Spectrum-Aware Beaconless Geographical Routing Protocol for Mobile Cognitive Radio Networks

Junseok Kim and Marwan Krunz
Dept. of Electrical and Computer Engineering, University of Arizona
Email: {junseok, krunz}@ece.arizona.edu

***Abstract*—A key challenge in routing in cognitive radio networks (CRNs) is how to adaptively and efficiently select a route and assign resources along that route according to the surrounding environment. In this work, we propose a distributed routing protocol for CRNs, in which path selection and resource allocation (e.g. spectrum, transmission power, and transmission rate) are determined by receivers. Because this process is done on a per-packet and per-hop basis, the proposed protocol can efficiently adapt to spectrum dynamics and node mobility. In addition, spectrum efficiency is increased through dynamic spectrum allocation and transmission power control. Simulation results show that delivery ratio and throughput are dramatically improved with our routing protocol.**

I. Introduction

Cognitive radio (CR) is a promising concept to resolve spectrum scarcity and meet a growing demand for wireless services. In contrast to classic spectrum assignment, CRs operate on unused licensed portions of spectrum without interfering with licensed primary radios (PRs). Routing in multi-hop CRNs faces unique challenges, compared with conventional mobile ad hoc networks (MANETs). In MANETs, the routing protocol is expected to adapt to node mobility and channel dynamics. In CRNs, in addition to that, PR activities and spectrum sharing among CRs necessitate modifying routes more quickly, according to spectrum availability.

Several routing protocols have been proposed for CRNs [2]. Most of these protocols establish the route during the route discovery phase and try to change it when messages are dropped and/or new PR activity is detected. Such an approach suffers a significant performance degradation when spectrum availability and/or node locations change faster than the rate of route update (e.g., as in the case of vehicular ad hoc networks).

In this paper, we propose a novel routing protocol for mobile CRNs, called Spectrum-Aware BEaconless geographical routing (SABE). We bring the concept of beaconless geographical routing to CRNs for the first time. The main idea in SABE is that the routing decision as well as the resource allocation strategy are made by *receivers* on a per-packet and per-hop basis. A source or an intermediate CR broadcasts a *forward request* packet, and includes in it its available resources. Receivers calculate a link weight, considering the available spectrum at the sender and receiver, as well as the distance to the final destination. Then, a timer to reply to the request is set depending on the link weight. The receiver with the highest link weight replies first, establishing itself as the relay node.

Because the route selection is done on a per-packet and per-hop basis, SABE can efficiently adapt to spectrum dynamics and node mobility. Another feature of SABE is that the spectrum, transmission power, and transmission rate are jointly selected so that more CRs in the same vicinity can share the spectrum. In SABE, noncontiguous spectrum holes are used opportunistically with one transceiver based on the non-contiguous orthogonal frequency division multiplexing (NC-OFDM) technique, which is feasible with commercial off-the-shelf radios [4].

The rest of this paper is organized as follows. Section II presents related works. We present our routing protocol in Section III and simulation results in Section IV. Section V concludes the paper.

II. Related Works

Many routing protocols for CRNs are extensions of the ad-hoc on-demand distance vector (AODV) protocol. They use different metrics for path selection. AODV establishes an end-to-end route by broadcasting a route request (RREQ) packet over the network, and it tries to modify the route when messages are dropped [6]. In [3], the routing metric depends on delay factors, such as the channel switching delay and medium access delay. The RREQ packet conveys the list of idle channels at each intermediate CR. The destination selects the path and the channel for each link such that the total delay is minimized. In [12], the routing metric depends on link quality as well as delay. In [1], the *PR activity degree*, which represents how many channels are occupied by PRs, is piggybacked on the RREQ packet to minimize interference to PRs.

