CRP: A Routing Protocol for Cognitive Radio Ad Hoc Networks

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***Abstract*—Cognitive radio (CR) technology enables the opportunistic use of the vacant licensed frequency bands, thereby improving the spectrum utilization. However, the CR operation must not interfere with the transmissions of the licensed or primary users (PUs), and this is generally achieved by incurring a trade-off in the CR network performance. In order to evaluate this trade-off, a distributed CR routing protocol for ad hoc networks (CRP) is proposed that makes the following contributions: (i) explicit protection for PU receivers that are generally not detected during spectrum sensing, (ii) allowing multiple classes of routes based on service differentiation in CR networks, and (iii) scalable, joint route-spectrum selection. A key novelty of CRP is the mapping of spectrum selection metrics, and local PU interference observations to a packet forwarding delay over the control channel. This allows the route formation undertaken over a control channel to capture the environmental and spectrum information for all the intermediate nodes, thereby reducing the computational overhead at the destination. Results reveal the importance of formulating the routing problem from the viewpoint of safeguarding the PU communication, which is a unique feature in CR networks.**

***Index Terms*—Ad Hoc Networks, Cognitive Radio, Optimization, Routing, Spectrum**

I. INTRODUCTION

COGNITIVE radio (CR) technology aims to enhance the spectrum utilization in the licensed frequencies, and also alleviate the congestion in the 2.4 GHz ISM band. Recent research in this area has mainly focused on spectrum sensing and sharing issues in infrastructure-based networks that relies on the presence of a centralized entity for collecting the spectrum information, deciding the best possible spectrum for use, and allocating transmission schedules to the CR users served by it. Moreover, such architectures are generally single-hop, with each CR directly communicating with the central entity as the end destination. Thus, the application of CR technology in distributed scenarios is still in a nascent stage, and several open research challenges are outlined in [1]. This paper proposes a CR routing protocol for ad hoc networks (CRP) that specifically addresses the concerns of end-to-end CR performance over multiple hops, and the problem of protecting the PU transmissions from interference with limited knowledge of the environment.

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Classical routing algorithms for wireless ad hoc networks attempt to optimize an end-to-end metric such as latency, number of hops, among others. There is a rich literature on classical routing protocols that use network-wide broadcast without any localization information, greedily forward packets based on the destination location, or use limited network information spanning several hops to improve the choice of path. However, these approaches are not suited for CR operation as there is no support for simultaneously choosing the spectrum band (each of which may have several channels), or considering the effect routes may have on other licensed devices sharing the spectrum. To address these issues, several works have been recently proposed for CR networks [7][9][13][16]. In our proposed approach, we consider several key CR-specific performance metrics that are not incorporated in these related works. We list them as follows:

A. Explicit protection for PU receivers:

CR users periodically sense the spectrum and decide on the spectrum availability. Typically, the CR users that are located in regions with fewer cases of positive PU transmission detections may be preferred for routing. However, this approach only guarantees protection to the PU transmitters that are within the range of the CR devices. For certain PU applications such as television broadcast, the transmission is uni-directional, and the PU transmitters do not suffer from CR network interference. Rather, transmission by neighboring CR users may affect the PU receivers that cannot be detected easily (no transmission, low leakage power from the reception circuitry). The CR routing protocol must provide protection to these PU receivers by avoiding entire regions where such devices may possibly be present, and this has yet not been addressed in the existing literature.

B. Allowing CR routing classes:

The protection provided to the PUs results in a performance tradeoff for the CR network operation. As an example, the CR network may proactively avoid regions of PU activity, thereby incurring longer paths with an aim of reducing the possibility of interference to the PUs. Depending upon the desired level of protection for the PU activity, and the CR user's end-to-end latency demands, multiple classes of routes are possible. CRP considers two routing classes, with *class I* assigning higher significance to end-to-end latency while meeting minimum PU interference avoidance. As opposed to this, *class II* routes prioritize the PU protection at a higher level by allowing a permissible performance degradation to the CR operation. The possibility of service differentiation through different traffic classes has not been explored well in the current state-of-the-art protocols.

C. Scalable joint route-spectrum selection

CR devices may use licensed bands spread over several different spectrum. As an example, the Federal Communications Commission (FCC) has initiated steps to free up bandwidth in the $54-72\,\mathrm{MHz}$, $76-88\,\mathrm{MHz}$, $174-216\,\mathrm{MHz}$, and $470-806\,\mathrm{MHz}$ bands. In addition, each spectrum band may be composed of multiple channels of varying bandwidths. Thus, the potential frequency range for CR transmission is very large, and transmitting route requests (RREQs) in each channel of the different bands adds a considerable overhead. Moreover, frequent network-wide broadcasts significantly increase the probability of interference to the PUs. One solution to this problem is the use of a single common control channel (CCC) during route formation. In CRP, the characteristics of the chosen spectrum by a given CR user are mapped to a delay function on the CCC, and this is independent of the number of possible spectrum bands. This design also allows the propagation of the RREQ packet over the CCC to accurately reflect the conditions on the actual spectrum that will be used for the data transfer. In addition, the spectrum and node selection are undertaken simultaneously, as sequentially undertaking these assignments does not guarantee a feasible solution.

The route setup in CRP follows two stages. In the first stage, each CR user identifies the best spectrum band based on local environmental observations. An optimization function is developed for each class of CR route, which also serves as a measure of the *initiative* displayed by the CR user for participating in the route. In the second stage, the *initiative* is mapped to a delay function for forwarding the RREQ message. This delay establishes a ranking of the neighboring candidate forwarding nodes, with the preferred users broadcasting the RREQ earlier. The destination chooses the final route that best meets the goals of the desired routing class by a route reply (RREP). Moreover a route maintenance scheme allows re-construction of a partially broken route caused by node mobility and PU activity. We make no limiting assumptions on the specific choice of the spectrum sensing method, or the MAC protocol at the link layer. We have adopted the classical IEEE 802.11b protocol to demonstrate that our routing approach can be used with any existing method preferred by the CR users. Our approach permits the tried and tested modular design, wherein individual protocol implementations can function without any changes to the other layers of the network protocol stack as long as information such as the (i) physical layer transmission parameters, (ii) channel coherence bandwidth, (iii) the link layer spectrum sensing, switching times, and (iv) variance in the link throughput are written to a common memory space and made accessible to CRP.

The rest of this paper is organized as follows. Section II describes the related work in this area. This is followed by a description of the working of our protocol in Section III. The two stages of the protocol, the spectrum selection stage and the next hop selection stage are detailed in Sections IV and V, respectively. Section VI gives the route maintenance, and a thorough performance evaluation is conducted in Section VII. Finally, Section VIII concludes our work.

