

Dynamic TDMA Slot Reservation Protocol for QoS Provisioning in Cognitive Radio Ad Hoc Networks

S. M. Kamruzzaman

Abstract—In this paper, we propose a dynamic TDMA slot reservation (DTSR) protocol for cognitive radio ad hoc networks. Quality of Service (QoS) guarantee plays a critically important role in such networks. We consider the problem of providing QoS guarantee to users as well as to maintain the most efficient use of scarce bandwidth resources. According to one hop neighboring information and the bandwidth requirement, our proposed protocol dynamically changes the frame length and the transmission schedule. A dynamic frame length expansion and shrinking scheme that controls the excessive increase of unassigned slots has been proposed. This method efficiently utilizes the channel bandwidth by assigning unused slots to new neighboring nodes and increasing the frame length when the number of slots in the frame is insufficient to support the neighboring nodes. It also shrinks the frame length when half of the slots in the frame of a node are empty. An efficient slot reservation protocol not only guarantees successful data transmissions without collisions but also enhance channel spatial reuse to maximize the system throughput. Our proposed scheme, which provides both QoS guarantee and efficient resource utilization, be employed to optimize the channel spatial reuse and maximize the system throughput. Extensive simulation results show that the proposed mechanism achieves desirable performance in multichannel multi-rate cognitive radio ad hoc networks.

Keywords—TDMA, cognitive radio, ad hoc networks, QoS guarantee, dynamic frame length.

I. INTRODUCTION

COGNITIVE radio (CR) has emerged as the solution to the problem of spectrum scarcity for wireless applications. It has been using the vacant spectrum of licensed band opportunistically. Cognitive radio networks (CRNs) refer to networks where nodes are equipped with a spectrum agile radio which has the capabilities of sensing the available spectrum band, reconfiguring radio frequency, switching to the selected frequency band and use it efficiently without interference to PUs [1] [2]. CR Ad hoc networks (CRANs) are emerging, infrastructure less multi-hop CRNs. The CR users (nodes) can communicate with each other through ad hoc connection.

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Time division multiple access (TDMA) is a conventional wireless communication technique that has the ability to provide the collision-free packet transmission regardless of the traffic load. There have been many studies for applying TDMA to ad hoc networks. However, most of them do not take into consideration autonomous behaviors of mobile nodes, and thus they cannot assign time slots for new incoming mobile nodes. A few conventional protocols [3] [4] that assign time slots for new incoming mobile nodes show poor channel utilization because they must provide enough time slots for new incoming mobile nodes and this causes a large number of unassigned slots.

In wireless networks, bandwidth is a scarce resource that can be shared either dynamically according to the amount of data required to be transferred to or from each node or deterministically. Providing QoS is more difficult in ad hoc networks due to at least two reasons [5]. First, unlike wired networks, radios have broadcast nature. Thus, each link's bandwidth will be affected by the transmission/receiving activities of its neighboring links. Second, unlike cellular networks, where only one-hop wireless communication is involved, ad hoc networks need to guarantee QoS on a multi-hop networks. Further, mobile nodes may join, leave, and rejoin at any time and any location; existing links may disappear and new links may be formed on-the-fly. All these raise challenges to QoS guarantee in ad hoc networks.

In this paper, we consider the problem of providing a QoS guarantee to users and simultaneously maintaining the most efficient use of scarce bandwidth resources. A dynamic TDMA slot reservation (DTSR) protocol for cognitive radio ad hoc networks has been proposed. This method efficiently utilizes the channel bandwidth by assigning unused slots to new nodes and enlarging the frame length when the number of slots in the frame is insufficient to support the neighboring nodes. This method also shrinks the frame length when the frame of a node is half empty.

