Spectrum Aware Virtual Coordinates Assignment and Routing in Multihop Cognitive Radio Network

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Abstract—We propose Spectrum Aware Virtual Coordinate (SAViC) for multi hop cognitive radio network (CRN) to facilitate geographic routing. The proposed virtual coordinates (VC) of any two secondary users reflect both geographic distance and opportunistic spectrum availability between them. As a result, geographic routing is able to detour the area affected by licensed users or cut through the area with more available spectrum. According to different spectrum occupation patterns of primary user, two versions of SAViC are designed based on the channel utility and primary user's sojourning time respectively. Simulation shows the proposed virtual coordinate facilitates geographic routing to achieve high success rate of path construction. When duty cycle on the licensed channel is heterogeneous in the network, channel utility based virtual coordinate supports geographic routing to outperform a state-of-the-art geographic routing protocol by 40% on packet delivery ratio. When the channel utility is identical on each secondary node, and the sojourning time of primary users for secondary users are different from each other, SAViC based on primary user's sojourning time achieves significantly shorter delay than other virtual coordinates.

I. INTRODUCTION

Cognitive radio technology is promising to solve the significant shortage of spectrum, which is due to proliferation of wireless devices. According to the definition of FCC (Federal Communications Commission in U.S.), cognitive radio is a device which is able to sense, measure, or learn its environment and accordingly tune its radio operating parameters (like center frequency, bandwidth and transmit power) on the fly, i.e. during operation. In this paper cognitive radio equipment is also called secondary user. Together with these features secondary users are allowed to reuse licensed spectrum which is authorized to so called licensed users.[1] The cognitive radio devices are capable of vacating a spectrum band if the licensed users reappears in order not to cause harmful interference to them.

Since primary users' activity demonstrates different patterns [7], the availability of licensed spectrum exhibits different dynamics accordingly. In certain scenarios the licensed spectrum occupancy stays available for fairly long time, e. g., TV white space [12]. In that case the licensed spectrum occupancy can be seen as static during a long period of time. In other scenarios primary users' states change frequently, but measurements [20], [14] show that the percentage of time that

licensed spectrum is occupied at a specific location or during a certain period of time doesn't change, i.e. in city down town during the work time, the duty cycle of spectrum occupancy by cellular network is stable.

To fully exploit the potential of the secondary spectrum, it is crucial to investigate routing in dynamic spectrum environment. The dynamic availability of spectrum causes frequent break down of links between secondary users, and leads to prevalent topology changes, which makes spectrum aware routing difficult but essential.

Recent measurement in [14] shows the spectrum occupancy doesn't have significant spatial correlations between different locations. It follows that licensed spectrum is used by primary users heavily in some areas, whereas in the other areas licensed spectrum is available over longer timespan for secondary users to use. It is obvious to see that a routing path is better to go through the areas where primary users occupation is lower, as this alleviates or avoids the burden to cope with the changing or totally occupied spectrum when forwarding packets potentially with latency requirements. Geographic routing is a natural choice to realize this geography sensitive routing path. Geographic routing is light weight regarding the determination of next hop, and achieves high scalability in various wireless networks [2]. Merely knowing the geographic locations of its neighbours and the destination, a node is able to locally choose the next hop which has the smallest distance to the destination. However, in CRN dynamic link state renders geographic routing unsuccessful since packets are forwarded to the destination along the shortest path rather than avoiding areas heavily influenced by primary users.

To enable geographic routing in CRN, in this paper we propose SAViC, spectrum aware virtual coordinates for secondary users in multi-channel multi-hop CRN. The virtual coordinate is independent of real geographic position, and has been proposed to represent the properties of the media like, link quality [3] or hop numbers [5]. Following this line of thought, our proposed virtual coordinate represents the spectrum occupancy of primary users. On top of this, we propose the geographic routing scheme which decides the next hop with Euclidean distance metric, and detours the areas affected by primary users, or cuts through the area with lower spectrum occupancy. With SAViC, geographic routing imposes little computation on deciding the next hop, and requires less communication cost transmitting

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[1]Terms licensed and primary, user and node, as well as spectrum band and channel are used indistinguishably in the following paper.

packet to next hop. As to our knowledge, this is the first work integrating the spectrum usage by primary users into network coordinates in order to support geographic routing in CRN, which carries meanings especially for those resource restricted devices which want to work with licensed frequency band. The remainder of the paper is organized as follows, after reviewing related work in Section II, system model is introduced in Section III. Assignment of SAViC is explained in Section IV, followed by opportunistic access during transmission in Section V. Section VI gives performance evaluation, concluding remarks are given in the last section.

