Cooperative Spectrum Sensing in Ad-Hoc Networks
(Invited Paper)

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Abstract. Spectrum sensing is a distinct feature of cognitive ad-hoc nodes that have the ability to opportunistically use vacant spectrum bands for its own communication purposes. Possible cooperation among the nodes may prove vital for increasing network performance. It yields the cognitive ad-hoc nodes to exchange relevant environmental and context information in order to enhance its own networking experience. This paper overviews the approaches, techniques and strategies for cooperative spectrum sensing and gives a practical example of a realized testbed implementation in an ad-hoc environment.

Keywords: spectrum sensing, cooperation, cognition, ad-hoc networks, RAC^{2}E.

1 Introduction

Ad-hoc networks represent temporary network structures formed whenever two or more wireless nodes exhibit a need for exchanging information [1]. They differ from traditional structured networks in terms that every ad-hoc network participant must be able to act as a potential router of information for other nodes. This opens the possibility for implementing various cooperation methods among the wireless nodes in ad-hoc environments that ultimately leads to increased network performance (e.g. increased throughput, increased reliability, lower delay etc.).

The introduction of cognitive radios [2] sheds new light on the ad-hoc networking paradigm. Cognitive radios are autonomous wireless devices able to optimize, learn and reason upon different network information (available both locally and globally in the network). Their quintessential feature is the ability to perform *spectrum sensing*, i.e. scan the available spectrum bands and find a suitable spectrum hole for their own communication purposes. Moreover, cognitive radios must also be able to anticipate the arrival of other users in the band they are currently communicating in and perform spectrum mobility (change the channel) in order to minimize the possible interference in the network. As a result, there is often a distinction between *primary* and *secondary* users of the available spectrum. The former ones are either licensed users or users with a higher priority on the spectrum whereas the latter ones may use the spectrum on an opportunistic basis stemming from their cognitive capabilities.

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The cooperation among cognitive radios in ad-hoc environments is a crucial step towards providing efficient network operation. It allows the cognitive ad-hoc devices to exchange data about the sensed spectrum which leads to a faster and more efficient convergence of the communication channel selection process [3-8] leading to improved spectrum management in cognitive environments.

This paper presents an overview of relevant spectrum sensing techniques and cooperation strategies in cognitive ad-hoc networks. Additionally, the paper gives a practical implementation example of a realized cognitive ad-hoc network whose participants are able to cooperatively scan the available spectrum band in order to find the most suitable communication channel. The cooperation among the nodes in the example yields a design of novel rendezvous protocol for cooperative data exchange.

The paper is organized as follows. Section 2 elaborates on the spectrum sensing techniques that are used by cognitive radios to detect spectrum activity in certain bands. Section 3 discusses the possible cooperation strategies among cognitive radios in ad-hoc environments. Section 4 gives details on a realized testbed platform for cooperation among cognitive radios in laboratory premises. Finally, section 5 concludes the paper.

2 Spectrum Sensing Techniques

Every cognitive radio in an ad-hoc network is able to perform spectrum sensing relying only on the locally available information. There are several ways to achieve this task, which are broadly classified as:

- Transmitter detection vs. Receiver detection approaches [9] (based on whether the primary user is transmitting or receiving information when the secondary one senses the spectrum);
- Blind sensing (non-coherent detection) vs. Signal specific (coherent) approaches [10] (based on the usage of specific signal features when sensing the spectrum) and
- Interference based approach (using a specially defined spatially dependent parameter for interference tolerance by the primary users).

2.1 Transmitter Detection vs. Receiver Detection Sensing Approaches

The *transmitter detection* approaches assume that a primary user is *transmitting* information to a primary receiver when a secondary user is sensing the primary channel band. The presence of the primary transmission can be extracted by a secondary user by several techniques such as:

- *energy detection* [11];
- *matched filter detection* [12] and
- *cyclostationary feature detection* [13].

