Cognitive Radio: Future Research Challenges in Collaborative Spectrum Sensing and their Solutions

Muhammad Nasir Iqbal and Muhammad Moinuddin

***Abstract*—Cognitive radio (CR) is considered as an innovative approach for improving the utilization of a precious natural resource: the radio electromagnetic spectrum. The CR is an enhancement on the traditional software radio concept wherein the built on a software-defined radio is used which is aware of its environment and its capabilities, is able to independently modify its physical layer behavior, and is capable of following complex adaptation strategies with an objective of efficient utilization of the available radio spectrum. Following the general discussion of CR, this paper provides an overview of the future challenges and some possible solutions for the design of collaborative spectrum sensing in CR networks.**

***Index Terms*—Awareness, cognition, competition and cooperation, emergent behavior, radio-scene analysis, spectrum analysis, spectrum holes, spectrum management, adaptive energy detection.**

I. Introduction

THE electromagnetic radio spectrum is a precious natural resource, the use of which by transmitters and receivers is licensed by governments.

Accessing spectrum in many bands is a more significant problem than inadequacy of spectrum. Present restrictions are due to legacy command-and-control regulation that limits the optimum utilization of potential spectrum [Simon].

Based on statistics related to the ineffective utilization of radio spectrum, the following three different types of spectrum spaces can be observed [1]–[3]:

1) Black spaces, which are occupied by high-power “local” interferers some of the time.
2) Grey spaces, which are partially occupied by low-power interferers.
3) White spaces, which are free of RF interferers except for ambient noise, made up of natural and artificial forms of noise

The ineffective utilization of the radio spectrum leads us to introduce the concept of spectrum holes (see Fig. 1) which can be defined as follows [1]:

A spectrum hole is a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user.

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Efficient spectrum utilization is possible by providing access to a secondary user (who is not being serviced) of a spectrum hole unoccupied by the primary user at the right location and the time in demand. CR, inclusive of software-defined radio, has been proposed as the means to promote the efficient use of the spectrum by exploiting the existence of spectrum holes.

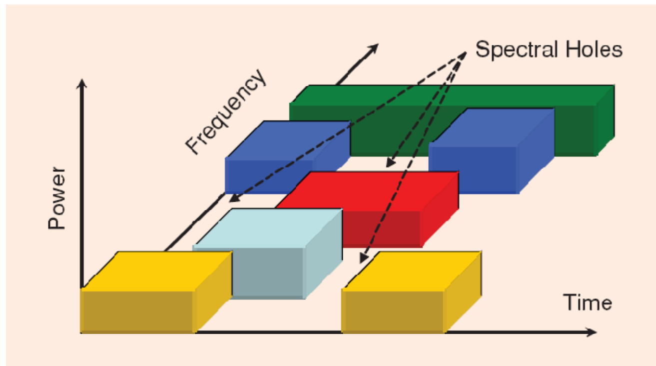

Fig. 1: A conceptual illustration of spectrum utilization over time and frequency. Within a certain geographical region and at a certain time, some frequency bands are not used by legacy systems [4].

In the light of above discussion, cognitive radio can be defined as [5]:

Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind: firstly, highly reliable communications whenever and wherever needed and secondly, efficient utilization of the radio spectrum.

A. An Overview of Cognitive Functions in a CR

Indeed, for reconfigurability, a CR relies on SDR whereas for the implementation of other cognitive tasks, the CR looks to signal-processing and machine-learning procedures. The cognitive process starts with the radio sensing of spectrum holes and end up with certain actions. Thus, primarily, there are three main cognitive tasks for a CR:

1) *Radio-scene analysis*, which includes the following:
- estimation of interference of the radio environment;
- detection of spectrum holes.

2) *Channel identification*, which encompasses the following:
- estimation of channel-state information;

- prediction of channel capacity for use by the transmitter.

3) *Transmit-power control and dynamic spectrum management*.

