Spectrum Sensing Techniques in Cognitive Radio Communications

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***Abstract*— In this paper, we review some of the recent patents on spectrum sensing techniques for cognitive radio (CR) applications. The presented patents are categorized under: 1) spectrum sensing algorithms and architectures, 2) spectrum sensing and data communication and 3) cooperative spectrum sensing. The presented patents include special sensing algorithms that are based on the multi-resolution spectrum sensing (MRSS) approach, which ensures reliability of the spectrum sensing in wireless RF environments. We also discuss a CR patent that includes multiple RF chains to perform simultaneous cognitive tasks. Several patents that consider cooperative sensing are also presented as a solution to the hidden terminal problem inherent in wireless networks. We review the advantages and disadvantages of the presented patents and propose future directions for developing spectrum sensing techniques for CR's.**

***Index Terms*— Cognitive radio, cooperative spectrum sensing, dynamic spectrum access, energy detection, multi-resolution spectrum sensing, opportunistic spectrum access, spectrum sensing.**

I. INTRODUCTION

The concept of cognitive radio (CR) was initially envisioned by Mitola to be a radio device that is able to learn and adapt to its environment [1]. Haykin refined this concept by defining CR's to be *brain-empowered* wireless devices that are aimed at improving the utilization of the electromagnetic spectrum [2]. This definition was motivated by an observation made in an FCC report which claimed that a large portion of the allocated spectrum resources is being underutilized [3]. In order to improve the efficiency of the spectrum usage, a dynamic spectrum access (DSA) CR would access licensed primary channels while satisfying the primary user's quality of service (QoS) requirements. In this process, however, the primary user is completely oblivious to the secondary cognitive users' activity. An alternative dynamic spectrum sharing scheme, called Dynamic Spectrum Leasing (DSL), allows the primary users to proactively manage the secondary CR spectrum usage [4]–[7].

Several spectrum sharing mechanisms have also been developed to facilitate the CR operation. These include underlay, overlay and interweave paradigms [8]. In underlay mode, a secondary user can simultaneously communicate over the same channel of a primary user, such that it does not exceed a certain interference cap. In overlay, the secondary user uses complex techniques (e.g. coding techniques) to communicate over a primary channel without affecting the licensed users. Interweave mode is based on the opportunistic spectrum access (OSA) and consists of a secondary user sensing the primary activity and communicating whenever the primary user is absent. Due to their simplicity, the underlay and interweave paradigms received the most attention in current CR literature. In order to achieve DSA, a CR should invariably sense and observe the primary users' activity before communicating, for, otherwise, the secondary users may collide with the primary user's transmission. Hence, spectrum sensing has become an essential step in CR operation, as identified in [2].

Many spectrum sensing techniques have been proposed over the last decade. These are primarily based on the matched filter, energy detection, cyclostationary detection, wavelet detection and covariance detection methods [9]. In addition, cooperative spectrum sensing was proposed as a means of improving the sensing accuracy by addressing the hidden terminal problem inherent in wireless networks [9]–[15].

On the other hand, many patents have been developed to address the implementation of spectrum sensing methods for CR applications: For example, [16] has invented a spectrum sensing technique that uses a dual threshold to detect primary activity, [17] has considered the problem of sensing and data communication by inventing a CR system with multiple RF chains and [18] has invented a robust cooperative spectrum sensing technique that takes advantage of the diversity of wireless channels to improve the spectrum sensing accuracy.

In this paper, we review some of the most recent patents for spectrum sensing in CR. First, we review two inventions that employ sophisticated sensing techniques to detect specific primary signals [16], [19]. Both these use wavelet-based schemes to ensure more robust signal detection. Next, we discuss a CR invention that makes use of location and time information in performing its cognitive tasks [20]. By knowing the time and the location, a CR may use certain spectrum utilization statistics to determine the spectrum usage during a particular time and at a particular location. This information may help the CR to be more selective (and more efficient) in performing cognitive tasks, such as spectrum sensing. Next, we look at patents that address the problem of communication efficiency in CR's by presenting a patent that is equipped with multiple RF chains to handle simultaneous cognitive tasks. In particular, we review the CR device that was invented in [17] which assumes a radio device with two RF chains to support simultaneous sensing and communications. We note that the above inventions are designed to operate independently in wireless environments, which makes them vulnerable to the hidden terminal problem [21], [22]. In general, a hidden terminal problem arises when a primary transmitter may fail to be detected by a certain CR due to the dynamic nature of the wireless environment. To resolve this issue, however, cooperative spectrum sensing has been proposed, in which multiple CR's share sensing results [10], [11], [13], [23]. We review the inventions of [18], [24] which consider CR networks with cooperative spectrum sensing abilities. In addition to solving the hidden terminal problem, cooperative CR architectures can also help extend the geographic coverage area of a CR by distributing the sensing nodes over a wide region. After describing each of those inventions, we present a table summarizing the characteristics, advantages and disadvantages of the reviewed patents.

