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Joint path and spectrum diversity in cognitive radio ad-hoc networks

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Abstract

The uncertain availability of the spectral resource imposes unique challenges in cognitive radio networks. One of the critical issues is to counteract the performance degradation experienced by cognitive users (CUs) due to the activity of primary users (PUs). Since the activity of PUs varies both in frequency and space domain, diversity techniques can represent an efficient way to address this issue. In this article, it is proposed to jointly exploit path and spectrum diversity for effective use of spectrum in cognitive radio ad-hoc networks (CRAHNs). By jointly exploiting both the diversities, CUs can switch dynamically to different paths and spectrum bands for communicating with each other in presence of frequency- and space-varying PU activity. This idea is adopted in a routing protocol, referred to as *Dual Diversity Cognitive Ad-hoc Routing Protocol*, and simulation results reveal the effectiveness of introducing joint path and spectrum diversity in CRAHNs.

Keywords: Cognitive, Ad-hoc, Path, Spectrum, Joint, Diversity, Routing

Introduction

Cognitive radio (CR) paradigm proposes to enhance the spectrum efficiency by allowing unlicensed users, referred to as cognitive users (CUs), to utilize dynamically and opportunistically the spectrum assigned to the primary users (PUs) when it is temporarily not used. To reach this aim, CUs must be able to change their transmission and reception parameters to communicate with each other without causing interference to the PUs.

The uncertain availability of the spectral resource imposes unique challenges in cognitive radio networks (CRNs). Specifically, in cognitive radio ad-hoc networks (CRAHNs), the distributed multi-hop architecture, the dynamic network topology and the spectrum availability varying in time and space are some of the key distinguishing factors [1]. Due to these factors, one of the critical issues in CRAHNs is to counteract the performance degradation experienced by CUs because of the activity of PUs. Since such an activity varies both in frequency and space domain, incorporating diversity techniques in routing can provide an effective solution to address this issue.

Most of routing protocols recently proposed for CRAHNs do not exploit diversity techniques [2-4]. However, few proposals have resorted to path- or spectrum-diversity techniques (we refer the reader to [5] for further details). In [6], a path-diversity routing protocol operating only on infrastructure-based network has been proposed. Another path-diversity based routing protocol is proposed in [7] for underlay CRNs. In this work, the authors assume a specific distribution of PUs and CUs in the network, which is not reasonable in CRAHNs. In [8], a source-based routing protocol with path diversity has been proposed for CRNs, and its application in CRAHNs is not reasonable due to high packet header overhead. In [9,10], a protocol, referred to as cognitive ad-hoc on-demand distance vector (CAODV), has been presented. In this work, the authors have exploited individually path- and spectrum-diversity. Since they have not jointly considered path and spectrum diversity, the effects of PU activity can still degrade the performance of the networks, as shown in Section “Motivation”. The article in [11] is the first work that studied joint routing and spectrum allocation problem in multi-hop CRNs. In this works, the authors achieve a near optimal solution for that problem by using global knowledge about the network topology, which is not reasonable in CRAHNs.

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In this article, we propose to jointly exploit path and spectrum diversity to counteract the PU activity by exploiting local knowledge about network topology, i.e., by exploiting next hop routing. To this aim, the route discovery process complexity increases so that an additional overhead has to be taken into account. Such an overhead, as confirmed by the simulation results in Section "Performance evaluation", is well paid if the scenario is heavily dynamic in terms of CU mobility and/or PU activity.

It is worthwhile to underline that the proposal assumes that the available channels (namely the licensed spectrum free from the PU activity) can be used by each CU at the same time. This assumption is reasonable if the CUs are equipped with multiple wireless interfaces. However, also in presence of a single wireless interface, the assumption holds if the presence of an underlying channel coordination mechanism is considered [12].

The rest of the article is organized as follows. Section "Motivation" presents the motivation of the proposed work, while Section "Dual diversity cognitive ad-hoc routing protocol" describes the main features of the proposed routing protocol, referred to as dual diversity cognitive ad-hoc routing protocol. Section "Performance evaluation" provides the performance evaluation of the protocol and, finally, Section "Conclusion" concludes the work.