II. Related Work

Recent work in the area of distributed CR routing protocols has been undertaken for (i) general ad hoc networks, and (ii) networks with specific architectural assumptions, as follows:

A. General ad hoc networks

In the multi-hop single-transceiver CR routing protocol (MSCRP) [9], analogous to the classical AODV, the RREQ is forwarded over all the possible channels to the destination. The latter then decides on the spectrum selection for the shortest path based on analytical estimates of the time for spectrum switching, channel contention, and data transmission. Similarly, the best routing paths are first identified and *then* the preferred channels along the path are chosen in [3]. In both these works, the sequential path selection and spectrum allocation does not guarantee that spectrum is available along the path optimized for classical metrics, such as latency or hop count. Moreover, the flooding of the RREQ in all the channels of the spectrum [9] or using the RREQ packet transmitted over the CCC to carry information of the entire spectrum [3] raises concerns of scalability. The protocol proposed in [15] uses a combination of routing and link scheduling to reduce intra-CR interference and spectrum switching costs. A multi-agent learning approach named adaptive fictitious play is described in [13]. The CR users exchange their channel selection information periodically that also provides information of the extent to which the different classes of traffic (delay sensitive or otherwise) on a given channel is affected. The fictitious play algorithm learns the channel decision strategies of the neighboring CR users over time to identify the channels that are likely to be used by them. However, it is not clear how long the network would take to converge on the optimal solution, with the assurance of a stable operating point in the presence of varying PU activity.

B. Networks with specific architectural assumptions

Several existing works assume knowledge of the entire topology graph, with known edge weights between any given node pair. Such an approach is seen in [7], wherein the edge weights represent the wireless capacity, and are calculated probabilistically based on interference from the PUs, the received signal strength, among others. A path-centric spectrum assignment framework (CogNet) is proposed in [16] that constructs a multi-layered graph of the network at each node such that the edge weights of the graph represent the spectrum availability between the nodes. In either case, a Dijsktra or Bellman Ford-like algorithm is run over the topology graph to find the optimal path. The dissemination of the network-wide edge weights to each node incurs a prohibitive overhead, as is hence not suited for ad hoc network routing. Other works have also been proposed for mesh networks arranged in a tree hierarchy [6][10].

Our work focuses on CR ad hoc networks, without assumptions of specific network topologies, and where each user has

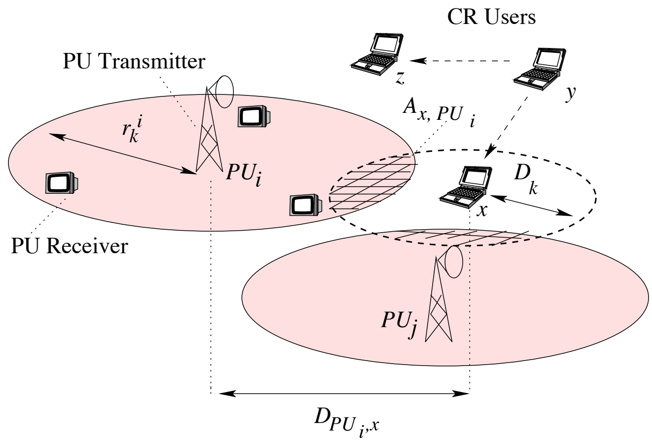


Fig. 1. Choosing next hop forwarding nodes based on spectrum selection.

limited knowledge of the environment. Moreover, we believe that the consideration of the PU receivers, CR traffic classes and scalable routing approaches uniquely distinguish CRP from the other works in the literature. Our aim in this paper is to provide network layer support for multi-hop CR networks, thereby allowing the use of any underlying MAC protocol or physical layer spectrum sensing techniques. Several works have been proposed that derive the transmission durations with respect to a target sensing error probability [14], use advanced signal processing techniques such as cycle-stationary feature detection [12], or leverage cooperation for increasing accuracy [11]. However, these approaches often (i) employ theoretical assumptions, such as simplified PU models, (ii) detect the PU transmitters only and not receivers, and (iii) are not guaranteed for perfect detection. Thus, while any of these methods can be used at the lower layers of the stack, we believe the network layer must also provide independently a measure of protection to the PU receivers.

III. CRP Routing Protocol Overview

The route-setup in the CRP protocol is composed of two stages - (i) the *spectrum selection* stage, and the (ii) *next hop selection* stage. The source node broadcasts the RREQ over the control channel, and this packet is propagated to the destination. Each intermediate forwarder identifies the best possible spectrum band, and the preferred channels within that band during *spectrum selection*. To enable this, we have proposed several unique CR metrics that are weighted appropriately in an optimization framework for choosing the spectrum. Moreover the function is cast differently for each Class of CR route. As an example, for the *class I* route, the CR network end-to-end latency is the key consideration. Here, the spectrum chosen by a given candidate forwarding node must (i) support the highest propagation distance, with the (ii) longest allowed duration for transmission given the sensing schedules of the neighboring nodes. Consequently, the optimization function for *class I* route attempts to maximize these two factors during the *spectrum selection* stage.

The next stage is the *next hop selection* stage, where the candidate CR users rank themselves depending on the choice of the spectrum and the local network and physical environmental conditions. These ranks determine which CR

TABLE I
Symbols used for CRP description

Symbols	Descriptions
ψ_D	Bandwidth requested by user
ψ_k	Bandwidth of each channel in spectrum k
N_s	Total number of spectrum bands
N_p	Number of stationary PU transmitters
M_B^k	Spectrum bandwidth availability probability
V_B^k	Variance in bandwidth availability
$T_\triangle^s$	Inter-spectrum switching time
$T_\triangle^c$	Intra-spectrum (channel) switching time
P_B	Minimum probability of channel availability
N_v	Number of sample measurements used for variance calculation
n_k	Total number of channels in spectrum band k
p_j^k	Probability of availability of channel j in spectrum k
D_k	Propagation distance of CR transmission in spectrum k
r_k^m	Coverage radius of PU transmitter m on spectrum k
C^k	The set of chosen channels for transmission in spectrum k
A_i^k	Fractional coverage overlap between CR user i and all PU transmitters on spectrum k
T_s^i	Spectrum sensing time for CR user i
T_t^i	Transmission time for CR user i
T_a^i	Effective tx. time with sensing schedules of neighbors of CR user i
T_f^i	Fractional allowed transmission time for CR user i
J_T	Allowed variance in number of bits sent over the link
I_i	Set of CR users within interference range of user i
L_j	Forwarding delay associated with the j^{th} segment

users take the initiative in the subsequent route formation. As an example, in Figure 1, the PU transmitters i and j are separated by distance $D_{PU\,i}x$. The shaded circles indicate their coverage ranges in which PU receivers may be present, though their locations are unknown to the CR users *x*, *y*, and *z*. Note that user *x* has greater overlap of its own transmission radius, given by D_k with the coverage regions of the PU transmitters, which implies higher possibility of interference with the PU receivers. Consequently, it also has a lower *initiative* than z for forwarding packets. Assume that the RREQ is broadcast by CR user *y*, and received by both users *x* and *z*. As CR user *z* has higher *initiative* as compared to *x*, it also has a lower forwarding delay. Hence, it transmits the RREQ earlier than user *x*. The arrival times of the RREQs at the destination (over several, possibly disjoint paths) is dependent on these forwarding delays. Hence, the earlier arriving RREQs also represent paths that pass through regions preferred for CR operation. This method reduces the overhead of forming routes in all possible channels over several different spectrum bands. It also tries to map the spectrum characteristics at the intermediate hops to the RREQ arrival times, thereby reducing both the need for transferring large volumes of node information over the RREQ packet, and the resulting computational complexity at the destination.

