Practical Distributed Channel Selection Protocol for single-hop Transmissions in Cognitive Radio Ad Hoc Networks

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ABSTRACT

In this paper we propose a practical distributed channel selection protocol for cognitive radio ad hoc networks considering single hop transmission. The proposed protocol uses the control channel in order to exchange information concerning the available data channels and also to establish communications. The channel selection is performed based on weights that are assigned to the channels. Each time a node receives over the control channel a message for which it is not the destination; it updates the weight of the channel included in the message. This methodology allows nodes to become aware of the distribution of the load over the different channels and therefore to perform channel selection in such a way that channel congestion is avoided. Moreover, the proposed protocol specifies a mechanism which uses sorting based on channel weights with the goal of reducing the sensing effort whenever this is possible. Simulation results show that the proposed protocol is up to 80% more efficient in terms of delay when compared to an algorithm that neglects the current load of channels and which allows nodes to randomly select one of the available channels. Moreover, the results show a relevant decrease in the average number of scanned channels.

1. INTRODUCTION

The non-efficient usage of the spectrum showed by the different measurement campaigns in the framework of the actual static spectrum management has lead to increasing interest for Dynamic Spectrum Access (DSA). The low efficiency in the static spectrum management is due to the hard and long-term constraints on spectrum assignment and allocation [1]. The new paradigm of DSA adds more flexibility that leads to a more efficient use of the spectrum.

One of the most active and prominent DSA approaches is the Opportunistic Spectrum Access (OSA) where secondary networks or cognitive radios have constrained rights to access licensed bands assigned to a primary network. One of the fundamental requirements for allowing secondary networks to use opportunistically licensed bands is that the impact of the secondary activities should not degrade the performance of the primary network. In order to avoid harmful interference to primary users all secondary users must perform spectrum sensing [2] before transmitting, such that they only transmit when primaries are not detected. The implementation of cognitive radios is now possible especially due to the advances in the Software Defined Radio (SDR) technologies that allow the radio to dynamically change several radio parameters such as modulation, frequency band and power using software [3].

The spectrum bands that are allowed to be accessed by a secondary user are called spectrum holes for this user. Based on sensing results, each cognitive radio can identify a list of spectrum holes that can be used while respecting the primary constraints.

Focusing on the case of ad-hoc networks of secondary users where there are no central units for managing spectrum allocation, the establishment of communication between two secondary users faces - in addition to spectrum holes detection - two main problems: spectrum handshake and internal interference management.

The problem of spectrum handshake involves the process of finding a mutually usable/available set of frequencies/channels[1] between two secondary users that need to communicate and the agreement between the two involved users on which channel(s) to communicate. Since the existence and the characteristics of spectrum holes may vary in time and space, the spectrum handshake is a challenging problem. One of the major approaches followed in the literature for dealing with this problem is to use a common control channel where the spectrum handshake negotiation is performed [4]-[6]. Over this common control channel, a pair of secondary users exchanges information on the channels that they have sensed to be idle. If mutually available channels are found the two users reach an agreement on which of those should be used. One option is to allow the communicating pair to “bundle” channels and transmit on all of those while the rest of the nodes are differed from accessing the channel. However, when this is not possible each pair of nodes should select one of the available frequencies to transmit to. In this case and also considering CSMA/CA based radios, frequency selection by secondary users will severely affect the performance of the secondary network, since the number of secondary users assigned to each of the available frequencies will determine the total network throughput.

In this paper, we propose a practical distributed frequency selection protocol that facilitates the establishment of communication in one-hop ad-hoc cognitive radio networks

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[1] Hereinafter the terms channel and frequency will be used interchangeably.

providing increased efficiency of spectrum usage inside the ad-hoc network. The proposed protocol uses the control channel to exchange information about the available frequencies between the cognitive radios in order to enable the latter to autonomously choose the suitable bands that respect primary constraints and also keep the load of the secondary ad-hoc network well balanced over the available frequencies.

2. Assumptions and Problem Formulation

In cognitive ad-hoc networks, there are two main problems:

- Identifying spectrum holes in time and space.
- Frequency selection for cognitive transmission.

In this paper, we assume that the identification of spectrum holes is performed using perfect sensing mechanisms. The availability of a frequency is assumed to be known for all cognitive nodes and therefore, we don't consider the problem of interference between primary and secondary networks. Moreover, we consider that all secondary nodes have the same pattern of channel availability (i.e. when a channel is available for a given node it is available for all nodes).

