Journal of Zhejiang University-SCIENCE C (Computers & Electronics)
ISSN 1869-1951 (Print); ISSN 1869-196X (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Mobility assisted spectrum aware routing protocol for cognitive radio ad hoc networks*

Omid ABEDI, Reza BERANGI
(*Department of Computer Engineering, Iran University of Science and Technology, Tehran, Iran*)
E-mail: {oabedi, rberangi}@iust.ac.ir

Received Nov. 23, 2012; Revision accepted Jan. 18, 2013; Crosschecked Oct. 15, 2013

Abstract: We propose a mobility assisted spectrum aware routing (MASAR) protocol for cognitive radio ad hoc networks (CRAHNs), providing robustness to primary user activity and node mobility. This protocol allows nodes to collect spectrum information during a spectrum management interval followed by a transmission period. Cognitive users discover next hops based on the collected spectrum and mobility information. Using a beaconless mechanism, nodes obtain the mobility information and spectrum status of their neighbors. A geographical routing scheme is adopted to avoid performance degradation specially due to the mobility of the nodes and the activity of the primary users. Our scheme uses two approaches to find either short or stable routes. Since mobility metrics have a significant role in the selection of the next hop, both approaches use a reactive mobility update process assisted by mobility prediction to avoid location errors. MASAR protocol performance is investigated through simulations of different scenarios and compared with that of the most similar protocol, CAODV. The results indicate that MASAR can achieve significant reduction in control overhead as well as improved packet delivery in highly mobile networks.

Key words: Cognitive radio, Ad hoc routing, Geographical routing, Mobility prediction, Spectrum awareness
doi:10.1631/jzus.C1200334 **Document code:** A **CLC number:** TP393

1 Introduction

Channel availability and primary user (PU) activity are main concerns as cognitive radio networks (CRNs) circulate around. Nodes in CRN have different capabilities, which distinguishes them from nodes in traditional networks; they search the spectrum to detect holes (spectrum sensing), decide on different holes to select the best idle channel (spectrum decision), compete to obtain a channel (spectrum access), and finally retain the obtained channel (spectrum mobility) (Akyildiz *et al.*, 2006). On the other hand, the main concerns in mobile ad hoc networks (MANETs) is the mobility prediction to improve route stability.

To address both requirements, cognitive radio ad hoc network (CRAHN) nodes must have mobility-aware capabilities besides spectrum awareness in order to increase route stability. Therefore, in this paper we combine two concepts in CRAHN, spectrum awareness and node mobility. The first comes from CRN while the second is inherited from MANET.

Recent works on CRN routing use spectrum information for joint channel and next hop selection while mobility parameters conform in traditional ad hoc networks. We categorize these works as follows:

1. Spectrum awareness routing

Cesana *et al.* (2011) reviewed the routing protocols for CRN and deduced that challenges such as spectrum-awareness, quality of service (QoS), and route maintenance need more attention in future routing protocols. Furthermore, node mobility is not well addressed and it should be considered in the new routing schemes.

A low cost distributed routing mechanism

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* Project supported by Iran Telecommunication Research Center (ITRC)

between nodes considering resource constraints is needed to manage routing in CRAHN (Akyildiz *et al.*, 2009). Hence, more complex centralized routing methods (Xin *et al.*, 2005; Alicherry *et al.*, 2006; Wang and Zheng, 2006) are too costly for these networks.

Due to resource and hardware constraints, it is more desirable to construct a network model with one transceiver to perform both control and data management between different frequency bands. There are a lot of works deploying an additional transceiver for monitoring a control channel to simplify spectrum management and channel scheduling; these designs are not cost effective for networks with hardware constraints (Draves *et al.*, 2004; Kyasanur and Vaidya, 2005; Lin and Rasool, 2007; Cheng *et al.*, 2007a; 2007b). Using an extra transceiver helps nodes easily synchronize on a data channel and also switch to a new channel when a primary user appears. An alternative routing protocol which operates in a distributed manner and negotiates with all nodes during a coordination process, is proposed in this paper to meet cost efficiency requirements and constraints.

Some researchers exploited location information to find the routes geographically, such as SEARCH (Chowdhury and Felice, 2009) and CRP (Chowdhury and Akyildiz, 2011a). Their protocols use greedy forwarding on each channel to find the next hop while avoiding PU's region. They proposed that adjacent nodes should be coordinated using underlying technologies (So and Vaidya, 2004). In SEARCH, the destination node combines discovered routes and selects the best routes while assigning channels to minimize end-to-end delay. Chowdhury *et al.* used destination mobility to reduce the mobility effects on routing under low speed and small network size without any solution for the mobility of intermediate nodes. In MASAR considering the mobility metrics of intermediate nodes helps the route to adapt to network mobility. In addition, loop may occur when SEARCH tries to remove dead-end while MASAR can avoid loop formation. SEARCH and CRP also have high routing overhead due to frequent location and spectrum status updating. In our work, we add a coordination mechanism to ensure the finding of the next hop while managing the control overhead by restricting forwarding nodes. Despite simple mobility awareness in SEARCH, strict mobility consideration in MASAR introduces a neighbor prioritization mechanism to assign different priorities to the intermediate nodes.

Angela *et al.* (2012) added cognitive radio capabilities to ad hoc on-demand distance vector routing and deployed it as a routing method, called CAODV, for CRAHNs. CAODV uses a single transceiver and, like SEARCH, assumes underlying channel coordination mechanism (So and Vaidya, 2004). This is different from MASAR, which itself coordinates adjacent nodes on the selected channel. CAODV sends control packets based on AODV to all neighbors without any restriction, while MASAR uses geographical forwarding and node mobility limitation to select next hop candidates and deploy an agile mobility update process.

2. Mobility metrics applications

Mobility metrics (speed, direction, and location), which are important features of MANET, can be used to improve the network performance. Topology control, clustering, routing, and medium access control are some examples of using mobility metrics to improve the performance.

Researchers in the field of ad hoc networks are very interested in using mobility metrics to predict movement of nodes in the face of topology changes. The most popular mobility prediction method was proposed by Su *et al.* (2001) who let nodes estimate the link expiration times along routes using information obtained from the Global Positioning System (GPS). The main drawback of this work is its weakness in coping with sudden changes in the movement, which results in unpredicted movement patterns and broken routes.

