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Performance of Cooperative Spectrum Sharing and Dynamic Sensing Strategies for Efficient Spectrum Utilization in Cognitive Radio

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Abstract—Due to crowd in the spectrum, interference protection is guaranteed through policy spectrum licensing. Cognitive radio and mesh network can facilitate spectrum sharing that improves spectral efficiency, provided spectrum policies are in place that supports these forms of sharing. This paper discusses the enhancement of Cognitive Radio which enable all the parameter. Cognitive Radios have been receiving increasing attention in academia, industry, and government. This has come after several studies indicating that up to 90% of the allocated radio spectrum less than 3GHz is idle most of the time. As a result, spectrum regulation around the world is in progress to allow unlicensed access on a non-interfering. Current researches are investigating different techniques of using cognitive radio to reuse more locally unused spectrums to increase the total system capacity. In this paper we address more spectrums sensing, protocol, hardware, measurement methodology, security and algorithmic challenges that could limit their performance or even make them infeasible. We also give some insight into the evolution of cognitive radios and characteristics. We conclude highlighting open research challenges in this exciting area.

Keywords-component: **Cognitive radio, Spectrum sensing, Dynamic spectrum access, Multi-dimensional spectrum sensing, Cooperative sensing, Radio identification.**

I. INTRODUCTION

Cognitive radio (CR) has been identified as a promising solution to the so-called *spectrum scarcity problem*, which results from the steady spectrum demand growth and the actual spectrum underutilization [1]. The basic underlying idea of the CR paradigm is to allow unlicensed users to access in an opportunistic and non-interfering manner some licensed bands temporarily to unoccupied by the licensed users. CR is expected to dramatically increase the spectrum usage efficiency. However, before this paradigm can turn into reality, a full understanding of the dynamic use of spectrum in real wireless communication systems is firstly required. To this end, spectrum measurements become an essential and unavoidable step. The measurement of real network activities constitutes an important step towards a realistic understanding of dynamic spectrum use and hence towards the practical deployment of the future CR technology.

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One of the most important uses of spectrum measurements will be not only to convince regulatory bodies and policy makers on the necessity of new spectrum access policies but also to support them in taking actions to enhance the use of the currently underutilized spectral resources. The investments required in order to develop dynamic spectrum access (DSA) technologies.

Cognitive radio arises to be a tempting solution to the spectral congestion problem by introducing opportunistic usage of the frequency bands that are not heavily occupied by licensed users [2], [3]. While there is no agreement on the formal definition of cognitive radio as of now, the concept has evolved recently to include various meanings in several contexts [4].

In this paper, we use the definition adopted by Federal Communications Commission (FCC):

"*Cognitive radio: A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets.*" [3].

Hence, one main aspect of cognitive radio is related to autonomously exploiting locally unused spectrum to provide new paths to spectrum access.

In this context, this work presents a comprehensive and in-depth discussion of several important methodological aspects that need to be carefully taken into account when evaluating spectrum occupancy. Certain issues discussed in this work are rather intuitive but they have never been assessed in a formal, rigorous and quantitative manner in the context of CR.

One of the most important components of the cognitive radio concept is the ability to measure, sense, learn, and be aware of the parameters related to the radio channel characteristics, availability of spectrum and power, radio's operating environment, user requirements and applications, available networks (infrastructures) and nodes, local policies

and other operating restrictions. In cognitive radio terminology, *primary users* can be defined as the users who have higher priority or legacy rights on the usage of a specific part of the spectrum. On the other hand, *secondary*

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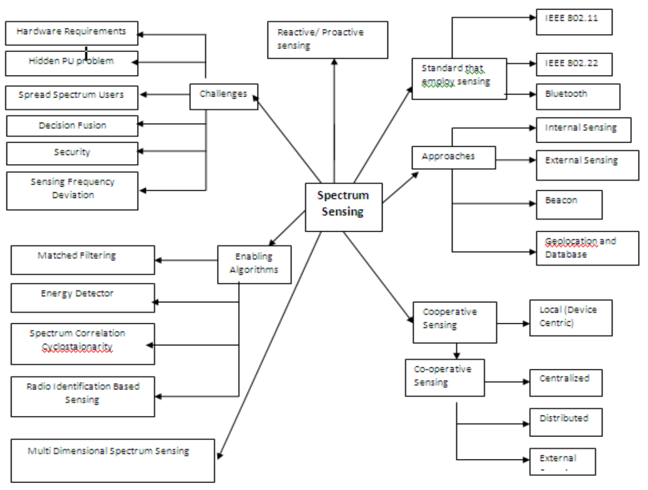