Geographical routing protocols for CRNs are presented in [11][5]. In geographical routing, each node knows its location, e.g., using a GPS device [6]. The greedy perimeter stateless routing (GPSR) is the best known geographical routing protocol for MANETs. In GPSR, a *forwarder* (a source or an intermediate node) forwards a message to the neighbor who is closest to the destination and is within the forwarding area. The forwarding area is generally defined as the intersection of two circles: the circle of the forwarder, defined by its maximum transmission range, and the circle centered at the destination whose radius equals the distance between the forwarder and the destination. The gray area in Figure 1 depicts the forwarding area of node u when the destination is node t. We refer to any neighbor in the forwarding area as a *candidate*. GPSR can lead to a *dead end*, where no candidate can be found in the forwarding area of a node. In this case, the message is detoured around the dead end until reaching a node that has one or more candidates.

In [11], CRs are assumed to know the locations of PRs. If there is no PR activity, the candidate that is closest to the destination is selected as the next relay node. When PR activity is detected, the candidate that is farthest from the destination is selected and the transmission power is adjusted so as not to disrupt PR transmissions. CRs operate over a single channel, so opportunistic spectrum allocation is not addressed in that paper. The spectrum aware routing for CRNs (SEARCH) [5] forwards RREQ packets similar to GPSR over each channel. The destination combines the routes and assigns channels for each link such that the end-to-end delay is minimized. When a dead end is encountered, SEARCH forwards a message to the closest node to the destination outside the forwarding area, until a node with candidates is encountered. As network size increases, SEARCH incurs large latency and message overhead for route discovery. Moreover, it is well-known that forwarding a message to nodes outside the forwarding area often leads to a routing loop [8]. Other works related to routing in CRNs are discussed in [2].

In GPSR, every node periodically broadcasts a beacon packet to update its location. Intuitively, the rate at which beacons are generated should be high enough to maintain the local topology up-to-date. If not, the packet drop rate can increase drastically. Beaconless geographical routing (BLR) does not require nodes to transmit beacons. The routing decision is made by the receiver [9]. In such protocols, a forwarder "broadcasts" a *request to send* (RTS), and candidates set their delay timer for the reply depending on their distance to the destination. The closer a node is to the destination, the shorter is its delay, allowing that node to be the first to reply. A drawback of this scheme is that a planar graph, used to avoid a dead end, cannot be constructed immediately, because a forwarder does not know the locations of its neighbors. To resolve this problem, the authors in [8] presented the beaconless forwarder planarization (BFP) technique. In BFP, when there is no candidate, the neighbor closest to the forwarder responds to the request first and other neighbors that overhear the response check whether that neighbor satisfies the planarity condition (i.e., no edge crosses any other edge). If this condition is not satisfied, one or more neighbors send a *protest packet* to cancel the previous response.

III. Spectrum-Aware Beaconless Geographical Routing

A. Problem Setup

We consider an ad hoc CRN that coexists geographically with PRs (e.g., TV receivers or wireless microphones). As illustrated in Figure 2, we place OFDM subcarriers over TV channels from 21 to 50. Hereafter, we refer to an OFDM subcarrier as a subcarrier, for brevity. Subcarrier spacing is 0.2 MHz, so that the symbol duration, with the 1/4 cyclic prefix, is $(1/(0.2 \times 10^6) \times 1/4)$ = 6.25 us, which is similar to that of WiMAX [7]. Subcarriers constitute a data or control subchannel. Three data subchannels are placed in a TV channel. More data subchannels can be placed, but there is a tradeoff between fine-grain spectrum allocation and packet header overhead. One control subchannel is placed between two consecutive TV channels. In [4], the authors showed that a few subcarriers can be placed between two consecutive TV channels so that the TV reception is not disturbed by CR nodes. The CR sender and receiver exchange control packets over the control channel, which consists of 31 non-contiguous control subchannels. The sender subsequently transmits a data packet over the data channel, which consists of multiple non-contiguous data subchannels, using one transceiver by suppressing subcarriers currently used by PRs and other CRs. A pilot subcarrier is placed in the middle of each control or data channel to aid the receiver with synchronization and channel estimation. Guard subcarriers are used to suppress the multi-access interference (MAI) from PRs and other CRs. As shown in Figure 2, there is no guard subcarrier between data subchannels 1 and 2, but to protect an ongoing CR transmission, three guard subcarriers should be placed between data subchannels 2 and 3.