Motivation

The aim of this section is two fold: *(i) to describe the effects of PU activity on routing when it varies in frequency and/or space domain*; *(ii) to show the benefits of jointly exploiting path- and spectrum-diversity in CRAHNs*. At this end, a simple scenario is considered in Figure 1, where CU_A and CU_D are the source and the destination node, respectively.

Path diversity

Path diversity allows CUs to switch dynamically among different paths for communicating with each other in presence of space-domain-dependent PU activity.

Figure 1a shows how the PU activity can affect a routing process whenever it varies in space domain. Here, CU_B and CU_C are under the transmission range of two different PUs. By exploiting the path diversity, CU_A can reach CU_D through the *optimal path*[a] $CU_A \rightarrow CU_B \rightarrow CU_D$ (when PU_2 is not active); or the sub-optimal path $CU_A \rightarrow CU_C \rightarrow CU_D$ (when PU_2 is active but PU_3 is not), without the need of a new route discovery process.

However, by only exploiting path diversity, CU_A can not reach CU_D when the effect of PU activity varies in frequency domain, as it is depicted in Figure 1b. In this example, CU_A must be able to establish paths through different spectrum bands to communicate with CU_D. Clearly, this requires to exploit spectrum diversity, as it will be described in Section "Spectrum diversity". Therefore, such an example shows that the performance degradation due to the activity of PUs can not be counteracted by the only exploitation of path diversity.

Spectrum diversity

Spectrum diversity allows CUs to switch dynamically among different channels for communicating with each other in presence of frequency-domain-dependent PU activity.

Figure 1b shows how the PU activity can affect a routing process whenever it varies in frequency domain. Here, CU_A and CU_D are partially affected by two different PUs on channel 2 and channel 1, respectively. By exploiting the spectrum diversity, CU_A can still communicate with CU_D through the optimal path composed by link $CU_A \rightarrow CU_B$ (on channel 1) and $CU_B \rightarrow CU_D$ (on channel 2) without interfering the PUs.

However, the performance degradation due to the activity of a PU, which fully affects a path (as shown in Section "Path diversity"), can not be counteracted by the only exploitation of spectrum diversity.

Joint path and spectrum diversity

As discuss in the previous sections, path diversity cannot counteract PU activity that varies in frequency domain, whereas spectrum diversity cannot counteract PU activity that varies in space domain. Differently, joint path and spectrum diversity can provide a promising solution that can solve both the above mentioned limitations.

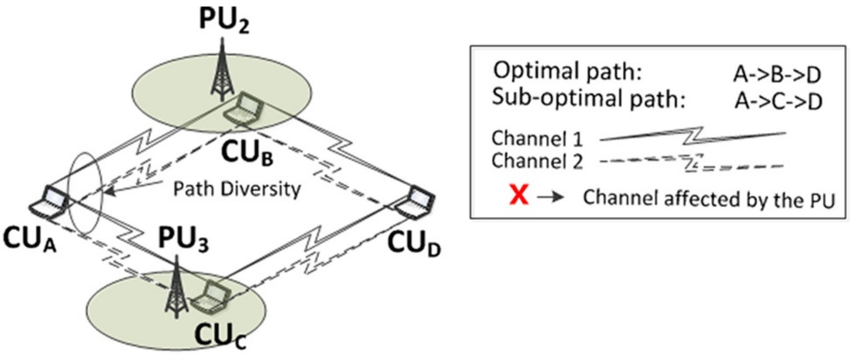
In fact, joint path and spectrum diversity allows CUs to switch dynamically among different paths and channels for communicating with each other in presence of frequency- and space-domain-dependent PU activity.