Alsaqour *et al.* (2012) investigated the effect of network parameters such as the updating interval, node speed, transmission range, network density, and network size on the performance of a geographical routing protocol, Greedy Perimeter Stateless Routing (GPSR). Since this protocol uses location information to find routes, the accuracy of this information has high effect on the routing performance. Thus, they suggested a new mobility prediction scheme based on the mobility metrics.

Ni *et al.* (2011) used mobility prediction for clustering. They predicted the mobility metrics (speed and direction) using the power of received signals and Doppler shifts to estimate the life time of cluster connections. In their strategy, node A receives two packets from node B at time t_1 and t_2, and the received power, Doppler shift, and law of cosines are used to estimate the movement patterns of node B at time t_3 ($t_1 < t_2 < t_3$).

Most of the proposed mobility prediction schemes suppose that after the prediction process, nodes have simple and constant movement without any changes. To achieve this supposition, mobility prediction schemes use small epochs or updating intervals, which increases the overhead (Wang and Chang, 2005; Taleb *et al.*, 2007). In our proposed scheme, a reactive mobility update process helps avoid sudden and unpredicted changes in node movements. We use mobility prediction to determine when the mobility update is required.

We define a timing system to support periodic spectrum management besides transmission slot. Our spectrum-aware routing scheme uses spectrum information to inform available channels of its next hops. The proposed scheme coordinates two adjacent neighbors on a common free channel by a restricted geographical handshaking; the requesting node sends a route request (RREQ) packet on the control channel and waits to receive at least one response. If after the expiration of its waiting time it cannot find any neighbor on its free channels, it will be checked as a dead-end node. To select the best forwarding neighbor, MASAR prioritizes neighbors using their mobility metrics. The mobility information is obtained in the coordination process and updated in a reactive location update process. MASAR predicts the exact time between two location update processes based on the occurrence of an unpredicted mobility event (e.g., changes in the direction or speed). Two proposed approaches help select either the shortest route in the high PU activity environments or the most stable route in the low PU activity environments.

2 Preliminaries and requirements

2.1 Network model

We consider N_{cu} cognitive users accessing opportunistically to N_{ch} licensed channels in the absence of primary users. A dedicated control channel is shared between cognitive users to transmit their control packets. Both primary and secondary users have channel switching capabilities and they can switch across different channels when needed. Cognitive users are unable to transmit or receive at the same time because they are equipped with a single half-duplex transceiver. We also assume that all cognitive users have similar transmission power and the same is true for the primary users. Two different nodes can communicate with each other if they are located within the same transmission range. Since there is no central coordinator in the network, two adjacent nodes should employ a channel coordination mechanism to set a free channel for data transmission. We assume that each cognitive user knows its location using GPS or location based services and that, like most geographical routing protocols, a source node knows the location of its corresponding destination node (Mauve *et al.*, 2001).

2.2 Timing structure

MASAR divides time into fixed intervals consisting of spectrum management τ_{s} and transmission slots τ_{d} (Fig. 1). Due to the requirement of spectrum information in CRN, spectrum sensing is considered in the spectrum management slot in the periodic manner (Lee and Akyildiz, 2008). Like other spectrum-aware routing protocols (Chowdhury and Felice, 2009; Chowdhury and Akyildiz, 2011a; Felicea *et al.*, 2011; Angela *et al.*, 2012), we assume that underlying technologies manage spectrum sensing in a perfect and optimal manner (Lee and Akyildiz, 2008) and prepare spectrum information for the network protocol. Thus, spectrum awareness can be performed using sensed information from the lower layer, and MSAR just uses this information to construct or update the free channels list (FCHL); hence, it is not responsible for managing spectrum sensing. In the transmission slot, CUs route a path or transmit data.

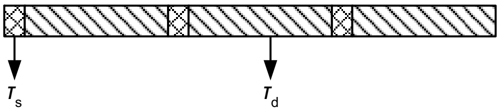

Fig. 1 The timing system of cognitive users

2.3 Common control channel

It is assumed that MASAR uses a common control channel (CCC) for exchanging control information. Such a CCC can be rented from a spectrum license holder or opportunistically obtained from relatively secure spectrum gaps, such as guard bands separating the licensed spectrum as offered by Chowdhury and Akyildiz (2011b). This channel acts like a rendezvous channel for idle nodes to participate in a route. This helps a requesting node easily locate the next hop candidates.

2.4 Primary users activity

In our network model, the primary users operate in the On/Off periods independently; their active (On) and passive (Off) periods are assumed to have an exponential distribution with the average times T_{On} and T_{Off}, respectively (Fig. 2). We also assume that the primary users have the same effects on different channels.

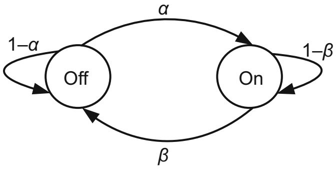

Fig. 2 Primary user activity

Due to the On/Off behavior of primary users, cognitive users are heterogeneous with respect to channel availability. A primary user selects one of N_{ch} licensed channels and occupies that channel by the probability of P_{On}; subsequently, it vacates this channel and goes to the Off (idle) state by a probability of P_{Off}. The arrival and departure rates of each primary user are exponentially distributed with the rates α and β, respectively ($P_{\mathrm{Off}} = \beta/(\alpha+\beta)$ and $P_{\mathrm{On}} = \alpha/(\alpha+\beta)$).

2.5 Mobility model description

A mobility model describes the movement patterns of nodes over the time. Three main mobility parameters of nodes (speed, direction, and location) are determined based on the mobility model. Random way point (RWP) is the most popular random mobility model used in MANET (Bai and Helmy, 2004). Despite vast deployment of RWP, sharp and sudden changes in the mobility parameters make it unusable for realistic environments. Therefore, we have sought a mobility model to offer a more realistic mobility aware routing protocol, and thus the smooth random mobility (SRM) model is deployed (Bettstetter, 2001).

In this model, speed and direction are two important parameters as changing them leads to new mobility patterns. In the SRM model, all nodes move in an independent manner while mobility patterns of any individual node has temporal dependency. Due to the smooth mobility property, the SRM model divides the total time into the time epochs as Δt. At each Δt the variation of speed is limited as follows:

$$v(t) = v(t-\Delta t) + \alpha(t)\Delta t, \tag{1}$$

while $\alpha(t)$ is the moving acceleration.

Similarly, the difference of the current direction with the direction in previous Δt can be expressed as

$$\phi(t) = \phi(t-\Delta t) + \Delta\phi(t), \tag{2}$$

where $\Delta\phi(t)$ is the maximum allowed variation of direction in each epoch.

