New Routing Protocol for Half-Duplex Cognitive Radio Ad-Hoc Networks over IoT Environment

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***Abstract*—In this paper, we consider non-time slotted cognitive radio ad-hoc networks in order to propose a routing protocol without a common control channel, thereby adhering to practicality. This is performed using multicast and unicast transmission of the control packets. The performance of this protocol is studied and compared with a quite relevant and recent protocol, called Probabilistic and Deterministic Path Selection (PDPS), using a special simulator, which is built in Java language and developed upon PDPS's simulator. The PDPS protocol creates two paths between the source and destination while using all the channels in the network. Interestingly, their results are promising in terms of throughput. On the other hand, our protocol builds as many paths as possible between the source and destination. Besides, in our protocol, we use all the channels in the network. The performance metric considered is the throughput whereas our results are even better than those of PDPS protocol.**

Keywords— Cognitive Radio Ad-Hoc Networks (CRAHN), no Common Control Channel (CCC), non-time slotted CRAHNs, and CRNs' Routing Protocol.

I. INTRODUCTION

Internet of Things (IoT) is defined as the connection of diverse items over the internet, operating with various communication technologies [1]. From which, there are wired and wireless technologies, the latter is more flexible, thus, more popular [1]. Nevertheless, major concerns arise in this case, for example there is the existence of massive data, and the shortage in spectrum availability. Interestingly, researchers have a desire to solve these challenges using cognitive radio networks (CRNs) [2]. CRNs search the spectrum for available bands, then dynamically change the transmitting parameters of the devices to opportunistically access the spectrum [1], [3]. There are many potential applications for CR-based IoT devices, such as healthcare applications, social activities (e.g., smart traffic lights), environmental related applications, in-home applications, smart grids, smart cities, and internet of vehicles [1].

Half-Duplex multi-channel non-time-slotted CR Ad-Hoc Networks (HD-CRAHNs) are considered a practical spectrum-efficient communication model. In this model primary and secondary networks are asynchronous. Specifically, Ad-hoc networks consist of wireless nodes communicating via multi-hop paths, without an infrastructure. Moreover, cognitive radio technology allows the nodes in the network to use the empty frequency bands without having bands of their own. In CRAHNs, a source node communicates with a destination by building a multi-hop path between the two nodes. All the nodes can communicate without a fusion center. This guarantees high coverage of the network, low cost, and easy maintenance.

At this point, it is apparent that having CR-based devices in IoT applications is very promising. Thus, we were motivated to work on an Ad-Hoc CRN that can be used in IoT applications, such as smart cities. In our work, we propose a routing protocol for multi-channel non-time slotted CRAHNs.

To create a routing protocol that is aware of the channel's availability and the Primary Users' (PUs) activity (i.e. spectrum-aware), one should think of the sensing and the spectrum allocation processes along with the routing process. This means creating cross-layer routing protocols is essential to enhance the performance of CRNs, especially for meeting the demands of multi-media applications [4]. The text below highlights two of the most relevant cross-layer routing protocols for CRNs.

A cross-layer routing protocol named CLRP is proposed in [5], which considered all available channels at every SU node. This protocol formed a full path before deciding which channels should be sensed by the PHY-layer of each node. Similarly, a protocol named Probabilistic and Deterministic Path Selection (PDPS), that extremely enhances the performance CLRP, is proposed in [6]. In which, the authors built two paths between the source and the destination and they let the source decide which path has better throughput.

The proposed protocol introduces new concepts and make modifications to CLRP. It also considers the existing CLRP modifications, such as PDPS. We name our protocol Multi-Cast-based Half Duplex Routing Protocol (MC-HDRP). Remarkably, for page length constraints and because PDPS outperforms CLRP, we compare our work only with PDPS.

The rest of the article is organized as follows: Section II illustrates the proposed protocol. The system and protocol's assumptions are detailed in Section III and VI, respectively. Mathematical model is presented in Section V. Extensive details of the proposed protocol are provided in Section VI. Section VII presents the simulation results. The article is concluded in Section VIII.

