Multihop Cognitive Radio Networks: to Route or not to Route

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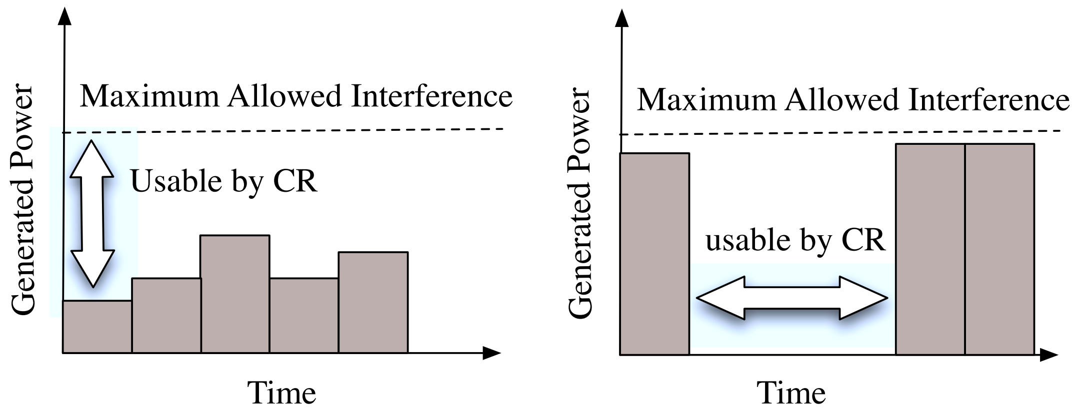
Abstract

Routing is a fundamental issue to consider when dealing with *multihop cognitive radio* networks. We investigate in this work, the potential routing approaches that can be employed in such adaptive wireless networks. We argue that in multihop cognitive radio environments no general routing solution can be proposed but cognitive environments can be classified into three separate categories, each requiring specific routing solutions. Basically, this classification is imposed by the activity of the users on the licensed bands that cognitive radios try to access. First, over a relatively static primary band, where primary nodes idleness largely exceeds cognitive users communication durations, static mesh routing solutions can be reused, whereas second, over dynamically available spectrum bands new specific routing solutions have to be proposed, we give some guidelines and insights about designing such solutions. Third, if cognitive radios try to access over highly active and rarely available primary bands, opportunistic forwarding without pre-established routing is to be explored.

I. Introduction

Research on Cognitive Radio Networks (CRNs) has been effectively launched since 2002 following a report by the FCC (Federal Communications Commission) [1]. The report challenges for the first time the common belief of spectrum scarcity by pointing that at any given time and in any geographic locality, less than 10% of the available spectrum is being utilized. The FCC also highlighted that a large portion of the licensed spectrum is used sporadically and that geographical variations in the utilization of licensed spectrum portions oscillates from 15% to 85% with a high variance in time. To exploit under-utilized portions of the spectrum, known as *white spaces* or *spectrum holes*, the report motivates the need for a new generation of smart, programmable radios that are capable of interference sensing, channel state learning, and dynamic spectrum access. In parallel, newly developed devices proved that this technology is physically feasible. Although still basic experimental prototypes, the devices published recently in [2] and [3] are the most typical examples. In the most common design considered today, *cognitive radios* (CRs) must transparently coexist with licensed users having obviously more priority on the licensed spectrum bands. In fact, CR can exploit the licensed bands either during the absence of their legacy users or by judiciously computing their transmission power in order to benefit from the underutilized portion of the spectrum. Both strategies (illustrated in Figure 1), should be carefully conducted, while avoiding any negative impact on the licensed users.

It is clear that an access control that gives optimal solutions in a single cell configuration may become largely inefficient in a multihop scenario. For example, an optimized MAC protocol may provide the best joint channel-power-rate assignment for a particular link, but such an assignment can be quite inefficient when considering the end-to-end path of a given flow possibly traversing several primary networks. Hence, the importance of finding appropriate cognitive multihop protocols capable of optimizing solutions over end-to-end paths. In fact, the issue in multihop cognitive radio networks is how to ensure radio resources for cognitive transmissions while guaranteeing the service for all ongoing Primary Radio (PR) communications over the exploited channels on the whole path. Besides, the number and the width of the "cognitively" used frequency bands can vary as required.