Based on SRM, a node moves with a constant speed v until a speed change event occurs with a probability p_v. The time between two speed change events is chosen from an exponential distribution with $\lambda_v = p_v/\Delta t$ and thus, the mean time between two speed change events is $\mu_v = \Delta t/p_v$. Higher p_v means nodes endure more changes in their speed. Furthermore, a node moves in a straight line until a direction change event occurs with a probability p_ϕ. The time between two direction changes follows an exponential distribution with $\lambda_\phi = p_\phi/\Delta t$ and thus, $\mu_\phi = \Delta t/p_\phi$ is the mean time between two direction change events. Higher p_ϕ results in a less stable mobility model in the case of direction changes.

3 MASAR protocol overview

Nodes in MASAR use two types of channels, receiving channel (RCH) and sending channel (SCH). RCH is a channel whose nodes are in agreement with previous hops, while SCH is a channel which connects the node with its next hop candidates. A node uses its RCH to receive packets and SCH to transmit packets. In addition, a node maintains an FCHL to support its link fault tolerance.

3.1 Neighbor coordination

The first step in the protocol is the neighbor coordination process. Like other contention based protocols (So and Vaidya, 2004; Madani *et al.*, 2010;

Kim and Krunz, 2011), in MASAR a node sends request while receiving nodes compete to respond to it based on their back-off timers. After this step, the requesting node finds its next hop candidates, RCH and SCH. The process starts by sending an RREQ and concludes by receiving the acknowledgement response.

The node broadcasts RREQ to its neighbors on CCC. The idle neighbors, listening to CCC and located in the forwarding area (Definition. 1), participate in a competition to accept this request. Thus, they initiate a back-off timer ($T_{\text{back-off}}$) based on their mobility parameters. $T_{\text{back-off}}$ allows the forwarding neighbors to get a priority to be selected as the next hop. When a node wins the competition by accepting the request, all the other forwarding neighbors in the winner's transmission range lose the competition and cancel their waiting time.

Definition 1 Node y is located in the forwarding area of node x toward destination node d if distance(y, d) <distance(x, d).

A node which has at least one free channel in common with the requesting node and is located in its forwarding area is known as the forwarding neighbor of the requesting node. A requesting node attaches its mobility parameters (speed, direction, and position), destination node position, and its channel status (RCH and FCHL) to the RREQ (Fig. 3).

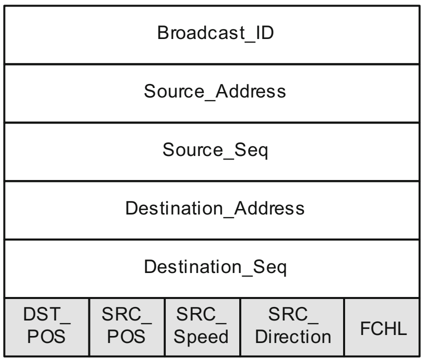

Fig. 3 Modified route request (RREQ) packet

The transmission and reception processes are as follows:

1. Sender operation: A sender can be either a source node which needs a route or a winner forwarding neighbor which is selected as the next hop candidate. After preparing necessary information, this node broadcasts RREQ on CCC and starts a waiting time. The waiting time here is referred to as the acknowledgement time (T_{ACK}) and must be adequate to allow all forwarding neighbors to participate in the competition. If the node does not receive any acceptance during this waiting time, it will be known as a dead-end node (without any forwarding connection). The requesting node which is engaged in the previous communication, has a deterministic SCH and cannot change it. Hence, regardless of the other free channels, SCH should be selected as the only free channel from the FCHL. Otherwise, for nodes without an SCH, any free channel from the FCHL can be selected as an SCH. Fig. 4 shows the sender operation in the route setup process.

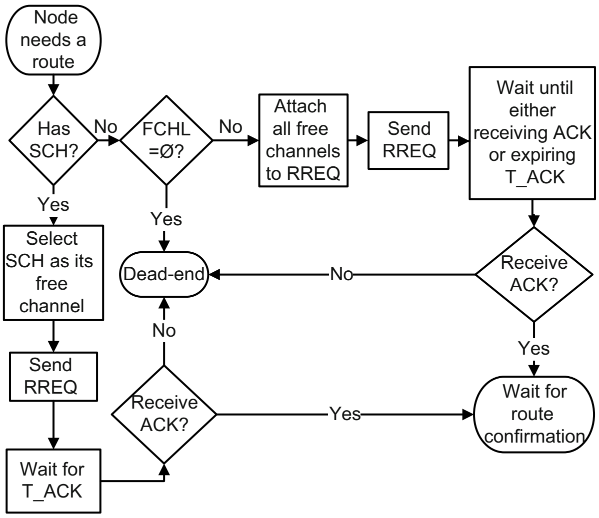

Fig. 4 The sender operation flowchart

2. Receiver operation: In MASAR each node has such states as 'idle', 'waiting for acknowledgement', 'back off', and 'waiting for route confirmation'. When an idle forwarding neighbor receives RREQ, it starts a back-off timer based on the mobility parameters. If during the waiting time ($T_{\text{back-off}}$) it does not receive an acceptance from the other waiting nodes, it wins the competition by forwarding the received request, and thus it is selected as a next hop candidate. Otherwise, it loses the competition by receiving an RREQ forwarded from the other competitors. Fig. 5 shows the operation of receiving nodes based on the current state.

Note that MASAR does not define a new packet for acknowledgement. A node uses the received RREQ forwarded from its forwarding neighbors as acknowledgement.

Fig. 6 describes the coordination process with three different scenarios in them. Node M broadcasts its request on CCC, and four forwarding nodes (A, B, C, and D) are competing to be selected as its next hop candidate.

