

An Energy Efficient QoS Routing Protocol for Cognitive Radio Ad Hoc Networks

S. M. Kamruzzaman, Eunhee Kim, Dong Geun Jeong

Department of Electronics Engineering, Hankuk University of FS, Korea

{smzaman, exeriment, dgjeong}@hufs.ac.kr

Abstract—The explosive growth in the use of real-time applications on mobile devices has resulted in new challenges to the design of routing protocols for cognitive radio ad hoc networks (CRANs). In this paper, we propose a new on-demand Quality-of-Service (QoS) routing, namely an energy efficient QoS routing (EQR) protocol for CRANs using TDMA. It can establish QoS routes with reserved bandwidth on a per flow basis in a multi-hop networks. The objective of this work is to establish bandwidth guaranteed QoS routes in small CRANs whose topologies change at low to medium rate. The protocol is based on DSR, and builds QoS routes only as needed. We assume the application is session-oriented and requires constant bandwidth. A session specifies its QoS requirement as the number of transmission timeslots it needs on its route from a source to a destination. For each session (flow), the QoS routing protocol will find both the route and the channel and timeslots for each link on the route. The simulation results show the effectiveness of our proposed approach with good generalization ability.

Keywords—Cognitive radio, ad hoc networks, QoS routing, energy efficiency, TDMA, channel assignment.

I. INTRODUCTION

With the cognitive radio (CR) technology, a wireless system can exploit opportunistically the radio spectrum licensed to other systems. Thus, CR is regarded as a solution to the problems resulting from the limited available spectrum and the inefficiency in the spectrum usage. The CR user is allowed to use only locally unused spectrum opportunistically so that it does not cause any interferences or collisions to the primary users (PUs) [1]. When CR users detect the presence of PU on the operating band, they must switch to other spectrum bands. The CR network refers to the wireless network using CR technology [1]. CR ad hoc networks (CRANs) are infrastructure-less multi-hop CR networks where CR users can communicate with each other through ad hoc connection.

In ad hoc networks consisting of portable devices (at least in part), energy management is of prime importance because of the limited energy availability in the portable devices. In energy constrained networks, energy efficient routing achieves higher performance than shortest path routing and, at the same time, reduces the power consumption of the relay users [2]. It also alleviates the network partitioning problem caused by the energy exhaustion of the relay users.

In wireless networks, bandwidth is a scarce resource that can be shared either dynamically or deterministically. QoS routing in multi-hop CRANs is very challenging due to interference among different transmissions. A QoS connection request usually comes with a bandwidth requirement and a QoS routing seeks a route from source to destination with requested bandwidth. If no such route can be found, the connection request should be blocked.

To the best of our knowledge, there has been no energy efficient QoS routing protocols for multi-hop CRANs. In this paper, we propose a routing protocol, called the energy efficient QoS routing (EQR) for multi-hop CRANs. Our goal is to provide robust high throughput routing, which involves not only route selection but also assignment of channel and timeslots. The proposed EQR protocol can select energy efficient route, and assign channels and timeslots for a connection request. By combining routing with channel-timeslot allocation, the EQR protocol can improve network throughput by decomposing the traffic over different channels and timeslots. As a result, the proposed scheme leads to significant increases in network throughput and decreases the end-to-end delay.

The rest of the paper is organized as follows. Section II describes the related work. The system model is presented in section III. The proposed QoS routing protocol is described in section IV. We present the performance evaluation using computer simulation in section V, and finally in section VI we conclude the paper.

II. RELATED WORK

A number of routing protocols for CR networks are available in the literature [3]–[6]. These protocols are based on the concept of the existence of a common control channel (CCC) and use separate control radio for exchanging the control message. Using additional control radio in each CR user is harmful for energy constrained CR networks. Using a single radio for data and control message exchange are available in [7] and [8], but the key problem with those protocols is control message must be broadcasted to all available channels which is time consuming and increases the network overhead.