II. THE PROPOSED PROTOCOL

Interestingly, both CLRP and PDPS consider the probabilistically and the deterministically available channels. Where the probabilistically available channels have specific idle probability, assumed to be found after conducting long term monitoring processes. However, the deterministically available channels represent a small set of channels that is assigned to each node based on the geographical area and is sensed periodically by the node. This is in order to mimic the process of serving other paths than the one in question and gaining the advantage of having channels ready to use whenever needed. In our protocol we do not assign this set of channels to every node, rather we consider all the channels only before the transmission starts. As we think that sensing this set of channels periodically wastes a portion of the slot time and negatively affects the transmission period, i.e., it reduces the throughput. Besides, we consider other paths to be served in the initial load inside each time slot. Hence, only the used channel is going to be sensed periodically using Listen Before Talk (LBT) protocol. Moreover, we study the probabilistically available channels too, in order to represent the activity of other Secondary Users (SUs) in the network. SUs are assumed to be arriving according to a Poisson distribution. This is deferent from CLRP and PDPS where they used the probabilistically available channels to mimic the behavior of PUs. Remarkably, to be fair, we removed the assignment of deterministic channels to the nodes in PDPS that we compared our work with.

We add timing to our protocol and simulate the existence of PUs. We use a delay variable and a set of files with PUs existences. However, for testing purposes, we represent the activity of PUs as various periods of time taken randomly from every channel. Besides, each channel can be used by various PUs, each one at a time

III. System Model

Each selected path in our protocol consists of a source node, intermediate SU nodes, and a destination node. Only one channel is used between each two nodes, i.e., each SU node has only one transceiver. Specifically, the used channel in each hop is chosen from all the channels in the network after the sensing process is conducted. Given that the availability of each channel has a specific probability, which is called idle probability. In our study, there exist three types of channels: "Available" (idle probability = 1) such that there is no PU nor SU, "Not available" (idle probability = 0) which only means a PU exists, and "Probabilistically available" (0 < idle probability < 1) such that SUs exist in the channel with the given idle probability. The last type of channels was named "unknown to be available" in [5], [6] but for PUs activities not SUs. Interestingly, the SU nodes should be contending, therefore, SUs activity will only be considered in the "probabilistically available" channels not in any other type. Obviously, the state of each channel is found after the first sensing process is conducted.

The first sensing process is conducted to all the channels before the network settles down. Then, there is a sensing process for the "probabilistically available" and the "available" channels at each node's position before message transmission. This is followed by a periodic sensing process for the channel used in transmission. Additionally, if the channel gets busy while the SU is transmitting (i.e., a collision) the transmitted packet will be dropped, and it will not be transmitted to the neighbor. This is because we do not have acknowledgments. Therefore, the node will look for another channel to transmit its packets over, only after the sensing period comes (using the LBT protocol). This is how we avoided the use of a CCC.

IV. Protocol's Assumptions

- We assume that there exist various PUs in the network, each one can occupy any channel. Every channel can be occupied by one user at a time.
- Given that a PU can tolerate interference for a specific interval, called the Tolerable Interference Delay (TID). We assume that TID is 1 second long. An SU is preferred to stop transmitting and monitor the PU activity every TID. This is done using LBT protocol for the sensing /transmitting tradeoff with overlay dynamic spectrum access model.
- We use energy-based and waveform-based detection. The first technique is used to detect whether there is a user or not. Only if there is a user, the second technique would be used; in order to check if that user is an SU. If it was another SU, then the SU in question will try to access the channel anyway but with throughput multiplied by the idle probability. Moreover, if the given SU was already transmitting on the channel and another SU appears, it will keep occupying the channel until the next sensing period in HD mode. This idea is inspired by [7], [8], where the authors handled many problems facing CRAHNs like SU's frequent handoffs.
- We simulate the activity of SUs only as if they are arriving according to a Poisson distribution with known birth and death rates. Intriguingly, we simulate the PUs as actual nodes occupying the channels randomly.
- We assume that all the channels have the same bandwidth (BW). Additionally, we adopt a bandwidth model that has 1 bit per Hz per second if the received Signal-to-Interference-plus-Noise-Ratio is higher than a predefined threshold, i.e., $R = BW\ [bit/sec]$.
- No Common Control Channel (CCC) is required. This is an advantage, because we avoid reserving a channel for sending control packets (i.e., spectrum efficiency). Besides, this way we follow the diffenetion of a CRN, as it is designed to operate over the empty channels.
- Some requirements are assumed to be known, such as the location of our SU nodes, the set of all channels in the CRN, the expected available time of the channel and the birth and death rates of contending SUs. Besides, the keep-out distance of channels which indicates the locations of contending SUs is also known. Note that, in PDPS, the information that should be known is about PUs' network. Thus, we have a more practical system because the cooperation between SUs and PUs is not required.
- We have the maximum power constraint of idle and probabilistically available channels. In this constraint, the channel is considered available only when its required power is less than the node's maximum transmission power.