(a) Underutilization of the primary band

(b) Full utilization but with some variance in time

Fig. 1. Over a primary spectrum band, the total capacity of the band in terms of power (interference) at any geographical location can be either underutilized or exploited fully for a period of time then left without any activity for another time duration

The topology and the connectivity map of the multihop cognitive radio networks are determined by the available PR frequency bands and their instantaneous variations. More specifically, finding the appropriate path from a source node to a destination in a topology that evolves dynamically can be considered as a highly challenging problem. Moreover, with regards to the timescale imposed by the specific primary nodes behavior, an appropriate routing approach should be considered. The activity and the holding time of the exploited primary bands by the cognitive radio determines the routing solution to use. We classify the possible environment created by the primary nodes activity over the primary channels into three separate categories. Practically, these categories are defined by the employed primary technology on the channel over which the cognitive radios exploit the spectrum holes:

- Static: The holding time of the used primary band offers a relatively static wireless environment. From a cognitive user point of view, once a frequency band is available it can be exploited for an unlimited period of time.
- Dynamic: In a dynamic scenario, the primary band can be exploited by a cognitive user, however its intermittent availability seriously affects the service offered for a CR.
- Opportunistic or highly dynamic: If surrounding primary radio users are highly active, then the availability of such frequency bands for a whole communication duration becomes an unrealistic assumption. Therefore, a possible solution for CRs is to opportunistically transmit over any available spectrum band during the short period of the spectrum existence.

We detail and discuss in the following sections, respectively, these three categories of multihop cognitive radio networks and give insights on possible routing solutions in each of them. A particular stress is put on the dynamic primary radio environment, since it necessitates new multihop routing techniques different from existing paradigms employed today in multihop wireless networking.

II. Routing in Multihop Cognitive Radio Networks

Research on CRN has mainly focused on MAC and physical layers protocols. Since it is clear from previous studies (especially [4]) that cognitive nodes can relay on each others to form a heterogeneous network spreading across different Primary Radio Networks "cells" (Figure 2), multihop CRN can be constructed whereby CRs relay information between a CR sender and a CR receiver. This task becomes even more challenging because the cognitive radio domain still lacks for many defining rules and principles. Clearly, routing is the first issue to deal with in order to construct cognitive radio aware multihop networks however not much research has been achieved today in that area.