Sampath *et al.* presented a paradigm for high throughput spectrum-aware routing for CR networks in [4]. They use separate control radio for exchanging control information. Our proposed protocol is different from them. We consider joint routing and channel-timeslot allocation in energy

constraint CRANs with only a single radio transceiver for data and control message exchange. Chen *et al.* presented a routing scheme for multi-radio CR networks known as CR networks local on-demand routing for CR networks consisting of opportunistic links in [9]. They decompose general CR networks into CR relay network, CR uplink relay network, CR downlink relay network, and tunneling network. However, the work in [9] does not cover the issues of channel-timeslot allocation and energy efficiency which are addressed in our protocol.

R. Hincapie *et al.* presented a QoS routing in wireless mesh networks (WMNs) with CRs in [10]. The routing problem handles not only route selection but also channel allocation and scheduling for a connection request to satisfy its end-to-end bandwidth requirement. They define the problem and present an Integer Linear Programming (ILP) formulation to provide optimal solutions. J. Tang *et al.* study the interference-aware topology control and QoS routing in multi-channel WMNs in [11]. They present an effective heuristic for the minimum INterference Survivable Topology Control (INSTC) problem which seeks a channel assignment for the given network. They then formulate the Bandwidth-Aware Routing (BAR) problem for a given network topology, which seeks routes for QoS connection requests with bandwidth requirements.

Cross-layer optimizations for CR networks have started investigating recently. Hou *et al.* formulated a cross-layer optimization problem for a network with CRs in [12]. Ma *et al.* model the channel heterogeneity and present a cross-layer optimization framework in [13], which jointly considers the spectrum sharing and routing with the objective of maximizing the fairness ratio. However, the work of [12] and [13] do not consider energy efficient routing that is addressed in our work.

III. SYSTEM MODEL

Consider the spectrum consisting of C non-overlapping channels, each with bandwidth B_c ($c = 0, 1, 2, \dots, C-1$). These C channels are licensed to PUs. Considering the fact that the spectrum opportunity is changing frequently with time and locations, a common control channel (CCC) is used by all CR users for spectrum access, which is always available. This CCC may be owned by the CR service provider. We consider a CR network consisting of M PUs and N CR users. PUs are license holders for specific spectrum bands, and can occupy their assigned spectrum any time and for any duration. CR users do not have any licensed spectrum and opportunistically send their data by utilizing idle spectrum of PUs. We model each of C channels as an ON-OFF source alternating between ON (active) state and OFF (idle) state. An ON/OFF channel usage model specifies the PU signals is or isn't using a channel. The CR users can utilize the OFF time to transmit their own packets. We assume that all CR users are equipped with a single half-duplex CR transceiver, which consists of a reconfigurable transceiver and a scanner.

A. Cognitive Radio MAC Model

We assume that system time is divided into fixed-length frames, where each frame consists of a sensing window, an ad hoc traffic indication message (ATIM) window, and a

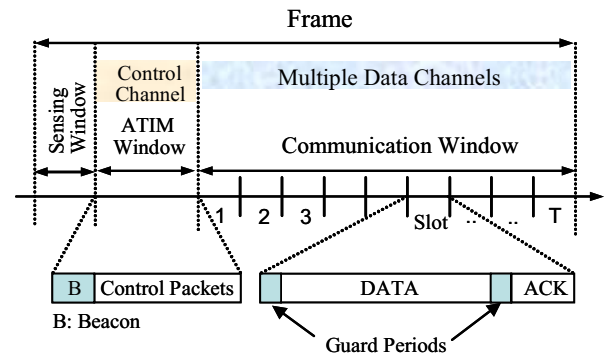


Figure 1. Structure of MAC protocol.

communication window as depicted in Fig. 1. The ATIM window is contention-based, and uses the same mechanism as in the IEEE 802.11 DCF [14]. The ATIM window is divided into the beacon and the control window. During the ATIM window, control channel (i.e. CCC) is used for beaconing and to exchange control message. The communication window is time-slotted, each of which is called a timeslot. The duration of each timeslot is the time required to transmit or receive a single data packet, including the time need to switch the channel, and the acknowledgement (ACK). In the communication window, CR users can send or receive packets or go to sleep mode to save power. If a CR user has decided to send or receive a packet in the j^{th} timeslot, it first switches to the decided channel and transmits or waits for the data packet in that timeslot. If a receiver receives a unicast packet, the receiver sends back an ACK in the same timeslot.

