Open Research Issues in Multi-hop Cognitive Radio Networks

S. Sengupta and K. P. Subbalakshmi

***Abstract*—Cognitive radio networks hold the key to achieving better radio bandwidth utilization and improving the quality of wireless applications. The next step in this fast emerging paradigm is the multi-hop cognitive radio network. Well designed multi-hop cognitive radio networks can provide high bandwidth efficiency by using dynamic spectrum access technologies as well as provide extended coverage and ubiquitous connectivity for the wireless end users. However, the special features of multi-hop cognitive radio network also raises several unique design challenges. In this article, we survey these unique challenges and open research issues in the design of multi-hop cognitive radio networks as well as discuss potential approaches to addressing these challenges. This article specifically focuses on the medium access control (MAC) and network layers of the multi-hop cognitive radio protocol stack. Issues considered include efficient spectrum sharing, optimal relay node selection, interference mitigation, end-to-end delay etc.**

***Index Terms*—multi-hop cognitive radio, dynamic spectrum access, spectrum decision, MAC-layer issues, network layer issues.**

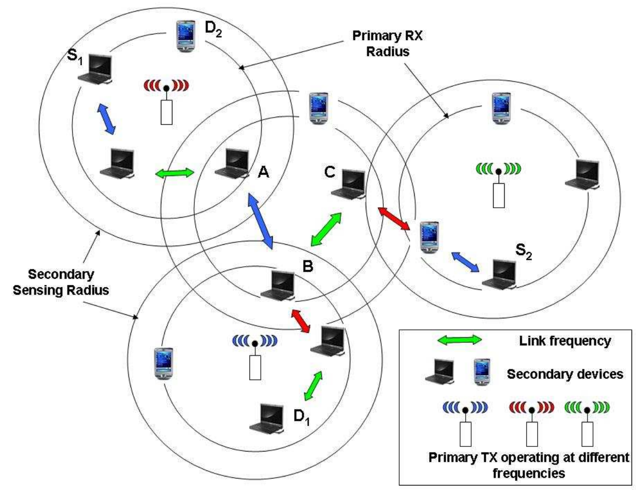

Fig. 1. Wireless multi-hop CRN

I. Introduction

With the ever increasing demand for new wireless services and applications, the need for spectrum is increasing exponentially in wireless networking. This increased need for bandwidth in some frequency bands coupled with under utilization in other bands has paved the way towards *Dynamic Spectrum Allocation* (DSA) policies for the use of radio spectrum in wireless networking. In contrast to the legacy fixed spectrum allocation policies, DSA allows license–exempt end–users (secondaries) to access the licensed spectrum bands when not in use by the licensed owners, also known as primary users (PU) of the bands. DSA is expected to enable more efficient use of frequency channels without impacting the primary licensees. Thus the Federal Communications Commission (FCC) recently defined provisions to open the sub-900 MHz TV bands for unlicensed services, provided that the secondaries pro-actively detect the return of and avoid disruption to the PU.

The newly proposed *cognitive radio* (CR) technology is anticipated to make DSA a reality. In its most general form, the CR was envisaged as an autonomous agent that perceives the user's situation and proactively assist in performing some tasks. Ideally in our scenario, the nodes in a cognitive radio network (CRN) will not only search for spectrum holes and use them when needed, but also act intelligently with enough co-ordination to enhance the overall system performance of the entire network.

Several layers of the *network protocol stack* will need to be enhanced to accommodate the additional functionalities of CRs. The physical (PHY) layer will need to sense for spectrum holes (scanning the spectrum and processing wide-band signals) and continuously adapt its operating power, spectrum band and modulation without human intervention. The medium access (MAC) layer must intelligently cooperate in sensing the spectrum and coordinate dynamic spectrum access. Subsequently, the network layer must be aware of several parameters gathered in the MAC and PHY layers to perform spectrum-aware routing.

Unlike infrastructure based networking, multi-hop point-to-point architecture can create wide-area CR back-haul networks where traffic can flow among the peers directly using relay/forwarding via multiple hops resulting in higher capacity, ubiquitous connectivity and increased coverage. However, currently, there is little understanding on how such a cognitive mesh architecture will operate so as to make the system feasible under DSA. Accordingly, the issues in the design of *multi-hop CRNs* must be better studied for the concept of CRNs to reach its full potential. An example multi-hop CRN is depicted in Fig. 1.