II. RELATED WORK

When secondary users are static and primary users' operation activity is known, i.e., primary users occupy a certain channel for long time, or they occupy a channel with fixed probability, then centralized routing schemes for CRN can be designed[13]. But as centralized scheme requires sensing result from each secondary user in the network, thus suffers from any change of channel state of secondary users [1], besides, one centralized controller is needed to calculate the routing path on the basis of collected information from the network [13], [15]. Considerable amount of distributed schemes are proposed to cope with routing in CRN where spectrum state is usually considered to be rapid changing. [4] proposes CAODV (Cognitive Ad-hoc On-demand Distance Vector) and let each CR node explore all channels and store route for each available channel. CAODV requires frequent message exchange between secondary users to maintain the up to date connections on each channel due to PU's activities, which is a burden for secondary user when primary users' activity is intense. [17] improving the DSR scheme (Dynamic Source Routing) by letting RREQ messages record spectrum availability, link quality and congestion possibility along routing paths, but it also suffers from frequently changing channel state.

To cope with the rapid change of channel state, some routing schemes abandon routing table and let the transmitter decide the next hop for each single packet based on spectrum state between transmitter and neighbours. When there is packet to send, secondary user evaluates channel availability based on the statistics of sensing history [10], or the prediction on channel availability in the forthcoming time slot [9], then secondary user chooses the favoured channel and next hop node to send out the packet. Distance to the destination is also a consideration for choosing next hop. Such per-packet forwarding paradigm reacts swiftly on the fast changing channel state, but it requires more powerful computation power on secondary users. Firstly, that scheme produces high computation complexity on determining the channel and next hop node, secondly, specifically designed MAC mechanism and large amount of control messages are needed to coordinate the communication between the sender and the potential next hop nodes, these aspects make it uneconomic for many networks, e.g, wireless sensor networks operating with licensed spectrum [18]. Furthermore, as this kind of routing paradigm emphasizes on finding the maximal transmission opportunity of secondary spectrum, the selection on preferred channel decreases the scope of next hop neighbours, thus it may yield route which does not reach the destination [7], [16].

Chowdhury et al. [6] proposes *SEARCH* which is a valuable attempt to avoid the primary users' influences on routing path on the basis of geographic routing. In *SEARCH*, the source node launches geographic routing on each channel, and every routing path bypasses the nodes where corresponding channel is unavailable. Paths on different channels will merge on the nodes where path circumvent happens, if such change of path and switch of channel lead to shorter time needed to send packets to destination. After receiving the routing message on each channel, the destination decides the shortest path and sends back notifications along the chosen path. The routing path is blocked when one primary user locating along it changes its state from OFF to ON, thus source node needs to periodically launch route request to update the routing path which may have been invalid. *SEARCH* adopts routing table and doesn't involve frequent overhead exchanges.

III. SYSTEM MODEL

We consider a CRN composed with secondary users which are randomly and statically deployed in a plane. There are orthogonal licensed channels denoted by set C, and secondary user is allowed to use any of them if no primary user is detected on that channel by the secondary user. One common control channel (CCC) in license-exempt band is available for all secondary users to exchange control messages. Only one licensed channel is used for payload transmission. Primary users are static, and they occupancy spectrum in a constant manner, e. g., the percentage of time that they access a certain channel is static in any period of time.

Proactive spectrum sensing is conducted locally and periodically as Figure 1 shows.
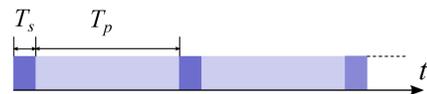

Fig. 1. Sensing duration T_s and sensing period T_p

The sensing duration T_s includes both detection time in physical layer and the decision synchronisation time. Sensing period T_p is the time between two successive sensing durations. If the channel is sensed as busy[2] in sensing duration, which means at least one primary user in the vicinity is in ON state, we say the state of primary user is labelled as ON in the following sensing period T_p. If not a single primary user is sensed, primary users in vicinity in the following sensing period is said to be in state OFF. Secondary user senses each licensed channel for time T_{access} with round robin scheduling, and records statistics of ON/OFF states of that channel at its place.

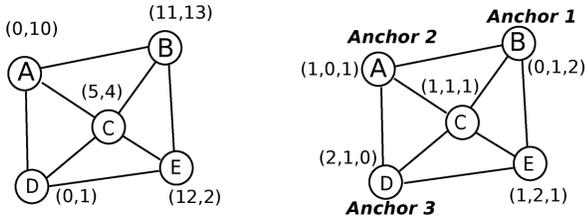[2]Concrete sensing techniques are not discussed in this paper.

Fig. 2. Left: nodes with physical locations, Right: nodes with doublet virtual coordinate, each element in the virtual coordinate is the number of hops away from corresponding anchor. Connecting lines denote the communication is possible.

Fig. 3. A network under primary users' influence assigned with SAViC, only anchor 1 is adopted. Flooding of anchor messages is not shown.

