability p_{ij}^m associated with each link from node i to node j for every channel $m = 1, \ldots, M$, a source node s, and a destination node set $\mathbf{d}$ (the number of nodes in set $\mathbf{d}$ is $N_{\mathbf{d}} = 1$ and $N_{\mathbf{d}} = N_B$ for routing within and outside CCH, respectively, and the destination set is made up of all the BSs as gateways when routing outside CCH.). **Problem:** Find the optimal least-cost anypath from node s to destination node set $\mathbf{d}$ such that D_s is minimized, and record the forwarding set for each forwarding channel at every node as well as their corresponding priorities along the path.

5 Spectrum-Aware Anypath Routing

In this section, we first present an overview of the SAAR protocol. Then, we present the proposed SAAR algorithm, which could compute the least cost anypath in polynomial-time.

5.1 Protocol Overview

SAAR is a centralized protocol. CR routers sense the channel and link statistics periodically and send these information to SSP with CCC. SSP calculates the anypath routing for each node with the statistical information of the networks. Given the channel quality q_i^m, the SSP could determine the priorities for every channel at each node by sorting q_i^m in a descending order, so that a channel with higher availability probability will be used with higher probability. As for the priorities of the nodes within a forwarding set, the SSP determines their priorities by sorting their anypath cost D_j in an ascending order, so that a node with lower anypath cost to the destination will become the actual forwarding node with higher probability. After the establishment of anypath routing, every node i participating in the routing process will know its own routing information, such as $\{\{1, \mathbf{J}_i^1\}; \ldots, \{m, \mathbf{J}_i^m\}; \ldots, \{M, \mathbf{J}_i^M\}\}$. To coordinate the transmissions at different nodes in anypath routing, when a node intends to transmit, it will first perform spectrum sensing to detect the channel state and find out all the available channels. Then, it selects the best one from the available channels and transmits to the nodes in the forwarding set of that channel without causing interference to primary users. We adopt an anycast MAC [14], [24], [37] to realize the aforementioned coordination task. The design of MAC protocol is out of the scope of this paper.

5.2 SAAR Routing Algorithm

Unlike the optimization based schemes in [14], [20], we present a polynomial-time SAAR algorithm to solve the routing problem in CRNs in this section. Specifically, we are interested in finding the least cost anypath between a pair of nodes (two BSs, two CR routers, or one BS and one CR router) to support routing within CCH, or between a source node (CR router) and multiple gateways (BSs) to route data to a destination outside CCH. Our aim is to develop an efficient routing scheme for CCH to make it a high-performance spectrum cloud so as to provide better service for the SUs.

The key idea behind the algorithm is that every node updates its forwarding sets and anypath cost in every iteration, based on the previous anypath cost of the neighboring nodes and the hyperlink cost for forwarding packets to these nodes. The task of the updating process is to find an optimal forwarding set $\mathbf{J}_i^m$ for every node i on every available channel m, such that

$$\mathbf{J}_i^m = \arg\min_{\mathbf{J} \subseteq \mathbf{N(i)}} \left(D_{i\mathbf{J}}^m + D_{\mathbf{J}}^m\right), \tag{12}$$

where $\mathbf{N}(\mathbf{i})$ indicates the neighbor set of node i. The forwarding cost $D_{i\mathbf{J}}^m$ can be calculated with the packet delivery probability p_{ij}^m and channel quality q_i^m based on Eq. (3) and Eq. (5), and the remaining anypath cost $D_{\mathbf{J}}^m$ can be updated with Eq. (6) by using anypath cost of the neighboring nodes. Intuitively, it needs the calculation and comparison of $2^{|\mathbf{N(i)}|} - 1$ possible forwarding sets in Eq. (12). Fortunately, it has been proved that if the anypath cost of the neighboring nodes follows $D_1 \leq \ldots \leq D_j \leq \ldots \leq D_{|\mathbf{N(i)}|}$, the optimal forwarding set is always one of $\{v_1\}$, $\{v_1, v_2\}$, $\ldots$, and $\{v_1, v_2, \ldots, v_{|\mathbf{N(i)}|}\}$ [22], [27]. Hence, the complexity can be greatly reduced from exponential to polynomial time $O(|\mathbf{N}(\mathbf{i})|)$.

