A Distributed Network Coded Control Channel for Multi-hop Cognitive Radio Networks

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Abstract—Designing a solution for Multi-hop Cognitive Radio Networks poses several challenges such as the realization of the control channel, the detection of primary users and the coordination of secondary users for dynamic spectrum access purposes. In this paper, we discuss these challenges, and we propose a solution which aims at meeting most of them. The proposed solution is completely distributed, and does not need dedicated spectrum resources for control purposes, but rather it leverages on a virtual control channel which is implemented by having users exchange control information whenever they meet in a particular channel, using Network Coding techniques for better dissemination performance. Due to these aspects, our proposal represents a significant improvement with respect to existing Dynamic Spectrum Access and Multi-Channel MAC solutions. We discuss the effectiveness of our scheme in multi-hop Cognitive Ad hoc Networks, where secondary users need to opportunistically access the spectrum at those locations and times in which it is not used by primary users. Finally, we report the results of an evaluation study assessing the performance of the proposed scheme with respect to different system and scenario parameters.

I. INTRODUCTION

Most of the electromagnetic spectrum is assigned by government agencies to companies or institutions for exclusive use over regional or national areas on a long-term basis. As a result of this static allocation of resources, several portions of the licensed spectrum are unused or underused at many times and/or locations [1]. On the other hand, several recent wireless technologies operate in unlicensed bands, such as IEEE 802.11, Bluetooth, Zigbee, and to some extent WiMAX; these technologies have seen such a success and proliferation that the spectrum they are accessing – mostly the 2.4 GHz ISM band – has become overcrowded. In an effort to provide further spectrum resources for these existing technologies, as well as to allow the potential development of alternative and innovative ones, it has been recently proposed to allow unlicensed devices, called secondary users, to access those licensed spectrum resources which are unused or sporadically used by their owners, called primary users. This approach is normally referred to as Dynamic Spectrum Access (DSA), and the ability of radio devices to opportunistically find and exploit unused or underused spectrum bands is normally called Cognitive Radio (CR) technology [2].

Both DSA and CR have recently attracted significant attention from the wireless communications and networking community. Two main applications are commonly envisioned. The first is Cognitive Wireless Access (CWA), according to which a cognitive access point takes care of identifying unused licensed spectrum, and uses it to provide access to secondary users. The second application, which is the one we investigate in this paper, is Cognitive Ad hoc Networks (CANs), i.e., the use of unlicensed spectrum for communications among the secondary users themselves, for purposes such as peer-to-peer content distribution, environmental monitoring, safety communications in disaster recovery scenarios, military communications, and many others.

Designing a system for CANs presents more difficulties than for CWA, for two main reasons. The first is the identification of unused spectrum. In CWA the access point is by its role connected to the Internet, and therefore it can infer spectrum availability using simple strategies, such as querying the spectrum regulator for spectrum availability at its geographic location, or directly negotiating spectrum availability with the primary user or with some intermediary spectrum broker [1]. On the other hand, in CANs the lack of direct communication with the spectrum regulator or the primary users requires secondary users to be able to identify unused spectrum by themselves, using detection techniques. The second difficulty is the coordination of secondary users for medium access purposes. In CWA, the presence of an access point and the fact that commonly all secondary users communicate directly with it (i.e., the network is single-hop) makes it straightforward to use centralized MAC solutions, such as TDMA or OFDMA. On the contrary, CANs are expected to span over multiple hops, and to lack a centralized controller; while several solutions to this problem are known for traditional single-channel multi-hop ad hoc networks, it is not straightforward to reuse them for CANs, due to the fact that, assuming we deal with cost-effective state-of-the-art technology which allows devices to access only a limited portion of the spectrum at a time, medium access is to be performed across several channels, and moreover the actual channels which can be used for secondary communications might vary with respect to location as well as time.

Due to the two issues just described, several practical design challenges arise in CANs, such as the realization of the control channel, the coordination of secondary users for medium access, the implementation of a reliable scheme for the detection of unused spectrum, etc. In this paper we will
discuss these challenges, and we will show that, while in prior literature there are several good solutions which can effectively solve one or some of these issues, no proposal so far has been successful in meeting all of them.