The first problem in this paper is to design an algorithm that integrates an initial handshaking without the mutual knowledge of the available channels in the transmitter and the receiver. The second problem is to find the best frequency selection methodology that avoids congestion while the signaling traffic and algorithm complexity are kept at acceptable levels.

The algorithm is described in a scenario where a licensed part of spectrum can be divided into *n* channels that can be used opportunistically by the secondary nodes and a control channel is always available at a fixed frequency. Channel availability is modeled using a two-state Markov chain as it is shown in figure 1. The channel that is considered as available for secondary access is represented by the IDLE state and the one that is considered to be not available by the BUSY state. We assume that each channel has a different pattern for state changes. The probability that a given channel transits from IDLE state to BUSY state is p, while the probability that a given channel transits from BUSY state to IDLE state is q. Then, the average channel availability can be written as [4]:

$$a = \frac{q}{p+q} \tag{1}$$

3. Related Work

The development of decentralized MAC protocols and frequency selection algorithms for cognitive radios is an active research domain. In recent papers [4]-[9], we can find different approaches to handle the frequency selection problem with the availability of multiple channels.

In [4], a cross-layer based opportunistic multi-channel MAC protocols is proposed for wireless ad hoc networks. The protocol requires the existence of two transceivers on every device: one for exchanging control channel information and one for data transmission. The control channel is used to exchange the state of the licensed channels and to negotiate transmission in those channels that are sensed idle. When a cognitive radio gets a permission to transmit, it uses all the available licensed channels for transmitting its data. The main drawback of this approach is the synchronization constraints.

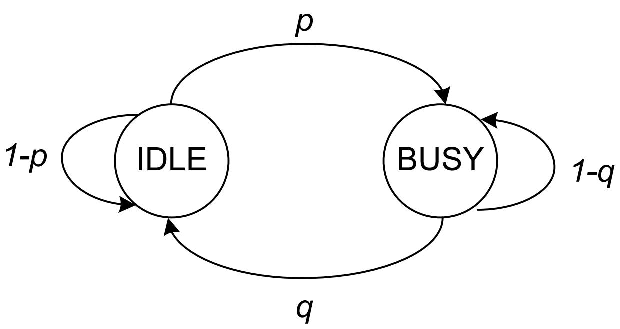

Figure 1. The two state Markov chain model for channel availability.

In [6], the authors propose an analytical framework for a Decentralized Cognitive MAC (DC-Mac) for ad hoc networks. Their approach is based on Partially Observable Markov Decision Process (POMDP). The main idea is that the frequency of sensing and accessing a channel is selected based on sensing history and channel usage statistics. However the synchronization problem remains a challenge for the implementation of this approach.

In [7], the dynamic open spectrum sharing (DOSS) MAC protocol has been proposed. However, the protocol requires three separated radio transceivers to operate on the control channel, data channel, and busy-tone channel, respectively.

In [8], the authors propose a CSMA/CA-based cognitive MAC protocol using statistical channel allocation where the cognitive radios select the channel that has the highest successful transmission probability to send packets based on statistics about the primary activity over the licensed channels. The negotiation to select the channel and the parameters of transmission is performed in a control channel for each packet transmission. The main drawback of this algorithm is the computational complexity for determining the successful transmission probabilities, since this complexity increases quickly with the number of licensed channels.

A multi-channel MAC is proposed in [9] where an ad-hoc cognitive network opportunistically accesses to the licensed channel of a GSM network. This approach has limited applicability though, since it is designed to operate only with a specific primary technology.

For each data packet transmission, most (if not all) of the approaches mentioned above require that a negotiation for frequency selection is performed over the common control channel. This however leads to high overhead in the control channel and may also cause unnecessary delays. As it will be shown in the following sections, in our proposed algorithm the access to the control channel is performed only in the case of establishing a new connection/communication session or when primary access is detected and the secondary users must renegotiate for changing to another (free) frequency (if one is available).

