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journal homepage: www.elsevier.com/locate/adhocReactive routing for mobile cognitive radio ad hoc networks [☆]Angela Sara Cacciapuoti ^a, Marcello Caleffi ^{a,*}, Luigi Paura ^{a,b}^a Department of Biomedical, Electronics and Telecommunications Engineering (DIBET), University of Naples Federico II, Naples, Italy^b Laboratorio Nazionale di Comunicazioni Multimediali (CNIT), Naples, Italy

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ABSTRACT

Although more than a decade has passed from the proposal of the Cognitive Radio paradigm, in these years the research has mainly focused on physical and medium access issues, and few recent works focused on the problem of routing in cognitive networks. This paper addresses such a problem by evaluating the feasibility of reactive routing for mobile cognitive radio ad hoc networks. More specifically, we design a reactive routing protocol for the considered scenario able to achieve three goals: (i) to avoid interferences to primary users during both route formation and data forwarding; (ii) to perform a joint path and channel selection at each forwarder; (iii) to take advantage of the availability of multiple channels to improve the overall performance. Two different versions of the same protocol, referred to as Cognitive Ad-hoc On-demand Distance Vector (CAODV), are presented. The first version exploits inter-route spectrum diversity, while the second one exploits intra-route spectrum diversity. An exhaustive performance analysis of both the versions of the proposed protocol in different environments and network conditions has been carried out via numerical simulations. The results state the suitability of the proposed protocol for small mobile cognitive radio ad hoc networks.

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1. Introduction

The *Cognitive Radio* paradigm has been recognized in 1999 [1] as an effective way to deal with bandwidth scarcity and/or un-efficient usage. Although more than ten years have passed, the research on cognitive radio networks has mainly focused on physical and medium access issues [2,3], including the definition of effective spectrum sensing, decision and sharing mechanisms. Only recently

the research community started to work in the area of cognitive radio routing, and few works address the problem of routing in Cognitive Radio Ad hoc Networks (CRAHNS).

In this paper, we contribute to such a problem by proposing a reactive routing protocol, referred to as Cognitive Ad-hoc On-demand Distance Vector (CAODV), that aims to provide end-to-end connectivity in mobile CRAHNS characterized by dynamic primary user (PU) activity [4]. In such a scenario, the cognitive user (CU) communications experience time-variant spectrum availability. Therefore, a spectrum dynamic awareness is required at the network layer to guarantee, at the same time, minimal interference to PUs and efficient utilization of the licensed spectrum.

The main characteristics of the proposed protocol can be synthesized as follows:

- in-band based communications: CAODV exchanges control packets only through the licensed (primary) portion of the spectrum, avoiding to resort to dedicated out-of-band control channels;

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- local spectrum knowledge: CAODV does not require a complete knowledge about PU activity, since each node is able to route the data packets and to exchange the

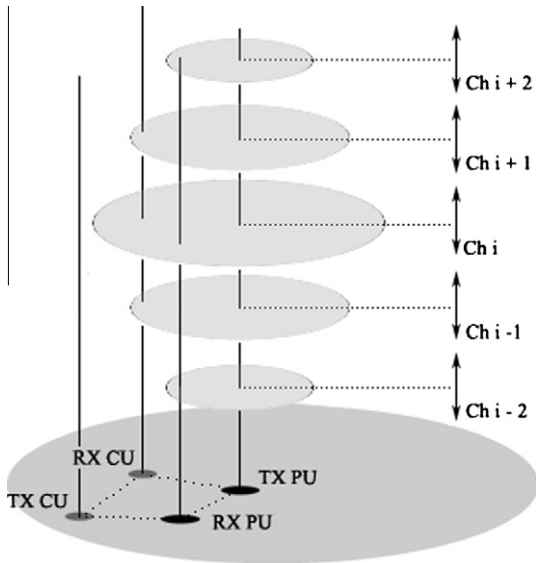


Fig. 1. Hidden primary user problem: due to the uncertainty about the location of the PU receivers, a CU can cause interference to PU communications also if it adopts a spectrum sensing mechanism. In the figure, the transmitting CU can not sense the PU transmission since it is located far from the transmitting PU, but it can cause interference to the receiver PU.

- control ones without interfering with PU communications, by exploiting only its local spectrum sensing capabilities;
- spectrum dynamic awareness: CAODV is able to adapt to PU activity changes, provided that the changing rate is reasonable (order of magnitude of minutes), by recomputing new routes when changes in the spectrum availability arises due to PU arrival or departure;
- imperfect spectrum sensing support: CAODV aims to minimize the interference to PU communications due to an imperfect physical spectrum sensing;
- local route decision: CAODV allows all intermediate nodes to cooperate to the route process decision by adapting both the next hop and the channel selection to the environmental conditions during the data forwarding;
- independence of underlying technologies: CAODV does not require underlying data-link technologies dedicated to the cognitive paradigm, although it can clearly benefits from their availability.

Through the paper we propose two different versions of CAODV. Both the versions are able to take advantage of the spectrum diversity provided by the cognitive paradigm, but they exploit two different approaches. The first version, referred to as *inter-R*oute diversity CAODV (ERI-CAODV), exploits *inter-route spectrum diversity*, namely, it is able to discover several routes and to use different channels for different routes, but each route is restricted to evolve through the same channel. The latter one, referred to as *intra-R*oute diversity CAODV (ARI-CAODV), exploits *intra-route*

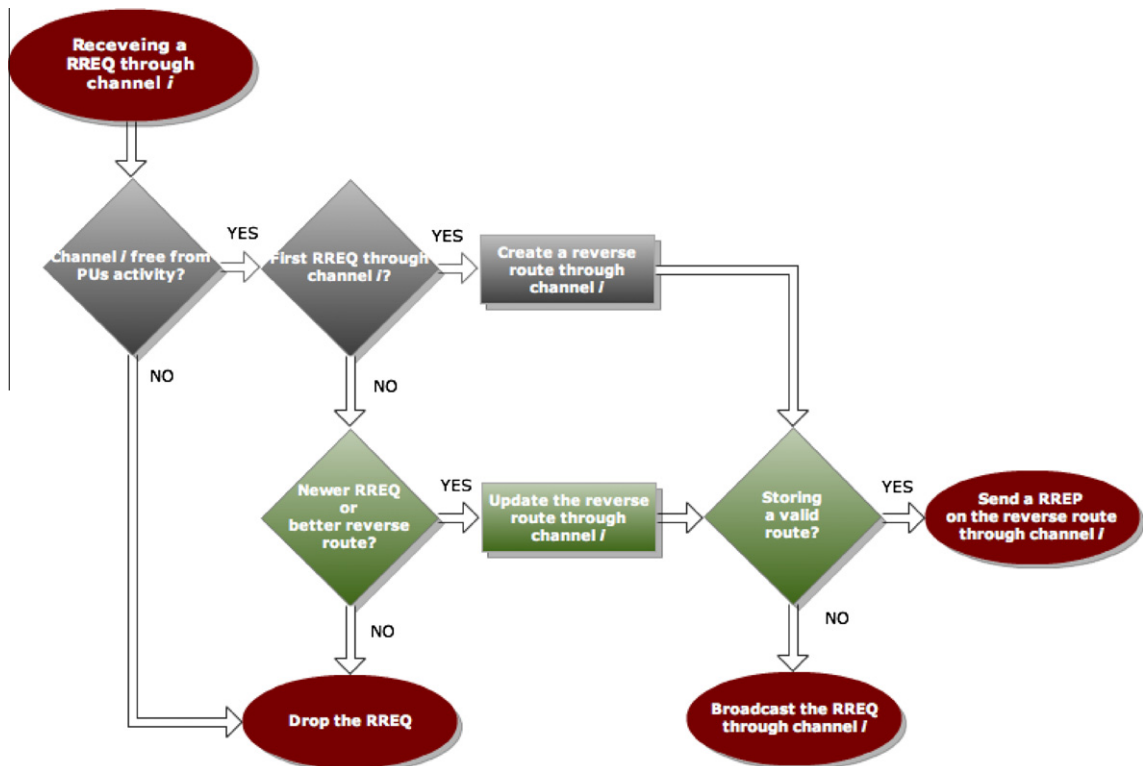


Fig. 2. Route request flow chart for ERI-CAODV.

spectrum diversity by discovering only one route that can evolve through all the available channels.