In this work, we assume the network architecture is composed of stationary PU transmitters with known locations and maximum coverage ranges, as seen in the case for television broadcast towers. In Figure 1, this implies the locations of PU i and j are known, and the range r_k^i to be fixed. The CR users are mobile, location-aware, and have no knowledge of the PU receivers. Additionally, the statistical knowledge of the channel availability is assumed for the different spectrum bands.

We next describe the constituent stages, and the detailed operation of the CRP protocol.

IV. Spectrum Selection Stage

In this stage we first list the different metrics that influence the choice of CR route and spectrum selection. Then, we propose optimization functions for the *class I* and *II* routes respectively, that weight these metrics appropriately.

A. Metrics for CR Route and Spectrum Selection

The CR-specific metrics considered during the route setup stage are (i) probability of bandwidth availability, (ii) variance in the number of bits sent over the link, (iii) spectrum propagation characteristics, (iv) PU receiver protection, and (v) spectrum sensing consideration, with the important variables used in the discussion summarized in Table I.

1) Probability of bandwidth availability: During formation of a new route, the source specifies the desired mean bandwidth (ψ_D) in the RREQ packet. We assume that the channel bandwidths may be defined differently for each of the N_s possible spectrum bands. The candidate CR users evaluate if the chosen spectrum band can probabilistically guarantee the bandwidth availability.

For a given spectrum band k composed of n_k channels, each having bandwidth ψ_k, the minimum number of simultaneously available channels must be $\lceil \frac{\psi_D}{\psi_k} \rceil$. Let $\frac{1}{\alpha_i^k}$ and $\frac{1}{\beta_i^k}$ be the average *on* and *off* times for the i^{th} channel of the k^{th} spectrum. The *on* time refers to the period where the channel is sensed to be occupied by a PU, while the *off* time indicates the channel is free for CR transmission. This information can be statistically known or simply obtained by averaging the past channel occupancy history. The probability of finding the i^{th} channel available is,

$$p_i^k = \frac{\alpha_i^k}{\alpha_i^k + \beta_i^k} \tag{1}$$

Owing to hardware limitations, we assume that the CR transmitter can only tune to one licensed spectrum at a time, though it may freely choose multiple channels within that spectrum. For spectrum k, let C^k represent the set of channels chosen by the candidate forwarding node to meet the user bandwidth requirements ($|C^k| = \lceil \frac{\psi_D}{\psi_k} \rceil$).

Using equation (1) set of channels C^k is chosen such that,

$$p_i^k > p_j^k, \quad \forall i \in C^k, \quad j \notin C^k, \quad 0 < i, j < n_k \tag{2}$$

We can now express the spectrum bandwidth availability probability M_B^k at the candidate forwarding node based on the availability of the chosen $|C^k|$ channels (and hence, the desired bandwidth) in spectrum k, as given below:

$$M_B^k = \prod_{i \in C^k} p_i^k \tag{3}$$

2) Variance in the number of bits sent over the link: Recent experiments at the transport layer in CR have demonstrated the difficulty in adjusting to large bandwidth fluctuations [4] when the spectrum availability changes. In CRP, the channels selected in the spectrum may, at times, become unavailable and this leads to undesirable end-to-end performance. The overall variance in the number of bits sent over the link (V_B^k) is a collective function of the bandwidth of the chosen channels for the spectrum k, and their current availability for CR transmission.

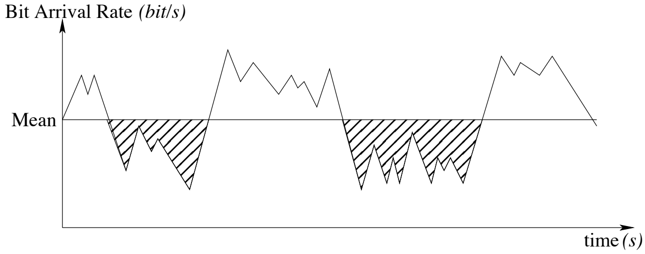


Fig. 2. Conceptual depiction of the variance in the arrival rate of the bits on the link owing to varying spectrum availability.

For the i^{th} channel in spectrum k, let ξ_i^k be the summation of the squares of the difference between the statistically known mean *off* time $\frac{1}{\beta}$, to its currently observed off time $t_s^{OFF(-)}$, considering past N_v samples. Formally,

$$\xi_i^k = \frac{1}{N_v} \sum_{s=1}^{N_v} [\frac{1}{\beta_i^k} - (t_s^{OFF(-)})]^2, \quad \text{where}$$
$$t_s^{OFF(-)} = \begin{cases} t_s^{OFF}, & t_s^{OFF} \in [0, \frac{1}{\beta_i^k}] \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

Here, s represents the sample count up to a maximum value of N_v. The term $t^{OFF(-)_s}$ is extracted from the mean *off* time t_s^{OFF} for each sample s. Note that $t^{OFF(-)_s}$ only considers the cases when the observed availability time of the channel is lower than the mean value. Intuitively, the availability of larger durations of licensed channel availability is not detrimental to the CR network performance, and hence, only the cases that adversely affect the performance are considered. Accordingly, the metric ξ_i^k does not simply imply the classical variance of the time for which the channel bandwidth is available. Rather, it accounts for the times the available bandwidth falls for a given channel, and the extent of the difference.

Assuming the PU activity in each channel is independent of the others, the variance V_B^k in the arriving number of bits over link for spectrum k considering all the chosen channels in C^k can now be expressed as,

$$V_B^k = \psi_k \sum_{i \in C^k} \xi_i^k \tag{5}$$

From Figure 2, we see that the bit arrival rate on the on link varies with the channel availability on the chosen spectrum. The metric V_B^k measures the cumulative shaded portion, i.e., the number of bits that arrive at the next hop when the link bit rate is lower than the mean value under perfect channel conditions. V_B^k directly translates to the packet jitter (variance in the packet arrival times) that affects time-critical applications, and must therefore be minimized.