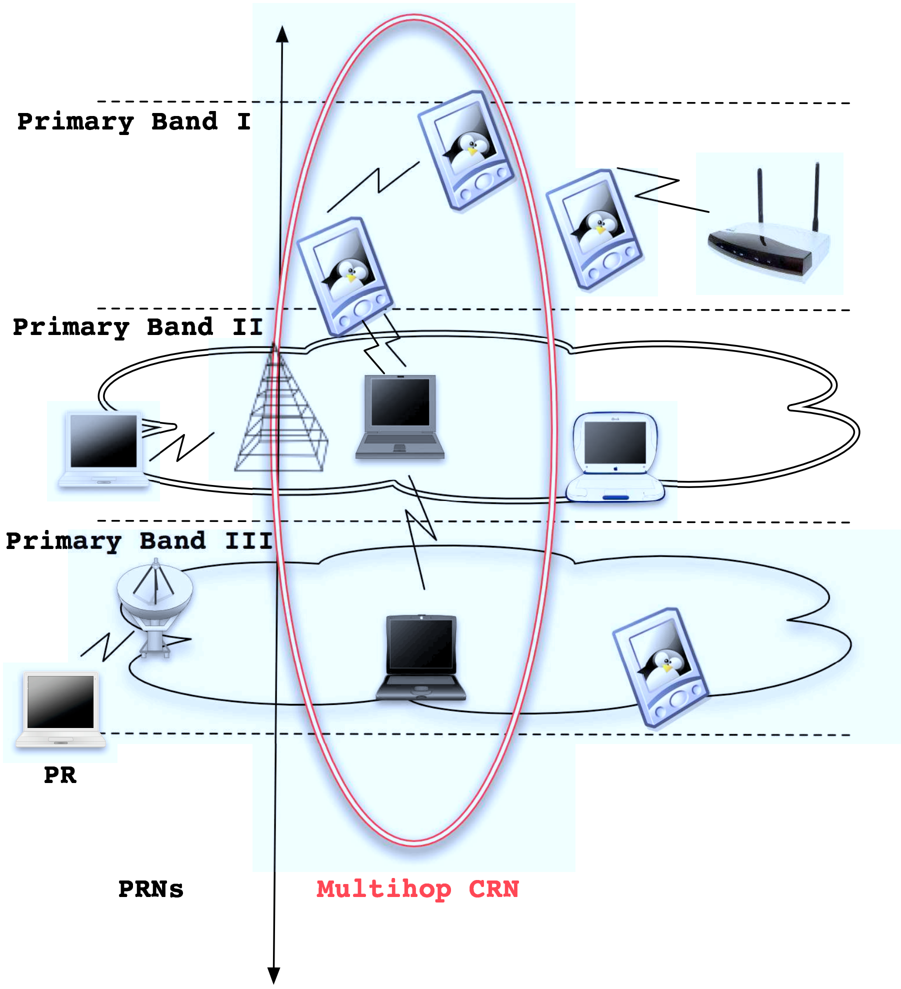


Fig. 2. A possible example of multihop CRN architecture and the interaction between primary radios and CRs

It is true that cognitive radio networks present some resemblance with multi-radio multi-channel mesh networks, however CR technologies add the new challenges of having to deal with transmissions over parallel channels and handling the PR-to-CR interference. Moreover, CRs possess physical capabilities that if efficiently exploited, allow them to sense, switch and transmit over many bands of the spectrum thus removing some physical constraints considered in previous wireless networks.

Nevertheless, if the primary spectrum band, once available, remains usable for an unlimited duration (counted in hours or in days for instance), the obtained network model does not differ in essence from any wireless environment considered today. In fact, the routing problem becomes very similar to the one defined and resolved in a multihop multi-channel mesh network. Besides, if the environment imposed by the primary nodes behavior gets more dynamic, then new cognitive specific approaches need to be proposed. Such dynamic routing approaches shall be used until the sporadic availability of primary bands becomes on average smaller than a (short) communication duration. Practically, this last dynamic environment requires per packet routing solutions since a path cannot be considered for a whole flow duration. Therefore, in such cases, an opportunistic forwarding approach based on the instantaneously available primary bands is a potential candidate to replace end-to-end routing approaches. Indeed, the overhead and the time duration required to establish a path for a short period usage make traditional routing an unthinkable solution. Similar approaches were explored in Delay Tolerant Networks (DTN) [5] where communications occur only when a physical contact with a neighbor is possible. However here, the forwarding opportunity for CRs is created by the spectrum bands mobility and not nodes physical movement and contact time as in DTN.

The three possible routing approaches are summarized in Figure 3, that shows that for every primary environment, an adequate routing solution has to be determined. However, how to define the boundaries that limit every approach applicability is a challenging task. For instance, selecting between a dynamic routing solution and an opportunistic approach in unstable environments is a hard decision to take. Intuitively, one can see that the undecided region that delimits opportunistic approach region and dynamic routing region can be large. Hence, selecting between these two approaches seems more tricky than between a dynamic and a static one when the availability period for a CR over a primary bands becomes larger.

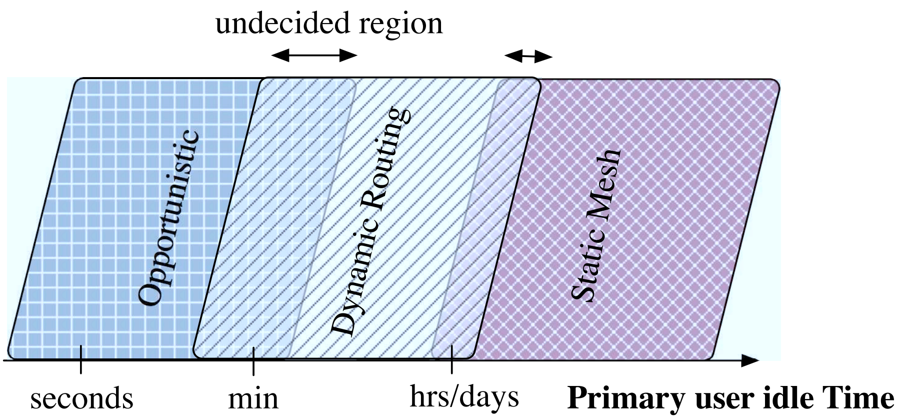


Fig. 3. The primary band holding time and its effect on routing in multihop cognitive radio networks

III. Static Multihop Cognitive Radio Networks

When a primary frequency band is available for a duration that exceeds the communication time, static wireless networking methods defined for ad hoc and mesh networking can be adapted for CRNs. In this context, a cognitive node considers an available frequency band as a permanent resource indefinitely available during its activity. Nevertheless, static wireless networking has attracted a huge amount of research during the last years thus many of its research problems were resolved. More specifically, many researchers have looked at routing and channel assignment in a multi-channel multihop mesh networks, they were able to derive optimal routing solutions depending on the traffic demands, the available channels capacity and the mesh routers position *i.e* the considered topology and traffic throughput.