The rest of the paper is organized as follows. Section 2 describes the related works in this area, while in Section 3 the network model is described. Section 4 presents the CAODV protocol in both the inter-Route diversity (ERI) and intra-Route diversity (ARI) versions. The results of an extensive performance evaluation are provided in Section 5, and, finally, in Section 6 some conclusions are drawn.

2. Related works

Basing on the assumptions about the spectrum-awareness, the works in the area of routing for cognitive radio networks can be classified in two main categories: *full spectrum knowledge* and *local spectrum knowledge*. In the former class a map of the spectrum occupancy is available at each node, while in the latter only a local knowledge about the spectrum availability is present. In the following, we briefly describe the proposals belonging to the second class, more suitable for the considered scenario. Further details about both the two approaches can be found in [3].

The works [5,6] propose an adaptation of the Ad-hoc On-demand Distance Vector (AODV) protocol [7] for

cognitive scenarios by piggybacking at each hop the spectrum status information into the route request packets, which are processed at the destination to compute the path. Although the proposed protocol allows intermediate nodes to modify the route decision during route reply forwarding, it requires that the spectrum availability does not change during packet delivery. Differently, our proposal allows each forwarder to modify both the next hop and the channel decisions during the packet forwarding for quickly adapting to spectrum availability changes.

Also the papers [8,9] propose to enhance the AODV protocol for cognitive scenarios. In [8], the authors propose to use a dedicated common control channel for route formation. Therefore, the data packets are routed along channels whose qualities have not been assessed. In [9], the authors do not resort to a dedicated channel but, since they assume that nodes are equipped with a single transceiver, a similar issue due to the use of un-assessed channels arises. Differently, in our work the packets are routed through channels whose qualities have been estimated by means of probe packets.

An approach based on identifying multiple available routes during the route formation stage and performing the optimal decision at the destination is adopted in [10].

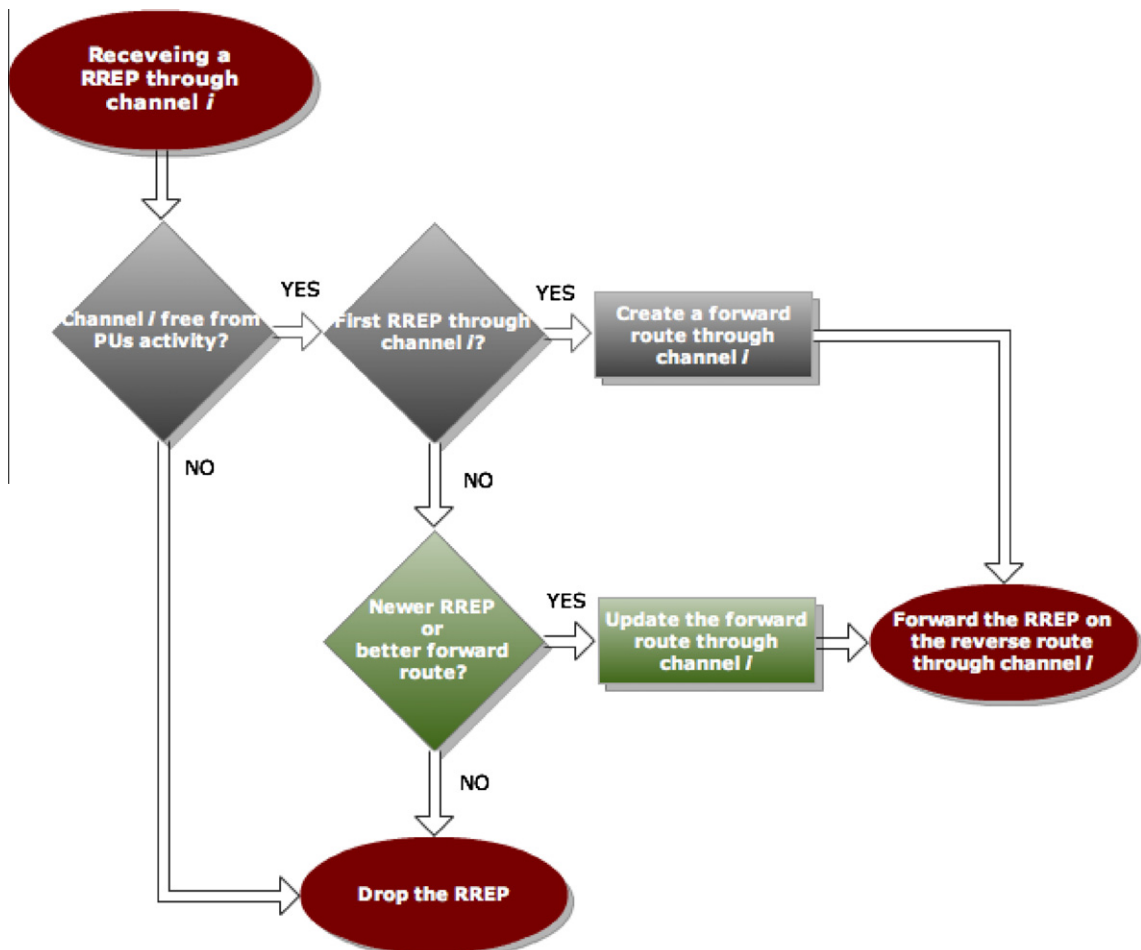


Fig. 3. Route reply flow chart for ERI-CAODV.

In this works, the authors propose to account for spectrum availability changes by allowing intermediate nodes to locally adapt the channel assignment for a flow. In [11], the authors propose to build a spectrum-tree structure for each channel, storing so all the information about the tree topology and the spectrum availability at the tree-root nodes. As a consequence, the frequency of the spectrum availability changes deeply affects the performance of the proposed protocol. Moreover, both the works [10,11] assume static or very slowly moving CUs. On the other hand, our work assumes both mobile CUs and dynamic spectrum availability.

In [12], a protocol for mobile CRAHNS based on the geographic forwarding paradigm has been proposed. The main idea of the protocol is to discover several paths, which are combined at the destination to form the path with the minimum hop count, and it is able to deal with reasonable levels of PU activity changing rate. However, it assumes that most of the nodes be GPS equipped and, most importantly, a mechanism for disseminating the destination location both at the source and at each intermediate node is required. Finally, in [13], the authors propose a reactive routing protocol that aims to minimize the interference caused by the CUs to the PUs' communications. The proposed protocol exploits the availability of knowledge about both the CUs and the PUs positions for route maintenance. Unlike the works in [12,13], our protocol do not require any location knowledge for both route discovery and route maintenance.

3. Network model

We assume that the network is composed by cognitive users (CUs) that freely move in a two-dimensional cartesian scenario. The primary users (PUs), whose positions are as-

sumed to be fixed, operate according to a two-stage on/off switching cycle [12]. The number, the locations and the transmission standards of the PUs are assumed unknown to the CUs, and the primary transmissions are sensed by a spectrum sensing mechanism available at each node. Although such a sensing mechanism is out of the scope of this paper, in this work we assume that it is imperfect, i.e. we assume that some strategies are needed at the network layer to assure the minimal interference to PU communications in presence of undetected PU activity.

