An Energy-Efficient and Reliable Routing Protocol for Cognitive Radio Sensor Networks

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Abstract. With rapid advances in wireless communications and networking technologies, the demand for high speed, wireless and ubiquitous connectivity continues to increase in order to cope with new services and applications. Increasing demand for spectral resources has introduced the problem of spectrum scarcity. Moreover, the static spectrum allocation policy for wireless communications can cause the issue of spectrum underutilization. Cognitive Radio (CR) offers promising solution for spectrum shortage and underutilization problem by means of dynamic spectrum management. Routing in Cognitive Radio Sensor Networks (CRSNs) is a very challenging task due to energy constraints, opportunistic spectrum access, dynamic topology changes as well as intermittent connectivity caused by activities of Primary Users (PUs). This paper proposes the Energy-efficient and Reliable Cognitive Ad-hoc Routing Protocol (ERCARP) with an aim to provide reliable transmission path and prolong network lifetime in CRSNs. The protocol takes account of packet loss probability, link latency and residual energy for path establishment. Furthermore, by utilizing the joint path and spectrum diversity in routing, the multi-path multi-channel routes are given for fast route recovery. The protocol performance is compared with that of the Dual Diversity Cognitive Ad-hoc Routing Protocol (D2CARP) through simulations using NS-2 simulator. The simulation results obviously prove that ERCARP outperforms D2CARP in terms of packet loss, energy efficiency, end-to-end delay and jitter.

Keywords: Reliable routing · Energy efficiency · Cognitive radio · Sensor network · Fast route recovery

1 Introduction

Cognitive Radio (CR) [1–3] is a candidate for the next generation of wireless communication system which applies the Dynamic Spectrum Access (DSA) scheme to improve spectrum utilization efficiency and communication quality. CR has the ability to know the unutilized spectrum in a licensed and unlicensed spectrum band. In Cognitive Radio Networks (CRNs) [4], unlicensed users (or Secondary Users (SUs)) are able to sense their environment and are allowed to opportunistically access the temporally unused licensed spectrum bands without harmful interference to licensed users (or Primary Users (PUs)).

In addition, recently, significant growth in the applications of Wireless Sensor Networks (WSNs) [5, 6] has been made such as air pollution monitoring, wildlife tracking, heal monitoring, intruder tracking, etc.

With recent advances in CR technology, it is possible to apply the DSA model in WSNs, called Cognitive Radio Sensor Networks (CRSNs) [7, 8], to mitigate over-crowded unlicensed spectrum bands. CRSN is a specialized ad hoc network of distributed wireless sensors that are equipped with CR capabilities. The components of CRSN architecture are shown in Fig. 1.
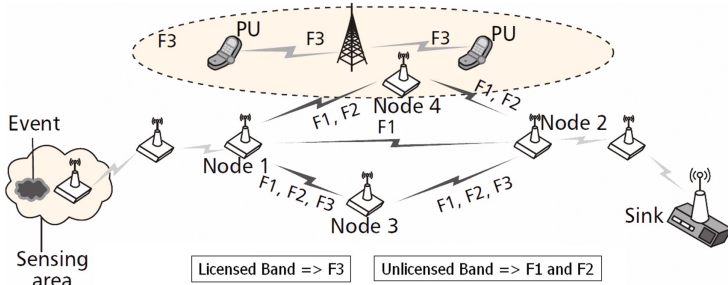

Fig. 1. Cognitive radio sensor network.

With unique characteristics of CRSNs, data routing in CRSNs faces various significant challenges that require in-depth studies [7, 9]. The main challenge is to deal with the dynamic spectrum availability. In CRSNs, the available spectrum bands are time and location varying because of dynamic PU activities. Another challenge is how to determine the optimal path for data transmission which provides high network performance. Furthermore, in CRSNs, a link failure frequently occurs caused by not only the node mobility but also the appearance of PU activity. The data transmission of SUs may be interrupted immediately after a PU activity is detected.