The energy detector estimates the signal power in the channel band where the primary transmission is occurring and compares that estimate with a predefined threshold. As in most general cases of spectrum sensing no a priori information for the primary transmission is known to the secondary user, the energy detection is the only possible solution for spectrum sensing. However, this technique has several drawbacks such as: the decision threshold is subject to variations with the SNR, the energy detector cannot distinguish between a user signal and interference, the energy detector is not effective for spread (i.e. wideband) signals etc. The matched filtering is an optimal way to detect signals in communication systems. The main advantage of this technique is that it can provide high processing gain in short time, however the drawback is the need for prior knowledge of some information for the primary transmission (e.g. modulation order, pulse type etc.). Finally, the cyclostationary feature detection uses the cyclostationary feature inherently present in many wireless communications signals. This feature means that the statistical properties of the transmitted signal (e.g. the mean value or the autocorrelation function) change periodically as functions of time. The cyclostationarity is either produced by modulation or coding or is intentionally incurred in order to aid the spectrum sensing. The cyclostationary feature detection is a promising technique able to extract signal features in the background of noise (since the noise is usually wide sense stationary) and, thus, be more effective than energy detection.

The *receiver detection* approaches assume that a primary user is *receiving* information from a primary transmitter when a secondary user is sensing the primary channel band. They rely on the fact that the primary user in a receiving mode is not passive, i.e. it produces leakage of electromagnetic waves. The secondary users can detect the *Local Oscillator* (*LO*) *leakage power* when the primary user is receiving information and, as a result, detect the primary user [14]. It is obvious that the receiver detection relies on the energy detection technique previously described. The advantages of the receiver detection approaches over the transmitter detection approaches lie in the ability to locate the primary user, locate the exact primary channel band in use and the high probability to find free spectrum even in high density of primary receivers. However, the disadvantages lie in the need for a highly sensitive energy detector, the price of the architecture, the near-far problem etc.

2.2 Blind Sensing vs. Signal Specific Sensing Approaches

Another classification of the spectrum sensing techniques may rely on whether the sensing uses some signal specific features or not. In this manner, there are:

- *blind sensing approaches*, which do not rely on any signal specific feature (i.e. non-coherent detection), and
- *signal specific sensing approaches*, which rely on various signal specific features (i.e. coherent detection) [10].

The *blind sensing* approaches comprise energy detection (previously elaborated), eigenvalue based sensing [15, 16] and multi-resolution sensing [17, 18]. The *eigenvalue based sensing* builds upon the robustness of the energy detection and requires knowledge of the eigenvalues of the covariance matrix of the received signal. Based on different ratios of varios eigenvalues (maximum, average and minimum), various algorithms can be defined [15, 16]. The *multi-resolution sensing* produces a multi-resolution Power Spectral Density (PSD) estimate using a tunable wavelet filter that can change its center frequency and its bandwidth. First, the total bandwidth is sensed using a coarse resolution and then a fine resolution sensing is performed on the portion of the interesting bands for the secondary user [17, 18]. Therefore, this method reduces sensing time and saves power from unnecessary computations. However, it increases chip area, power consumption and imposes challenges on the mixer design for multiple frequencies operation.

The *signal specific* sensing approaches consist of the previously elaborated matched filtering and cyclostationary feature detection and some ATSC signal related sensing techniques [10]. Extensive overview on both blind sensing and signal specific sensing approaches can be found in [19].

In addition to the previously elaborated spectrum sensing techniques, there is also an interference based detection method that has its own specifics and is separately elaborated in the following subsection.

2.3 Interference Based Detection

Interference is a general limiting factor of useable range and effectiveness of communication systems. As a result of the increase of wireless devices and services lately, current approaches to interference management may no longer be adequate. Therefore, the Interference Protection Working Group of FCC Spectrum Policy Task Force recommended the use of *interference temperature* metric as a mean to quantify and manage interference [20]. The interference temperature metric is a measure of the RF power available at a receiving antenna to be delivered to a receiver, i.e. the temperature equivalent of the RF power available at a receiving antenna per unit of bandwidth measured in units of Kelvin [K]. It is generated by other emitters and noise sources in the vicinity of the receiver.

The interference-based detection strategies for spectrum sensing rely on the prior knowledge of secondary users of a parameter called *interference temperature limit*. This parameter is defined for different geographic regions and represents the maximum amount of tolerable interference for a given frequency band in a particular location. Thus, the secondary users are allowed to transmit in the given frequency band only if they guarantee that their transmissions added to the existing interference must not exceed the interference temperature limit at a licensed receiver in the same frequency band and in the same location. The use of the interference temperature metric allows the secondary users to adapt the transmit power and the bandwidth of their communication schemes (inevitably causing throughput variations) leading to a maximization of their QoS while minimizing the interference to the primary users [21].