The CUs communicate only through the licensed portion of the spectrum (i.e. there is no dedicated spectrum for CU control messages), constituted by l channels, each having the same bandwidth. If a primary user is active and its transmission frequency overlaps a CU channel, say channel i , this channel is affected by PU activity in the circular region centered at the PU location with radius equals to the PU interference range. Moreover, to take into account the co-channel interference effects, we assume that the adjacent channels $i - 2, i - 1, i + 1, i + 2$ are affected by the PU activity in regions with a radius that decreases with the separation of the channels from channel i [12], as shown in Fig. 1.

Each CU is able to use the channels in the licensed spectrum free from PU activity [12], maybe 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 assuming the presence of an underlying channel coordination mechanism [14,15].

4. Cognitive ad-hoc on-demand distance vector

The Cognitive Ad-hoc On-demand Distance Vector (CAODV) is a reactive routing protocol based on the Ad-hoc

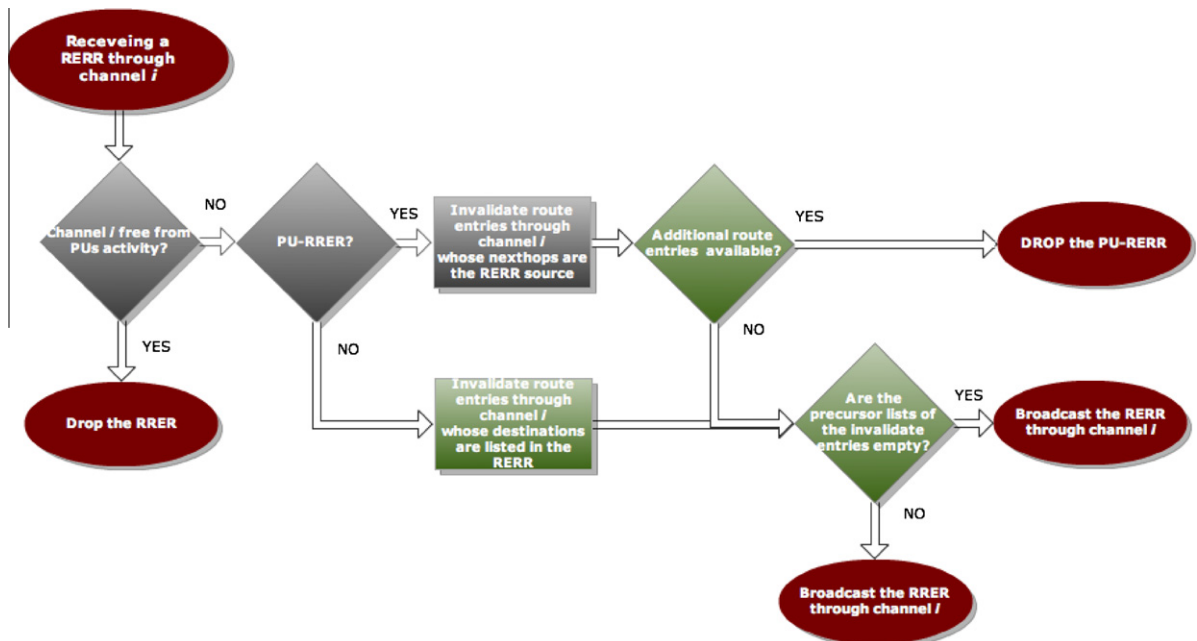


Fig. 4. Route error flow chart for ERI-CAODV.

On-demand Distance Vector (AODV) protocol and designed for operating in mobile cognitive radio ad hoc networks. As a consequence, CAODV inherits some AODV features: the route setup is based on an expanding ring search mechanism and it exploits route request (RREQ) and route reply (RREP) packets. Moreover, the route maintenance uses route error (RERR) packets for reacting to topology changes due to CU mobility or wireless propagation instability.

The similarities end at this point. Differently from AODV, the CUs should be able to exchange the control packets through the licensed spectrum without causing harmful interferences to the primary users also in presence of imperfect spectrum sensing mechanisms, as shown by Fig. 1. Although cooperative approaches at the physical layer are recognized as a viable solution to improve the reliability of the spectrum sensing, in this work we do

not make any assumption about the adopted sensing mechanism and, therefore, a mechanism to enforce the PU activity detection at the network layer is required.

Moreover, the CUs should be able to exploit the spectrum diversity provided by the cognitive radio paradigm without causing excessive overhead for route formation. To this aim, we exploit two different approaches for spectrum diversity utilization: the inter-route diversity and the intra-route one. Finally, the route maintenance process should be able to locally handle the changes in spectrum availability due to PU arrival or departure, avoiding so to waste the bandwidth with a new route setup process.

In the following, we present both the versions of CAODV, highlighting the main differences between the two approaches for spectrum diversity utilization.

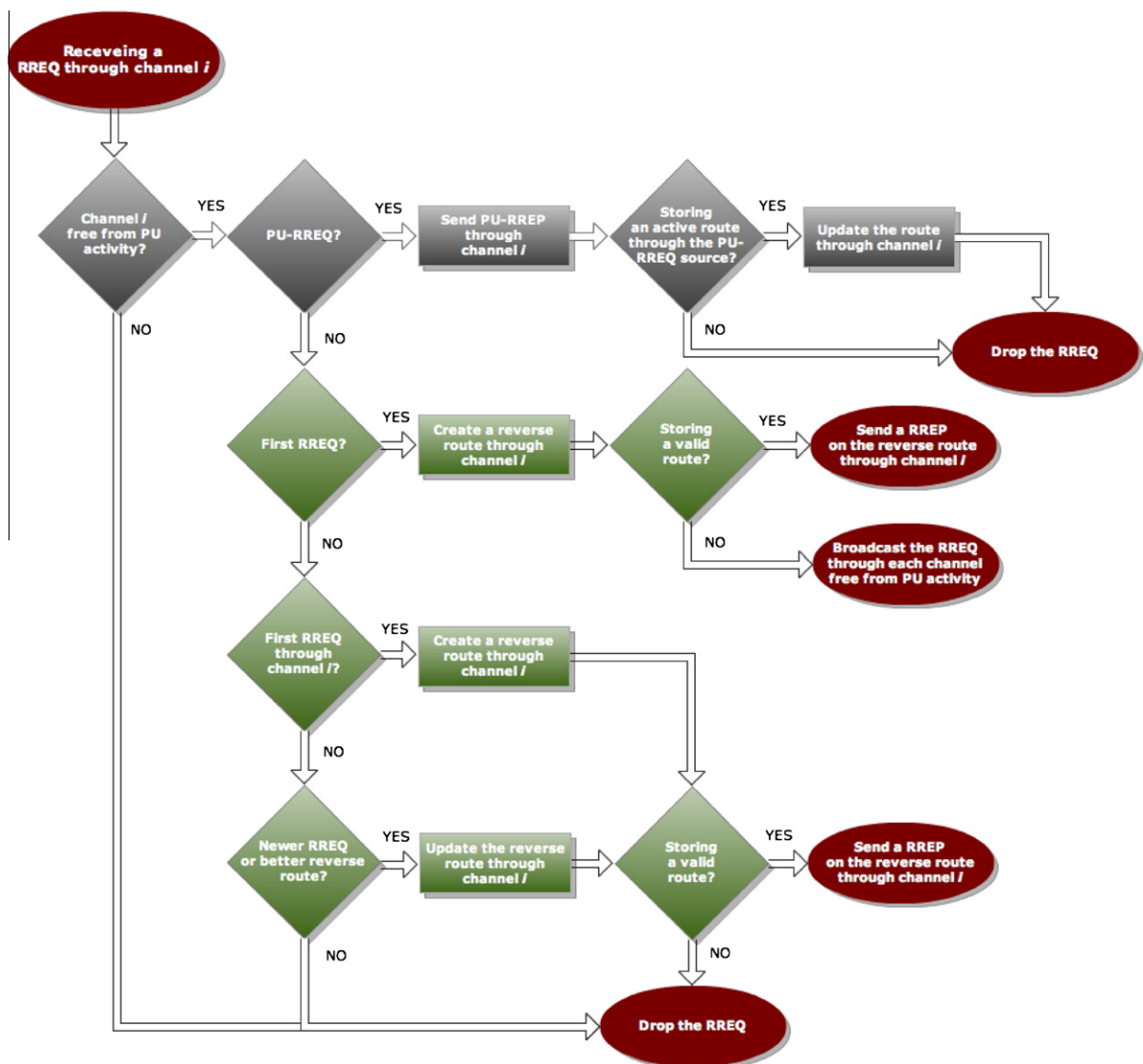


Fig. 5. Route request flow chart for ARI-CAODV.