The remainder of this paper is organized as follows: Section II describes the major challenges in spectrum sensing. Afterwards, we review the above recent inventions in spectrum sensing by presenting in Section III sophisticated spectrum sensing techniques that rely on wavelet detection. In Section IV, we describe a CR architecture invention that includes a dual-radio chain to enhance the communication efficiency. Next, in Section V, we present several cooperative CR architectures that help solve the hidden terminal problem. Finally, we present in Section VI a comparison among the reviewed patents and conclude this paper in Section VII.

II. MAJOR CHALLENGES IN SPECTRUM SENSING IN COGNITIVE RADIO APPLICATIONS

In this section, we give a brief overview of the spectrum sensing challenges in CR and point out some of the recent inventions that address those problems. A comprehensive survey of spectrum sensing algorithms can be found in [25]. According to [25], *spectrum sensing is the process of obtaining awareness about the spectrum usage and existence of primary users in a geographical area*. This involves determining, not only the existence of a certain signal in a particular band, but also the types of signals that are occupying the spectrum including the modulation, bandwidth, carrier frequency, etc. This can be achieved through various signal analysis techniques that range from simple energy detection to more sophisticated sensing methods. Note that, the challenges faced in spectrum sensing for CR applications we review below are mostly due to [25].

A. Hardware Requirements

In order to be able to process detected RF signal, a CR requires a high sampling rate, high resolution analog-to-digital converters (ADC's) with large dynamic range and high speed signal processors. Since CR's search for all possible spectrum opportunities, they may need to sense a wide frequency band, requiring high speed clocks for sampling the corresponding RF waveforms. Thus, hardware components of CR's can impose serious limitations on spectrum sensing capabilities in some applications.

On the other hand, the capabilities of CR platforms can be enhanced by introducing parallel hardware. In general, sensing can be performed via two different architectures: single-radio and dual-radio [25]. A single-radio architecture consists of a single RF chain that performs both sensing and data communication in different time slots. Of course, this architecture is simple in its implementation but is inefficient for data communication because a portion of time is used for spectrum sensing. On the other hand, the dual-radio architecture includes two separate RF chains. A first chain is dedicated for spectrum sensing whereas the second chain is intended for data communication. This architecture ensures better sensing performance as well as efficient data communication since one chain continuously senses the RF spectrum and the second chain communicates over the available channels. However, it suffers from high power consumption and RF interference. In this paper, we review a CR patent that includes a dual-radio architecture and describe its advantages and limitations [17].

B. Hidden Terminal Problem

In CR applications, the hidden terminal problem refers to the problem of primary signal interference to the CR receiver due to those primary users that were undetected by the CR transmitter. This can be caused by many factors including, for instance, limited sensing range of a CR transmitter, severe multipath fading, and/or shadowing. Cooperative sensing has been proposed in recent literature for handling such hidden terminal problems [23], [26], [27], in which multiple CR's cooperate in a network and either share their sensing results (distributed cooperation) or send sensing results to a central node (centralized cooperation). This technique is efficient in solving the hidden terminal problem but it suffers from communication overhead required for data exchange. In this paper, we will review two patents that employ cooperative spectrum sensing to address the hidden terminal problems [18],[24].

C. Detecting Spread Spectrum Primary Users

There are two main types of technologies found in commercially available RF devices: 1) fixed frequency, and 2) spread spectrum. The two major spread spectrum technologies are frequency-hopping spread-spectrum (FHSS) and direct-sequence spread-spectrum (DSSS) [28]. Fixed frequency devices operate at a single frequency or in a single channel. An example is the WLAN systems based on IEEE 802.11a/g standards. FHSS devices, on the other hand, change their operational frequencies dynamically to multiple narrowband channels. This frequency hopping is performed according to a sequence that is known to both transmitter and the receiver. The DSSS devices spread their energy over a single frequency band. Primary users that use spread spectrum signaling are difficult to be detected due to distributed signal power over a wide frequency range [29]. This problem can be partially avoided if the hopping pattern is known and perfect synchronization to the primary signal can be achieved. However, it is not straightforward to design algorithms that can do the estimation in code dimension. A patent, as is reported in [19], is supposed to address the detection problem of DSSS primary signals by relying on multi-resolution spectrum sensing (MRSS) techniques.