Algorithm 1 summarizes the procedure of the SAAR routing algorithm, which consists of 3 major phases. In the initialization phase, the anypath cost of every node D_i and the anypath cost of every node on every channel D_i^m are initialized to ∞, and the forwarding set $\mathbf{J}_i^m$ is initialized to $\emptyset$ (lines 3-7). To support routing to one of multiple gateways, the SAAR initializes all nodes in the destination set with a cost value of 0 (lines 8-11), which guarantees that a node would route packets to the closest BS (the one with the least cost) if it intends to send a packet to a destination outside CCH. In addition, if the source node locates among multiple BSs, the anypath may build paths to multiple BSs simultaneously, *i.e.*, both the path and gateway are determined on-the-fly, depending on which nodes in the forwarding set successfully receive the packet at each hop and their corresponding priorities. If the BSs are deployed uniformly, the above scheme could ensure the load balance in CCH. If one BS breaks down, the delivery probability to this BS will drop to 0, and the SAAR will automatically route the load to other nearby BSs. Hence, with the SAAR routing algorithm, CCH can be automatically configured as a robust and highly efficient spectrum cloud.

Algorithm 1: SAAR Routing Algorithm

Input:
Hypergraph $\mathbf{G} = (\mathbf{V}, \mathbf{E})$.
Channel quality q_i^m.
Packet delivery probability p_{ij}^m.
Destination node set $\mathbf{d}$.
Output:
The optimal least-cost anypath from every node to the destination node set $\mathbf{d}$, and the forwarding set for each forwarding channel at every node as well as their corresponding priorities along the path.

1 **Initialization:**
2 **for** $i = 1$ *to* N **do**
3 $\quad D_i = \infty$,
4 $\quad$ **for** $m = 1$ *to* M **do**
5 $\quad\quad D_i^m = \infty$,
6 $\quad\quad \mathbf{J}_i^m = \emptyset$.
7 $\quad$ **end**
8 $\quad$ **if** $i \in \mathbf{d}$ **then**
9 $\quad\quad D_i = 0$,
10 $\quad\quad D_i^m = 0$ for $m = 1$ to M.
11 $\quad$ **end**
12 **end**
13 **Anypath Cost Calculation:**
14 **for** $Loop = 1$ *to* $N - 1$ **do**
15 $\quad$ **for** $i = 1$ *to* N **do**
16 $\quad\quad$ **for** $m = 1$ *to* M **do**
17 $\quad\quad\quad \mathbf{N(i)} = GetNeighbors(i)$,
18 $\quad\quad\quad \hat{\mathbf{J}} = \emptyset$,
19 $\quad\quad\quad D_i^m = \infty$,
20 $\quad\quad\quad$ **while** $\mathbf{N(i)} \neq \emptyset$ **do**
21 $\quad\quad\quad\quad j = \underset{j=1,\ldots,|\mathbf{N(i)}|}{\operatorname{argmin}} (D_j)$,
22 $\quad\quad\quad\quad \hat{\mathbf{J}} = \hat{\mathbf{J}} \cup j$,
23 $\quad\quad\quad\quad \hat{D}_i^m = D_{i\hat{\mathbf{J}}}^m + D_{\hat{\mathbf{J}}}^m$,
24 $\quad\quad\quad\quad$ **if** $\hat{D}_i^m < D_i^m$ **then**
25 $\quad\quad\quad\quad\quad D_i^m = \hat{D}_i^m$,
26 $\quad\quad\quad\quad\quad \mathbf{J}_i^m = \hat{\mathbf{J}}$.
27 $\quad\quad\quad\quad$ **else**
28 $\quad\quad\quad\quad\quad$ **Break**.
29 $\quad\quad\quad\quad$ **end**
30 $\quad\quad\quad\quad \mathbf{N(i)} = \mathbf{N(i)} - \{j\}$.
31 $\quad\quad\quad$ **end**
32 $\quad\quad$ **end**
33 $\quad\quad D_i = \sum_{m=1}^{M} \alpha_i^m D_i^m$.
34 $\quad$ **end**
35 $\quad$ **if** *none of value of* D_i *changes in this loop* **then**
36 $\quad\quad$ **Break**.
37 $\quad$ **end**
38 **end**
39 **Forwarding Set Determination:**
40 **for** $i = 1$ *to* N **do**
41 $\quad$ Sort the forwarding sets of different channels for node i according to the values of q_i^m in descending order.
42 **end**

In the anypath cost calculation phase, SSP updates the values of D_i, D_i^m, and $\mathbf{J}_i^m$ of each node with the previous values of their neighbors (lines 15-34), and finishes the anypath cost calculation phase after running the updating process for N rounds or until the anypath cost of all nodes do not change anymore (lines 35-37). For every node i, the updating process for every channel is shown in lines 16-32. The neighboring nodes of node i are obtained in line 17. Then, SSP tests the neighboring nodes one by one in an ascending order according to their anypath cost value, and checks whether adding a new node into the forwarding set decreases the anypath cost D_i^m (lines 20-31). If so, SSP adds this node to the forwarding set and updates anypath cost D_i^m. Otherwise, the updating process for this channel is completed. After updating D_i^m and $\mathbf{J}_i^m$ for every channel, the anypath cost D_i of node i can be calculated in line 33.