In this paper, we propose the Energy-efficient and Reliable Cognitive Ad-hoc Routing Protocol (ERCARP) with an aim to provide reliable transmission path and prolong network lifetime in CRSNs. In ERCARP protocol, the novel routing metric that takes account of packet loss probability, link latency and residual energy is introduced and implemented. The protocol establishes a transmission path with small delay, low packet loss and high residual energy. Moreover, to offer fast route recovery, the protocol applies the joint path and spectrum diversity in routing to provide multi-path multi-channel routes so that the source node is able to dynamically switch to different paths or channels when PU activity is detected during data transmission. The performance evaluations are conducted through simulations using NS-2 simulator [10]. The simulation results obviously show that ERCARP protocol outperforms the Dual Diversity Cognitive Ad-hoc Routing Protocol (D2CARP) [11] in terms of the number of dropped packets, energy efficiency, end-to-end delay and jitter.

The remainder of the paper is organized as follows. In Sect. 2, we present the related work. The overview of ERCARP protocol is provided in Sect. 3. The protocol's routing metric is described in Sect. 4. Section 5 explains the protocol operations including route discovery and route maintenance process. In Sect. 6, the simulation configuration is described. We show the simulation results and discuss the protocol performance evaluation in Sect. 7. Finally, we state the concluding remarks in Sect. 8.

2   Related Work

Several routing protocols have been proposed in the literature in order to address the different concerns for CR ad hoc networks which can be applied in CRSNs. In [12], Chowdhury and Felice has proposed a spectrum aware routing protocol for cognitive scenarios based on geographic routing paradigm, i.e. each SU can determine the location of other nodes, to elude regions of PU activity during the route formation. In [13], Beltagy et al. has presented a multipath routing protocol with a purpose to improve the reliability of transmission paths. The "Route Closeness" metric has been introduced to create transmission routes based on non-closeness to each other. The main goal of this routing design is to provide less vulnerability to the impact of PU activity as an active mobile PU is unable to interrupt all the selected paths in the same time if they are not close to each other. The authors of [14] has proposed the on-demand Spectrum and Energy aware Routing (SER) protocol to support the energy-constraint multi-hop CR ad hoc networks, where each SU has limited energy supply, with an objective to give high throughput and robust routing as well as prolong the network lifetime. The protocol provides the channel access scheduling and balances the network load by dividing the data traffic over different channels and timeslots according to the channel-timeslot assignment. The article in [15] has introduced the Cognitive Ad-hoc On-demand Distance Vector (CAODV) routing protocol, which applies individually path and spectrum diversity, with an aim to support dynamic CR ad hoc networks. In [11], the Dual Diversity Cognitive Ad-hoc Routing Protocol (D2CARP) has been proposed by sharing some common functionalities with the CAODV. The protocol exploits the joint path and spectrum diversity in routing to reduce the impact of performance degradation experienced by SUs due to PU activities. Nevertheless, both CAODV and D2CARP consider the number of hops as the routing metric in order to select the transmission path with minimum hop count. Although the main advantage of this metric is its simplicity, the quality of wireless links and the energy efficiency of the network are not taken into account, resulting in the establishment of non-optimal transmission paths which can significantly cause poor protocol performance. Additionally, scalable routing protocols for CRSNs have been proposed in [16, 17]. Even though, the protocols take account of the network scalability, energy efficiency, resource constraint and spectrum efficiency, the issue of efficient route recovery has not provided.

