An Energy-Efficient MAC Protocol for QoS Provisioning in Cognitive Radio Ad Hoc Networks

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Abstract. *The explosive growth in the use of real-time applications on mobile devices has resulted in new challenges to the design of medium access control (MAC) protocols for ad hoc networks. In this paper, we propose an energy efficient cognitive radio (CR) MAC protocol for QoS provisioning, called ECRQ-MAC, which integrates the spectrum sensing at physical (PHY) layer and the channel-timeslots allocation at MAC layer. We consider the problem of providing QoS guarantee to CR users as well as to maintain the most efficient use of scarce bandwidth resources. The ECRQ-MAC protocol exploits the advantage of both multiple channels and TDMA, and achieves aggressive power savings by allowing CR users that are not involved in communication to go into doze mode. The proposed ECRQ-MAC protocol allows CR users to identify and use the unused frequency spectrum of licensed band in a way that constrains the level of interference to the primary users. Our scheme improves network throughput significantly, especially when the network is highly congested. The simulation results show that our proposed protocol successfully exploits multiple channels and significantly improves network performance by using the licensed spectrum opportunistically, and protects QoS provisioning over cognitive radio ad hoc networks.*

Keywords

Cognitive radio, multichannel MAC, energy efficiency, QoS, ad hoc networks, frequency spectrum, TDMA, channel sensing.

1. 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 [2]. The CR network refers to the wireless network using CR technology [3]. 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. Sometimes it becomes very difficult to recharge or replace the battery of mobile devices. Furthermore, replacing or recharging batteries is often impossible in critical environments. Over time, various users will deplete their battery and drop out from the network; hence the network will eventually become partitioned [4]. In such situations energy conservations are essential to prevent network failures by maximizing the battery lifetime.

In multichannel environment throughput of multi-hop wireless networks can significantly be improved compared with single channel environment, since the interference influence can be reduced by using multiple channels [5], [6]. We consider a multichannel CR network, in which every CR user is equipped with single half-duplex CR transceiver and can be tuned to one of the available channels. A pair of CR users can communicate with each other if they are on the same channel and are within the transmission range of each other.

In wireless networks, bandwidth is a scarce resource that can be shared either dynamically or deterministically. Providing quality of service (QoS) is more difficult in CRANs due to a number of reasons: (1) because of the broadcast nature of the wireless transceiver each link's bandwidth will be affected by the transmitting/receiving activities of its neighboring links, (2) QoS guarantee needed for multi-hop communications, and (3) because of the dynamic network topology CR users may join, leave, and rejoin at any time and anywhere, as a result, existing links may disappear and new links may be formed in a time varying manner. All these raise challenges to QoS guarantee in CRANs.

We use bandwidth as a 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.

In designing efficient CR networks, new challenges arise that are not present in the traditional wireless networks [7]–[9]. Specifically, identification of the available channel imposes a number of nontrivial design problems to the CR MAC protocols. One of the most difficult, but important, design problems is how the CR users decide when and which channel they should tune to in order to transmit/receive packets without interference to the PUs. This problem becomes even more challenging in CRANs where there are no centralized controllers.

In multichannel environment, the MAC layer should be designed to use multiple channels in parallel for fully utilizing the spectrum opportunities. Multichannel MAC protocols have clear advantages over single channel MAC protocols: They offer reduced interference among users, increased network throughput due to simultaneous transmissions on different channels, and a reduction of the number of CRs affected by the return of the PUs [10]. By exploiting multiple channels, we can achieve a higher network throughput than using single channel, because multiple transmissions can take place without interference.

In this paper, we propose an energy efficient multichannel MAC protocol which enables CR users to dynamically select channel-timeslots such that multiple communications can take place in the same region simultaneously, each in different channel. The main idea is to divide time into fixed-length frames, and have a small window in each frame to indicate traffic and negotiate channels and timeslots for use during the interval. The proposed scheme can eliminate contention between CR users, decomposes contending traffics over different channels and timeslots based on actual traffic demand. As a result, the proposed scheme leads to significant increases in network throughput and enhances the network lifetime, consequently decreases the end-to-end delay in an efficient way.

The rest of the paper is organized as follows. Section 2 describes the related work. A background is given in section 3. The system model is presented in section 4. The proposed ECRQ-MAC protocol is described in section 5. An analysis for throughput is given in section 6. We present the performance evaluation in section 7, and finally, in section 8 we conclude the paper.

2. Related Work

Recently, several attempts were made to develop MAC protocols for CR networks. A number of multichannel contention-based MAC protocols for CR networks have been proposed in [12]-[18]. The IEEE 802.22 is a centralized MAC protocol that enables spectrum reuse by CR users operating on the TV broadcast bands [12]. For a CRAN without centralized control, it is desirable to have a distributed MAC protocol that allows every CR user to individually access the spectrum.

Multichannel power/rate assignment is jointly optimized in the CR networks MAC protocol proposed in [13] by assuming a given power mask on CR transmissions. How to determine an appropriate power mask remains an open issue. Distance and traffic-aware channel assignment (DDMAC) in CR networks is proposed in [14]. It is a spectrum sharing protocol for CR networks that attempts to maximize the CR network throughput through a novel probabilistic channel assignment algorithm that exploits the dependence between the signal's attenuation model and the transmission distance while considering the prevailing traffic and interference conditions. A bandwidth sharing approach to improve licensed spectrum utilization (AS-MAC) presented in [15] is a spectrum sharing protocol for CR networks that coexists with a GSM network. CR users select channels based on the CR networks' control exchanges and GSM broadcast information. In AS-MAC, explicit coordination with the PUs is required.