In the forwarding set determination phase, since the nodes in $\mathbf{J}_i^m$ have been added to the set according to their anypath cost values in the ascending order (line 21-22), we only sort the forwarding sets of different channels for every node according to the value of q_i^m in the descending order.

After the execution of Alg. 1, we could find the least cost anypath from every node to a given destination set, together with the forwarding sets of every channel and their corresponding priorities along the anypath.

For easy understanding, we use an example to illustrate the execution procedure of SAAR routing algorithm in Fig. 4. The network topology and notations are similar to that used in Fig. 1 and Fig. 3. We have 2 nodes in the destination node set (BSs in CCH), d_1 and d_2, and 6 normal nodes (CR routers in CCH), v_1 to v_6. From the figures, we can see that after the execution of SAAR algorithm, every node finds its optimal anypath to 1 or 2 of nodes in the destination node set, *e.g.*, nodes v_4 and v_6 have anypath connecting to 2 gateway nodes, while nodes v_1, v_2, and v_3 have anypath only connecting with gateway d_1, and node v_5 could only route to d_2. Meanwhile, we can see that different nodes have different number of paths to the gateways, *e.g.*, the anypath of node v_5 is a single path, while the anypath of v_4 consists of 5 paths, with 3 paths to d_1 and 2 paths to d_2.

The computational complexity of the SAAR algorithm is analyzed as follows. In the initialization phase, the computational complexity is $O(NM + N_{\mathbf{d}})$. Suppose the total number of links in the network is $|\mathbf{E}|$, the computational complexity of the anypath cost updating process for each channel (lines 17-31) is $O(|\mathbf{E}|N)$ at most. The complexity of the anypath cost calculation phase is $O(N^3M|\mathbf{E}|)$ in total. In the forwarding set determination phase, the complexity of sorting operations is $O(NM \log M)$. Therefore, the total complexity of the SAAR algorithm is $O(NM + N_{\mathbf{d}} + N^3M|\mathbf{E}| + NM \log M)$. Compared with the values of N and $|\mathbf{E}|$, the values of M and $N_{\mathbf{d}}$ are always smal-

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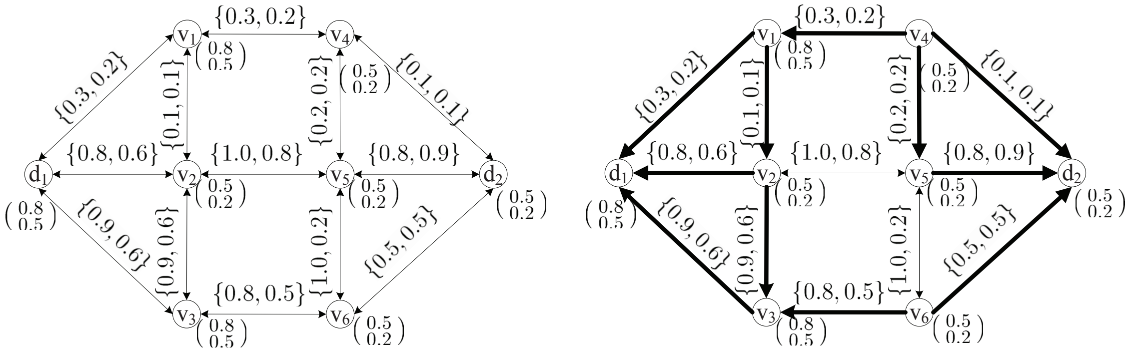

Fig. 4 Illustration of the execution of SAAR algorithm. (a) Initialization. (b) The resulted anypath computed with the SAAR algorithm.

l. Hence, the total complexity is approximately equal to $O\left(N^3M|\mathbf{E}|\right)$. Since the SAAR routing algorithm is running by the SSP which has strong computational power, this time complexity is acceptable.

Next, we prove the optimality of the proposed routing algorithm SAAR. SAAR is an anypath routing algorithm, and therefore it inherits the features of anypath routing algorithms for traditional wireless networks. We first introduce two lemmas to show a few properties of anypath routing. Based on these two lemmas, we then prove the optimality of SAAR. In what follows, we use $v_1, v_2, ..., v_{|\mathbf{N(i)}|}$ to denote the neighbors of node i, which satisfies $\delta_1 \le \delta_2 \le ... \le \delta_{|\mathbf{N(i)}|}$. Here, δ_j is defined as the cost of the shortest anypath from a node v_j to the destination.

Lemma 1: If the lowest cost from the neighbors of a node i to the destination satisfies $\delta_1 \le \delta_2 \le \ldots \le \delta_{|\mathbf{N(i)}|}$, then the optimal forwarding set $\mathbf{J}_i^m$ for node i on channel m is always of the form $\mathbf{J}_i^m = \{v_1, v_2, \ldots, v_k\}$ for some $k \in \{1, 2, \ldots, |\mathbf{N(i)}|\}$.