V. Mathematical Model

In our protocol we adopt equations used by [5], [6], thus there will be no need to re-write the equations in this work. However, the most important equations are mentioned, such as the transmsission time, which is given by

$$T_{T_x\,max} = TID - L_w - ST_{Ch_1} - ST_{Ch_2} - \alpha\left|f_1 - f_2\right| \qquad (1)$$

where (TID) is the periodic time slot, it is actually the PU's tolerable interference delay and it is assumed to be 1 sec. The initial load is (L_w) which is the time to serve other paths. The sensing time is (ST). The frequency step or switching time constant (α) is in seconds per Mega Hertz. Finally,(f_1) and (f_2) are the central frequencies of the two channels (Ch_1) and (Ch_2), respectevly.

To get the throughput in bits per second we multiply the transmission time ($T_{T_x max}$) by the bandwidth of the channel (BW) then divide it by the number of time shares, such as the following equation.

$$TH_{max} = \frac{T_{T_x\,max} \times BW}{\text{time shares}} \qquad (2)$$

A time share means the time slot where we have simultaneously active nodes in a path. But another definition states that it is the existence of a split in time between the activities of the nodes in the path. Based on both definitions, in HD we have the number of time shares equals to the number of hops in the path.

VI. Details of the MC-HDRP Protocol

A. Route Request Packets in MC-HDRP

A setteling time was added to every node to guarantee that the node senses all the channels and knows its neighbors.This delay is added before the start of any transmission.

At the beginning of any transmission, the source senses a channel from its surroundings to detect the PUs and the secondary neighbors. The detection relies on the transmission of PUs and on the leaked oscillator signals that accompany the sensing process of SUs [7], [9], [10]. Hence, each leaked signal must have a unique ID. This idea is an optimistic thinking in the light of [11]–[14]. The oscilator power leakage of any reciever (or sensing device) is discussed in [15] and [16].

The source sends a multicast Route Request Packet (RRQP) over the channels that have SUs sensing them. The transmission happens without repetition, i.e., the neighbors who received the RRQP will be eliminated from other transmissions throughout the channels. This can happen because the SUs can be detected based on an ID of their signals, thus, multicast or unicast is used. The idea of multi-casting was mentioned in [17]. Remarkably, an SU neighbor can be detected over various channels because the nodes sense the channels and transmit over them in diferent orders.

The source adds its neighbors to a queue and each neighbor will add its neighbors to the queue without repetition. Most importantly, this queue is sent in the RRQP. This queue is devided into "next in queue" and "transmitters" lists as seen in Table I and as will be explained in the following scenario.

TABLE I. The RRQP Contents for Multi-Casting in MC-HDRP and MC-HDRP-CA.

Channel ID	Node ID	Upstream channel	Upstream node	Downstream quality	Entity length
The downstream channel	This node ID	Previous channel	Previous node	The time for transmitting from the slot	In bits
. .	. .	. .	. .	. .	. .
The Queue: …					
The transmitters' list: …					

1) Scenario for RRQP delivery

Figure 1 shows a scenario for RRQP delivery in our proposed protocol. In particualer, a queue and a transmitters' list are two entries added in the RRQP along with an entry for every downstream channel to carry the channel's downstream quality, upstream node ID, corresponding upstream channel ID, entry's length (indication of the message length), and this node's ID.