The gain from opportunistic band selection by deriving an optimal skipping rule is analyzed in [16], which balances the throughput gain from finding a good quality band with the overhead of measuring multiple bands. Dynamic open spectrum sharing (DOSS) MAC protocol is proposed in [17]. This protocol allows nodes to adaptively select an arbitrary spectrum for the incipient communication subject to spectrum availability. It offers real-time dynamic spectrum allocation and high spectrum utilization without relying on any infrastructure. It also coexists with legacy wireless applications, while avoiding the hidden and exposed terminal problems. A cognitive wireless networking system (KNOWS) is proposed in [18]. KNOWS is a hardware-software platform that includes a spectrum-aware MAC protocol and algorithms to deal with spectrum fragmentation.

A cognitive MAC protocol for multichannel wireless networks (C-MAC) is proposed in [19], which is a multichannel MAC that mitigates the effects of distributed quiet periods utilized for PU signal detection. In C-MAC, each channel is logically divided into recurring superframes which, in turn, includes a slotted beaconing period (BP) where users exchange information and negotiate channel usage. Each user transmits a beacon in a designated beacon slot during the BP, which helps in dealing with hidden users, medium reservations, and mobility.

CR based multichannel MAC protocol for wireless ad hoc networks (CRM-MAC) is proposed in [20], which integrates the spectrum sensing and packet scheduling. In CRM-MAC, each CR user is equipped with two transceivers. One of the transceivers operates on a dedicated control channel, while the other is used as a CR that can periodically sense and dynamically utilize the unused channels. CR-enabled multichannel MAC (CREAM-MAC) protocol is proposed in [21], which integrates the spectrum sensing at PHY layer and packet scheduling at MAC layer, over the wireless networks. In CREAM-MAC protocol, each CR user is equipped with a CR-enabled transceiver and multiple channel sensors. The CREAM-MAC enables the CR users to best utilize the unused frequency spectrum while avoiding the collisions among CR users and between CR users and PUs.

The cross-layer based opportunistic MAC protocols for QoS provisionings over CR wireless networks are presented in [22]. They develop the Markov chain model and the $M/G^Y/1$-based queuing model to characterize the performance for the saturation non-saturation network scenarios. In the non-saturation network case, they quantitatively identify the tradeoff between the aggregate traffic throughput and the packet transmission delay, which can provide the insightful guidelines to improve the delay-QoS provisionings over CR wireless networks.

Rendezvous protocols for ad hoc network establishment in CR networks have been proposed in [23]. Such capability is needed when deploying CRs in an area whose existing fixed communications infrastructure has been destroyed, such as after a natural disaster. They present the analytical models for the single-channel and multiple-channel synchronous problems then discuss possible extensions of these analytical models for the corresponding asynchronous cases. Finally, they present an empirical solution for the four user instance using data collected from experiments on a network testbed.

A cognitive radio MAC (COMAC) protocol is presented in [24] to dynamically utilize the spectrum by unlicensed users while limiting the interference on PUs. COMAC provides a statistical performance guarantee for PUs by developing probabilistic models for the PU-to-PU and the PU-to-CR user interference under a Rayleigh fading channel model. A distributed multichannel MAC protocol for multi-hop CR networks (MMAC-CR) with distributed control is proposed in [25]. In addition to the spectrum scarcity, energy is rapidly becoming one of the major bottlenecks of wireless operations. MMAC-CR presents an energy-efficient distributed multichannel MAC protocol for CR networks. A cross-layer distributed scheme for spectrum allocation/sensing, called decentralized cognitive MAC (DC-MAC) for dynamic spectrum access is presented in [26]. It provides an optimization framework based on partially observable Markov decision processes, with no insights into protocol design, implementation, and performance.

A CSMA/CA based protocol that exploits statistics of spectrum usage for decision making on channel access, called statistical channel allocation (SCA-MAC) is presented in [27]. In SCA-MAC control channel is used for channel negotiation. Synchronized MAC protocol for multi-hop CR network (SYN-MAC) is proposed in [28], which avoids the concept of common control channel (CCC). The scheme is applicable in heterogeneous environments where channels have different bandwidths and frequencies of operation.

A TDMA based energy efficient CR multichannel MAC (ECR-MAC) protocol for CRANs has been proposed in [29]. ECR-MAC requires only a single half-duplex radio transceiver on each CR user. In addition to explicit frequency negotiation, which is adopted by conventional multichannel MAC protocols, ECR-MAC introduces lightweight explicit time negotiation. However, a major drawback of the ECR-MAC protocol is that the synchronization and the channel-timeslot negotiation are done before channel sensing, which may be affected by the out-of-date spectrum sensing results. A cross-layer based cognitive radio multichannel MAC (CR-MAC) protocol has been proposed in [30]. This protocol enables CR users to utilize multiple channels by switching channels dynamically, thus increasing network throughput. Our proposed ECRQ-MAC protocol is different from these works. The ECRQ-MAC protocol provides QoS guarantee to CR users as well as to maintain the most efficient use of scarce bandwidth resources. We have also included the analysis of the system throughput with mixed delay-sensitive (*ds*) and non-real-time (*nrt*) data traffic flows in a single-hop network that are not reported in [29], [30]. Furthermore, in ECRQ-MAC channel sensing is done at the beginning of each frame to avoid the out-of-date spectrum sensing results.

3. Background

We first present some background information on the distributed coordination function (DCF) of IEEE 802.11 [11], which is the standard reference for MAC operations in an ad hoc network, and its PSM. Finally, we discuss the multichannel hidden terminal problem at the end of this section.

