

Segment-Based Channel Assignment in Cognitive Radio Ad Hoc Networks

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Abstract—In the opportunistic spectrum sharing (OSS) paradigm, unlicensed users (a.k.a. secondary users) “opportunistically” operate in fallow licensed spectrum on a non-interference basis to licensed users (a.k.a. primary users). Each secondary user is equipped with a cognitive radio (CR) that has the capability to selectively operate in fallow licensed bands. In the OSS paradigm, the temporal and spatial spectrum variability caused by the primary users’ spectrum utilization adds another dimension of complexity to the problem of channel assignment. Because existing channel assignment approaches (which were originally designed for conventional wireless networks)—such as link-based and flow-based approaches—do not consider spectrum variability, they do not offer the best trade-off in terms of complexity and performance. In this paper, we investigate the channel assignment problem in single radio interface, CR ad hoc networks. We present a novel channel assignment scheme that assigns channels at the granularity of *segments*. The proposed scheme is significantly simpler than existing approaches, and offers several practical advantages. Using simulation results, we show that the proposed segment-based channel assignment strategy outperforms link-based channel assignment under realistic network conditions.

I. INTRODUCTION

The proliferation of wireless applications operating in unlicensed spectrum bands has resulted in the overcrowding of those bands. In contrast, recent studies have shown that most licensed bands are underutilized [5]. To address the spectrum shortage problem, the Federal Communications Commission (FCC) is considering the adoption of a new regulatory spectrum management paradigm in which licensed bands are opened up to unlicensed operations [6]. This new regulatory model is often called “opportunistic spectrum sharing (OSS)”. The *cognitive radio* (CR) is seen as the key enabling technology for realizing OSS¹.

A cognitive radio has the capability to sense its environment and adapt its mode of operation to achieve its performance objectives [1, 7]. In CR networks, spectrum opportunities (“white spaces”) in licensed bands are identified by the process of *spectrum sensing*. Once spectrum opportunities are identified, those spectrum resources are mapped into logical channels, where each logical channel is the unit of channel assignment.

In the past few years, several channel assignment strategies have been proposed for conventional² multi-channel wireless networks. In link-based channel assignment, channel assignment is performed at the granularity of a link between two given nodes. All packets on this link are transmitted on the same channel as long as the channel assignment does not change. The flow-based approach assigns channels at the granularity of a flow, i.e., packets of a flow are scheduled on the same channel. In [16], Vedantham et al. proposed *component*-based channel assignment. (See [16] for a precise definition of a component.) In this approach, nodes belonging to a set of intersecting flows (defined as a “component”) are assigned to the same channel. Vedantham et al. showed that the component-based approach’s theoretical performance does not lag significantly behind finer granularity channel assignment (i.e., link- and flow-based) approaches. They also showed that their channel assignment strategy has several practical advantages over existing strategies, such as the avoidance of channel switching delay and overhead as well as synchronization requirements.

It is not possible to apply component-based/flow-based channel assignment to CR networks because not all of the secondary nodes within a given component/flow have access to the same set of channels due to the temporal and spatial spectrum variability caused by primary user’s spectrum utilization. Hence, it is no surprise that existing channel assignment schemes for CR networks use the link-based approach [3, 4, 19, 20]. Unfortunately, the link-based approach suffers from the practical limitations mentioned above, degrading the overall performance of CR networks. In this paper, we propose a novel channel assignment strategy for CR networks that avoids most of the practical limitations of link-based channel assignment while conforming to the spectrum access rules of OSS.

In this paper, we consider the channel assignment problem in a single radio interface, CR ad hoc network, where each secondary user is equipped with a half-duplex cognitive radio. We propose a channel assignment strategy that uses the “segment” as the granularity of channel assignments. Nodes within intersecting flows (i.e., a component) can be grouped into one or more sets according to the set of channels available to each node—i.e., all nodes

¹ Throughout the paper, we assume that CR networks operate in licensed bands according to the OSS paradigm.

² We use the term a “conventional” wireless network to describe any network that does not operate in the OSS paradigm.

in the same segment have access to the same set of common channels. In Section IV, we present the details of a *segment*-based channel assignment strategy.

The channel assignment problem has an added dimension of complexity in the context of CR networks that does not exist in the context of conventional wireless networks. This complexity is the need to switch channels due to the temporal and spatial spectrum variability caused by primary users' spectrum utilization. Recall that in the OSS paradigm, secondary users operating in licensed bands must limit their transmissions to fallow bands and must vacate the current operating band and move to another band if the appearance of a primary user signal is detected. The proposed segment-based channel assignment strategy deals with the spectrum variability problem by incorporating an adaptive segment maintenance mechanism that includes mechanisms for segment merging and segment splitting. During the lifetime of a flow, a given segment may need to split into smaller segments or merge as part of a larger segment due to the appearance/disappearance of primary user signals in the current operating band. The splitting/merging of segments leads to channel switching. Channel switching is one of the major factors leading to performance degradation in link- and flow-based schemes. Practical limitations caused by channel switching include switching delay, scheduling overhead, and synchronization requirements. Although channel switching cannot be avoided completely in the context of OSS, the proposed channel assignment scheme minimizes the need for it by using the segment as the granularity of channel assignment. The contributions of this work are three-fold:

- We propose a segment-based channel assignment strategy for CR ad hoc networks that addresses the spectrum variability problem while avoiding the practical limitations of existing strategies.
- We present a distributed algorithm for realizing the proposed channel assignment scheme. It includes a joint channel assignment, segment formation and routing algorithm, and an adaptive segment maintenance mechanism.
- We provide analysis and simulation results that compare the performance of segment- and link-based channel assignment in the context of a CR ad hoc network.