4.1. Inter-route diversity CAODV

4.1.1. Route formation

The route setup process of inter-Route diversity CAODV (ERI-CAODV) has been designed to exploit inter-route diversity by imposing that: (i) different routes evolve through different channels; (ii) each route evolves through the same channel. Although such a design principle is sub-optimal since it requires the availability of a channel idle (i.e. free from PU activity) in the whole region traversed by the route, it allows us to exploit spatial diversity by dis-

covering multiple routes (at most l as the number of channels) through different intermediate CUs.

More in detail, as shown by Fig. 2, when an intermediate CU receives a route request (RREQ) packet through an idle channel, say channel i , it sets up a reverse route toward the source through the same channel. If the CU can supply a valid route for the desired destination, then it sends a unicast route reply (RREP) packet back to the sender through the reverse route. Otherwise, it re-broadcasts the received route request through the same channel. If an additional request for the same pair source-destination

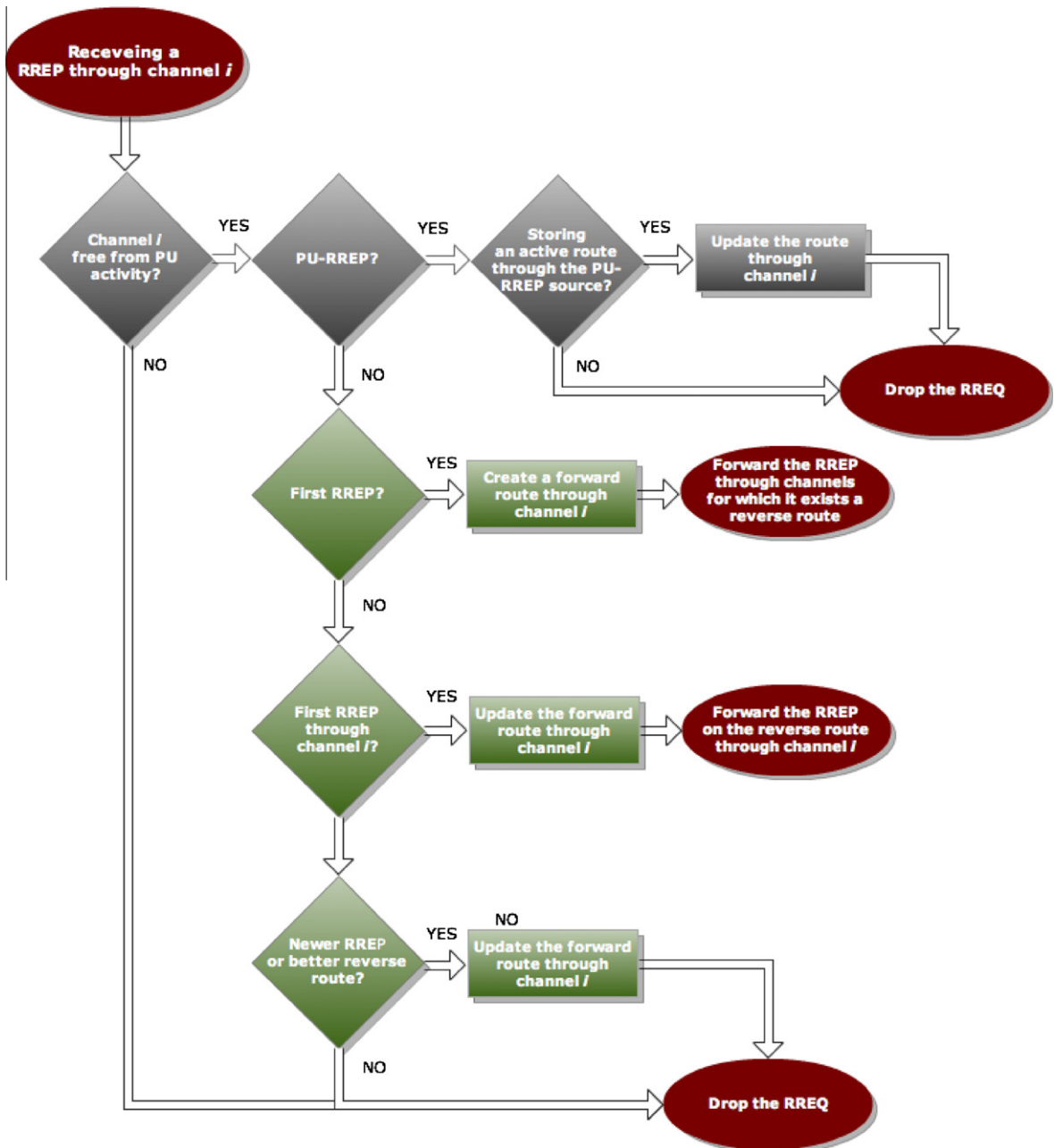


Fig. 6. Route reply flow chart for ARI-CAODV.

is received by the same CU through the same channel, it is processed only if it refers to a newer route discovery session or to a better reverse route than the one stored in the routing table. Otherwise, it is simply discarded.

The route reply process is shown in Fig. 3. When an intermediate CU receives the first route reply through an idle channel, say channel i , it sets up a forward route through the same channel toward the destination and it forwards a copy of the reply along the reverse route stored in its routing table (through the same channel). If an additional reply for the same pair source-destination is received by the same CU through the same channel, the CU processes such a reply only if it refers to a newer route discovery session or to a better forward route than the one stored in the routing table.

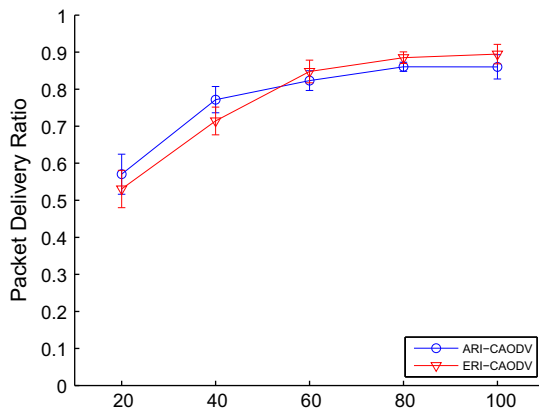
4.1.2. Route maintenance

Topology changes due to node mobility or wireless propagation instability are handled with traditional route error (RERR) packets, while the route maintenance due to changes in spectrum availability exploits an additional type of packets, namely, the primary user route error

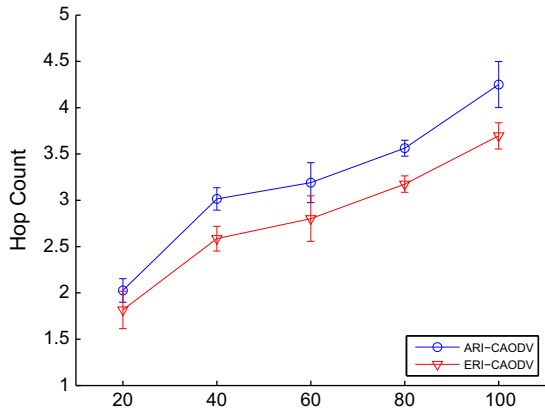
(PU-RERR) packets. The main difference between the two type of packets is the scope. The RERRs generally have a wide scope, since they are used to advise all the intermediate nodes belonging to a route that a link is failed and a new route discovery session is needed. On the other hand, the PU-RERRs have a local scope, since they are used to inform the neighbors that some PU activity has been sensed on a certain channel and, therefore, it is necessary to use a different channel for packet forwarding.