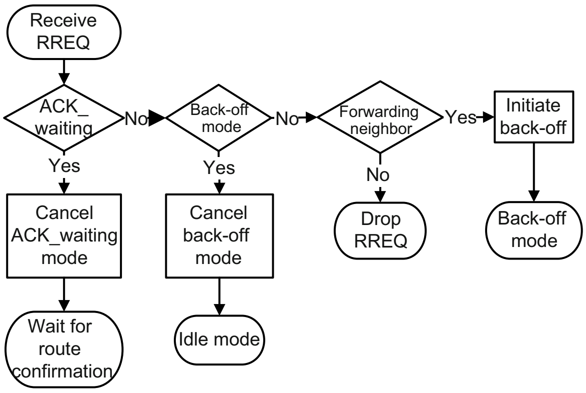

Fig. 5 The receiver operation flowchart

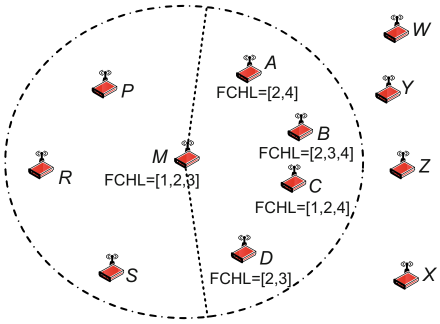

Fig. 6 An example of the coordination process

In the first scenario, the back-off times of forwarding neighbors satisfy

$$T^{C}_{\text{back-off}} < T^{D}_{\text{back-off}} < T^{A}_{\text{back-off}} < T^{B}_{\text{back-off}}.$$

Node C is the first forwarding neighbor with an expired timer. It selects channel 1 as its RCH and forwards RREQ. Three types of nodes receive the forwarded request and perform the corresponding action:

1. Node M cancels its timer, adds node C to its next hop candidates, and goes to the 'waiting for route confirmation' state.

2. Other competitors (A, B, and D) lose the competition and go to the idle state.

3. Those nodes that have heard this request for the first time (nodes X, Y, Z) start their back-off time to be selected as the next hop candidate of node C and go to the back-off state.

In the second scenario, we change the back-off times as

$$T^{A}_{\text{back-off}} < T^{C}_{\text{back-off}} < T^{D}_{\text{back-off}} < T^{B}_{\text{back-off}}.$$

Node A as the first winner selects channel 2 and forwards RREQ. Node M does the same things as the previous scenario but there is a difference here about the competitors; nodes B and C are the competitors which cancel their timers by hearing the request. Since node D is out of the transmission range of node A, it cannot hear the forwarded request and thus continues its waiting time. After expiring its timer, node D is the second winner that forwards RREQ by selecting channel 2 as its RCH. When node M hears this request, it adds node D as the second next hop candidate to its list.

For the third scenario, every thing is the same as in the previous scenario except that node D selects channel 3 as its RCH. In this case, node M has two next hop candidates with different channels. The main advantage of the third scenario over the second scenario appears in the dead-end solution.

If node M does not hear any request acknowledgement (forwarded RREQ) due to not having a forwarding neighbor, it will be known as a dead-end node. Otherwise, receiving at least one acknowledgement ensures that the requesting node can participate in the route, and thus it should wait for the route confirmation to receive the final confirmation from the destination node.

3.2 Neighbor prioritization

To restrict the routing overhead while covering a large spectrum opportunity, MASAR assigns different priorities to the forwarding neighbors. Forwarding neighbors start competition by initiating their back-off timers. The first neighbor whose timer has expired should be selected as the first winner. The other forwarding neighbors that are in the winner's transmission range cancel their back-off timers and go to the idle state. By this strategy, the forwarding area is divided into several partitions to restrict the control overhead while covering large spectrum opportunities. Each partition has a representer that is the only node allowed to participate in the route. Hence, selecting the next hop candidate is a crucial task that should be investigated in an appropriate manner. Since nodes in mobile CRNs should care about both primary user activity and node mobility, the proposed protocol considers node mobility in neighbor prioritization as well as considering user activity in neighbor coordination. In this study, we use two approaches to estimate back-off times: (1) short route (SH) approach and (2) stable route (ST) approach.

In both approaches forwarding neighbor j receives a request packet from node i and calculates its back-off time using the mobility metrics of the requesting node (ϕ, v, and (x, y)) and the position of the destination node stored in RREQ.

3.2.1 Short route approach

In this approach, nodes find shorter routes using the mobility metrics. The least difference in mobility parameters (direction dir and speed sp) plus the least distance dist to the destination node gives the most priority to the node:

$$T_{\text{back-off}} = \left(W_\phi \text{dir}_{i,j} + W_\text{s}\text{sp}_{i,j} + W_\text{d}\text{dist}\right) T_\text{MAX}, \tag{3}$$

where $\text{dir}_{i,j} = |\phi_j - \phi_i|/(2\pi)$, $\text{sp}_{i,j} = |v_j - v_i|/(v_\text{max} - v_\text{min})$, dist $= d_j/\text{max\_dist}$, and T_MAX is the maximum waiting time (Witt and Turau, 2005). W_ϕ, W_s, and W_d are the weights for direction, speed, and position, respectively ($W_\phi + W_\text{s} + W_\text{d} = 1$). In addition, v_max, v_min, and max_dist are the maximum speed, minimum speed, and network area length, respectively.

$$d_j = \sqrt{(x_\text{dest} - x_j)^2 + (y_\text{dest} - y_j)^2}. \tag{4}$$

Eq. (3) implies that the nodes having less difference in speed and direction with the requesting node have higher priorities to be selected as the next hop candidates compared to the other forwarding neighbors. It also expresses that the higher priorities should be assigned based on the proximity of nodes to the destination node.

3.2.2 Stable route approach

In this approach, the most stable link has the highest priority to be selected as the communicating link. To determine link stability, Su *et al.* (2001) estimated link expiration time (LET) using the mobility metrics of the requesting and the forwarding nodes and also their positions as in Eq. (5). Therefore, nodes with more stable links are more likely to be selected as the next hops.

$$\text{LET}_{i,j} = \frac{-(ab+cd) + \sqrt{(a^2+c^2)r^2 + (ad-bc)^2}}{a^2+c^2}, \tag{5}$$

where $a = v_i \cos\phi_i - v_j \cos\phi_j$, $b = x_i - x_j$, $c = v_i \sin\phi_i - v_j \sin\phi_j$, $d = y_i - y_j$, and r is the transmission range of nodes.

In this approach the back-off time depends on LET; a higher LET implies a lower waiting time as follows:

$$T_{\text{back-off}} = \frac{\text{LET}_\text{max} - \text{LET}_{i,j}}{\text{LET}_\text{max}} T_\text{MAX}. \tag{6}$$

T_ACK is equal to the maximum back-off time for requesting nodes. For both approaches, the maximum back-off time is T_MAX. Therefore, $T_\text{ACK} = T_\text{MAX}$ allows all forwarding neighbors to participate in the competition.

Fig. 7 describes the effect of each approach on the next hop selection. Node M is a requesting node with three neighbors (i, j, k) in its forwarding area toward the destination node dest.