In DSA, the ability to switch between multiple frequencies allows better spectrum efficiency, and also lower radio inter-

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ference by simply switching to orthogonal frequency bands when needed. Hence a multi-hop CRN can (i) increase efficient spectrum utilization, (ii) reduce interference among users, (iii) increase network throughput through usage of multiple simultaneous packet transmissions on different channels, (iv) increase ubiquitous connectivity and (v) increase service area coverage.

However, without careful design of MAC and routing protocols specifically for multi-hop CRNs, the very features of these networks can turn into disadvantages. In this article, we study current open research issues in dynamic spectrum access and management in multi-hop, wide-area CRNs. We devote particular attention to the challenges arising in the *MAC and Network layer* and discuss potential solutions and directions that will further enhance the performance of multi-hop CRNs.

The rest of the article is organized as follows. In Section III, we present an elaborate discussion of the MAC and Network layer challenges in multi-hop CRN. The approaches to solving the MAC layer challenges are discussed in Section IV. In Section V we discuss existing solutions as well as new directions to solving the network layer challenges. Conclusions are drawn in the last section.

II. Cognitive Radio Networks vs. Multi-channel ad-hoc networks

CRNs based on DSA allows unlicensed secondary users to share licensed spectrum in time and space variant manner with minimal interference to PUs. Although the ability of multi-hop CRNs to operate over multiple spectrum bands gives the impression that these CRNs are similar to traditional ad-hoc networks with multi-channel support, in reality, there are numerous features that make CRNs unique. We describe these below:

- ***Dynamic availability of spectrum:*** The importance of protecting the primary transmissions from secondary CRNs (FCC primary-secondary spectrum etiquette) is a major unique criterion resulting in spatio-temoprally dynamic spectrum environment for the CRNs. Hence, the CR nodes may find the spectrum availability to be high at some time and place, and very low at another time in the same place. This is in contrast with traditional multi-channel ad-hoc networks, where the networks operate on a *pre-decided set of channels that remains unchanged over time*. Essentially, the choice of channels (single or multiple) is only impacted by self-coexistence constraints and not on the activity of an extraneous entity like the PU in CRNs.
- ***Wide rage of frequencies:*** The second point of difference is the potentially wide range of frequencies available to the CRN, which are envisioned to operate on a wide range of both unlicensed and licensed bands. Examples include the 54-862 MHz (noncontiguous TV and FM radio spectrum bands), and public safety bands in the 700MHz range (example: 764-776MHz and 794-806MHz) as well as 4.9GHz bands, 5GHz range bands.

  Also in traditional multi-channel ad-hoc networks, the number of supported channels is fixed and low (mostly less than ten or at most in the order of tens), whereas it ranges in the order of thousands for a CRN.

  In traditional ad-hoc networks, with pre-decided set of channels, nodes exchange information as necessary by periodic beacon messaging. However, in CRNs, with such wide range of frequencies and dynamically varying PU activity, it is not possible to beacon over all the channels, so coordination among the CR nodes is a unique challenge.
- ***Heterogeneity of radio frequencies:*** The varying physical propagation characteristics of electromagnetic waves over different spectrum bands is another concern for CRNs. A low frequency signal (e.g., 700MHz) can travel farther, penetrate walls and other obstacles but its information capacity is lower and the accuracy in determining direction of arrival is poorer. However, a higher frequency signal (e.g., 5.0GHz) can only travel a shorter distance, but will be able to carry more information and will exhibit better directionality. The diversity in spectrum bands and their policies for accessing them implies that the CR nodes must adapt their bandwidth, carrier, power and modulation techniques as well.

  This type of heterogeneity does not arise in the traditional multi-channel ad-hoc networks, where the allowable channels are generally from one spectrum band with similar physical characteristics. For e.g., the multi-channel IEEE 802.11 ad-hoc networks based on 2.4GHz spectrum band operates on 13 channels, although effectively 3 out of these 13 channels are orthogonal and can be used for simultaneous transmission without excessive interference. These channels possess similar propagation characteristics in terms of coverage, power management, modulation etc. The legacy radio nodes are statically configured to operate over these channels with fixed propagation characteristics and cannot operate on any other channel with different physical characteristics.
- ***Dynamically changing topology and incomplete information:*** As the ad-hoc networks lack any centralized controller support, the nodes in the ad-hoc networks must rely on their neighbors to gather topology information. In traditional ad-hoc networks, this is simply achieved by nodes exchanging beacon information periodically over the pre-defined operational channel.