II. RELATED WORK

A good channel assignment scheme should not only guarantee successful data transmissions without collisions but also enhance channel spatial reuse to maximize system throughput [6]. In the dynamic channel assignment (DCA)

approach, the channels are not pre-allocated to any user. A channel is dynamically assigned to any user who requires data transfer. Channel reuse is also observed based on the spatial reuse concept. Thus, the DCA approach can automatically adapt to traffic variability in both space and time [7].

Most of the present studies do not consider the autonomous behaviors of new neighboring nodes. Conventional protocols that assign time slots for new neighboring nodes show low channel spatial reuse because they are required to provide a sufficient number of time slots for new neighboring nodes, thereby resulting in a large number of unassigned slots [3] [4]. In [8], the authors have proposed a channel assignment method to resolve the hidden terminal problems in ad hoc networks. However, the fixed channel assignment scheme is considered in their method.

In [9], the authors propose the unifying slot assignment protocol (USAP). This method considers the autonomous behaviors of new nodes and assigns a frame to each node. In this method, each frame has a fixed number of slots. In USAP, a sufficient number of frames and slots must be assigned to each node in the network. Consequently, when the network expands, the channel utilization becomes low due to a large number of unassigned slots. USAP multiple access (USAP-MA) [10] improves USAP by reducing the number of unassigned slots taking into consideration the number of nodes in the network topology. However, this method does not indicate when to change the frame length or how to select a slot to be assigned to a new node. Moreover, the use of this method wastes an excessive number of slots and results in lower channel utilization.

A dynamic TDMA slot assignment (DTSA) technique based on USAP has been proposed in [11]. This method takes into account more autonomous behaviors in a wireless multi-hop ad hoc network. However, this method is still a pre-planned channel assignment method, where a time slot is pre-assigned to each node. The pre-assigned slot is not released even when the node has no data transmission. Therefore, the channel spatial reuse results in lower utilization. This method cannot provide more slots when a node requires them to deal with burst traffic. Therefore, in wireless ad hoc networks, the use of this method results in lower channel spatial reuse.

Dynamic frame length expansion and recovery method called dynamic frame length channel assignment (DFLCA) has been proposed in [12]. This strategy is designed to make better use of the available channels by taking advantage of the spatial reuse concept. However, this scheme is designed for single channel network. An evolutionary-dynamic TDMA slot assignment protocol (E-DTSAP) for ad hoc networks has been proposed in [13]. According to the topology density of the network and the bandwidth requirement, proposed protocol changes the frame length and the transmission schedule dynamically. Moreover, it allows the transmitter to reserve one or more unscheduled slots from the set of unassigned slots in its neighborhood by coordinating the announcement and confirmation with the neighboring nodes up to two hops away.

Conventional channel assignment methods do not provide a solution to minimize or shorten the frame length. The performance is lowered when the amount of connections flowing through a node reduces after its frame length has been enlarged. The number of unused slots increases in certain cases, and a part of the channel bandwidth is wasted.

III. SYSTEM MODEL

We consider a multi-hop CRANs composed of a set of CR users, each of which is equipped with a single half-duplex CR transceiver. We assume CR users are stationary or moving very slowly. In our CRN, PUs are also assumed to be stationary and they coexist with the CR users. Each PU operates with an ON-OFF switching cycle that is unknown to the CRN. Figure 1 shows channel state for the c -th channel. Consider the spectrum consisting of C non-overlapping channels, each with bandwidth B_c ($c = 1, 2, \dots, C$). 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, we assume that CR users exchange control information in a dedicated channel which is always available. This dedicated channel may be owned by the CR service provider [14].

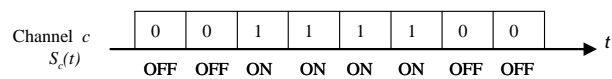


Fig. 1 Channel state for the c -th channel

We assume 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 [15], 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 $c \in C_u \cap C_v$. Where C_u and C_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 when transmitted on the same channel but links on different channels do not interfere.

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 [16]. 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 following 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 [17]. The interference model can be represented by a conflict graph F whose vertices corresponds 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.