4. Protocol Description

The main objective of the proposed algorithm is to find an efficient way for frequency selection for secondary transmission. The algorithm is distributed and only requires the presence of a common channel that, to the authors' best knowledge, is the only feasible solution for the first handshaking between the transmitter and the receiver [4]-[6]. Therefore, each secondary node should have two transceivers. The first transceiver is equipped with an SDR module that enables spectrum mobility and the use of the *n* channels. This transceiver is used to exchange data packets. The second transceiver is used to monitor the control channel and collect the required information for performing frequency selection.

In the proposed algorithm, we need to define *n* counters C_f for each node, where *f* is the index of the channel. For a given frequency *f*, C_f represents the number of nodes using this frequency. Moreover, each node has a set *F* of available frequencies (those that are sensed as idle).

The access to the control channel is based on CSMA/CA protocol. Moreover secondary nodes that share the same data frequency will use this protocol to avoid collision and data loss. However, other multiple access techniques can be also used for spectrum sharing.

The control channel is used by a node in one of the following five cases (see figure 2):

- A node wants to initialize a new connection with another node. In this case the Select Frequency (SF) control message is sent and a timer is triggered. It contains the identities of the source and the destination, the proposed frequency and an empty field that corresponds to the previously used frequency. The two last fields are used to update the C_f counters. If no confirmation is received from the destination after the expiration of the timer, the proposed frequency will be eliminated from the set of available frequencies and a new frequency will be selected.
- A node receives an SF message and it is the destination of this message. If the proposed frequency is available, this node will confirm the availability of the proposed frequency using the Confirm Selected Frequency (CSF) message that contains the proposed frequency. Otherwise, no message will be sent.
- A node is transmitting its data on one of the data channels and gets interrupted by the appearance of a primary user. The node will halt its transmission, wait for a backoff time, perform the scanning process and send a new SF which contains the identities of the source and the destination, the proposed frequency and the previously used frequency.
- A node has ended its data transmission. It will send a Release Frequency (RF) message to notify every other secondary node that it releases this frequency. This message contains the frequency that has been used for the data transmission in order for all nodes that are listening to the control channel to update their counters.
- A node receives an RF message and it is the destination of this message. It will reply with a CSF message to confirm the release of the frequency

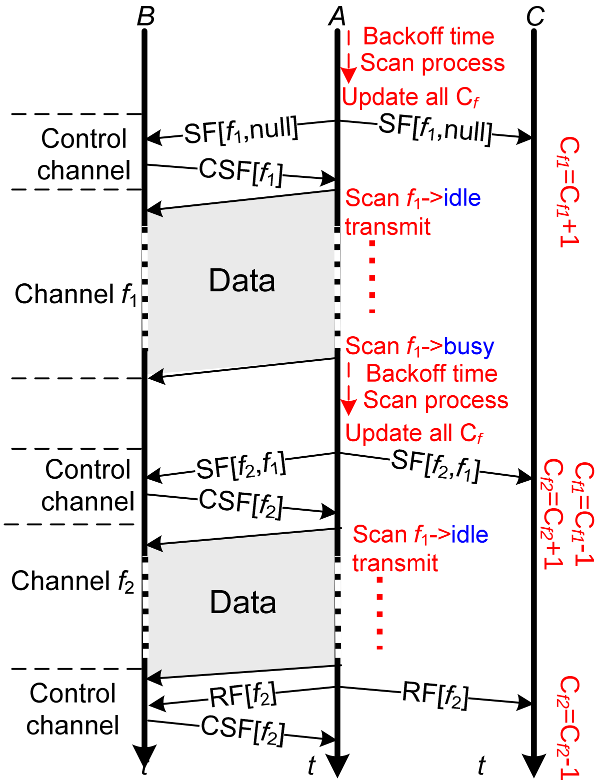

Figure 2. Illustrative Example of the protocol

When a node receives an SF and it is not the destination, the counter corresponding to the first frequency is increased by one and the second one, when it exists, is decreased by one. Moreover, if it receives an RF and it is not the destination, it decreases the counter that corresponds to the frequency. The node will set to 0 any counter that has a negative value that may happens due to lost SF or RF messages. The value of the counter reflects the number of neighboring secondary nodes that are using the corresponding frequency. Therefore, the node will attempt to choose the frequency with the lowest counter in order to avoid frequency congestion.