Figure 1c shows how the PU activity can affect a routing process whenever it varies in both space and frequency domain. Here, we assume that CU_A, CU_B, CU_C and CU_D are under the transmission range of four different PUs. More in detail, CU_A and CU_D are partially affected by PUs on channel 2 and channel 1, respectively, and CU_B and CU_C are fully affected by PU_2 and PU_3, respectively. Due to the benefit of jointly exploiting path and spectrum diversity, CU_A can communicate with CU_D through the optimal path composed by link $CU_A \rightarrow CU_B$ (on channel 1) and $CU_B \rightarrow CU_D$ (on channel 2) when PU_2 is not active; or the sub-optimal path composed by link $CU_A \rightarrow CU_C$ (on channel 1) and $CU_C \rightarrow CU_D$ (on channel 2) when PU_2 is active but PU_3 is inactive.

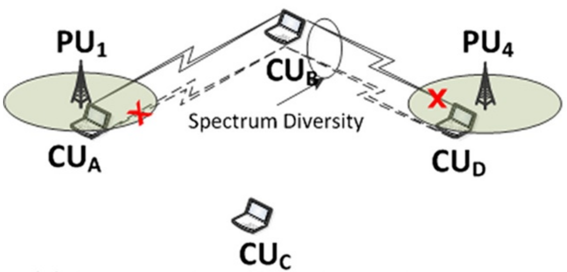
Thanks to both the path and spectrum diversity, CU_A can now reach CU_D counteracting the effect of PU activity.

Dual diversity cognitive ad-hoc routing protocol

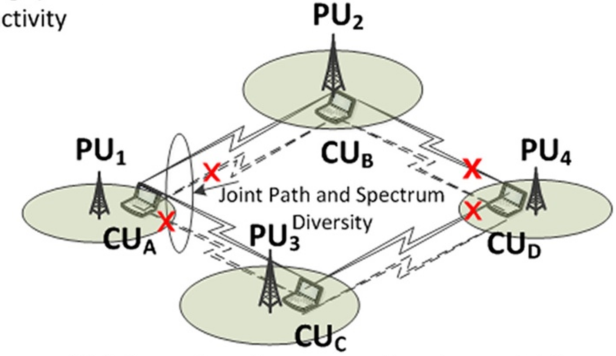
Dual diversity cognitive ad-hoc routing protocol (D^2-CARP) is a routing protocol designed for CRAHNs, which



(a) Path diversity: exploiting space domain dependent PU activity



(b) Spectrum diversity: exploiting frequency domain dependent PU activity



(C) Joint path and spectrum diversity: exploiting space and frequency domain dependent PU activity

Figure 1 Motivation of the proposed work.

takes into account the local observations of PU activity. The main feature of D^{2}CARP is to jointly exploit the path and spectrum diversity in routing. This feature allows CUs to switch dynamically among different paths and channels accounting for the local route decisions during the data forwarding time. As a consequence, D^{2}CARP is able to adapt to dynamic scenarios caused by PU activity. Since D^{2}CARP shares some common functionalities with CAODV, only its distinguishing features will be discussed in the following, whereas we refer for further details to [9]. More specifically, the route discovery process of D^{2}CARP starts with a Route REQuest (RREQ) packet broadcasted by the source to neighbors on each channel not affected by a PU activity, and it ends with one or several routes set up after the reception of Route REPlies (RREPs) from the destination. At the end of the route discovery procedure, the source can take advantage of joint path and spectrum diversity by means of multi-path and multi-channel routes. In a situation, where PU occurs while the channel is occupied by a CU, it vacates the channel and looks for another available channel for continuing the communication with its neighbor. If there is no free channel for its neighbor then CU recalls the route discovery process. The processes of RREQ and RREP phases are described in the following.

RREQ phase

In RREQ phase, we consider an arbitrary node, say X, receiving a RREQ packet from node Y through an idle channel (namely that is free from PU activity), say channel c. Here, we mainly discuss how D^{2}CARP exploits joint path and spectrum diversity in RREQ phase, as described in Algorithm 1.