3.1 IEEE 802.11 Distributed Coordination Function (DCF)

The IEEE 802.11 DCF relies on a continuous sensing of the wireless channel. The algorithm used is called carrier sense multiple access with collision avoidance (CSMA/CA). If a user has a packet to transmit, then it transmits if the medium is sensed to be idle longer than a DCF interframe space (DIFS). If not, then it randomly chooses a backoff value from the interval [0, W-1], where W is defined as the contention window. This backoff

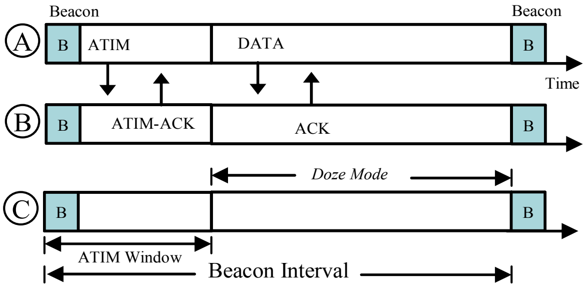

Fig. 1. Operation of IEEE 802.11 PSM.

counter is decremented every slot after the channel is sensed idle longer than a DIFS. If the backoff counter reaches zero, then the station transmits. Two different intervals, DIFS and Short Interframe Space (SIFS), enable each packet to have different priority when contending for the channel. A user waits for a DIFS before transmitting a ready to send (RTS) packet, but waits for a SIFS before sending a clear to send (CTS) packet or an acknowledgement (ACK). Thus, an ACK packet will win the channel when contending with RTS or DATA packets because the SIFS duration is smaller than DIFS.

A user is also able to reserve the channel for data transmission by exchanging RTS and CTS packets. If a user has a packet ready for transmission, then it can try to send an RTS frame using the DCF. After receiving an RTS frame, the destination replies with a CTS packet. Both RTS and CTS frames carry the expected duration of transmission. Nodes overhearing this handshake have to defer their transmissions for this duration. For this reason, each host maintains a variable called the network allocation vector (NAV) that records the duration of time it must defer its transmission. This whole process is called virtual carrier sensing, which allows the area around the sender and the receiver to be reserved for communication, thus avoiding the hidden terminal problem.

3.2 IEEE 802.11 Power Saving Mechanism (PSM)

In this section, the IEEE 802.11 PSM is explained. The idea is to let the users enter a low-power doze mode if they do not receive packets. This solves the energy waste due to idle listening. In doze mode, a user consumes much less energy compared to normal mode, but cannot send or receive packets. In IEEE 802.11 PSM, this power management is done based on ad hoc traffic indication messages (ATIM). The time is divided into beacon intervals, and every user in the network is synchronized by periodic beacon transmissions. This means that each user starts and finishes each beacon interval at about the same time.

Fig. 1 illustrates the process of IEEE 802.11 PSM. At the start of the beacon interval, a small time frame, i.e., ATIM window is reserved for the exchange of ATIM/ATIM-ACK handshakes. Every user should be awake during this window. If user *A* has packets buffered for user *B*, then it sends an ATIM frame to *B* during the ATIM window. When *B* receives the packet, it replies with an ATIM-ACK frame. Both *A* and *B* then stay awaken during the entire beacon interval. Nodes that did not send or receive an ATIM frame enter a doze mode until the next beacon interval.

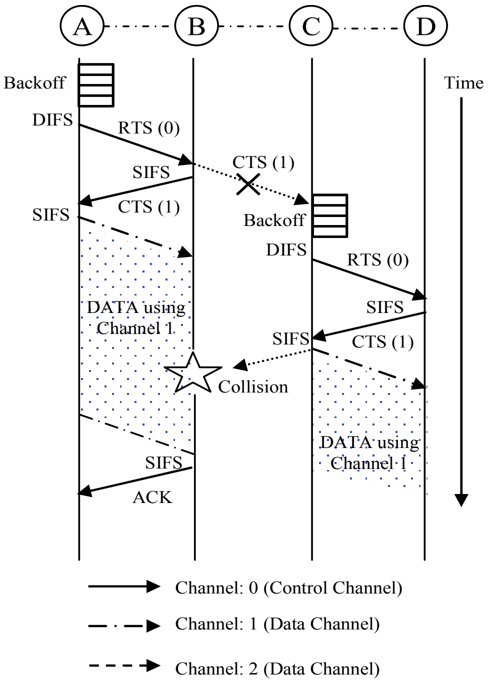

Fig. 2. Multichannel hidden terminal problem.

3.3 Multichannel Hidden Terminal Problem

The multichannel hidden terminal problem is depicted in Fig. 2. When a user is neither transmitting nor receiving, it listens to the control channel. When user *A* wants to transmit a packet to user *B*, *A* and *B* exchange RTS and CTS messages to reserve the channel as in IEEE 802.11 DCF. RTS and CTS messages are sent on the control channel. When sending an RTS, user *A* includes a list of channels it is willing to use. Upon receiving the RTS, *B* selects a channel and includes the selected channel in the CTS. After that, user *A* and *B* switch their channels to the agreed data channel and exchange the DATA and ACK packets.

Now consider the scenario in Fig. 2. Node *A* has a packet for *B*, so *A* sends an RTS on channel 0 which is the control channel. *B* selects cannel 1 for data communication and sends CTS back to *A*. The RTS and CTS messages should reserve channel 1 within the transmission ranges of *A* and *B*; so that no collision will occur. However, when user *B* sent the CTS to *A*, user *C* was busy receiving on another channel, so it did not hear the CTS. Not knowing that *B* is receiving on channel 1, *C* might initiate a communication with *D*, and end up selecting channel 1 for communication. This will result in collision at user *B*. The above problem occurs due to the fact that users may listen to different channels, which makes it difficult to use virtual carrier sensing to avoid the hidden terminal problem. If there was only one channel that every user listens to, C would have heard the CTS and thus deferred its transmission. Thus, the above problem is called the multichannel hidden terminal problem. As presented in section 5, we solve this problem using synchronization, similar to IEEE 802.11 PSM.