  However, in the CRNs, as there are wide range of frequencies available dynamically, transmitting beacons over all possible channels is not a feasible solution. So the CR node is only able to gather incomplete information about the topology of the network. Moreover, the spatio-temporal dynamics of spectrum availability and heterogeneity in the available spectrum in CRNs bring in the additional challenge of dynamically changing topology based on PU activities. Hence traditional spectrum access solutions will not work in multi-hop CRNs. New solutions which adapt to the dynamic conditions of the network will have to be devised.

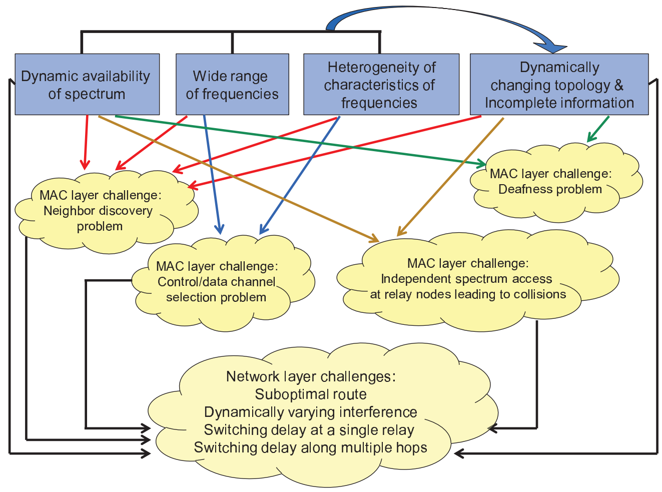


Fig. 2. Overview of design challenges in Wireless multi-hop CRN and how they are interconnected

III. Design Challenges in Multi-hop CRN

Although multi-hop CRNs have the potential to achieve efficient spectrum usage, interference mitigation, higher throughput and extended coverage, there are several open research issues in the design of multi-hop CRNs that need to be addressed first before they can be successfully deployed. Firstly, multi-hop CRNs face all the challenges that are inherent in single hop CRNs. For example, CR devices are inherently heterogeneous in nature due to diversity in wireless access technologies, user terminals, types of services and applications as well as the spectrum bands. Apart from these, multi-hop CRN design must deal with challenges that arise from the multiple hop nature of the communications. For example, it is not just sufficient to identify unused spectrum bands but to also regulate resource sharing (dynamic spectrum sharing/accessing) among all *flows* in the network and more importantly accomplish efficient *end-to-end* communication by establishing routing amidst the dynamically changing sets of cognitive relay nodes. Moreover, since PU transmissions must be protected, the biggest challenge for the CRNs is to enhance and ensure quality of service (QoS) of secondary networks themselves *without jeopardizing the PU's performance.* In what follows, we will address some of the open research challenges arising in the design of MAC and Network layers of a multi-hop CRN and how they are interconnected (Fig. 2).

A. MAC Layer Challenges in Multi-hop CRN

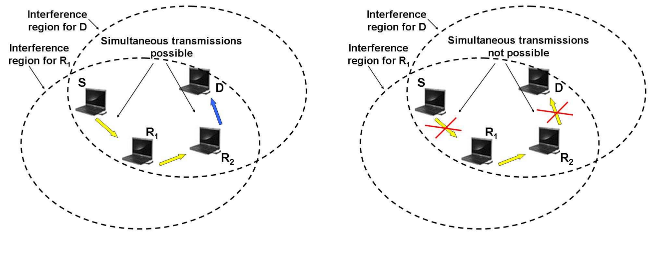
In a wireless multi-hop network comprising of CR-enabled devices, nodes can tune to different spectrum bands at any point in time. This varying channel activity gives rise to several MAC layer issues.