Consequently, it is clear that static cognitive radio networks do not constitute a completely unexplored research area. In fact, the basic differences between mesh networking and cognitive radios are basically the dynamic and heterogeneous spectrum access and the physical capability to transmit simultaneously over multiple frequency bands. However in a static environment, the dynamic dimension of the spectrum band is reduced to statically available channels and moreover the physical capability of transmitting over multiple channels can only be exploited on similar almost static bands. Indeed, selecting an end-to-end path over both a static channel and a dynamic one may cause path instability problem since the failure of the dynamic spectrum band may cause the route to become inefficient. Naturally, a special consideration to the detection of new arriving primary nodes over the exploited bands and the reaction it should trigger has to be included in the routing design. So far, the latter problem is largely neglected in most of today's routing solutions.

Typical examples of a static cognitive radio network can be observed over a satellite or analog TV bands where the bandwidth occupied by the primary users in a geographic location allows for continuous CR activity over this channel. Or even, a GSM or CDMA base station in a rural area where an activity of a primary user in the vicinity is very scarce, can also create a static cognitive radio network.

Unfortunately, most of the work on multihop cognitive radio networks target primary bands with long holding times. Essentially, these works assume that primary channels properties are defined by the primary nodes operating over these frequency bands, however once a band is available it is kept accessible and its properties unchanged for the whole network life. Practically, [6], [7] and [8] are recently published samples. Clearly, such assumptions do not differ from the ones considered in multi-channel mesh networking. Here, in addition to the intra-cognitive nodes interference, the primary nodes interference (statically) produced on the considered channel is added and has to be accounted.

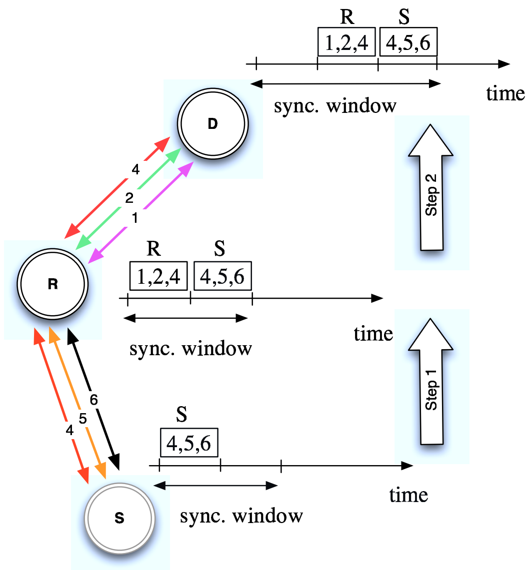
IV. Dynamic Multihop Cognitive Radio Networks

Designing routing algorithms and protocols for *dynamic* CRNs raises several new challenges. The issues are related to route stability, exchanging control information and channel synchronization. More importantly, in dynamic CRNs the first priority is for finding an *available* and *stable* path. Therefore, in order to select a stable path that achieves acceptable performance, an option can be to cumulate the achieved throughput over many bands on every hop of the path. So, even if a first ineffective channel is selected, it could be reinforced by other channels later. However, these selected channels must be *really* available and stable. Essentially, path stability can be ensured by including spectrum information in the path selection algorithm. This can be done by proposing routing metrics that capture spetcrum fluctuations and favor stable (less dynamic) spectrum bands over the unstable ones. Moreover, the computation must be quick and allows dynamic changes, thus a complex optimization algorithm similar to the ones existing in mesh networks is inappropriate.