The rest of this paper is organized as follows. Background and related work are presented in Section II, followed by a discussion of motivation in Section III. In section IV, we provide details on a distributed algorithm for supporting segment-based channel assignment. In section V, we present the simulation results and conclude the paper in Section VI.

II. BACKGROUND AND RELATED WORK

A. Channel Assignment in Conventional Multi-Channel Wireless Networks

1) *Packet-based channel assignment*: Channel assignment is performed on a per-packet basis by MAC

layer transmitter and receiver in a common control channel. The assignment does not apply to subsequent packets or other entities. Since different packets may be transmitted on different data channels, frequent switching between channels may be incurred, resulting in significant channel switching delay. Recent studies have found that channel assignment at such a fine granularity is not practical [2, 15, 16].

2) *Link-based channel assignment*: All packets on a wireless link between two nodes are transmitted on the same channel until the channel assignment decision expires. Each link in a flow can choose any one of the free channels. Two approaches SSCH [2] and MMAC [15] fall under the category of link level assignment. Note that existing channel assignment strategies for CR networks take the link-based approach, such as [3, 4, 19, 20]. The major pitfall of a link-based approach is the significant channel switching delay incurred when a node serves two links on different channels.

3) *Flow- and component-based channel assignment*: In flow-based channel assignment, all packets belonging to a flow are transmitted on the same channel. Different flows may operate on different channels.

A graph is connected if there is a path connecting every pair of vertices. A graph that is not connected can be divided into connected components (disjoint connected sub-graphs). A component in the context of channel assignment is similarly defined as a connected sub-graph in the network flow graph, which is composed of nodes belonging to intersecting flows. In component-based channel assignment, all nodes within a component are assigned the same channel. If there are no intersecting flows, the component-based assignment is equivalent to the flow-based assignment.

B. Spectrum Allocation in Cognitive Radio Ad Hoc Networks

Existing MAC protocols for CR networks employ the link-based channel assignment strategy [3, 4, 19, 20]. Therefore, they suffer from the practical limitations of the link-based strategy. Those limitations include switching delay, synchronization requirements, and scheduling overhead. Note that channel switching is required in the link-based approach when an intersection node serves two links in different channels.

In [4], the authors formulated the spectrum allocation problem as a graph multi-coloring problem. They proposed a protocol that uses a distributed local bargaining algorithm to maximize the network throughput. In [20], Zheng et al. propose a spectrum management scheme in which users observe local interference patterns and act independently according to a set of rules that define the tradeoff relationship between performance and complexity and communication costs.

A common feature shared by some cognitive MAC protocols (i.e., MAC protocols designed for CR networks) is the use of a global or local common control channel. Two neighboring nodes can exchange available channel information or negotiate channel assignments for a link via the control channel. In [11, 13], the authors propose a

global control channel to carry out MAC-layer control mechanisms in the OSS paradigm. The cognitive MAC protocol presented in [14] is based on the Dynamic Channel Assignment protocol [18]. Those protocols take the packet-based channel assignment approach. In [19], Zhao et al. proposed a distributed coordination scheme for spectrum allocations that addresses the spectrum variability problem without using a global control channel. Instead, their scheme uses a group coordination channel which is a local control channel.

Schemes that rely on a global or local control channel are hampered by the control channel saturation problem [15]. Furthermore, in a single radio interface scenario, frequent switching between data channels and the control channel is required when a channel/spectrum assignment scheme that requires a control channel is employed. The proposed segment-based channel assignment scheme does not require a control channel.

III. MOTIVATION FOR SEGMENT-BASED CHANNEL ASSIGNMENT

In this section, we compare the segment-based channel assignment strategy with the link-based approach.

A. Segment-Based Channel Assignment

In conventional multi-channel wireless networks, all channels are fixed in terms of frequency and bandwidth. In CR networks, the spectrum opportunities dynamically vary according to the primary users' transmissions. A flow that traverses through areas within the range of transmitting primary users experiences dynamically changing channel availability. Thus, it is not possible to assign the same channel to all the links within a flow or component due to the presence of primary signals. This means that flow- and component-based channel assignment algorithms used in conventional wireless networks cannot be applied in CR networks. For this reason, existing channel assignment schemes for CR networks use the link as the granularity of channel assignment. Unfortunately, the link-based approach incurs performance disadvantages due to frequent channel switching. Note that an intersection node that serves multiple links or flows in different channels needs to carry out channel switching. The aforementioned drawbacks include switching delay, synchronization requirement, and scheduling overhead. The latter two drawbacks can be mitigated by employing a control channel. This approach, however, is not desirable with single radio nodes as it requires frequent switching between the control channel and the data channels.