IV. PROPOSED PROTOCOL

The frame format of the proposed protocol has N frames with T slots in each frame shown in figure 2. The N value represents the number of nodes in the network and is fixed in our simulation. M is a changeable value and is adjusted when the frame does not have enough slots to support new neighboring connections. This protocol controls the expansion and recovery of unassigned time slots by dynamically changing the frame length according to the traffic load and the number of mobile nodes in the contention area.

The detailed frame structure of the proposed protocol is shown in figure 3. We assume that time domain is divided into fixed frames and each frame consists of a sensing window, an ad hoc traffic indication messages (ATIM) window, and a communication window. The ATIM window is contention-based and uses the same mechanism as in the IEEE 802.11 DCF [18]. The ATIM window is divided into the beacon and the control window. During the ATIM window, control channel is used for beaconing and to exchange control message. All of the CR users are synchronized by periodic beacon transmissions. In this scheme, channel sensing is performed in the starting of each frame to avoid possible collisions with PUs. If any chosen channel is found to be busy, that channel will not used in the ATIM window.

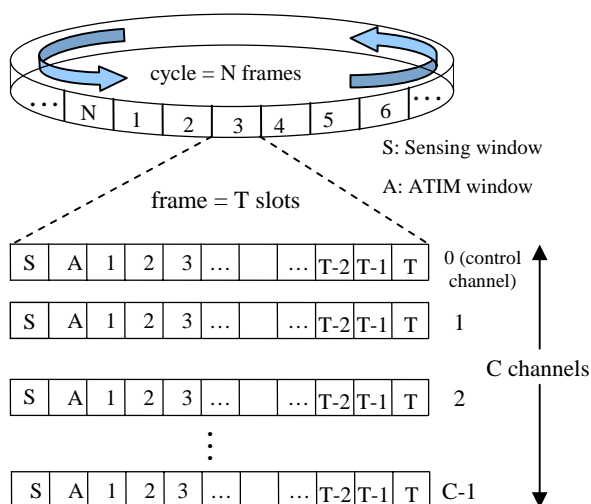


Fig. 2 Frame format of the proposed protocol

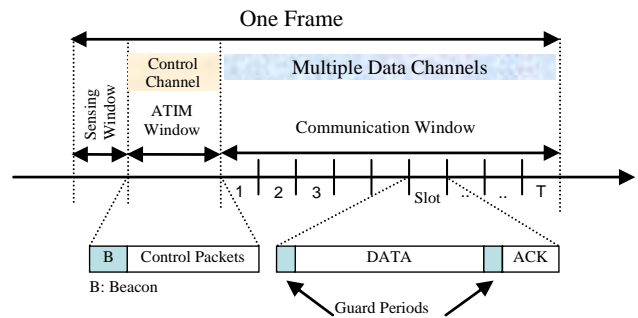


Fig. 3 Detailed frame structure of the proposed protocol

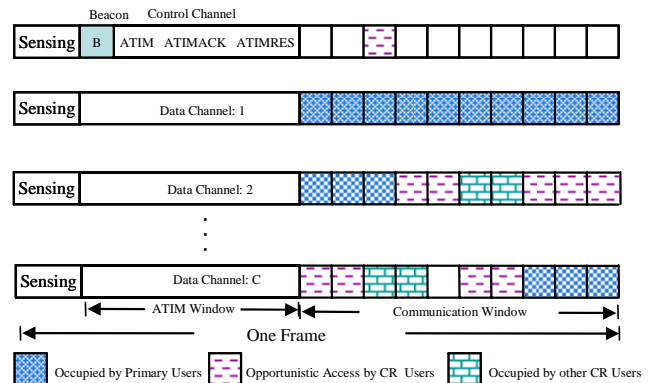


Fig. 4 Process of channel negotiation and data exchange

The communication window is time-slotted and uses TDMA scheme. The duration of each timeslot is the time required to transmit or receive a single data packet and it depends on the data rate of PHY layer and the size of data unit. In order to minimize possible collision with transmission from PUs, the slot size is restricted for a single data packet. The duration of the timeslot is long enough to accommodate a data packet transmission, including the time need to switch the channel, transmit the data packet and the acknowledgement. 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 is to accommodate the propagation delay and the transition time from T_x mode to R_x mode. In the communication window, nodes can send or receive packets or go to sleep mode to save power.