Fig-1:Block-Diagram of Various aspects of spectrum sensing for Cognitive radio

users, which have lower priority, exploit this spectrum in such a way that they do not cause interference to primary users. Therefore, secondary users need to have cognitive radio capabilities, such as sensing the spectrum reliably to check whether it is being used by a primary user and to change the radio parameters to exploit the unused part of the spectrum.

When cognitive radio is considered, it is a more general term that involves obtaining the spectrum usage characteristics across multiple dimensions such as time, space, frequency, and code. It also involves determining what types of signals are occupying the spectrum including the modulation, waveform, bandwidth, carrier frequency, *etc.*. However, this requires more powerful signal analysis techniques with additional computational complexity.

Recently developed wireless standards have started to include cognitive features. Even though it is difficult to expect a wireless standard that is based on wideband spectrum sensing and opportunistic exploitation of the spectrum, the trend is in this direction. In this section, wireless technologies that require some sort of spectrum sensing for adaptation or for dynamic frequency access (DFA) are discussed. However, the spectrum knowledge can be used to initiate advanced receiver algorithms as well as adaptive interference cancellation [5].

II. MEASUREMENT SETUP

Many factors need to be considered when defining a strategy to meet a particular spectrum measurement need. As detailed in Reference [6], there are some basic dimensions that every spectrum measurement strategy should clearly specify: *frequency* (frequency span and frequency points to be measured), location (measurement site selection), *direction* (antenna pointing angle), *polarization* (receiving antenna polarization) and *time* (sampling rate and measurement period). The measurement setup employed in the evaluation of spectrum occupancy should be designed taking into account the previous factors since they play a key role in the accuracy of the obtained results. The measurement setup should be able to detect, over a wide range of frequencies, a large number of transmitters of the most diverse nature, from narrow- to wide-band systems and from weak signals received near the noise floor to strong signals that may overload the receiving system. Depending on the purposes of the study, different configurations have been used in previous spectrum measurements ranging from simple setups with a single antenna directly connected to a spectrum analyzer [7] to more sophisticated and complex designs [8,9]. Different configurations between both extreme points may determine various tradeoffs between complexity and measurement capabilities. Our study is based on a spectrum analyzer setup where different external devices have been added in order to improve the detection capabilities of the system and hence obtain more accurate and reliable results (a simplified scheme is shown in Figure 1). The design is composed of two broadband discone-type antennas that cover the frequency range from 75 to 7075 MHz, a single-pole double-throw (SPDT) switch to select the desired antenna, several filters to remove undesired signals, a low-noise pre-amplifier to enhance the overall sensitivity and thus the ability to detect weak signals, and a high-performance spectrum analyzer to record the spectral activity. These components are discussed in the following. When covering small frequency ranges or specific licensed bands a single antenna may suffice. However, in broadband spectrum measurements from a few mega hertz's up to several gigahertz's, two or more broadband antennas are required in order to cover the whole frequency range. Most of spectrum measurement campaigns have been based on Omni-directional measurements in order to detect licensed signals coming from any directions. To this end, Omni-directional vertically polarized antennas have been the most common choice. Our antenna system comprises two broadband discone-type antennas, which are wideband antennas with vertical polarization and Omni-directional receiving pattern in the horizontal plane. Even though some transmitters are horizontally polarized, they usually are high-power stations, such as e.g. TV stations, that can be detected even with vertically polarized antennas. The exceptionally wideband coverage (allowing a reduced number of antennas in broadband spectrum studies) and the Omni-directional feature (allowing the detection of licensed signals coming from any directions) make discone antennas an attractive alternative in radio scanning and monitoring applications, and have been a preferred option for many past spectrum occupancy measurement studies. In studies where the direction of the incoming signal needs to be resolved, it is possible to use multiple antenna arrays along with beam forming techniques in order to selectively receive or suppress (filter) signals in the angular domain.