More in detail, when some PU activity is detected by a CU on a certain channel, say channel i , the CU invalidates all the routing entries through such a channel and it informs the neighbor CUs that the channel is now unavailable with a PU-RERR packet as shown in Fig. 4. The CUs that receive the PU-RERR invalidates the routes through channel i that involves the PU-RERR source. In such a way, the routing protocol is able to minimize the interference to PU communications in case of imperfect spectrum sensing.

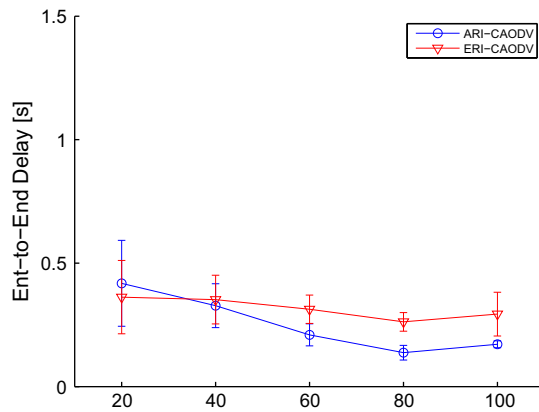
We note that the PU-RERR packets allows CAODV to handle dynamic spectrum availability without introducing excessive overhead. In fact, when a CU receives a PU-RERR, it checks if additional routes are available in its routing



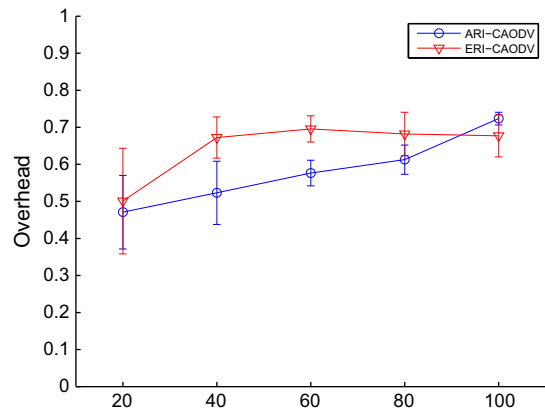
(a) Packet Delivery Ratio



(b) Hop Count



(c) End-to-End Delay



(d) Overhead

Fig. 7. Experiment 1: number of cognitive users.

table. If so, the CU can forward the traffic through the additional route(s), otherwise, a new route discovery session is started by using a traditional RERR packet.

4.1.3. Packet forwarding

In order to maximize the spectrum efficiency, ERI-CAODV exploits the inter-route spectrum diversity. To this aim, each forwarder first singles out among the discovered paths the shortest ones. Then, the data flow is randomly partitioned on the available shortest paths. In such a way, the spectrum diversity (different routes evolve on different channels) allows the protocol to counteract the spectrum availability changes, while the spatial diversity (different routes evolve on different intermediate nodes) is an efficient solution for handling node mobility.

4.2. Intra-route diversity CAODV

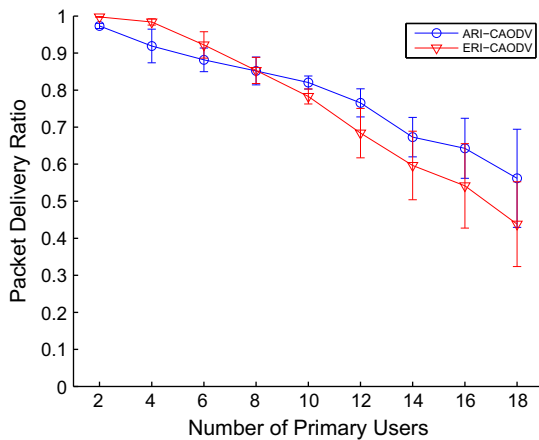
The route setup process of intra-Route diversity CAODV (ARI-CAODV) has been designed to allow CUs to exploit intra-route spectrum diversity by relaxing the constraint that the same channel is available in the whole region tra-

versed by the route. The drawback of the intra-routing diversity is that we cannot exploit spatial diversity as we made for the IRA-CAODV protocol to avoid route loop.

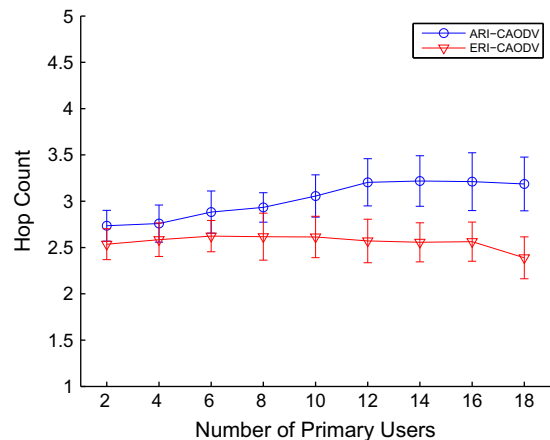
4.2.1. Route formation

When an intermediate CU receives the first route request through an idle channel, it sets up a reverse route through the same channel and it broadcasts a copy of the RREQ packet through each available channel, as shown in Fig. 5. As a consequence and differently from ERI-CAODV, a further route request on a different channel will be broadcasted only if it refers to newer discovery session or better reverse route. This mechanism allows an intermediate CU to try to establish several links toward the next hop by sending a route request through each idle channel.

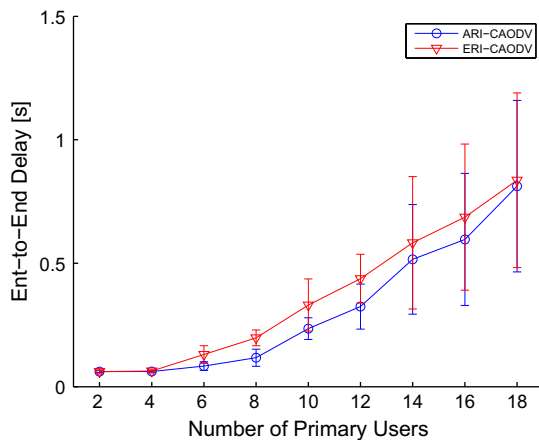
We note that in Fig. 5 a new class of packets, the PU-RREQ packets, are used when the local spectrum sensing mechanism recognizes that a channel previously used by a PU has been released. If it happens, the sensing node locally broadcasts a PU-RREQ so that it can benefit from this spectrum availability by establishing for each active route a link on that channel.