D. Sensing Duration and Frequency

In order to better utilize spectrum opportunities and to prevent interference to and from spectrum license owners, sensing strategies of CR's should be carefully designed. For instance, sensing frequency (i.e. how often a CR should perform spectrum sensing) is a design parameter that needs to be chosen carefully, since it directly affects the performance of the CR in terms of the probability of collision with primary signal and the transmission throughput, etc. The optimum value depends not only on the capabilities of a CR itself but also the temporal activity characteristics of primary users in the RF environment [30], [31]. Moreover, due to the fact that a channel being used by a CR cannot be sensed at the same time, the CR must interrupt its data transmission for spectrum sensing. This, however, decreases the spectrum efficiency of the overall system. As a result, the selection of sensing parameters brings about various tradeoffs, for example, between the sensing time duration and reliability of sensing, and between the power consumption and transmission throughput.

E. Security

A selfish, or malicious, cognitive user may modify its RF characteristics to mimic a primary user in order to gain benefits in terms of data throughput. Such a behavior has been investigated in [32]–[34] and termed as primary user emulation (PUE) attack. The challenging problem is to develop effective strategies and countermeasures for the other CR's and legitimate primary users once an attack is identified.

III. SOPHISTICATED SPECTRUM SENSING TECHNIQUES FOR COGNITIVE RADIOS

In wireless communications, the detected RF signals are affected by fading, scattering and many other environmental perturbations. These perturbations cause the magnitude of the received signals to vary drastically, thus resulting in a wide dynamic range of the received signals magnitude. Furthermore, these variations can be affected by the varying distance between a certain transmitter and a receiver (due to motion, for example), which makes the received signals statistics almost unpredictable by the receiver. Hence, the conventional energy detection may not be suitable for detecting RF signals under such circumstances, since energy detectors require accurate estimations of the noise levels and perfect knowledge about the noise statistics [35].

The inventors of [19] further argue that the conventional energy detection is not suitable for detecting sophisticated digital signals, such as direct sequence spread spectrum (DSSS), frequency hopping and multi-carrier modulation. That is, the energy detector does not differentiate among modulated signals, noise and interference signals and is vulnerable to unknown varying noise levels. Hence, more sophisticated sensing techniques are required to accurately identify such RF activity. In particular, wavelet-based signal detection has recently being considered for identifying certain signals based on the computed correlation between the received signal and a wavelet pulse. The correlation coefficients are analyzed to identify the existence of a particular signal of interest. This technique is becoming more popular in the design of CR spectrum sensing modules since it can be robust against wireless channels perturbations, as compared to the energy detection [16], [19].

In this section, we first review two recent patents that use wavelet transform to detect primary signals. The first invention proposed in [16] describes a spectrum sensing algorithm to detect the primary activity. The second patent [19] describes the system architecture of a wavelet-based spectrum sensing module. Afterwards, we discuss a CR platform that combines the location and time information with the cognitive tasks (e.g. spectrum sensing, etc.) in order to provide a spectrum utilization database to assist the CR operation [20].

A. A Spectrum Sensing Algorithm based on the Wavelet Transform

The invention claimed in [16] proposes a spectrum sensing algorithm for CR's that aims at detecting multiple active channels in a received signal. The sensing is performed at three stages. In the first step, a coarse scan of the spectrum determines the possibly occupied and vacant candidate channels. In the next step, a fine sensing is applied to determine the actually vacant and actually occupied channels. At the third stage, a final decision is made on the state of each channel, whether being occupied or vacant. The proposed MRSS applies the wavelet transform [36], [37] to a time-varying signal to determine the correlation between a time-varying signal and a basis function (i.e. the wavelet pulse) [37], [38]. This correlation is known as the wavelet transform coefficient [37]. The wavelet pulse used can be varied to allow detecting of different signal shapes. For example, the wavelet pulse can change in carrier frequency, bandwidth and/or time period to provide an analysis of the spectral content of the time-varying signals. The patent described in [16] proposes a spectrum sensing algorithm that can be applied to reliably detect multiple signals transmitting on different channels. The proposed algorithm assumes no prior knowledge about the primary signals. As mentioned earlier, the spectrum sensing algorithm is made of the following tri-stage procedure:

1) A coarse-scanning stage: The coarse-scanning procedure examines input RF spectrum over a wide span with a coarse resolution MRSS. The coarse MRSS scan is repeated several times to obtain an accurate estimate of average power on a certain channel. This average power estimate is compared to a dual-threshold to specify whether a particular channel contains a strong or weak candidate signal, or whether it does not contain any candidate signal.

2) A fine-scanning stage: After performing the coarse-scanning, the candidate channels labeled as strong, weak and vacant are provided for strong-bin, weak-bin and vacant-bin testing, respectively, as shown in Fig. 1. Each type of candidate channels will be tested appropriately to decide on the actual state of each candidate, whether being strong, weak or vacant channel.