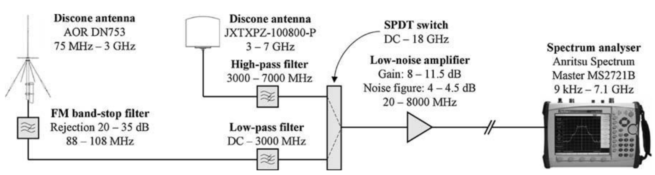

Figure 2: Measurement setup.

Directive antennas (e.g. log-periodic antennas) may also be used to this end as well as in order to improve the system's sensitivity at the cost of an increased complexity in the measurement procedures.

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For example, if a directive antenna with α-degree beam width is used in order to provide an additional G-dB gain with respect to an Omni-directional antenna, it would be necessary to repeat the measurements $N = (360/\alpha)$ times in order to cover the entire 360-degree range of azimuths. An alternative option to obtain additional gain is the use of amplification. Most spectrum analyzers include built-in high-gain pre-amplifiers. Nevertheless, in some measurement conditions there may be high losses between the antenna port and the spectrum analyzer. In this case a better option to improve the system's noise figure is to place a low-noise pre-amplifier right after the antenna system, as show in Figure 1. This amplifier will compensate for device and cable losses and increase the system's sensitivity. It is worth noting that choosing an amplifier with the highest possible gain not always is the best option in broadband spectrum surveys, where very different signal levels may be present. The existing trade-off between sensitivity and dynamic range must be taken into account. Thus, the correct pre-amplifier has to be chosen based on the specific measurement needs. If we wish absolutely the best sensitivity and are not concerned about measurement range, we would choose a high-gain, low-noise pre-amplifier. If the maximum input level is exceeded, some spurs might arise above the system's noise floor and be detected as *signals* in truly unoccupied bands, thus resulting in inaccurate results and erroneous conclusions about the spectral occupancy. As shown in Figure 1, the use of band stop filters to remove undesired overloading signals, such as those coming from FM audio broadcast stations, as well as low/high-pass filters to remove out-of-band components, which might create harmonics or inter modulation products, can be very helpful in satisfying the SFDR criterion without any loss in sensitivity at other frequencies.

III. FREQUENCY DIVISION

When the measurement equipment is designed, the next required step is to decide the frequency blocks (frequency spans) to be measured. This task basically consists in dividing the entire frequency range under study into smaller frequency blocks/spans over which measurements are performed individually. This is necessary, especially in broadband measurement campaigns, because measuring the whole frequency range under study as a single measurement block would result in an extremely poor frequency resolution and hence in a very coarse spectrum occupancy estimation. However, when little is known about the spectrum bands to be measured and their spectral activity, a more reasonable approach is to follow a two-stage measurement procedure as performed in References [10,11]. In the first stage, the whole frequency range is divided into relatively large frequency blocks/spans. The measurement of such wide frequency blocks enables obtaining a first picture of spectrum occupancy very quickly since only a few frequency blocks need to be measured. This information may be useful to determine which spectrum bands are subject to higher activity levels and are therefore worthy of a more detailed study. Based on this first impression and following the local spectrum allocations, the entire frequency range can then be divided into smaller blocks/spans in such a way that higher frequency resolutions are obtained in those bands where some spectral activity is detected and/or the transmitted signals' bandwidth is narrower [11]. The relation between the transmitted signal's bandwidth and the frequency resolution is an important aspect to be accounted for that, unfortunately, has received little attention in previous spectrum measurement campaigns. For a given number of measured frequency points per block/span, the frequency bin size (i.e. the separation between two consecutively measured frequency points) increases with the frequency span. In general, higher frequency bins tend to result in higher spectrum occupancy rates, for the Digital Cellular System (DCS) and the Universal Mobile Telecommunications System (UMTS) downlink bands. However, the exact behavior in both cases is different. In the case of DCS 1800, for frequency bins lower than the bandwidth of the transmitted DCS signal (200 kHz), the average duty cycles (45.16 and 58.91%) indicate that the band is subject to moderate usage levels. For a frequency bin of 1 MHz, which is quite greater than the signal bandwidth, the obtained duty cycle of 84.68% incorrectly concludes that the same band experiences a high level of utilization.