IV. Spectrum Aware Virtual Coordinates

Virtual coordinate has been proposed in sensor and ad hoc networks [5], [3]. In the left part of Figure 2, nodes are labelled with physical positions. The right hand side part shows the same network assigned triplet virtual coordinate for each node according to VCap [5], where each element of the coordinate denotes the minimal number of hops away from corresponding anchor. This kind of virtual ordinate belongs to tree based virtual coordinates, and is obtained based on anchors which locate at the edge of network. Anchor messages are broadcast from anchors, each of them contains a counter recording the number of hops travelled. The minimum counter of the arriving anchor messages constitutes the corresponding element of the virtual coordinate on the arrival node. Except for the hope numbers away from certain anchor node, virtual coordinate can also be composed with link quality [3] in wireless sensor networks. The hop based virtual coordinate is independent on actual physical position, but supports greedy geographic routing successfully [5], [3]. For example, when the source-destination is B and D, and Euclidean distance calculated with virtual coordinate is adopted in the routing decision, then the greedy geographic routing achieves the same routing path in both networks: $B \to C \to D$. This path is one with the shortest traversal distance.

In this paper, we propose licensed spectrum aware virtual coordinate in CRN, which enables geographic routing to find the path with better available spectrum. Figure 3 shows one CRN where secondary users are assigned virtual coordinate according to anchor 1. The transmission opportunity of the nodes locating within primary users' transmission range, e. g., node A and C, is decreased due to sporadic spectrum, as a result, the cost for packet transmission, e. g., transmission delay and energy consumption, is increased. We integrate this obstacle caused by spectrum scarcity to transmission into virtual coordinate.

A. Assign Spectrum Aware Virtual Coordinate

As to SAViC, anchors broadcast anchor messages which flood over the network and result in virtual coordinate for each secondary user. Several anchors are needed to assign unique virtual coordinate for each secondary user. How to select anchors is out of the scope of this paper. In the following, we introduce how is virtual coordinate decided on each node with respect to anchors.
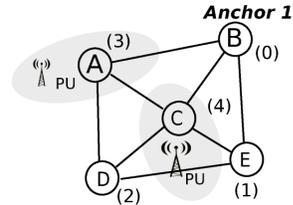
Each secondary user maintains its virtual coordinate which is one r-tuple where each element contained corresponds to one anchor, and the tuple length is r. The elements of virtual coordinate on each node is set as big positive value. An anchor message is generated on the anchor, which contains a counter whose value is set as 0. The anchor message is broadcast on control channel. The influence of primary users on a secondary user is quantified as spectrum utility λ on that secondary user. The bigger value indicates heavier spectrum occupation by primary users. λ will be discussed in Section IV.B and IV.C.

When a node i receives an anchor message from the tth anchor, i compares the tth element in its current virtual coordinate with the sum of the λ and $counter1$ which is contained in the arriving anchor message. If the sum is greater than the tth element in its current virtual coordinate, which indicates that the path traversed by this anchor message exposes to more active primary users, node i drops the anchor message. If the sum is smaller than the tth element in its current virtual coordinate, the node set the tth element as the sum and updates $counter1$ contained in the anchor message before forwarding it. This process is presented as Algorithm 1. This phase ends after a period of time to make sure each node obtains tth element in its virtual coordinate.

All the anchors sequentially broadcast the anchor messages which are flooded over the network, so that a secondary user obtains its virtual coordinate which respects all anchor nodes.

In the following two subsections, we introduce two normalized spectrum utilities on secondary user respectively, one of them is called *normalized spectrum availability* which is on the basis of duty cycle of primary users' absence, the other is called *normalized longest blocking time* which as the name tells, is based on the lengths of time durations that primary users are detected.

B. Normalized Spectrum Availability on Secondary User

Based on the statistics of primary user's ON/OFF states in time duration $T_{assement}$ which contains multiple T_s, secondary user i characterizes the likelihood that one licensed channel, say k, is available at its own position with *duty cycle*, which is

$$\gamma_i^k = \frac{\Delta_{\text{OFF}}}{\Delta_{\text{OFF}} + \Delta_{\text{ON}}}, \tag{1}$$

Algorithm 1: Secondary user i obtains one element vc_i in its VC with respect to an anchor

Input: $vc_i = M$, M is one big positive number

1 **if** i *is anchor* **then**
2 $\quad$ $vc_i = 0$;
3 $\quad$ set $counter1 = \lambda_i$ in anchor message;
4 $\quad$ broadcast anchor message;
$\quad$ **end**
5 **if** *receive anchor message* **then**
6 $\quad$ **if** $counter + \lambda_i \geqslant vc_i$ **then**
7 $\quad\quad$ drop anchor message;
$\quad$ **else**
8 $\quad\quad$ $vc_i = counter + \lambda_i$;
9 $\quad\quad$ set $counter = vc_i$ in anchor message;
10 $\quad\quad$ broadcast anchor message;
$\quad$ **end**
end

Fig. 4. Normalized spectrum availability with respect to the likelihood of spectrum being available one a node

where Δ_{OFF} is the number of sensing periods when channel k is sensed as OFF in $T_{assement}$. To implement SAViC whose resultant Euclidean distance between two nodes reflects both influence from primary users and distance in terms of hops, we need to design a normalized quantified spectrum availability λ_i.