After this discussion, we will present the scheme that we designed in an effort to overcome this lack of a complete solution for CANs. Our scheme is based on a virtual control channel which exploits the fact that users visit channels in a pseudo-random fashion and exchange control information whenever they happen to meet in any channel. Efficient dissemination of the control information to all users is achieved by means of Network Coding [3]. The control information exchanged by the users consists of all the information (such as bandwidth requirements, primary user presence and location, etc.) which is needed to determine channel switch patterns as well as resource allocation for data communication according to a pre-defined deterministic algorithm. We will discuss the performance of the proposed scheme by presenting and discussing simulation results which show that it is an effective solution for the practical realization of CANs.

II. TECHNICAL CHALLENGES IN MULTI-HOP COGNITIVE AD HOC NETWORKS

The first issue we encounter in CANs is a chicken-egg problem: secondary devices need to coordinate among themselves to perform spectrum access, but they also need to access the spectrum in order to communicate among themselves and achieve coordination. This issue is often referred to as the Control Channel problem, and unfortunately it is often neglected in work related to DSA. The fact is that most DSA-related publications focus more on the problem of primary user detection and/or efficient spectrum allocation, and in doing so they assume that some control channel implementation is available to secondary users.

For the practical realization of the control channel, some authors [4] propose to statically allocate some spectrum band. This practice presents two major issues: first, it requires static spectrum regulation, which is exactly what DSA aims at avoiding, and second, the chosen control band could easily become the bottleneck; this is especially true in multi-hop scenarios, where the need for control information exchange is potentially very high (e.g., not only for medium access, but also for routing purposes). Some other solutions have been proposed which attempt to solve the first issue by dynamically choosing an unused licensed band to perform secondary user control communications; however, the control bottleneck issue is not addressed by these proposals.

In our opinion, the most interesting way to solve the control channel problem is actually to overcome the need for dedicating a channel (i.e., a fixed portion of the spectrum) to control communications only. To some extent, this issue has been investigated in the context of multi-channel medium access for traditional (non-cognitive) ad hoc networks. In [5] the authors discuss a scheme according to which control information is exchanged in all available channels; this is done by having all users hop synchronously on unused channels while they are not transmitting application data. Other proposals [6], [7] follow the so called multiple rendezvous approach, in which every user has an associated channel hopping sequence to be used for reception, and senders synchronize on the hopping sequence of the intended receiver to perform transmissions. A comparison between different multi-channel access strategies in single-hop scenarios can be found in [6].

The peculiarity of the multiple-rendezvous approach is that it eliminates the need for a control channel for medium access purposes. A side effect of it, however, is that the hopping sequences are defined over a static set of channels, and therefore it is not straightforward to adopt this solution in Dynamic Spectrum Access scenarios, in which the set of usable channels varies with both location and time. Moreover, the above mentioned multiple-rendezvous strategies provide no means for the exchange of broadcast packets. Both traditional ad hoc routing strategies, and more recent ones such as [8] developed explicitly for CANs, require the availability of broadcast communication services in order to be implemented. As a consequence, implementing a routing solution over a legacy multiple-rendezvous MAC scheme is not at all straightforward. Still, multiple-rendezvous is interesting due to the fact that it mostly solves the issue of the control problem. For this reason, we suggest that extending the multiple-rendezvous approach to accommodate effective means for exchanging control information might yield a very good solution for CANs.

A first step in this direction was taken in [7], where the authors evaluate the effectiveness of performing broadcast communication for routing signaling purposes within a multiple-rendezvous MAC solution by just having users rebroadcast the control packets whenever they switch channel. The authors show that this broadcast strategy may not always be effective in reaching all nodes. This difficulty is exacerbated as the number of nodes and/or hops increases. Thus, in order to support effective and reliable dissemination of control signaling information, a more suitable solution is required. Of course, the ideal solution for CANs needs not only to address the issue of the exchange of control information, but also to effectively enable an efficient usage of the available spectrum resources. In this respect, it is to be noted that the multiple-rendezvous strategies that we discussed earlier were originally proposed as an extension to single-channel technologies, most notably IEEE 802.11; in particular, the advantage that was seen in these solutions was that, just by enabling the use of multiple channels, a significant increase in network capacity could be achieved with respect to the single channel case. However, it is to be noted that the capacity limit of multi-channel networks is still far from being reached by multiple-rendezvous schemes, which are more of a practical solution to the problem and do not take a systematic approach in maximizing the channel utilization efficiency.