3) Spectrum propagation characteristics: The frequencies in the lower MHz range have better propagation characteristics wherein the emitted electromagnetic radiation travels farther with lower attenuation. This phenomenon also helps in reducing the per-hop distance thereby allowing the destination to be reached in fewer hops that improves the end-to-end latency. When latency is a consideration, CR networks must prefer spectrum with better propagation characteristics. Assuming the simple path loss propagation model with β as the attenuation constant, P_{tx}^{CR} as the maximum transmit power, P_{rx}^{CR} as the receiver threshold, c as the speed of light, and f_k as the representative frequency of the spectrum selected[1], we get the propagation distance D_k as,

$$D_k = \left[\left(\frac{c}{4\pi f_k} \right)^2 \cdot \frac{P_{tx}^{CR}}{P_{rx}^{CR}}) \right]^{\frac{1}{\beta}} \quad (6)$$

4) PU receiver protection: CR users decide on the availability of the spectrum based on the detection of the PU signal. Thus, they primarily rely on *transmitter detection*, and do not account for possible interference with PU receivers. Though there have been some initial efforts towards receiver detection based on leakage power, such techniques are not guaranteed to be applicable in general scenarios. Moreover, spectrum sensing itself suffers from occasional missed-detection events that can seriously undermine the PU protection. To lower the probability of interference, the routes for the CR network may be so chosen that they pass through regions that have minimum overlap between transmission coverage areas of the CR users and PUs. The region of the overlap represents the area where the PU receivers may be present, and therefore must be minimized at each forwarding CR user in the chosen route for the protection of these receivers.

In Figure 1, CR user y is forwarding the RREQ packet to both the candidate forwarding nodes x and z. Here, user x calculates the fractional area of its transmission range under the coverage of the PUs in its vicinity, shown by the shaded region. From geometrical calculations, the overlap area A_{x,PU_i} between a given PU transmitter PU_i and x, separated by distance $D_{PU_i,x}$, is given by,

$$\begin{aligned} A_{x,PU_i} =& D_K^2 cos^{-1} \left\{ \frac{D_{PU_i,x}^2 + D_k^2 - {r^i}_k^2}{2D_{PU_i,x} \cdot D_k} \right\} \\ &+ {r^i}_k^2 cos^{-1} \left\{ \frac{D_{PU_i,x}^2 + {r^i}_k^2 - D_k^2}{2D_{PU_i,x} \cdot r_k^i} \right\} \\ &- \frac{1}{2}\sqrt{s(s-2D_{PU_i,x})(s-2D_k)(s-2r_k^i)}, \quad (7) \end{aligned}$$

where $s = (D_{PU_i,x} + D_k + r_k^i)$. Here, D_k is obtained from equation (6), and r_k^i is the transmission range for the PU, if it chooses to occupy the k^{th} spectrum. Considering the sum of all the other N_p PU transmitters (PU_i and PU_j in Figure 1), we get the fractional overlap as A_x^k for CR user x on spectrum k, which must be minimized for preventing interference:

$$A_x^k = \frac{\bigcup_{i=1,\ldots,N_p} \{A_{x,PU_i}\}}{\pi {D_k}^2}, \quad \text{if} \quad D_{PU_i,x} < D_k + r_k^i \quad (8)$$

We note that the spectrum occupancy changes over time, and hence A_x does not represent the current exact proportion of coverage overlap. Rather it serves as the worst case overlap bound assuming that all the PU transmitters occupy the chosen spectrum at a future time.

[1]As an example, $f_k = 2.4$ GHz for the frequencies in the range $2.412 - 2.462$ GHz used by classical WiFi operation in the ISM band

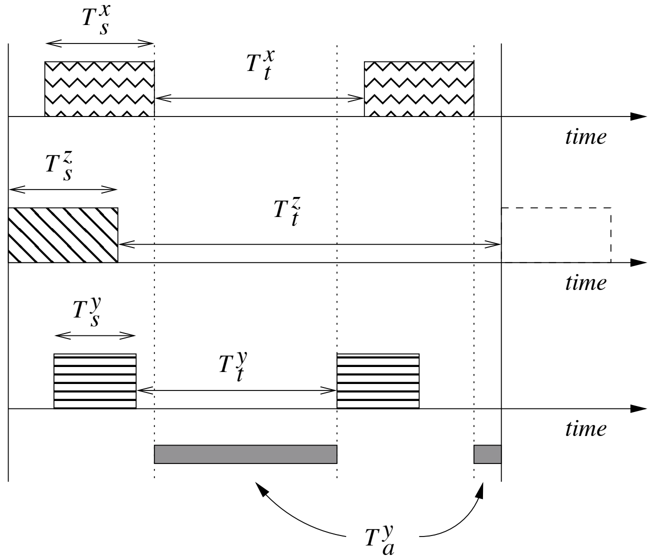


Fig. 3. The effective time available for transmission T_a^y for the CR user *y*.

5) Spectrum sensing consideration: CR users undertake spectrum sensing at periodic intervals to maintain an updated information regarding the spectrum occupancy. During this sensing duration, especially for the commonly used energy detection techniques, the adjacent CR users must be silenced. Thus, the path latency is considerably affected when CR users along the packet forwarding path are unable to transmit owing to the enforcement of the silence zone. The effective duration for which transmission is allowed at the candidate forwarding node, for a given choice of spectrum, is hence an important criterion for the end-to-end latency of the CR network.

For the selected spectrum k, let T_s^z and T_t^z be the spectrum sensing and transmission times for a given CR user z that lies within the carrier-sense range of CR user y (Figure 1). When considered together, $T_s^z + T_t^z$ gives the frame time for the user z. Using similar notations for users x and y, we show the respective sensing and transmission schedules of the three users in Figure 3. We observe that the effective time allowed for the CR user y to transmit (T_a^y) is reduced, and takes into account the duration for which the spectrum k is unusable to facilitate the sensing functions of the neighboring nodes. T_a^y is calculated by subtracting the individual (possibly overlapping) sensing durations from the maximum frame time of all the users given by the set I_y within the interference range, as shown next:

$$T_a^y = \max\{T_s^j + T_t^j\} - \bigcup \{T_s^i\}, \quad \forall i \in I_y \quad (9)$$

The maximum frame time is given by considering the maximum duration of the sensing-transmission cycle of all the neighbors. In our example (Figure 3), $\max\{T_s^j + T_t^j\} = T_s^z + T_t^z$. Similarly, $\bigcup\{T_s^i\} = T_s^x \bigcup T_s^z \bigcup T_s^y$, with the respective sensing durations for CR users x, y and z shown by the shaded blocks.

From equation (9), the fractional time available for transmission at CR user y (T_f^y) is the ratio of the effective time for transmission in equation (9) to the maximum frame time.

$$T_f^y = \frac{T_a^y}{\max\{T_s^j + T_t^j\}} \quad i \in I_y \tag{10}$$

B. Spectrum Selection Optimization

The metrics described above are combined to formulate the spectrum selection optimization problem, in which each CR user identifies the best spectrum spectrum band available locally for the desired class of route. The optimization functions for the *class I* and *class II* routes, along with the constraints are given below with respect to a given CR user x:

$$\textit{To find}: \text{Spectrum } k \in N_s \tag{11}$$
$$\textit{To Maximize}: O_{Class-I} = D_k \cdot T_f^x \tag{12}$$
$$(or)$$
$$\textit{To Minimize}: O_{Class-II} = D_k \cdot A_x^k \tag{13}$$
$$\textit{Subject to}:$$
$$M_B^k > P_B{}^{|C^k|} \tag{14}$$
$$V_B^k < J_T \tag{15}$$
$$B_c^k > \psi_k \cdot |C^k| \tag{16}$$
$$T_\triangle^s + T_\triangle^c(1 - M_B^k) < T_{th} \tag{17}$$

1) Class I routes: In this class, the end-to-end CR route latency is considered more important than PU protection. The optimization finds the best spectrum k out of N_s possible spectrum bands to maximize the function $O_{Class-I}$ (equation 12).