If a node has negotiated to send or receive a packet in the j^{th} time slot, it first switches to the negotiated channel and transmits or waits for the data packet in that slot. If a receiver receives a unicast packet, the receiver sends back an ACK in the same time slot as shown in the slot structure of figure 3. If a sender does not hear an ACK after it sends a unicast packet, may be because of the collision with other transmissions, the sender may perform random backoff before attempting its retransmission using free time slots. If the number of retransmissions exceeds the retry limit, the packet is dropped. The process of channel negotiation and data exchange is shown in figure 4. It is noted that along with other channels control channel can also be used for data transmission in the communication window as shown in figure 4, if needed. If a

node has not negotiated to send or receive a data packet in the j^{th} time slot, the node switches to doze mode for power saving.

We consider a dynamic traffic model in which route requests arrive randomly. Each route request has a bandwidth (data rate) requirement r . A channel-timeslot pair (c, t) is defined as the "communication segment". The resource allocation problem in the MAC layer is actually to determine how to assign available communication segment to links subject to the interference constraints [19]. We define the capacity of communication segment as $\omega(c, t) = B_c / |T|$, where B_c is the channel capacity (bandwidth) of channel c , which is the maximum data rate support by the channel; and $|T|$ is the total number of time slots in the communication window. In this paper, the bandwidth is measured in terms of the capacity of communication segments.

With the help of periodic beaconing, each node 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 secondary node updates the status of its communication segments as occupied or free. Free communication segment of node v , $free_segment(v)$, is defined as the communication segments for all available channels, which are not used by node v to communicate with adjacent nodes, and are not interfere by other transmissions. Status of the communication segments on a link is determined by finding the intersection of the status of both end nodes of the link.

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 $B(u, v) = free_segment(u) \cap free_segment(v)$.

A. Frame Length Descriptions

In DTSR, the frame length can be dynamically changed depending on the number of nodes and the network topology. Figure 4 shows the working of DTSR for a node in its contention area. Here, the contention area is defined for each mobile node as the set of mobile nodes that can cause collisions of sending packets with each other, i.e., mobile nodes within two hops from the node. Node D is simultaneously present in both the hop contention areas of node A and node K. Node D is the hidden terminal node. It must consider the problem of collision when selecting the slot. There is a QoS requirement of 2 slots in each connection. All other pairs of connections have timeslot assignments of 2 slots in each connection. Therefore, for collision free connection D must select different communication segment (channel-

timeslots) from any other pairs of nodes in its contention area. But no communication segment is vacant right now to address the new connection. So, frame length is needed to increase to accept new connection with maintaining the QoS requirement.

The frame length of each node is set as a power of 2; this can avoid packet collision at a node that is at the boundary between two-hop contention areas with different frame lengths. For example, in figure 5, node D, which belongs to two one-hop contention areas whose frame length is 4, can transmit packets without collision in both the contention areas by setting its frame length as 8.