IV. TIME DIVISION

The time dimension of spectrum measurements is mainly defined by two parameters, namely the sampling rate, i.e. the rate at which PSD samples are captured, and the measurement period. While the former is constrained (and in some cases automatically adjusted) by the measurement device, the latter can be easily controlled. The measurement period depends on the trade-off between the overall time required to complete the measurement campaign and the particular objectives of the measurement study. Some previous studies have been aimed at identifying spectrum usage patterns over long periods and understanding any potential seasonality in the visible spectrum usage. For such kind of studies, long-term measurement campaigns with measurement periods of several years have been suggested [12,13]. However, from the standpoint of resource utilization, a short-term evaluation and characterization of spectrum usage is frequently more interesting since in practice it has an important impact on the behavior and performance of a DSA/CR network. In such a case, long-term measurements are not necessary. Although the employed measurement periods can be drastically shortened, a minimum number of PSD samples is required to correctly characterize the spectral activity of the measured bands. In this context, and from a statistical viewpoint, the question is how long spectrum bands should be measured in order to obtain a representative estimate of the actual spectrum usage in such bands. . To this end, a portion of the DCS downlink band (1862.5–1875.5 MHz) was selected and measured during 24 h. The average duty cycle for each measured frequency point was computed over 1-h periods, thus obtaining the time evolution of the duty cycle for different frequencies along one day. Although a 24-h measurement period can be regarded as adequate, it is certainly true that a relatively large number of recorded traces and thus reasonably long measurement periods are required to correctly characterize the spectral activity in allocated spectrum bands.

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For example, 48-h periods would provide more realistic estimates. Moreover, 7-day periods would also include the potentially different usage patterns of some spectrum bands in weekdays and weekends. A 24-h measurement period properly chosen can be considered as a reasonable trade-off between reliability of the obtained results and time required to complete the measurement campaign.

V. DATA POST-PROCESSING

One of the very first steps of data post-processing is to determine which captured PSD samples correspond to occupied and unoccupied channels. To detect whether a frequency band is used by a licensed user, different sensing methods have been proposed in the literature [14, 15]. They provide different trade-offs between required sensing time, complexity and detection capabilities.

Depending on how much information is available about the signal used by the licensed network different performances can be reached. However, in the most generic case no prior information is available. If only power measurements of the spectrum utilization are available, the energy detection method is the only possibility left. Due to its simplicity and relevance to the processing of power measurements, energy detection has been a preferred approach for many past spectrum studies. Energy detection compares the received signal energy in a certain frequency band to a predefined decision threshold. If the signal lies above the threshold the band is declared to be occupied by the licensed system. Otherwise the band is supposed to be idle. Therefore, the measured PSD samples need to be compared to a threshold in order to determine whether they correspond to occupied channels or not. The decision threshold is a critical parameter in data post processing since its value severely impacts the obtained occupancy statistics. High decision thresholds may result in underestimation of the actual spectrum occupancy due to the misdetection of faded signals. On the other hand, excessively low decision thresholds may result in overestimation caused by noise samples above the threshold.

There are some algorithms which is used to determine the decision threshold without any *a priori* knowledge of the noise properties. Some examples are the Otsu's algorithm [19] and the Recursive One-sided Hypothesis Testing (ROHT) algorithm proposed in Reference [20]. The main drawback of these algorithms is that they are more complex and based on some assumptions that may not hold.

Moreover, such assumptions are not necessary when noise properties can be known as it is our case. These methods are not considered in this study.

VI. COGNITIVE RADIO ISSUES

A. Advance spectrum management: Cognitive radios have a great potential to improve spectrum utilization by enabling users to access the spectrum dynamically without disturbing licensed primary radios. A key challenge in operating these radios as a network is how to implement an efficient medium access control mechanism that can adaptively and efficiently allocate transmission powers and spectrum among Cognitive radios according to the surrounding environment. Most existing works address this issue via suboptimal heuristic approaches or centralized solutions [21].