Tasks 1) and 2) are carried out in the receiver, and task 3) is carried out in the transmitter. Through interaction with the RF environment, these three tasks form a cognitive cycle, which is pictured in its most basic form in Fig. 2. In this paper, we have focused on Task 1), for which we have highlighted some of the research challenges and their solutions.

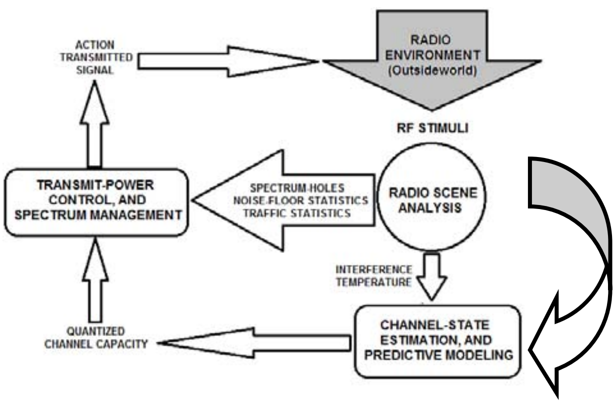

Fig. 2: Basic cognitive cycle which demonstrate three fundamental cognitive tasks.

B. CR as A Feedback Communication System

From the above arguments, it is noticeable that the cognitive processing element in the transmitter must work in a harmonious manner with the cognitive modules in the receiver. In order to maintain this harmony between the cognitive radio's transmitter and receiver at all times, we need a feedback channel connecting the receiver to the transmitter. Through the feedback channel, the receiver is enabled to convey information on the performance of the forward link to the transmitter. Thus, the CR is a *feedback communication system* [5].

C. Historical Background

The term "cognitive radio" was coined by Joseph Mitola. In an article published in 1999; Mitola described how a cognitive radio could enhance the flexibility of personal wireless services through a new language called the radio knowledge representation language (RKRL) [6]. The idea of RKRL was expanded further in Mitola's own doctoral dissertation, which was presented at the Royal Institute of Technology, Sweden, in May 2000 [7]. This dissertation presents a conceptual overview of cognitive radio as an exciting multidisciplinary subject.

The FCC published a report in 2002, which was aimed at the changes in technology and the profound impact that those changes would have on spectrum policy [8]. That report set the stage for a workshop on cognitive radio, which was held in Washington, DC, May 2003. The papers and reports that were presented at that Workshop are available at the Web site listed under [9]. This Workshop was followed by a Conference on Cognitive Radios, which was held in Las Vegas, NV, in March 2004 [10].

CR technology has already been adopted as a core platform in emerging wireless access standards such as the IEEE 802.22-Wireless Regional Area Networks (WRANs) [11]. The most important application of IEEE 802.22 WRANs is wireless broadband access in rural and remote areas, delivering performance comparable to that of existing broadband access technologies, digital subscriber line (DSL) and cable modems, serving urban and suburban areas [12,13]. IEEE 802.22 networks are expected to exploit the unused ultra-high frequency (UHF) TV bands provide wireless services such as data, voice, audio, and video traffic with appropriate quality of service (QoS) support [14].

D. Contribution and Organization of this Paper

The main contribution of this paper is to present an overview of CR and its core tasks and to highlight some of the major challenges faced by CR in spectrum hole detection. In this context, some possible solutions are also provided.

The paper is organized as follows: Following the introduction in Section I, the problem of spectrum hole detection is introduced in Section II. Section III addresses some of the future research challenges faced by CR in spectrum sensing. Some proposed solutions for the highlighted problems are provided in Section IV. Simulation results for the statistics of the proposed analytical model are presented in Section V. Finally, concluding remarks are given in Section VI.