Co-ordination challenges in neighbor discovery: Neighbor discovery period is defined as the time taken by a node to discover its neighbor(s). Neighbor discovery is invoked when a node does not have any information about its "closest" neighbor(s) and needs to find a neighbor for transmission or information exchange. When a CR node switches on or moves to a new frequency channel, it performs *listen before talk* to detect the presence of the PU as well as nearby neighbor (relay) node(s) within its communication range in order to establish a route to the intended destination. Since it is possible for each node in the network to choose its own spectrum band, it is necessary for the given CR node to listen in the preferred channel(s) of *each* of the relay node(s). Hence the number of channels to scan can be potentially large. Moreover due to the dynamic nature of the configuration of a multi-hop network, the relay node(s) can switch channels even within the discovery period. A co-ordination policy that keeps the neighbor discovery period to a minimum is needed between the probing node and the respondents.

Heterogeneity in radio frequency ranges: The physical propagation characteristics of electromagnetic waves over different spectrum bands can be another concern for multi-hop CRNs. *Radio frequency range* is defined as the maximum distance up to which a signal can be transmitted and *successfully* received. As mentioned earlier, given constant transmit power, a low frequency signal can travel farther, penetrate walls and other obstacles but its information capacity is lower and directionality poorer, compared to a higher frequency signal. Thus transmissions on different frequencies will have different multi-path effects and attenuation resulting in heterogeneous radio frequency range. Also FCC regulates the maximum transmit power depending on the physical location of the frequencies in the spectrum band. These factors together imply that the selection of an *optimal relay node at the MAC layer now involves the selection of optimal spectrum bands as well* and hence becomes a multi-variable optimization problem.

Moreover FCC regulates the maximum transmit power depending on the physical locations of the different frequency channels in the spectrum band, which also contributes to the heterogeneity in radio frequency range. Thus the selection of *optimal* relay node(s), at the MAC layer also involves the selection of the best spectrum bands for control signaling and data transmission.

Deafness problem: Consider a CR source S_1, that wants to transmit to a destination node, D_1, using multiple hops as shown in Fig. 1. Upon detecting the presence of the PU, any or all of the relay node(s) can trigger dynamic frequency switching and move to a new channel. Let us assume that the relay node A forwards S_1's packets to relay node B using a spectrum band color coded blue in the figure. Suppose a primary TX now returns to the "blue" band near the relay node B, but outside the sensing region of A or S_1. B can detect the incumbent transmission in-band and will switch to a new channel. As A is outside the range of the primary TX, it can neither detect the primary, nor guess that a frequency switching has occurred resulting in the "deafness" problem. Hence A would continue to re-transmit the same packet several times, assuming packet loss due to unreliable wireless medium. Hence, synchronization is required in the channel switching protocols in the MAC layer to guard against the deafness problem.



(a) (b)

Fig. 3. a) Relay nodes accessing different frequency channels making simultaneous transmissions possible; b) Relay nodes accessing same frequency channels making simultaneous transmissions not possible

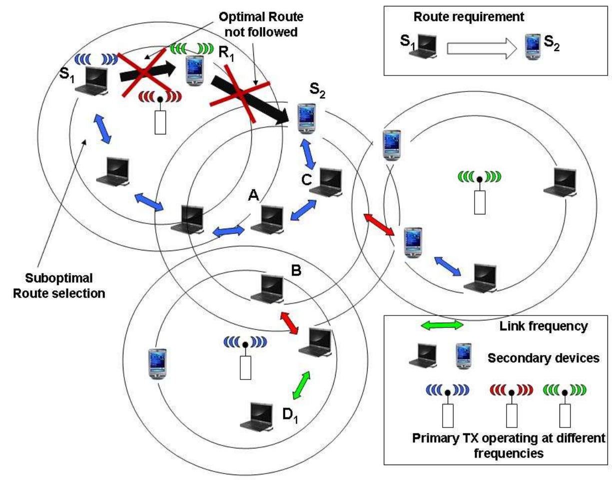
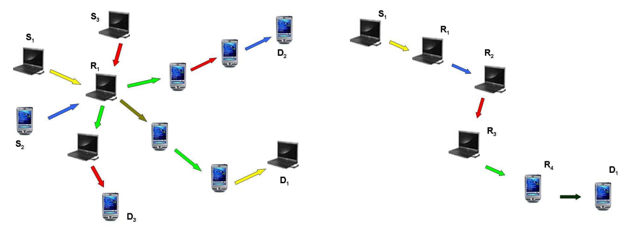


Fig. 4. Suboptimal path selection



(a) (b)