B. Unlicensed spectrum usage: It is this discrepancy between FCC allocations and actual usage, which indicates that a new approach to spectrum licensing is needed [22].What is clearly needed is an approach, which provides the incentives and efficiency of unlicensed usage to other spectral bands, while accommodating the present users who have higher priority (primary users) and enabling future systems a more flexible spectrum access

C. Spectrum sharing strategies: Spectrum sharing is allocation of an unprecedented amount of spectrum that could be used for unlicensed or shared services. Opportunistic communication with interference avoidance faces a multitude of challenges in the detection of sharing in multi-user cognitive radio systems. Because of the presence of user priority (primary and secondary), they pose unique design challenges that are not faced in conventional wireless systems. A major issue in a multiple secondary user environment is sharing, a topic that has generated a lot of research interest in the recent past [23] [24]

D. Hidden node and sharing issues: Cognitive radio sensitivity should outperform primary user receivers by a large margin in order to prevent what is essentially a hidden node problem of cognitive radios to ensure cognitive radios do not interfere with each other [25].

E. Trusted access and security: With increased focus over the past few years on system security and survivability, it is important to note that distributed intelligent systems, such as cognitive radio, offer benefit in the event of attacks. Intelligence and military application require application-specific secure wireless systems [26] [27].

F. Complexity issue: Cognitive radio is being proposed as a future way of tackling the problem of increasingly radio spectrum. To achieve this it requires that the communications nodes themselves are intelligently capable of sensing, and dynamically selecting, the appropriate spectral resources without causing excessive interference on other users. To achieve this researchers are proposing a variety of increasingly complex methods of implementing cognitive radio, which incorporate software defined radio, dynamic spectrum management and intelligence[28][23][22][24]. The drawback of this complexity is that it is predicted that Cognitive Radio is still years away from implementation. The challenge is to understand whether such complexity is justified, and what benefits it brings to overcome the current regulatory constrained spectral assignment process. It is foreseen that it should be possible to develop reduced complexity strategies that will deliver much of the functionality of proposed systems, enabling more rapid adoption, and wider use in systems where cognitive radio is currently not being considered due to prohibitive complexity.

G. Cross-layer design: The flexibility of cognitive radios has significant implications for the design cross layer algorithms which adapt to changes in physical link quality, radio interference, radio node density, network topology or traffic demand may be expected to require an advanced control and management framework with support for cross-layer information [29][30].

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Spectrum handoff and mobility management will face some new challenges which are required to do a cross-layer design, especially when required providing the necessary capabilities in terms of quality of service at the same time.

H. Hardware and software architecture: The potential for Cognitive radio is a novel efficient methodology, extension of software-defined radio, to transmit and receive information over various wireless communication devices [31]. According to the existing operators in the environment, Cognitive radio chooses the best available option based on performance for each application. The different performance measuring parameters include frequency, power, antenna, transmitter bandwidth, modulation and coding schemes etc. This means that the radio has to deal with different radio frequencies spectrum and baseband varieties at the same time, thus requiring a more robust, efficient and reconfigurable hardware and software architecture.

VII. COGNITIVE RADIO PROTOCOL

The contribution of some recent studies has studied the spectral efficiency of cognitive systems with respect to classical approaches by allowing the cognitive users to transmit simultaneously with the primary users in the same frequency band.

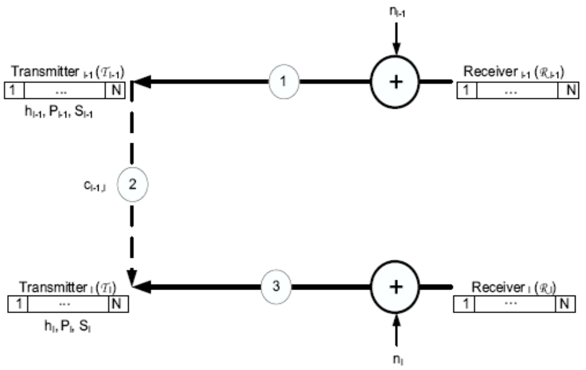

Fig. 3: The cognitive radio channel in a wideband/multiband context with N sub-bands.