Its noteworthy to mention, before explaining the example, that the neighbors were found in the settling time, however, before transmitting the RRQP the node must sense every channel to recognize the existing neighbors in that channel. Therefore, the queue depends on which node was discovered first and on which channel. Additionally, only in the example, the nodes are discovered from the west of the node and clockwise. Besides, we assume in the example that each node is found on a separate channel at every transmission process.

The following text explains the example given in Figure 1.

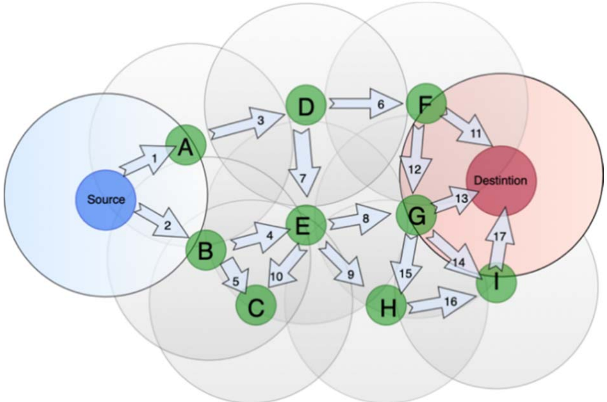

Figure 1. RRQP Delivery in the Route Discovery Stage

- In the settling time, the source (1) discovers nodes "A and B" each on a separate channel. Then, (2) the source senses the first channel and adds node "A" to the queue, right before (3) transmitting over the first channel. This is followed by (4) sensing the next channel, finding node "B", then adding it to the queue (after "A"). At this point, node "B" will receive the RRQP with the new queue over the second channel. the transmitters' list has only the source in it.
- The first node in the queue has the priority to send its version of the RRQP to its pre-defined neighbors. In this case the first node is "A" and (recall) it sees itself as the only one in the queue. Consequently, node "A" has "B and D" as neighbors known right before transmission starts (i.e., node "A" will sense the channels separately to find the neighbors). Then, (assuming the west-clockwise discovery in the example) "A" will send the RRQP to node "D" then node "B" because they are not in the transmitters' list received from the source. Additionally, node "A" will be moved from the queue to the transmitters.
- Node "B" will keep waiting until it receives the new RRQP from node "A" (the first in queue). In the same manner node "B" discovers that it has "A, E and C" as neighbors on separate channels. Node "A" is in the transmitters' list (from the updated RRQP). Therefore, node B will send the RRQP only to nodes "E" then "C" each with a queue, (D and E) then (D, E and C), respectively. It is important to note that node "B" will consider both RRQPs received from the "source" and node "A". As for the quality, "B" will get the best quality for every downstream channel. However, for the queue and the transmitters' list node "B" will get the latest received ones (from A). Interestingly, the transmitters list at "B" has: "Source, A and B".

This process keeps going in the same manner. Thus, for space constraints we will jump to node "I" without considering the details.

- Node "I" handles the updates of the transmitters and the queue lists received from node "H" not "G" because "H" is the latest to transmit. Node "I" has "H, G, and Destination" as neighbors. Thus, it will send only to the destination; because "H" and "G" are in the transmitters list. The queue has no entries and the transmitters' list has: "Source, A, B, D, E, C, F, G, H and I".

B. Route reply packets in MC-HDRP

The destination processes the received RRQPs and creates its Route Reply Packet (RREP) with the best received RRQP for every channel. Then it will send the RREP (one message item per node) to its neighbors. Only the ones who sent the RRQP to the destination. As for transmission, the "destination" uses the best channels in terms of throughput. This is done to create multiple paths.

The reverse paths have consequent nodes working simultaneously (i.e., the paths are multi threaded). Additionally, each node in the reverse path will take the best channel to transmit the RREP to the upstream node. The throughput of the path is the minimum of all the hops in that path (i.e., bottleneck throughput). At the end of path discovery stage, the source decides which path has the maximum throughput.

VII. Simulation Results

This section begins by introducing the simulation parameters and the performance metric used in the comparisons between protocols.