Algorithm 1 RREQ phase

```
    // node $X$ receives RREQ from node $Y$ through channel $c$.
2:  if channel $c$ is free from PU then
        // D$^2$CARP exploits spectrum diversity by
    establishing multi-channel reverse routes in RREQ phase
    (line 4 to 12).
4:      if it is the first RREQ for $X$ then
            create a reverse route through the channel $c$ and
    broadcast RREQ through the channels free from PU;
6:      else if it is additional RREQ from $Y$ but on different
        channel then
            create a reverse route through that channel;
8:      else
            if it is the new or better RREQ then
```

```
10:           update a reverse route through the channel $c$;
          end if
12:     end if
        // D$^2$CARP exploits path diversity by establishing
      multi-path reverse routes in RREQ phase (line 14 to 20).
14:     if $X$ receives RREQ from multiple paths then
        if $X$ == destination node and FHN of RREQ packet
        != stored FHN in RT and $Y$ != NHN in RT and
        $hop_{rreq} \le min_{\text{hop}}$ then
16:           create a reverse route through the channel $c$
          else
18:           $X$ discards the RREQ;
          end if
20:     end if
    if $X$ has valid route for destination then
22:     send RREP to $Y$;
    else

24:
    end if
26: else
          $X$ discards the RREQ;
28: end if
```

D^{2}CARP exploits spectrum diversity by establishing multi-channel reverse routes in RREQ phase, as it is shown from line 4 to 12 in Algorithm 1. When node X receives the first RREQ, then it creates a reverse path toward the sender node Y through the channel c and it broadcasts a copy of the RREQ packet through each idle channel. If node X receives a further RREQ from the same neighbor Y, but on a different channel, then it creates a reverse route only through that channel. In such a way, node X is able to create reverse routes through the multiple idle channels. Moreover, if node X receives a new or better[b] RREQ, then it updates the reverse route through the channel c.

D^{2}CARP exploits path diversity by establishing multi-path reverse routes in RREQ phase, as it is shown from line 14 to 20 in Algorithm 1. D^{2}CARP singles out the paths according to the first hop node (FHN), which is a field of RREQ packet. When a node receives a RREQ directly from a source then the receiving node's ID will be stored in the FHN. If the FHN inside the RREQ packet is different to the stored FHN in the routing table (RT), then this RREQ is received from a different path. In that case, if the multi-path conditions are satisfied, then the node creates a reverse route through channel c, otherwise it drops the packet. The multi-path conditions to be assured are: (i) the receiving node must be the destination; (ii) the candidate path must not share any intermediate node with previous established paths (i.e., when FHN of RREQ is not already present in other FHN of RT and node Y is not a Next Hop Node (NHN) in RT); iii) the value of the hop count field in RREQ packet (hop_{rreq}) must be less or equal than minimum hop (min_{hop}) for the particular source. The first condition implies that the multi-path discovery procedure is confined to the final destination in order to limit the overhead. The second condition introduces a robust behavior when a node is not any more available due to the PU appearance. The third condition easily assures the shortest (in terms of hops) paths. Finally, if node X has a valid route for the destination, then it sends RREP to node Y, otherwise drops the RREQ packet.

Route reply phase

In RREP phase, we consider an arbitrary node, say P, receiving a RREP packet from node Q through an idle channel, say channel c. Here, we mainly discuss how D^{2}CARP exploits joint path and spectrum diversity in RREP phase, as described in Algorithm 2.

Algorithm 2 Route reply phase

```
      // node $P$ receives RREP from node $Q$ through channel $c$.
2:  if channel $c$ is free from PU then
        // D$^2$CARP exploits spectrum diversity by establishing
        multi-channel forward routes
        RREP phase (line 4 $\rightarrow$ line 12).
4:  if it is the first RREP for $P$ then
        create a forward route through the channel $c$ and
    forward RREP to all channels that exists a reverse route;
6:  else if it is additional RREP from $Q$ but on different
    channel then
        create a forward route and forward RREP through that
    channel;
8:  else
        if it is the new or better RREP then
10:         update a forward route through the channel $c$;
        end if
12: end if
        // D$^2$CARP exploits path diversity by establishing
    multi-path forward routes in RREP phase (line 14 to 18).
14:       if $P$ receives RREP from multiple paths then
    if $P$ == source node and FHN of RREP packet != stored
    FHN in RT and $Q$ != NHN in RT and
        $hop_{rrep} \le min_{\text{hop}}$ then
16:           create a forward route through the channel $c$;
          end if
18:     end if
    end if
20: $P$ discards the RREP;
```