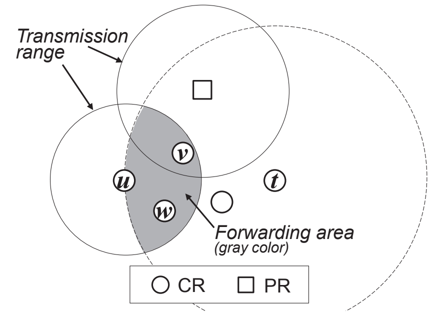

Fig. 1. Example that illustrates beaconless geographical routing.

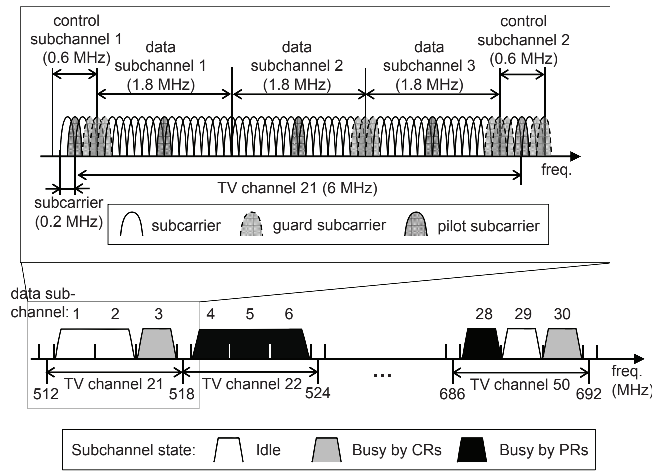

Fig. 2. Data and control subchannels in the TV whitespace.

Consider a CR node u that is about to transmit a data packet to CR node v using data subchannels of equal bandwidth W. The maximum channel capacity between CRs u and v over the ith data subchannel $C_{uv}^{(i)}$ is given by Shannon's equation:

$$C_{uv}^{(i)} = W \log_2 \left(1 + \frac{P_R^{(i)}}{N_0 + P_I^{(i)}}\right) \tag{1}$$

where N_0, $P_R^{(i)}$, and $P_I^{(i)}$ are the powers of the Gaussian noise, the desired signal, and the measured interference at receiver v, respectively. We assume that CRs periodically sense the spectrum and learn what portions of it are used by PRs and other CRs. It is also assumed that CRs can distinguish a PR signal from noise using a cyclostationary or a waveform-based sensing technique. Let Ψ_{uv} be a set of unused subchannels in the vicinity of link (u, v). For a given rate demand D (in bits/second), we define the weight of link (u, v) as follows:

$$l_{uv} = (d_{ut} - d_{vt}) \cdot \min \left\{ \sum_{i \in \Psi_{uv}} C_{uv}^{(i)}, D \right\} \tag{2}$$

where d_{vt} denotes the Euclidean distance between CR node v and the CR destination t. The link weight represents how much further a message can be forwarded towards the destination per time unit over the given link. In this subsection, we rely on Shannon's formula and ignore frequency overhead such as pilot subcarriers and guard subcarriers. In the next subsection, we show how to compute the link weight in a more realistic way.

B. Protocol Description

CRs periodically scan the available spectrum and estimate the allowable transmission power $\overline{P}_T^{(j)}$ for each data subchannel j. A source or an intermediate node (say CR u) broadcasts a *request-to-forward* (RTF) packet using the maximum transmission power P_{max} over the control channel. It includes in this RTF packet D, $\overline{P}_T^{(j)}$, the set of available data subchannels, and the location of destination and itself.