4. System Model

We consider an energy constrained CRANs composed of a set of CR users each of which has limited battery energy. We assume CR users are stationary or moving very slowly. In our CR networks, PUs are also assumed to be stationary and they coexist with the CR users. Consider the spectrum consisting of C non-overlapping channels, each with bandwidth B_c ($c = 1, 2, ..., C$). These C channels are licensed to PUs. CR can dynamically access any one channel to deliver its packets. Considering the fact that the spectrum opportunity is changing frequently with time and locations, a common control channel (CCC), which is always available, is used by all CR users for spectrum access. This CCC may be owned by the CR service provider [31]. We consider a CR network consisting of Z 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. For accessing the channel CR user must sense channel first and can access the channels if any of these C channels is not being used by PUs. Any efficient spectrum sensing scheme proposed in the literature can be used to detect the locally available channels. We assume that each CR user has enough capability of accurate sensing the presence of PU on any channel and keeps track a list of channels available for transmission.

We consider that each transceiver always transmits at a fixed transmission power and hence, their transmission range R_c and interference range I_c, which is typically 2 to 3 times of transmission range [32], are fixed for a particular channel c. We use a communication graph $G(V, E)$, to model the network where each node $v \in V$ corresponds to a CR user in the network and E is the set of communication links each connecting a pair of nodes. There is a link $l = (u, v) \in E$ between nodes u and v, if two nodes 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 node u and v, respectively. A communication link $l = (u, v)$ denotes that u can transmit directly to v if there are no other interfering transmissions. Due to the broadcast nature of the wireless links, transmission along a link may interfere with other link transmissions.

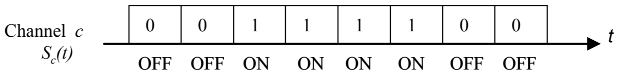

Fig. 3. Channel state for the c-th channel.

An interference model defines which set of links can be active simultaneously without interfering. We model the impact of interference by using the well known protocol model proposed in [33]. A transmission on channel c through link l is successful if all interferes in the neighborhood of both nodes u and v are silent on channel c for the duration of the transmission. Two wireless links (u, v) and (x, y) interfere with other if they work on the same channel and any of the given expression is true: $v = x$, $u = y$, $v \in Nb(x)$, or $u \in Nb(y)$, where $Nb(v)$ represents the set of neighbors of node v. If links (u, v) and (x, y) are conflicting, nodes u and y are within two-hops of each other [34]. The interference model can be represented by a conflict graph F whose vertices correspond to the links in the communication graph, G. There is an edge between two vertices in F if the corresponding links can not be active simultaneously. Two links sharing a common node conflict with each other, and will have an edge in between. In addition, links in close proximity will interfere with each other if they are assigned with the same channel and hence connected with edges.

5. ECRQ-MAC Design

We assume that system time is divided into fixed-length frames and each frame consists of a sensing window, an ad hoc traffic indication messages (ATIM) window, and a 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 [11]. The ECRQ-MAC scheme has some similarities with ECR-MAC [29] and TMMAC [35]. However, the ECRQ-MAC is different from ECR-MAC in the context of spectrum sensing. A major drawback of the ECR-MAC protocol is that the synchronization and the channel-timeslot negotiation are done before channel sensing, which may be affected by the out-of-date spectrum sensing results. In ECRQ-MAC, channel sensing is done at the beginning of each frame to avoid the out-of-date spectrum sensing results. On the other hand, TMMAC is designed for traditional multichannel networks, whereas our protocol is for CR networks. The ATIM window is divided into the beacon and the control window. During the ATIM window, control

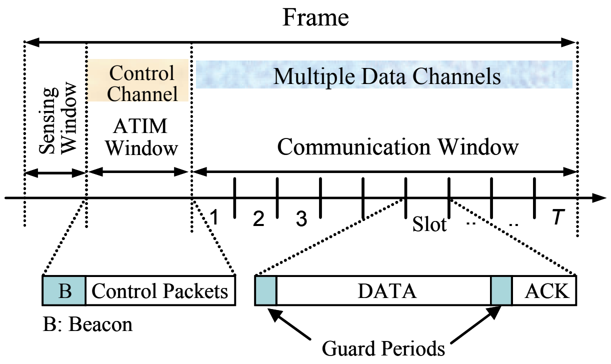

Fig. 4. Structure of proposed ECRQ-MAC protocol.

channel (i.e. CCC) is used for beaconing and to exchange control message. A TDMA scheme is used in the communication window of our proposed ECRQ-MAC protocol as depicted in Fig. 4. 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 needed to switch the channel, and the ACK. According to our MAC structure, the duration of each slot is $D_{slot} = D_{data} + D_{ACK} + 2 \times D_{guard}$. The use of guard period (D_{guard}) is to accommodate the propagation delay and the transition time from T_x mode to R_x mode. In the communication window, CR users can send or receive packets or go to doze 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 as shown in the slot structure of Fig. 4.

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 doze 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 neighbor, 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 defined as the communication segments for all available channels, which are not used by CR user *v* to communicate with adjacent CR users, and not interfered by other transmissions.

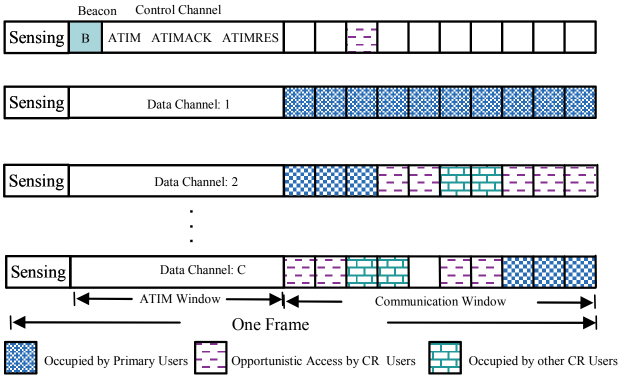

Fig. 5. Process of channel negotiation and data exchange in ECRQ-MAC.