1) Single licensed channel: When there is only one licensed channel in CRN (the superscript of channel λ is omitted), the normalized spectrum availability on node i is proposed as,

$$\lambda_i = -\ln \gamma_i + c \cdot \gamma_i \quad (2)$$

With Formula 2, when one anchor message which originates from anchor X is forwarded from node a to b without being dropped, the distance based on virtual coordinate reflects both the spectrum availability and geographic distance in terms of hops between the two nodes. Based on Algorithm 1 and Formula 2, the distance in dimension X is,

$$|x_b - x_a| = \sum_{i \in P_{(a,b]}} (-\ln \gamma_i + c \cdot \gamma_i)$$
$$= -\ln(\prod_{i \in P_{(a,b]}} \gamma_i) + c \cdot \sum_{i \in P_{(a,b]}} \gamma_i \quad (3)$$

here x_a and x_b are virtual coordinates of node a and b in dimension X respectively. $P_{(a,b]} = (\cdots, b)$ denotes the list of nodes after a and till b, which forward the same anchor message.

The reason to choose the form of Formula 2 is as follows. As Formula 3 shows, the first item is logarithm of the product of consecutive spectrum availability likelihood of the nodes in $P_{(a,b]}$. The product is the likelihood that one message travels from node a to b without hampered by primary users, which is an important property we want to integrated into our virtual coordinate system. The second item denotes number of hops, which can be seen clearly when $\gamma_i = 0$ for node $i \in P_{(a,b]}$.

As λ_i needs to be monotonically decreasing with respect to γ_i, so that the less spectrum availability results in bigger cost
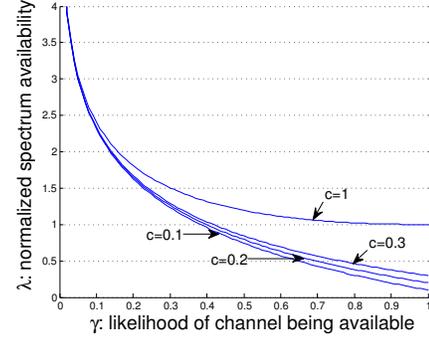
for communication, thus there should be

$$\frac{\partial \lambda_i}{\partial \gamma_i} = c - \frac{1}{\gamma_i} < 0 \quad (4)$$

hence the tuning parameter c should be smaller than 1. In the simulation part, we choose $c = 0.2$ so that λ visibly reflects the changes of γ when γ is not too small, as Figure 4 shows.

2) Multiple licensed channels: When multiple licensed channels are allowed to use without interfering primary users, one node can switch to an another channel which is at present available to send or forward packet, then the normalized channel availability is,

$$\gamma_i = 1 - \prod_{k=1}^{|C|} (1 - \gamma_i^k) \quad (5)$$

Based on Formula 2, the normalized spectrum availability on node i when multiple secondary channels are available is,

$$\lambda_i = -\ln \gamma_i + c \cdot \gamma_i$$
$$= -\ln(1 - \prod_{k=1}^{|C|} (1 - \gamma_i^k)) + c \cdot (1 - \prod_{k=1}^{|C|} (1 - \gamma_i^k)) \quad (6)$$

C. Normalized Longest Blocking Time on Secondary Users

Channel utility introduced in previous subsection characterizes the likelihood that secondary user is allowed to forward packets, but it fails to reflect the availability of spectrum in a finer granularity of time. For instance, in the period of time T_{access} to access the spectrum availability, one channel which frequently changes between state ON and OFF due to primary users' violent operation may have the same likelihood of available spectrum with the channel where primary user sojourns on state ON for long time. This difference has direct consequence on delay when the likelihood of spectrum availability on PU affected secondary nodes is homogeneous.

Let T_{ON}^k be the length of time period that channel k is not available, there is $T_{ON}^k = n \cdot (T_s + T_p)$, where n is the number of consecutive sensing duration that channel k is sensed as busy. T_{ON}^k is recorded within T_{access}, and we use $\tau^k = \overline{T_{ON}^k}$ to denote the average value of the time duration that channel k is occupied by primary user, which is the maximum time period that secondary user is blocked from sending/forwarding.

1) Single licensed channel: In single licensed channel scenario, the normalized maximum blocking time on node i is (superscript k is omitted),

$$\lambda_i = f(\tau_i) = \gamma_i \cdot \tau_i + b \cdot e^{-\gamma_i \cdot \tau_i} \qquad (7)$$

The first item is the product of blocking time and the duty cycle of available spectrum, note that we assume the duty cycle is identical for any PU affected secondary user and thus can be regarded as constant. As to the secondary users which locate out of any primary user's transmission range, there is $\tau_i = 0$, then $\lambda_i = b$, λ_i denotes hop count in this case. This is the reason that the second item is needed.