One of the aspects which should be taken into account for an efficient usage of the spectrum is that in a multi-hop network typically only a subset of the users are in the interference range of a given user. This opens up the possibility of a higher spectrum utilization efficiency by means of frequency reuse. Unfortunately, in practice this requires more complex spectrum allocation strategies, as well as the availability of
more information (e.g., knowledge of the location of each user). Doing this in a distributed fashion is very challenging. Coupled with this problem is the issue of Link Scheduling and Routing: traditional ad hoc network routing strategies are not effective in multi-channel networks, due primarily to the fact that a given link cannot be activated at all times because of the requirement that both the sender and the receiver are on the same channel. Ideally, Channel Allocation, Link Scheduling and Routing should be jointly performed in order to maximize spectrum utilization efficiency as well as network performance. In this respect, some interesting solutions have been proposed [9], which however have the drawback of requiring a centralized scheduler. Given the nature of CANs, a distributed solution would be needed in order to allow their practical implementation.

So far, we still have not dealt with what is possibly the most peculiar trait of CANs, i.e., the fact that the identification of those parts of the spectrum which are suitable for secondary spectrum access must be performed by the secondary users themselves using sensing techniques. The topic of sensing from the point of view of a single secondary user has been intensively investigated in the recent literature, and several solutions have been proposed, from simple Energy or Matched Filter Detection to complex Cyclostationary Feature Detection techniques. However, as discussed in [1] for the case of unlicensed access of TV spectrum, the requirement of maintaining secondary interference to primary users below a certain threshold translates into a sensitivity requirement for single-user detection strategies which is so high that it is not cost-effective, if not completely impractical, to implement such detectors with current technology.

For CWA, thanks to the fact that the cognitive access point is by its role connected to the Internet, a straightforward solution is to adopt alternative strategies for the identification of reusable spectrum, such as the consultation of a database reporting available spectrum by geographic location, or explicit negotiation with the owner of the spectrum or with an intermediary spectrum broker. However, for CANs the situation is much harder, since Internet connectivity cannot be assumed to be available. A possible solution to overcome the strict sensitivity requirements is to exploit the use of cooperative detection techniques. Two are the main factors that make these techniques more effective. The first is that, thanks to the fact that more sensing data is available, a better sensing performance can be achieved. The second is that the sensitivity requirement can be softened due to the multi-hop nature of CANs. In fact, the stringent requirement on single user detection sensitivity is motivated by the need to provide a significant margin to overcome the hidden primary user problem, but if the detection is based on sensing data gathered by several secondary users at different locations, it is more likely that at least some of the secondary users will receive a clear signal from the primary user, and therefore a softer sensitivity can be allowed.

Several cooperative primary user detection strategies have been investigated in recent literature, such as [10], and could possibly be exploited for the design of a CAN solution. However, it is to be noted that most of these studies were carried out while dealing with neither multi-channel medium access nor control channel issues. Therefore, we can conclude our discussion of the challenges in CANs by noting that, while several solutions have been proposed in the recent literature to jointly address one or a few of these challenges, no solution so far has been proposed which attempts to address all of them. In the next section we will describe our own attempt at providing such a solution.

III. A SCHEME FOR DYNAMIC SPECTRUM ACCESS IN MULTI-HOP COGNITIVE AD HOC NETWORKS

We consider the case in which each secondary user has a single transceiver, and thus can be tuned only on a single channel at any given time. We have a set of secondary users, and a set of channels available for unlicensed access. In order to design a spectrum access scheme which is effective in this scenario, we need to solve the following two problems: 1) how to make secondary users coordinate among themselves, and 2) how to assign spectrum resources to these users in an efficient way. As we discussed in the previous section, most prior work in this area addressed only one of these problems; by contrast, our approach aims at solving both problems simultaneously.

Intuitively, the spectrum allocation and transmission scheduling is best performed using knowledge about the particular communication needs (e.g., Quality of Service requirements) and spectrum availability (e.g., expressed by primary user detection information) of all the users. We will refer to this knowledge as the control information, obtained by collecting the control packets generated by all users. In the literature, most of the times in which the complete control information is used for resource allocation purposes, a centralized scheme is assumed. This means that there is a centralized controller which gathers the control packets generated by all users, determines the global resource allocation, and then tells each user what resources to use for data communications.