3) *A* final decision stage: At this stage, the occupied channels from the strong and weak channels tests are merged together to provide a final list on the actually occupied

channels, as shown in Fig. 1. The vacant channels that are obtained in the fine-scanning stage are the actually vacant channels. These decisions are then reported to a medium access control (MAC) unit to control the actions of the CR.

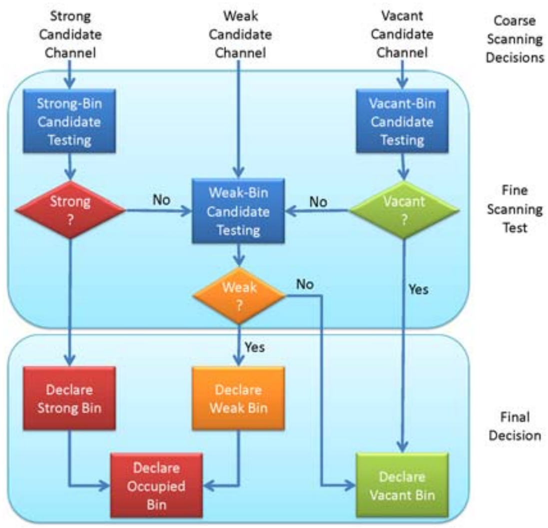

Fig. 1: The fine-scanning algorithm of [16] classifies the candidate channels into vacant, weak and strong channels. A final decision is made on the occupancy of each candidate channel at the end of the final decision stage.

The contribution of this patent is in providing a dual-threshold hypothesis testing for identifying the actual states of the primary channels. According to the inventors, this dual-threshold technique helps combating the variations in the dynamic range of the received signal powers. A similar approach was proposed in [39] for designing a CR system that is suitable for wide-band, wide dynamic-range spectrum sensing. The proposed sensing method of [39] consists of two steps in which different threshold values are applied to the received signal. However, in each step, [39] completely relies on energy detection. On the other hand, the use of MRSS in conjunction with the wavelet transform in [16] provides an analysis of the spectral contents of time-varying signals and leads to possibly more accurate sensing decisions. This is similar to many other wavelet-based multi-resolution and cyclostationarity-based spectrum sensing techniques which have been shown to outperform the simple energy detection by exploiting the spectral components of the measured signals [40], [41]

B. A System Architecture of a Cognitive Radio with a Wavelet-based Spectrum Sensing Module

Similar to [16], the inventors of [19] propose a spectrum sensing module that is based on MRSS. The inventors provide an algorithm for the claimed invention and they give a detailed description of the system architecture and its physical components. Similar to [16], the invention in [19] assumes coarse- and fine-scanning steps for detecting primary signals. The coarse-sensing module may detect the existence or presence of suspicious spectrum segments (e.g. potentially utilized spectrum segments), while the fine-sensing module may analyze the detected suspicious spectrum segments to determine the types of the existing signals.

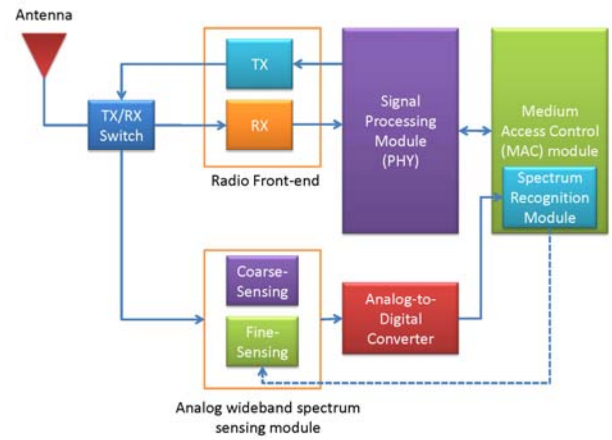

Fig. 2: The system architecture of the CR of [19] includes both fine- and coarse-scanning modules to perform wavelet detection.

The invention in [19] assumes a plurality of wavelet pulses that can be correlated with the received signals to identify their types. Moreover, a spectrum usage database may be used to determine the type of the transmitted signals in a particular frequency band. More importantly, [19] assumes reconfigurable hardware that can change its mode of operation to adapt to different RF environmental conditions and to achieve certain objectives. In particular, due to its reconfigurable abilities, the assumed radio front-end may operate on various frequencies.