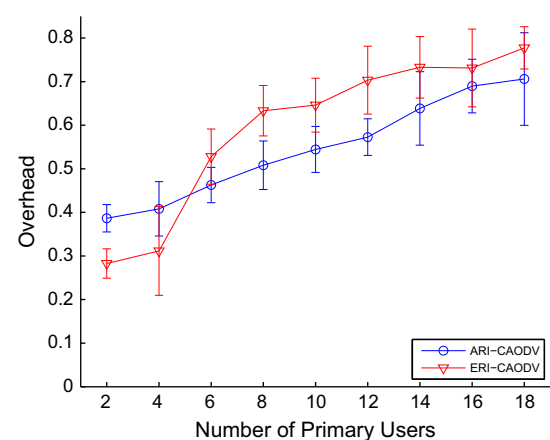
(a) Packet Delivery Ratio



(b) Hop Count



(c) End-to-End Delay



(d) Overhead

Fig. 8. Experiment 2: number of primary users.

The route reply management is shown in Fig. 6. Similarly to route request management, when an intermediate CU receives the first route reply, it sets up a forward route through the same channel and it forwards a copy of the reply along each channel for which a reverse path has been set in the routing table. A further route request on a different channel will be re-broadcasted only if it refers to newer discovery session or better reverse route.

This mechanism allows the intermediate CU: (i) to establish a forward link on a channel only after the reception of a reply on such a channel, i.e. to establish a forward link only for bidirectional idle channels; (ii) to forward a reply for establishing a reverse link for each channel through which a request has been received, independently from the reception of a reply on such a channel. In such a way, the protocol is able to maximize the spectrum utilization for a given route, by establishing a link on each symmetric channel free from PU activity.

For sake of brevity, we do not describe the route maintenance and the data forwarding processes since they are similar to those of ERI-CAODV.

5. Performance evaluation

In this section we state a performance comparison of both the versions of CAODV by means of numerical simulations via Network Simulator 2 (ns-2) [16] under different environments, network conditions and PU activities. Ns-2 has been extended to multi-radio multi-channel environments according to [17]. Unfortunately, since any reactive or proactive routing protocol for CRAHNS has been publicly released as source code, we cannot assess a performance comparison with previously proposed protocols. However, we set the simulation scenarios as close as possible to those adopted in [12] so that a qualitative comparison can be stated.

5.1. Simulation setup

CUs move according to the *random waypoint model* in a square area, whose size has been set such as it fits with a node density equal to 400 nodes/Km². The transmission

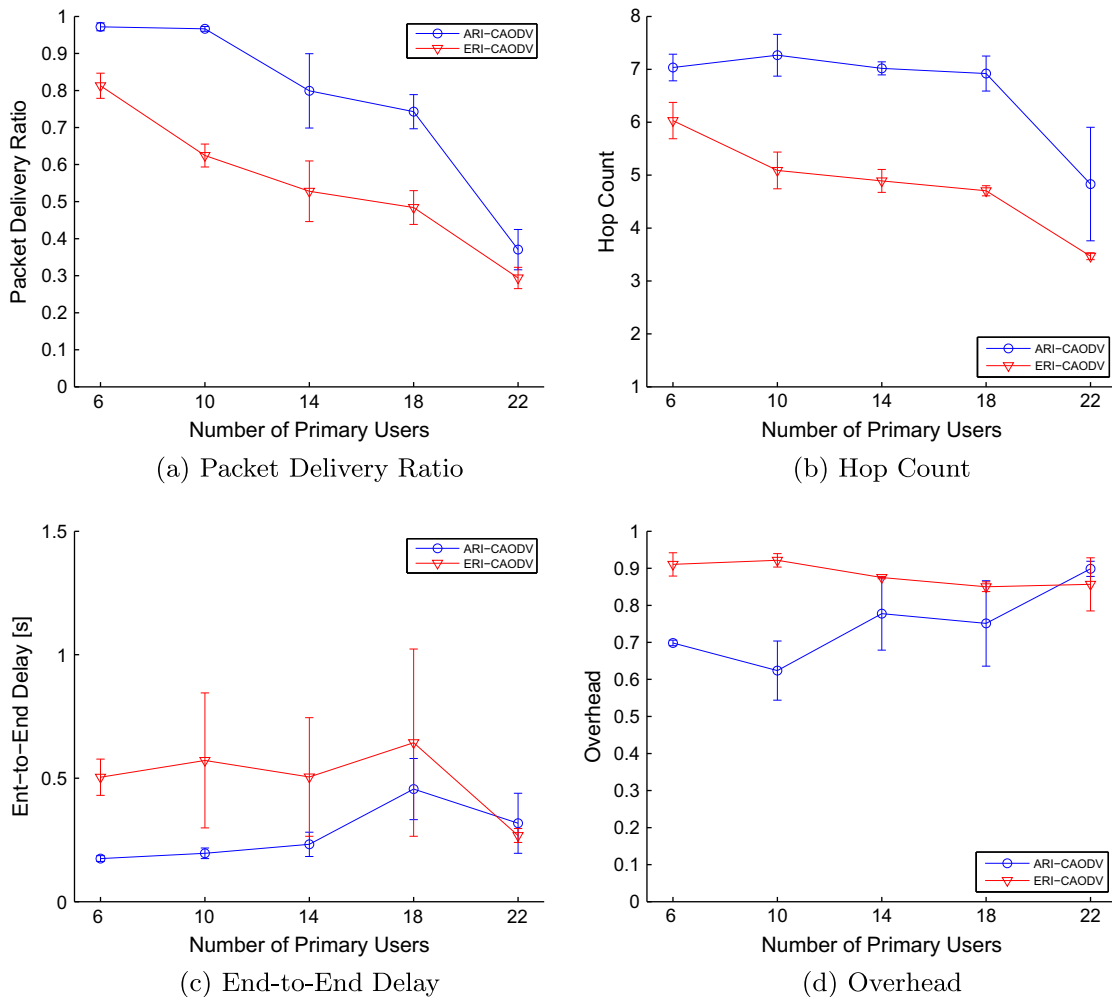


Fig. 9. Experiment 3: number of primary users in large networks.

range of the CUs has been set to 120 m, the transmission standard is the IEEE 802.11b and the propagation model is the *Two-Ray Ground* one. The transmission range of the PUs, whose positions are assumed static, has been set to 300 m and their activity is modeled according to a two-stage on/off process with exponential distribution with rate parameter λ . In the following we refer to $\frac{1}{\lambda}$ as the PU activity time.

The workload is modeled as CBR data packets 1000 bytes long over UDP connections, and each node generates one data flow toward a destination selected randomly. Accounting for the Gupta–Kumar [18] bound, the throughput generated by each source has been set to $\frac{W}{10\sqrt{n}}$, where W is the link data throughput and n is the number of CUs in the network.

The duration of each run is 1060 s and the data traffic is active in the interval [60,1000] seconds. For each experiment, we performed five runs computing both the average value and the standard deviation for each metric: (i) packet delivery ratio; (ii) hop count; (iii) end-to-end delay; (iv) routing overhead.