In order to determine the available frequencies out of the set of the *n* licensed frequencies, our protocol can use two possible algorithms. With the first algorithm called Full Scan (F-Scan) a node will scan all the frequencies before transmitting each packet. The node will then select that available frequency with the least load in terms of secondary users (the value of its counter will be the least among all the values of counters for the available channels). With the second algorithm called Sorted Scan (S-Scan) the node first sorts the *n* frequencies with an increasing order of their respective counter values. Then, the node will scan these frequencies one by one until it finds an available frequency, which will be chosen for transmission. This will decrease the number of scanned frequencies. In turn, also the sensing time and the energy consumption will be decreased. A short note on the process is that if the counter of a scanned frequency is higher than 0 and the frequency is found to be not available, the counter is set to zero. This mechanism corrects the errors originated from the possible loss of RF and SF messages and can be used only in the case where all secondary nodes have the same pattern of frequency availability.

5. Simulation Results

In order to evaluate our proposed protocol we have used the ns-2 simulator. We have simulated a network comprising of 60 non-mobile nodes located in an area of 250x250 square meters. Our protocol was implemented as a modification of the standard 802.11 model with a rate of 2Mbits/sec for each channel, including the common control channel. The total number of channels is set to 30. The total number of nodes is 60. At each point of time a node can be either a receiver or a sender. Receivers accept connections from one sender each time, and also senders do not initiate communications with more than one receiver at the same time. During a simulation run, each node pair establishes 40 communication sessions, each of which involves the transmission of 10.000 packets with a rate of 200 packets per second (the size of a data packet is equal to 64 bytes). As stated earlier we assume that the primary usage for each frequency is given using a Markov model. In order to evaluate our proposed algorithm under a variety of channel availability patterns (in time), we examine 4 different cases of average channel availability (30%, 50%, 70% and 90%). According to the existing studies on primary activities, frequency availability in time can vary in this range depending on the spectrum band under study (and also the location) [10]. Moreover, we consider two different scenarios where the values of probabilities p and q are changed in order to see the impact of the frequency of changes in the channel availability on the performance of the algorithm. The values of p and q for the two scenarios are depicted in table 1.

Table 1. Parameters of the two scenarios

	p	q			
Channel availability	30%-90%	30%	50%	70%	90%
Scenario 1 (S1)	0.08	0.186	0.080	0.034	0.008
Scenario 2 (S2)	0.16	0.373	0.160	0.068	0.017

Using the aforementioned settings, we simulate our proposed protocol (evaluating it for both F-Scan and S-Scan) and perform comparisons with a protocol which neglects the current secondary use of the data channels when performing channel selection. In this later protocol, called Blind Selection - Random Scan (BSR-Scan), each node starts to scan randomly one by one the n channels until it discovers the first available channel which is immediately chosen for the node's transmission.

In figure 3 we present the achieved delay per packet using our protocols (F-Scan and S-Scan) versus the BSR-Scan protocol under the two aforementioned scenarios. Actually the F-Scan and S-Scan differ only in the number of scans that they perform but since for both algorithms the least loaded available channel is selected for transmission, the achieved per packet delay is the same. Since both in F-Scan and S-Scan a node uses the counters which are updated by overhearing the common control channel the node selects (almost always[2]) the least loaded channel, thus managing to keep the per packet delay low. The obtained results also show that the BSR-Scan protocol cannot achieve load balancing especially for the cases of low to medium average channel availability since with this protocol the nodes select one of the available channels randomly. This leads frequently to unnecessary congestion in some channels while at the same time other available channels are underutilized. However, the BSR-Scan behaves better (as was expected) in terms of per packet delay with increasing availability of the channels. This is due to the fact that as more channels become available (while keeping traffic constant) random selection becomes less harmful since it becomes less and less likely that the same channel will be selected by many nodes. The difference between the results for the two scenarios is that the random selection of channels seems to be more sensitive to the frequency of changes in the channel state in terms of primary user activity, while less sensitivity to the primary usage pattern is observed for our proposed protocol using F-Scan or S-Scan.