All CR users are synchronized by periodic beacon transmissions. In this MAC scheme, channel sensing is performed in the starting of each frame not to disturb PUs. If any chosen channel is found to be busy, that channel will not be used in the ATIM window. If a sender does not hear an ACK after it sends a unicast packet, because of the possible collision with other transmissions, the sender may perform random backoff before attempting its retransmission. If the number of retransmissions exceeds the retry limit, the packet is dropped. It is noted that along with other channels CCC can also be used for data transmission in the communication window, if needed. If a CR user has not decided to send or receive a data packet in the j^{th} timeslot, the CR user switches to sleep mode for power saving.

A channel-timeslot pair (c, t) is defined as the "communication segment". To assure collision-free communications, all neighborhood users of the intended receiver except the intended transmitter should remain silent on the particular channel during a given timeslot. With the help of periodic beaconing, each CR user is aware of (1) the identities and list of available communication segments within its two-hop neighborhood, and (2) existing transmission schedule of communication segments of its one-hop neighbor. Based on the collected neighbor information and its own information, each CR user updates the status of its communication segments as occupied or free. Free communication segment of CR user v , $free_segment(v)$, is the communication segments for all available channels, which are not used by CR user v to communicate with adjacent CR users.

For each link in the network, the communication segment assignment algorithm marks each communication segment as one of the following:

- Occupied: this segment is using by other transmissions and hence can not be used.
- Free: unassigned idle segment.
- Assigned: this segment shall be used for packet transmission on a specific link.

B. Network Model

We consider energy constrained multi-hop CRANs where each CR user has limited battery energy. We assume that CR users are stationary or moving very slowly. In our CR network, PUs are also assumed to be stationary and they coexist with the CR users. There is a link $l = (u, v) \in E$ between CR users u and v , if two users are in the transmission range and there is an available channel $c \in H_u \cap H_v$, where H_u and H_v represent list of available channels at CR users u and v , respectively, and E is the set of communication links each connecting a pair of CR users. We model the impact of interference by using the well known protocol model proposed in [15].

IV. PROPOSED QoS ROUTING PROTOCOL

A. Preliminaries

We use bandwidth as the main QoS parameter in this paper. “Bandwidth” in time-slotted network can be defined as the number of “free” timeslots. Accordingly, link bandwidth is the number of common free timeslots between two users and path bandwidth of the two users is the set of free timeslots available between them. If the two users are adjacent, the path bandwidth is the link bandwidth. In general, calculating available bandwidth of a path in wireless network based on timeslots not only needs information about the available bandwidth on the links along the path, but also needs to know how to allocate the free timeslots. Therefore, computing available bandwidth in CRANs is difficult and is actually NP-complete. Let P be a given routing path for the current route request. We need to find a channel-timeslot assignment for the links on the path P to avoid any contention. There are two types of potential contentions: interflow contention and intra-flow contention [9]. Interflow contentions are the contentions caused by the interference between a link for the current route request and a link for an existing route request. Intra-flow contentions are the contentions caused by the interference between a link for the current route request and another link for the current route request. Inter-flow contentions can be easily resolved if we always assign aforementioned free timeslots to the path of the current connection request. Intra-flow contentions are harder to solve as the routing path for the current connection request is not known a priori. To solve this problem, we define the following contention-free channel-timeslot allocation. *A contention-free channel-timeslot allocation for the path P is an assignment that allocates free channel-timeslots for every link on the path such that it does not create any interflow contention or intra-*

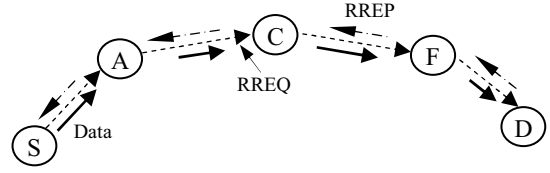


Figure 2. Routing path in CRANs.