In order to derive a distributed approach, we choose a different strategy: each user gathers the complete control information, and independently determines for the whole network the resource allocation. The key point is that if the same control information is successfully disseminated to all users, and if the resource allocation algorithm is deterministic, then each user will be able to determine the same resource allocation, without any further interaction among users. This is the underlying principle of the multi-channel scheme that we first presented in [11] for single-hop multi-channel networks, and that we discuss here for use in multi-hop CANs. In the rest of this section we will provide more details on how our scheme works in general; the rest of this paper will focus more in particular on multi-hop and opportunistic spectrum access issues.

For our scheme, we assume that time is divided in allocation periods of a pre-determined duration. Each allocation period is divided into slots of equal duration. The interval corresponding to each slot is further divided into two sub-intervals: the first is reserved for the transmission of application data by one or more selected users, and the second is used by all users to exchange control information. Both data and control
transmissions in a given channel are performed using TDMA with a pre-determined schedule. Moreover, in every slot, each user will tune to one of the available channels according to a pre-determined channel switch pattern. For a given allocation period, both the channel switch pattern and the TDMA schedule are determined using scheduling algorithms whose output is a deterministic function of the control information gathered in the previous allocation period.

At the beginning of an allocation period, each user generates its control packet; subsequently, in every slot, all the users which happen to be in the same channel will exchange control packets. The objective of this process is to disseminate to all users the needed control information. We require the channel switch pattern to have pseudo-random properties, so that the dissemination of the control information is possible to all nodes with high probability after a sufficient number of slots. At the end of an allocation period, each user will have retrieved the control information, and will use it to run the deterministic scheduling algorithm. This way, each user will be able to determine the channel switch pattern and transmission schedule that will be followed by all users in the next allocation period. The overall process is represented in Figure 1.

The exact nature of the control information is determined by the particular scheduling algorithms which are chosen. As an example, in [11] we discussed a relatively straightforward algorithm for uniform resource allocation in single-hop networks. This algorithm only needs knowledge of the set of users participating in the allocation, and of the seed for the random number generator which was used to determine the pseudo-random channel switch pattern. As a consequence, the control information packets generated by each user consisted only of a unique identifier for the user (e.g., its MAC address) and of a random bit string which was used, together with the bit strings by all other users, to determine a common seed for the random number generator.

An important requirement for our scheme to work properly is that the dissemination of control information reach all users. Whenever a particular user fails to retrieve the control information at the end of an allocation period, that user will potentially determine a wrong channel switch pattern and transmission schedule for the subsequent allocation period, possibly starting transmissions using resources (transmission slots in certain channels) which were meant to be allocated to other users. In the rest of this article, we will refer to this event as spectrum collision, and we will refer to the users that failed to retrieve the control information as misinformed users. In general, the chances of having a spectrum collision, and hence the average amount of wasted spectrum resources, increase with the number of misinformed users. For this reason, we want a dissemination scheme in which the retrieval probability $P_{\text{retr}}$, i.e., the probability that a generic user successfully retrieves the control information from all other users, is high.

The issue of how to disseminate control information in our scheme is somewhat related to the more generic problem of performing broadcast communication in a multi-channel system. This is still an open issue, since previous work on multi-channel medium access had very limited support for broadcast. As an example, in [7] the authors achieve this by just having all users transmit their own control information whenever they switch on a particular channel; this is not efficient, as it requires that either a flooding technique is used, which has a very high overhead, or that the transmitting user meets all other users in some channel at some time, which means that the dissemination process will last very long, and would not work in multi-hop scenarios.