- The optimization function itself is composed of two metrics, the distance covered for the given transmission power D_k, and the fractional time for transmission considering the different sensing schedules of the neighboring users, T_f^x (equation 12). The product $O_{Class-I}$, when maximized, can be interpreted as the time for which the highest number of packets may be transmitted over the maximum possible transmission distance.
- The choice of spectrum must, however, meet probabilistically the user specified constraints of bandwidth availability at each hop in (equation 14). In this work, we assume $P_B = 0.25$ that requires the probability of the combined channel availabilities M_B^k (equation 3) of the $\frac{\psi_D}{\psi_k} = |C^k|$ channels to be at least 10^{-4}.
- The bit arrival variance indicated by V_B^k must meet the minimum threshold for the given application J_T, which is specified by the user (equation 15).
- The physical channel fading conditions are checked to ensure that the spectrum selection will not cause severe multi-path related fading losses (equation 16). If the coherence bandwidth (B_c^k) of the spectrum is lesser than the signal bandwidth, it results in frequency selective fading, wherein the lost data is generally not recoverable through error correction techniques. The coherence bandwidth may be unique for the choice of spectrum, and recent experimental work has been undertaken to determine it in the 2.4 [8] and 5 GHz [2], respectively.
- Finally the switching time latency is given in (equation 17), with $T_\triangle^s$ and $T_\triangle^c$ being the inter- an intra-spectrum switching, respectively. These switching times are non-negligible and have significant bearing on the route performance. Here, $T_\triangle^s = 0$ if the spectrum used in the previous hop is the same as the current CR user. For the intra-spectrum operation, the channels in the preferred set C^k may not be always available. Thus, the channel switching time ($T_\triangle^c$) for the case of at least one channel unavailable is considered, and the cumulative switching latency must be contained within the pre-decided threshold T_{th}

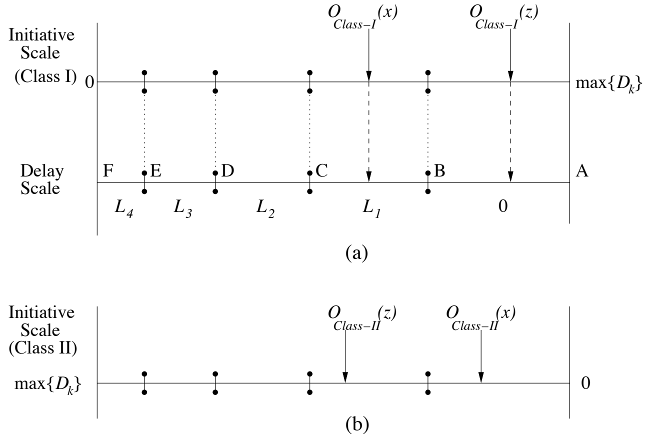


Fig. 4. Forwarding delay for CR users x and z.

Each CR user updates two fields in the RREQ. The first is the <spectrum> field which has the choice of the spectrum, and the <opt> field containing the value of the optimization function. The <spectrum> is over-written at each intermediate node with the current choice, while the <opt> value is replaced as <opt> = <opt> + $O_{Class-I/II}$, depending upon the class of route. Thus, the additional information in the RREQ does not increase with either the path length, or the number of spectrum bands.

We observe that the optimization framework requires limited information exchange between next hop CR nodes, i.e. only for gathering the sensing durations for calculating T_f^x. For the rest, CRP relies on the knowledge of performance thresholds that can be directly input by the network administrator before deployment. Moreover, the optimization is undertaken only when a new RREQ is received. This is critical in lowering both the communication and processing overhead of the CR users.

2) Class II routes: For this class, CRP assigns a greater importance to the protection of PUs, especially the PU receivers that are generally undetected. The optimization function is now defined as the minimization of the product of the fractional area of overlap between the CR-PU coverage ranges, A_x^k, and the propagation distance, D_k (equation 13). Lower the value of the metric A_x^k, the better is the protection to the PU receivers. Also, larger distances for propagation cause a greater probability of interference with the PUs. This product term is hence minimized so that the route is composed of several hops of smaller transmission range, and passes through regions as far away as possible from the known PU transmitter locations resulting in higher route latency. The other constraints of the optimization (equation 14-17) remain the same.

V. Next Hop Selection Stage

The candidate forwarders decide on their preference for participating in the route in this stage by calculating the so called *initiative* from the results of the optimization equations (12) and (13). This initiative is then mapped to a forwarding delay. The destination chooses the final route depending on the arrival time of the RREQ requests in the route confirmation, as described next in this section.

A. Forwarding Delay based on Spectrum Selection

Each user maps the result of the optimization function on an absolute initiative scale shown in Figure 4 (a). For *class I* routes, the higher the value of $O_{Class-I}$, greater is the user's initiative. We observe that this optimization value for user x, $O_{Class-I}(x)$ is greater than that for user y, $O_{Class-I}(y)$. This initiative is then used to calculate the forwarding delay for the RREQ packet at a given CR user by mapping the *initiative scale* to the *delay scale* (Figure 4 (a)). The delay scale is divided into discrete segments, each of which is associated with a constant forwarding delay. As an example, segment $A-B$ represents a delay of 0, while $B-C$ gives a delay of L_1. Moreover, the delays have magnitudes satisfying the order relation $L_n > L_{n-1} > \ldots > L_1 > 0$, and decide when the RREQ packet should be sent to the lower layer for forwarding. Note that multiple neighboring CR users may have the same forwarding delay, and their link layer backoff-timers prevent collision between their RREQ broadcasts. For *class I* traffic, CR user z has a lower value on the delay scale. As it incurs a wait period of 0, it forwards the RREQ before CR user x that must wait for a duration of L_1.

The *initiative scale* has an upper limit of $\max D_k \; \forall k \in N_s$, which represents the maximum possible propagation distance considering all the N_s spectrum bands. From equation (12) and (13), we observe that the optimization functions for both the classes of CR routes consist of propagation distance D_k for the chosen spectrum k as one of the product terms. The second term in either case is a fractional quantity, which has the highest value as 1. Hence, $\max O_{Class-I} = \max O_{Class-II} = \max D_k \; \forall k \in N_s$. The lower bound in both cases is 0.

Our approach is trivially extended for the Class-II route, by reversing the *initiative scale*, as shown in Figure 4 (b). Here, the lower the value of the minimized optimization function, lower is the forwarding delay when the initiative is mapped on to the *delay scale*. As shown in the figure, CR user x has better PU protection as compared to CR user z, and hence maps to a lower forwarding delay for *class II* routes.