Same with the analysis in section IV.B, when one anchor message travels through path $P_{(a,b]}$, the distance on the corresponding coordinate dimension is the sum of the normalized longest blocking time, which is the function of the sum of maximum blocking time on the cascaded nodes on the trajectory of anchor message,

$$
\begin{aligned}
|x_b - x_a| &= \sum_{i \in P_{(a,b]}} \left(\gamma_i \cdot \tau_i + b \cdot e^{-\gamma_i \cdot \tau_i} \right) \\
&= \gamma_i \cdot \sum_{i \in P_{(a,b]}} \tau_i + b \cdot e^{-\gamma_i \cdot \sum_{i \in P_{(a,b]}} \tau_i}
\end{aligned}
\qquad (8)
$$

Normalized longest blocking time λ is monotonically increasing with τ_i, which requires

$$
\frac{\partial \lambda_i}{\partial \tau_i} = \gamma_i - \gamma_i \cdot b \cdot e^{-\tau_i \cdot \gamma_i} > 0 \qquad (9)
$$
$$
b < e^{\gamma_i \cdot \tau_i}
$$

then we set the tuning parameter b as 1.

2) Multiple licensed channels: In multiple licensed channel scenario, τ_i equals to the smallest maximum blocking time over all secondary channels on node i,

$$\tau_i = \min \tau_i^x, x \in C \qquad (10)$$

The normalized maximum blocking time on node i is as Formula 7 shows.

In following part of this paper, the virtual coordinate based on normalized spectrum utility is referred as *spectrum availability based VC*, and The virtual coordinate based on normalized maximum blocking time is denoted as *blocking time based VC* out of convenience.

When λ on secondary nodes is identical, the resultant SAViC appears to be similar with hop based virtual coordinate. In reality, as the measurement shows in [14], heterogeneity of spectrum usage by primary users is very normal, besides, the two kinds of virtual coordinates make it easier to find out such heterogeneity. [14] also shows within certain frequency band, primary users' activity is stable for hours, e. g., cellular network. When primary user's operation pattern changes, e. g., occupy spectrum with increased duty cycle, then SAViC needs to be reimplemented.

V. GEOGRAPHIC ROUTING AND OPPORTUNISTIC SPECTRUM ACCESS

Although spectrum aware virtual coordinate is the main concern of this paper, we also introduce the geographic routing to be used as it affects the routing result directly. With geographic routing, packet sender/forwarder chooses the neighbour which has smaller Euclidean distance to the destination. The distance between node i and destination d is $\sqrt{(x_d - x_i)^2 + (y_d - y_i)^2 + (z_d - z_i)^2}$, when virtual coordinate can be denoted as $\{x, y, z\}$. A trivial improvement on greedy geographic routing is implemented in network layer to mitigate the dead end problem. When routing protocol reaches dead end node u which is closest to destination, u adds its ID to the packet as taboo before forwarding the packet to v which is closest to the destination in its neighborhood. The packet will not be sent to the nodes whose IDs appear to be taboos.

Buffer is implemented on each node, where packets stay temporally when no unoccupied licensed spectrum is available. Secondary user resends buffered packet every period of time, and drops it if there is still no available channel after trying for 10 times.

In multiple channel CRN, after one node deciding on the next hop via geographic routing, which channel to use needs to be answered. This problem involves considerations from many aspects, such as minimizing channel switch cost [16], mitigating co-channel interferences [8] etc.. We adopt a lightweight heuristic method in this paper. When there is packet to send and the next hop is decided, packet sender chooses the channel in descending sequence with channel's metric, i.e., likelihood of channel availability, or blocking time. The sender chooses the channel with the best metric, then conducts spectrum sensing in the immediately following sensing duration to determine the channel's usability. If the channel is sensed as free to use, sender transmits *request_channel_x* to the next hop on the control channel, when it receives the answering message *channel_x_available* from that node, it starts communication on channel x in the following sensing period. If the channel is sensed to be busy before or among the transmission, or it receives *channel_x_unavailable* message from next hop node, the sender moves to the channel with the second best metric, and conduct the same procedure as described above.

VI. PERFORMANCE EVALUATION

In this section, we present the performance of geographic routing together with SAViC. Both virtual coordinates based on metrics of spectrum availability and blocking time respectively are evaluated. Prior to that, the set-up of simulation is introduced.

A. Simulation Setup

In this section, we introduce the deployment of the primary users to generate various spectrum availability in the network, then introduce the important parameters in simulation. Different from [5] where simulation is conducted without considering any activities in MAC and physical layer, simulation in this paper

deploys a wireless environment which is close to reality, e. g., interferences and channel shadowing are involved.

1) Primary Users: In simulation, primary user alternates state between ON and OFF as a two-state discrete time Markov chain (2TDMC) [11]. The probability that it changes from one state to the other, or stays in the same state is called transition probability. Transition probability further decides the stationary probability of 2DTMC, which represents the percentage of time that primary user is in state ON or OFF in a long run. The relationship between stationary probability $\Pi = \{\pi_{\text{ON}}, \pi_{\text{OFF}}\}$ and duty cycle γ is,

$$\lim_{T_{assement} \to \infty} \gamma = \pi_{\text{OFF}} \tag{11}$$

Transition probability also decides the continuous sojourning time of primary user on a certain state, which affects the longest blocking time sensed by secondary users. Hence, by adjusting transition probability, we can let primary user operate with desired intensity, i.e. stationary probability for being in state OFF, or continuous sojourning time of being on state ON. We denote stationary probability of state OFF as P_{OFF}, and the maximal blocking time as T. In the following, we only use P_{OFF} and T to define primary user's dynamics, and omit mentioning the transition probability. The time unite of the DTMC for primary user to follow is 0.1s.