II. Spectrum Hole Detection

The problem of spectrum hole detection is to detect a weak primary signal, *s(n),* confined inside some noisy signal, *v(n),* in the presence of *N* available measurements. Thus, this problem can be considered as a binary hypothesis problem which can be formulated as follows:

$$H_0 : x(n) = v(n),$$
$$H_1 : x(n) = hs(n) + v(n), \qquad n = 1,2,....,N \qquad (1)$$

where H_0 and H_1represent the scenarios of the absence of the primary signal and presence of primary signal, respectively. The parameter *h* is representing the channel gain which is assumed to be constant during detection interval (*N* samples).

Now, consider a non-coherent energy detector also called radiometer [9] which decides between the binary hypotheses mentioned above by using the following decision rule

$$T(x) \overset{\Delta}{=} \sum_{n=1}^{N} | x(n) |^2 \underset{H_0}{\overset{H1}{\gtrless}} \gamma, \qquad (2)$$

where γ is the decision threshold. Next, the concept of collaborative spectrum sensing will be presented.

A. *Collaborative Spectrum Sensing*

In case of collaborative spectrum sensing, a secondary user performs spectrum sensing via collaboration of decision statistics from other secondary users. Let us consider a CR with K number of secondary users collaborating with each other. The decision statistics for each secondary user can be obtained using equ. (2).

The objective of collaborative spectrum sensing is to design efficient cooperation schemes for the K spatially distributed nodes to improve the sensing reliability, i.e., to maximize probability of correct detection while maintaining the probability of false detection as small as possible. This can be achieved via fusing the decisions from K nodes either centralized or distributed methodology as shown in Fig. 3. The centralized implementation uses a fusion center to fuse the sensing results from multiple CRs and arrive at the final decision. In the distributed case, each CR collects the sensing results from its neighbors and performs its own local decision fusion.

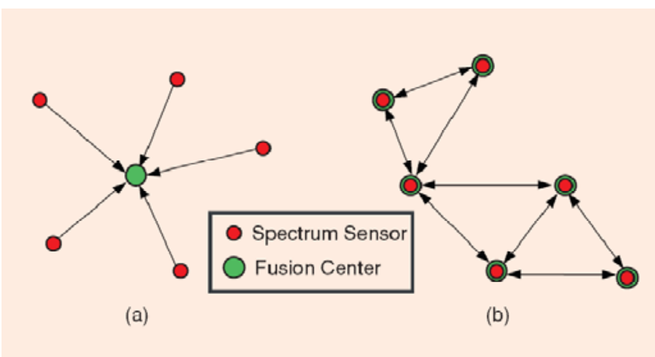

Fig. 3: Data fusion for cooperative sensing. (a) In centralized implementation, the sensing results of individual CRs are sent to a fusion center in which a global decision is made. (b) In distributed implementation, each CR acts as a fusion center, collecting the sensing measurements from its neighboring nodes and making its decision independently [4].

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III. FUTURE RESEARCH CHALLENGES IN SPECTRUM SENSING

There a number of design challenges faced by spectrum sensing which includes reliable sensing, collaborative wideband sensing, efficient opportunistic spectrum sharing, and hardware considerations at physical layer. In this paper, we will focus on the issues related to reliable spectrum sensing for CRs and are discussed as follows.

1) Given a single frequency band, the first challenge for CRs is to reliably detect the existence of primary users to minimize the interference to existing communications. Since the signals are usually undermined by channel shadowing or multipath fading between the target-under-detection and the CRs, it is generally difficult to distinguish between a white spectrum and a weak signal attenuated by a bad channel. Fading or shadowing may result in the hidden terminal problem, as illustrated in Fig. 4, where one CR node (CR1) inside the protection region of a primary transmitter (PTx) cannot detect the primary signal due to shadowing; in this case, CR1 may assume that it is outside the protection region of PTx and may cause harmful interference by transmitting in the primary frequency band.