TABLE 1. FIELDS OF RREQ PACKET

<i>req_id</i>	Unique route request sequence number determined by the source node
<i>src_id</i>	Address of the source node
<i>dst_id</i>	Address of the destination node
<i>mE_{res}</i>	Minimum residual nodal energy in a route
<i>route_seq</i>	List of the address of nodes from the source to the current traversed node
<i>B</i>	Bandwidth (QoS) requirement from source to destination
<i>FSeg</i>	List of free communication segments (channel-timeslot) of each node from the source to the current traversed node
<i>SSeg</i>	List of the selected communication segments of each node from the source to the current traversed node
<i>HC</i>	Hop count
<i>TTL</i>	The limitation of hop-length of the search path

flow contention. The path P is said to be an admissible path if there exists such a contention-free allocation.

The bandwidth requirement B in this paper is measured as the number of timeslots in one frame. Here we assume that a route always uses a single path for data transmission. If the bandwidth requirement B of a route is larger than 1, we need to allocate each link B timeslots in one frame. We only allocate free channel-timeslots to every link on a path and update node status accordingly. In this way, transmissions along the path of a new established route will not contend with transmissions of existing routes. However, two links on the current routing path may interfere with each other resulting in intra-flow contention [9] and need to be resolved by the timeslot allocation algorithm.

We use Fig. 2, Fig. 3, and Fig. 4 to explain the allocation of contention-free channel-timeslots for multichannel CRANs. In this example, we have $B = 2$. The routing path P is given as $(S \rightarrow A \rightarrow C \rightarrow F \rightarrow D)$ shown in Fig. 2. The status of the communication segments in each user and links are shown in Fig. 3. Here we consider 8 timeslots in a frame and there are 4 channels available in the CRANs. The communication segment status of each user is shown in the top the user's ID and the links status is shown in between the users. In this figure, different types of boxes are used to distinguish different status. The labels of the communication segment status are shown in the bottom of this figure. In this example, there exists a contention-free channel-timeslot allocation, which is picked from Fig. 3 and shown separately in Fig. 4 with showing channels and assigned slots.

B. Routing Algorithm

The proposed energy efficient QoS routing is an on-demand routing protocol proposed for multi-hop CRANs. The basic operations of EQR include route discovery, data transmission, and route maintenance. We now describe the components of EQR in further detail.

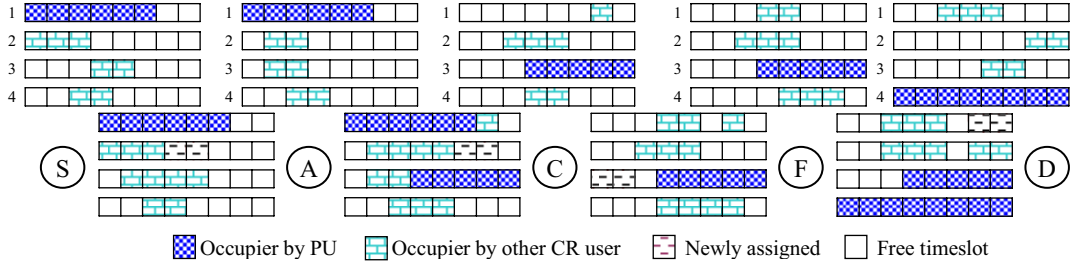


Figure 3. Contention-free channel-timeslots assignment in routing for CRANs.



Figure 4. Resultant channel-timeslots assignment for the routing path of Fig. 2.

The proposed route request (RREQ) broadcast procedure is based on DSR protocol. When the source CR user S has packets to send to the destination CR user D , it will initiate a route discovery process by broadcasting a spectrum aware RREQ message on the CCC to all of its neighbors. The fields of RREQ packet are shown in Table 1.

For selecting the energy efficient path, we consider maximal minimal nodal residual energy with lower hop count as routing metric. Initially, at the source CR user, the value of mE_{res} equals the initial energy of the battery. To avoid CR users having very poor energy in a route; intermediate CR users should have a threshold energy E_{th} .

Furthermore, because of the opportunistic properties of CRANs, a CR user should also have at least one channel common with its previous hop. When the forwarding intermediate CR users receive the RREQ packet, they compare their own residual battery energy E_{res} with the mE_{res} and update accordingly in order to keep the value of mE_{res} lowest among all the CR users in this route. This will ensure the route which has the minimal nodal residual battery energy.