As spectrum availability based and longest blocking time based virtual coordinates are designed for CRN which is influence by certain primary user activity, we design two primary user distributions. As a result, we design two categories of primary user settings to evaluate the routing performance assisted by the two categories of virtual coordinate respectively.

- As to spectrum availability based virtual coordinate, two primary users are located in the CRN which can not affect all the nodes in CRN, as shown in Figure 6.1.
- For blocking time based virtual coordinate, network is evenly covered by primary users which have the same duty cycle, but some primary users have different blocking time with the others, as Figure 9 shows.

When multiple channel scenario is to be investigated, existing primary users simply start to work with current and additional channels, and there is no new primary users appear.

2) Parameter Setting: Simulation is conducted with INET framework provided by OMNeT++ simulator [19], which comprises both generation of SAViC and following geographic routing. Secondary users are randomly distributed in a square area and 6 nodes which locate at the edge are deployed as anchors.

B. Success Rate of Geographic Routing on Finding Path

We evaluate SAViC's reachability, i.e. given the virtual coordinate of destination, geographic routing forwards packet from source to the node with the desired virtual coordinate. The comparisons are real geographic location, and hop based virtual coordinate according to VCap [5]. We deploy 6 anchors and then there is no duplicated virtual coordinate among the resultant virtual coordinate system.
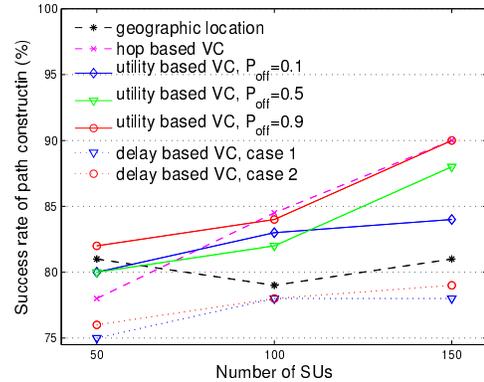

Fig. 5. Reachability of different virtual coordinates, the average number of neighbors is 6, 12, and 14

In order to evaluate the effectiveness of coordinates to support geographic routing, we design different configurations of primary users. As to duty cycle based VC, two primary users are randomly deployed in the network. As to delay based VC, we configure 9 primary users to evenly cover the network, among of them, 4 primary users have different maximal blocking time with the rest. Under one configuration of primary users, 1000 random CRN is generated and in each CRN one far departed pair of source and destination is chosen to test.

Figure 5 shows, spectrum availability based virtual coordinate supports geographic routing to achieve similar reachability with hop based virtual coordinate[3], which is better than that with real geographic location. Blocking time based virtual coordinate performs a little bit worse than other coordinates. In summary, after integrating the primary user's influence, SAViC supports geographic routing to achieve comparable success rate of path construction with conventional virtual coordinate and real geographic location.

C. Routing Performance

We sequentially present the routing performance of SAViC based on spectrum availability and blocking time respectively. In more details, spectrum availability SAViC is compared with hop based virtual coordinate VCap and *SEARCH*. The reason to choose *SEARCH* [6] is it is on the basis of geographic routing and utilizes routing table in the interval of updates, thus it requires less computation ability and overhead exchanges. The time interval for *SEARCH* to update routing tables of the nodes on routing path is 5s. Both single and multiple licensed channel scenarios are investigated for the three solutions.

*1) Spectrum Availability Based Virtual Coordinate:*
We start by looking into the performance of SAViC in single channel scenario.

We start with a case study, two primary users locate at the centers of dashed cycles as shown in Figure 6.1. VC based on spectrum availability and VCap (hop is its metric) are assigned

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[3]The numerical result of hop based virtual coordinate coincides with the simulation result presented in [5] under the same network density
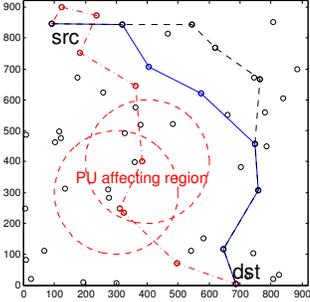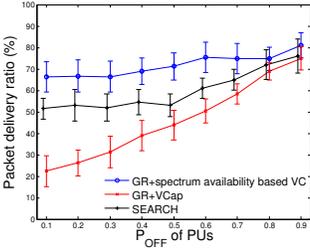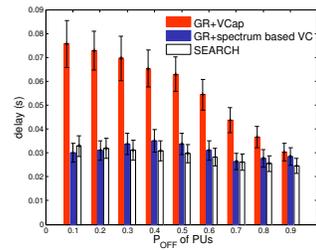
6.1: Routing paths
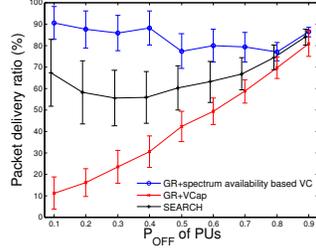
6.2: PDR over 50 random CRN network, PU's location is fixed as shown in Figure 6.1