D^{2}CARP exploits spectrum diversity by establishing multi-channel forward routes in RREP phase, as it is shown from line 4 to 12 in Algorithm 2. When node P receives the first RREP packet, then it creates a forward route through channel c and forwards RREP to all channels that have reverse route. If node P receives a further RREP from the same neighbor Q, but on a different channel, then it creates a forward route and forwards RREP only through that channel. In such a way, node P is able to create forward routes through the multiple idle channels.

Table 1 a per style

Simulation parameters	
CU number	160
CU transmission range	120 m
CU node density	400 nodes/Km^2
CU speed	2 m/s
Mobility model	Random way-point model
Data Traffic model	Constant bit rate (CBR) over UDP
Propagation model	Two-ray ground model
PU number	$[10, 12\ldots, 18]$
PU Tx range for the overlapped channel i	300 m
PU Tx range for adjacent channels $(i-1, i+1)$	150 m
PU Tx range for adjacent channels $(i-2, i+2)$	75 m
PU activity parameter	200
Duration of Simulation	1,060 s
Active data traffic interval	[60–1000]

D^{2}CARP exploits path diversity by establishing multipath forward routes in RREP phase, as it is shown from line 14 to 18 in Algorithm 2. Like in RREQ phase, D^{2}CARP singles out the paths according to the FHN of RREP packet. When a node receives a RREP directly from a destination, then the receiving node's ID will be stored in the FHN. If the FHN inside the RREP packet is different to the stored FHN in the RT, then this RREP is received from a different path. In that case, if the multi-path conditions are satisfied, then the node creates a forward route through the same channel. The multi-path conditions to be assured are: (i) the receiving node must be the source; (ii) the candidate path must not share any intermediate node with previous established paths (i.e., when FHN of RREP is not already present in other FHN of RT and node Q is not a Next Hop Node (NHN) in RT); (iii) the value of the hop count field in RREP packet ($\mathrm{h}op_{rrep}$) must be less or equal than minimum hop ($\mathrm{min}_{\mathrm{hop}}$) for the particular destination. Finally, node P drops the RREP packet.

Performance evaluation

In this section, a performance comparison of D^{2}CARP with CAODV [9] is carried out to assess the benefits of joint path and spectrum diversity. Since CAODV is designed for CRAHNs by exploiting path or spectrum diversity, it is considered as a reference protocol. We have carried out the performance comparison by using the network simulator 2 (ns-2) [13] and by considering the same simulation setup adopted in [9], and summarized in Table 1.

In Figures 2, 3, 4, 5, 6 and 7, it is shown the performance comparison between D^{2}CARP and CAODV versus the PUs or CUs. We use four different metrics to compare the performance of the considered protocols, namely, packet delivery ratio (PDR), overhead, delay, and hop count.

In Figure 2, the performance behavior of D^{2}CARP and CAODV in terms of PDR versus the number of PUs is analyzed in relatively large network (160 CUs). We observe