Fig. 5. a) Switching delay at relay node R_1 due to multiple communication flows ($S_1 \rightarrow D_1, S_2 \rightarrow D_2, S_3 \rightarrow D_3$): R_1 becoming bottleneck; b) Switching delay along one single communication flow due to multiple relay nodes operating over different frequency channels

Distributed spectrum access at relay nodes: Fig. 3(a) shows a communication flow from source S to destination D through the relay nodes R_1 and R_2. For simplicity, let us assume only two frequency channels are available for this CRN. Now if $S \rightarrow R_1$ and $R_2 \rightarrow D$ access different frequency channels (colored yellow and blue respectively), simultaneous transmissions can take place. However, if the relay nodes are allowed autonomous and independent channel access, there is a finite probability that both the communication links ($S \rightarrow R_1$ & $R_2 \rightarrow D$) will choose the same frequency channel leading to interference and subsequent failure of communication as shown in Fig. 3(b). As the number of multi-hop communication flows increases, there is likely to be an increase in number of links attempting parallel transmissions in a certain region and a simultaneous decrease in available frequency channels. This will lead to an increase in the number of failed transmission attempts. Thus it is clear that *distributed* MAC layer scheduling is necessary at the relay nodes in multi-hop CRNs.

B. Network Layer Challenges in Multi-hop CRNs

In conventional networks, whenever a new node switches on, it announces its presence by broadcasting beacons and listens to broadcast announcements (if any) from its peers on a single static frequency. In multi-hop CRN, generally, there is no pre-defined channel for the newly arriving nodes, which gives rise to several key routing issues that are unique to multi-hop CRN.

Suboptimal route selection: A major challenge for routing in multi-hop CRNs is the current lack of coordination between neighbor/route selection and spectrum decision. Unlike in traditional ad-hoc networks, the *optimal* CR node in the sense of transmission range (or delay) may not be the closest *functional* neighbor (relay) in multi-hop CRN. Choosing the closest node will result in suboptimal route for data forwarding in the multi-hop CRNs as depicted in Fig. 4. Thus, not only the distance between the source CR and the relay nodes, but also their operating frequency bands play a key role in deciding network connectivity. Depending on the presence of PUs, relay nodes will dynamically access and switch between frequency channels which will introduce dynamic routing even within the same topology. So the transmission/routing strategies will need to be coordinated with the spectrum decisions made at both the source CR and at the relay nodes in order to optimize routing decisions in multi-hop CRNs.

Varying interference: Traditionally, multi-hop routing requires finding the best signal-to-interference routes for communication before start of transmission. However, in a multi-hop CRN, the interference from the surrounding may vary rapidly throughout the communications as the CR nodes in the interference range change their band of operation dynamically and potentially rapidly.

Switching delay at a *single* relay node: In multi-hop CRN, if a single relay node serves too many communication flows *operating at different frequency bands*, it must constantly switch between frequency bands in order to serve all flows. Thus additional switching delay will be introduced at the relay node. This delay can become significant as the diversity of frequency bands across all communication flows increase, thereby making the relay node a *bottleneck* in the network.

As an example, node R_1 in Fig. 5(a) accommodates three different communication flows ($S_1 \rightarrow D_1, S_2 \rightarrow D_2, S_3 \rightarrow D_3$). R_1 relays flow $S_1 \rightarrow D_1$ by receiving packets on the yellow frequency and transmitting on the gray, flow $S_2 \rightarrow D_2$ by receiving packets on blue and transmitting on the green band and flow $S_3 \rightarrow D_3$ by receiving packets on the red and transmitting on green band respectively. This implies that to serve all three communication flows, the relay node R_1 has to switch between the yellow, blue, red, green and gray bands. Thus it is clear that delay at R_1 is dominated by switching delay. This frequency switching and re-synchronization causes data transmission to pause, thereby adversely affecting data throughput.

CR prototypes have been designed with sensing and switching times in the order of seconds [1] as well as tens of milliseconds [2]. Fig. 6 shows the effective throughput of the CR prototype built in [2] for varying switching intervals (1,2,3, 5 and 10 seconds) For benchmarking purpose, we calculate the ideal maximum throughout achieved under the same environment and conditions without any frequency switching (dotted line in the figure, maximum throughput 3.353 MB/second). As evident from the figure, with frequent switching, the effective throughput decreases.