3   Overview of ERCARP Protocol

The ERCARP protocol is a reactive routing protocol which triggers the process of route discovery when a source node requires data delivery. The protocol shares some common features with D2CARP protocol [11]. Each node in the network is unnecessary to know the complete path from source to destination for data transmission. To circumvent the routing loop problem [18], the sequence number is utilized to indicate the freshness of routing information. Furthermore, the protocol applies the joint path and spectrum diversity in routing to provide multi-path multi-channel routes for rapid route recovery. The protocol's routing metric takes account of energy efficiency, packet loss probability and link latency. A transmission path with small delay, low packet loss and high residual energy is established in order to provide reliable communications and prolong network lifetime in CRSNs. The protocol also enables sensor nodes to go into sleep mode when they do not have any packet to transmit or receive in order to conserve their battery resources. The main routing packets include RREQ (Route REQuest), RREP (Route REPly), RERR (Route ERRor), ETX (Expected Transmission Count) probe, RTT (Round-Trip Time) probe and RTT acknowledgement packet.

4   Routing Metric

In CRSNs, a SU selects an appropriate available channel among various channels for communication with each other based on a routing metric. The ERCARP protocol relies on the combined routing metric that is composed of three essential components: packet loss probability, link latency and residual energy. The protocol selects a path with small delay, low packet loss and high residual energy for data transmission. The link cost, $C(l)$, is calculated by using the following equation:

$$C(l) = RE(l) * \left(\frac{1}{ETX(l)} \right) * \left(\frac{2}{RTT(l)} \right) \tag{1}$$

where $RE(l)$ is the residual energy of a node on the link l. The $RTT(l)$ is the round-trip time of the link l, denoting the interval between the sending of an RTT probe packet and the receiving of the corresponding RTT acknowledgement packet over the link l. The $ETX(l)$ is the Expected Transmission Count of the link l, representing the expected number of retransmissions required to successfully transmit an ETX probe packet over the link l. The $ETX(l)$ can be measured as:

$$ETX(l) = \frac{1}{[1 - P_f(l)][1 - P_r(l)]} = \frac{1}{[d_f(l) * d_r(l)]} \tag{2}$$

where $P_f(l)$ and $P_r(l)$ are the probability of packet loss in the forward and reverse direction of the link l respectively. The $d_f(l)$ (forward delivery ratio) denotes the

probability that an ETX probe packet is successfully transmitted to the neighbor over the link l during the time window (i.e. *ETX_PROBE_WINDOW*). The $d_r(l)$ (reverse delivery ratio) represents the probability that an ETX probe packet sent from the neighbor is successfully received through the link l during the time window (i.e. *ETX_PROBE_WINDOW*). The $d_f(l)$ and $d_r(l)$ can be calculated as:

$$d_f(l) = \frac{n_f(l)}{\text{ETX\_PROBE\_WINDOW}} \tag{3}$$

$$d_r(l) = \frac{n_r(l)}{\text{ETX\_PROBE\_WINDOW}} \tag{4}$$

where $n_f(l)$ is the number of ETX probe packets successfully sent to the neighbor through the link l. While $n_r(l)$ denotes the number of ETX probe packets successfully received from the neighbor via the link l.

In ERCARP protocol, a path from source to destination with highest path cost, $C(p)$, is always selected for data delivery. With maximum value of $C(p)$ for the path, the value of ETX and RTT is minimized and the RE value is maximized. The maximum value of RE ensures that the selected path has high residual energy, i.e. energy-efficient path. On the other hand, the smaller ETX and RTT value give the data transmission with low packet loss and delay respectively. The $C(p)$ is calculated by using the following equation:

$$C(p) = \sum_{l \in p} C(l) \tag{5}$$

5   Protocol Operations

5.1   Route Discovery

When a source node requires a path towards a destination node for data communication, it broadcasts a Transmission Route REQuest (T-RREQ) packet to its all neighbors through all its available channels (i.e. not occupied by a PU).

If a T-RREQ packet reaches the destination node or an intermediate node which has a valid route towards the destination, it generates a Transmission Route REPly (T-RREP) and sends it back to the previous node through the same channel that the T-RREQ packet has been transmitted. The destination node will not discard the further T-RREQ packets received from the same node but on different channels.