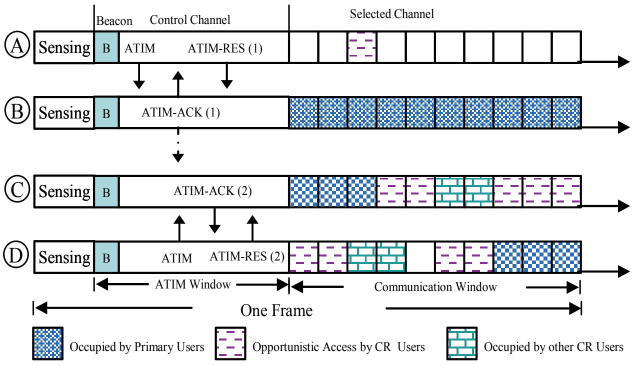

Fig. 6. Solution of multichannel hidden terminal problem using ECRQ-MAC protocol.

The resource allocation problem in the MAC layer is actually to determine how to assign available communication segments to links subject to the interference constraints. 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.

We define the set of common free communication segments between two nodes to be the link bandwidth. If we let $B(u, v)$ be the available bandwidth of the link between nodes u and v then $B(u, v) = free\_segment(u) \bigcap free\_segment(v)$.

In Fig. 6, suppose that CR user *A* has packets for *B* and thus *A* sends an ATIM packet to *B* during the ATIM window, with *A*'s free communication segment list included in the packet. On receiving the ATIM request from *A*, *B* decides which segment(s) to use during the beacon interval, based on its free communication segments and *A*'s communication segments. The communication segment (channel-timeslot) selection procedure is discussed in the next sub section. After selecting the channel and timeslot, *B* sends an ATIM-ACK packet to *A*, specifying the channel and timeslots it has chosen. When *A* receives the ATIM-ACK packet, *A* will see if it can also select the channel-timeslot specified in the ATIM-ACK packet. If it can, it will send an ATIM-RES packet to *B*, with *A*'s selected channel-timeslot specified in the packet. If *A* cannot select the channel-timeslot which *B* has chosen, it does not send an ATIM-RES packet to *B*. The process of channel-time-slot negotiation and data exchange in ECRQ-MAC is illustrated in Fig. 5. Fig. 6 shows how multichannel hidden terminal problem can be solved by using our ECRQ-MAC protocol. During the ATIM window, *A* sends ATIM to *B* and *B* replies with ATIM-ACK indicating to use channel 1 and timeslots. This ATIM-ACK is overheard by *C*, so channel 1 will not be selected by *C*. When *D* sends ATIM to *C*, *C* selects channel 2 and timeslots. So, after the ATIM window, the two communications (between *A* and *B*, and *C* and *D*) can take place simultaneously in communication window.

5.1 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 (c, t) to assign for the link $l = (u, v)$:

- 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', $R_x(l') \in Nb(u)$.

Here $T_x(\cdot)$ and $R_x(\cdot)$ represent the set of transmitters and receivers, respectively, 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, the communication segment (c, t) is assigned to the link $l = (u, v)$. This procedure continues until the bandwidth requirement is satisfied.

6. Throughput Analysis

In this section, we analyze the system throughput of our proposed MAC protocol with mixed delay-sensitive (*ds*) and non-real-time (*nrt*) data traffic flows in a single-hop network. To ease the analysis, we make the following assumptions: (1) the spectrum usage information is correctly obtained by the spectrum sensing; (2) the channel is ideal without transmission errors; (3) a fixed number of *nrt-nodes* always have packets to send; (4) the delay-sensitive traffic of a fixed number of *ds-nodes* is characterized by the "ON/OFF" model with the exponentially distributed inter-arrival and departure time [36]. Recall that CR users can send packet only in the spare time of the PU's transmissions. Thus, the model only considers the throughput performance during the time available for CR users.

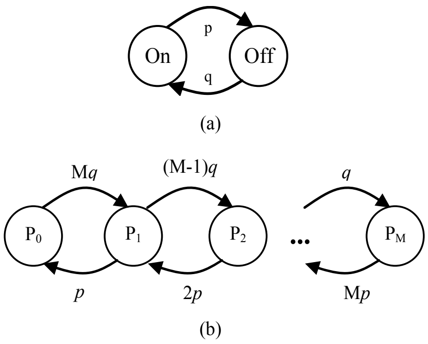

Fig. 7. (a) Interrupted Poisson process model for delay-sensitive traffic. (b) Markov modulated Poisson process (MMPP) model for one type delay-sensitive traffic with *M* users.

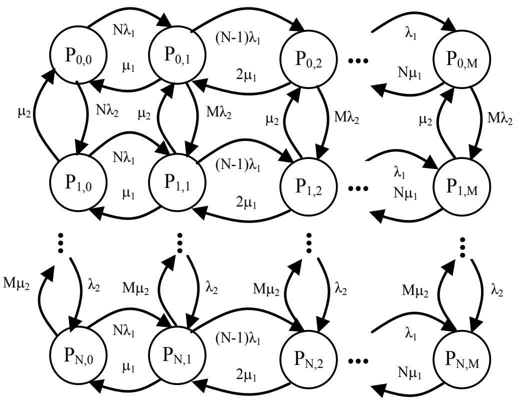

Fig. 8. Two-dimensional Markov chain for the analysis of two delay-sensitive traffic types.

We consider a mixed traffic model with delay-sensitive and non-real-time data traffic flows. Let *M* and *K* are the number of *ds-nodes* and *nrt-nodes*, respectively, and let $n_{ds}(t)$ be the number of *ds-nodes* requesting for frame transmissions at the time instant *t*. For simplicity, it is assumed that only one delay-sensitive traffic flow requests to establish in each round.