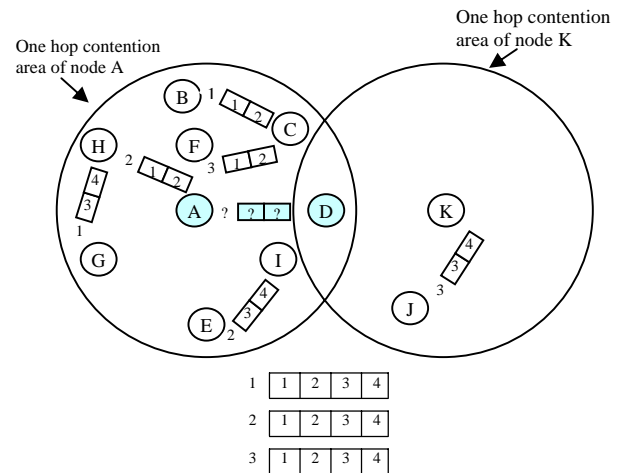


Fig. 5 Working of DTSR for a new node in its contention area

B. Dynamic Channel-Timeslot Assignment

We have developed an efficient scheme for dynamic channel-timeslot assignment for a wireless multi-hop CR ad hoc network. Our proposed protocol controls the number of unassigned timeslots by dynamically changing the frame length according to the traffic loads and the number of mobile nodes in the contention area. When a new node detects a conflict, it solves the conflict by listening and collecting assigned time slot information of the nodes in the contention area. Our proposed protocol improves the channel spatial reuse and maximizes the system throughput. The channel-timeslots assignment of DTSR is performed as follows:

- A CR node that has not acquired a slot in the frame wants to transmit data (findslot = F).
- The node requests for network topology information in its contention area by listening to the data frames transmitted from other nodes.
- The node sets its frame length as the maximum frame length among its neighbors.
- The node updates its frame table by listening to the frames transmitted from its neighbors.
- If there is an unassigned slot in the frame, findslot = T then assigns a slot according to the communication segment allocation algorithm discussed in subsection 4.4.
- If findslot = F and there are neighbors using more than one slot, then the node removes a slot from one of the nodes using the most number of slots.

g). If $\text{findslot} = F$, the node doubles its frame length, thereby copying the assignment information from the former frame to the latter part of the doubled frame and using the empty slot created.

h). The node is assigned a slot, and it sends a reserve packet to its neighbors to update their frame table.

The neighbors transmit back a confirmation packet to confirm the reserve packet sent from the node and to notify this assignment to the two-hop neighbors of the node that are reserving a slot.

C. Effective Frame Recovery Method

A limitation of the most timeslot allocation protocol is that the frame length, set as a power of 2, may expand very quickly when there are many nodes in the network. When many connections end their transmissions and are released, this may lead to a node in the network containing a long frame with many unused slots.