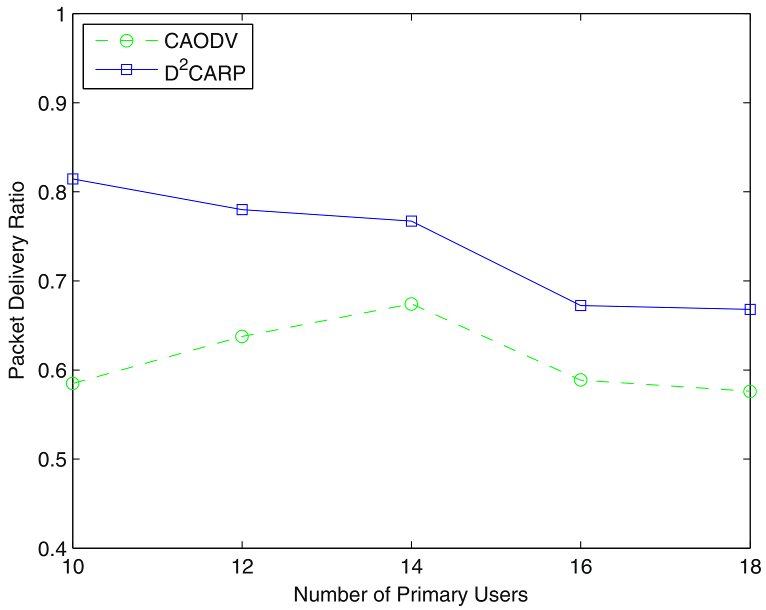


Figure 2 **Performance behavior of D^{2}CARP and CAODV in terms of PDR versus the number of PUs.**

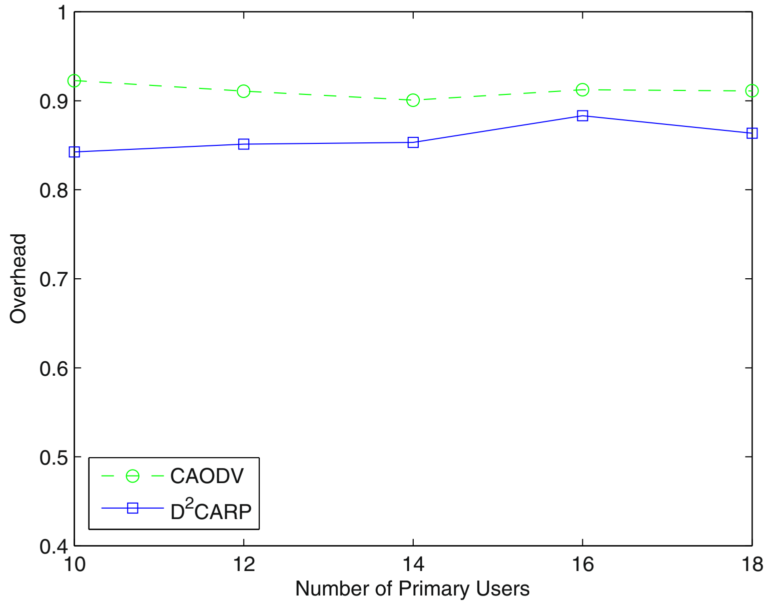


Figure 3 **Performance behavior of D^{2}CARP and CAODV in terms of Overhead versus the number of PUs.**

that the D^{2}CARP exhibits a significant improvement compared to CAODV when the PUs number is low, while it performs better or comparable to CAODV when the PUs number is higher. This behavior can be justified because the load of a crowded network is distributed by using multi-path routes in D^{2}CARP. Therefore, a less path congestion will occur.

In Figure 3, the performance behavior of both the protocols versus the number of PUs is analyzed in terms of overhead. Since we consider a relatively large network (160 CUs), in both the cases the overhead is high (around 90%). However, we note that the overhead of D^{2}CARP is lower than CAODV for both low and high number of PUs. This behavior can be explained by considering how