In [32], the cognitive user is assumed to obtain an a-priori knowledge of the information that will be transmitted by the primary user. In [33], authors allow the primary and the secondary systems to cooperate and jointly design their encoder-decoder pairs. However, in practice, primary system should be unaware about the existence of the cognitive radio (unlicensed) system and operates according to the demands of the population of primary terminals. This implies that it is the role of cognitive radios to recognize their communication environment and adapt the parameters of their communication scheme to maximize the QoS for the secondary users.

Under the proposed protocol however, cognitive users listen to the wireless channel and determine, either in time or frequency, which part of the spectrum is unused. Then, they successively adapt their signal to fill detected voids in the Spectrum domain . Each transmitter T_l for l = 1, ...,L estimates the pilot sequence of the receiver R_l in order to determine the channel gain h_l (see links (1) and (3) in fig. 1). Notice here that since we are in a TDD mode, when we estimate the channel in one way, we can also know it the other way. Thus, each user l is assumed to know only his proper channel gain hl and the statistical properties of the other links.

Specifically, the primary user comes first in the system and Estimate his channel gain. Then, cognitive users come after in an asynchronous way so that they will not transmit at the same moment. The second user who comes in the system randomly, for instance in a Poisson process manner, and estimates his channel link. Thus, within this setting, the primary user is assumed not to be aware of the cognitive users. Then, he communicates with his receiver in an ad-hoc manner while a set of cognitive radio transmitters that are able to reliably sense the spectral environment over a wide bandwidth, decide to communicate with their respective receivers only if the communication does not interfere with the primary user. Thus, under our opportunistic approach, a device transmits over a certain sub-band only when no other user does. Such an assumption is motivated by the fact that in an asynchronous context, the probability that two users decide to transmit at the same moment is negligible as the number of users is limited. The sensing algorithms for the cognitive users as well as the performance analysis of such an approach are proposed [34].

Moreover, here allocate transmit powers for each user in order to maximize his transmission rate over a total power budget constraint. In fact, when channel state information is made available at the transmitters, users know their own channel gains and thus they will adapt their transmission strategy relative to this knowledge. The corresponding optimum power allocation is the well-known water filling allocation [35] expressed by2:

$$P_l^i = \left(\frac{1}{\gamma_0} - \frac{N_0}{|h_l^i|^2} \right)^+ \qquad (1)$$

Where 0 is the Lagrange's multiplier satisfying the average Power constraint:

$$\frac{1}{N} \sum_{i=1}^{N} P_l^i = \overline{P}; \qquad (2)$$

Without loss of generality, throughout the rest of the paper, we take $\overline{P} = 1$.

For clarity sake, let us take the following example with $N = 8$ sub-bands. As shown in figure 2, the primary user is always prioritized above cognitive users by enjoying the entire band while cognitive users adapt their signal to fill detected voids with respect to their order of priority. As a first step, the primary user maximizes his rate according to his channel process. As mentioned before in expression (1), only user with a channel gain h^i above a certain threshold equal to $\gamma_0 . N_0$ transmits on the sub-band i (Ψ_2). User 2 senses the spectrum and decides to transmit only on sub-bands sensed idle. Thus, following his fading gains, user 2 adapts his signal to fill these voids in the spectrum domain in a complementary fashion (Ψ_3). Similarly, user 3 will sense the remaining sub-bands from user 1 and user 2 and decide to transmit during the remaining voids (Ψ_4).

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VIII. CONCLUSION

The limited spectrum for dense wireless communications and inefficient spectrum utilization necessitate a new communication paradigm cognitive radio which can exploit the unutilized spectrum opportunistically. This paper presents some of the cognitive radios issues used to determine the effectiveness in wireless communication. These characteristics are crucial when applying the cognitive radios in order to determine the effectiveness and reliability of wireless networks. Spectrum management, unlicensed spectrum usage, spectrum sharing, hidden node and sharing issues, security, complexity, cross-layer design hardware and software architecture are introduced. Many researchers are currently engaged in developing the communication technologies and protocols required for cognitive radio networks .The recent and evolving research efforts have made big progress on cognitive radios both in theory and in practical implementations. Thought there are methods available in cognitive radios, none is considered to be the most reliable method in a wide ranging wireless environment, and so more research is needed along the lines introduced in this paper.

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