Lemma 2: Given node i and channel m, assume that $\mathbf{J}_i^m = \{v_1, v_2, \ldots, v_k\}$ with cost $\delta_1 \le \delta_2 \le \ldots \le \delta_k$. If $D_i^m(j)$ is the transmission cost from node i to the destination using channel m via the forwarding set $\{v_1, v_2, \ldots, v_j\}$, for $1 \le j \le k$, then we always have $D_i^m(1) \ge D_i^m(2) \ge \ldots \ge D_i^m(k) = \delta_i$.

The proofs of Lemma 1 and Lemma 2 can be found in [27]. According to Lemma 1, the optimal forwarding set is always one of $\{v_1\}$, $\{v_1, v_2\}$, ..., and $\{v_1, v_2, \ldots, v_{|\mathbf{N(i)}|}\}$. Lemma 2 indicates that given the optimal forwarding set $\mathbf{J}_i^m = \{v_1, v_2, \ldots, v_k\}$ where $\delta_1 \le \delta_2 \le \ldots \le \delta_k$, the cost D_i^m monotonously decreases as we choose $\{v_1\}$, $\{v_1, v_2\}$, ..., and $\{v_1, v_2, \ldots, v_k\}$ as the forwarding set.

We prove this the optimality of SAAR using mathematical induction. Intuitively, SAAR works from the destination backwards to the source node in an expanding ring fashion. In each iteration, SAAR determines the forwarding nodes one-hop farther away from the destination. Since there are N nodes in the network, all the nodes must be within $N-1$ hops away from the destination. Thus, SAAR is guaranteed to converge within $N-1$ iterations.

Initialization: We initialize the anypath cost from any node in the destination set to the destination set over any channel to be zero, *i.e.*, $\{D_i = 0, D_i^m = 0 | i \in d, m = 1, \ldots, M\}$.

Inductive step: Suppose after l iterations we have $D_i = \delta_i$ for every node i that is within l hops from the destination. We have to prove that after $l+1$ iterations, we have $D_i = \delta_i$ for every node i that is within $l+1$ hops from the destination.

Suppose node i is $l+1$ hops away from the destination. Without loss of generality, assume that the cost of the shortest anypath between the neighboring nodes and the destination satisfies $\delta_1 \le \delta_2 \le \ldots \le \delta_{|\mathbf{N(i)}|}$. Since node i is $l+1$ hops away from the destination, all the nodes in its optimal forwarding set must be no more than l hops away from the destination. Then, based on the induction hypothesis, every node j in the optimal forwarding set of node i must have $D_j = \delta_j$. Based on Lemma 1 and Lemma 2, after examining the forwarding sets $\{v_1\}$, $\{v_1, v_2\}$, ..., and $\{v_1, v_2, \ldots, v_{|\mathbf{N(i)}|}\}$, node i will find the optimal forwarding set and calculate the cost D_i^m for channel m. After that, we have $D_i = \delta_i$ for every node i within $l+1$ hops from the destination.

It should also be mentioned that the proposed SAAR can also be implemented in a distributed manner, where each node keeps calculating the anypath cost based on local information and exchanging the cost information with its neighbors, until the anypath cost and the optimal forwarding set are stable. The distributed implementation is more suitable for distributed cognitive radio networks, such as cognitive radio ad hoc networks.

6 Performance Evaluation

In this section, we evaluate the performance of the proposed SAAR scheme with extensive simulations, and present the simulation results on packet delivery

TABLE 2 Simulation parameters

Number of channels	4
Channel available probability	{0.7, 0.3, 0.6, 0.8}
Expected channel OFF time	50ms
Number of PUs per channel	16
PU transmission range	250m
Number of BSs	4
Number of CR routers	150
CR router and BS transmission range	120m
CR router CCC rate	2Mbps
CR router data channel rate	2Mbps
Sending buffer size	8KBytes
Retransmission times	5
Sensing time	1ms
Channel switching time	1ms

ratio (PDR), end-to-end delay, and throughput, under different network settings, *e.g.*, channel conditions, number of CR routers, and source rates, by using Network Simulation Version 2 (NS2) software.

6.1 Simulation Settings

All simulations are conducted on a 4GHz PC with 32GBytes of memory. In the simulations, PU activities over each channel are modeled as an exponential ON-OFF process [14]–[16]. The channel status is updated by periodic sensing and on-demand sensing before data transmissions. We set up a CCH network with a SSP, multiple PUs, BSs, and CR routers. The SSP locates at the center of the networks, while all other network entities distribute randomly in a 1000m*1000m square region. We generate 500 test cases by choosing the distribution of all the nodes in CCH and the source-destination pair randomly in each test. A constant bit rate flow is associated with the node pair with packet size of 512Bytes and flow rate of 5Kbps. The physical layer is implemented using the log-normal shadow fading model. Since the anypath routing needs a MAC that supports anycast with relay priority enforced, we use the anycast MAC [14], [24], [37] in our simulation. The default network parameters are summarized in Table 2.