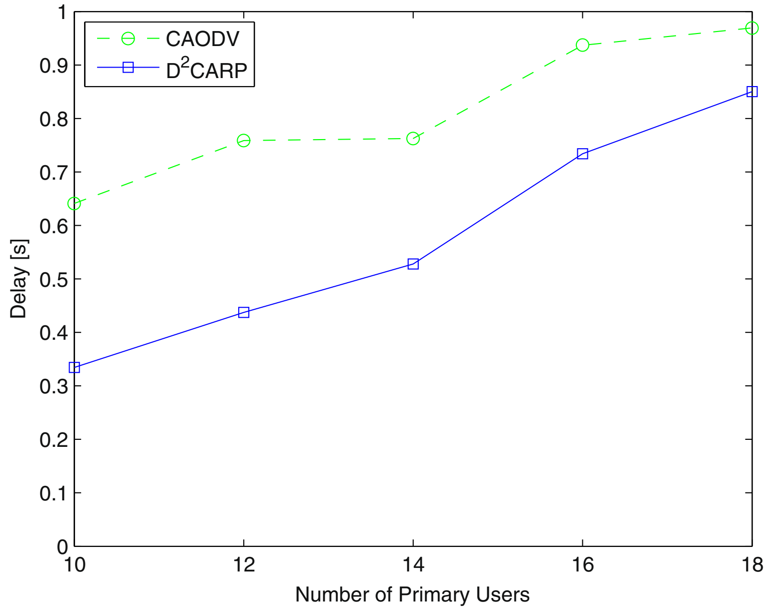


Figure 4 **Performance behavior of D^{2}CARP and CAODV in terms of Delay versus the number of PUs.**

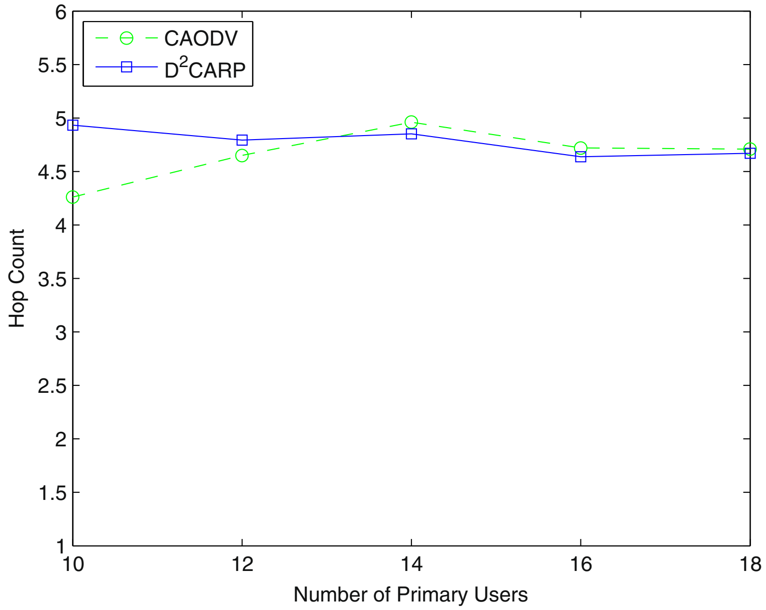


Figure 5 Performance behavior of D^{2}CARP and CAODV in terms of Hop Count versus the number of PUs.

D^{2}CARP handles the PU arrival on a certain channel and a path. Due to the dynamic use of different paths and channels, the probability that a new path must be established during data sending time is lower, reducing so the overhead of D^{2}CARP with respect to CAODV.

In Figure 4, the performance behavior of both protocols is analyzed in terms of delay-time with the number of PUs. We observe that for both the protocols when the PU number is low, the delay is low as well, while for higher values the delay increases. However, the D^{2}CARP outperforms CAODV in both low and high number of PUs. Due to the robustness of the path, assured by the second multi-path condition, less interruption occurs during the communication, reducing so delay-time of D^{2}CARP.

In Figure 5, the performance behavior of both the protocols is analyzed in terms of hop count when the number of