We propose the use of Network Coding in order to implement a reliable and efficient dissemination scheme for the control information. Network Coding is a recently introduced paradigm for data dissemination, according to which the packets generated by multiple sources are jointly coded at intermediate nodes, and decoded at the final destination. This coding strategy can be very effective in increasing throughput, reducing delay, and enhancing robustness. In order to have a practical implementation of network coding we refer to [3], where the authors proposed a distributed scheme for network coding which obviates the need for a centralized knowledge about the encoding and decoding functions, and, at the same time, allows asynchronous data exchange between nodes. According to this approach each node stores all incoming packets in an internal buffer and transmits an encoded packet which contains a random linear combination of all packets in its own buffer. At transmission time this packet is forwarded to all nodes situated within transmission range. Now, if the encoding vectors are generated randomly and the symbols lie in a finite Galois field of sufficient size, then the information will be disseminated to all users with high probability [3]. Based on this approach, every time a node receives an encoded packet, it has to know the coefficients used to perform the encoding, in order to recover the original information packets. A simple solution consists of appending within each encoded packet the corresponding encoding vector that describes which linear combination of information packets it contains. This way, the encoding coefficients needed to decode the information stored in encoded packets can be found within the encoded packets themselves. Any node can thus recover the information packets generated by all nodes simply by inverting the matrix that
stores all the coefficients of the packets received during data dissemination. Appending the encoding vectors to the packets incurs an additional overhead, which will need to be accounted for in the determination of the total control overhead of our dynamic spectrum access solution; for a detailed discussion of this issue, the reader is referred to [11]. Finally, in order to have a practical implementation of network coding, we adopt the buffering model and the concept of generation which were also introduced in [3]. In our case, a generation is confined within an allocation period, and at transmission time each node sends a linear combination of the control packets in its own buffer.

As we discussed in our prior work [11], Network Coding vastly outperforms other strategies for the purpose of disseminating the control information in single-hop multi-channel networks. In other words, the use of Network Coding in conjunction with a pseudo-random channel switch pattern provides us with a virtual control channel, which allows users to efficiently share control information. This network coded virtual control channel is robust against packet losses and link failures, and most importantly does not require the presence of static spectrum resources dedicated to the exchange of control information.

As for the detection of unused spectrum resources suitable for secondary access, we note that the network coded control channel is naturally fit for the implementation of a cooperative primary user detection solution. Given that all secondary users already switch over all available channels in a pseudo-random fashion for control information dissemination purposes, it is possible for them to carry out a comprehensive primary user detection just by using a signal detection technique whenever they switch channel. The detection information by all users is then disseminated via network coding together with all the other control information, so that every user can independently run the same cooperative detection algorithm in order to determine the available spectrum resources. As a consequence of the dissemination of detection data, a huge amount of information can be fed to the primary user detection scheme, which can therefore lead to a significant improvement in performance with respect to what a single secondary user could achieve. Thanks to this feature, it is possible to adopt simple and relatively poor performing techniques, such as Energy Detection (ED) [12], which contributes to making the realization of cognitive devices more cost-effective.

To better illustrate how the proposed scheme works, we consider the scenario depicted in Figure 2. Figure 3 shows the channel allocation obtained for one allocation period. As can be seen from the figure, the secondary users communicate with each other in all those channels which are not occupied by primary users transmission, enabling spatial and frequency reuse.

IV. Performance evaluation

A. Control Information Dissemination in CANs

In order to provide an efficient dissemination of the control information our scheme has to assure a high retrieval probability with the lowest possible number of slots. In [11] we showed that in single-hop scenarios with no primary users our scheme significantly outperformed other legacy schemes. Unfortunately, the presence of primary users at some frequencies and locations affects the effective dissemination of control information, which is crucial for our DSA scheme to work. The reason is that, in order for primary user detection to be effective, each secondary user needs to tune periodically into all channels in order to perform detection attempts. Clearly, only those channels in which it is inferred that no primary user is active will be used for data communications. For this reason, the degree of connectivity of the CAN decreases as primary activity increases, and this makes dissemination more difficult.

We hereby describe the simulation study we performed using Matlab, with the aim of quantifying these issues and understanding in which conditions our solution is practical. In our simulations, secondary and primary users are randomly placed in a 500 m × 500 m square area. The parameters we vary in our simulations are the number of primary and secondary users, and the number of hops in the network of secondary users, which is defined as the minimum number of hops needed for secondary users to transmit a packet along the diagonal of the square area. The transmission range of the secondary users is adjusted to obtain the desired number of hops; i.e., the transmission range is obtained as $500 \sqrt{2} / H$ m, where $H$ is the number of hops. The interference range of the primary users, i.e., the range in which secondary access is not allowed, is set to 1.5 times the transmission range of the secondary users. In all simulations, we use a total of 10 channels, some of which cannot be used by secondary users at some locations due to the presence of primary users. We assume that primary users do not change their transmission channel during at least an allocation period. The results presented in this section have been averaged over 500 random topologies per set of parameters.