Fig. 6. Routing paths and corresponding PDR

7.1: PDR

7.2: Delay

Fig. 7. Packet delivery ratio with single secondary channel, over 50 randomly located CR nodes and PUs

to secondary users separately. The red dashed path in Figure 6.1 is formed by geographic routing with VCap, which cuts across the primary users' affecting area and thus suffers great packet loss. The black dash and blue solid paths are formed with spectrum availability based virtual coordinate, the two paths are formed when primary user's working intensities P_{OFF} is 0.1 and 0.9 respectively. These two paths vividly illustrate that utility based virtual coordinate successfully integrates the spectrum scarcity in CRN network, and decomposes a large part of routing decision. The paths of SEARCH is not drawn here as the routing path is possible to change after path update. We keep the primary users in the middle of the network, for each activity intensity, 50 CRNs where secondary users are randomly located are generated. Figure 6.2 shows the PDR of spectrum availability based virtual coordinate is high except for a minor decline when P_{OFF} is between 0.5 and 0.8, which is contradictory to the monotonically increasing trend of hop based virtual coordinate. This can be explained by the path snapshot in Figure 6.1. When channel is sensed to be scarce (primary users access channel intensively), path generated is far away from the affected area and circumvents completely. When primary users become less intensive, routing path moves closer to that area. In other words, the weaker dynamics of primary users attracts path and result in packet drop. When P_{OFF} approaches to 1, spectrum availability based virtual coordinate becomes actual hop based virtual coordinate as the link metric in formula 2 becomes zero.

The paradox of more licensed spectrum leads to worse PDR

also happens to *SEARCH*, which declines first and increases later on. When channel is heavily utilized by primary users, the routing request is more likely to encounter operating primary user, then a node out of the primary user affecting area is chosen as next hop, so that the path experiences less packet loss (with the price of more hops). When primary users become less intense, routing request is more likely to traverse the affected areas, as a result, the routing path experiences packet loss due to the primary users in that area before next route update.

Figure 7.1 shows the PDR when both primary and secondary users' locations are random. SAViC's performance deteriorates because the source and destination may be influenced by primary users, so that a path completely detour the primary users' area is impossible. where geographic routing has no means to detour the affected areas. In figure 7.2, SAViC and SEARCH achieve lower delay although forwarding more packets, which means SAViC is effective to facilitate geographic routing to avoid PU affecting areas.

Now we introduce the routing performance in multiple channel scenario, where two licensed channels available, but only one is allowed for payload transmission.
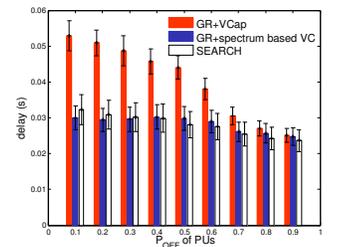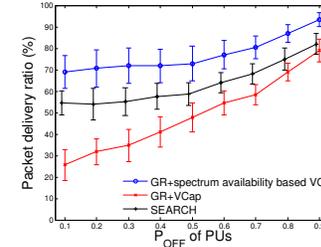
8.1: PDR over 50 CRNs where SUs and PUs are randomly located

8.2: PDR over 50 CRNs where SUs and PUs are randomly located

Fig. 8. Packet delivery ratio with multiple secondary channel scenario

In this part of simulation, we follow the setting of single channel scenario, except that secondary users have at most two licensed channels.

Thanks to the second channel, the packet delivery radio is increased as shown in Figure 8.1, and delay is decreased as depicted in Figure 6.1. SAViC still outperform the other schemes especially in the aspect of PDR.

2) Longest Blocking time Based Virtual Coordinate:

As discussed in section IV.C, spectrum availability based virtual coordinate doesn't reflect the sparsity or abundance of spectrum well when the likelihood of spectrum availability is homogeneous in CRN. A CRN working with single licensed channel in Figure 9 is used to show the fail of spectrum availability based virtual coordinate. Two items are used in the following to make the analysis tidy.

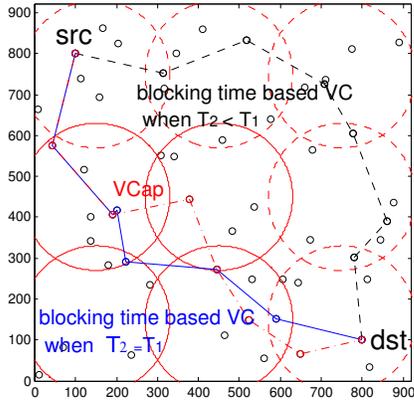|	
T_1	Maximal blocking time of primary users whose transmission ranges are solid cycles in Figure 9
T_2	Maximal blocking time of the other primary users

Fig. 9. Routing paths in one network, $T_1 = 3s$. cycles denote the transmission range of primary uers.