To address the drawbacks of the link-based approach, we propose a new channel assignment strategy that uses the *segment* as the granularity of channel assignment. The proposed approach addresses the spectrum variability problem (caused by primary user transmissions) by considering spectrum sensing results in channel assignment decisions, and outperforms the link-based approach by requiring less frequent channel switches.

Before defining the terms *segment* and *segment-based channel assignment*, we need to define the term *component*. A *component* in a flow graph³ is defined as a maximally connected sub-graph [17] such that there exists a path from any node in the sub-graph to all other nodes in the sub-graph. Next, we define the following terms:

Definition 1: A *segment* is defined as the maximal sub-graph of a component in which all nodes in the sub-graph have access to at least one common channel.

Definition 2: The two nodes at both ends of a link that connects two segments of the same component are defined as *segment gateway nodes*.

The segment-based channel assignment strategy assigns the same channel to all nodes within a segment while conforming to the spectrum utilization rules of the OSS paradigm. The assigned channel is called the *operation channel* of that segment. An illustration of the segment-based channel assignment strategy is shown in Fig. 1.

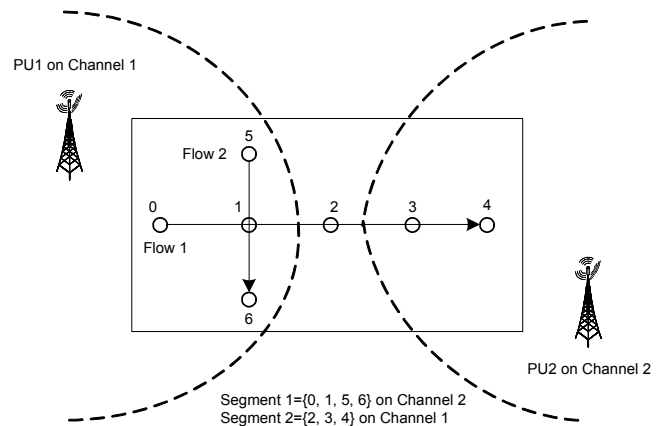


Fig. 1: An illustration of segment-based channel assignment.

Due to the spatial variability in spectrum opportunities, secondary users in different locations may detect different spectrum “white spaces”. Suppose there are two primary user transmitters, PU_1 and PU_2 , transmitting in channels 1 and 2, respectively. We assume that the primary network is a TV broadcast network. There is an ad hoc network composed of CR nodes, coexisting with those two primary users. There are two channels in total and two data flows: *Flow 1* from node 0 to node 4 and *Flow 2* from node 5 to node 6. Due to PU_1 on channel 1 and PU_2 on channel 2, the only available channel for nodes $\{0, 1, 5, 6\}$ is channel 2, while the only available channel for nodes $\{3, 4\}$ is channel 1. Node 2 is outside the interference range of the two primary transmitters, and hence has access to both channels. If Definition 1 is applied to the scenario given in Fig. 1, then one can see that nodes $\{0, 1, 5, 6\}$ form one segment and nodes $\{2, 3, 4\}$ form another segment. Note that node 2 can belong to either segment by Definition 1. In Fig. 1, nodes 1 and 2 are the gateway nodes.

In the above discussions, we have implicitly assumed that the channels of a primary network are equivalent to those of

³ The set of active links carrying flow traffic in a network.

a secondary network. However, this may not be true. For example, the IEEE 802.22 standard [8] supports *channel bonding* such that up to 3 TV channels of a primary network can be bonded to one channel for use by the secondary network to support high-bandwidth applications. Since our assumption regarding the channels does not affect our discussions of the proposed segment-based channel assignment scheme, we will continue to make this assumption for the sake of simplicity.

B. Performance Considerations

Link- and flow-based approaches require channel switching when a node serves two links or two flows on different channels. The segment-based approach requires channel switching when two segment gateway nodes on different channels need to communicate with each other. In the following discussions, we compare the segment-based approach with the link-based approach using flow capacity and network capacity.

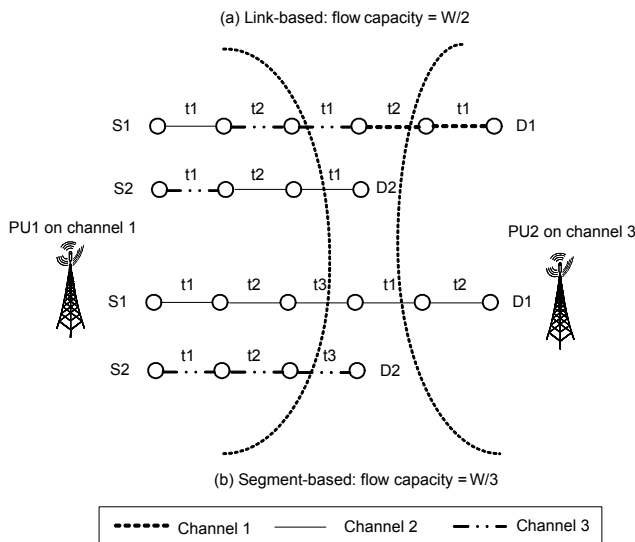


Fig. 2. Channel and slot assignments for contending flows.