In the simulation, we compare SAAR with OCR [14], which is also a multi-path opportunistic routing scheme for cognitive radio networks. It exploits the geographic location information of CR routers, adopts distance advancement and link delay to form a cognitive transport throughput routing metric, and develops a heuristic algorithm to calculate the forwarding set for each node. Meanwhile, to demonstrate the advantage of multi-path routing, we also define a unicast routing algorithm SAAR-1 which limits the forwarding set size to 1 and selects the node with the highest packet delivery probability and distance advancement as the forwarding node. We compare the proposed SAAR with the aforementioned algorithms, and run each experiment for 200s. The results are averaged over 100 tests.

6.2 Simulation Results

We first evaluate the performance of different algorithms under different PU activities. We set the channel availability to be 0.7, 0.3, 0.6, and 0.8, respectively, and evaluate the algorithms under different expected channel OFF time $E[T_{off}]$ varying from 10ms to 150ms. The PDR and end-to-end delay performance are shown in Fig. 5(a) and Fig. 5(b). A small $E[T_{off}]$ indicates that the PU has frequent avtivity, and thus the transmissions of CR routers are more likely to be interrupted. Therefore, the PDR is relatively smaller and the end-to-end delay is larger. With the increase of $E[T_{off}]$, the PDR will increase and the end-to-end delay will decrease gradually. We also evaluate their performance under different channel availability, where we set the expected channel OFF durations of the 4 channels to be 100ms, 80ms, 50ms, and 30ms, respectively. The results are shown in Fig. 5(c) and Fig. 5(d). Compared with the single-path routing algorithm, SAAR and OCR algorithms achieve significantly better performance. Meanwhile, the performance of SAAR outperforms that of the OCR algorithm. We can also observe that the performance of SAAR is affected by both the channel availability and the channel ON/OFF durations.

We also evaluate the performance of different algorithms under different node densities. The number of CR routers in CCH varies from 100 to 400. The PDR and end-to-end delay performance are illustrated in Fig. 6. With the increase of the number of CR routers, more nodes will be selected and included into a forwarding set, which will increase the chance to take a better channel and choose a better forwarding node from the forwarding set. This will significantly increase packet delivery ratio and reduce end-to-end delay, which compensates the increase of end-to-end delay due to increasing communication overhead. Hence, the end-to-end delay observed in Fig. 6 decreases with the increase of the number of CR routers.

Since the proposed SAAR algorithm is not only suitable for routing within CCH, but also support routing outside CCH, we also evaluate its performance for routing outside CCH. Fig. 7 and Fig. 8 illustrate the results of SAAR and the modified version of SAAR which uses only one BS as the gateway to route to the outside of CCH. We can see that with the utilization of multiple gateways, SAAR algorithm achieves significantly better performance. It not only makes the routing more robust, but also distributes the load to multiple paths. Hence, the PDR is improved and the end-to-end delay is reduced simultaneously.

6.3 Analysis of SAAR Properties

Fig. 9 shows the throughput of different algorithms. From the figure, we can see that the throughput is higher when routing outside CCH, which is benefited from the multiple gateway scheme that distributes

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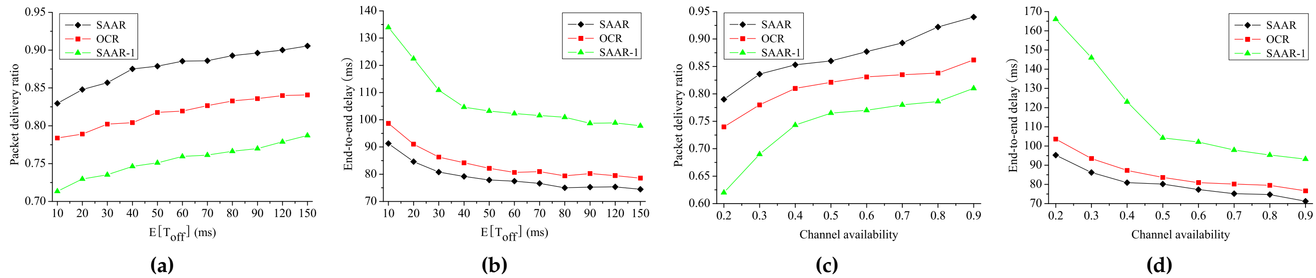

Fig. 5 Performance comparison under different channel conditions. (a) PDR vs. expected channel OFF time. (b) end-to-end delay vs. expected channel OFF time. (c) PDR vs. channel availability. (d) end-to-end delay vs. channel availability.