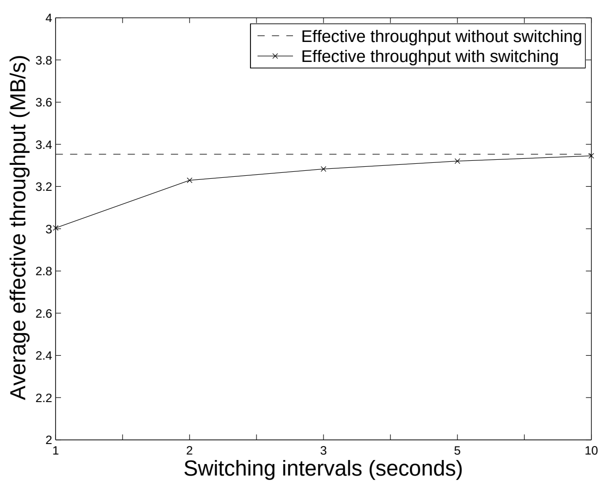


Fig. 6. Average effective throughput with various frequency intervals

Even with the very low switching time (of the order of milliseconds), this would be detrimental to the secondary networks' performance.

Although using multiple transceivers may potentially reduce the number of switching across communication flows at a relay node, it could be energy consuming and inefficient in terms of processing at the operating systems level because the operating systems of CR nodes are interrupt-driven. Also, having multiple transceivers in one radio device does not automatically imply concurrent transmissions over multiple channels.

Frequency switching delay along multiple hops: While the previous metric measured the delay at one single relay node, it is also essential to consider the cumulative delay incurred over all hops of a *single flow*. In Fig. 5(b) the complete end-to-end communication from $S_1 \rightarrow D_1$ employs five distinct frequency channels. To serve this communication flow, each of the intermediate relay nodes (R_1, R_2, R_3 and R_4) receives packets on one frequency channel, switches its transceiver to another channel and then transmits the packets out to next relay neighbor. The delay in this multi-hop communication is dependent on the cumulative channel switching delays at the transceivers along the flow. Hence routing protocols must aim toward minimizing cumulative delay along the entire path as well.

IV. MAC Layer Solutions and Approaches

In this section, we analyze several approaches to address the MAC layer challenges and present future research directions. Consider a generic multi-hop wireless network formed by a group of CR-enabled nodes (Fig. 1). The CR transceivers of these nodes can operate on any of the channels from the set of all available channels, $\mathcal{N}$. However, the set of available channels at any given time and space can vary depending on the primary's usage pattern. With this network model, we first discuss the approaches to address the MAC layer challenges. In next section, we present methods to overcome multi-hop routing issues.

In multi-hop CRNs, with all nodes accessing the spectrum bands dynamically and independently, some coordination among the nodes for neighbor discovery is necessary; otherwise the advantage of DSA would be offset by random and greedy access to frequency bands. A popular approach is to reserve one mutually agreed upon frequency band as the *common control channel* (CCC). When a newly arriving CR has data to send to a remote destination, it transmits control signal requests on the CCC for *discovering* neighbor (relay) nodes in the vicinity.

Pros: One or more relay nodes listening in the CCC will receive the control requests and reply to the requesting CR. In this neighbor discovery process and initial handshake, a common data channel available to both the transmitter and relay nodes is picked and both the nodes switch to the new channel to start data communication.

Cons: Multiple CR nodes attempting to capture the CCC simultaneously will lead to collisions resulting in delay. A multi-transceiver, multi-channel MAC protocol [3] was proposed to avoid this problem, using at least two transceivers (one dedicated for transmitting and the other for receiving) at each of the relay nodes. An available channel is chosen as the home channel (HCH), to which the receiver of the relay node's transceiver is tuned.

Pros: Relay nodes try to avoid sharing HCH with any of the neighbors within two hops for interference reasons and periodically broadcast their HCH information using the CCC. A newly arriving CR would perform *listen before talk* in the CCC to collect information about relay nodes in the vicinity. Upon discovering a relay node, the transmitter CR would simply tune itself to the HCH of the relay node.

Cons: Though this CCC based neighbor discovery is simple, using multiple transceivers at each of the CR nodes is energy consuming and inefficient in terms of processing data at each node (as explained earlier). Moreover, the CCC needs to be always available to all the CR nodes. In an opportunistic DSA scenario, the availability of the CCC itself may not be guaranteed over the entire network.