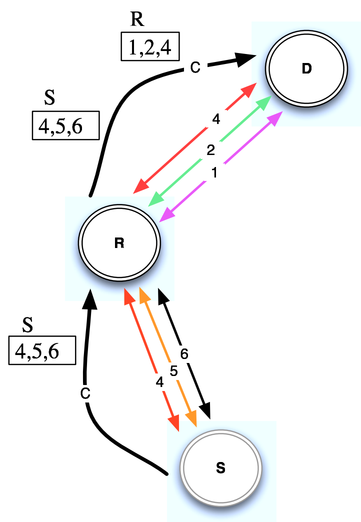
A. Conventional vs. Channel-aware Routing

The first question we discuss is whether *dynamic* routing in CRNs should consider the presence of multiple channels for parallel transmissions or the channel selection and the spectrum management should only be treated at the MAC layer. In the latter case, any proposed routing algorithm for wireless ad-hoc networks can be reused. In fact, the interaction between the MAC and routing layers should be carefully studied since the channel decision usually happens at the MAC layer whereas the path to the destination is obtained by the routing layer.

Selecting the channel by the cognitive MAC implies the selection of the next hop which means that different channels may lead to different neighbors. This could be optimized locally based on MAC related information to choose all next hops (at each hop) to the destination. But, the obtained paths may not be optimal for all flows in the cognitive network because the selection process considers only local information and lacks the global vision of the network. Moreover, picking a node as a next hop on a set of available channels may yield to a route that simply does not reach the destination. On the other hand, running the routing at the network layer while using a MAC layer feature as a routing metric, would lead to instability even if the constructed routes are optimal regarding to interference and transmission power. Here, any change in the MAC and physical environment (caused for instance by primary users activity) will initiate a spectrum handover and possibly a new route lookup. Furthermore, enhancing routing with a MAC layer information is a cross-layer technique that has a non negligible effect on overhead and complexity. A solution in between these two approaches is needed to trade-off between feasibility and stability from one side and reactiveness and complexity on the other side. A good compromise is to assist the routing by a metric from lower layers that remains usable for a long period of time. This metric should also reflect the spectrum availability and its quality. Probabilistic metrics as the one proposed in [9] constitute a valid approach.



(a) Using a synchronization window



(b) Using a control channel

Fig. 4. Conveying control information between nodes S and D using a synchronization window or a control channel. In both multihop scenarios a minimum delay is required so that the newly sent information becomes available for nodes located few hops away. The arrows and numbers identify the available frequency bands. D needs two steps to receive S's control information.

B. Control Information

In order to gather global information about the network (primary and cognitive), and follow its dynamic evolution, cognitive nodes need to exchange control information about the spectrum status and routing specific data. In the common configurations considered today, no feedback or interaction between cognitive and primary nodes is allowed, thus CR need to find intelligent techniques to convey control information without affecting first the primary nodes traffic and second the valuable resources (capacity) available for their data exchange.

Two approaches have been advocated for CRNs. The first is based on the use of a synchronization window. It consists of using a fixed time slot before every transmission where all the nodes are tuned to all the frequencies (or specific ones) and exchange all possible control messages. However, this method needs a centralized clocking between the nodes so that they can exchange the synchronization information in this precise time slot. Thus, the implementation of such mechanisms in multihop scenarios seems challenging.

The second approach uses a specific common control channel for exchanging control information. The control channel can be seen as a low frequency reserved band that can be sensed all the time by all the nodes in the network. More precisely, every node accesses the control channel periodically (or when needed) to update its related information carried on that channel. Clearly, this technique eliminates the synchronization problems that may arise from neighbors tuned to different channels. Moreover, the common control channel replaces the need of large scale broadcasts over multiple channels. Usually, the control channel is chosen to be a low frequency channel, if possible from the unlicensed pool, that covers long distances but on the other hand supports low rates. The challenges are to keep the size of information exchanged relatively low and to reduce the convergence time of the information carried on the control channel in multihop scenarios. For instance, if a node updates its profile on the control channel, the time needed until this new information is available for every node should be bounded.

Note also that before every single transmission at the MAC layer, nodes should go through a synchronization phase in order to make sure that both CRs sender and receiver, are tuned to the same channels. This can be also done using either the synchronization window or the control channel before every transmission depending on the employed technique. The control messages exchange process over a synchronization window and a control channel is shown respectively in Figures 4(a) and 4(b). Both figures highlight the fact that the delay required for the control information to reach all the nodes in multihop environments grows with the number of hops of the topology.