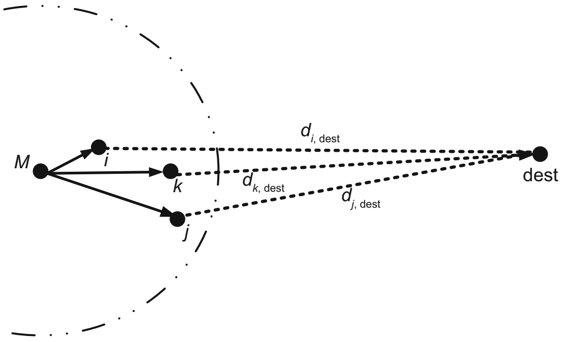

Fig. 7 Next hop selection based on the priorities of neighbors

We also consider:

1. $d_{i,j}, d_{i,k}, d_{j,k} < r$,
2. $\text{dir}_{i,M} < \text{dir}_{k,M} < \text{dir}_{j,M}$,
3. $\text{sp}_{i,M} < \text{sp}_{k,M} < \text{sp}_{j,M}$, and
4. $d_{j,\text{dest}} < d_{k,\text{dest}} < d_{i,\text{dest}}$.

Under the first condition, nodes i, j, and k are within the same transmission range and the first winner will cancel the waiting times of the others. If MASAR uses the stable route approach, the node with the highest LET (node i) will be selected as the next hop, and nodes j and k lose the competition and go to the idle state. On the other hand, the short route approach is highly dependent on the assigned weights (W_ϕ, W_s, and W_d). If $W_\phi = W_\mathrm{s} = W_\mathrm{d} = 1/3$, node k is the winner; by increasing W_d, the priorities of nearer nodes to the destination will also increase, and thus node j will be chosen as the next hop candidate.

3.3 Mobility metric update

In this subsection, we describe how a node can access accurate mobility metrics of its neighbors. A requesting node attaches its mobility parameters to RREQ and sends it. Afterwards, forwarding neighbors receive these metrics and calculate their RCH expiration time using Eq. (5). The winner forwarding neighbor also sends its mobility information using RREQ. The requesting node receives the information carried in the packet and calculates its SCH expiration time. Both the sender and receiver in the synchronization process save the calculated expiration time as the predicted link expiration time for their corresponding channels (the sender saves it for SCH and the receiver saves it for RCH).

Any intermediate node in the route maintains two different predicted expiration times: predicted RCH expiration time (PRET) and predicted SCH expiration time (PSET). PRET is related to the previous hop and PSET is related to the next hop. A node checks for mobility update on each of the following two conditions:

1. $v(t) == v(t - \Delta t)$ and $v(t) \neq v(t - 2\Delta t)$,
2. $\phi(t) == \phi(t - \Delta t)$ and $\phi(t) \neq \phi(t - 2\Delta t)$.

The node calculates the new expiration times using its current mobility metrics and the previously received mobility metrics of its adjacent nodes along the route as real RCH and SCH expiration times (RRET and RSET) while comparing them with the predicated values (PRET and PSET). If $|\mathrm{PSET}-\mathrm{RSET}| > \mathrm{LET}_{\max}/10$ or $|\mathrm{PRET}-\mathrm{RRET}| > \mathrm{LET}_{\max}/10$, the corresponding mobility update process should be called.

3.3.1 Updating PSET

When changes in the movement lead to $|\mathrm{PSET}-\mathrm{RSET}| > \mathrm{LET}_{\max}/10$, the node should inform its next hop about variations in the mobility metrics. Hence, it broadcasts a mobility update packet (MOB) on its SCH and listens to hear the acknowledgement. The next hop channel, which is also listening, is able to hear this packet. After updating the previous hop mobility metrics and constructing new PRET, the next hop replies using MOBACK on its RCH. Using the received acknowledgement packet, the previous hop also updates itself about the next hop mobility metrics if any change had occurred (Fig. 8).

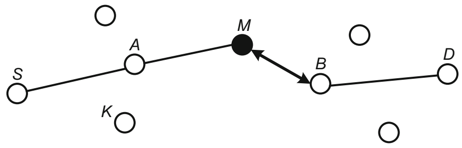

Fig. 8 Updating PSET: node M informs its next hop on its SCH

3.3.2 Updating PRET

During the check for mobility update, finding that $|\mathrm{PRET}-\mathrm{RRET}| > \mathrm{LET}_{\max}/10$ means the RCH will break sooner than the expected time. Hence, it should update its previous hop about the new mobility parameters. The node sends MOB on RCH of its previous hop, and thus the previous hop updates the information about its next hop. The previous hop after updating PSET sends a MOBACK to inform its next hop that the updating process was successful. The MOBACK also includes the updated mobility parameters of the sender, which helps the next hop update PRET.

The main problem here is that the RCH of the previous hop is not free for the node, and therefore the next hop cannot send MOB on this busy channel. To solve this, the next hop uses its neighbors to deliver MOB to the previous hop. It broadcasts MOB on CCC, and those neighbors listening to the control channel can deliver this packet if the RCH of the previous hop is free for them. If the neighbors cannot inform the previous hop, the node waits until it receives an MOB from its previous hop to send MOBACK to inform its previous hop about the new mobility metrics. Fig. 9 shows the PRET update process.

3.4 Dead-end problem

A dead-end node is a node that cannot find any agreed neighbor after sending RREQ. In this situation, this node generates a dead-end error packet (DEER) and sends it to the previous hop on the control channel. If the previous hop has another

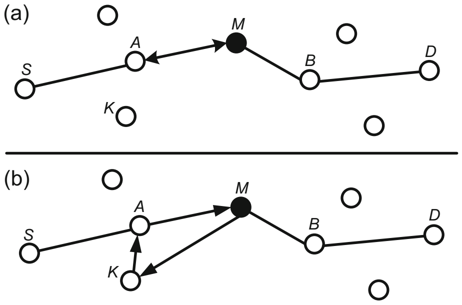

Fig. 9 Updating PRET: (a) RCH of the previous hop A is also free for node M; (b) the next hop uses its neighbors to deliver MOB to its previous hop. In both subfigures, the previous hop replies on its SCH

next hop candidate (the second and third scenarios in Fig. 6), it just drops this error; otherwise, by sending a new RREQ, it starts neighbor synchronization while the dead-end node cannot participate in the new competition.