Upon receiving an RTF packet, a neighbor (say CR v) first checks whether it is a candidate. If CR v is a candidate, it measures $P_R^{(i)}$ and derives the channel gain h for each control subchannel i, as follows:

$$h_{uv}^{(i)} = P_R^{(i)} / P_{max}. \tag{3}$$

For all $j \in \Psi_{uv}$, $P_R^{(j)}$ is estimated from as follows [10]:

$$P_R^{(j)} = h_{uv}^{(i)} \cdot (f^{(i)} / f^{(j)})^2 \cdot \overline{P}_T^{(j)} \tag{4}$$

where $f^{(j)}$ ($f^{(i)}$) is the central frequency of the jth (ith) data (control) subchannel. A control subchannel i that is closest in frequency to data subchannel j can be used, or multiple control subchannels can be used to average out.

Let $\mu^{(j)} = P_R^{(j)} / (N_0 + P_I^{(j)})$ be the SINR at node v over data subchannel j. Let $\overline{\mu}^{(j)}$ be the SINR threshold that maps to the highest possible transmission rate in the rate-SINR relationship. The minimum transmission power at CR u over data subchannel j that meets the SINR threshold at CR v is:

$$P_{min}^{(j)} = \overline{\mu}^{(j)} \cdot \frac{1}{h_{uv}^{(j)}}. \tag{5}$$

If $P_{min}^{(j)} > \overline{P}_T^{(j)}$ due to interference from other CRs, data subchannel j is excluded from Ψ_{uv}.

Finally, the link weight l between CR u and v is taken as:

$$l_{uv} = (d_{ut} - d_{vt}) \cdot \min \left\{ \sum_{j \in \Psi_{uv}} \rho^{(j)}, D \right\} \tag{6}$$

where $\rho^{(j)} \leq W \log_2 \left(1 + \mu^{(j)}\right)$ is the transmission rate over data subchannel j, obtained from the rate-SINR table. If a link has enough idle data subchannels to meet the rate demand, the set of best data subchannels $\overline{\Psi}_{uv} \subset \Psi_{uv}$ should be selected. We later explain how to obtain $\overline{\Psi}_{uv}$.

After obtaining l_{uv}, CR v sets a delay timer δ to reply to the RTF. The value of δ is set as follows:

$$\delta = \delta_{max} \cdot \left(1 - \frac{l_{uv}}{\tau \cdot D}\right) \tag{7}$$

where δ_{max} and τ denote, respectively, the maximum allowable delay and the maximum transmission range. The value of δ_{max} is set to the minimum contention window size times the slot time. τ can be calculated a priori from the path loss formula. The higher the link weight, the smaller is the delay. If the timer expires, CR v transmits an *accept-to-forward* (ATF) packet to node u. The ATF packet conveys $\rho^{(j)}$, the transmit power $P_T^{(j)}$, and the tolerable interference power $\overline{P}_I^{(j)}$ for $j \in \overline{\Psi}_{uv}$. We later explain how to obtain $P_T^{(j)}$ and $\overline{P}_I^{(j)}$.

While waiting for an ATF packet, there are three scenarios that can happen: (1) Candidates exist and all of them satisfy D, (2) candidates exist but some of them do not satisfy D, and (3) no candidates exist. In the first case, the candidate that is closest to the destination sends its ATF first, and is thus selected as the relay node. In the second case, the candidate with the highest link weight is selected as the relay node. For example, in Figure 1, if CR v has enough available data subchannels to meet the rate demand, it sends ATF first. When the PR activity is high and/or many CR links are active around CR v, CR w in Figure 1 may be the relay node although it is not the closest neighbor to the destination. The third case occurs when a dead end is encountered. In this case, the BFP scheme, explained in Section II, is used. Because BFP does not take into account interference to PRs, we slightly modify it by excluding, from the planar graph, CRs that have no available channels.

If a candidate detects a carrier before its ATF timer expires, it cancels the timer. Because the carrier sensing range is typically larger than the transmission range, it is assumed that all candidates of a given forwarding node can sense the carrier of each other. Upon receiving the ATF packet, the forwarder u transmits a *decide-to-send* (DTS) packet. It is possible that more than one candidate have the same link weight, resulting in multiple ATF transmissions that could potentially collide at CR u. So, if a DTS packet does not arrive within a certain amount of time, the ATF packet is retransmitted after a random backoff.