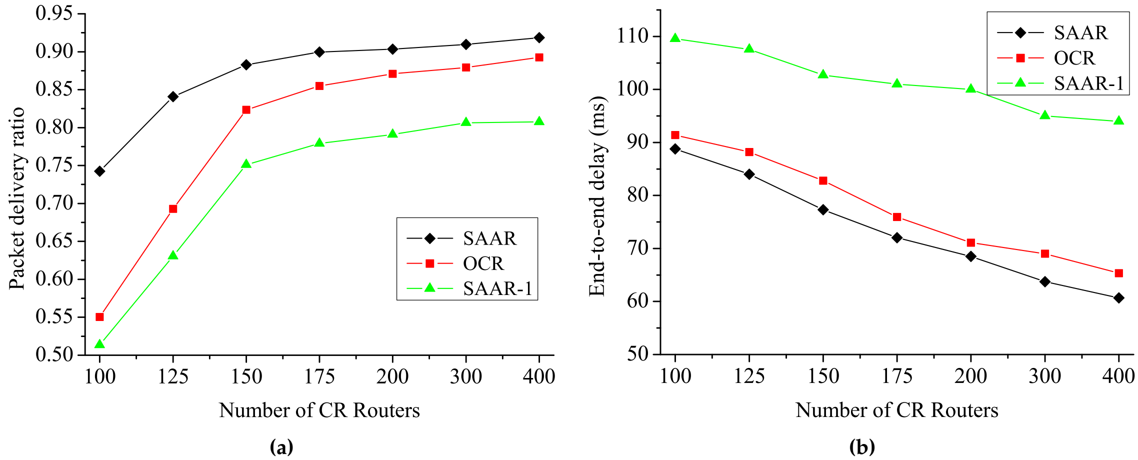

Fig. 6 Performance comparison under different CR routers densities. (a) packet delivery ratio. (b) end-to-end delay.

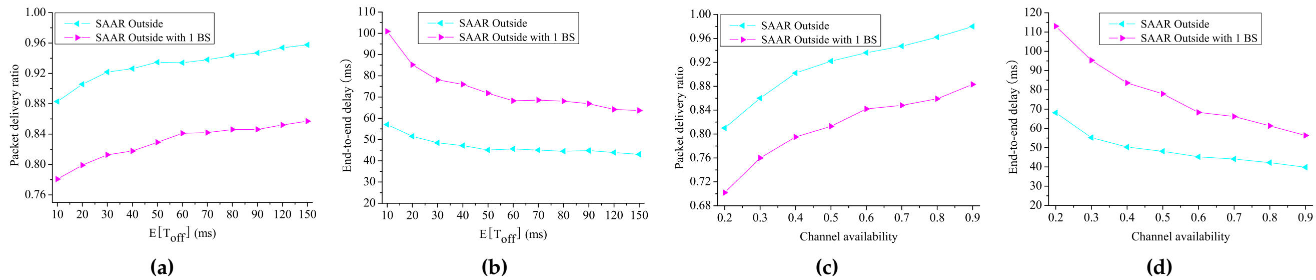

Fig. 7 Performance of routing outside CCH under different channel conditions. (a) PDR vs. expected channel OFF time. (b) end-to-end delay vs. expected channel OFF time. (c) PDR vs. channel availability. (d) end-to-end delay vs. channel availability.

the load to multiple paths. Compared with OCR, the SAAR algorithm could provide much higher throughput, which makes it more suitable for CCH.

We have also compared the throughput of different routing algorithms when the maximum size of forwarding sets decreases from 10 to 2. The results are illustrated in Fig. 10. From Fig. 10, we can observe that the throughput of SAAR does not decreases as the maximum size of forwarding sets changes from 10 to 4, and it starts to degrade when the maximum size is smaller than 4. This is due to the fact that SAAR always select the nodes with highest forwarding capability and add them into the forwarding set first. As more nodes are added into the forwarding set, their contribution on the throughput improvement of SAAR is diminished. Therefore, the performance of SAAR is primarily determined by a few nodes, as shown in Fig. 10.

The communication and computation overhead of SAAR and OCR are compared in Fig. 11. In SAAR, to compute the anypath routing table, SSP should collect the channel and link statistics of every node using the CCC, and broadcast the routing table to all the nodes in the network. As shown in Fig. 11(a), the communication overhead of SAAR increases as the number of CR routers increases. Since the sizes of