3.5 Route setup process

MASAR starts the routing process by neighbor coordination. To find the most qualified neighbor, the protocol uses neighbor prioritization mechanism. Both coordination and prioritization are done using RREQ, which carries channel status and the mobility metrics. The mobility metrics help nodes predict when their links toward the next hop will break. RREQ traverses one or more paths to arrive at the destination. The destination node replies to the first RREQ by a route reply packet (RREP), which contains the mobility metrics of the destination node. Intermediate nodes forward RREP toward the source node. All nodes along a route before receiving RREP are listening to CCC while after that they listen to their RCH. When the source node receives RREP, it starts data transmission on its SCH after updating itself about the destination location.

During data transmission, two types of updating occur: spectrum status and mobility metrics. Using the MASAR timing system, all nodes update their spectrum status in the spectrum management slot. The mobility metrics can be updated based on detected mobility changes and the predicted expiration times.

Before expiring RSET, the node should try to find a new next hop candidate. It broadcasts RREQ on the control channel and repeats the route setup process.

4 Performance evaluation

MASAR has been implemented in the extended version of the NS-2 simulator for multi-radio multi-channel environments (Calvo and Campo, 2007). Forty CUs and seven PUs are deployed in an ad hoc manner in a 1000 m × 1000 m area. There is one dedicated control channel between cognitive nodes while there are seven data channels. Note that we use an equal number of PUs and channels to achieve small spectrum opportunity. The transmission range of a primary user is 300 m, whereas the transmission range of cognitive users is 200 m. The primary users are stationary while the cognitive users can move freely. Their minimum speed is zero ($v_{\min} = 0$) while the maximum speed depends on the simulation scenario. The primary users in the network have an exponential On-Off behavior. There are five active connections in the network with the UDP-CBR traffic at a rate of 5 packets/s. Chowdhury and Akyildiz (2011a) considered 0.1 s and 0.6 s for periodic sensing and transmission slots, respectively. Since in our proposed protocol part of location update and route maintenance processes may be performed in the spectrum management slot, we extend the proposed times in Chowdhury and Akyildiz (2011a) and consider 0.2 s and 0.8 s for spectrum management τ_{s} and data transmission τ_{d}, respectively. We also consider T_{MAX} is 50 ms (Madani *et al.*, 2010). Furthermore, we choose equal weights, $W_{\phi} = W_{\mathrm{s}} = W_{\mathrm{d}} = 1/3$, for mobility metrics and geographical routing as in Eqs. (3) and (6). Mobility metrics are tuned based on Bettstetter (2001); α (the acceleration) and $\Delta\phi$ (maximum direction changes in an epoch) vary between $(-2, 2)$ m/s^2 and $(\pi/12, \pi/6)$, respectively. LET$_{\max}$ is considered 55 s for all simulations; this value is determined using an exhaustive simulation on the mobility model based on this configuration. Apart from MASAR approaches, we simulated CAODV (Angela *et al.*, 2012) in this section as a reference to be compared.

Before any experiment, we show the efficiency of the mobility update process. Afterward, we use three parameters to compare MASAR with CAODV: (1) packet delivery ratio (PDR), which is the ratio of the number of data packets received by destination nodes to the number of all the packets sent by the source nodes, (2) average end-to-end delay, which is the average time required to transmit packets from the source to the destination node, including sensing and spectrum management delay, and (3) routing (control) overhead, which is the ratio of the number of control packets to the number of successfully delivered data packets. The routing overhead also refers to the overhead of exchanging location and spectrum information. We run each simulation 10 times and the duration of each run is 900 s.

The performance metrics are compared under three scenarios: node mobility, PU activities, and network load. For the first, we use node speed and the probability of changes occurring in the mobility metrics. As described in Section 2.5, nodes in the SRM model can change their speeds or directions in an epoch with a probability of p_v or p_ϕ, respectively. Here, we use these probabilities as the probabilities of changes occurring in the mobility metrics and refer to them as p_{m} ($p_{\mathrm{m}} = p_v = p_\phi$). Thus, changes in p_{m} result in varying mean time between two mobility change events.

4.1 Mobility update efficiency

In this experiment, we monitor the mobility update efficiency for a node in the SRM model. We define location errors as the distance between real and predicted locations. For this experiment, we consider the node moving at a maximum speed of 30 m/s ($v_{\max} = 30$ m/s) and a direction of ϕ ($0 < \phi < 2\pi$). We also consider that after predicting LET and before the expiration of the link time, at least one change occurs in the mobility metrics (in speed or direction). Since SRM uses smooth changes in speed or direction at any epoch (Eqs. (1) and (2)), we compare the effect of the mobility update process under two different Δt ($\Delta t = 1$ and 3). As depicted in Fig. 10, when a node predicts the next position of its neighbor based on the current mobility metrics, it cannot detect any changes in the speed or direction since it has considered a constant movement after prediction. Therefore, without a mobility update process, nodes cannot monitor the exact moving trajectory of their neighbors. Conversely, in our scheme, the mobility update process is called after changes in mobility metrics, which leads to smaller errors in location prediction.

4.2 Effect of node mobility

Here we study node mobility using two parameters: moving speed and the probability of changes occurring in the mobility metrics (p_{m}).

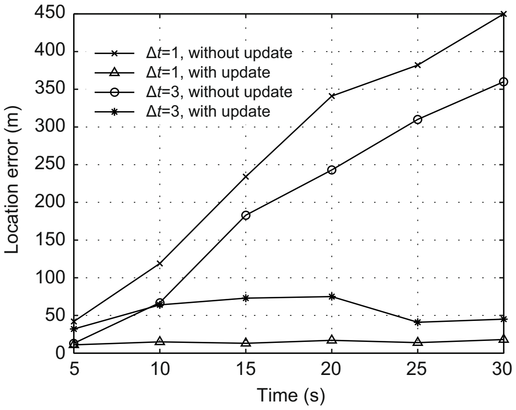

Fig. 10 Location error vs. the time between two consecutive predictions

4.2.1 Effect of node speed

The impact of moving speed is evaluated by varying the maximum speed of nodes. In this experiment, we consider PUs' On probability is 0.5, Δt is 1 s, and p_{m} is 0.06 ($p_v = p_\phi = 0.06$). Considering $\Delta t = 1$ and $p_{\mathrm{m}} = 0.06$ means the mean time between two different mobility metrics events (v and ϕ) is 16.6 s. By varying the maximum speed from 5 to 35 m/s, the packet delivery ratio, delay, and overhead are evaluated.