B. Route Confirmation

As the packet delay corresponds to the quality of the route, low-performing routes result in the RREQs reaching the destination comparatively later in time. The destination waits for a duration $T^D_{\triangle}$ where there may be multiple arriving RREQs indicating different routing paths. From this set, it chooses the route with $\max\{\sum_{\forall j} O_{Class-I}(j)\}$ or $\min\{\sum_{\forall j} O_{Class-II}(j)\}$, for *class I* and *II* routes, respectively. While the route-setup delay is increased by not immediately responding to the first arriving RREQ, introducing a wait period at the destination reduces the influence of the CCC MAC layer link delays in the final selection of the route.

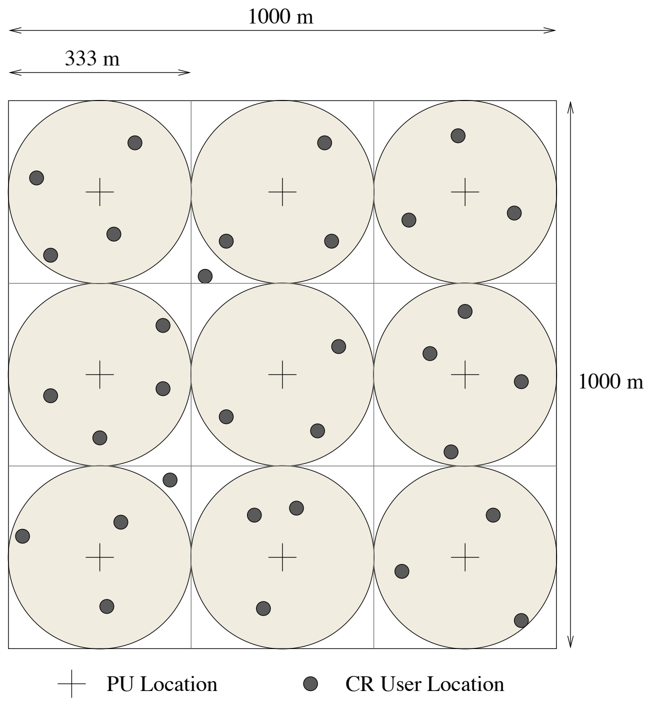


Fig. 5. Topology used for performance evaluation

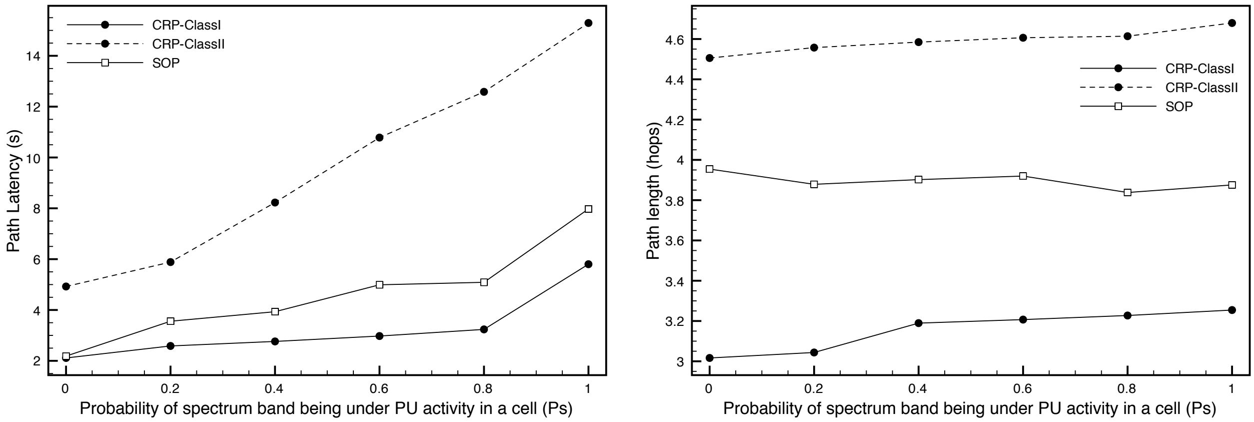
VI. Route Maintenance

The route maintenance has a proactive and a reactive component. During proactive maintenance, each CR user continuously monitors its own location with respect to the known PU transmitter locations. Let (x_0^i, y_0^i) be the coordinates of the CR user i at the time $t = 0$ of forwarding the RREQ. Under mobility conditions, the CR user may move towards the PU affected regions, and this stage may lead to possible route failure in the near future. Thus, when the displacement of the node towards one or more PUs is determined, it is beneficial to proactively discover a new path in case the current route fails. Considering the new location of the user at (x_T^i, y_T^i) at time T, the displacement vector is given by,

$$D_i^{\vec{T}}, i = (x_T^i - x_0^i)\hat{x} + (y_T^i - y_0^i)\hat{y}, \qquad (18)$$

where $\hat{x}$ and $\hat{y}$ are unit vectors along the x and y axes, respectively. Along similar lines, the vector joining the initial location and PU j, $D_i^T, \vec{P}U_j$, is calculated from the known coordinates of the locations. The advance D_{adv} at the current time T with respect to the original location of the CR user is given by the dot product,

$$D_{adv}^{i,PU_j} = \frac{D_i^{\vec{T}}, i \cdot D_{i,PU_j}^{\vec{T}}}{|D_{i,PU_j}^{\vec{T}}|} \qquad (19)$$



(a) (b)

Fig. 6. The end-to-end path latency (a) and the path length (b) are shown for varying probability of spectrum band being under PU activity in a cell (P_s).

The cumulative positive advance of CR user i considering all the PUs is now calculated as,

$$D_{adv}^{i} = \sum_{j=1}^{N_p} D_{adv}^{i,PU_j} \quad \text{if } D_{adv}^{i} > 0 \tag{20}$$

Thus, D_{adv}^{i} indicates how close the node is moving towards the PU transmitter locations in network. If this value is greater than a pre-decided threshold, the CR user signals its previous hop node to initiate a new route discovery on the CCC. This is undertaken in anticipation of possible route disruption in the future, and follows the class-specific constraints of the route setup stage. It is however, not used in the forwarding of packets till the threshold advance is reached. For the cases of the next hop being unreachable owing to mobility, nodes exiting the network, or due to PU activity, the previous hop node initiates the route setup and the path given by the first arriving RREQ at the destination is immediately used. The CCC can be a bottleneck in case the control traffic is high. Fortunately, the network layer only uses the CCC occasionally, i.e. only when (i) a new route is to be created, or (ii) a mobility condition is detected that may potentially cause a route failure. While a novel OFDM based CCC design for in-band operations has been proposed by the authors [5], for the current paper, a simple out-of-band CCC in the $2.4\,\text{GHz}$ unlicensed band is used. Simulation runs reveal about $15-22\%$ utilization of the CCC owing to the network layer control traffic (route formation and disconnections are infrequent events), and the MAC layer channel coordination packets.