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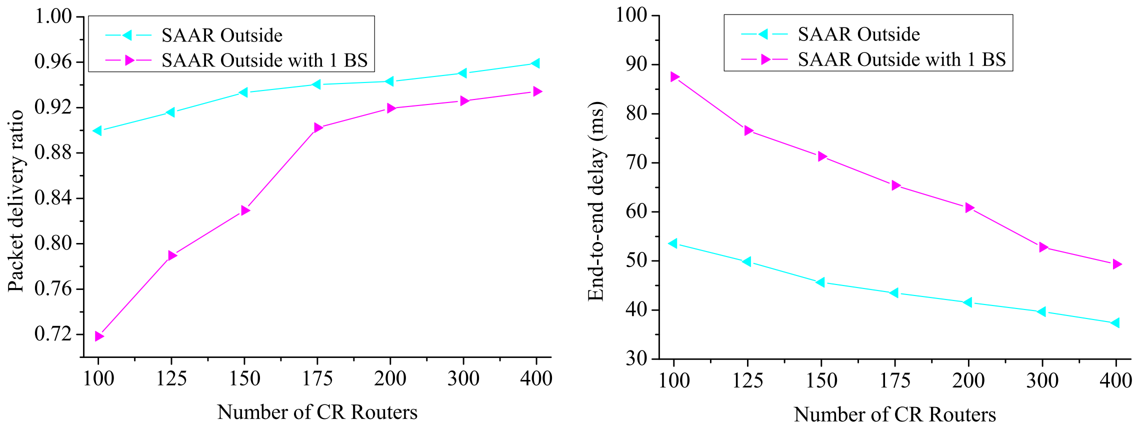
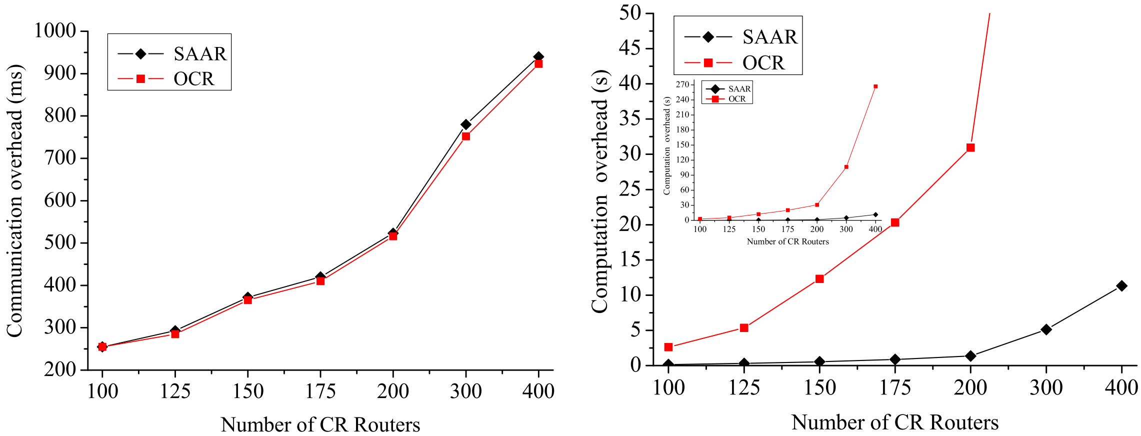


(a) (b)

Fig. 8 Performance of routing outside CCH under different CR routers densities. (a) packet delivery ratio. (b) end-to-end delay.



(a) (b)

Fig. 11 Overhead comparison. (a) communication overhead. (b) computation overhead.

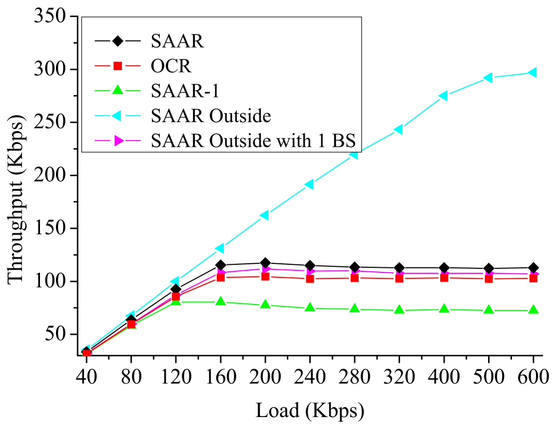


Fig. 9 Throughput analysis.

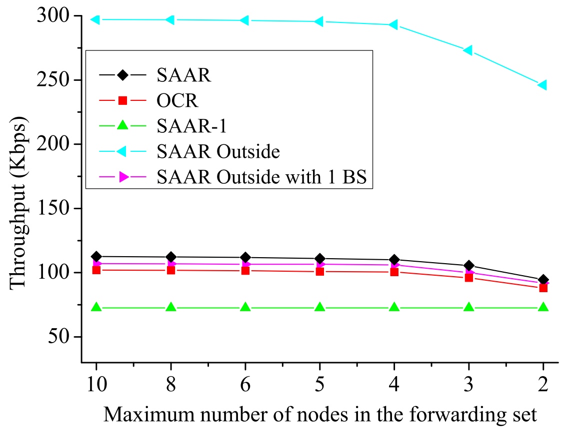


Fig. 10 Throughput under different maximum sizes of forwarding set.