As is illustrated in Fig. 2, in the CR system invented in [19] the antenna receives the RF input signal and passes it to the spectrum sensing module. The assumed antenna has wide-band characteristics enabling an operation from several megahertz (MHz) to the multi-gigahertz (GHz) range. Upon receiving the input RF signal, the spectrum sensing module processes the signal and determines the spectrum occupancy. The sensing results are then sent to an ADC which converts the spectrum occupancy information to digital values. This information is sent to the spectrum recognition module in the MAC module which analyzes the digital spectrum occupancy to decide whether one or more spectrum segments are currently in use or occupied by some users. The CR may then make suitable actions based on these spectrum occupancy results.

C. A Time and Location Information Assisted Cognitive Radio Platform

The CR architecture invented in [19] includes a spectrum usage database that provides information about the spectrum usage in certain frequency bands. Such information may be location- and/or time-dependent since the spectrum allocation may vary from place-to-place and also with respect to time. To exploit this additional information, an invention was claimed in [20] to make a CR time and location-aware while performing its cognitive tasks. The invented device includes both hardware and software inter-connections and operation procedures, and techniques for determining whether or not a CR device may perform a cognitive task. The considered possible cognitive tasks may include: 1) radio-scene analysis, which may encompass: 1)(a) estimating interference temperature (a metric that quantifies sources of interference in an RF environment); and 1)(b) detecting spectrum holes by spectrum sensing; 2) channel identification, which may encompass: 2)(a) estimation of channel-state information; and 2)(b) prediction of channel capacity; and 3) transmit-power control and/or dynamic spectrum management.

The main idea behind the patent [20] is to include time and location determining devices to the system architecture so that the CR may determine whether or not to perform a cognitive task, or whether to perform a cognitive task in a certain way, at a particular time and at a particular location. For example, time information may be used to determine, for particular points or periods of time during the day, which portions of the RF spectrum are typically being used, whereas location information may be used to determine, for particular locations, which portions of the RF spectrum are typically being used. As a result, the CR device may determine, based on the time and location information (either both or one of them), whether or not to scan the entire RF spectrum, or which portions of the RF spectrum are likely to include spectrum opportunities and to scan those specific portions only, thus being efficient. The corresponding CR architecture, the schematic representation of the communication system and hardware and software operation procedures were also provided in [20].

IV. Spectrum Sensing and Data Communications

During the sensing process, a CR tries to identify the RF activities in a spectrum band of interest. In many situations, the operating spectrum band can be very wide making it difficult to sense the whole band at once due to hardware limitations (e.g. low sampling rate at the ADC). In this case, the CR may split the whole spectrum band into smaller sub-bands and use several RF chains to operate in each of the assumed sub-bands. Hence, the different RF chains would have different operating frequency ranges, enabling them to operate in different spectrum bands. On the other hand, a CR equipped with multiple RF chains can have other advantages. For example, a CR that is equipped with multiple RF chains may use one RF chain to communicate in a certain frequency band, while performing either in-band or out-of-band sensing[1] by using a different RF chain. In this case, the different RF chains would have similar operating frequency ranges, but different architectures (i.e. communication chain, sensing chain with energy detection, sensing chain with matched-filter detection, etc.).

In [17], the inventors have designed a CR device that includes at least two different RF chains to perform multiple tasks, as mentioned above. The sensing CR RF chains may be equipped with energy detection, feature detection or matched filter. By forming different combinations of sensing and data communication chains, the inventors in [17] propose several CR devices that are suitable for in-band sensing and communication, while performing out-of-band sensing. The importance of out-of-band sensing is in ensuring backup channels that can be used whenever the current in-band channel becomes busy [42]. This is a major requirement for achieving efficient multiband operability of the CR. However, in order to implement such operations, it is required to have parallel hardware configurations since each RF chain can operate only in a single band at any given time.

[1] In-band sensing refers to the process of sensing a channel that is currently being used by the secondary user, whereas out-of-band sensing refers to sensing a channel that is currently being unused [42].

In the following, we give a brief description of the different CR devices that were proposed in [17]. The general structure of these devices is shown in Fig. 3 and consists of three main blocks: 1) RF chains, 2) MAC processor and 3) upper layer processor. The RF chain forms, with the antennas, the RF front-end of the CR device. The RF front-end is responsible for sensing and for modulation/demodulation of incoming and outgoing RF signals. It also includes an ADC that forms the interface between the analog RF chain and the digital MAC processor. The MAC processor performs control resource management and scheduling for various operations that are performed by the RF chains. The MAC processor is also responsible for transmitting and receiving various types of signals to and from an upper layer processor.

The first system architecture that was described in [17] consists of two RF chains. The first chain is dedicated for in-band sensing and data communication, whereas the second chain is responsible for out-of-band sensing. In this setup, the out-of-band sensing chain finds backup channels that can be used by the CR when the current communication channel becomes unavailable.