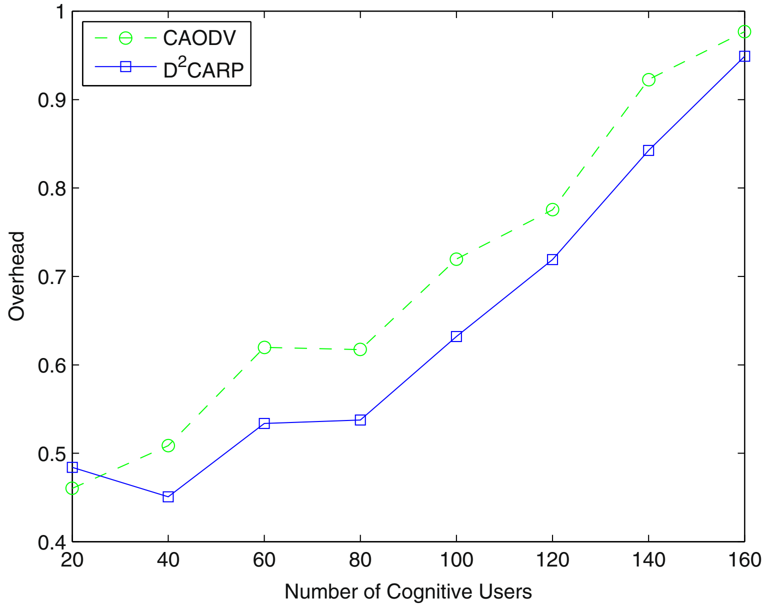


Figure 6 Performance behavior of D^{2}CARP and CAODV in terms of Overhead versus the number of CUs.

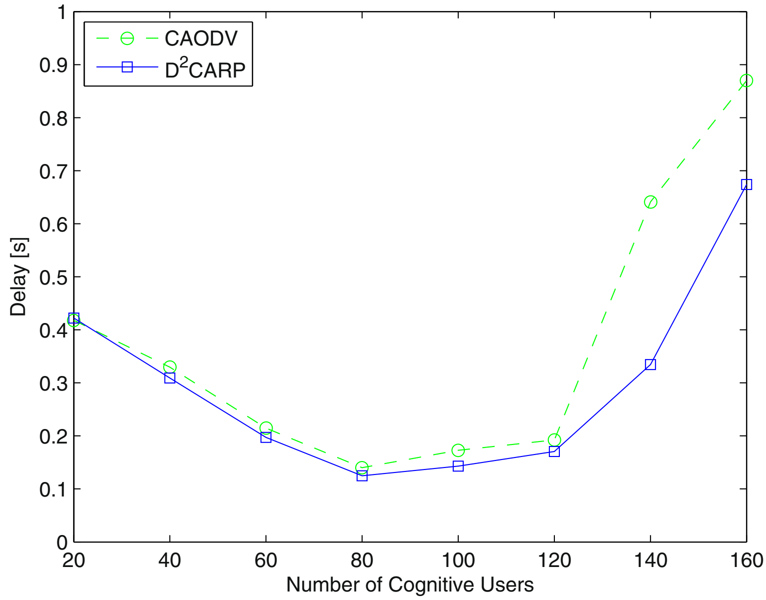


Figure 7 Performance behavior of D^{2}CARP and CAODV in terms of Delay versus the number of CUs.

PUs increases. We observe a similar behavior of both the protocols with low and high number of PUs. This behavior is reasonable because, during the route discovery process, both the protocol choose the path in according to the minimum number of hop.

In Figure 6, the performance behavior of both the protocols is evaluated in terms of overhead when the number of CUs increases. We observe that D^{2}CARP exhibits an improvement compared to CAODV for both low and high number of CUs. This behavior can be justified according to the same reasoning related to Figure 2b.

In Figure 7, the performance behavior of both the protocols is analyzed in terms of delay-time when the number of CUs increases. We observe that D^{2}CARP performs better or comparable to CAODV when the CU number is lower but it significantly outperforms CAODV when the CU number is high. This behavior can be justified according to the same reasoning regarding Figure 2c.

Conclusion

In this article, we propose to exploit the joint path and spectrum diversity to counteract the performance degradation experienced by CUs due to the activity of PUs in CRAHNs and, this idea is adopted in a routing protocol named D^{2}CARP. To assess the effectiveness of the proposal, we have carried out a performance comparison between the proposed protocol and a recent one which does not exploit jointly path and spectrum diversity. The results confirm the effectiveness of the proposal.

Endnote

[a] Optimal according to the adopted metric, i.e., minimum hop count or minimum Expected Transmission Count (ETX).

[b] Better RREQ according to the adopted metric (i.e., hop count).

Competing interests

The authors declare that they have no competing interests.

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