The delay-sensitive traffic is modeled by an interrupted Poisson process (IPP). As shown in Fig. 7(a), the "ON" state represents a talk spurt, whereas the "OFF" state is for a silent spurt [36]. The durations for both states are exponentially distributed with a mean value of $1/q$ and $1/p$, respectively. In addition, an *M*-stage Markov-modulated Poisson process (MMPP) shown in Fig. 7(b) is applied to model delay-sensitive traffic flows sent by at most *M ds-*

nodes. Let each state in the figure stands for the number of *ds-nodes* requesting for frame transmissions. Then, given $\rho = q/p$, the state probability (P_i) can be expressed as

$$P_i = P\{n_{ds}(t) = i\} = \binom{M}{i} \rho^i P_0 \,. \tag{1}$$

Let L and L_{ds} be the entire duration of each round and the total duration for sending a delay-sensitive data packet as well as the control packets, respectively. Note that L is fixed because it excludes the duration of PU's transmissions. Let $T(M, K)$ be the throughput of M *ds-nodes* and K *nrt-nodes* in an overlaying ad hoc network, and it can be given by

$$\begin{aligned} T\ (M,\ K) &= E[\text{throughput of } M\ rt-nodes \text{ and } K\ nrt-nodes] \\ &= \sum_{i=0}^{M} P_i \cdot \left(\frac{iL_{ds}}{L} T_{ds} + \frac{L - iL_{ds}}{L} T_{nrt}(K) \right), \\ &= T_{nrt}(K) + (T_{nrt} - T_{nrt}(K)) \frac{L_{ds}}{L} \frac{M\rho}{1+\rho} \end{aligned} \tag{2}$$

where $T_{nrt}(K)$ represents the throughput of the system with K *nrt-nodes*; T_{ds} contains the delay-sensitive data packets. According to [37], the system throughput T_{nrt} can be written as

$$\begin{aligned} T_{nrt}(K) &= \frac{E[\text{transmitted payload in a timeslot}]}{E[\text{length of a timeslot}]} \\ &= \frac{P_s(K) P_{ds}(K) E[P]}{(1 - P_{ds}(K))\sigma + P_{ds}(K) P_s(K) T_s + P_{ds}(K)(1 - P_s(K)) T_c}, \end{aligned} \tag{3}$$

where $E[P]$ is the average payload size; σ is the duration of an idle slot; T_s and T_c are the average successful transmission and collision time, respectively. In (3), $P_{ds}(K)$ and $P_s(K)$ respectively are the probability of at least one packet being transmitted in one slot, and the successful packet transmission probability in one slot, both of which can be found in [37].

The above analysis can be extended to the mixed traffic model containing various delay-sensitive traffic types by using a multi-dimension Markov chain. Take two delay-sensitive traffic types as an example and let N and M be the numbers of CR users sending these traffic types, respectively. Then, the state probability $P_{i,j}$ of the two-dimensional Markov chain model shown in Fig. 8 can be expressed as

$$P_{i,j} = \binom{N}{i} \binom{M}{j} \rho_1 \rho_2 P_{0,0} \,, \tag{4}$$

where $\rho_1 = q_1/p_1$ and $\rho_2 = q_2/p_2$ are similar to the definitions in (1). Thus, with all the parameters defined in (2), the total throughput $T(M, N, K)$ can be written as

$$\begin{aligned} T\big(M,\ N,\ K\big) &= T_{nrt}(K) + (T_{nrt1} - T_{nrt}(K)) \frac{L_1}{L} \frac{M\rho_1}{1+\rho_1} \\ &\quad + (T_{nrt2} - T_{nrt}(K)) \frac{L_2}{L} \frac{N\rho_2}{1+\rho_2}, \end{aligned} \tag{5}$$

7. Performance Evaluation

The effectiveness of the proposed ECRQ-MAC protocol is validated through computer simulation. This section describes the simulation environment and the experimental results. To evaluate ECRQ-MAC protocol, 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 results of our approach are compared with those of SYN-MAC [28], SCA-MAC [27], CRM-MAC [20], and IEEE 802.11 DCF [11]. We have selected these protocols for comparison as because they are very closely related to our proposed ECRQ-MAC protocol. The simulated network is composed of 100 CR users deployed randomly within a 500 m × 500 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: $ETx = (1.65 \times \text{packet size in bits})/2 \times 10^6$ Joules and receiving energy: $ERx = (1.15 \times \text{packet size in bits})/2 \times 10^6$ Joules [38]. 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. A statically chosen shortest path routing is used to show the performance in multi-hop scenario. We initiate the route request (RREQ) between randomly selected but disjoint source-destination pairs. 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, which is set to 300 m.

We impose the best effort traffic with message generation time exponentially distributed with mean value 1/ {(msg. gen. rate)/(no. of CR users)} second. Average message length is geometrically distributed with mean value 4000 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 10 runs where each run uses a different random network topology. The simulation time of each run is set to 500 seconds.

The following performance metrics are used to evaluate the proposed protocol:

- *Aggregate Throughput*: The total bits received by the destinations during the whole simulation time divided by the total simulation time.
- *Average End-to-End Delay*: Average latency incurred by the data packets between their generation time and their arrival time at the destinations.
- *Normalized Control Overhead*: The number of control packets transmitted per data packet delivered at the destinations.
- *Energy Efficiency*: The energy efficiency that is measured in data packets delivered to the destinations per Joule.
- *Network Lifetime*: The duration from the beginning of the simulation to the first time a CR user runs out of energy.

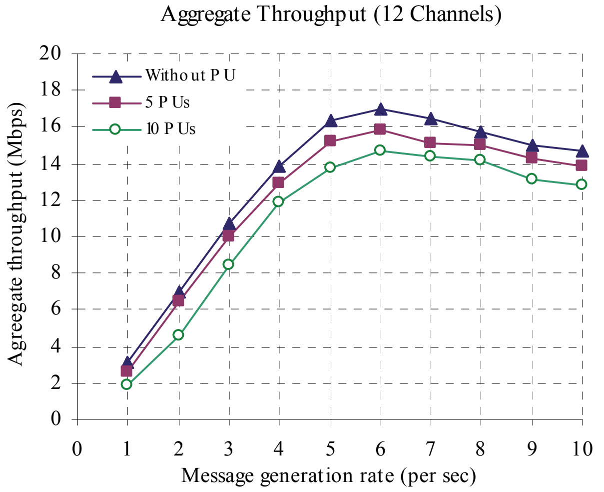

Fig. 9. Aggregate throughput with 12 channels and different number of PUs.