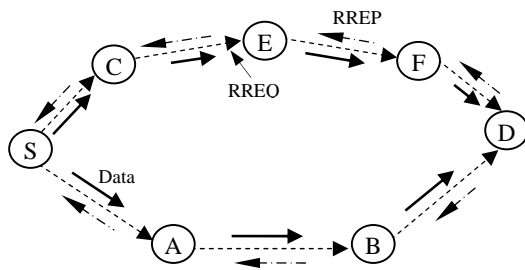


Fig. 6 Multipath routing in CRANS

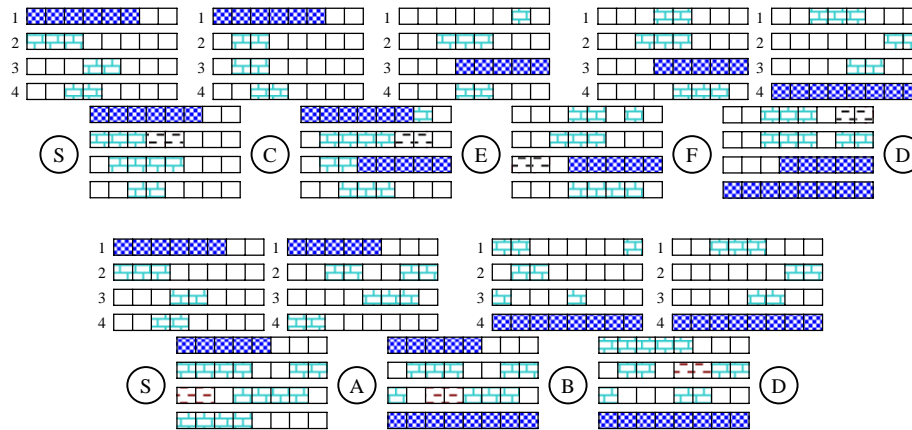


Fig. 7 Channel-timeslots assignment in multipath routing for CRANS

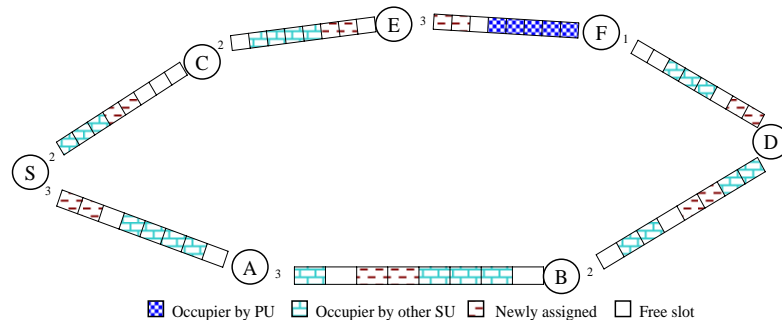


Fig. 8 Channel-timeslots assignment in multipath routing for CRANS

Our frame recovery method in the DTSR protocol improves the efficiency of the frame. When a slot in the frame is released after not receiving anything for a certain amount of time, the node checks its channel-timeslots assignment table to see if half or more of the slots in the frame are unreserved. If this situation occurs, the node immediately releases the unused slots. Then, it sends a request control packet for frame recovery to the neighbors. The neighbors try to assign slots for it after they receive this type of request packet, and they confirm the accepted request made by the recovery requesting node. Then, they send a response control packet to their neighbors notifying them of their update. This method significantly increases the frame efficiency. A node releases its unused slots in the data channel, if half or more of the slots in the frame are unreserved.

The effective frame recovery method of DTSR is performed as follows:

- After a slot is released in a node, the node checks if half of the slots in the frame are unused.
- If the number of unused slots is larger than or equal to $\text{frame length}/2$, then the node sends a request packet for frame recovery to its neighbors.
- This request packet informs the receiving neighboring nodes to also try to update their channel-timeslots tables and reschedule the slots they were using previously and to confirm the receipt of the request packet sent from the node requesting for frame recovery.
- The neighboring nodes send a confirmation packet.

D. Selection of Communication Segments

In this subsection, we present a heuristic algorithm to select communication segments for the link $l = (u, v)$. Let us consider $r_r(z)$ be the remaining data rate requirement for the session z of a connection request. Initially $r_r(z) = r(z)$. The basic idea of this approach is to select minimum number of free communication segments to satisfy the given rate requirement within the interference constraint. In order to maintain minimum number of communication segments in a link we will use high capacity segments. Sort all the free communication segments in the descending order of their capacities. Pick a communication segment (c, t) from the sorted list and check the capacity of the chosen segment $\alpha(c, t) = B_c / |T|$ is not less than the $r_r(z)$, then it is selected. The selected segment is then removed from the free segment list and update the remaining rate requirement $r_r(z)$. To ensure the collision-free transmissions, the following conditions must be satisfied in selecting the communication segments. Let 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 node u ,
- Timeslot t is not assigned to any outgoing link from node v ,
- Timeslot t is not used on channel c by any link l' , $T_x(l') \in Nb(v)$, $Nb(v)$: set of neighbors of node 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 node can be assigned same timeslot [17]. If all the above conditions are satisfied, communication segment (c, t) is assigned to the link $l = (u, v)$. This procedure continues until the rate requirement is satisfied.

Figure 6 and 7 show the arbitrary multipath routing paths and the channel-timeslots assignment for that multipath routing in CRANs. The resultant channel-timeslots assignment is shown in figure 8.