In the route reply phase, an intermediate node which receives the first T-RREP packet creates a forward route pointing to the packet sender through the same channel that the packet has been received and then forward the copies of the packet over all its valid reverse routes with different vacant channels (i.e. not used by a PU) towards the source of the T-RREQ packet.

When a T-RREP packet arrives at the source node, a path from source to destination is created and the node can begin sending data packets. Also, the source node will not discard the additional T-RREP packets received from the same sender but on different channels.

5.2 Route Maintenance and Recovery

As data packets flow from source to destination, each node over the transmission path updates the lifetime (i.e. expiration time) of its forward and reverse routes in order to maintain the link connectivity. However, if a route's lifetime is expired, the routing entry for that route will be invalid.

In the ERCARP protocol, each SU sets a timer for every specific time to sense a PU activity. During data transmission, if a SU detects a PU activity, it is unable to transmit a data packet through the channel which overlaps the PU's transmission frequency, thus resulting in a link failure. For that case, with the fast and efficient route recovery mechanism, the node responds to the failure by immediately selecting another available channel or path for data delivery without the need to trigger a new route discovery process.

In addition, a link failure, which is detected by link-layer feedback, can result from not only PU activity but also node mobility, node fault, link degradation, etc. During data delivery, if a node detects a link breakage and no alternative available channel or path is found, a new route discovery process will be triggered.

6 Simulation Configuration

The efficiency of the ERCARP protocol is evaluated by using NS-2 simulator [10] with an extension to support the CR environments. The simulation area of 1000×1000 m^2 in which 100 movable SUs are located is specified. There are 10 PUs randomly placed in the simulation area. The PU activities are modeled according to the ON/OFF process with exponential distribution with parameter λ of 250, referred to as PU activity parameter [12]. Each SU sets a timer of every 5 s to sense a PU activity. There are 5 non-overlapping channels given for multi-channel data communications. The transmission range of SUs and PUs is set to 150 m. Additionally, to calculate the updated link cost, an ETX and RTT probe packet are periodically broadcasted to the neighboring nodes every 1 and 0.5 s respectively. The ETX time window is set to 10 s. The simulation parameters are summarized in Table 1.

In our network model, we assume that each SU is equipped with multiple wireless interfaces. Each interface can operate only on one of non-overlapping channels. The locations of PUs are assumed to be unknown to SUs.

Table 1. Simulation parameters.

Parameter name	Value
Simulation area	$1000 \times 1000 \text{ m}^2$
Simulation time	500 s
Number of SUs	100
Number of PUs	10
PU activity parameter (λ)	250
Number of channels	5
Source node	Node 0
Destination node	Node 99
Traffic type	CBR
Data packet size	512 bytes
MAC layer	IEEE 802.11
Transport layer	UDP
SU transmission range	150 m
PU transmission range	150 m
Radio propagation	Two-Ray Ground Reflection
PU activity checking interval	Every 5 s
RTT probe interval	Every 0.5 s
ETX probe interval	Every 1 s
ETX probe window	10 s

7   Performance Evaluation

The protocol performance is evaluated through simulations (with varying data rate) based on the performance metrics including percentage of packet loss, average end-to-end delay, average jitter and minimum node lifetime. The NS2 Visual Trace Analyzer [19] is used to analyze the simulation results. To validate the performance improvement of ERCARP protocol, the simulation results are compared with that of the D2CARP protocol [11] under identical scenarios.
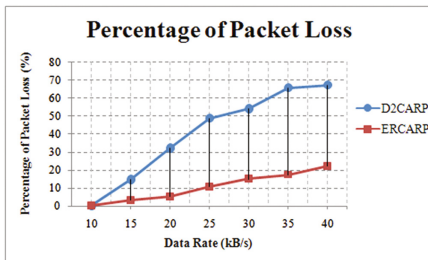

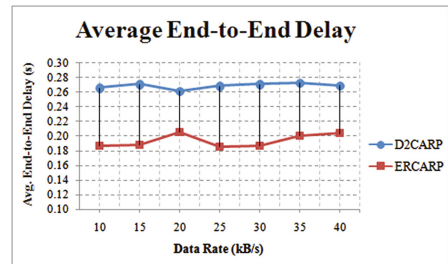**Fig. 2.** Simulation results of percentage of packet loss.