C. Routing Technique

It is clear that a proactive routing such as OLSR or DSDV, that requires time to converge and to build a network topology map, is not suited to the *dynamic* properties of the considered CRNs. Further, a choice should be made between a destination-based routing and a source-based routing approach. The first case necessitates a periodic routing table exchanges and potentially broadcasting Route Requests and Route Replies as it is done in many ad-hoc routing protocols such as AODV. These broadcasted messages could be initiated on all channels. An intuitive and better solution is to include them in the exchanged control messages over the control channel or during the synchronization window. Besides, if a source-based routing approach similar to DSR is employed, every node before starting a new communication, acquires the control information concerning all the nodes of the network from the control channel or the synchronization window. The node can then compute locally a path to the destination that also contains the channel assignment information without any need to flood the network with control messages. The advantage of source routing in CRN is in eliminating the need to construct routing tables and exchanging them (broadcasting on multiple channels) with the overhead required to maintain them. With a source routing algorithm, a node will forward a received packet based on the information written in the packet's header. Any dynamic routing approach should also consider in its design route recovery mechanisms as a mandatory feature. Such task is required to re-establish routes that fail due to primary nodes activity.

In the category of dynamic routing, few work has been accomplished. A routing algorithm based on a probabilistic metric that captures stochastically the PR behaviors was proposed in [9]. A hybrid approach combining static mesh routing and per packet dynamic routing was also proposed in [10]. Here, the authors first build a proactively a graph then adapt regularly their transmissions to the multihop network variations.

V. Opportunistic Forwarding in Multihop Cognitive Radio Networks

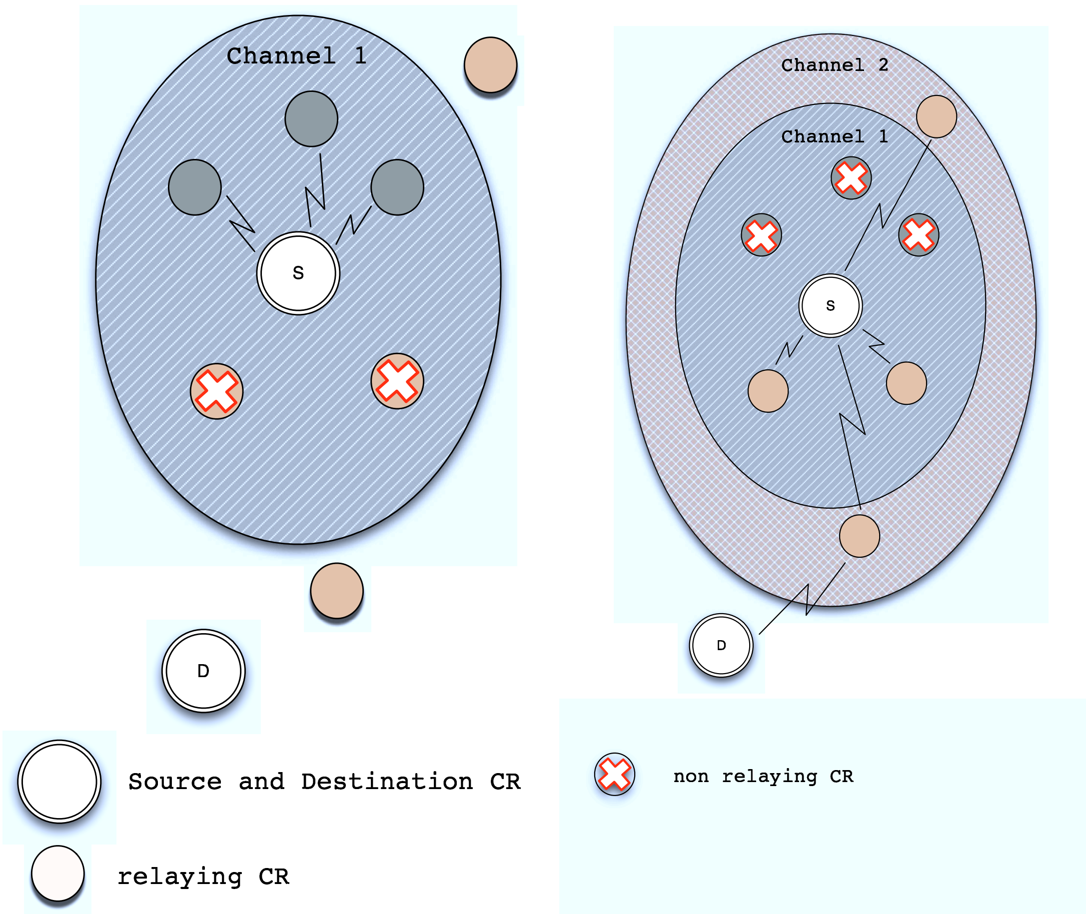
If the available time for a CR activity over a primary band becomes shorter than the time needed to undergo a communication by the cognitive radios over these bands, establishing a route for a whole flow is clearly an unthinkable solution. Furthermore, computing an end-to-end path cannot be considered, because in this scenario for every sent packet the network properties may change thus requiring a new path computation for every single transmission. This operation can be very heavy computation wise and control message overhead wise, even if a source routing is employed. Moreover, since the primary bands availability period is short, it is highly probable that once a path computation is achieved no data transmission can take place over the obtained path since the primary properties have already changed.