After elaborating the spectrum sensing techniques employed by individual cognitive radios in ad-hoc networks, the following section will report on possible cooperation strategies that increase the reliability of the spectrum detection in the ad-hoc network.

3 Cooperative Spectrum Sensing Strategies

The cooperative detection strategies for spectrum sensing rely on information exchanges among secondary users. The exchanged information can facilitate the detection of spectrum holes and increase the efficiency of the spectrum sensing. It must be stressed that the secondary users may sometimes also exchange minimal information with the primary ones [22, 23]. Also, the information exchange must be accompanied by defining a control channel used for rendezvous of secondary users and their information exchanges. Based on the amount of the shared information, the cooperative detection strategies can be further classified as [24, 25]:

- **Partial cooperation approaches** and
- **Total cooperation approaches**.

Partial cooperative detection approaches are also referred as *centralized* (controlled) spectrum sensing approaches, whereas the total cooperation approaches are viewed as *decentralized* (uncontrolled) ones.

3.1 Partial Cooperation

The partial cooperation approaches refer to a scenario where the secondary users detect the primary channel by using some of the techniques elaborated in the subsection 2.1 (usually energy detection) either independently or with the aid of some local cooperation with nearby secondary users. The detection information is then sent to a common controller which is also a secondary user (sometimes named as spectrum broker or a fusion center). The common controller is responsible to decide upon the spectrum availability for secondary users' transmissions.

There are numerous examples found in the literature that deal with the partial cooperation approaches to spectrum sensing and various enhancements in terms of finding the optimal local secondary node information to be collected and optimal decision making at the common controller side. They usually differ according to the implemented mechanism for data processing in the common controller which may be based on:

- *voting* or
- *various statistical combinations* of the gathered data.

Voting schemes, e.g. [26, 27], perform decision making upon the collected spectrum occupancy decision from every secondary user. Ref. [26] elaborates the cluster-collect-forward scheme based on secondary users' own confidence, i.e. the common controller collects information about the sensed spectrum only when the secondary users are confident about their sensing results. This scheme provides 65% to 95% transmission energy saving compared to traditional broadcasting schemes. Ref. [27] proves that the optimal fusion role at the fusion center is the half-voting rule if energy detection is used by the secondary users locally. If all secondary users have identical energy detectors and the received signals are modeled as correlated log-normal random variables, then a Linear-Quadratic (LQ) fusion strategy based on a deflection criterion that takes into account the correlation among the nodes proves to significantly outperform other fusion strategies under the mentioned assumptions [28].

Instead of voting, another approach to optimal partial cooperation strategy is to make various statistical combinations of the gathered data from the secondary users. Ref. [29] shows a linear combination of local test statistics from individual secondary users at a fusion center (i.e. the common controller) method. The result is to either optimize the probability distribution function of the global test statistics or maximize the global detection sensitivity under constraints on false alarm probability [29]. Furthermore, [30] shows an approach where a Maximal Ratio Combining (MRC) and Equal Gain Combination (EGC) is being used at the fusion center as they are able to provide close to optimal solutions in low SNR regions (which is a common scenario in the context of cognitive radio) over the hard combination technique. Therefore, [30] introduces a new softened hard combination scheme with two-bit overhead for each user that achieves a good tradeoff between detection performance and complexity.

The collected information by the common controller under partial cooperation must be robust against Byzantine failures which require specific data fusion techniques. Most of the existing data fusion techniques rely on using a fixed number of samples, but there are also techniques that use a variable number of samples [31].

The spectrum sensing capabilities of a cognitive radio network employing partial cooperation detection can be enhanced by exploiting spatial diversity [32] in multiuser networks and providing either fixed or variable relay sensing schemes. The spatial diversity is especially important allowing higher confidence of the decision making process since the local node decisions can better extract the spectrum occupancy information due to their physical separation and the fading feature of the wireless ad-hoc environment. This also minimizes the probability of misconceptions in spectrum sensing as the physical separation of the nodes exhibits different viewpoints on the wireless medium conditions. Additionally, the average detection time can be reduced.