5.2. Numerical results

In the first experiment (Fig. 7) the CAODV performance behavior is analyzed when the number of CUs n increases. We set the PU number to 10, the PU activity time $\frac{1}{\lambda} = 200$ s and the throughput parameter $W = 0.54$ Mbps. With reference to the PDR shown in Fig. 7a, we observe that for both the protocols when the CU number is low ($n = 20$ or $n = 40$) the PDR is low as well, while for higher values the performance increases, reaching almost 90% of delivered packets for the largest network. This behavior is reasonable and confirmed by the results in terms of hop number shown in Fig. 7b. For the lowest values of n , i.e. for small areas (the node density is fixed), each node is affected by the activity of all the PUs and, hence, it is often isolated due to the unavailability of free channels. Therefore, the packets delivered are mainly those sent when most of the PUs are inactive and directed to destinations very close to the sources, as confirmed by the average value of the hop count metric, roughly 2. On the other hand, when n increases, the area increases as well, and thus CAODV is able

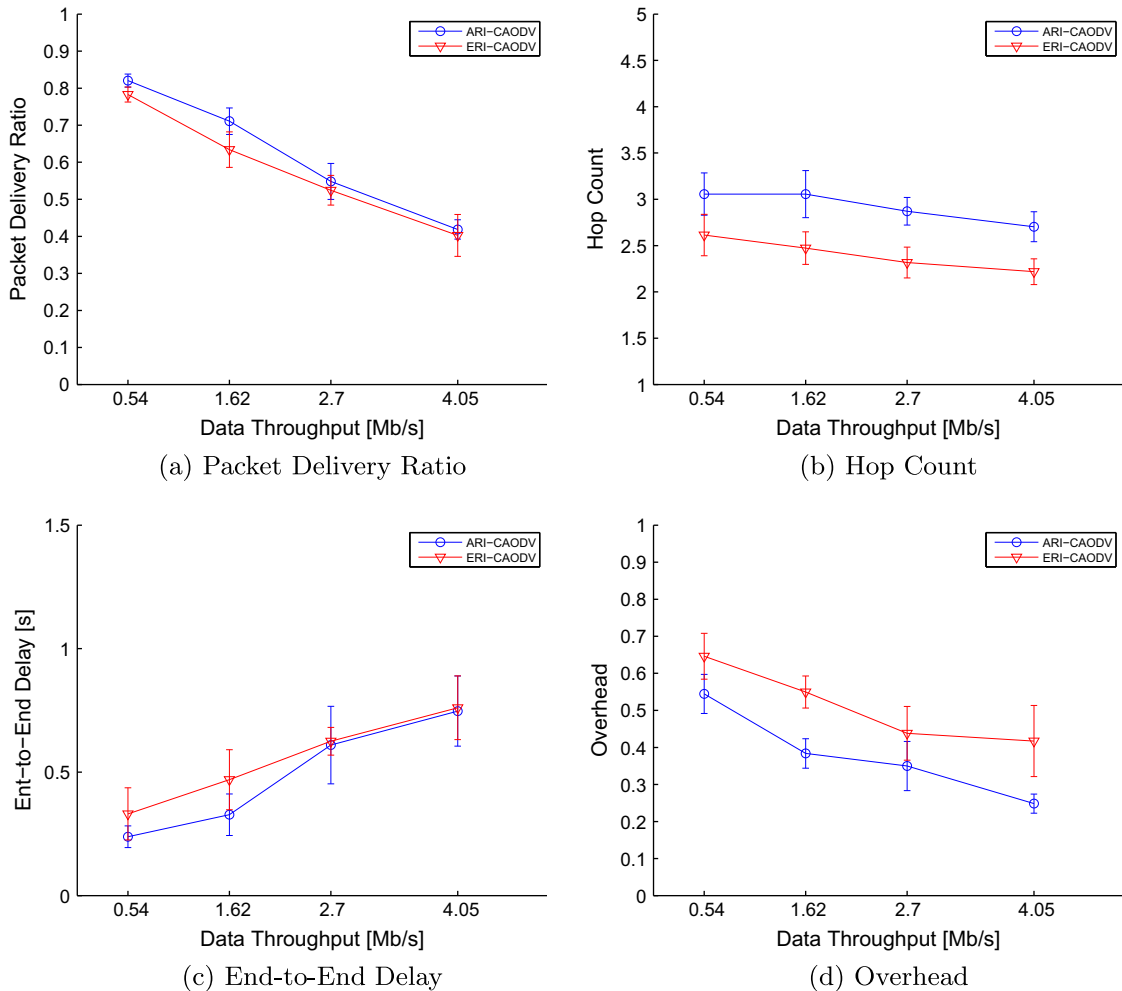


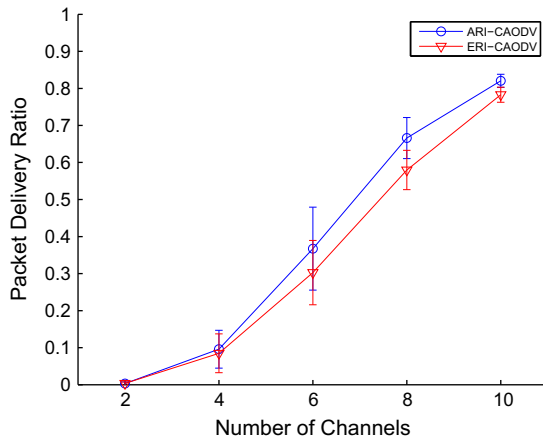
Fig. 10. Experiment 4: data throughput.

to build paths unaffected by PU activity for most of the flows. Also the results in term of routing overhead agree (Fig. 7d) with the previous comments: for lower values of n the unavailability of free channels inhibits the nodes from starting route requests, reducing so the routing overhead. We note that, although the PDR performance of both the protocols are comparable, ARI-CAODV exhibits a higher hop count with respect to ERI-. This behavior can be explained by considering how the two versions handle the PU arrival on a certain channel and the topology changes due to the mobility. ARI- exploits a different channel (if available) on the same route thanks to the intra-route diversity, and thus it achieves the same hop count on all the routes. A route discovery process is started only if all the available channels fail. Differently, ERI- must forward the traffic on a different route, which can be characterized by a smaller hop count due to node mobility. Finally, the results in term of end-to-end delay (Fig. 7c) of the two protocols are very similar.

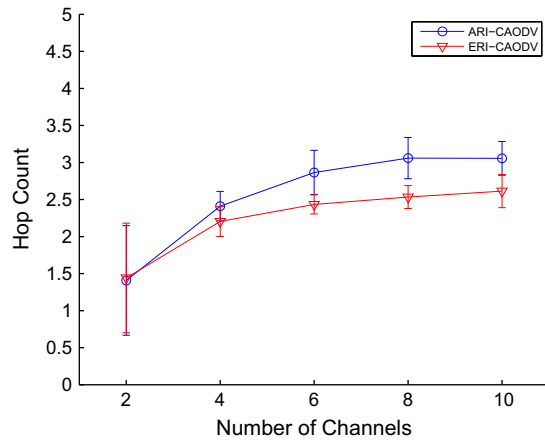
In the second experiment (Fig. 8), we analyze the performance as the number of PUs increases. We set the CU number to 50, while λ and W are the same of the previous

experiment. As expected, we observe that the performance in terms of PDR (Fig. 8a) decreases as the number of PUs decreases, this is due to the number and the duration of the free channels. Moreover, although ARI- exhibits a higher hop count for all the values of PU number as in the previous experiment, in this case it is able to outperform ERI- in terms of PDR when the PU number increases. The results are reasonable, since the PU number highly affects the ERI- performance in term of PDR due to its incapacity to exploit different channels for the same route. We note also that, although ARI- is more complex than ERI- and it use an additional type of control packets (PU-RERR), it outperforms ERI- in terms of routing overhead (Fig. 8d) for most of the values of PU number, namely, when the PU activity is not negligible.