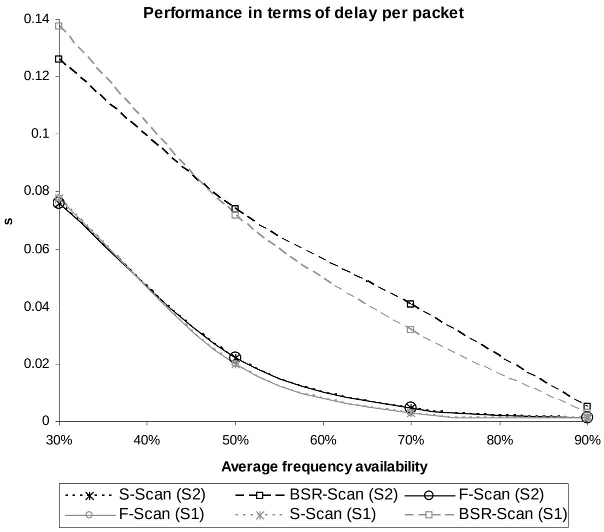

Figure 3. Performance in terms of delay per packet.

In figure 4 we show the percentage gain in scanning effort of S-Scan and BSR-Scan compared to the F-Scan algorithm. In F-Scan when a node detects that it can no more use a channel, due to a primary that starts transmission on it, it always scans all the channels before selecting the new channel (if any is available) to transmit to. Results show that for the given primary access pattern there are no high gains in scanning efforts from using S-Scan or BSR-Scan under scenario S1. This is due to the fact that the used pattern specifies that the channels which are busy by the primaries will most likely remain busy through the lifetime of one data transmission session. In such a case the node senses that the channel that it was already using for the previous data packet is still available and thus does not need to scan again for finding a

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[2] In case that a node misses some control packets, its counter may not reflect the current load accurately. However, this is corrected by resetting counters to zero when a node detects that a channel with a positive counter is not available any more due to the presence of a primary.

new frequency. In this case the total number of scans is dominated by the cases of single scans of the already used frequency that is performed for every new packet that a node wants to transmit during a communication session. However, in scenario S2 (as shown in table 2) the primary usage pattern specifies that on the average channel state changes twice as fast compared to the pattern specified in scenario S1. In this case we observed that also the gains from using S-Scan and BSR-Scan increase. Tracing our simulation data we found that this trend is due to the fact that each secondary node is forced to scan for a new frequency more times during the lifetime of a session. Hence the dominance of single scan for each packet becomes less and less in the total amount of scans since it is now less possible that a secondary node can find the channel that it was using for the previous packet transmission as being still available. As explained earlier this means that the node, besides scanning the previously used channel (which is no more available), should start the scanning process (S-scan, F-Scan or BSR-Scan) and perform an additional number of channel scans in order to find the available channel.

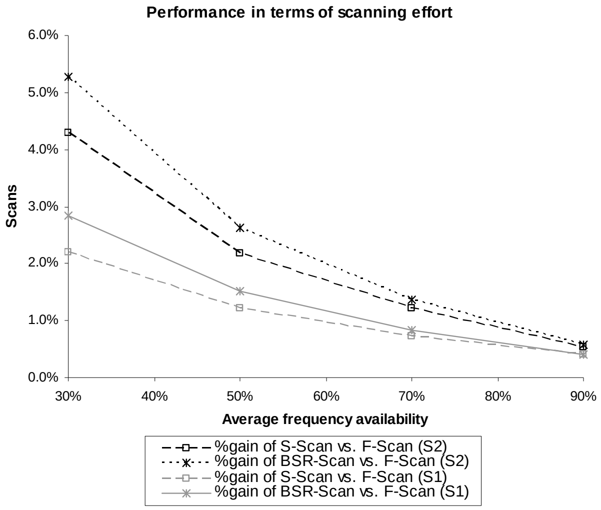

Figure 4. Performance in terms of channel scanning effort.

6. Conclusions and Future Work

In this paper we have presented a Practical Distributed Channel Selection Protocol for single-hop Transmissions in Cognitive Radio Ad Hoc Networks. The proposed protocol is designed to achieve load balancing in a secondary network by giving the appropriate information (through a common control channel) to each node in order to select the least congested available channel to transmit its data. It has been shown through simulations that the proposed protocol can achieve up to 80% less per packet delay compared to a protocol that neglects the available channels' current load in terms of secondary usage.

In our future work we plan to implement our proposed algorithm into a real-life testbed. Moreover, we plan to extend our simulation based evaluation by implementing additional channel selection protocols that are based also on in-band common control channels. Finally, we plan to enhance our proposed protocol by adding QoS-based thresholds to assist the channel selection process.

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