In the proposed protocol, an intermediate CR user v starts a timer whenever it receives the first RREQ. For each RREQ received from a neighbor CR user u before the timer expires, CR user v runs the communication segment assignment algorithm, discuss later on, to find out good feasible communication segments for the link $l = (u, v)$. If it fails to find a feasible assignment, it drops the corresponding RREQ. Otherwise, it attaches itself to the current partial path, includes $SSeg$ in the header, updates the other information and rebroadcast it by appending its own information to $route_seq$ and $FSeg$. Consequently, the CR user increases the value of hop count (HC) and decreases the value of time to live (TTL).

Similarly, the destination CR user D sets up a timer to collect multiple RREQs for a connection request. It will run the same algorithm to select feasible communication segments for the last hop. After receiving the first RREQ packet, destination CR user waits for a time period to get more RREQs before it makes route reply (RREP). Destination CR user D then computes route utility using (1) and selects the route using (2).

$$U_k = \frac{mE_{res,k}}{HC_k}, \quad \forall k; \quad (1)$$

$$P = \max\{U_k\}, \quad \forall k; \quad (2)$$

where U_k is the route utility of path $k = 1, 2, \dots, K$, the number of received RREQ by the destination. U_k is used to evaluate the selected routes to find the maximum value of P for which the value of $mE_{res,k}$ is maximized and HC_k is minimized. Maximum value of $mE_{res,k}$ ensures that the selected path has high energy *i.e.* energy efficient path; on the other hand, the smaller hop count gives the packet transmission with comparatively low delay.

Destination CR user D then reply to the source CR user with RREP along the selected paths through CCC. Accordingly, the communication segments selected for each link along the path are reserved for data transmission. Moreover, all the other CR users in the neighborhoods of the CR users in the selected paths are notified that these communication segments are going to be used by the new incoming connection. While RREP is forwarding towards source CR user, intermediate CR users reserve the communication segments in accordance with the information in the RREP packet. However, if the timeslots that have been decided to reserve during route discovery phase may be reserved by another RREP during the reservation phase. Hence, instead of rediscovering new route, communication segment assignment scheme is initiated to coordinate the conflicting CR users with its one-hop neighbors' scheduling to recover the route reservation. Finally, after receiving the RREP packet by the source CR user data transmission begins. In addition local route recovery (RREC) and route error (RERR) based scheme is used for route maintenance.

C. Assignment of Communication Segments

In this subsection, we present a heuristic algorithm to assign communication segments for the link $l = (u, v)$. To ensure the collision-free transmissions, the following conditions must be satisfied in selecting the communication segments. Let a communication segment (c, t) is trying to assign for the link $l = (u, v)$ such that:

- Timeslot t is not assigned to any link incident (connected) on CR user u ,
- Timeslot t is not assigned to any outgoing link from the CR user v ,

- Timeslot t is not used on channel c by any link l' , $T_x(l') \in Nb(v)$, where $Nb(v)$ represents the set of neighbors of CR user v ; and
- Timeslot t is not used on channel c by any link l' , $R_x(l') \in Nb(u)$.

without confusions, $T_x(\cdot)/R_x(\cdot)$ represent both the transmitter/receiver of the given link. Note that one of the necessary constraints for collision-free communication is that no two links incident at CR user can be assigned same timeslot. If all the above conditions are satisfied, communication segment (c, t) is assigned to the link $l = (u, v)$. This procedure continues until the bandwidth requirement is satisfied.

V. PERFORMANCE EVALUATION

The effectiveness of the proposed EQR protocol is validated through computer simulation. This section describes the simulation environment and the experimental results. To evaluate EQR, we have developed a packet-level discrete-event simulator written in C programming language, which implements the features of the protocol stack described in this paper. The simulated network is composed of 50 CR users deployed randomly within a $500 \text{ m} \times 500 \text{ m}$ square region. The transmission and interference range of each CR user is approximately 150 m and 300 m respectively. The two-ray-ground reflection model is used as propagation model. We set an initial energy of 100 Joules per CR user. We consider the transmitting energy of each CR user: $ETx = (1.65 \times \text{packet size in bits})/2 \times 10^6$ Jules and receiving energy: $ERx = (1.15 \times \text{packet size in bits})/2 \times 10^6$ Jules [16]. We ignore the energy consumptions of CR users in PUs sensing sessions.