The DTS packet contains $P_T^{(j)}$ for $j \in \overline{\Psi}_{uv}$. It is used to inform u's neighbors of the upcoming data transmission and spectrum allocation. After transmitting the DTS packet, CR u transmits a data packet to the relay node (say CR v) over data subchannels $j \in \overline{\Psi}_{uv}$, using $P_T^{(j)}$ and $\rho^{(j)}$. Upon receiving the DATA packet, CR v replies with an acknowledgment (ACK) packet, sent over the control channel. Note that all control packets are transmitted over the control channel using P_{max} and the lowest transmission rate. ACK can be delayed until the control channel becomes idle.

C. Concurrent Transmissions via Power Control

Suppose that CR z is (or will be) receiving a data packet from CR w. From the SINR definition, the $\overline{P}_I^{(j)}$ is defined as follows:

$$\overline{P}_I^{(j)} \leq \frac{P_R^{(j)}}{\mu^{(j)}} - N_0 \tag{8}$$

and CR z included this value in the ATF packet. When CR u overhears an ATF packet from z, it decides $\overline{P}_T^{(j)}$ not to disrupt z's reception as follows:

$$\overline{P}_T^{(j)} = P_I^{(j)} \cdot \frac{1}{h_{uz}^{(j)}} \cdot \epsilon \tag{9}$$

where $0 < \epsilon \leq 1$ is a deflation factor that scales down interference at CR z. If there are several ongoing transmissions in the vicinity, the lowest of the allowable transmission powers is used in (4). Note that SABE can improve spectrum efficiency not only through subchannel allocation, but also by using transmission power control.

D. Data Subchannel Selection

After obtaining $\rho^{(j)}, j \in \Psi_{uv}$, a candidate selects $\overline{\Psi}_{uv}$ that meets D. Hereafter, we refer to a data subchannel as a subchannel, for brevity. If only one subchannel is used in a TV channel (e.g., subchannel 29 in Figure 2), guard subcarriers should be placed at the ends of that subchannel to suppress MAI. If more than one contiguous subchannel is selected (e.g., subchannels 1 and 2), no guard subcarrier needs between those subchannels. This problem can be formulated as a variant of the Knapsack problem, which is known to be NP-hard. The $\rho^{(j)}$ is the transmission rate of subchannel j which has guard subcarriers on both side. Let β be the ratio of the number of guard subcarriers and the number of data subcarriers in a noncontiguous subchannel. Formally, the data subchannel selection problem can be stated as follows:

$$\text{minimize} \sum_{j \in \Psi_{uv}} X(j) \tag{10}$$

$$\text{s.t.} \sum_{j \in \Psi_{uv}} \left(X(j) + \sum_{k \in \Psi_{uv}} Y(j,k) \cdot \frac{\beta}{2} \right) \rho^{(j)} \geq D \tag{11}$$

where $X(j)$ is the indicator function, taking a value of 1 if subchannel j is selected, and $Y(j,k)$ is the indicator function, taking the value 1 if two contiguous subchannels j and k are selected.

We present a simple heuristic algorithm to solve this problem. Let Φ be a set of subchannel combinations. For each combination, each element has one or more contiguous available subchannels. For example, in Figure 2, $\Phi = \{(1,2), (1), (2), ..., (29)\}$ where numbers in parentheses denote subchannel indexes. A candidate sorts Φ in a decreasing order of the transmission rate. If there are elements whose transmission rates are more than D, the smallest of these elements is selected. If not, the candidate selects subchannels from the first element until the cumulative transmission rate exceeds D.

IV. Experimental Results

We used NS-3 to simulate SABE and compare its performance with GPSR. In our simulations, 46 CRs are randomly distributed over 1500 m x 1500 m square. They move according to the random way-point model with speed in the range [5, 20] m/s and 10 second pause time. Two source / destination pairs have fixed positions. Each source CR generates a 1000-byte UDP packet every 1 ms. The source CRs are placed at locations (0, 0) and (0, 1500), and the corresponding destinations are placed at (1500, 1500) and (1500, 0), so that two routes cross in the middle. We use the rate-SINR table shown in Table I.The SINR values are taken from the 802.16 standard [7]. The cumulative transmission rate of control subchannels is 4.96 Mbps. The maximum transmission power of CRs is 16 dBm. Each TV channel from 21 to 50 is used by one PR. PRs behave as an independent ON/OFF source with an activity factor α. PR activities are homogeneous. GPSR is modified to allow for adjusting the transmission power and selecting one data channel with the highest transmission rate. In GPSR, every node broadcasts a beacon packet every 1 or 2 second(s).