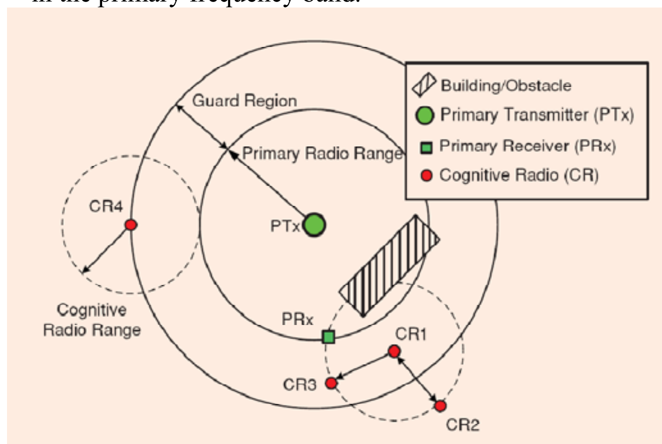

Fig. 4 The hidden terminal problem in CR networks, in which the guard region and the area covered by the primary radio range together form the protection region of the primary transmitter [4].

2) Another serious challenge for CR systems is to keep an eye on and process ultra-wide frequency bands (up to several Giga hertz) in order to reliably find spectral holes for opportunistic spectrum access. Such a requirement presents inimitable challenges to both hardware design at the RF front-end and the development of reliable signal processing algorithms. First, spectrum sensing requires a wideband RF front-end with a high-resolution high-speed analog-to-digital (A/D) converter, which is expensive to implement [15]. Second, spectrum sensing should accurately identify both occupied and unoccupied frequency segments in real time to improve spectrum utilization and avoid introducing harmful interference to the primary radios.

3) Efficient collaborative spectrum sensing should be developed to mitigate the problem of erroneous detection. In dealing with energy detection for collaborative spectrum sensing, decision statistic based on signal energy is usually assumed to be Gaussian by employing central limit theorem which is not always true in practice. Consequently, the efficiency of these detection algorithms is expected to be poor in the presence of fewer nodes. Thus, efficient detection algorithms based on more realistic statistics of the signals should be designed.

4) Adaptive fusion techniques in order to fuse the sensing results of multiple CRs and exploit spatial diversity among distributed CRs to enhance the sensing reliability should be designed as most of the existing works in literature are non-adaptive in nature.

5) One important design consideration is the overhead reduction associated with sensing information exchange and the feasibility issue of control channels.

6) Previous works on wideband sensing do not consider joint decisions over multiple frequency bands, which is essential for implementing efficient wideband CR systems. A little amount of work has been devoted to joint multiband detection. Hence, joint multiband detection for wideband spectrum sensing technique will be more suitable which will jointly optimize a bank of narrowband detectors instead of processing only one narrow band at a time.

7) Since CRs usually have limited knowledge about the primary signals, energy detection becomes a most important technique for spectrum sensing. In dealing with energy detection for spectrum sensing in CRs, decision statistic based on signal energy is usually assumed to be Gaussian by employing central limit theorem which is not always true in practice. Consequently, the efficiency of these detection algorithms is expected to be poor in the presence of fewer nodes. Thus, efficient detection algorithms based on more realistic statistics of the signals should be designed.

IV. Proposed Solutions To Some Of The Highlighted Research Issues

In this section, we have proposed to solutions to some of the research challenges mentioned above.

A. Employing Accurate Probability Distribution for Decision Statistics used in Collaborative Spectrum Sensing

As mentioned in the previous section that decision statistic used in collaborative spectrum sensing for signal energy detection is usually assumed to be Gaussian by employing central limit theorem which is not always true in practice. As a result, the performance of these detection algorithms is expected to be poor in the presence of fewer nodes. To alleviate this problem, we proposed to use accurate probability distribution of decision statistics appeared in energy detection. For example, the decision statistics can be considered as chi-square distribution or weighted sum of chi-square distributed random variables [16]. One possible solution is to evaluate this problem is to use statistics by employing the approach of indefinite quadratic form [17]. Thus, we proposed to apply the methodology given in [17] for signal energy detection. It is shown via simulations, in Section V, that the proposed analytical model matched very well with simulations.