A possible solution is to identify a *minimum* set of control channels by each of the relay nodes which would cover all the neighbors of the relay nodes [4]. Control information can then be periodically broadcast over these channels by the relay nodes to advertise themselves. To mitigate energy consumption, a transceiver can always go to sleep mode when not transmitting.

As discussed in the previous section, different channels exhibit different physical characteristics of electromagnetic propagation thus making the frequency channels heterogeneous in terms of transmission which can potentially result in dynamically changing neighbor (relay) nodes. For example, suppose a relay node uses a low frequency (hence high range) CC. A transmitter CR in the multi-hop CRN may discover this relay node by tuning to the CC. Let us assume that the transmitter CR node and the relay node agree on a high frequency channel (lower range) for data transmission. It is now possible that the range of the data channel is too small for the relay node to be able to hear the transmission, causing a break in the route.

Cons: Route disruption due to heterogeneous transmission range will inevitably result in another cycle of relay node discovery process and loss of data packets.

A potential solution would be to use adaptive modulation schemes on different channels to equalize the transmission range of all frequency channels.

Cons: This, however, will imply that all channels will now operate at the shortest transmission range among the group of channels resulting in more hops per flow and consequently more delays.

This could be avoided by using low transmission range frequency channels for control signaling and handshaking, while setting aside higher transmission range channels for data transmission.

Cons: While this conservative approach will ensure that the route is not broken between the transmitter CR and the relay nodes for data transmission channels; potential relay nodes within radio hearing range on these frequencies may be missed. More work will be needed to determine optimal CC assignments that will result in the best over all network performance.

Changing availability of channels: To achieve high network throughput, all the CR nodes and communication links have to be assigned a combination of frequency channels such that interference is mitigated and maximum number of parallel communications can be accommodated, requiring coordination among nodes. The MAC layer scheduling problem for single-hop, single radio interface networks has been modeled as a distributed vertex coloring or edge coloring problem or a combination of the two [5], [6]. In the case of multi-hop networks, however, the problem is a little more complex since transmissions between nodes that are two or more hops away may also cause interference. Joint allocation of frequency channels and time slots would allow for efficient and more parallel transmissions than the MAC layer scheduling solutions that offer only time slot or channel assignment.

In [7], the problem of joint <timeslot, channel> assignment for multi-hop CRN is formulated as an Integer-Linear Program and a distributed heuristic for MAC layer scheduling is proposed. In the first phase of the algorithm, a node decides on its <timeslot, channel> tuple for all its outgoing flows. In the second phase, the information is propagated throughout the network. Using local topology information, nodes rank themselves based on one of three metrics (degree, channel set cardinality or a hybrid metric combining the two) and higher rank nodes obtain priority over acquiring <timeslot, channel> tuples over lower rank nodes.

Deafness Problem: Hidden incumbent (deafness) problem was first mentioned in IEEE 802.22 2006/2007 draft [8] and an “Incumbent Detection Recovery Protocol” (IDRP) was proposed to address this issue. However, the IDRP was proposed mainly for single hop centralized infrastructured CRNs where the core components are base stations (BSs) and consumer premise equipments (CPEs). A BS typically manages its own cell by controlling on-air activity within the cell, including access to the medium by CPEs. The IDRP was based on the use of backup (candidate) channels, information about which is entirely stored in the BS and periodically updated.

Cons: The IDRP cannot be directly applied to multi-hop ad-hoc CRNs as there are no BSs controlling the on-air activity and each CR acts independently and autonomously. Moreover, with the dynamic availability of spectrum bands and incomplete topology information, gathering and periodically updating information about candidate channels can cost too much in terms of CPU cycles. Also with the presence of various other PUs (TV, AM/FM, public safety radios), it is highly probable that two or more communicating CRs suffer from the deafness problem simultaneously but due to different PUs. A modified and more sophisticated distributed protocol must therefore be devised for channel switching. This is still an open area of research.

V. Routing in multi-hop CRN

As explained in the previous section, a myriad of challenges are caused by the ability of the CR nodes to dynamically switch between frequency bands. These challenges imply that the routing algorithms developed for multi-hop CRNs need to address issues that are not encountered in conventional wireless networks. Examples of the parameters (discussed in greater detail in Section III) that need to be taken care of include switching delay at each of the relay nodes along a communication flow, congestion/queuing/switching delay at a single relay node and the fluctuating interference in the surrounding areas. Note that this problem is inherently cross-layer in nature and calls for joint consideration of MAC layer scheduling and on-demand network layer routing.