The second CR device also has two RF chains. The first chain is dedicated for communication and in-band fast sensing. The fast sensing consists of energy detection that is applied to the received signal. Energy detection is applied periodically (or aperiodically) in the in-band, while CR is communicating. The other chain performs fine sensing in the in-band and sensing in an out-of-band. If the first chain detects high energy levels, the CR may perform fine sensing (feature detection) in the in-band through the second RF chain. The CR device stops communicating if a certain signal is detected by the fine detection at the second RF chain and it switches to a backup channel that is detected by the out-of-band sensing of the second RF chain.

Note that, the CR communication device may include a separation module to reduce interference between the first and the second RF chains. The interference may interrupt the feature detection by the second RF chain due to the transmission signal of the first chain. The inventors in [17] describe the signal detection in the presence of interference: Essentially, the CR transmission signal is subtracted from the received signals at the sensing chain. Signal detection algorithms are then applied, as usual, to detect primary signals based on threshold testing.

Based on the invention in [17], we note two main advantages of having multiple RF chains in a CR communication device:

1) Multi-band operability: If the operating spectrum band of interest is very wide, it cannot be sensed and used for communication by a single RF chain. That is because RF components have a limited frequency range of operation. Thus, it is required to have multiple RF chains on the same CR device, having different operating frequencies.

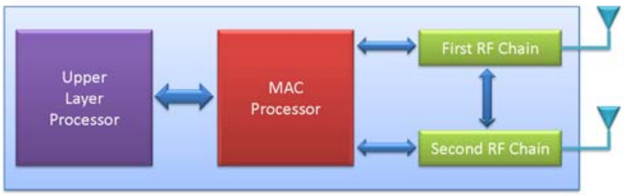

Fig. 3: A system architecture of the CR of [17] which includes multiple RF-chains to perform multiple cognitive tasks, simultaneously.

2) Uninterrupted communication: In in-band operation, it is impractical to perform both sensing and communication simultaneously with the same RF chain. By having parallel RF chains, data communication can be performed on a certain chain, while the other chain is sensing the in-band channel to detect any primary activity. Otherwise, a single RF chain would have to periodically or aperiodically interrupt the data communication in order to perform in-band spectrum sensing.

However, one disadvantage of such multiple RF chains based techniques is in the complexity of designing parallel RF chains and multiple antennas for a single CR device [42], [43]. The major drawbacks of these designs are due to high power consumption and to interference and coupling between multiple RF components [43]. Possible alternative solutions to reduce parallel hardware can be obtained by using reconfigurable RF chains and reconfigurable antennas [44]–[46].

V. Robust Cooperative Spectrum Sensing for CR's

During the last few years, cooperative spectrum sensing was introduced as a technique to provide more accurate and robust estimation of the primary signals activity [9]–[15]. Given a network of CR's, each node senses a certain primary channel and reports the result to a base station or a central unit. The central unit processes the sensing results of all the sensing nodes and makes a decision on the availability of a certain channel.

There are several advantages of cooperative spectrum sensing, compared to independent spectrum sensing. First, it has been shown that cooperative spectrum sensing can combat fading in wireless channels, due to the spatial diversity that is offered by distributed wireless networks [9]–[15]. Second, cooperative spectrum sensing can cover a larger area by cooperatively detecting available spectrum across multiple energy detector locations [18]. Thus, cooperative spectrum sensing is very appealing for spectrum sensing in highly turbulent and dynamic wireless environments. To illustrate the importance of this concept, we present two inventions of cooperative spectrum sensing systems that were reported in [18], [24], and present their contributions.

The inventors in [18] propose a robust cooperative spectrum sensing system that is able to accurately detect the primary activity by using the energy detection. In general, the cooperative spectrum sensing is conducted in two stages: 1) spectrum sensing and 2) decision reporting. At the first stage, each sensing device performs local detection and makes a decision on the existence of a certain RF signal. Afterwards, the local decisions are reported to a common receiver which indicates the spectrum resources that are available for secondary use in the area covered by the plurality of the energy detectors. The reporting channel can be a wired connection, wireless connection or combination thereof [18].

If the reporting channel is a wireless channel, it will be subject to noise and interference. For this reason, wireless reporting channel cannot be considered to be perfect channels and they may cause reporting errors, which are manifested by false alarm or miss detection at the common decision center. In order to improve the decision reporting, the inventors of [18] include, in their model, several techniques that enhance the decision reporting. The first technique uses space-time (ST) coding [47], [48] for transmitting the local decision results to the common receiver. The ST coding takes advantage of the spatial and temporal diversity of the wireless channels [47], [48]. To implement ST coding, the local detectors form a virtual antenna and the nodes coordinate to generate ST codes. Thus, ST coding can be achieved even without multiple-input multiple-output (MIMO) antennas, thanks to the virtual antenna that can be formed by the different detectors [49]–[51]. The ST coding is suitable for flat-fading in which the channel conditions do not change over the spectrum band of interest. However, in the case of frequency-selective fading channels, the inventors of [18] suggest the space-frequency (SF) coding [52] as a means of achieving higher diversity in the link between the detectors, from one side, and the common receiver, from the other side. In addition to that, a third reporting technique based on signal relaying can be implemented to relay the decision of one detector to the common receiver, through another detector [53]. This technique is efficient whenever the direct link from the detector to the common receiver is subject to high fading or blocked due to certain physical conditions. In this case, relay diversity can be made more robust by employing algebraic coding [18], [54].