3.2 Total Cooperation

The total cooperation approaches to spectrum sensing refer to a scenario where all secondary users operate in an ad-hoc manner using optimal transmission parameters. This means that the secondary users cooperatively sense the spectrum in order to reduce the detection time of spectrum holes and increase the agility of the secondary users. The coordination among the secondary users in this case aids the control of the uncertainty, that limits the ability of a cognitive radio network to reclaim a band or not, which is actually caused by the presence/absence of secondary users. It can be shown that the degree of coordination among the secondary nodes in total cooperation approaches can vary based on the coherence times and bandwidths involved, as well as the complexity of the detectors themselves [33].

There are several total cooperation approaches to spectrum sensing found in the literature. Due to their versatile nature, it is not easy to provide a unified classification. However, all of them usually employ:

- *relaying schemes* [34] or
- *various mathematical transformations* [35] of the received data.

For example, ref. [34] uses relaying based on the Amplify-and-Forward (AF) cooperation protocol in order to reduce the detection time. In [35], multiple secondary users are used to infer on the structure of the received signals using Random Matrix Theory (RMT). The secondary users share information among them making the scheme not dependable on the knowledge of the noise statistics or its variance, but relying on the behavior of the largest and the smallest eigenvalue of random matrices.

Further on, the benefits of total cooperation approach for a simple two user cooperative cognitive network is elaborated in [36]. The improvement in agility is shown by exploiting the inherent asymmetry in the network. The same authors extended their work on total cooperation approaches to spectrum sensing in [37] to account for a multiuser single carrier network. They have found the sufficient conditions under which asymptotic agility gain is achievable and developed a pairing protocol that ensures asymptotic agility gain with probability equal to 1. The authors in [38] show that the total cooperation approach can increase the throughput of the secondary users while limiting the interference to the primary users.

4 Practical Implementation Example

After elaborating on the possible spectrum sensing techniques and cooperation strategies, this section reflects on a practical testbed implementation of a cooperative behavior among cognitive radios in an ad-hoc network [39]. As all cooperation strategies require a common control channel for information exchange among the cognitive radios, the example will rely on the usage of a novel rendezvous protocol, named RAC^{2}E, that allows complete *asynchronous* behavior of the cognitive radios in the ad-hoc environment.

4.1 Scenario Setup and Protocol Description

The targeted scenario comprises a secondary network of CSMA/CA based cognitive radio nodes with spectrum sensing capabilities (energy detection based) that operates in the 2.4 GHz ISM band and coexists with a primary IEEE 802.11 based network. All cognitive radios are able to create a local spectrum map (a top-down power ranking of the available channels). If two cognitive radios want to establish direct link communication by opportunistically using the temporary unused channels from the primary network terminals, they should exchange their spectrum maps in order to select the mutually best channel (i.e. the channel having the lowest level of interference for both nodes). Afterwards, the initiator node should request connection and the destination node should confirm the requested connection allowing the data channel to be established. All these control messages should be exchanged through on demand dynamically established control channel and should prove that the cooperation among the cognitive radios will yield more efficient network operation. The control channel is mutual for all simultaneous active secondary nodes and serves for cooperative spectrum sensing info exchanges as well as for communication parameters negotiation. When a new secondary node becomes active it first searches for control channel where it can obtain the spectrum maps from other nodes and find some node for communication.

The cooperative rendezvous protocol in use (RAC^{2}E) has two phases, i.e. *initialization* and *exchanging control information* phases. The former phase is used to select the control channel if such pre-exists in the secondary network from prior CR communication. In this case, the initialization phase requires that the node listens long enough on each channel frequency in order to detect any control message. However, if a control channel is not detected, then the node selects the best channel from its spectrum map and declares it to be the control channel. The second phase is used for cooperative exchange of control information (sensing reports exchange) on the selected control channel. It should be stressed that RAC^{2}E operates upon an application request, i.e. when two cognitive radios want to establish a data session between. The second phase of the protocol, after detection of the control channel, operates in a time division mode, i.e. the node spends T_s seconds for spectrum sensing and creating a spectrum map and T_c seconds for sending and listening on the control channel. The total period of (T_s + T_c) seconds is continuously repeated until the communication link on an appropriate data channel between the two cognitive radios that want to communicate is established. The duration of the spectrum sensing intervals T_s should be fixed to a long enough value to get accurate sensing information for all channels. The time duration of the control channel attendance T_c is fixed for each node and is randomly chosen from an interval [T_1, T_2], where the values for T_1 and T_2 can be fine tuned depending on the number of nodes. The value of T_c remains constant for each node until data communication is established (Fig. 1) and is changed for each subsequent control channel establishment procedure.