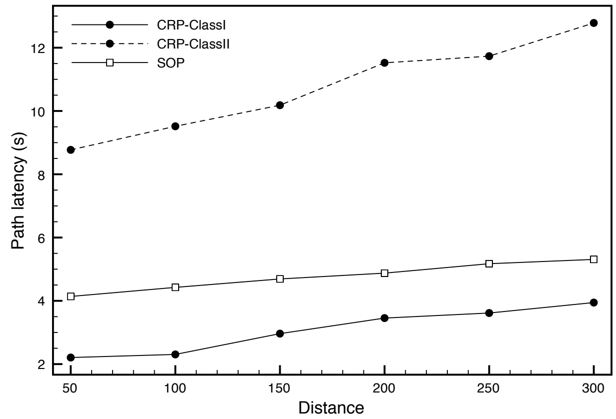
VII. Performance Evaluation

We have implemented CRP in the ns-2 simulator, with the network topology as seen in Figure 5. A square region of side $1000\,\text{m}$ that is further divided into square *cells* of side $333\,\text{m}$. There are $N_s = 5$ different spectrum bands composed of six $\psi_k = 5\,\text{MHz}$ channels, which may be freely occupied by the PUs located at the centre-points of the cells. The PUs have a transmission range of $150\,\text{m}$. Moreover, the transmission range of the CR user progressively increases from $D_k = 50$ to $150\,\text{m}$ in steps of 25 for $k \in [1, 5]$. A total of 100 CR users are randomly deployed in the region, each having the sensing and transmission times given by $T_s^i = 0.1\,\text{s}$ and $T_t^i = 0.6\,\text{s}$, respectively. We use 802.11b protocol that transmits packets of size $1000\,\text{bytes}$ at $11\,\text{Mbps}$. The RREQ forwarding delay has a maximum limit (L_n) of $0.05\,\text{s}$, and the intermediate time segment size is $0.01\,\text{s}$. From table I, the other environmental parameters are $N_v = 10$, $T_{\triangle}^{s} = 1\,\text{ms}$, $T_{\triangle}^{c} = 200\,\mu\text{s}$. Similarly, the user specified requirements are assumed as $\psi_D = 2\,\text{MHz}$, $J_T = 75\,\text{kb}$, $P_B = 0.5$, $T_{th} = 1.2$ ms. As the focus of this paper is on the network layer, we assume perfect PU transmitter detection at the physical layer. A finite detection error (mostly $2-5\%$) can be easily introduced based on the values of T_s^i and T_t^i [14], though the trends observed in the result will remain unchanged.

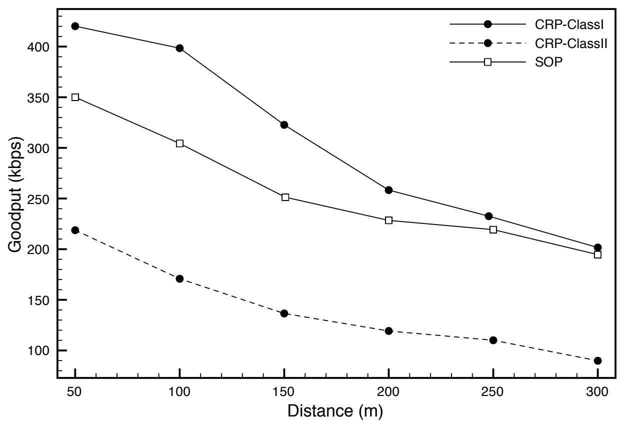
We compare our CRP protocol with the spectrum opportunity (SOP) based routing protocol proposed in [15] as they are both distributed protocols over CR ad hoc networks. We vary the (i) probability of spectrum bands being under PU activity, say P_s, and (ii) distance between the source and destination CR users. In particular, the first metric gives the probability with which all the spectrum bands in a given cell experience PU activity. For each spectrum that is found to be actively used by a PU, the mean on ($\frac{1}{\alpha}$) and off ($\frac{1}{\beta}$) times are randomly selected from from the interval $[0.25, 4]$. We focus primarily on the (i) end-to-end CR performance, (ii) PU receiver protection, and (iii) route maintenance in this study.

A. End-to-end CR Performance

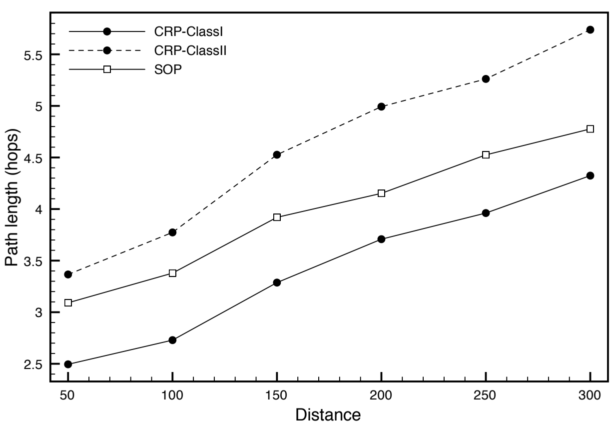
In the first set of experiments, we evaluate the performance of the routing protocols from the viewpoint of the CR network, by measuring the path latency, the goodput and the path length of the chosen route. In Figure 6(a), we observe that the path latency for data packets in the CRP *class I* protocol is nearly 50% lower than that for SOP. However, the CRP *class II* incurs a significantly increased latency for the added protection to the PU receivers. From Figure 6(b), the path length does not undergo a major change in the SOP protocol. The primary reason for this is that the contention of the other CR users on the same spectrum is used in the route latency calculation at the destination, rather than the activity of the PUs. However, both the CRP *class I* and *II* protocols exhibit



(a)



(b)



(c)

Fig. 7. The end-to-end path latency (a), the goodput (b), and the path length (c) are shown for varying distance between the source and destination CR users.

a gradual increase in the path length as the probability of availability of the desired bandwidth is taken into account during route formation. Consequently, CR users on the shortest path to the destination but under the PU coverage range for the chosen spectrum are no longer selected when the P_s increases.

We vary the distance between the source and destination CR users in the next set of experiments. The linear nature of the path latency (Figure 7(a)) implies that large separation distances does not affect the scalability of our proposed approach. Especially for the case of CRP *class II*, the longer the separation, the greater is the probability of significant deviation from the straight line path. However, results reveal a graceful performance degradation of CRP *class II* latency with the distance. Interestingly, the goodput (Figure 7(b)) is nearly similar for routes given by the SOP and the CRP *class I* protocols for larger separation distances. The reason for this is apparent in Figure 7(c), where the difference between the path lengths given by the above protocols progressively increases for larger separation. This directly results in higher packet arrival times for CRP *class I*, while lowering the goodput.