We vary the number of channels from 4 to 12, each of which has a data rate of 2 Mbps. Among them, one channel is CCC and the others are data channels. The packet size is set to 1000 bytes. Based on our simulation experience, we set the frame interval for the MAC scheme to 45 ms where the communication window is 34 ms and the sensing window is 3 ms. The number of timeslots in the communication window is set to 8 and each slot duration is 4.25 ms, which is calculated for a 1000 bytes packet to be sent through the channel of data rate 2 Mbps. The length of the ATIM window is 8 ms where 2.5 ms is assigned for beacon period. Channel switching delay is set to 80 μs . The bandwidth (i.e. number of timeslots) requirement in an RREQ is set to a random integer from the range [1, 4]. We place 5 or 10 PUs at some random locations in the region. The active and idle time duration of PUs are exponentially distributed with mean value 100 seconds, respectively. Each of the active PUs randomly chooses a channel to use, which is then considered to be unavailable for all the CR users within their coverage range set to 300 m.

We impose the best effort traffic with message generation time exponentially distributed with mean value $1/\{(\text{msg. gen. rate})/(\text{no. of CR users})\}$ second. Average message length is geometrically distributed with mean value 1000 packets. We vary the message generation rate to vary the offered load to the network. Each data point in the plots is an average of 5 runs where each run uses a different random network topology. The simulation time of each run is set to 500 seconds.

In Fig. 5, we measured the aggregate throughput, which is defined as the data packet received by the destinations (the sum of individual routes throughput), in Mbps by varying the offered load. We can see from the Fig. 5 (a), when the offered load increases, aggregate throughput increases up to message generation rate 1.25 and then slightly decreases till the end of simulation. EQR without PU outperforms in all level of offered load compare to the 5 PUs and 10 PUs cases. Throughput without PU achieves 6% more throughput than with 5 PUs and 9% more than with 10 PUs. This figure shows the impact of PUs on aggregate throughput. When the number of PUs increases throughput decreases because of available resources are decaying. Fig. 5 (b) shows the effect of channels and PUs on throughput. When the number of channels decrease and PUs increase aggregate throughput decreases. One point is noted here that even though we have multiple channels with 2 Mbps data rate each but the obtained aggregate throughput is closed to 2 Mbps that is because of the multi-hop routing nature. For the PUs activities we are unable to utilize the whole resources of the multichannel we have. For any reason, if a link supports lower data rate, then the aggregate throughput of all routes passing through that link is decreased.

Fig. 6 shows the average end-to-end packet delay of the protocol by varying the network offered load with 12 channels where 1 channel is CCC. The effect of PUs on the average end-to-end packet delay is shown in this figure. EQR without PU shows lower delay in all level of the offered load because of the network resources are static in this scenario. EQR with 10 PUs shows comparatively higher delay because of the limited spectrum resources availability.

The normalized routing overhead which is defined as the number of routing packets transmitted per data packet delivered at the destinations is shown in Fig. 7. When the PUs increase, the routing overhead increases due to the increase of RREQ, RREP, RREC, and RERR. The result shows that our proposed protocol needs lower routing overhead per data packet delivery. The energy efficiency that is measured in received data packets by destinations per Joule shown in Fig. 8. The graph shape is identical with aggregate throughput. It is shown in the figure that received packets at the destinations per Joule increases up to the saturation level of the offered load and then slightly decreases till the end of simulation.

The network lifetime which is defined as the duration from the beginning of the simulation to the first time a CR user runs out of energy is shown in Fig. 9. The effect of PUs on the network lifetime is shown in this figure. EQR without PU shows lower lifetime because all CR users are participated in the routing tasks in whole simulation time. When the number of PUs increase the routings are distributed to the other CR users having higher residual nodal energy; thus prolongs the lifetime of individual CR users and overall network. When the offered load increases the network lifetime decreases because of the increasing of the number of routes.