V. PERFORMANCE EVALUATION

The effectiveness of the proposed DTSR approach is validated through simulation. This section describes the simulation environment, performance metrics, and experimental results. The result of our approach is compared with DTSA [11], DFLCA [12], E-DTSAP [13], and DSR [20]. We used network simulator-2 (NS-2) version ns-2.33 [21] to evaluate the performance of the proposed routing protocol. We generate 15 random topologies, and the result is the average over the 15 random topologies. The simulated network is composed of 50 static CR nodes deployed randomly within a $1000m \times 750m$ rectangular region. Based on the IEEE 802.11a standard, the number of channels is set to 12 including 11 data channels and one control channel. The data channels are divided into three groups that include 3 channels in the first group and 4 channels each in last two groups. Based on the IEEE 802.11b, data rates for these

groups are set to 2 Mbps, 5.5 Mbps, and 11 Mbps. Nodes can respectively transmit 1, 3, or 5 consecutive packets depending on their channel condition. The data rate for control channel is 2 Mbps.

The transmission and interference range of each CR user (node) is approximately $150m$ and $300m$ respectively. The control channel can support a transmission range of $200m$. Channel switching delay for CR transceiver is $40\mu s$. We randomly placed 5 PUs in the region. Each of them randomly chose a channel to use, which is then considered to be unavailable for all the CR users within their coverage range, which is set to $300m$. We initiate sessions between randomly selected but disjoint source-destination pairs. The two-ray-ground reflection model is used to propagation model. The traffic demand for each communication session is given by a random number uniformly distributed in $[0.1B_c, 0.6B_c]$, where B_c is the channel capacity of channel c . The packet size of each flow is set to 1000 bytes (excluding the size of IP layer and MAC layer headers). Data traffic was generated using constant bit rate (CBR) traffic sources generating 4 packets/second. All traffic sessions are established at random times near the beginning of the simulation run and they stay active until the end. Simulations are run for 500 simulated seconds. The following performance metrics are used to evaluate the proposed protocol:

Normalized Throughput: The ratio of throughput obtains using DTSR protocol to the throughput obtain when using DSR on a single channel environment. The normalized throughput quantifies the performance improvement of DTSR protocol with respect to a single channel network.

Average End-to-End Delay: Average latency incurred by the data packets between their generation time and their arrival time at the destination.

Normalized Control Overhead: The number of control packets transmitted per data packet delivered at the destination.

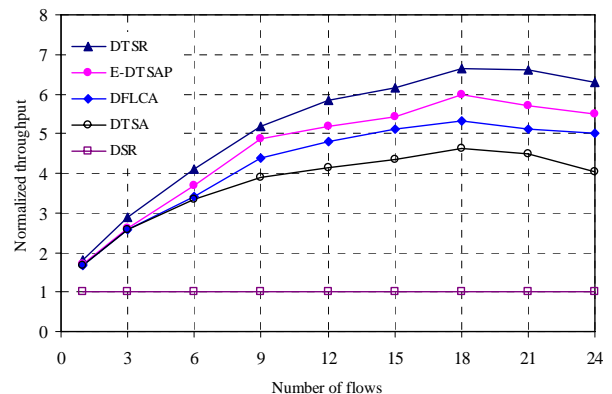


Fig. 9 Network throughput varying number of flows

In the first simulation, we measured the normalized throughput varying the number of flows shown in figure 9. The throughput of DTSR is compared with other protocols including DSR single channel network using UDP traffic. The number of simultaneous UDP flows is varied from 1 to 24. As we can see from the figure, when the number of flows increases, DTSR offers significantly better performance than

all other protocols especially compared with DSR single channel network. The throughput of DTSR is 7.4 times that of DSR. When the network is overloaded, DTSR achieves 8% more throughput than E-DTSAP, 26% more than DFLCA, and 72% more than DTSA protocol.