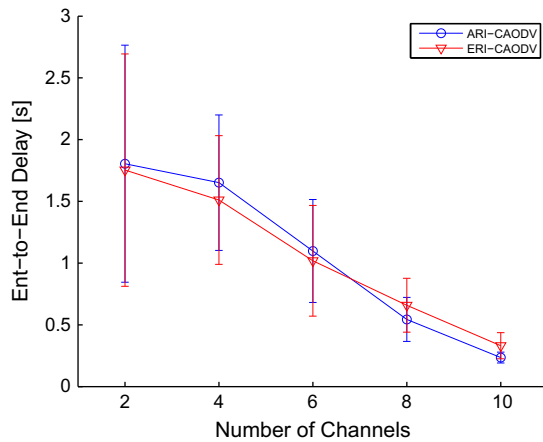
In the third experiment (Fig. 9), we evaluate the performance in larger scenarios ($n = 100$) keeping active the PUs for all the simulation. As regard to the hop count (Fig. 9b), we observe that ERI- outperforms ARI- as in the previous experiments. However, in this case we note that ARI- outperforms significantly ERI- in terms of PDR (Fig. 9a) thanks to its capability to exploit frequency



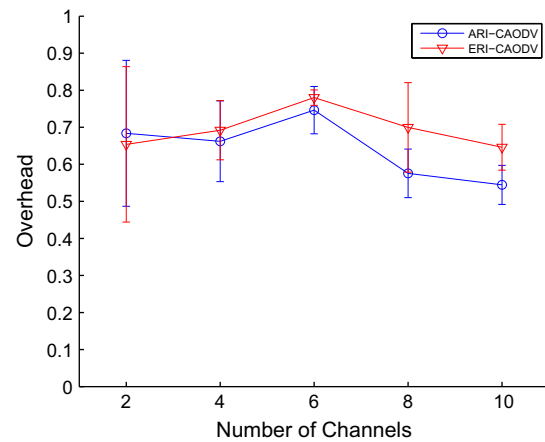
(a) Packet Delivery Ratio



(b) Hop Count



(c) End-to-End Delay



(d) Overhead

Fig. 11. Experiment 5: number of channels.

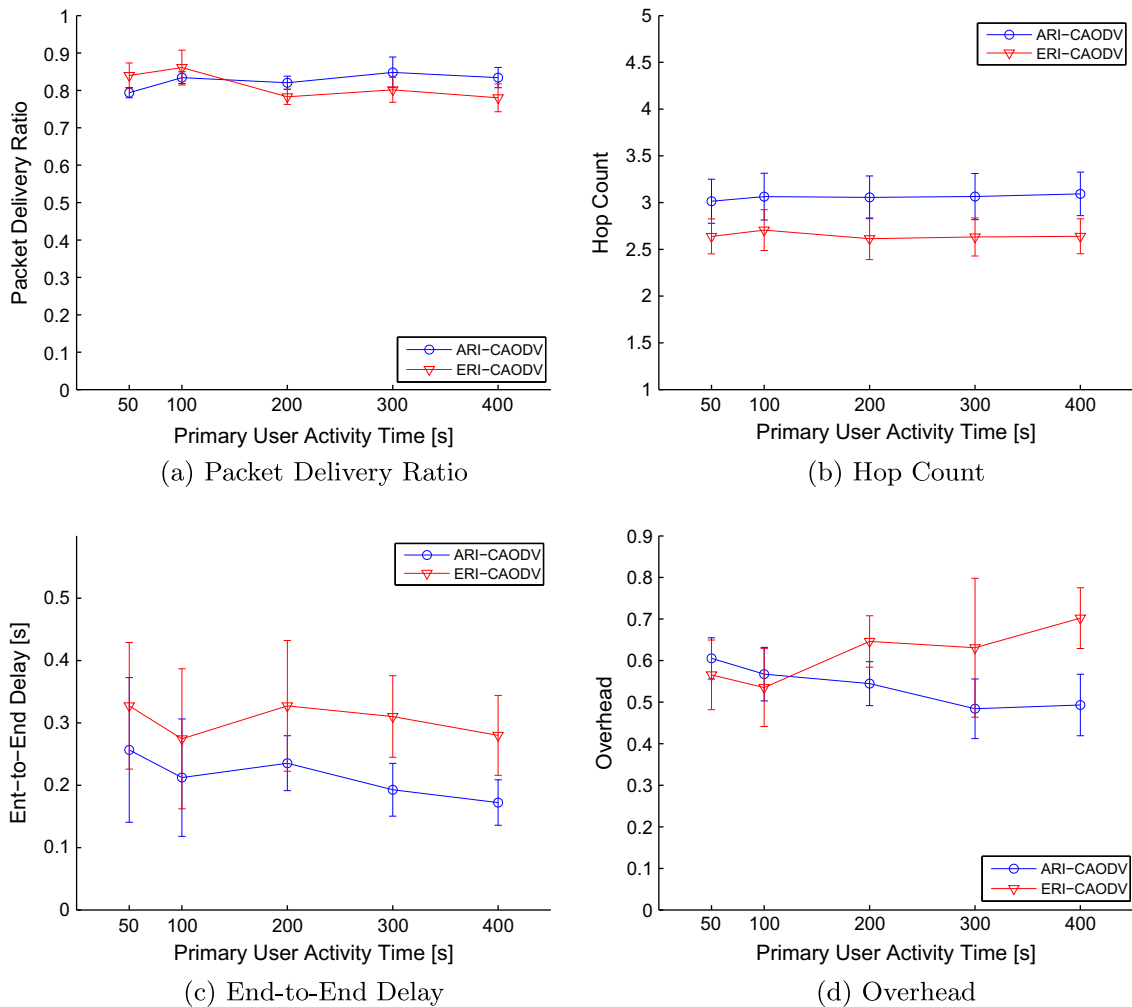


Fig. 12. Experiment 6: primary user activity time.

diversity, as confirmed also by the delay metric. As regard to the routing overhead (Fig. 9d), the same considerations of the previous experiment hold, while, as regard to the delay (Fig. 9c), we note that both the protocols exhibit delays with order of magnitude of seconds due to the PU activity.

In the fourth experiment (Fig. 10), we analyze the effects of different data throughput W on the performance of the two protocols. As in the second experiment, we set $n = 50$ and $\frac{1}{\lambda} = 200$ s. We note that both the protocols are significantly affected by the data throughput, and in particular both exhibit a low PDR (50%) for values of W near the Gupta–Kumar bound (5.4 Mbps for a 802.11b link due to MAC layer inefficiencies) as shown by Fig. 10a. As a consequence, both the protocols are not suitable for large networks, as expected from their reactive approach.

In the fifth experiment (Fig. 11), we evaluate the effects of the channel number with $n = 50$, $\frac{1}{\lambda} = 200$ s, and 10 PUs. In such a case, we have that the PDR increases roughly in a linear manner for both the protocols as the number of channels increases (Fig. 11a). Moreover, the overhead is roughly constant (Fig. 11d), although the run number lim-

its the statistical accuracy of the results. For all the considered metrics, except the hop count one (Fig. 11b), the ARI- protocol slightly outperforms the ERI-one.

Finally, in the last experiment (Fig. 12), we analyze the effects of the PU activity dynamic with $n = 50$ and 10 PUs. We note that both the protocols perform well in terms of PDR (Fig. 12a) for all the considered values, with ERI- outperforming ARI- for the lowest values of λ , i.e. when the PUs exhibit fast activity dynamic. As regards to the other metrics (Fig. 12b–d), the same considerations previously made hold.

6. Conclusions

In this paper, a routing protocol for mobile cognitive ad hoc networks is proposed. The protocol, referred to as Cognitive Ad-hoc On-demand Distance Vector (CAODV), is able to achieve three goals: (i) to avoid interferences to primary users during both route formation and data forwarding; (ii) to perform a joint path and channel selection at each for-

warder; (iii) to take advantage of the availability of multiple channels to improve the overall performance. Two different versions of CAODV are presented: a version able to exploit the inter-route spectrum diversity and a version able to exploit the intra-route spectrum diversity. An exhaustive performance comparison of the proposed protocols in different environments and network conditions has been carried out via numerical simulations. The results confirm the suitability of the proposed protocol for small mobile cognitive radio ad hoc networks. A version of CAODV which exploits both spatial diversity and intra-route frequency diversity is currently under study.

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