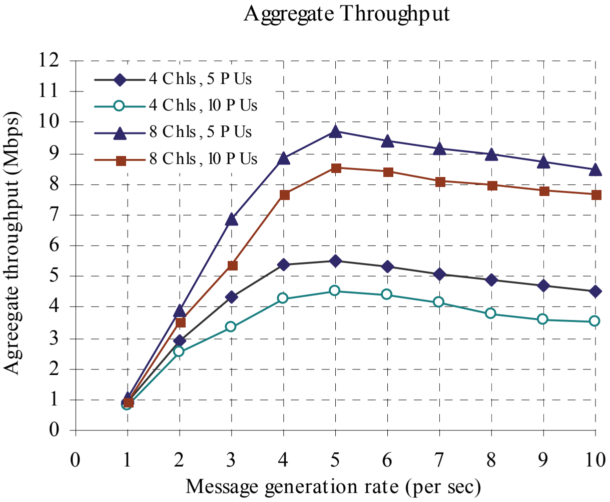

Fig. 10. Aggregate throughput with different number of channels and PUs.

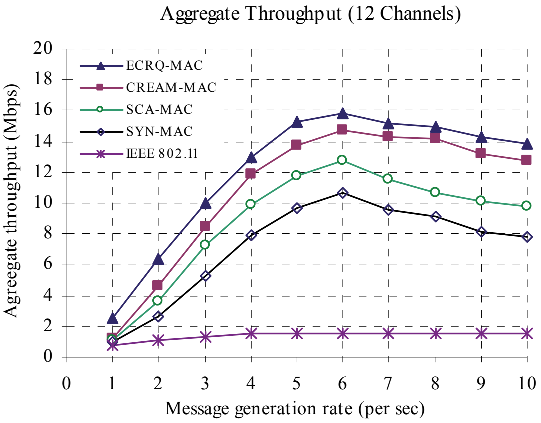

Fig. 11. Comparison of aggregate throughput of ECRQ-MAC with other protocols.

In Fig. 9, 10, and 11, we measured the aggregate throughput by varying the offered load. We can see from Fig. 9, when the offered load (message generation rate) increases, aggregate throughput increases up to message generation rate 6 and then slightly decreases till the end of simulation. ECRQ-MAC without PU outperforms in all level of offered load compare to the 5 PUs and 10 PUs cases. Throughput without PU achieves 7.6 % more throughput than that of with 5 PUs and 19.5 % more than that of 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. 10 shows the effect of channels and PUs on throughput. When the number of channels decreases and PUs increase aggregate throughput decreases. Throughput with 4 channels and with 5 PUs is 23.4 % more than the throughput with 10 PUs. On the other hand, ECRQ-MAC with 5 PUs achieves 14.3 % more throughput than with 10 PUs when there are 8 channels available in the CRANs.

Fig. 11 compares the aggregate throughput of ECRQ-MAC with other protocols. As we can see from Fig. 11, when the offered load increases, ECRQ-MAC offers significantly better performance than all other protocols especially compared with IEEE 802.11 DCF on single channel network. The throughput of ECRQ-MAC is 9.73 times that of IEEE 802.11. When the network is saturated, ECRQ-MAC achieves 11 % more throughput than CREAM-MAC, 30% more than SCA-MAC, and 56.73 % more than SYN-MAC protocol. Throughput of SYN-MAC is less because there is no CCC for conveying the control messages. As a result many connection requests are dropped resulting less throughput. In addition, when the message generation rate is high, the available channel diversity can be better exploited by our ECRQ-MAC protocol. That’s because the channel assignment algorithm can balance the channel load. So the traffic is allocated on different channels in an approximate average manner. Finally, ECRQ-MAC achieves higher performance because ECRQ-MAC eliminates inter- and intra-flow interference using a non-conflicting channel-timeslot assignment.

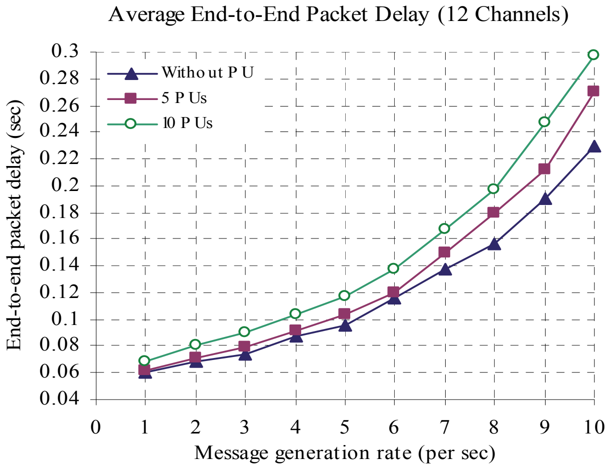

Fig. 12. Average end-to-end packet delay with 12 channels and different number of PUs.

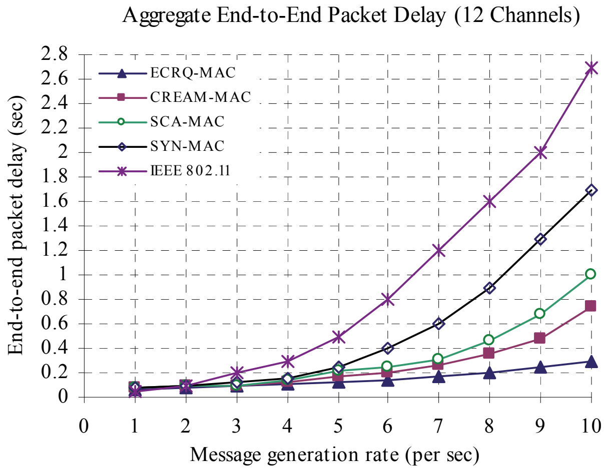

Fig. 13. Comparison of average end-to-end packet delay of ECRQ-MAC with other protocols.