A. Simulation Environment

The simulations were conducted using a special simulator built in Java language that was heavily edited over CLRP and PDPS's simulators. The computer used was Apple MacBook with 1.8 GHz Intel Core i5 processor and 8 GB 1600 MHz DDR3 RAM.

The simulator was built with various classes, such as network, node, channel, basic message, basic message item, control message, message item, data message, packet, path, and primary user. The thread used in the simulator was the RREP delivery thread.

B. Simulation Parameters

The default values of some parameters are listed in Table II, however, any change in the parameters is mentioned before every figure. Each point in the figures is an average of 100 trials. The random values follow uniform distributions except the arrival of SUs, which is Poisson. However, in PDPS the arrival of PUs is considered.

C. Performance Metric

We use the throughput as our performance metric. The throughput in our study can be described as the transmission time in each time slot multiplied by the channel bandwidth and divided by number of time shares in the path. We can express the throughput in terms of bit/sec/Hz if we did not multiply by the bandwidth; as we have the same channel bandwidth in our simulations. More to the point, the theoretical description of the throughput is the average rate of successfully delivered packets per second.

D. Discovery Phase

This section provides performance evaluation of the proposed protocol in the route discovery phase.

Figures 2-a, 2-b and 2-c show the effect of increasing the number of channels on the behavior of our proposed protocol compared with PDPS in low idle probability conditions, moderate and high, respectively. Both protocols have fixed throughput after the number of channels is enough; because the extra channels will not be used to increase the throughput.

TABLE II. Table 1. Default Simulation Parameters.

Parameter	Value
Number of SU Nodes	50 nodes
PU TID	1 second
Number of Channels	12 channels
Transmission Range of SUs	50m
Transmission Range of Contending SUs, or PUs in PDPS	500m
SUs Network Dimensions	200m×200m
Contending SUs Network Dimensions, or PUs Network in PDPS	1000m×1000m
Idle Probability $P_r(H_0)$	As given in each graph (low 0.1, moderate 0.5, and high 0.9)
SU source position	At (0, 0)
SU destination position	At (200, 200)
Number of PU nodes	5 nodes
Initial load [5]	Random between 0.1 and 0.7 seconds
Switching Constant α.	1 milli sec / MHz
Sensing time of a channel [5]	Random between 1 milli sec and 100 milli sec Max 1/10 of the TID for the channel
Channel Bandwidth	6 MHz

MC-HDRP has higher throughput compared to PDPS, with increment ratio equal to 2.84% (with idle probability = 0.1). This can be explained as MC-HDRP uses all the possible paths between the source and the destination. Thus, the chances of gaining better throughput are higher.

As for the second experiment, default values are used and number of SU nodes is variable. In Figures 3-a, 3-b and 3-c, as the number of nodes increases then the connectivity increases, which results an increment in the throughput in both protocols. The throughput will not increase significantly, because of the interference effect on the throughput when number of SUs increase.

VIII. Conclusions

The use of CR technology in Ad-Hoc networks guarantees using the spectrum efficiently to handle the increasing demands on wireless communications, especially IoT applications. In this paper, a practical HD-based CRN routing protocol is introduced. The proposed protocol does not use a CCC, rather it uses multi- and uni-cast for sending the RRQPs. Our protocol (MC-HDRP) outperforms the PDPS protocol introduced by [6] in terms of throughput. This is because our protocol uses all the possible paths and avoids having frequent handoffs by the SUs.