In such highly dynamic and often disconnected environment, every sent packet may be forced to follow a different path based on the primary bands availability. In fact, as shown in Figure 5, the exploited primary bands dictate the cognitive neighbors that can be observed on every channel. Therefore opting for a complete opportunistic solution, where every packet can be sent and forwarded over opportunistically available channels constitutes a potential solution. Such approach is even more interesting because the cognitive radio networks, through their intermittent channels availability, give immediate opportunistic networking possibilities (for free). Using this feature can reduce the complexity of establishing end-to-end routes and increase the efficiency of the proposed solutions. Very few researchers have looked at multihop CRNs under these assumptions. We give herein some insights and guidelines for future research in this direction.

A. Selecting Vacant Channels

In an opportunistic multihop CRN, the choice of the channels on which information should be forwarded is of a major importance. In fact, one may envisage first to select a number of vacant bands in a complete random manner. However, more intelligent techniques, that enhance such forwarding decisions can be considered. The approach based on history seems a good candidate. Clearly, the channels history can guide the forwarding decision in a way to increase the delivery ratio over already available spectrum. For instance, a spectrum band that has been unreliable for a long period of time still has to be avoided even if PR activity over it halted. One can also look on how history can be constructed and used to decide before every forwarding decision. Practically, on every channel a node can keep a history of the conducted actions and the achieved success rate.

Besides, history can contain implicit information of a major importance about the underlying topology and the network connectivity map. An interesting approach is to study how gathered information about primary nodes help enhance history



(a) Forwarding over unadequate frequency band

(b) Forwarding over a better frequency band

Fig. 5. Forwarding over two different channels in a multihop cognitive radio network. A different subset of receiver is obtained by selecting different radio bands.

information then forwarding decisions. Clearly, such constructed history should be capable to evolve based on users (PRs) behaviors and CRs activity and mobility. Furthermore how to combine gathered history data and how to dimension the history time intervals should be carefully defined.

It is worth saying here that this approach is different from the probability based approach already developed in [9] for routing in dynamic cognitive radio networks, since it chooses among the opportunistically existing channels the ones that have the best history regarding the information to be transmitted. Hence, the exact opposite of probabilistic approaches that selects only based on the probability (i.e. history). Other possible approaches for selecting opportunistically channel bands in multihop CRNs still to be defined.

B. Control Information and Synchronization

Practically, the potential forwarding techniques cited above still lack for basic aspects in order to fully operate in a cognitive radio environment. The previously defined principles are somehow known and were investigated in a DTN context. However, to operate in a multi-frequency environment and to exchange control messages, additional procedures need to be deployed. For instance, if unlicensed channels are not available, how to disseminate control information on sporadically available spectrum bands is still an open question and no research have already explored this aspect. Such control information can be related to a neighbor history and available channels or even topology information that can help to reach the destination of a sent packet. Particularly, the topology and the history information can be very helpful in increasing the delivery success ratio and lowering the delivery time in opportunistic environments. It is clear that neither a synchronization window nor a control channel can be envisaged in such opportunistic configurations. Indeed, the state of channels and in particular their availability can change while control informations are exchanged between cognitive nodes.