The total asynchronies among users, stemming from the randomly chosen T_c periods, provides lower or higher overlapping of the different nodes control channel periods, depending on T_c and T_s values. It is obvious that the ends of the T_c periods will be overlapped most frequently (Fig. 1). Consequently, this imposes sending the control channel messages at the *start* and at the *end* of the control channel period in order to maximize the probability of packet reception from other nodes. In the period between the two control messages in one T_c interval, the nodes switch to a *listening* mode in order to detect other nodes' potential control messages.

If an already established control channel is being interrupted (e.g. primary user appearance), the control channel band must be changed. Since every node has other nodes' spectrum maps, all nodes know which channel is mutually the best suitable to be the new control channel. This will result in faster control channel reestablishment.

RAC^{2}E envisions several control messages such as *sensing report* message, *connection request* message and *connection reply* message. These messages are sent twice from each node in a T_c period. The *sensing report* message carries sensing results obtained during the T_s period and is the most frequently sent cooperative control message. Upon reception of such message, a node stores it locally. Therefore, each node can keep information of other active nodes in the network and their spectrum maps. Moreover, before initiation of any communication, a node must first detect the sensing report message. When a node wants to communicate with another node, it checks its own spectrum map and the destination node's spectrum map and selects mutually acceptable channel. Then, it sends a *connection request* message to the other node with all proposed connection parameters and waits for *connection reply* message. When affirmative connection reply is received, the pair of nodes is switched to a selected data channel and starts communication. In case of a negative reply, the node that initiated the communication continues to sense the spectrum, searches for spectrum maps and sends new connection requests.

When an already established connection is finished, the nodes return to the previous mode when T_s seconds sense the spectrum and create spectrum maps and T_c seconds send their sensing maps and listen for other nodes sensing maps. If, for some reason, the control channel is switched to other band during the data communication, then the nodes start to search the control channel as in the *initialization* phase, but now first looking into the mutually best channel from its previous spectrum maps.

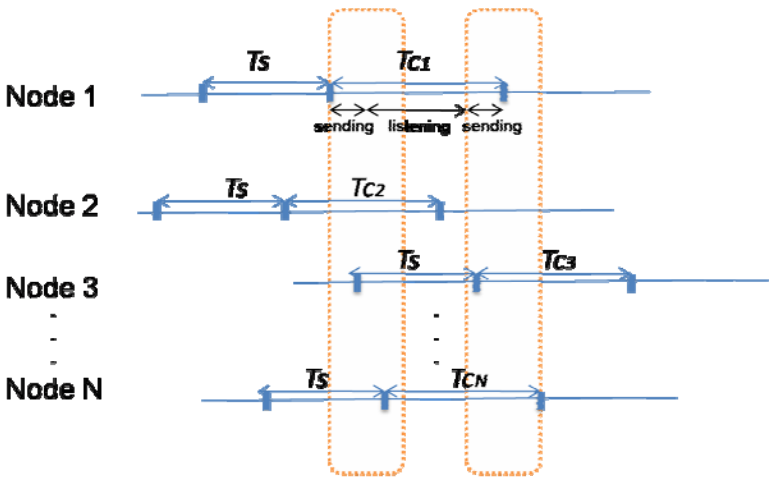

Fig. 1. RAC^{2}E time operation

After elaborating the RAC^{2}E operational details, the following section will give more insight into the performance behavior of the protocol and the cooperation process among the cognitive radios in the ad-hoc environment in general.