As depicted in Fig. 11, increasing moving speed drops the packet delivery ratio. Since CAODV has no plan against node mobility, increasing speed leads to the increase in packet loss. Selecting neighbors with the least mobility difference helps both approaches of MASAR avoid high packet loss with increasing speed. Since MASAR-ST discovers more stable routes and has less breakage than MASAR-SH, MASAR-ST can deliver more packets.

The next parameter, routing overhead, increases by increasing the node speed (Fig. 12). Increasing moving speed leads to increase in the number of broken links; thus, it is necessary to exchange many control packets to manage the broken links. The approach with more stable routes (MASAR-ST) experiences fewer broken links and subsequently lower routing overhead than the MASAR-SH approach.

The last experiment of this scenario shows that CAODV has high end-to-end delay due to more frequent link breakage and the required time to repair the broken route with respect to the spectrum status (Fig. 13). In MASAR, selecting the most qualified neighbors as the next hops improves the number of broken links.

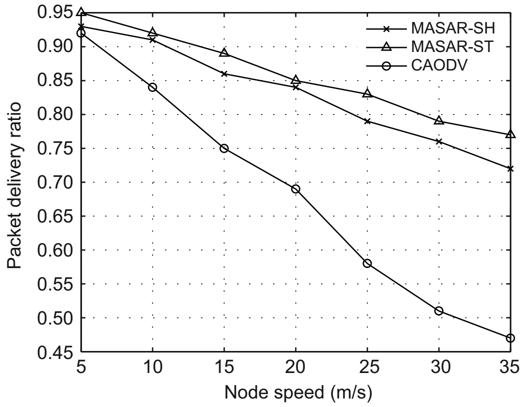

Fig. 11 Packet delivery ratios vs. different maximum moving speeds

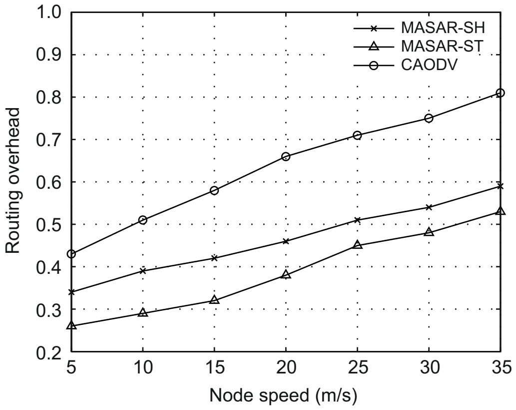

Fig. 12 Routing overhead vs. different maximum moving speeds

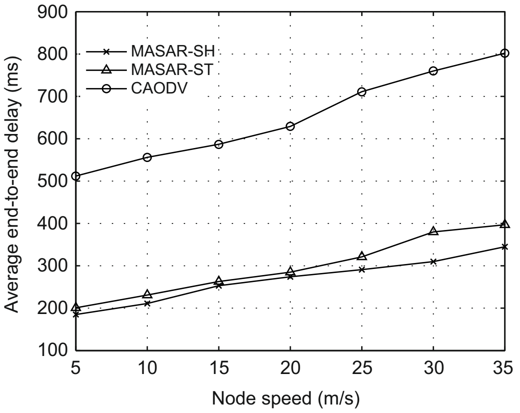

Fig. 13 Average end-to-end delay vs. different maximum moving speeds

4.2.2 Effect of mobility change event probability

By increasing the mobility change event probability ($p_{\rm m}$), mobility patterns become more unpredictable. Higher probabilities cause more dynamic mobility patterns, which results in weak performance metrics. For instance, as depicted in Fig. 14, increasing $p_{\rm m}$ leads to decreasing mean time during which nodes have constant mobility, and thus the packet delivery ratio decreases due to increasing broken links. Mobility update policy in MASAR helps both approaches find new next hops before links break and deliver more packets than CAODV.

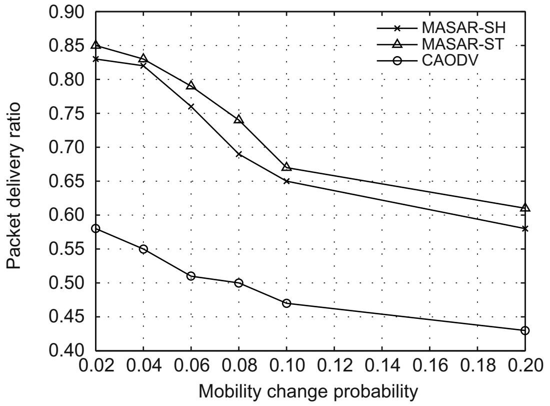

Fig. 14 Packet delivery ratio vs. mobility change probability

In addition, dynamic movement patterns need strict route maintenance and mobility updates, which increases both routing overheads. As Fig. 15 shows, CAODV is not resistive against dynamic mobilities and it can only repeat the route discovery process to cope with the broken routes. As a result, broken routes increase the routing overhead as well as the average end-to-end delay (Fig. 16).

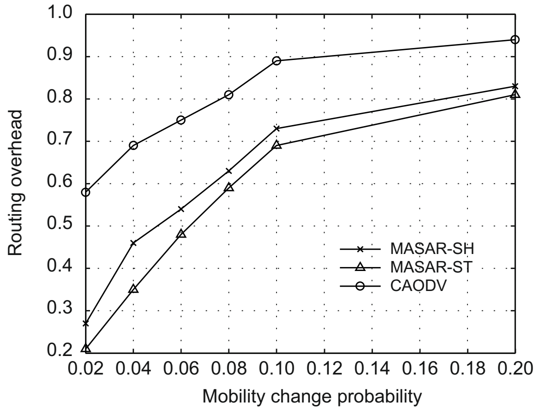

Fig. 15 Routing overhead vs. mobility change probability

4.3 Effect of PU activity

In the next scenario, we change the primary user activities by varying the On/Off probability. In this scenario, $v_{\max}$ is 30 m/s, $p_{\rm m} = 0.06$. A higher On probability of PUs decreases spectrum opportunities and obtains hard routing conditions. In Fig. 17 CAODV has a very low packet delivery ratio under high PU activity. MASAR approaches have higher packet delivery ratios than CAODV because they use mobility information and spectrum status to select short and stable routes.