VI. CONCLUSION

We proposed a spectrum and energy aware on-demand protocol for routing and channel-timeslot assignment in multi-hop CRANs. The proposed EQR protocol combines two simple but powerful features: the integration of spectrum

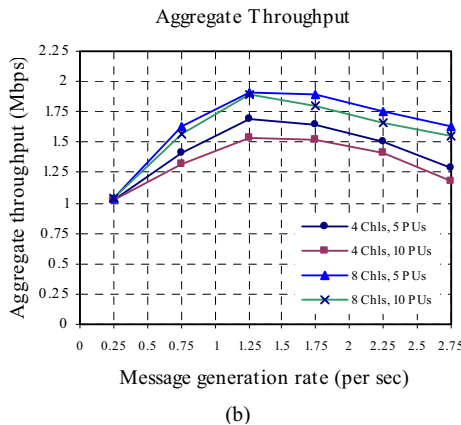
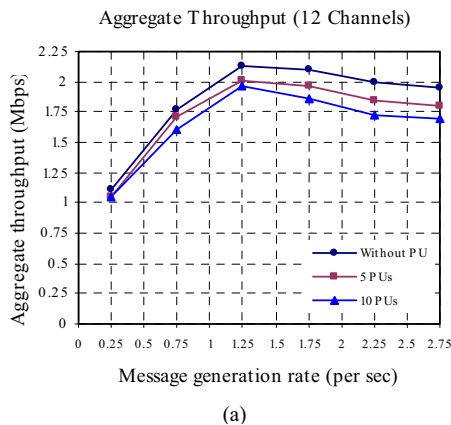


Figure 5. Aggregate throughput (a) with different number of PUs and 12 channels and (b) with different number of channels and PUs

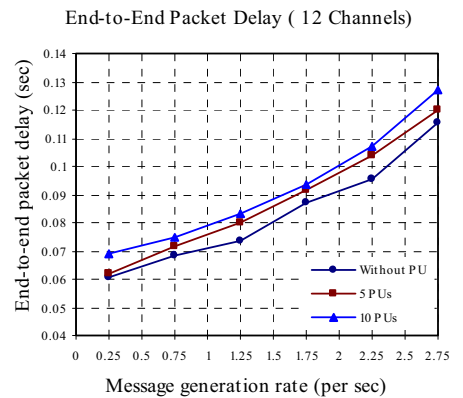


Figure 6. Average end-to-end packet delay with different number of PUs and 12 Channels

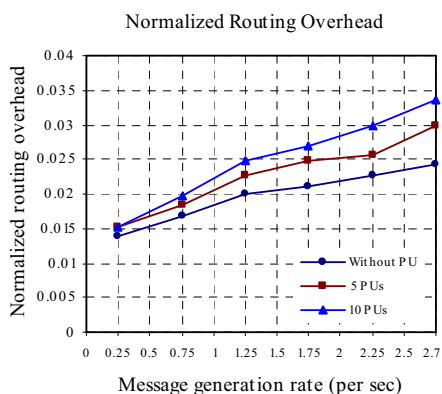


Figure 7. Normalized routing overhead per data packet.

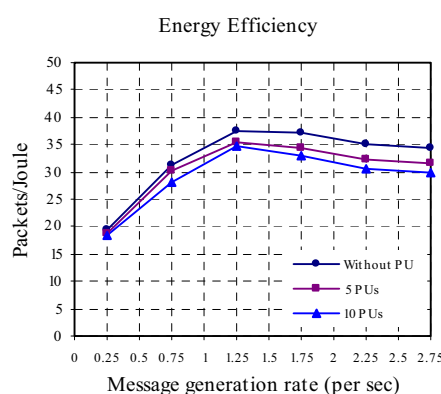


Figure 8. Energy efficiency measured in data packets/Joule with different number of PUs.