B. Adaptive Time Frequency Approach for Joint Multiband Detection in Wideband Spectrum Sensing

It is already highlighted in the previous section that existing works on wideband sensing either do not consider joint decisions over multiple frequency bands or employ non-adaptive approach for joint multiband detection. This motivates to develop some adaptive spectrum sensing algorithms which can efficiently provide joint estimation over multiple frequency bands. For this purpose, one possible solution is to employ time varying wavelets based adaptive estimation algorithms [18].

C. Design of Adaptive Fusion Techniques for Collaborative Spectrum Sensing

Collaborative spectrum sensing requires fusion of spectrum sensing results from multiple CRs and exploit spatial diversity among distributed CRs to enhance the sensing reliability. Since, the wireless channels are of random and time varying nature. Thus, we proposed to design some adaptive strategies for fusing the sensing results. One possible choice is blind adaptive algorithms [16] based fusion mechanism. This will be well suited for the spectrum sensing scenario. Another choice is to develop a constrained adaptive algorithm by employing the knowledge of noise and interference power as was done in [19].

V. Simulation Results

In this section, we have simulated the cumulative distribution function (CDF) of the decision statistics for energy detection encountered in spectrum sensing in CRs. The decision statistic given in equation (2) is simulated by generating correlated complex Gaussian random variables.

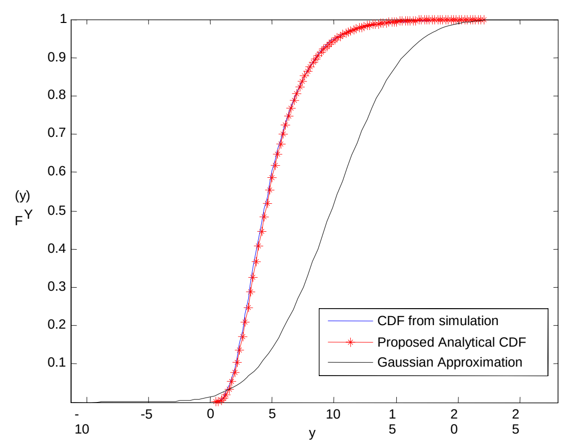

Fig. 5: CDF of decision statistics for energy detection, N=10

In order to compare this result, two analytical models are used: one with Gaussian approximation as used in [4] and the other proposed by us using the methodology of [17]. Two different scenarios are considered for simulations: one with N equal to 10 nodes and the other with N equal to 20 nodes shown in Fig 5, and Fig. 6, respectively. It can be easily depicted from these simulation results that the proposed model suited well for energy detection problem.

VI. Conclusion

This paper presents an overview of CR and its different operations. The problem of spectrum hole detection is investigated. Current research issues related to spectrum sensing along with some of its solutions are highlighted. It is proposed to use an accurate decision statistics for collaborative spectrum

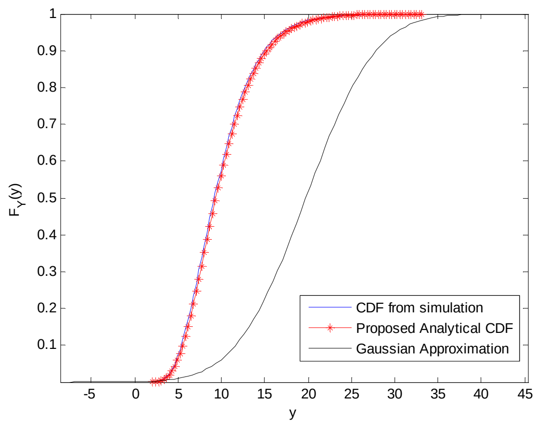

Fig. 6: CDF of decision statistics for energy detection, N=20

sensing instead of Gaussian approximation. Simulation results for the decision statistics in collaborative spectrum sensing based on proposed model is presented to support our proposed idea. It is found that the proposed model is well suited for the concerned scenario. Thus, this give us a motivation for the future work to develop spectrum hole detection algorithm using the proposed mathematical model for decision statistics.

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