Another reporting technique invented in [24] based on user clustering reduces the channel fading effects on the wireless reporting channel. The inventors propose to cluster the cognitive users by an upper layer using any previously known clustering algorithms. Then the most favorable user with the largest reporting channel gain, referred to as the cluster head, will be designated to report the sensing decisions to the common receiver. Each cluster head collects energies of a reporting channel measured by the cognitive users within the cluster and decides whether a primary user is absent from a given spectrum. A common receiver then aggregates the cluster-level decisions made by the cluster heads, and makes a decision whether the primary user is absent based on a fusion function of the cluster-level decisions. By separating secondary users into a few clusters and selecting the most favorable user in each cluster to report to the common receiver, the cluster-based cooperative spectrum sensing methods exploit the user selection diversity to enhance the sensing performance and reduce the reporting error caused by the channel fading. Moreover, both decision fusion and energy fusion can be applied at the common receiver.

To give a more detailed description of the cooperative spectrum sensing process, we describe the system that was

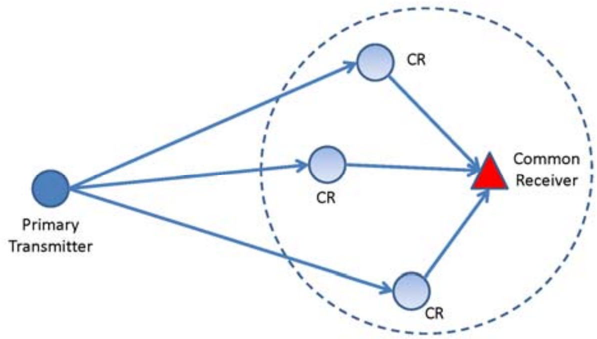

Fig. 4: The cooperative spectrum sensing scheme developed in [24] helps improve the primary detection probability by combining the observations of multiple CR's.

invented by [18] which assumes a CR network consisting of *K* CR devices and a common receiver, as shown in Fig. 4. The common receiver could be one of the CR's that is designated to act as a central node which can manage the other CR's in the CR network. Each CR device is equipped with a sensing component and a reporting component. The CR senses a frequency band of interest and decides whether a primary signal exists or not. This is a hypothesis testing problem with the observation signal:

$$x_i(t) = \begin{cases} n_i(t) & ,H_0 \\ h_i s(t) + n_i(t) & ,H_1 \end{cases}, \quad (1)$$

where $x_i(t)$ is the observed signal of the *i*-th sensing component, *s(t)* is the primary user signal, $n_i(t)$ is the additive white Gaussian noise (AWGN), h_i is the complex channel gain of the sensing channel between the primary transmitter and the *i*-th sensing component, H_0 hypothesis corresponds to a signal not being transmitted from a primary user and H_1 hypothesis corresponds to a signal being transmitted from a primary user. The energy collected in the frequency domain by the *i*-th sensing component is expressed as:

$$E_i = \begin{cases} \chi^2_{2u} & ,H_0 \\ \chi^2_{2u}(2\gamma_i) & ,H_1 \end{cases}, \quad (2)$$

where χ^2_{2u} denotes a central chi-square distribution with $2u$ degrees of freedom and $\chi^2_{2u}(2\gamma_i)$ denotes a noncentral chi-square distribution with $2u$ degrees of freedom and a noncentrality parameter $2\gamma_i$ [55]. The parameter γ_i is the instantaneous signal-to-noise ratio (SNR) of the received signal at the i-th sensing component and $u = TW$, where T is a time window and W is the bandwidth. Given a certain energy threshold λ_i, the resulting false alarm probability is [35]:

$$P_{f,i} = \frac{\Gamma_l(u, \lambda_i/2)}{\Gamma(u)}, \quad (3)$$

where Γ_l is the lower incomplete gamma function and Γ is the gamma function. Thus, based on the Neyman-Pearson test, the energy threshold can be selected to satisfy a certain false alarm probability.