Such cross-layer, on-demand routing algorithm coordinated with frequency band selection have been proposed in [9], [10] The routing protocols in the above mostly consist of three phases: *(i) MAC based multi-flow multi-frequency scheduling, (ii) on-demand routing and (iii) local coordination*.

Multi-flow multi-frequency scheduling: For any intermediate relay node acting as a gateway for multiple communication flows operating on different frequency channels, scheduling flow by flow would introduce unnecessary additional switching delays if a subset of flows use identical frequency bands. For example, let a relay node, A, forward data for two communication flows simultaneously. Suppose A receives the incoming flows on frequency channel f_0 while forwarding data on frequency channel f_1 and f_2 respectively for the first and second communication flows. Now, if A employs a flow by flow scheduling, it needs to switch frequencies three times: $\{f_0 - f_1 - f_0 - f_2\}$ to serve the communication flows in a round robin manner. It is possible to reduce the number of times the node switches frequencies by using a band-by-band scheduling approach [9], where each relay node processes all packets from flows operating on one frequency band at a time, thus avoiding additional switching delays. In our example, the new schedule would be $\{f_0 - f_0 - f_1 - f_2\}$, implying only *two* frequency changes.

On-demand routing: When a CR transmitter or any of the relay nodes decide on the next hop neighbor node for routing, control information needs to be exchanged to identify the number of communication flows at the intermediate relay nodes and the number of different frequency bands these communication flows are operating on. Depending on this information, switching and queuing delay at the bottleneck relay nodes are estimated and used to evaluate the route.

Local coordination: A local coordination mechanism is applied to every node in a multi-hop CRN. Depending on the number of communication flows and amount of service delays at the intersecting nodes, the local coordination helps decide whether to perform new flow accommodation or flow redirection to other relay nodes for fast optimization of routes.

The problem of varying interference in the CRN is not considered in the above protocol. Moreover, the proposed protocol uses the service delay (switching & queuing) measurement by each of the nodes for only the next hop neighbor in the entire communication path. This makes for a "greedy" approach and has the potential of ending up in a bad locally optimal solution. A communication flow with high service delay at each of the intermediate nodes but a smaller hop count may result in smaller cumulative delay at the intended receiver than the communication flow with small individual delays at each of the intermediate nodes and a large hop count. Thus instead of considering the individual service delay at each of the relay nodes, the optimal parameter for selecting best multi-hop routing in CRN would be to learn/estimate the end-to-end cumulative service delays along the hops. One may argue that in a distributed system, estimating all the hops is not possible and hence this leads to a trade-off between speed and optimality of the decision.

One possible approach could be to apply a gradual backward propagation of control information from the relay nodes to the source CRs to estimate the cumulative delay along the communication path. In such mechanism, each of the relay nodes would create a *vector of control information* locally which will consist of the perceived SINR along the incoming flows from the upstream relay nodes and locally coordinated information of routing metrics (e.g., switching and queuing delay at this particular relay node due to number of communication flows passing through it). This vector of control information coupled with similar control vectors received from the downstream relay nodes would then be propagated back to the upstream relay nodes and so on and until eventually it reaches the source CR. The source CR thus would have the complete estimate about the multiple routes through the relay nodes. Since the spectrum usage map of the CR nodes is dynamically varying, periodic propagation of control vector information would be necessary to update the source CR. Note that, this mechanism has several advantages in terms of dynamically locating high interference zones in a CRN and avoiding such zones. Moreover, as the source CRs would now have the periodically updated information about the network spectrum usage map, it will be easier to employ efficient minimum delay end-to-end routing and even to switch channels and change routes in case of PU arrival.

VI. Conclusions

This article investigated issues arising in the design of distributed multi-hop cognitive radio network with particular emphasis on MAC and Network layers. The major challenges in multi-hop CRNs include: distributed yet regulated spectrum sharing, heterogeneous radio frequency ranges, dynamically changing relay nodes, varying interference and switching delay at relay nodes. Some insights and potential directions towards enhancements to the existing MAC and multi-hop routing were proposed.

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