Figure 3 shows the end-to-end message delivery ratio as a function of node speed with $\alpha = 0.2$. It is observed that SABE losses significantly fewer messages compared with GPSR. The message delivery ratio of GPSR decreases as the node speed increases. The reason is that GPSR forwards a message using the locations of neighbors and these locations are updated through beacon packets. If the rate of beacon broadcasts is not high enough relative to node speeds, the sender can transmit a message to a node not in its transmission range anymore. In contrast, in SABE the sender does not need locations of neighbors and the route is decided by receivers with their up-to-date information.

Figure 4 illustrates the end-to-end latency as a function of α when the node speed is 15 m/s. SABE results in a lower latency than GPSR because it uses multiple non-contiguous spectrum holes and adjusts transmission powers to improve spectrum efficiency. The latency in SABE increases monotonically with α but is still much lower than that of GPSR. The latency in GPSR is constant because GPSR exploits only one spectrum hole at a time.

The spectrum efficiency of SABE is also validated by the end-to-end goodput performance, shown in Fig. 5. GPSR gives lower goodput than SABE because it can use only one contiguous spectrum hole. The goodput of GPSR decreases with the node speed, due to a higher rate of lost messages.

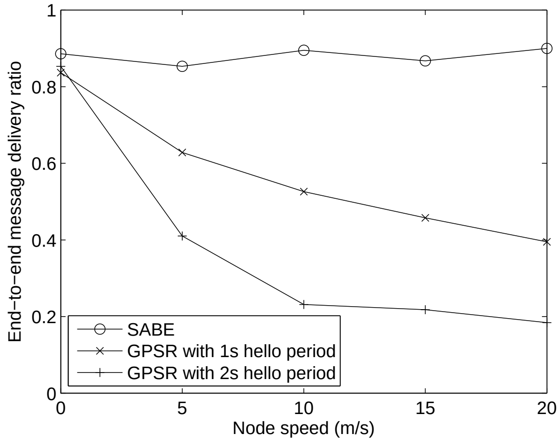

Fig. 3. Message delivery ratio vs. node speed ($\alpha = 0.2$).

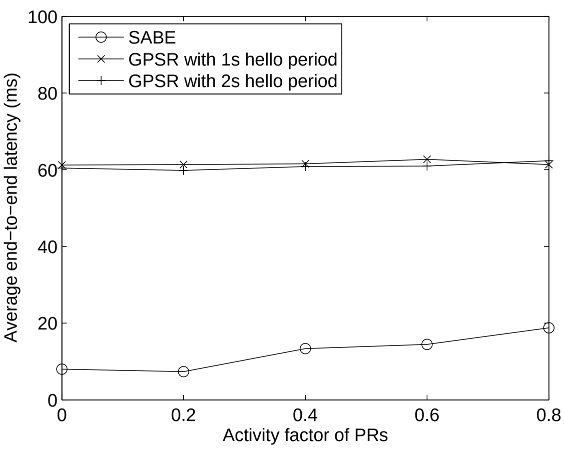

Fig. 4. Latency vs. activity factor of PRs (node speed = 15 m/s).