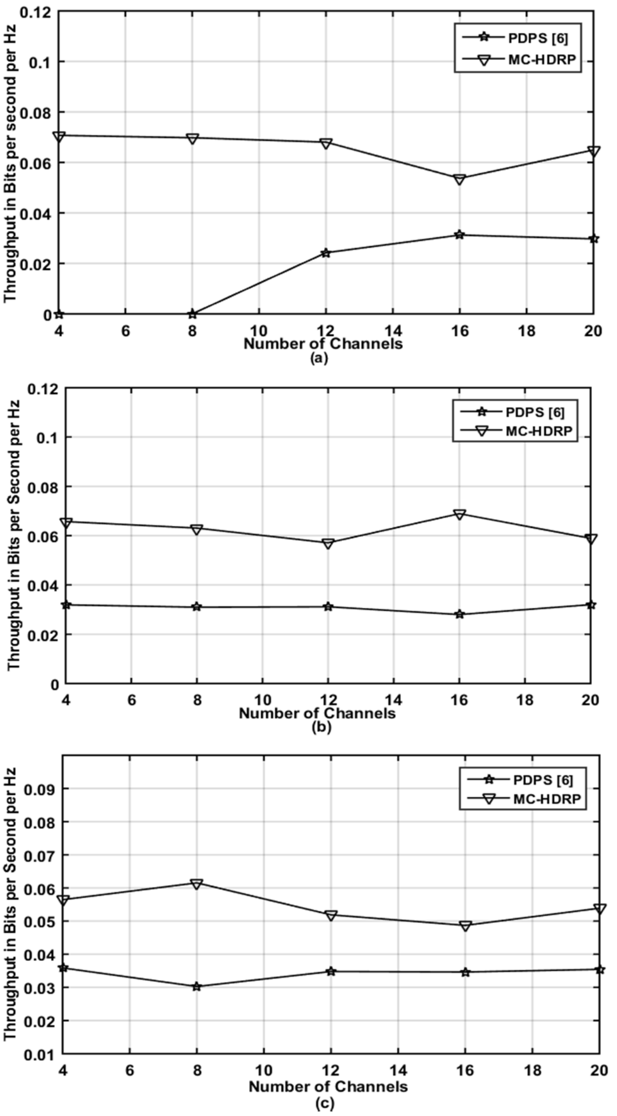

Figure 2 Discovery Throughput vs Number of Channels: (a) Idle Probability 0.1, (b) Idle Probability 0.5, and (c) Idle Probability 0.9

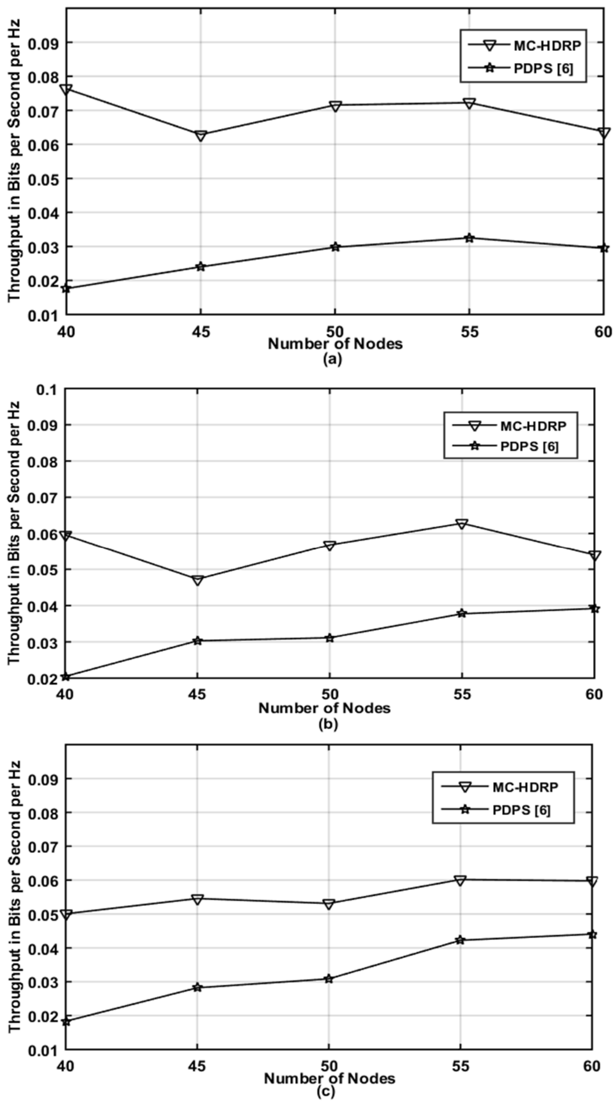

Figure 3 Discovery Throughput vs Number of Nodes: (a) Idle Probability 0.1, (b) Idle Probability 0.5, and (c) Idle Probability 0.9

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