Fig. 3. Simulation results of average end-to-end delay.

Figure 2 shows the results of percentage of packet loss against the increased data rate. For D2CARP protocol, it is obvious that the percentage of packet loss grows dramatically when increasing the data rate. In contrast, the packet loss result for ERCARP protocol increases slowly in the same situations. In ERCARP protocol, the impact of packet loss is taken into account as a routing metric for path selection. Therefore, the ERCARP protocol provides significantly lower number of dropped data packets than the D2CARP protocol.

In Fig. 3, the simulation results of both protocols are evaluated in terms of the average end-to-end delay by increasing the data rate. Although the figure shows the fluctuation in the results of average end-to-end delay as the data rate increases, it is observed that the ERCARP protocol outperforms the D2CARP protocol in all cases. As expected, the ERCARP protocol utilizes the routing metric which considers the link delay for path decision, i.e. a path with lower latency is chosen for data transmission. As a result, the D2CARP protocol provides higher end-to-end delay result.

Figure 4 exhibits the comparative results of average jitter as the data rate increases. From the graph, when the data rate is increased, the ERCARP protocol provides lower average jitter as compared with that of the D2CARP protocol. The reason behind that is because, with more effective routing metric, the ERCARP protocol provides more reliable transmission paths. In addition, by utilizing the multi-path multi-channel routes, the ERCARP protocol keeps the data delivery process running continuously even in presence of path failures caused by PU activities. Therefore, the ERCARP protocol gives lower communication interruptions which produce smaller average jitter result.

In Fig. 5, the minimum node lifetime result of ERCARP protocol is compared with that of D2CARP protocol under the different data rate. For ERCARP protocol, a transmission path that has high residual energy is selected. From the simulation results, as compared to the D2CARP protocol, the ERCARP protocol can prolong the lifetime of individual SUs and overall network. As expected, with new routing metric in ERCARP protocol, the data packets are forwarded to SUs which have higher residual nodal energy; thus providing longer minimum node lifetime.
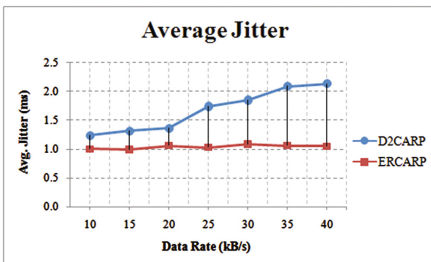

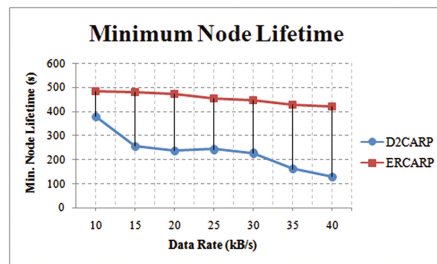**Fig. 4.** Simulation results of average jitter.

Fig. 5. Simulation results of minimum node lifetime.

8   Conclusion

In this article, we have proposed the ERCARP protocol which is an energy-efficient and reliable routing protocol for CRSNs. The novel routing metric that takes account of packet loss probability, link latency and residual energy is applied in the protocol. It ensures the selected transmission path has small delay, low packet loss and high residual energy. Furthermore, to offer the efficient route recovery mechanism, multi-path multi-channel routes are provided to cope with path failures caused by a PU activity. To evaluate the protocol effectiveness, the performance comparison between the proposed protocol and the D2CARP protocol has been conducted. As compared with D2CARP protocol, the simulation results obviously prove that ERCARP provides lower percentage of packet loss, reduces average end-to-end delay, decreases average jitter, and achieves longer minimum node lifetime in CRSNs.

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