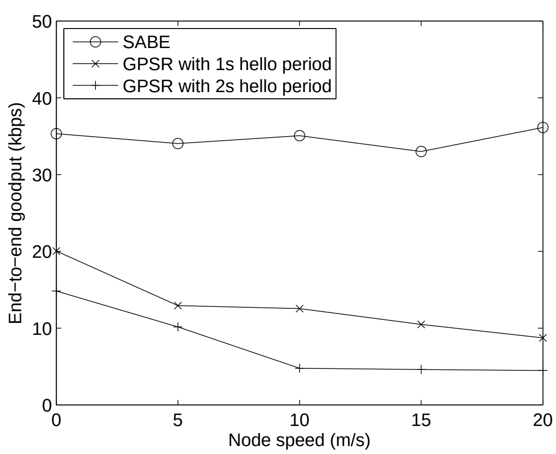

Fig. 5. Goodput vs. node speed ($\alpha = 0.2$).

TABLE I
TRANSMISSION RATE VS. SINR TABLE.

Modulation	FEC	TX rate (Mbps)	SINR (dB)
QAM64	3/4	10.0	21.0
QAM64	2/3	8.96	19.0
QAM16	3/4	6.72	15.0
QAM16	1/2	4.48	11.5
QPSK	3/4	3.36	8.5
QPSK	1/2	2.24	6.0
BPSK	1/2	1.12	3.0

V. CONCLUSION

We presented the routing protocol, SABE, which jointly selects routes, transmission powers, and transmission rates. Simulation results showed that SABE improves throughput and delivery ratio even when node locations and spectrum availabilities change frequently.

ACKNOWLEDGMENT

This research was supported in part by NSF (under grants CNS-1016943, CNS-0721935, CNS-0904681, IIP-0832238), Raytheon, and the Connection One center. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

[1] A. Abbagnale and F. Cuomo, "Gymkhana: a connectivity-based routing scheme for cognitive radio ad hoc networks," in *Proc. IEEE INFOCOM*, Mar. 15–19, 2010.

[2] M. Cesana, F. Cuomo, and E. Ekici, "Routing in cognitive radio networks: challenges and solutions," *Ad Hoc Networks*, vol. 9, no. 3, pp. 228–248, May 2011.

[3] G. Cheng, W. Liu, Y. Li, and W. Cheng, "Joint on-demand routing and spectrum assignment in cognitive radio networks," in *Proc. IEEE ICC*, May 23–27, 2010, pp. 6499–6503.

[4] K. Chowdhury and I. Akyildiz, "Ofdm-based common control channel design for cognitive radio ad hoc networks," *IEEE Trans. Mobile Comput.*, vol. 10, no. 2, pp. 228–238, Feb. 2011.

[5] K. Chowdhury and M. Felice, "Search: a routing protocol for mobile cognitive radio ad-hoc networks," *Computer Communications*, vol. 32, no. 18, pp. 1983–1997, Dec. 2009.

[6] S. Giordano, I. Stojmenovic, and L. Blazevie, "Position-based routing algorithms for ad hoc networks: a taxonomy," *Ad Hoc Wireless Networking*, pp. 103–136, 2004.

[7] *Air Interface for Broadband Wireless Access Systems*, IEEE Std. 802.16, May 2009.

[8] S. Ruhrup, H. Kalosha, A. Nayak, and I. Stojmenovic, "Message-efficient beaconless georouting with guaranteed delivery in wireless sensor," *IEEE/ACM Trans. Netw.*, vol. 18, no. 1, pp. 95–108, Feb. 2010.

[9] J. Sanchez, P. Ruiz, and R. Marin-Perez, "Beacon-less geographic routing made practical: challenges, design guidelines, and protocols," *IEEE Commun. Mag.*, vol. 47, no. 8, pp. 85–91, Aug. 2009.

[10] F. Wang and M. Krunz, "Multi-channel spectrum-agile mac protocol with adaptive load control," in *Proc. IEEE WOWMOM*, Jun. 15–19, 2009.

[11] M. Xie, W. Zhang, and K. Wong, "A geometric approach to improve spectrum efficiency for cognitive relay networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, pp. 268–281, Jan. 2010.

[12] G. Zhu, I. Akyildiz, and G. Kuo, "Stod-rp: a spectrum-tree based on-demand routing protocol for multi-hop cognitive radio networks," in *Proc. IEEE GLOBECOM*, Nov. 30–Dec. 4 2008.