1) Flow capacity:

In the following analysis, we make the following assumptions: (1) a total of three channels; (2) switching delay is ignored; (3) a two-hop interference region for the secondary network; and (4) links within the same interference region in the same channel are assigned to different slots. We analyze two different cases.

Case 1: Contending flows

We compare the flow capacity of link- and segment-based approaches for the case of contending flows⁴. Fig. 2 shows the slot and channel assignments for two contending flows. The operation channels of the two primary users are also shown. We observe that it is possible to assign the slots in such a way that links within the same contention region

⁴ Two flows are said to be contending, if there is at least one node in the set of active nodes of one flow that is within the interference region of the set of active nodes of the other flow.

are assigned to different slots. In the following discussions, we assume that the link capacity is W .

Using the link-based channel assignment, the per-flow capacity is limited to $W/2$, irrespective of the number of channels and the slot schedule if we assume that each node is equipped with a single, half-duplex radio. In Fig. 2 (a), the two contending flows each achieve a per-flow capacity of $W/2$ by using channel and slot assignment schemes that utilize three channels and two slots, t_1 and t_2 .

In the segment-based approach, a single flow may be divided into one or multiple segments. The per-flow capacity is limited by the segment that has the smallest capacity value within the flow. In Fig. 2 (b), there is only one segment in each flow. The maximum flow capacity of each contending flow is $W/3$, which is equal to the maximum per-flow capacity of a single flow using segment-based channel assignment.

From the above discussions, we can conclude that the per-flow capacity for both link- and segment-based channel assignment strategies is $O(W)$ for non-intersecting, contending flows.

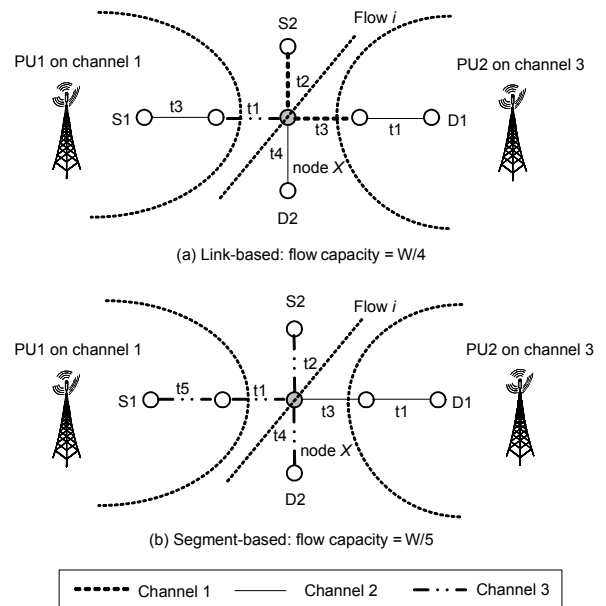


Fig. 3. Channel and slot assignment for intersecting flows.

Case 2: Intersecting flows:

Fig. 3 shows an example of intersecting flows. Node X is the intersection node. Note that when two flows intersect, the per-link capacity is upper bounded by $W/4$ because the capacity of the links around the intersection node is limited to $W/4$ due to the fact that each node is equipped with a single half-duplex radio. In the link-based approach, the per-flow capacity is $W/4$, as shown in Fig. 3 (a). In the segment-based approach, we need to schedule five slots to avoid interference around the intersection node X . Hence, the per-flow capacity is $W/5$.

If we add one more flow (Flow i in Fig. 3) intersecting at node X , two more slots need to be scheduled. Suppose n flows intersect at node X , then the *aggregate* flow capacity

of n flows under the link- and segment-based approaches are each given by the following equations:

$$\text{Aggregate capacity}_{\text{link}} = \frac{W}{2n} \cdot n = \frac{W}{2}, \quad (1)$$

$$\text{Aggregate capacity}_{\text{segment}} = \frac{W}{2n+1} \cdot n = \frac{W}{2+1/n}. \quad (2)$$

From the above equations, we observe that the aggregate flow capacity of n intersecting flows under both channel assignment strategies is $O(W)$.

In the above discussions, we ignored the detrimental effects of channel switching on network performance; we investigate this issue next.

2) Network Capacity:

When forwarding a packet, a secondary node needs to switch channels if two neighboring links are assigned to different channels. For a typical 802.11 card, the switching delay is of the order of 80-100 μs , and the transmission time for a 1 KB packet at 54 Mbps is 160 μs [16]. Thus, the switching delay in the aforementioned example is of the same order as the transmission time of a data packet. The switching delay contributes to the increase in the end-to-end delay of each packet's transmission as the switching delay is additive across all nodes that perform switching. According to [10], a wireless network's capacity C degrades as a function of $S / (S + T)$, where S is the switching delay and T is the transmission time. Suppose that there are x intermediate nodes in one flow that serve two neighboring links on different channels. Also, suppose that the flow is divided into y segments. The channel switching delay is t_s . The additive switching delay for link- and segment-based approaches is given by the following relations:

$$S_{\text{link}} = x \cdot t_s \text{ and } S_{\text{segment}} = (y-1) \cdot t_s.$$

Typically, the number of segments in a given flow (when using segment-based channel assignment) is much less than the number of nodes that need to perform channel switching (when using link-based channel assignment), thus $y < x$. Assuming other factors are the same, the capacity degradation caused by the switching delay in the link-based approach is greater than that in the segment-based approach. Thus, we can conclude that $\text{Capacity}_{\text{link}} < \text{Capacity}_{\text{segment}}$.