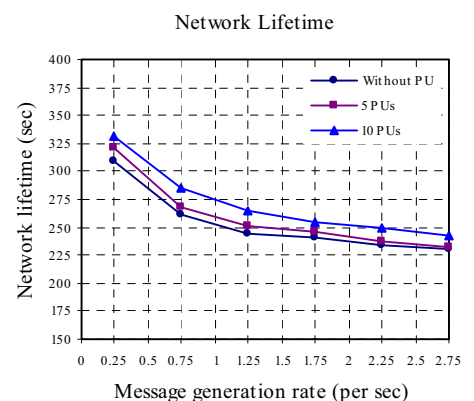


Figure 9. Network lifetime till first CR user die.

and route discovery to establish communications across areas of varying spectrum availability; the distributed path reservations. Our protocol balances the traffic load among different CR users according to their nodal residual battery energy and prolongs the lifetime of individual CR user and the overall networks. Our proposed EQR protocol coordinates channel usage among timeslots using a schedule based channel access mechanism. Simulation results show that EQR achieves a reasonable throughput improvement and lower average end-to-end packet delay.

REFERENCES

- [1] I. F. Akyildiz, W. Y. Lee, M. Vuran, and S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Comput. Netw.*, vol. 50, no. 13, pp. 2127-2159, Sep. 2006.
- [2] M. Li, L. Zhang, V. O. K. Li, X. Shan, and Y. Ren, "An energy-aware multipath routing protocol for mobile ad hoc networks," in *Proc. ACM SIGCOMM Asia Work.*, Apr. 2005, pp. 166-174.
- [3] G. Cheng, W. Liu, Y. Li, and W. Cheng, "Joint on-demand routing and spectrum assignment in cognitive radio networks," in *Proc. IEEE ICC*, Jun. 2007, pp. 6499-6503.
- [4] A. Sampath, L. Yang, L. Cao, H. Zheng, and B. Y. Zhao, "High throughput spectrum-aware routing for cognitive radio networks," *Invited Paper, CrownCom*, May 2008.
- [5] A. C. Talay and D. T. Altılar, "RACON: A routing protocol for mobile cognitive radio networks," in *Proc. CoRoNet*, Sep. 2009, pp. 73-78.
- [6] L. Ding, T. Melodia, S. N. Batalama, J. D. Matyas, and M.J. Medley, "Cross-layer routing and dynamic spectrum allocation in cognitive radio ad hoc networks," *IEEE Trans. Veh. Tech.*, vol. 59, no. 4, pp. 1969-1979, May 2010.
- [7] T. Fujii and Y. Yamao, "Multi-band routing for ad hoc cognitive radio networks," in *Proc. SDR Tech. Conf.*, Nov. 2006.
- [8] H. Ma, L. Zheng, X. Ma, and Y. Luo, "Spectrum aware routing for multi-hop cognitive radio networks with a single transceiver," in *Proc. CrownCom*, May 2008.
- [9] K.-C. Chen, B. K. Cetin, Y.-C. Peng, N. Prasad, J. Wang, and S. Lee, "Routing for cognitive radio networks consisting of opportunistic links," *Wirel. Commun. Mob. Comput.*, vol. 10, no. 4, pp. 451-466, Apr. 2010.
- [10] R. Hincapie, J. Tang, G. Xue, and R. Bustamante, "QoS routing in wireless mesh networks with cognitive radios," in *Proc. IEEE Globecom*, Nov.-Dec. 2008.
- [11] J. Tang, G. Xue, and W. Zhang, "Interference-aware topology control and QoS routing in multi-channel wireless mesh networks," in *Proc. ACM Mobihoc*, May 2005, pp. 68-77.
- [12] Y. T. Hou, Y. Shi, and H. D. Sherali, "Optimal spectrum sharing for multi-hop software defined radio networks," in *Proc. IEEE Infocom*, May 2007, pp. 1-9.
- [13] M. Ma and D. H. K. Tsang, "Joint design of spectrum sharing and routing with channel heterogeneity in cognitive radio networks," *Physical Communication*, vol. 2, no. 1-2, pp. 127-137, Mar. - Jun. 2009.
- [14] IEEE 802.11 Working Group, "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," IEEE 802.11 Standard, 1997.
- [15] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Information Theory*, vol. 46, no. 2, pp. 388-404, Mar. 2000.
- [16] J.-C. Cano and P. Manzoni, "A Performance comparison of energy consumption for mobile ad hoc network routing protocols," in *Proc. MASCOTS*, 2000, pp. 57-63.