Besides, channel synchronization between a CR sender and the CR receiver becomes even more complicated when the spectrum band availability is shortened. In other words, if a forwarding opportunity for a CR sender is available, the receiver should be tuned to the same channel during this short time period. In fact, a transmission initiated without making sure that the intended receiver is listening on the same frequency bands and ready to receive, can cause data loss and valuable resource wasting. Here again, if the holding time of such bands is too short, no possible handshake is possible between the sender and the receiver. Consequently, in order to exploit opportunistic forwarding in multihop cognitive radio environment, two open questions still to be resolved. One needs first to find intelligent techniques to disseminate control information with minimum resource consumption and second, to synchronize the sender and the receiver once frequency bands that both can exploit become opportunistically vacant.

VI. Conclusion

Multihop cognitive radios is one of the most promising research area in already well explored wireless environments. A growing number of solutions targeting essentially routing and channel assignment in such environments are getting proposed by the research community. Nevertheless, no one has a clear vision on how multihop cognitive radios will look like and what is the time granularity the primary nodes will offer to cognitive radios communications. For this reason, we focus in this paper on multihop cognitive radio networks and on the routing solutions they can support.

Essentially, we categorize cognitive radio networks into three separate categories depending on the timescale of the primary bands idle time compared to the cognitive communication duration. In fact, if the availability periods of the primary bands is greatly larger than the CR exchanges, the created multihop can be considered as a static mesh. In contrast, if the primary nodes activity gets more dynamic, the resource availability for the CR becomes unstable, consequently new routing solution need to be proposed. Indeed, if the holding time of an available primary resource still allows a whole flow of a communications to be transmitted over the same bands, specially conceived routing solutions are to be envisaged. These solutions take into account the channel stability in their paths selection and spectrum assignment computation. Whereas, if the primary band availability becomes too short to convey a whole flow, per packet opportunistic forwarding is to replace end-to-end routing in such contexts. Optionally, forwarding solution advocated for Delay Tolerant Networks can be re-adapted.

Practically, it is not obvious which routing approach to use in cognitive radio networks. Clearly, the answer to this question depends on the environment in which the deployment of cognitive radios will take place. If cognitive radios will be exploited over well defined primary bands in terms of activity and holding time, a single routing approach of the three defined in this paper can be exclusively used. However, if cognitive radio implementation will offer more flexibility in terms of the available spectrum bands and their usage, the appropriate routing approach should be judiciously chosen first for every environment, depending on the traffic to carry and second based on the availability of the primary bands and their history in the considered environment.

REFERENCES

[1] FCC, “spectrum policy task force report,” *ET docket no. 02-155, November*, 2002.

[2] H. Rahul, N. Kushman, D. Kattabi, C. Sodini, and F. Edalat, “Learning to share: Narrowband-friendly wideband networks,” in *Proceedings of the ACM SIGCOMM conference*, 2008.

[3] H. Harada, “A small-size software defined cognitive radio prototype,” in *Proceedings of the IEEE PIMRC symposium*, 2008.

[4] I. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, “Next generation dynamic spectrum access cognitive radio wireless networks: A survey,” *Computer Networks Vol. 50, Issue 13, pp. 2127-2159*, 2006.

[5] K. Fall, “A delay-tolerant network architecture for challenged internets,” in *Proceedings of the ACM SIGCOMM conference*, 2003.

[6] G.-M. Zhu, I. Akyildiz, and G.-S. Kuo, “STOD-RP: A spectrum-tree based on-demand routing protocol for multi-hop cognitive radio networks,” in *Proceedings of the IEEE Globecom conference*, 2008.

[7] G. Cheng, W. Liu, Y. Li, and W. Cheng, “Joint On-demand Routing and Spectrum Assignment in Cognitive Radio Networks,” in *Proceedings of the IEEE ICC conference*, 2007.

[8] C. Xin, B. Xie, and C.-C. Shen, “A novel layered graph model for topology formation and routing in dynamic spectrum access networks,” in *Proceedings of the IEEE DySPAN conference*, 2005.

[9] H. Khalife, S. Ahuja, N. Malouch, and M. Krunz, “Probabilistic path selection in opportunistic cognitive radio networks,” in *Proceedings of the IEEE Globecom conference*, 2008.

[10] I. Pefkianakis, S. H. Wong, and S. Lu, “SAMER: Spectrum Aware Mesh Routing in Cognitive Radio Networks,” in *Proceedings of the IEEE DySPAN conference*, 2008.