4.2 Performance Evaluation

This section provides performance evaluation of cooperative spectrum sensing in ad-hoc environment demonstrating a testbed implementation of RAC^{2}E on a platform with four USRP2 nodes [40]. Fig. 2 depicts the testing scenario. The application profile of the scenario is that node 1 wants to establish data connection (video streaming) with node 2, while simultaneously node 3 wants to communicate with node 4. The parameters used in the proposed USRP2 demo scenario are as follows. T_s is chosen to be 2.6s, the bit rate on the control channel is 200kbps (using gmsk modulation), T_c period length is chosen randomly in the interval [T_s, $2T_s$] and the video streaming application being used is “VLC media player”.

Once the control channel is established, the nodes start sending and collecting the spectrum maps on the mutually common control channel. The process of creating local spectrum map and exchanging spectrum maps among nodes is illustrated on Fig. 3 for node 1. After the exchange of the spectrum maps, node 1 tries to initiate the video streaming communication to node 2 by sending a *connection request* message through the control channel by proposing to the node 2 channel 6 as mutually the best channel. Fig. 4 shows the *connection reply* message from node 2 and the actual choice of the WiFi channel to be used for data communication. Similar conclusions and figures are valid for the other nodes (i.e. 3 and 4) that want to start other video streaming in the demo. Finally, Fig. 5 provides a snapshot from a spectral analyzer that was used to prove the actual cooperative sensing info exchange and to demonstrate the functionality of the proposed rendezvous approach. The detected channels in use from both pair of nodes are channel 6 and channel 8. Other spectrum emissions, besides the ones stemming from the demo's video streaming applications, are caused by surrounding IEEE 802.11 access points at the laboratory premises where the demo was set up.