Figure 10 shows the average end-to-end packet delay of the protocols as the network load increases. The difference between DSR and other protocols in delay is due to the fact that with only one channel, a packet has to wait longer to use the channel when the network load is high. When comparing with other protocols DTSR shows lower delay in all network scenarios. DSR achieves better performance than other schemes when the number of flows is less. However, according to increase of number of flows, queuing delay is raised. The queuing delay makes the performance of each protocol worse. Specially, the end-to-end packet transmission delay of DSR is increased dramatically according to increase of flows because DSR uses only a single channel for every data transmission. On the other hand, the data traffic is split into multiple channels in the case of DTSR. Therefore the end-to-end packet transmission delay of DTSR is increased slowly according to increase of flows.

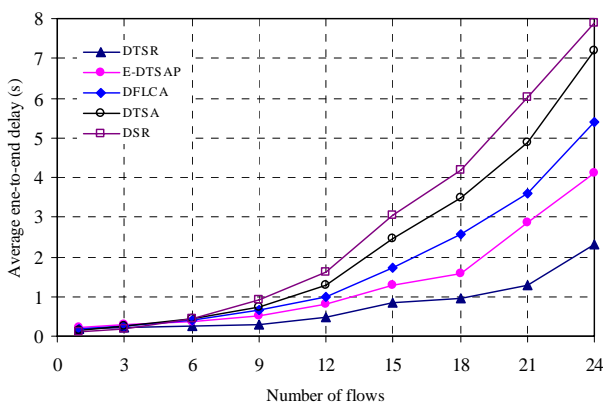


Fig. 10 Average end-to-end delay varying number of flows.

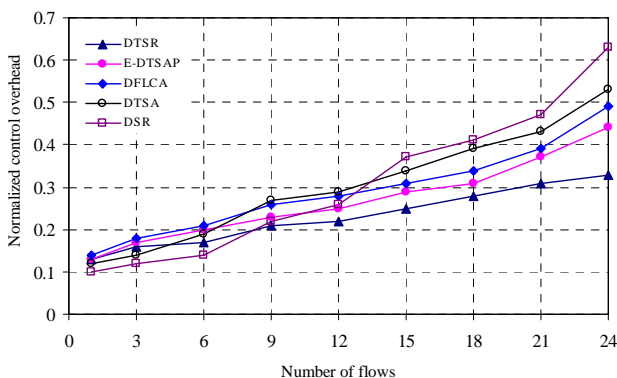


Fig. 11 Normalized routing overhead varying number of flows.

Figure 11 shows the control overhead of the protocols as the network load increases. The overhead includes the cost of sending "Hello" messages and routing control messages (RREQ, RREP, and RERR). As we can see from the figure, the overhead increases as the number of flows increase. For

each flow, overhead is incurred in discovering and maintaining a route. Initially our protocol has slightly more overhead than DSR and DTSA but when number of flow increases, our scheme outperforms all protocols. Our protocol shows that overhead traffic consumes only a small fraction of the available channel capacity (even at the lowest data rate of 2 Mbps supported by IEEE 802.11b).

VI. CONCLUSION

In this paper, we have proposed a dynamic TDMA slot reservation (DTSR) protocol for cognitive radio ad hoc networks which can change the frame length and the transmission schedule dynamically according to the number of nodes and the bandwidth requirement in the contention area. This method utilizes the bandwidth resources in an efficient way thus increase the channel utilization. Our protocol can effectively assign slots to nodes when a node joins and leaves from the network. When a connection is released in the network, the frames in many of the nodes may contain a large number of unassigned slots. Our frame recovery extension scheme decreases the amount of unused slots by allowing the nodes to release the unused slots and shrink their channel tables when the frame is inefficient. Extensive simulations confirm the efficiency of DTSR protocol and demonstrate its capability to provide high throughput in robust multi-hop communications. Our proposed DTSR protocol is ideal for communications under unknown and dynamic spectrum conditions.

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