IV. SEGMENT-BASED CHANNEL ASSIGNMENT

In this section, we present a distributed approach for realizing the segment-based channel assignment strategy. The proposed approach includes a channel assignment scheme and an adaptive segment maintenance scheme.

A. Initial Handshake

Before communicating with neighboring nodes, a secondary node needs to inform its neighbors about its current operation channel and the list of channels that is available to it. Each node in the network is required to broadcast an *initial message* (IM) on all of its available channels in a round-robin manner; this procedure is similar to the initial handshake procedure proposed in [19]. The IM

of node i includes information regarding its available channel set A_i and its operation channel. Through the received IMs, a node acquires knowledge about the available channels and the operation channel of each neighboring node. Once the initial handshake is finished, the channel assignment process can start. Note that the proposed channel assignment scheme performs channel assignment, segment formation, and route discovery in an integrated manner. A node needs to broadcast an updated IM to its neighbors every time it changes its operation channel or revises its list of available channels.

B. Channel Assignment

The proposed channel assignment scheme can be integrated into any routing protocol for wireless ad hoc networks in which the source node of a flow initiates the route discovery process. Here, we take Dynamic Source Routing (DSR) [9] as an example.

1) Route request propagation

The proposed scheme's route request propagation phase is similar to the route request broadcast in DSR, and is described below.

(1-1). A source node broadcasts a route discovery request (RREQ) message on all of the operation channels of its neighboring nodes. The operation channels of the neighbors are obtained from the IMs collected in the initial handshake phase.

(1-2). When an intermediate node j receives the RREQ message, it piggybacks channel contention information on it and broadcasts the modified RREQ message to its neighbors. Specifically, $(cl_j(i_1), cl_j(i_2), \dots)$ is piggybacked on the RREQ, where $cl_j(c)$ is the *contention level* of channel $c \in A_j$ perceived by the intermediate node j . The contention level of a channel is defined as the number of neighboring nodes that may potentially access this channel. The contention level value is calculated using the information in the IMs exchanged in the initial handshake procedure. As an example, let us calculate the value $cl_j(c)$. Suppose an intermediate node j has a set of neighbors represented by N_j , and each neighbor r has an available channel set A_r —both values can be obtained from the IMs. For $\forall c \in A_j$ and $r \in N_j$, we define an indicator function as

$$I_j(c, A_r) = \begin{cases} 1, & \text{if } c \in A_r, \\ 0, & \text{otherwise.} \end{cases}$$

Then, the contention level of channel $c \in A_j$ perceived by node j can be calculated according to

$$cl_j(c) = \sum_{r \in N_j} I_j(c, A_r).$$

The channel contention level values are used in making channel selection decisions.

(1-3). Using the received RREQs, the destination node constructs a set of disjoint paths and selects the shortest path from the set. Here, we assume the shortest-path (i.e., the path with the minimum hop number) selection policy. Then the destination node transmits a route reply (RREP) message back to the source via the reverse path, and prepares for channel assignment and segment formation.

2) Route reply and channel assignment

In a network of secondary nodes, different portions of a route may use different channels due to channel availability influenced by spectrum variability. Suppose A_j denotes the list of available channels for node j . Then, each route has a corresponding available channel set, represented by A_1, A_2, \dots, A_k , where k is the number of nodes on the route. In order for a route to be valid, relation (3) needs to be satisfied:

$$A_j \cap A_{j+1} \neq \emptyset, j = 1, \dots, k-1. \quad (3)$$

Relation (3) is satisfied when every pair of neighboring nodes on the route has at least one common channel available to both nodes. The RREP message transmitted by the destination node traverses through the k nodes towards the source node via the reverse-path.

(2-1). Destination node k selects an available channel i^* with the smallest contention level value from set A_k , i.e.,

$$i^* = \arg \min_{i \in A_k} \sum_{j=1}^k cl_j(i). \quad (4)$$

Destination node k records its assigned channel as $ch_k = i^*$. The contention level values are obtained from the piggybacked information in the RREQs. Destination node k creates a new segment s_k and assigns itself to this segment. This new segment currently includes only one node, namely node k . The destination node piggybacks the 3-tuple (s_k, ch_k, A_k) in an RREP and sends it on the operation channel of the next node upstream⁵ (i.e., node $(k-1)$).