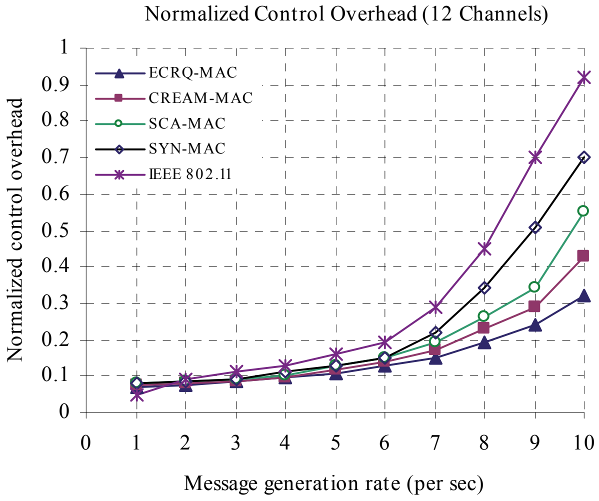

Fig. 14. Comparison of normalized routing overhead per data packet of ECRQ-MAC with other protocols.

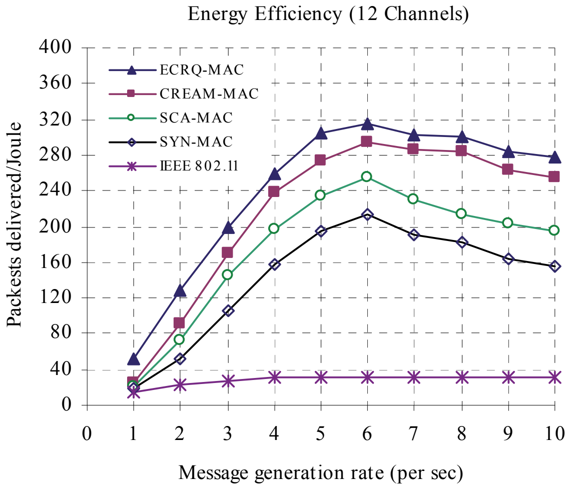

Fig. 15. Comparison of energy efficiency of ECRQ-MAC with other protocols.

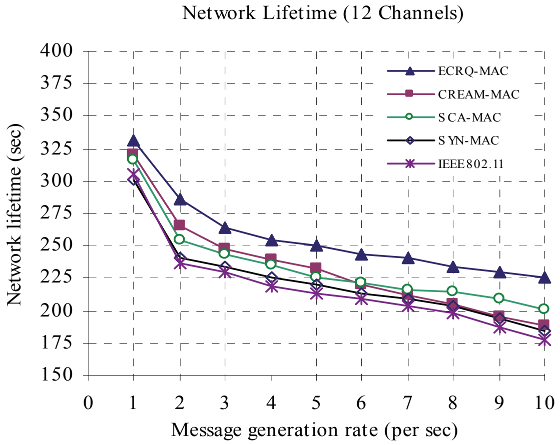

Fig. 16. Comparison of network lifetime, till first node die, of ECRQ-MAC with other protocols.

Fig. 12 and Fig. 13 present the average end-to-end packet delay by varying the message generation rate with 12 channels. The effect of PUs on the average end-to-end packet delay is shown in Fig. 12. ECRQ-MAC without PU shows lower delay in all level of the offered load because the network's resources are static in this scenario. ECRQ-MAC with 10 PUs shows comparatively higher delay because of the limited spectrum recourses availability. Fig. 13 shows the comparison of average end-to-end packet delay of the protocols as the network load increases. In IEEE 802.11 DCF, due to only one channel, a packet has to wait longer to use the channel when the network load is high. When comparing with other protocols ECRQ-MAC shows lower delay in all level of offered load. IEEE 802.11 DCF achieves better performance than other schemes when the message generation rate is low. However, when offered load increases, queuing delay is raised. The queuing delay makes the performance of each protocol worse. Specially, the end-to-end packet transmission delay of IEEE 802.11 DCF is increased dramatically. On the other hand, the data traffic is split into multiple channels in the case of ECRQ-MAC. Therefore the end-to-end packet transmission delay of ECRQ-MAC is increased slowly according to increase of offered load.

The comparison of normalized control overhead is shown in Fig. 14. With the increase of the number of PUs, the control overhead increases due to the frequent route failure. The result shows that our proposed protocol needs lower control overhead per data packet delivery. The energy efficiency is shown in Fig. 15. 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 is shown in Fig. 16. Our proposed ECRQ-MAC protocol handles battery energy in an efficient way thus prolongs the lifetime of individual CR users and overall network as well. When the offered load increases the network lifetime decreases because of the increasing of the number of routes.

8. Conclusion

We have proposed and analyzed the ECRQ-MAC protocol, which is a multichannel MAC protocol using a single half duplex transceiver for CRANs. The protocol enables the CR users to identify and utilize the available frequency spectrum without causing harmful interference to the PUs. Our proposed ECRQ-MAC protocol does not need any centralized controller since the negotiation between the sender and receiver of the CR users is conducted using the IEEE 802.11 DCF. Applying the Markov chain model, we have also developed analytical models to evaluate the performance of our proposed protocol.

ECRQ-MAC has several distinct features. First, it exploits the advantage of both multiple channels and TDMA, and achieves aggressive power savings to enhance the network lifetime. Second, it significantly improves the network throughput by balancing the traffic load over all spectrum bands. Third, it incurs little control overhead, and supports broadcast in an effective way. Finally, it dynamically adapts the network traffic load to achieve higher performance with QoS guarantee while minimizing the control overhead and access delay. The performance of ECRQ-MAC is evaluated using simulation, which shows that ECRQ-MAC is far more effective than current protocols from both the network's and the user's perspectives.

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