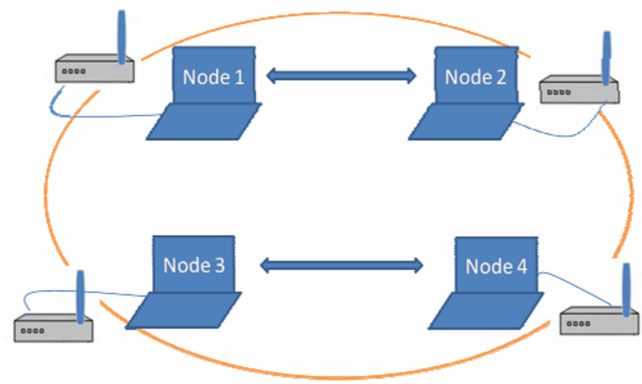

Fig. 2. RAC^{2}E testbed platform

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payload: 0 2 0 -58 -56 -58 -62 -56 -64 -59 -59 -61 -61 -57 -57 -59
Rx: ok = True  len(payload) =  57
payload: 0 3 0 -44 -62 -61 -58 -57 -57 -69 -62 -62 -61 -61 -60 -56
Rx: ok = True  len(payload) =  57
payload: 0 4 0 -41 -60 -65 -59 -59 -56 -62 -66 -62 -59 -62 -60 -68
Rx: ok = True  len(payload) =  57
payload: 0 2 0 -58 -56 -58 -62 -56 -64 -59 -59 -61 -61 -57 -57 -59
SRx Frequency set to  2417000000 Hz
SRx Frequency set to  2422000000 Hz
SRx Frequency set to  2427000000 Hz
SRx Frequency set to  2432000000 Hz
SRx Frequency set to  2437000000 Hz
SRx Frequency set to  2442000000 Hz
SRx Frequency set to  2447000000 Hz
SRx Frequency set to  2452000000 Hz
SRx Frequency set to  2457000000 Hz
SRx Frequency set to  2462000000 Hz
SRx Frequency set to  2467000000 Hz
SRx Frequency set to  2472000000 Hz
SRx Frequency set to  2412000000 Hz
([-29, -39, -64, -59, -63, -63, -63, -58, -56, -58, -57, -56, -56], [-58, -56, -
58, -62, -56, -64, -59, -59, -61, -61, -57, -57, -59], [-44, -62, -61, -58, -57,
 -57, -69, -62, -62, -61, -61, -60, -56], [-41, -60, -65, -59, -59, -56, -62, -6
6, -62, -59, -62, -60, -68])
```

Spectrum info messages from other nodes

Switching over the entire WiFi band

Spectrum maps from all 4 nodes

Fig. 3. Spectrum information at node 1

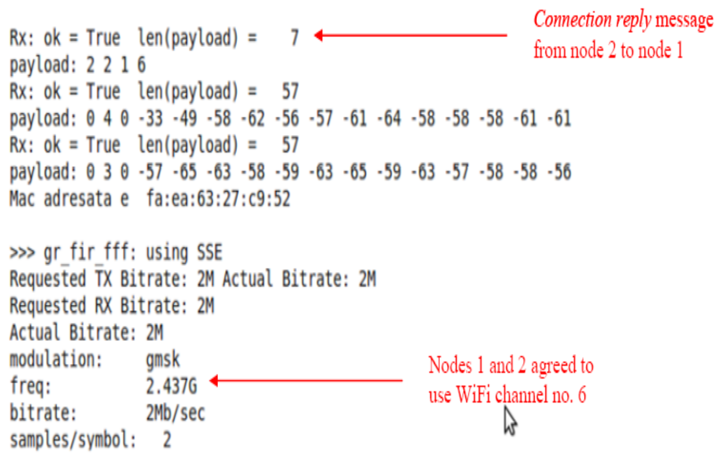

Fig. 4. Data channel agreement, from node 1 viewpoint

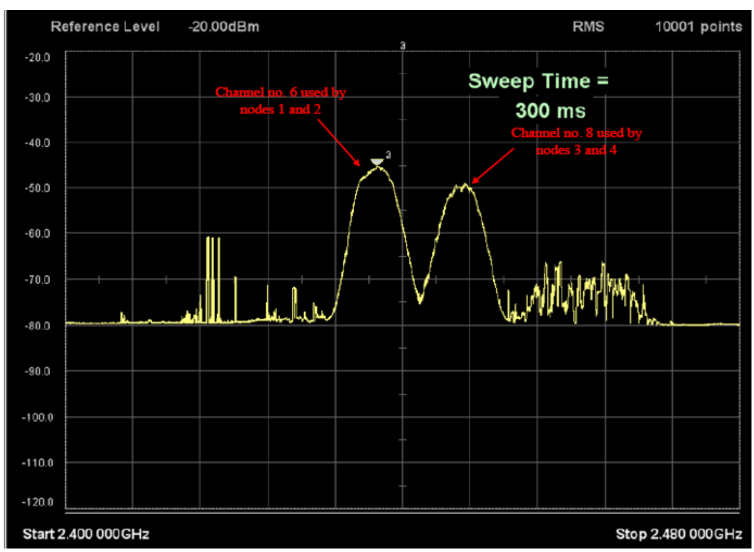

Fig. 5. Spectrum analyzer snapshot of the established connections

This section gave a practical demonstration of a cooperative spectrum sensing in an ad-hoc environment. It showed how cognitive radios can dynamically establish a control channel and cooperatively exchange information in order to perform efficient spectrum sensing and spectrum management in general.

5 Conclusions

Ad-hoc networks are increasingly gaining momentum owing to their ability to provide access domain in the integral future 4G networking paradigm. On the other side, the development of different wireless technologies leads to the concept of cognitive radios that alter the viewpoint on the ad-hoc networking. Cognitive radios can autonomously optimize and adapt their transmission parameters according to the environmental scenario they operate in. For this purpose, cognitive radios are able to perform spectrum sensing allowing them a broader view on spectrum bands and vacant spectrum positions that may be opportunistically used. The introduction of cognitive radios in ad-hoc environments imposes novel research challenges. The spectrum sensed information must be cooperatively used in order to extract the global network context and enhance the overall network performance.

There are different cooperation strategies that may be engaged by cognitive radios in ad-hoc environments. This paper gives an overview of the spectrum sensing techniques and the cooperation strategies among cognitive radios in ad-hoc networking context. It showed details and novel classifications of the plethora of solutions found in the literature today. Moreover, the paper reported on an ongoing research work on practical implementation of a testbed with USRP2 cognitive radios that cooperatively exchange spectrum maps and optimize the spectrum management process in the ISM band.

Future work will be concentrated on implementation of different spectrum sensing techniques in the testbed (not only energy detection), testing in larger scenarios, dynamic control channel establishment protocol enhancements etc.

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