(2-2). When an RREP (with the piggybacked tuple) is received on its operation channel, an intermediate node j checks to see whether it is already associated with an existing segment, s^* , and assigned to a channel, ch_{s^*} . i.e., it checks whether $s_j = s^*$ and $ch_j = ch_{s^*}$. If node j is already associated with a segment, it ignores the piggybacked information in the RREP. Then, node j notifies all the downstream nodes in its flow that are within the same segment about the channel assignment and the segment association. After receiving the notification message, each notified node resets its assigned channel as ch_j and segment association as s_j . Next, node j piggybacks the tuple (s_j, ch_j, A_j) in the RREP and sends it to the next node upstream (i.e., node $(j-1)$) on the operation channel of node $(j-1)$.

(2-3). Suppose that an intermediate node j has not committed to any existing segment and

$$ch_{j+1} \in A_j, j = 1, \dots, k-1. \quad (5)$$

That implies that node j can access the operation channel of the downstream neighbor node $(j+1)$. Thus, node j selects the same channel and associates itself with the same segment as node $(j+1)$, i.e., $ch_j = ch_{j+1}$ and $s_j = s_{j+1}$. Node j piggybacks the tuple (s_j, ch_j, A_j) in the RREP and sends it to the next upstream node (i.e., node $(j-1)$) on the operation channel of node $(j-1)$.

(2-4). If node j is not committed to any existing segment and relation (5) does not hold, then node j creates a new segment, s_j , and selects a channel from A_j as its operation channel, ch_j . When selecting a channel, node j applies the

same rule that the destination node applied in selecting its operation channel (see step (2-1)). Node j piggybacks the tuple (s_j, ch_j, A_j) in the RREP and sends it to its upstream node.

(2-5). When the RREP arrives at the source node, the source generates an ACK and sends it to downstream nodes of this route on their current operation channels to notify them that it has received the RREP. When a downstream node receives an ACK from the source, the operation channel and segment association selected by this node take effect. In Fig. 4, we have applied the aforementioned channel assignment scheme to a simple two-segment network as an example.

Note that our protocol uses the RREP messages to perform channel assignment as opposed to using RREQ messages (cf. [16]).

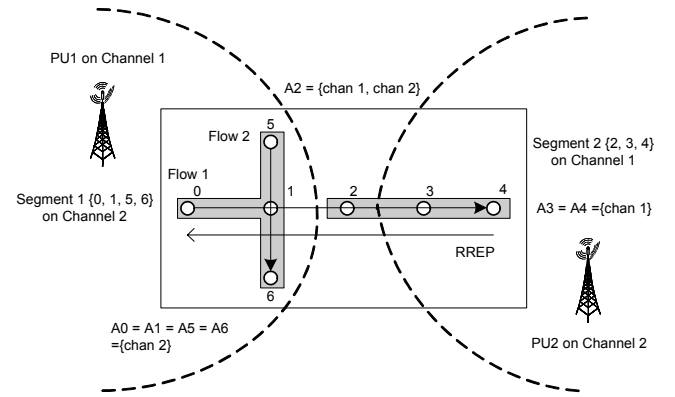


Fig. 4. Two segments are formed via the segment-based channel assignment approach.

C. Segment Maintenance

The temporal changes in the primary users' utilization of the spectrum would cause changes in spectrum availability for the secondary users, in turn, causing some of the secondary nodes to switch to a different channel. This, in turn, would induce changes in the segments within a secondary network. Two scenarios can occur: *segment splitting* and *segment merging*. In the following discussions, we discuss both scenarios.

1) Segment splitting:

The appearance of a primary user's signal in a spectrum band that is currently occupied by secondary nodes causes those secondary nodes to vacate that band and move to a fallow band by switching to another channel. Note that the appearance of a primary user does not necessarily require all of the nodes within a segment to switch channels; only a subset of the nodes may need to switch. Suppose that an intermediate node j detected the presence of a primary user signal and needs to switch to a different channel. Node j triggers a Channel Change message (CCHG) which is propagated towards the source (using the current operation channel). After receiving the CCHG, the source node generates a Route Repair message (RR) and sends it downstream via the current route. RR is forwarded towards the destination until it reaches node j^* . Node j^* is the node

⁵ The upstream direction is the direction from the destination to the source. The downstream direction is the converse of upstream.

closest to the source node among the nodes that generated a CCHG. Node j^* initiates a route request propagation procedure to re-establish a new route to the destination. The procedure is the same as the one described in Section IV-B. This triggers another round of channel assignments for all nodes downstream of node j^* . This new channel assignment procedure will lead to the splitting of the current segment into two or more smaller segments.

2) Segment merging and its tradeoffs:

As noted in [16], the performance limitation of link- and flow-based channel assignment schemes is primarily due to the switching delay and overhead incurred when an intersection node serves two links/flows in different channels. Hence, minimizing the number of channel switchings can enhance performance significantly. In the context of the proposed segment-based channel assignment scheme, the number of channel switchings can be reduced when one takes advantage of a scenario in which an active primary user halts transmitting and releases a previously occupied band. By utilizing the recently released band, the secondary network may be able to reduce the number of segments, thus reducing the number of segment gateway nodes that need to carry out channel switching. An example is shown in Fig. 5. In this figure, Primary User 2 (PU_2) has halted its transmission, thus releasing Channel 2, and enabling nodes 2, 3, and 4 to use Channel 2. Now, all nodes can be associated with a single segment that uses Channel 2. Comparing Figs. 4 and 5, we can see that the merging of the two segments into one will no longer require node 1 to carry out channel switching.