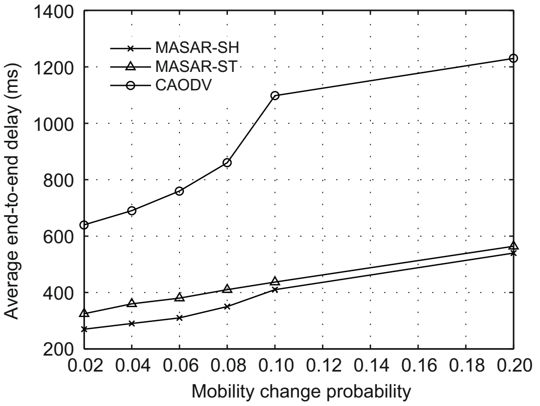

Fig. 16 Average end-to-end delay vs. mobility change probability

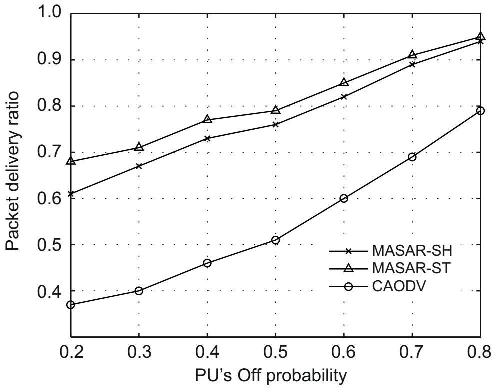

Fig. 17 Packet delivery ratio vs. primary user (PU) activity

By increasing PU activity, all discussed protocols should endure high overhead to find routes. Since MASAR approaches consider spectrum status in the coordination process, they have less overhead than CAODV (Fig. 18). By decreasing PU activity, there is a decrease in the overhead for MASAR, which is faster than CAODV.

As depicted in Fig. 19, increasing spectrum opportunities makes it easy for all protocols to find next hop candidates with lower latency, and thus average end-to-end delay will decrease. MASAR-SH finds short routes by assigning higher priorities to closer nodes to the destination node; therefore, packets traverse fewer hops than the other approach. Although MASAR-ST has higher end-to-end delay, the difference between MASAR approaches in the case of end-to-end delay is very marginal (about 60 ms on average).

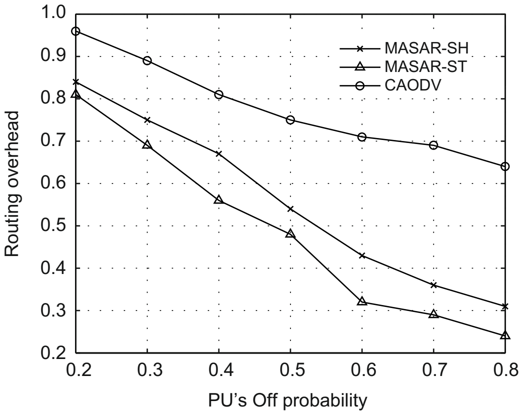

Fig. 18 Routing overhead vs. primary user (PU) activity

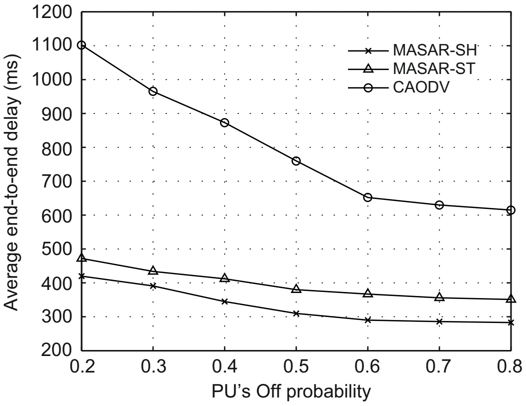

Fig. 19 Average end-to-end delay vs. primary user (PU) activity

4.4 Effect of network load

We apply two changes in the previous network conditions (Section 4.3): (1) PUs' On probability is 0.5, and (2) there are two active connections. For this experiment, we vary the load of each connection and evaluate PDR and delay. As depicted in Figs. 20 and 21, MASAR approaches show better performance in the high load networks.

Since $W_\phi = W_{\rm s} = W_{\rm d} = 1/3$, both approaches show approximately the same performance (or slightly better performance for a stable approach). Due to the effect of mobility on CAODV, increasing connection load besides mobility leads to performance degradation.

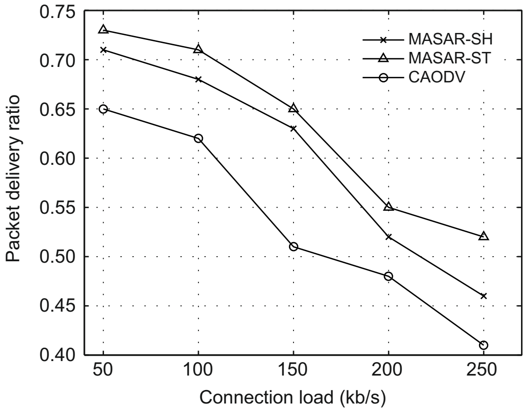

Fig. 20 Packet delivery ratio vs. connection load

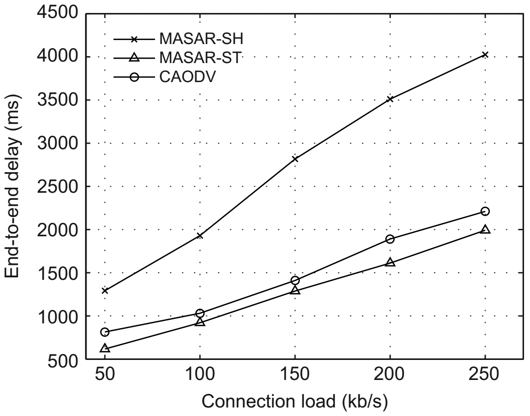

Fig. 21 Average end-to-end delay vs. connection load

5 Conclusions

To manage spectrum access in highly mobile cognitive radio networks, an elaborate routing protocol (MASAR) is proposed. Mobility and spectrum awareness allow MASAR to increase packet delivery using short and stable routes while decreasing end-to-end delay as well as control overhead. MASAR uses two approaches in the case of short and stable routes. Both approaches restrict routing overhead while covering large spectrum opportunities by neighbor coordination and prioritization mechanisms. Due to the significant role of mobility metrics in the joint next hop and channel selection, the mobility update process allows nodes to obtain accurate mobility information about their neighbors to avoid location errors. The expected improvements for MASAR in mobile cognitive radio networks is proved by sophisticated simulations.

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