In the network, 9 primary users evenly distributed, $P_{\text{OFF}} = 0.5$ for each of them. For the primary users denoted by the solid cycles, maximal blocking time $T_1 = 3s$, and $T_2 = 1s$ and $3s$ for the other primary users. When $T_2 < T_1$, the resultant routing path is in black and dashed, which goes through area where primary users have shorter maximal blocking time. When $T_2 = T_1$, the resultant routing path largely converges with the path with VCap.

The ineffectiveness of spectrum availability based virtual coordinate in case of identical P_{OFF} is observed in Figure 9. In this case a different characteristic, i.e., the longest blocking time, which shows the geographically diverse characteristics of spectrum can be used. In our simulation, $P_{\text{OFF}} = 0.9$ for all primary users, but they are diverse on sojourn time, i.e. T_1 of primary user is 3s, and T_2 is shorter. We randomize the location of secondary users in 50 networks, and present the performance of blocking time based virtual coordinate to show its superiority on decreased end to end delay and PDR. In this part of simulation, we don't show the result of *SEARCH*, as it performs as bad as geographic routing with hop based virtual coordinate. The reason is the widespread primary users seriously hamper the routing requests to arrive at destination, consequentially most paths for forwarding the packets can not be constructed successfully.
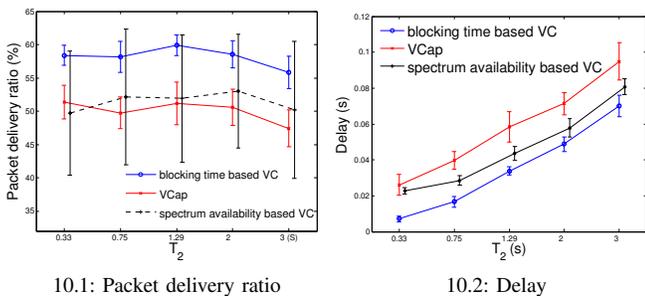

10.1: Packet delivery ratio

10.2: Delay

Fig. 10. Geographic routing in single secondary channel scenario, $P_{\text{OFF}} = 0.9$ for all primary users, $T_1 = 3s$, T_2 varies.

Figure 10.2 shows as T_2 increases from 0.33s to 3s, the delay of successfully delivered packets also increases for both block-

ing time based virtual coordinate and VCap, but a constant gap exists in between. Whereas, the delay of spectrum availability based virtual coordinate is random as respect to sojourn time, the reason is the routing metric in this scenario doesn't involve blocking time imposed by primary users.

The packet delivery ratio shown in Figure 10.1 is constant with both blocking time based virtual coordinate and VCap, because all the primary users have the same P_{OFF} which is 0.9. Particularly, blocking time based virtual coordinate achieves higher packet delivery ratio than the other two virtual ordinates, the reason is when the former is applied, less packets are dropped from buffer as the time of being blocked is shorter for the secondary users on the path.

Now we have a look at the CRN with two licensed channels. As to performance of delay, because of the second available channel, blocking time based virtual coordinate achieves very delay, in contrast, spectrum availability based virtual coordinate still demonstrates obvious randomness, as is shown in Figure 11.2. Compare Figure 11.1 and 10.1, we can see the packet delivery ratio in two channel network is obviously higher than that in single channel network, as the second channel provides extra transmission opportunities. Blocking time based virtual coordinate achieves up to 10% better performance than that with spectrum availability based VC, the reason is packets in buffer have greater likelihood to be sent out before getting dropped.
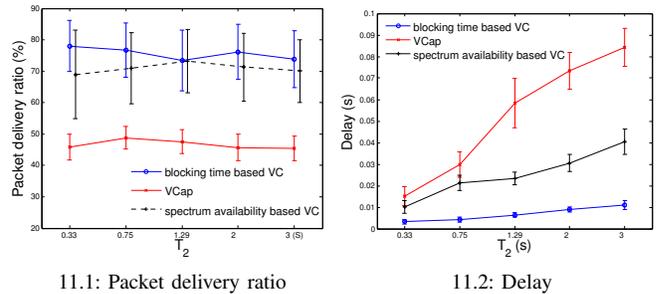

11.1: Packet delivery ratio

11.2: Delay

Fig. 11. Geographic routing in two secondary channel scenario, $P_{\text{OFF}} = 0.9$ for all primary users, $T_1 = 3s$, T_2 varies.

VII. CONCLUSION

The proposed virtual coordinate SAViC reshapes the topology of cognitive radio network based on sensing results of spectrum availability. As SAViC adjusts the distance between nodes based on the communication obstruction caused by primary users, the virtual coordinate comprises a part of the routing decision, so that geographic routing is able to detour the areas seriously affected by primary user. Geographic routing with SAViC greatly simplifies the computation and communication burden on each secondary user involved in routing in CRN. Together with SAViC, geographic routing achieves better performances than other geographic routing designed for CRN through extensive simulation. This paradigm of routing is especially suitable for CRN network where the resource limited CR nodes can only support geographic routing. This

work emphasises on avoiding primary users' influence with geographic routing, and doesn't consider the interference issue among the secondary users, which should be addressed in the future work.

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