the statistical information packet and the routing table packet in SAAR are almost the same as those in OCR, the communication overhead of SAAR and OCR is nearly identical. Fig. 11(b) shows that the computation overhead of both SAAR and OCR increases as the number of CR routers increases. It is also observed that the computation overhead of SAAR is reduced remarkably as compared with OCR, which makes SAAR more suitable for practical implementation. In the default setting, the computation overhead of SAAR is about 0.53s, while the overhead for OCR is 12.31s. In SAAR, the routing table needs to be recomputed only when the channel and link statistics change significantly. In [38], it is observed that channel and link statistics change very slowly in practice. Therefore, the update of the routing table in SAAR occurs infrequently, and the overall communication and computation overhead of SAAR is bearable.

7 Conclusion

To improve the performance of multi-hop CRNs and make it a robust spectrum cloud, taking cognitive capacity harvesting network as an example, we have developed a novel anypath routing mechanism SAAR. SAAR considers both the spectrum uncertainty of CRNs and the unreliable transmission characteristics of wireless medium. It could build an anypath between a source node and a set of destination nodes efficiently, where the path and gateway for each packet are determined on-the-fly. We evaluate SAAR with extensive simulations, and compare it with a multi-path routing algorithm OCR and a unicast routing algorithm SAAR-1. We demonstrate that SAAR significantly outperforms other routing algorithms in terms of packet dropping ratio, end-to-end delay, and throughput. With SAAR algorithm, CRNs can become a high performance spectrum cloud to harvest network resource and handle the spectrum uncertainty more effectively.

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Jie Wang (M'12) received his B.S. degree from Dalian University of Technology, Dalian, China, in 2003, M.S. degree from Beijing University of Aeronautics and Astronautics, Beijing, China, in 2006, and Ph.D degree from Dalian University of Technology, Dalian, China, in 2011, all in Electronic Engineering. From Jan. 2013 to Jan. 2014, he is a visiting researcher at University of Florida.

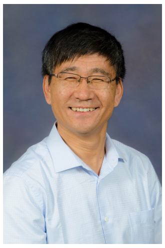
He is currently an associate professor at Dalian University of Technology. His research interests include wireless localization and tracking, wireless sensor networks, and cognitive radio networks.

Hao Yue (M'15) received his B.S. degree in Telecommunication Engineering from Xidian University, Xi'an, China, in 2009, and Ph.D. degree in Electrical and Computer Engineering from University of Florida, Gainesville, FL, USA, in 2015.

He is now an Assistant Processor with the Department of Computer Science, San Francisco State University, San Francisco, CA, USA. His research interests include cyber-physical systems, cybersecurity, wireless networking, and mobile computing.

Long Hai (S'13) received his B.S. degree in Electronic Engineering from Shenyang Jianzhu University in 2008, M.S. degree in Electrical and Computer Engineering from Northeastern University in 2010, and Ph.D degree from Dalian University of Technology, Dalian, China, in 2016.

He is currently a postdoctor at Shenzhen University. His research interests include network coding in lossy networks and routing algorithm design in ad-hoc networks.



Yuguang "Michael" Fang (F'08) received a BS/MS degree from Qufu Normal University, Shandong, China in 1987, a Ph.D degree from Case Western Reserve University in 1994 and a Ph.D. degree from Boston University in 1997. He joined the Department of Electrical and Computer Engineering at University of Florida in 2000 and has been a full professor since 2005. He holds a University of Florida Research Foundation (UFRF) Professorship from 2006 to 2009, a Changjiang Scholar Chair Professorship with Xidian University, China, from 2008 to 2011, and a Guest Chair Professorship with Tsinghua University, China, from 2009 to 2012.

Dr. Fang received the US National Science Foundation Career Award in 2001 and the Office of Naval Research Young Investigator Award in 2002, and is the recipient of the Best Paper Award from IEEE ICNP (2006). He has also received a 2010-2011 UF Doctoral Dissertation Advisor/Mentoring Award, 2011 Florida Blue Key/UF Homecoming Distinguished Faculty Award, and the 2009 UF College of Engineering Faculty Mentoring Award. He is the Editor-in-Chief of IEEE Transactions on Vehicular Technology, was the Editor-in-Chief of IEEE Wireless Communications (2009-2012) and serves/served on several editorial boards of journals including IEEE Transactions on Mobile Computing (2003-2008, 2011-present), IEEE Transactions on Communications (2000-2011), and IEEE Transactions on Wireless Communications (2002-2009). He has been actively participating in conference organizations such as serving as the Technical Program Co-Chair for IEEE INOFOCOM2014 and the Technical Program Vice-Chair for IEEE INFOCOM'2005. He is a fellow of the IEEE.