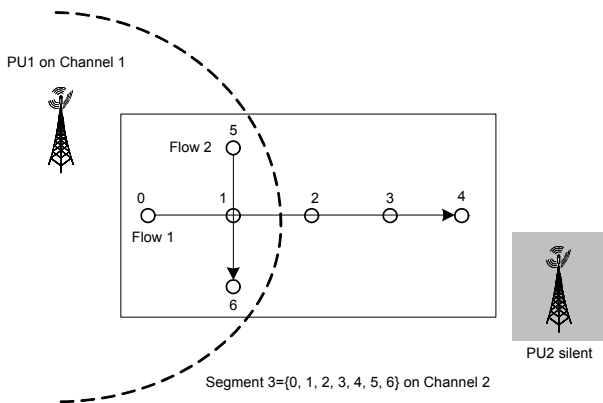


Fig. 5. Two segments merge into one if primary user 2 is silent.

As noted above, the primary benefit of segment merging is the reduction of costs associated with channel switching (such as delay and overhead). However, segment merging is not always beneficial. Note that the segment merging process itself requires some nodes to perform a one-time channel switch. In fact, segment merging may even degrade performance when the period of the primary users' on/off cycle is short relative to the lifetime of a flow. For instance, if primary signals occupy and release the current band occupied by the segment's channel with high frequency, then multiple instances of segment merging and splitting

may occur during the lifetime of a flow. In such a scenario, the overhead of segment merging/splitting would outweigh the benefits of segment merging, thus leading to poor performance. An interesting avenue for future research is investigating the tradeoffs of segment merging and its relationship to the performance of the secondary network.

V. PERFORMANCE EVALUATION

A. Simulation Environment

Throughout this section, we compare the proposed segment-based channel assignment scheme with the link-based channel assignment scheme. The simulations are carried out for a $1000m \times 1000m$ square area with 50 secondary nodes placed randomly via a uniform distribution. All nodes are stationary. The transmission range of each secondary node is $250m$. We assume the existence of two primary signal transmitters—one transmitting in channel 1 and located at coordinates $(0, 500)$, and the other one transmitting in channel 2 and located at coordinates $(1000, 500)$. Fig. 6 illustrates a snapshot of a randomly generated network topology in one simulation run. The two semicircles in Fig. 6 represent the interference range of the primary users. In each simulation run, we randomly selected 10 pairs of secondary nodes to create 10 UDP flows. We only illustrate five source-destination pairs among those ten pairs in Fig. 6. The source and destination of each pair is connected by a dashed line. The solid lines represent the routing paths. In Fig. 6, a node with a circle around it means that it is a source, while a node with a square around it means that it is a destination. The default channel capacity is 1Mbps, and the channel switching delay has a constant value of $100\mu s$. To simulate the proposed channel assignment scheme, we modified DSR to support channel assignments at the granularity of segments. In the simulated link-based approach, a link is assigned to a channel that has the smallest contention level value. For comparing the two channel assignment approaches, two evaluation metrics were used: average throughput and end-to-end delay. All results shown here are the results of averaging 10 simulation runs for each experiment.

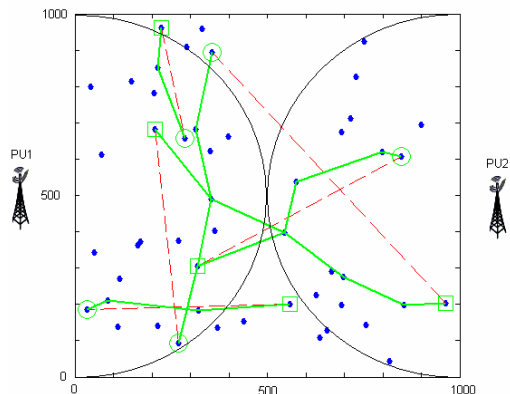


Fig. 6. A snapshot of a randomly generated network topology used in one simulation run.

B. Simulation Results

The simulation result shows superiority of our segment-based approach in performance over the link-base approach.

1) Invariant primary user transmission

We assume that the two primary users transmit during the entire duration of the simulation time interval. The total number of available channels is five. In Fig. 7, we compare the two channel assignment approaches using the average throughput of 10 UDP flows. The abscissa axis represents the simulation time interval.

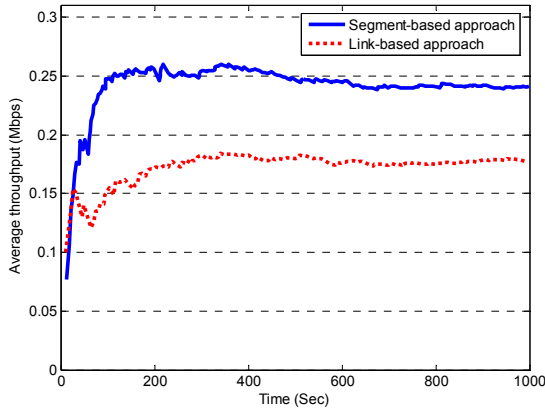


Fig. 7. Average throughput vs. time.