After making their local decisions about the state of the primary user, the sensing components report their results to the common receiver. At the common receiver, an OR-rule can be applied to decide on the availability of the sensed channels [56]. However, the reporting channel is subject to errors due, for example, to interference, shadowing, flat-fading and/or frequency-selective fading [57], [58]. To solve this problem, special coding techniques can be used to report the sensing decisions [50], [51]. As mentioned earlier, three coding methods are proposed by [18] for three different situations. First, in the case of flat-fading channels between the sensing components and the common receiver, ST coding can be used to transmit the sensing decisions. To implement this coding scheme, the sensing CR's are grouped into clusters. Each cluster acts as a virtual MIMO antenna [50], [51]. For example, a possible ST coding can be described as:

$$\frac{1}{\sqrt{2}}\begin{pmatrix} D_1 & D_2 \\ -D_2 & D_1 \end{pmatrix}, \quad (4)$$

where D_1 and D_2 are the decisions of the sensing components in a cluster of two elements. Similar coding schemes can be applied to SF coding when the reporting channels suffer from frequency-selective fading. On the other hand, if signal relaying is employed, algebraic coding could be applied instead. In order to show the robustness of their model, the inventors of [18] showed, through simulations, that the use of ST, SF and relaying in cooperative sensing permits to exploit the diversity in the wireless channels and leads to a smaller error probability in the reporting channel.

VI. A Comparison of the Different Patents

In Table 1, we list most of the patents that were presented in this paper and we describe their main characteristics. We show the advantages and disadvantages of each of those patents when applied to the CR's. For instance, the inventions in [16], [19] present single-user schemes and do not incur control overhead among multiple CR's. However, they both require relatively complex algorithms to compute the wavelet transform coefficients. On the other hand, the inventions in [18], [24] use lower complexity algorithms (i.e. energy detection algorithm), but they incur control overhead due to their cooperative schemes. The invention in [17] has an intrinsic hardware difference, compared to the above inventions, since [17] proposes a dual-RF chain for designing CR devices. The advantage of this technique is in ensuring uninterrupted communication since one RF-chain can be responsible for performing spectrum sensing while the other chain performs communications. However, this invention suffers from high power consumption and RF interference between the two RF chains.

VII. Current and Future Directions

Due to the importance of spectrum sensing in CR applications, more advanced spectrum sensing inventions need to be developed to address the main challenges in this field. First, there is a need for more advanced spectrum sensing algorithms that will be robust against noise and interference. The MRSS techniques that were used in [16],

Patent	Sensing Method	Centralized/ Decentralized	Radio Architecture	Hardware Complexity	Advantages	Disadvantages
Hur et al. [16] US 7860197 B2	Wavelet Transform	Decentralized	Single-radio	Low	▪ No control overhead ▪ Robust to noise	▪ High computational complexity
Choi et al. [17] US 0100086010A1	Energy detection/ Matched filter	Decentralized	Dual-radio	High	▪ No control overhead ▪ Efficient communications	▪ High power consumption ▪ High hardware cost
Ben Letaief et al. [18] US 7965641 B2	Energy detection	Centralized	Single-radio	Low	▪ Solves the hidden node problem	▪ Control signals overhead
Woo et al. [19] US 7668262 B2	Wavelet transform	Decentralized	Single-radio	Low	▪ Robust to noise ▪ Wide-band operation	▪ High computational complexity
Sun et al. [24] US 20080261639	Energy detection	Centralized	Single-radio	Low	▪ User selection diversity ▪ Reduces power consumption ▪ Reduces reporting error	▪ Requires additional algorithms for clustering

Table 1: A comparison among the reviewed spectrum sensing patent

[19] help solve this problem by using wavelet detection methods. However, further investigations need to be made on similar sensing techniques, such as cyclostationarity-based detection.

Second, given the hardware limitations and their impact on spectrum sensing, new inventions might consider reconfigurable RF hardware in implementing CR platforms. Such architectures can help reduce the power consumption and the RF interference among hardware components while expanding the operation range of the CR (e.g. wider frequency bands, etc.). However, the feasibility of such reconfigurable RF hardware is yet to be demonstrated.

Third, new inventions should aim at achieving autonomous CR behavior by including learning and reasoning algorithms to the CR designs. Such algorithms can help improve the performance of the CR through artificial intelligence techniques [44].

Fourth, new spectrum sensing schemes must be able to operate over a wide frequency range in order to detect most of the spectrum opportunities. However, the implementation of wide-band spectrum sensing techniques is still a challenging problem since it requires high speed ADC's. Moreover, wide-band sensing antennas have low gain due to their inherent gain-bandwidth product limitations [59]. Thus, the received signal would have low SNR, which makes it harder to be detected.

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IX. CONFLICT OF INTEREST

The authors declare no conflict of interest.

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