In Figures 4 and 5 we report the number of slots required to have $P_{\text{retr}} = 0.95$ versus the number of hops and the number of primary users, respectively. We observe that the scheme is robust in most cases, although it is to be noted that when
the primary users occupy most of the available channels, the number of slots needed to provide a high retrieval probability increases significantly. Despite this, it is still possible to retrieve all the needed information even in cases where almost all channels are occupied given that the number of slots inside an allocation period is large enough.

We also note that our proposed scheme scales well with the number of secondary users, achieving successful dissemination with a reasonable number of slots even in the very challenging scenario where 9 out of 10 channels are occupied at some locations by primary users, and 40 secondary users are accessing the remaining bandwidth opportunistically. The behavior of the scheme in scenarios where the primary users use only a fraction (up to 60%) of the available channels is of particular interest, as is expected to be common in real scenarios. In these cases, the proposed scheme provides a high $P_{\text{retr}}$ with a significantly lower number of slots (roughly one third) with respect to the worst case. Finally, it is to be mentioned that we also repeated the same experiments using the dissemination scheme in [7] instead of our network coded control channel solution. Even with an allocation period of 500 slots, this choice resulted in an almost zero $P_{\text{retr}}$ in all scenarios, which is of course not adequate for data dissemination in multi-hop multi-channel networks.

### B. Goodput performance

In [11] we derived the goodput performance of the scheme in a single-hop scenario taking into account spectrum collisions due to misinformed users and the additional overhead introduced by the control information exchange. Following the same approach we can derive the achievable goodput in the case of multi-hop networks as well. In this case, in order to calculate the goodput achievable by a given node, it is sufficient to account for spectrum collisions only due to misinformed neighbors. Moreover, the goodput is normalized over its maximum possible value for a given neighborhood, which is equal to the minimum between the total number of channels available, $C$, and half the number of secondary nodes in the neighborhood. Based on these considerations equation (6) in [11] has been modified accordingly.

The resulting performance is reported in Figure 6 for $C = 10$, $N = 40$ and $T_{\text{all}}/T_{\text{ctrl}} = 6000$, where $T_{\text{all}}$ is the duration of the allocation period and $T_{\text{ctrl}}$ is the duration of a control packet transmission. In general, the goodput decreases as the number of hops in the network increases. This is because as the number of hops increases the number of slots needed to assure a high $P_{\text{retr}}$ increases significantly. This degradation is especially high when the secondary users are sharing the spectrum resources with 9 primary users, that is only 10% of the spectrum resources is available for secondary data exchange. Note that, even in this worst case, the scheme is able to assure network connectivity. On the other hand, the performance is very good for a small number of hops, as the dissemination process is always successful, and therefore provides all the required information for correct channel selection. In this case the slight goodput degradation is due to the overhead introduced by the scheme for control information exchange.
Fig. 5. Number of slots required for a retrieval probability of 0.95 vs number of primary users in a 10 channel, 7 hop scenario.

Fig. 6. Goodput performance vs number of hops, for different number of slots $S$ and of primary users $P$. $C = 10$ channels, $N = 40$ secondary users.

Note that the increase of the number of slots has a twofold influence: on one side, the fewer slots per given allocation period, the greater the maximum achievable goodput in normal conditions as the control information overhead is reduced; on the other side the scheme suffers in heavy conditions (high number of primary users and number of hops) as the number of slots is not sufficient to effectively disseminate control information during the allocation period.

V. CONCLUSIONS

In this article, we discussed the main challenges that arise in Cognitive Ad hoc Networks, and presented a practical solution to these challenges which is based on a virtual network coded control channel. We presented simulation results that proved how it can achieve effective dissemination of control information and efficient spectrum utilization in several scenarios. Our solution was shown to be robust against primary user activity and scalable with respect to the number of secondary users. Future research directions include the integration of more elaborate spectrum allocation, transmission scheduling and routing strategies in the proposed solution.

ACKNOWLEDGEMENT

The work at the University of Padova was partially supported by the European Commission through the ARAGORN project (FP7 ICT-216856).

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