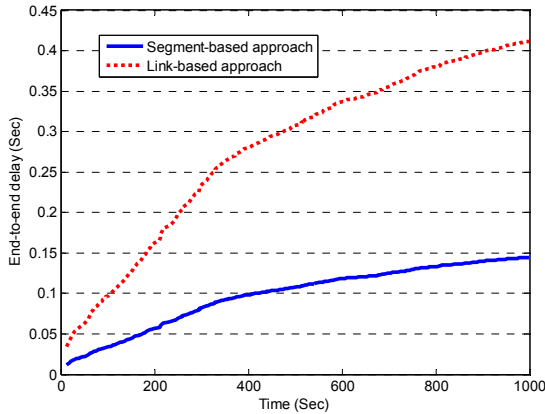


Fig. 8. Average end-to-end delay vs. time.

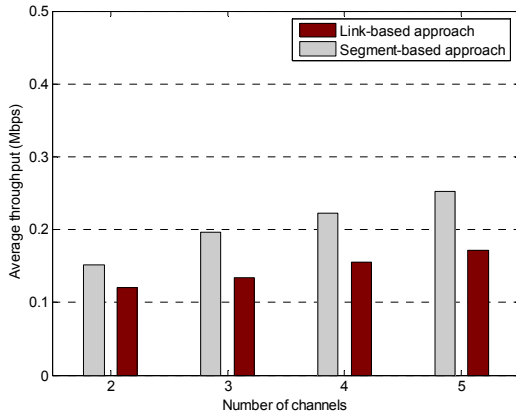


Fig. 9. Average throughput vs. number of channels.

In Fig. 8, the average end-to-end delay versus time is plotted. Note that the link-based approach incurs a higher

end-to-end delay because it requires a greater number of channel switchings. We also compared the average throughput of the two channel assignment schemes while varying the number of available channels. The results are shown in Fig. 9. We varied the total number of channels from 2 to 5.

2) Segment merging in the presence of variant primary user transmission

To maintain an adequate level of performance, it is expected that the secondary network will choose to use licensed spectrum bands in which primary users' transmission pattern is not extremely dynamic (i.e., do not change very frequently). Thus, here we do not consider the case in which the primary users' transmission pattern varies frequently. We carried out a set of simulation experiments in which the primary user PU_2 (operating in channel 2) has the following transmission schedule: it starts transmitting at the 0th sec; turns off at the 600th sec; restarts transmitting at the 1000th sec; and turns off again at the 1600th sec. The total simulation time is 2000 seconds. We compared the average throughput of three channel assignment schemes: segment-based approach without segment maintenance, segment-based approach with segment maintenance (i.e., segment merging and segment splitting), and link-based approach. The second approach performs segment merging when PU_2 turns off to utilize the freed channel, and performs segment splitting when PU_2 turns back on to avoid interfering with the primary signal transmission.

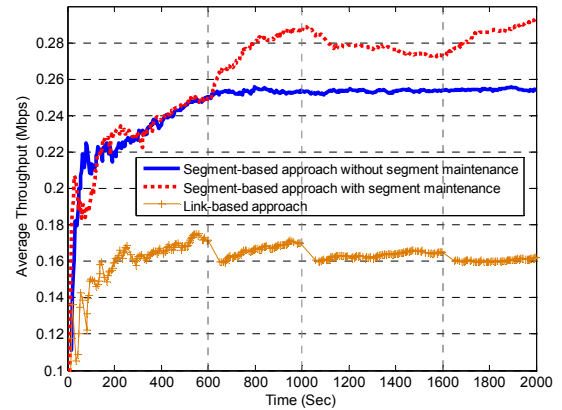


Fig. 10. Comparisons on the average throughputs of three protocols.

In Fig. 10, we observe that the segment merging process used by the second channel assignment scheme causes the average throughput to improve. We can clearly see the throughput curve of the second scheme follow a positive slope during PU_2 's two off time periods (i.e., [600, 1000] and [1600, 2000]). During the interval [1000, 1600], the throughput curve of the segment-based channel assignment scheme with segment maintenance follows a negative slope due to the delay and overhead involved in segment splitting.

VI. CONCLUSION

In this paper, we have considered the channel assignment problem in single radio interface, CR ad hoc networks. We

have proposed a novel channel assignment scheme that assigns channels at the granularity of *segments*. In the OSS paradigm, the temporal and spatial spectrum variability caused by the primary users' spectrum utilization adds another dimension of complexity to the problem of channel assignment. Existing channel assignment approaches—such as link-based and flow-based approaches—do not consider spectrum variability because they were originally designed for conventional wireless networks. Therefore, those approaches do not offer the best trade-off in terms of complexity and performance in the OSS model. The proposed channel assignment scheme is significantly simpler than the existing approaches, and offers practical benefits. Using simulation results, we have demonstrated that the segment-based channel assignment scheme outperforms the link-based channel assignment approach under realistic network conditions.

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