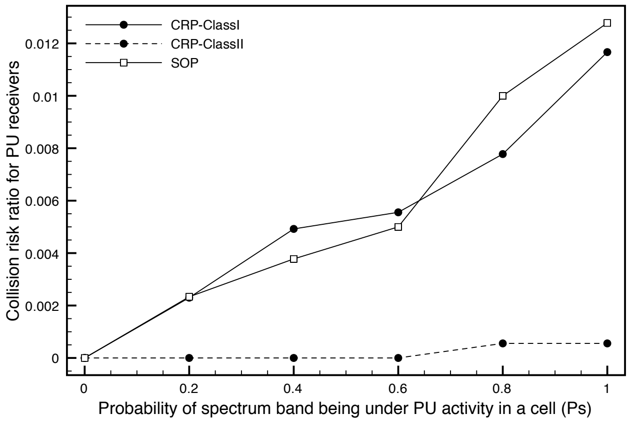
B. PU receiver protection

We measure how our proposed approach lowers the collision to the PU receivers, and also the extent of interference power introduced by the CR operation at the locations of these receivers. In Figure 8(a), we vary P_s and measure the collision risk ratio for PU receivers, i.e., the ratio of the number of colliding transmissions to the total number of CR transmissions at the PU receivers. We observe that the collisions are reduced by more than 50% for moderate P_s, and is as high as 90% for higher values of P_s for the CRP class II protocol, when compared to the others. Choosing spectrum bands based on their occupancy probability in CRP *class I* results in lower collision risk, and this trend it seen clearly for higher P_s. The effect of source-destination distance on the collision risk is shown in Figure 8(b). It is observed that CRP *class II* has the best protection by circumventing the PU coverage regions altogether. CRP *class I* continues to outperform SOP for increasing distances as the nodes have a lower probability of using spectrum that see high PU transmissions (without specifically considering receiver protection).

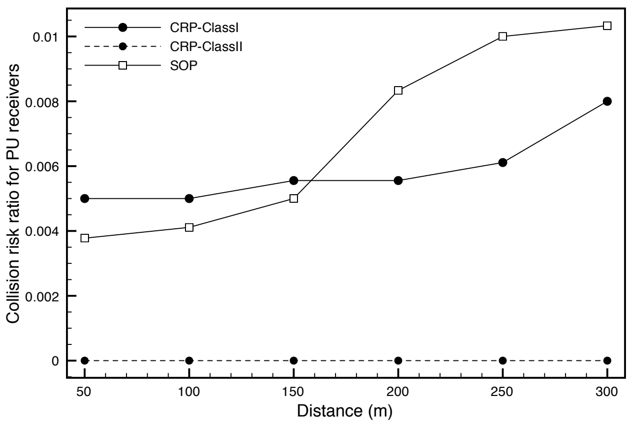
Next, we measure the interference-time product that gives the average CR transmitted power incident on the PU receivers, and the duration for which this power is observed at their locations. For this, we sum the product of the received powers and the time for which this power is observed at the PU receivers in their operational spectrum, considering all the CR transmitters in the network. A non-intuitive observation from Figures 8(c) is that though the collision risk is negligible for the CRP *class II*, the interference-time product is disproportionately high (similar results are observed for varying source-destination distance). This occurs because of the significantly higher number of hops present in the CRP *class II* routes. While the interference contributed at each hop is low owing to the appropriate choice of forwarding nodes and spectrum, the higher number of hops results in a greater cumulative value of the interference-time product. Similarly, the comparatively higher path length in the case of CRP *class I* results in a slightly higher value for both increasing distance and P_s.

C. Route Maintenance

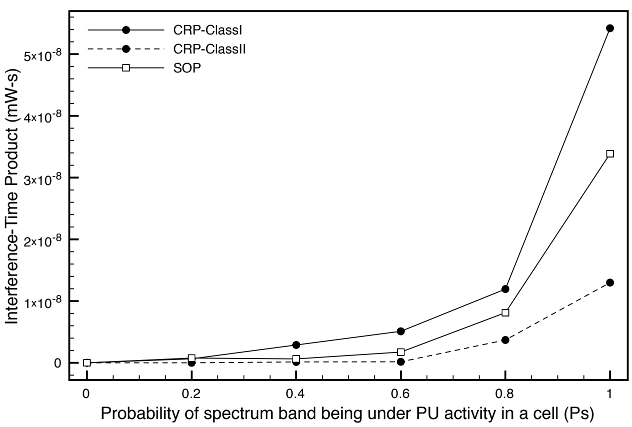
Finally, we evaluate the delay incurred in CRP *class I* and *II* when the CR users venture into areas under coverage of PUs, owing to their mobility (Figure 9). This delay is measured from the instant of route failure to the reconnection between



(a)



(b)



(c)

Fig. 8. The effect on the PU receivers due to transmissions of the CR users on the chosen route

the source and destination. We observe that the both the classes of the CRP protocol require a considerably large time in the absence of route maintenance. This is because the route failure results in searching of a fresh path *after* the failure has occurred. As opposed to this, when the proactive maintenance is included in the design, there is no sudden increase of latency for both the CRP classes as an alternate round is already is

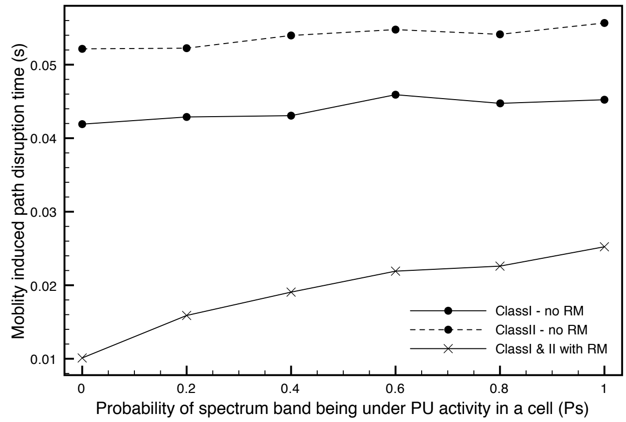


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Fig. 9. Performance of CRP with the route maintenance (RM) scheme.

existence. The traffic is simply switched to the secondary route immediately on the event of actual failure of the route.

VIII. Conclusion

In this paper, we proposed the CRP routing protocol that specifically addresses the problems the PU receiver protection, service differentiation in CR routes, and joint spectrum-route selection. Our protocol allows for two classes of routes - *class I* routes that provide better CR network performance, while *class II* routes aim to achieve a higher measure of protection for the PUs. Our performance evaluation shows the tradeoff that incurs in the CR performance to reduce the interference to PU receivers, thereby motivating separate routing classes based on the specified operational limits of the CR network. Our future work will include the following: We assume the "on-off" PU activity model in our work, which we propose to update with the recent experimental findings of an exponential distribution of the *on* times. Also, the coherence bandwidth B_c^k is known for selected frequency bands, and we would like to study the channel characteristics of the different licensed bands to extract accurate values for B_c^k. In addition, spectrum sensing has a finite probability of detection error, which we would like to incorporate for a realistic performance analysis. Finally, our work considers two classes depending upon the level of protection to the PU receivers. We will extend this concept further to incorporate traffic class requirements for the CR users.

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